

CRYSTAL SETS TO SIDEBAND

By Frank W. Harris, KØIYE

© Frank W. Harris 2002

© Frank W. Harris 2010, Revision 12.

FOREWORD

Dear Radio Amateur,

I began writing this book when I realized that my homebuilt station was almost unique on the air. For me, the education and fun of building radios is one of the best parts of ham radio. It seemed to me that homebrewing was disappearing rapidly, so I wrote articles about it for my local radio club newsletter. My ham friends liked the articles, but they rarely built anything. I realized that most modern hams lack the basic skills and knowledge to build radios usable on the air today. My articles were too brief to help them, but perhaps a detailed guide might help revive homebuilding.

I have tried to write the book that I wish had been available when I was a novice operator back in 1957. I knew that rejuvenating homebuilding was probably unrealistic, but I enjoy writing so I pressed on. I thought of myself as Don Quixote battling the windmills of modern apathy toward the details of technology and science in general. It seemed to be a hopeless quest. But even if it turned out that no one else cared, I found the project satisfying and extremely educational.

Modern book publishers don't print books that will have few readers. Because of its length and numerous color illustrations, this book would be expensive to put on paper. Not surprisingly, several publishers of electronics books had no interest in it. Fortunately, CDs cost no more than a postage stamp, so I began sending out CD copies with my QSLs to those radio contacts that showed an interest in my rig. It was great fun. I often got back thank-you letters and pictures of their homebrew equipment along with their QSL cards. Eventually, the book appeared on several websites and was even translated into Spanish.

This book has now been in circulation for 8 years. It is no longer new, so naturally interest has faded and some of the websites have dropped it. What I should be doing is continuing to build new designs and continually updating it. However, life must be lived in series and I seem to be spending more time hiking in the mountains than I do working on ham radio. My electronics projects these days are nearly all related to mountain rescue. As examples, as I'm writing this, I have several rope force dynamometers to modify waiting on my workbench and some data cables for our climbing equipment test tower that I need to rebuild. My mountain rescue work gets me out in the fresh air and in contact with people face to face. This is important for retired guys like me. I have added to two articles to chapter 16 about PIC programming and class D audio amplifiers that came from my rescue work but should also be interesting to hams. Sigh. Life is too short!

We homebrewers are nearly extinct, but there are still hundreds of us scattered around the world, some are even in the USA. Yes, there *ARE* American homebuilders! We're rare, but thanks to the QRP hobby, the number is growing. Even if we homebrewers don't change the

2.

world, I guarantee you will enjoy learning radio technology and building your own equipment. Someday I hope to meet you on the air ... or at least on the Internet. Hi!

73s, Frank Harris, KØIYE

Frwharris@live.com

CRYSTAL SETS TO SIDEBAND

A Guide to Building an Amateur Radio Station

By Frank W. Harris, KØIYE

© Frank W. Harris 2010, Rev 12

(Note: This document is in PDF format. If schematics and drawings appear to have insufficient resolution, increase the display magnification.)

Table of Contents

Chapter 1

THE FASCINATION OF RADIO

Exploring the shortwave bands

Growing up in the Morse code era

The joy of building it yourself

A brief history of radio communication

Henry, Maxwell, Hertz, Tesla, and Marconi.

Fessenden, Edison, Flemming, DeForest and Armstrong

The sinking of the RMS Republic and the birth of ham radio

Ham radio in the last 80 years

Becoming a radio amateur

Chapter 2

HOMEBUILDING AMATEUR RADIO EQUIPMENT

What qualifies as homebuilding?

When homebrewing is not appropriate

Barriers to modern homebuilding –

Time, frequency stability, and lead inductance

Basic electrical knowledge

Magnets and static electricity

Voltage, current, resistance, energy, and power

(Illustrated with drawings of water and mechanical analogies)

Conductors, Insulators, and semiconductors

Capacitors, inductors, transformers, and alternators

Home power distribution, transformers at low and high frequencies

Chapter 3

SETTING UP AN ELECTRONICS WORKSHOP

R&D as recreation

How to build radios (or anything else) in your basement

Persistence, read books, keep a notebook, and work in small increments

Minimum tools needed

The ARRL Amateur Radio Handbook

Soldering irons and small tools

Drills & thread taps

Wood carving gouges for making PC boards

>50 MHz Oscilloscope

Frequency counter

Quality multimeter

Lab power supply

Calculator

Lab notebook

Collection of electronic junk

Parts catalogs

Capacitance meter

Test leads and socket boards

Nice-to-have tools

RF and audio generators, spice software, and spectrum analyzer

Chapter 4

HERTZIAN WAVES IN THE BASEMENT

The nature of radio waves

Mechanical and LC electrical oscillators

Antenna and transmission line theory

Crystal set components

LC tuner

PN junction diode detectors

P-type and N-type semiconductors

Detection of AM signals

Homebuilding the parts for a crystal set

The Jamestown diode

The Caribou headphone

Revisiting Crystal Sets in 2006

Learning to troubleshoot

Selective tuning

Recreating Hertz's radio equipment

Transmitting and receiving as simply as possible

The 1880 ten-meter communicator

Proving that radio waves exist and aren't just capacitive or magnetic coupling

Demonstrating standing waves to measure frequency

Building homebrew transistors

Bipolar transistors, PNP and NPN

Demonstrating power gain

The Boulder Rock Radio

Chapter 5

GETTING ON THE AIR

- DECIDING WHAT TO DO FIRST

How to earn a license

The rules of the homebuilding game – Whatever makes you happy!

Picking an HF band

Getting acquainted with the HF ham bands, 160 – 10 meters + 6 meters

Instant high quality HF communications

VHF/ UHF handheld transceivers

Building an antenna

Dipoles, regular and folded

Multi-band dipoles

80 meters when you don't have room for a dipole

The curtain rod vertical

A multi-band vertical antenna

Lightning protection

Chapter 6

BUILDING A QRP HOMEBREW

A single-band, crystal-controlled, QRP module

The transmitter mainframe

HF construction methods

Making your own PC boards

“Dead Bug” and “Gouged Board” construction

Superglue “Island Boards”

Coax jumpers

Shielded boxes

The complete QRP crystal-controlled transmitter

Transistor amplifiers and oscillators

How an amplifier becomes an oscillator

Class A and Class C amplifiers

Stabilizing the operating point, bypass caps, and emitter resistors

Quartz crystals – the key to frequency stability

The 40 meter QRP circuit

Oscillator and buffer

Inductors, RF transformers, and impedance matching

Tapped toroid inductors

How to wind them (and mistakes you might make)

The final amplifier stages for the QRP

Tuned versus broadband - Use both for best results

Bifilar wound, broadband transformers

How to wind them (and how you might screw up)

Ferrite bead RF chokes, expensive RF power transistors, heat sinks, & output connectors

Conquering inductors

- Calculating resonance
- Calibrating trimmer capacitors
- Calculating turns on powdered iron and ferrite toroids
- Chebyshev output low pass filters
- Keying your QRP
 - MOSFET power transistors
- A “spot switch” for the QRP

Chapter 7

BUILDING A CODE PRACTICE RECEIVER

- A simple, direct-conversion receiver
 - A great first project for a new ham
 - Excellent sensitivity and good stability
 - Poor selectivity
- Adding 700 Hz audio filtering
 - High pass and low pass filters
 - Cascaded bandpass filters increase selectivity
 - Operational amplifiers
- Building with integrated circuits
- AM broadcast filter
- Getting rid of the image

Chapter 8

POWER SUPPLIES

- Line powered power supplies
- Power supply safety features
 - Isolation, 3-conductor cords, fuses, switches, ratings
- Supply performance and regulation
 - Rectification, ripple, chokes, capacitors, and bleeders
 - Zeners, linear regulators, switching regulators
 - A QRP regulated power supply
- A battery power supply for the radio shack
 - Solar cell charging, low drop-out regulators
 - Battery powered shack lighting

Chapter 9

ACCESSORIES FOR THE TRANSMITTER

- A straight key
- An electronic bug
- Building dummy loads
- “T” type antenna coupler
- A low pass filter
- How to stay legal with a homebrew transmitter

Antenna and power relays
Homebrew QSL cards

Chapter 10

VARIABLE FREQUENCY OSCILLATORS

Drift is a big deal today
Low frequency VFOs drift less than high frequency VFOs
JFET transistors
The oscillator circuit
The buffer, final amplifier, and output filter
The 50 secrets of avoiding drift

- JFETs, single-side PC boards, cast metal box, multiple NPO caps, small variable caps, precision voltage regulation, and more

 Vernier tuning
Varactor tuning elements – advantages and disadvantages
A precision power supply
A voltage doubler power supply for battery use

- Square wave generator with a multivibrator
- Squaring up the square wave
- Charge pump, diode/ capacitor voltage doubler
- Schottky diodes for efficiency

 Temperature compensation methods

- Positive coefficient capacitive trimmer compensation
 - How to adjust the compensator
- Thermistor/ varactor temperature compensation

Chapter 11

Building a VFO for the higher bands (PMOs)

Old approaches that no longer work

- Frequency multiplication
- High frequency oscillators

 Pre-Mix Oscillator method of frequency translation
A VFO-controlled QRP module
Crystal oscillators are stable, aren't they?

- Crystal oscillator circuits
- Butler oscillators and big crystals

 Mixers, bipolar transistor and dual-gate MOSFET

- Optimum drive requirements
- Direction of tuning, drift error cancellation

 Multistage filters and filter/amplifiers
The QRP final amplifier stages
Spot switches for PMO QRPs

Chapter 12

FINAL AMPLIFIERS

The basic features of a modern linear power amplifier

It looked easier in the Handbook

- Linear “noise mode” operation

A tuned 50 watt class B amplifier

- Ferrite balun transformers

An untuned, sort-of-linear, class B, amplifier

- Keying the 50 watt transmitter

A linear Class AB amplifier, this time for sure

- Single Sideband (SSB) needs a linear

- Biasing without thermal runaway

- Clamp diodes prevent runaway

- Mechanical construction

Chapter 13

BUILDING A HOMEBREW HF RECEIVER

Building a receiver - an unusual adventure

What’s a reasonable goal?

An “adequate performance” HF communication receiver

Does it have to be so complicated?

Planning your receiver

- Direct conversion versus superhetrodyne

- Why not single conversion?

- Start with a single-band, single-conversion superhetrodyne

- How do modern digital receivers do it?

Receiver construction – build with shielded modules connected by thin coax.

The 80 meter preselector

- Reception on 80 meter and 160 meters is aided by a tuned transmatch

The Variable Frequency Oscillator

Mixer magic

- Mixers will give you lots of static – and howls and squeals

- A practical homebrew mixer made from discrete parts – it’s harder than it looks

- Dual gate MOSFET mixers

- Not all MOSFETS work equally well

- A JFET alternative mixer

Crystal ladder filters – essential for CW

- All 9.000 MHz crystals aren’t equal

- Using the BFO oscillator to match crystals

- Switch in filters with a rotary switch

The IF amplifier

- Lessons learned from a dual-gate IF amplifier

- The cascode amplifier strip - variable gain with constant Q

Automatic Gain Control (AGC) - not a luxury

- The product detector
 - Nearly anything works at least a little
- The AF amplifier – a vital part of the signal dynamic range
 - Protecting your ears from strong signals
 - How Hi-Fi should it be?
 - Driving a speaker
- HF converters for the other ham bands
 - Crystal oscillators
 - Band switching
- Receiver power supplies
 - Use a linear regulator, not a switching regulator

Chapter 14

OLD-TECH VACUUM TUBE RADIO

- How old can radio technology be and still be used on the air today?
- Why bother with vacuum tubes?
 - Glowing filaments, colored plasmas, and Jules Verne glass envelopes
- Power supplies for tubes
 - High voltage power supply safety
- The old-tech QRP transmitter
 - Vacuum tube amplifiers
 - The three roles of the triode filament
 - RF sinewave oscillator
 - Quartz crystals
 - Triode and pentode oscillators
- Old-tech voltage regulation – big, crude, expensive, but beautiful
- The travails of triode tubes
 - The oscillator and buffer
 - The final amplifier – triodes chirp
- The transmitter power supply
 - An inadequate supply from a 1935 radio
 - A good power supply made from cheap, modern, boring parts
 - How to check out junk power transformers
 - A complex but adequate supply made from ancient parts
- It works! No one suspects it's old and it's a success on today's 40 meter band
- An old-tech receiver
 - A super regenerative receiver made from ancient tubes
 - The power supply
 - Super-regen on the modern hambands
 - Lots of fun, but not up to modern QRM & QRPs - back to the drawing board!

Chapter 15

THE NOBEL PRIZE FOR SIDEBAND

It can't be that hard! Want to bet?

8.

The sideband generator – how it works

The 9 MHz oscillator / amplifier

The audio amplifier

The balanced modulator

Building your own crystal ladder filter

Decoupling the power supply leads

Getting rid of RF feedback - RF filtering for all inputs

Tuning and testing

Using the generator for AM modulation and CW

Moving the 9 MHz SSB signal to a hamband

Move the SSB only once!

No wonder most ham rigs are transceivers

Moving the 9 MHz signal to the difficult HF hambands

Move the VFO first, then mix it with the SSB 9 MHz.

Pick your oscillator and VFO frequencies carefully

Hearing your own VFO in the receiver

The hardest band – 17 meters

40 meters and 12 meters

Covering the widest band – 10 meters

A linear sideband QRP, VFO-tuned module

All stages must be linear and low distortion

All gain stages should be broadband to prevent oscillation

Sometimes high pass filter output is needed and not the usual low pass

Checking out the generator

Driving a 50 watt linear amplifier

Chapter 16

ANCIENT MODULATION & OTHER TOPICS

Defining amplitude modulation

AM modulation for vacuum tube final amplifiers

Plate, screen, & cathode modulation

A "collector modulator"

Converting a MOSFET keyer into an AM modulator

Generating AM with an SSB balanced modulator

Compensating for non-linearity

Compression by accident

You probably don't need to build a voice compressor

Ham TV - The old way.

Fun with an ancient flying spot scanner TV camera.

Getting on 60 meter sideband – lots of work, little reward

PIC programming and class D audio amplifiers

In conclusion,

Homebrew ham radio is never complete - when it works perfectly and does all the latest stuff, the hobby is over. Not likely. Long live homebuilding!

CRYSTAL SETS TO SIDEBAND

A guide to building your own amateur radio station

By Frank W. Harris, KØIYE

3850 Pinon Drive
Boulder, Colorado 80303-3539

© Frank W. Harris 2010, Rev 12

Chapter 1

THE FASCINATION OF RADIO

Radio produces action at immense distances with no physical connection that can be perceived by our senses. A modern way to demystify radio is to say that radio is simply a kind of light that our eyes cannot see. To those of us addicted to shortwave radio, it's an adventurous realm that can be explored. When we listen to our radio receivers it is comparable to using the Hubble telescope to explore the heavens. Shortwave is fascinating because you can't predict what you are going to hear. You might hear a radio broadcast from an exotic foreign capitol. You might pick up an SOS from a ship sinking in a storm or maybe weather reports from a radio amateur on Pitcairn Island. The next evening the same frequency band might be completely empty except for two hams on the other side of your own town discussing the Super Bowl. Or you might receive coded messages intended for some undercover spy lurking in our country.

I'm not kidding. I routinely hear such coded messages consisting of groups of letters on the 10.1 and 28.1 MHz ham bands. The codes are usually sent in Morse code, but sometimes you will hear a voice reciting the letter groups. Sometimes the woman announcer finishes by saying, "Thank you for decoding this message!" Since hams are forbidden to use codes or modulation modes that are not easily decoded, these communications are at least illegal.

Yes, it's true that shortwave isn't as vital to world activities as it once was, but if there's any romance in your soul, shortwave is still entrancing and always will be. This book is about using amateur radio to recapture the adventure of early day radio and bring it into the present. It is also about learning electronics and radio technology. If you can get through this book, shortwave radio will still be fascinating, but no longer mysterious.

Admiral Byrd at the South Pole

I first became intrigued by shortwave when I read Admiral Byrd's book on his last expedition to the Antarctic. Admiral Richard Byrd was in the business of launching expeditions to explore the Earth's poles. These expeditions had no inherent commercial value except for book sales and sponsoring grants from companies hoping to gain visibility for their products. In order for Byrd to get those grants, the public had to be sufficiently interested in the expeditions to generate advertising value. With each polar expedition, finding new expedition goals that would be exciting to the public became increasingly difficult. Studying rocks, glaciers, and penguins was scientifically important, but not particularly interesting to the public. By the 1940's all the

2. Chapter 1, Harris

neat stuff, like walking to the North and South Poles had been done decades before.

On his last expedition to Antarctica, Byrd established a base on the Antarctic coast like all previous large expeditions. However, he succeeded in maintaining public interest by setting up a tiny second outpost on the polar icecap hundreds of miles south of the coast. Then he attempted to spend the Antarctic winter alone in his little under-snow cabin totally isolated from the world in the cold and dark. His one connection with his base camp at “Little America” and the outside world was Morse code radio contact. Other than producing some interesting weather reports, the outpost had little real value. However, it did attract attention. Who could help but be captivated by the ordeal of a man totally isolated, hundreds of miles from the nearest humans? It was like being marooned on the moon, utterly alone.

Byrd’s messages were relayed from his big base back out to the rest of the world. As a boy I was fascinated by Byrd’s lonely vigil. I imagined what it would be like to be shut off from the world for months on end. I pictured Byrd bundled up in a fur parka huddled over his little table sending and receiving Morse code. His connection with the world was reduced to musical notes barely audible above the soft purring static of the polar night. The Morse tones came into his headphones and he wrote down their meaning, one letter at a time. The decoded messages appeared on his pad, one word at time. He fumbled with his pencil. “Was that a ‘C’ or a ‘K?’” he asked himself. He pushed his indecision aside and kept writing down new letters. Fretting about one letter can destroy the whole sentence. A radiotelegraph operator learns to focus on the stream of characters and not dwell on each one.

After a few weeks in his frozen prison, Byrd began to suffer from headaches, nausea, weakness, and confusion. His Morse code became harder and harder to read and his team back at Little America became greatly concerned. Unknown to Byrd, his cabin heater was leaking carbon monoxide and was slowly killing him. Finally, when Byrd’s condition became desperate, his crew drove hundreds of miles over the ice cap through winter darkness, howling wind, and below zero temperatures to rescue him.

Growing up at the end of the Morse code age

As late as 1960, Morse code was still commonly used commercially and by the military. Since Morse code had an exotic sound, news broadcasts were routinely introduced by snippets of code. When the word “NEWS” is spelled out in Morse and repeated rapidly, it makes a pleasant, rhythmic, musical phrase that blends in well with Hollywood-style introduction music. The public often assumed that messages from the other side of the world arrived by Morse code, although in reality its importance had been fading since the 1930s.

The Morse code used for radio communications in the English language

The “dashes” are three times longer in duration than the “dots.”

A . _	G _ _ .	M _ _	S . . .	Y _ . _ _
B _ . . .	H	N _ .	T _	Z _ _ . .
C _ . _ .	I . .	O _ _ _	U . . _	
D _ . .	J . _ _ _	P . _ _ .	V . . . _	

3. Chapter 1, Harris

E . **K** _ . _ **Q** _ _ . _ **W** . _ _
F . . _ . **L** . _ . . **R** . _ . **X** _ . . _

Numbers and Commonly Used Punctuation

1 . _ _ _ _ **3** . . . _ _ **5** **7** _ _ . . . **9** _ _ _ _ .
2 . . _ _ _ **4** _ **6** _ **8** _ _ _ . .
Ø(zero) _ _ _ _ _ **(, comma)** _ _ . . _ _ **(. Period)** . _ . _ . _ **(/ slash)** _

When I was a kid in New Jersey, my closest friend was Garth McKenzie. My introduction to ham radio was through his dad, Alexander (“Mac”) McKenzie. Mac’s call letters were W2SOU and his radio station was crammed into an alcove off the dining room. In the 1940s, quality radio equipment was packaged behind somber black aluminum panels 22 inches wide, eight inches high, and mounted in tall racks. The controls were enigmatic black knobs with strange labels like “grid drive” and “loading.” The displays were usually just meters with equally arcane titles such as “S-meter” and “plate current.”

The McKenzies had a cabin up in New Hampshire. Mrs. McKenzie and the kids spent most of every summer up at the cabin. Mac went up to New Hampshire on weekends when he could, but most of the time he stayed in touch with his family by radio. A friend of Garth’s dad, Mr. Henny, lived near the McKenzies’ cabin. He was also a ham, so on Saturday mornings Mac had a regular schedule to talk with Mr. Henny using Morse code, or CW (continuous wave) as it is still known. I was intrigued when I heard about these scheduled contacts and wanted to see Mac operate his station. I arrived at the McKenzie house at the appointed time. Sure enough, right on schedule, Morse code appeared out of the static. Mac wrote down the letters on a pad. I watched over his shoulder and stared at his pencil tip. It was mesmerizing to hear the code and watch the words and sentences appear on the paper. Unfortunately I couldn’t understand even one letter of what Mac was sending, so I quickly tired of the one-sided conversation. In spite of that, Morse code had a mysterious, other-world quality and I was hooked.

Among the other equipment in Mac’s radio shack was a Loran set. Loran was a long-range direction finder, the 1950 version of today’s global positioning system (GPS). Mac demonstrated for me how to find latitude and longitude using a tiny green oscilloscope screen. The little round screen was only 2 or 3 inches wide and peered out from another one of those black, 22-inch wide black rack panels. Mac had it set up just for fun, of course. The Loran was designed for use on a ship and the McKenzie’s house certainly wasn’t going anywhere. Other toys included a pair of war surplus teletype machines. He could type on one machine and the other would print out his message 5 feet away.

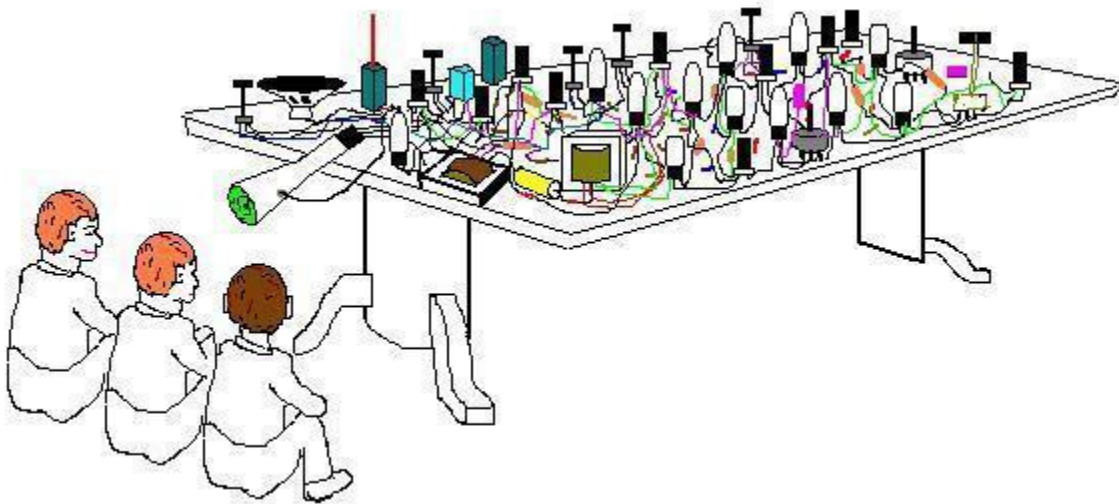
The joy of building it yourself

It was hard for an eight year old like me to imagine getting a ham license and affording all that massive equipment. The Loran was quite alien to me and the teletype machines were interesting, but seemed like clumsy typewriters. What turned me on was Mac’s television set. In

4. Chapter 1, Harris

the late 1940s, television stations were on the air, but no one I knew other than Mac actually owned a TV. That wasn't surprising. TVs cost as much as an automobile. Talk about a luxury! Undaunted, Mac built his own television from old radio parts and an army surplus, five-inch diameter, green oscilloscope tube.

A real, white phosphor, (black and white) TV cathode ray tube cost a fortune back then, so Mac couldn't even afford the picture tube. And because the TV tubes were designed for magnetic deflection and the oscilloscope tube used electric deflection, Mac couldn't just copy the deflection circuits from an RCA TV. Instead, he had to design his own custom picture tube drive and sweep circuits. Perfecting a new circuit meant that it had to be built and tested one small piece at a time. Since Mac had little idea how large the final circuit would be, he couldn't assemble his TV in a cabinet right away. Instead, he built his TV as a giant "breadboard" circuit with all the glowing tubes, wires, resistors, transformers, capacitors, and components all laid out in a huge spider-web matrix.



A TV is extremely complicated and a large breadboard was needed. Fortunately Barbara McKenzie was a tolerant woman. For several months the dining room table, including the extension leaves, was completely covered with about four by eight feet of television circuitry. Then Mac moved it upstairs into the master bedroom - probably not much of an improvement from Barbara's perspective. Toward the end of the year the TV began to work. We kids used to come home from school and sit on the floor and watch programs on the tiny five-inch round picture tube dangling off the end of the table. The pictures were in living "black and green." We watched "Zoo parade" with Marlin Perkins and our favorite program, "Flash Gordon," an early Star Trek-like show. TV was different back then. Flash Gordon was 15 minute film clips but most other programs were live. Even the commercials were live. I remember laughing silly over a commercial for a vacuum cleaner in which the fellow plugged the hose into the wrong end of the cleaner. The machine blew dust all over the room while the announcer tried to pretend it was working perfectly.

Eventually Mac installed his TV in an old record player cabinet. To make the picture larger, he put a big magnifying lens in front of the screen. When he watched TV, he propped up

the hinged lid of the cabinet at a 45 degree angle and watched the enlarged picture in a mirror mounted on the underside of the lid. Mac showed me that, with patience, you can build almost anything. And, in the long run, it's usually much more rewarding to build a possession rather than to buy it. He also taught me that projects must be built and tested one tiny part at a time. *If you build it all at once without testing the parts as you go, it might fit in the cabinet, but it almost certainly won't work.* There are very few short cuts.

The complete radio amateur

This book is about building ham radio equipment. To be sure, it's much, much easier to buy the equipment. In fact, commercial ham equipment today is so cheap, that buying it is far less expensive than buying the parts one at a time. The good news is that equipment you build yourself will have a value and meaning for you that can't be purchased. Along the way you'll learn more about electricity than you will ever learn reading the operator's manual of commercial equipment. Most of us will never be an Edison, Marconi, or Armstrong, but we can learn what they knew and we can share some of the thrill they felt when their inventions began to work. When your homemade station is finally on the air, you'll have all the same fun the other hams are having. But unlike the rest of the herd, you will be "*The Complete Radio Amateur.*"

A brief history of radio communication

Radio is based on phenomena that have been known since ancient times, namely static electricity and magnets. These phenomena also produce action at a distance with no visible connection, but only over extremely short distances. In 600 BC the philosopher Thales of Miletus described how, after rubbing amber with cloth, the amber could attract bits of straw. At about the same time the Greeks observed that natural magnetite ore (iron oxide, Fe_3O_4) could attract other bits of magnetite rock. This strange rock was found in a region of Turkey then known as "Magnesia," hence the name. Knowledge of natural magnets eventually led to the discovery of the magnetic compass. Compasses were a Godsend to sailors lost in fog and must have seemed magical to those who first used them. The compass was in wide use in Europe by 1000 AD.

Magnets and electricity appeared to be separate phenomena until 1820 when Hans Christian Oersted noticed that an electric current in a wire generates a magnetic field that can move a compass needle. Faraday and Henry studied and quantified the generation of magnetic fields produced by coils of wire that we now call "inductors." In one of the all-time greatest triumphs of theoretical physics, James Maxwell published four equations in 1864 that summarized the connection between magnetism and electrical force. Maxwell's equations not only quantified and connected what was already known about these forces, they also predicted that magnetism and electric force could be combined to form a free-flying radiation. From the equations it appeared that these radio waves should be able to propagate great distances through space, much like light and heat. He may or may not have known that light and infra-red heat are also forms of electromagnetic radiation - radio!

What exactly is a radio wave?

An electric field and a magnetic field can both temporarily store energy in free space. For example, a refrigerator magnet generates a magnetic field in the space surrounding it. This magnetic energy hovers in "cloud" or "field" surrounding the metal magnet. Similarly, electric

6. Chapter 1, Harris

field energy is present in the space between the terminals of an ordinary flashlight battery. Suppose that magnets and charged batteries were sent into outer space and turned loose to float in the void. These devices would still generate their magnetic and electric fields in the vacuum surrounding the devices. However, if the devices could suddenly disappear, the magnetic and electric fields would not be maintained. The fields would quickly collapse and the energy would dissipate in all directions at the speed of light.

A battery or a magnet can be compared to a glass of water on a table. The glass holds the water in place and the water will rest there indefinitely. But if the glass were to suddenly break or vanish, the water would flood out in all directions. If either a magnet or battery floating in free space could be made to suddenly disappear, it would generate a radio wave that would propagate outward in all directions making a spherical shell of expanding waves. It turns out that ***collapsing magnetic field energy in free space is converted into electric field energy***. Then, ***a moment later, the electric field energy similarly collapses back into a magnetic field***.

One way to look at it is that the collapsing magnetic field forces the storage of that same energy as an electric field in neighboring space. In other words, a collapsing field becomes a “device” that establishes the opposite kind of field in adjacent space. The end result is a wavefront of energy propagating across the void. As it travels, the energy oscillates back and forth in its form between electric and magnet fields. In the vacuum of space there is no dissipation of the original energy except that the energy becomes more dilute as it spreads out in all directions like ripples from a stone thrown into a pond.

The water analogy has other similarities with radio waves. The crests of the ripples on the pond represent the storage of mechanical energy as ***potential energy***. The potential energy is proportional to the height of the ripples or waves. The higher the wave, the more energy it stores. As the water falls back down, the energy from this descent is converted into ***kinetic energy***, that is, the outward velocity. As the wave spreads outward, the water stacks up to form another wave crest, restoring the energy to its potential energy form.

In 1887 Heinrich Hertz, a professor at the University of Bonn, Germany, managed to demonstrate in his laboratory that Maxwell’s radio waves actually existed. From then on other experimenters built “Hertzian apparatus” and tried to use it for communication or remote control. Experiments much like the ones Hertz performed are described in Chapter 4. Using rocks, copper wire, iron, and other materials available in 1880, you can build a short-range communicator to send and receive radio waves from one end of your house to the other. You can even demonstrate “standing waves” on an antenna.

How inventions happen

Big inventions usually begin with a novel observation. Faraday first invented the AC transformer with independent coils. An alternating current (AC) introduced into one coil on the transformer causes a second current to appear in a tightly coupled similar coil a fraction of an inch away. Today we still routinely use transformers to convert the ratio of current to voltage. For example, inside your flashlight battery charger, there is a transformer that converts a tiny current at 120 volts AC into a large current at 1.5 volts AC. If you applied 120 volts directly to your battery, it could be disastrous. Chargers would be quite impractical (or at least horribly inefficient) without transformers. We shall discuss these principles in detail in later chapters.

7. Chapter 1, Harris

Getting back to Faraday, he must have marveled when he thought about the implications of electrical energy fed into one coil appearing in a neighboring coil. That is, the energy was “transmitted” across a gap. Yes, the gap may have only been a fraction of an inch, but certainly the thought must have occurred to him, “how far can it transmit?” In a letter in 1832 he proposed to a friend that electric energy could probably travel through space as waves. Unfortunately, he had no evidence, experiments, or equations to support this idea.

Many early radio communication experiments began when the first high frequency transformers were made. Unlike low frequency, like our 60 Hz line current, high frequency transformers of 500 KHz and above readily couple energy several inches through air. High frequency currents couple from one coil to another and begin to resemble radio.

It’s surprisingly easy to build a high frequency transformer and demonstrate crude, short-range radio communications. All that’s needed is a powerful battery, a large coil of wire, and a second coil wrapped around the first coil. The second coil is arranged so that the two ends of the wire are fixed a tiny distance apart, perhaps a sixteenth of an inch. The two ends of the first coil of wire are scratched transiently across the terminals of the battery. Huge currents flow in the first coil and establish a magnetic field around that coil. Since the same space is shared with the second coil, the magnetic field induces voltage across the second coil and a spark appears in the gap on the second coil. In other words, electric current was converted into magnetic energy, jumped across a short distance and then was reconverted back into electrical current. Now if the two coils are moved far apart, there will continue to be energy transmitted from one coil to other. However, with such a crude detection system, a spark probably won’t be visible and a much more sensitive detector would be needed to prove that energy was actually transmitted.

Inventions appear when all the conditions are in place

New technologies appear whenever the necessary knowledge and affordable raw materials become available. For example, cell phones could have been built 50 years ago, but they would have been the size of suitcases, served few people and would have only been available to the most wealthy. Even today it’s possible to introduce useful technology too early to be profitable. The Iridium phone system is a world-wide direct satellite telephone system. Unfortunately, the Iridium “phone” is big and clumsy and the phone calls cost a fortune. Sure, you can reliably talk to a guy on dog sled at the North Pole, but there aren’t many people who actually need to do that. As of 2008 the Iridium satellites were still working, but five years ago there was talk of Iridium going bankrupt and crashing the satellites into the Pacific Ocean.

Radio was invented between the years 1884 and 1910 at a time when all the pieces to make it practical were in place. Many inventors had the chance to pursue radio communication, but most turned it down. To be more than a parlor trick, radio had to have a commercial reason for its development. The concept of broadcasting voices, music, and even motion pictures to the masses seems obvious to us now. But in 1900 it wasn’t obvious that radio could be more than an unreliable way to send telegrams. Hardly anyone back then imagined that speech and music might be transmitted.

Nicola Tesla, the archetype “mad scientist”

Nicola Tesla was born in Smiljan near Gospić in Croatia in 1856. In college he studied what was then the exotic field of electrical engineering. He once proposed to his professor that

an AC generator could be built that would be simpler than DC power generation and which would have several other advantages. The professor ridiculed his idea mercilessly. Today we call these “alternators.” We use gigantic alternators to generate electricity in all large power plants. And we use little ones in our cars to recharge our batteries. When his father died, Nicola was forced to leave school and go to work. Like most electrical engineers of his time, he worked on DC motors and DC generators. At that time the DC motor was beginning to replace the belt and pulley as a means of powering industrial machinery such as looms and mine hoists.

Tesla migrated to America and arrived almost penniless. He even worked briefly as a ditch digger in order to eat. He applied for work with Edison who tested his skills by assigning him to fix a DC generator on a ship. Tesla rebuilt the generator right on the ship and made it produce more electricity than its original design. Tesla worked briefly for Edison, then he struck out on his own. He built his own small laboratory and worked on gadgets of all sorts. He soon acquired a reputation as a “science wizard.” He enjoyed putting on “magic shows” with giant sparks flying off his fingers and whirling fluorescent light bulbs. His reputation as a science magician encouraged him to put show business into everything he did. After reading his biography, it appears to me that his ability to gain awe and respect through showmanship eventually ruined his career. (1)

As money ran short, Tesla got a job with the Westinghouse Company and developed the alternator into a practical power generator. Tesla’s greatest contribution to the world was the power generation and distribution system which he demonstrated at a brand new power plant at Niagara Falls, New York. He invented the three phase AC alternators, transformers, and high-tension power lines that are still in use world-wide. After Tesla left Westinghouse, he set up his own laboratory in New York City to experiment with uses for radio frequency current.

The missed opportunity

Ship owners have probably always wished they could communicate with ships at sea. Until the late 19th century the fate of a ship might be totally unknown for months or even a year. When the ship finally sailed into homeport, the owner might suddenly learn that he was extremely wealthy. Or the ship might never return and the owner would have lost a huge investment. Being able to communicate a few hundred miles or even a dozen miles out to sea might be life saving in an emergency.

By 1900 scientists knew that “wireless telegraph” could communicate across the English Channel using giant transmitters and antennas, but no one had been able to transmit a message much farther than that. At that time J.P. Morgan was a financier and banker and one of the richest men in the world. Among his empire of enterprises he owned a fleet of ships. If a practical long-range telegraph could be developed, he wanted it on his ships. Marconi already had a good start on a ship-to-shore radio and had already demonstrated short-range ship-to-shore communication, both in England and America. In spite of that lead, Morgan approached Tesla who certainly had the knowledge and experience to develop practical radio communications. J.P. Morgan gave Tesla a big financial grant to do this work. Tesla set up a laboratory in Colorado Springs to invent long distance radio, or so he allowed Morgan to believe.

Unfortunately, merely talking to ships was boring to Tesla. Tesla wanted to develop what he called “The World Telegraphy Center.” Tesla planned to set up a communications center that could not only talk to ships, but also to everyone else on earth. His vision of what he was trying

9. Chapter 1, Harris

to build sounds to modern ears like a one-way Internet or perhaps CNN. He doesn't seem to have thought about the difficulties of handling all the messages in the world through one single gigantic low frequency transmitter. Back then, there were no Internet servers to organize all that message traffic into digital streams of information. Considering the operating frequency of his transmitters, his data rate would have been limited to a few kilobytes per second rather than the terabytes handled today by a single node on the Internet.

Tesla's radio transmitters were certainly adequate for transoceanic communication. But instead of also developing a sensitive radio receiver, Tesla spent nearly all his effort developing ever larger low frequency radio transmitters. His transmitters were so powerful, he experimented with transmitting electric power as well as information. Tesla proposed using tuned coils to energize fluorescent light bulbs miles away from his transmitter. Yes, his idea worked, but only at an extremely low efficiency. Yes, the lights glowed just as he said, but damp soil, cows, people, barbed wire fences, and every other electric conductor within range would be heated with wasted energy, just like a microwave oven.

Tesla built an enormous "Tesla coil" that produced radio frequency sparks 60 feet long. Always the showman, Tesla liked to be photographed sitting among the sparks and fire, while calmly reading a book. Actually, he used double exposures to create the illusion of sitting among the sparks. Tesla's machine was so huge and had such unique capability that the U.S. Air Force built a copy of it 80 years later for research.

With all this dramatic futuristic activity, Tesla never got around to building the dinky ship-to-shore radio that Morgan was paying him to develop. When he gave Morgan a progress report, Tesla tried to sell Morgan on his futuristic schemes. Morgan was furious at him for not sticking to the assignment and had little interest in any of Tesla's ideas. Morgan did however force Tesla to assign him the ownership of any useful patents that might arise out of the work. Morgan was not known for generosity.

After Morgan gave Tesla a tongue lashing, he also gave him a second chance. But instead of getting serious about ship-to-shore communication, Tesla blew the money on building his "World Telegraphy Center" out at Wardencliff, Long Island, New York. It was an imposing building with a huge tower housing the Tesla coil transmitter. The communications center came to nothing and Morgan stopped the funds. Thereafter Tesla lived at the Waldorf Astoria Hotel in New York City and became a sort of self-absorbed lounge lizard. He dressed in a Tuxedo and top hat and mooched off his friends.

In the following decades Tesla dabbled in inventing and came up with several interesting devices that were almost good enough to become standard technology. For example, he designed a "bladeless turbine" heat engine, the functional equivalent of a steam engine or the internal combustion engine. There are few successful heat engine designs that are fundamentally different, so inventing a new one was an intellectual triumph. Unfortunately, Tesla's heat engine was not as efficient as other methods and, so far, there have been no good uses for it. He also developed a speedometer gauge that was excellent and was used in several luxury cars. Converting the speed of a rotating shaft into smooth, linear needle movement is much harder than it looks. Unfortunately Tesla's method was more expensive than the meter design that eventually became universally used for that purpose.

Tesla ended up as a lonely old man feeding pigeons in a third rate hotel in New York.

After he died in 1943, it turned out that he had paid his rent for several months by giving the hotel manager a “death ray” to hold as collateral. Tesla told the manager the death ray was worth \$10,000. The ray gun was actually a Wheatstone bridge, a sensitive resistance-measuring device commonly found in electrical labs.

Marconi gets the job done

Guglielmo Marconi was born into a prosperous family in Bologna, Italy on April 25, 1874. He was educated in Bologna then later in Florence. He studied physics at Leghorn College. He was fascinated by Hertz’s discovery of radio waves and he became interested in wireless telegraphy in 1890. Starting in 1894, Marconi worked at home building prototypes in his basement.

Today most of us think of a radio receiver as a kind of amplified stethoscope that lets us listen in on the hidden world of the radio spectrum. In Marconi’s time the main precedent for radio was telegraphy. This concept of one telegraph operator banging out telegrams to another operator using Morse code dominated Marconi’s vision of what he was trying to build. In conventional telegraphy the signal over the wire triggered a “sounder” which was a kind of electro-magnetic relay. The sounder made clickity-clack noises that the receiving operator interpreted as dots and dashes.

Similarly, Marconi’s first radio transmission to another room in the house rang a bell when the signal was detected. There were no headphones that a person listened to. Most early experimenters built radios that resembled radio control systems rather than listening devices. As the technology developed, the radio operator gradually became a vital part of the system. The operator’s skill and trained ears became responsible for most of the range and practicality of the system. A trained operator can hear Morse code signals that are no stronger than the atmospheric static. Unlike a simple bell system, an operator can copy one Morse code signal while ignoring another. It took a hundred years for computerized digital signal processing to exceed the ability of a trained radio operator and return to Marconi’s vision of a robotic receiver.

Radio detectors – An early challenge

The most popular early radio detector, the “*coherer*,” was invented by the English physicist Lodge. Coherers were first used with long distance wire telegraph lines. They greatly extended the practical range of a telegraph wire and it was natural that they would be applied to the earliest radio experiments.

A coherer was a small glass vial containing loose powdered carbon or iron filings. This powder contacted two electrodes in the vial. When a small voltage appeared across the powder, it would break down the contact resistance between the powder granules and cause the resistance of the coherer to suddenly drop. The decrease in resistance was used to cause current to flow through the sounder relay. Coherers were often built onto the frame of a sounder so that the vibration of the sounder would keep the powder loose, thereby continually resetting the coherer to its original state.

The set - reset action of a coherer resembles a modern silicon controlled rectifier. A small input current causes a much bigger current to flow. Unfortunately, just like a silicon-controlled rectifier, the current through the coherer doesn’t shut off by itself when the input is turned off. Because coherers turned on and off at rates below 20 cycles per second, the output

11. Chapter 1, Harris

from a coherer wasn't an audio signal that someone could listen to directly.

At first Marconi's receiver sat on the table next to the transmitter. Then he was able to transmit across the room and then to other rooms in the house. As his range increased, he moved his operation into an unused granary behind his parents' house where he could string up antennas. His next triumph was a transmission from the granary to the end of the garden, 100 meters away. During these years the existence of radio was widely known to scientists, but it was believed that radio waves were inherently line-of-sight, much like a signal lantern. Marconi had already observed that he was able to transmit to the receiver when it was behind walls and trees. Since he already knew the experts were wrong, he worked on the big question of whether radio waves could travel over mountains and perhaps over the horizon.

About this time Marconi must have graduated from coherers to some kind of rectifier detector. This detector produced an audio output that an operator could listen to directly with earphones. The earphone was already in use as a component in Alexander Graham Bell's telephone. The earliest rectifiers consisted of "crystals" which consisted of a piece of wire pressed against a crystalline chunk of sulfide ore. Crystal detectors are described in detail in chapter 4.

Marconi had a servant named Mignani. To test his receiver over distances, Mignani manned the receiver while Marconi sent test signals. One of Marconi's breakthrough improvements was a directional antenna that focused his weak transmitter output directly toward the feeble receiver and thereby extended the range. Radio stopped being a toy the day that Marconi transmitted a test signal two miles over a hill. Mignani signaled back to Marconi that he had received the Morse code letter "S," by firing a rifle into the air from the hilltop.

Radio reaches across the Atlantic

Following the success of his experiments at home, Marconi became obsessed with the possibility of transmitting a signal across the Atlantic. If he could do that, radio communication could cover the world. There was essentially no interest in radio in Italy. He was even unable to get a patent for his device. An Italian government minister told him that radiotelegraphy "was not suitable for communications." Marconi moved to England where he patented his method of transmitting signals in 1895. In 1897 he was financed by the British Post Office to continue his experiments. Gradually the range of his transmissions was extended to 8, 15, 30, and 100 kilometers. In 1897 he founded the Marconi Wireless Telegraph Company, Ltd. in London. In 1899 he established a communications service across the English Channel.

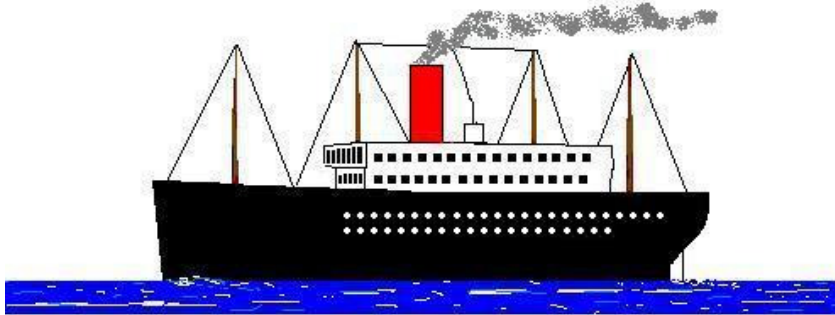
Marconi built a huge transmitter, 100 times more powerful than any earlier transmitter, and set it up at Poldu, Cornwall in South-west England. One approach to building very large transmitters was to construct large, high-speed AC alternators. These resembled Tesla's power generation alternators but ran at such high speeds that they produced a sinewave, not at 60 cycles per second like a modern power plant, but at low radio frequencies, 20,000 cycles per second. Marconi also built a complementary station at St. Johns, Newfoundland and on December 12, 1901, he received the first signals from across the ocean. Actually, modern analysis of the propagation conditions of that first communication suggests that the guys listening to the static may have been imagining Morse code that wasn't really there hiding in the hiss and crackle. Even if the first reports may have been premature, Marconi's team soon established real communication.

12. Chapter 1, Harris

The British and Italian Navies promptly adopted his system and ship-to-shore radio became reality. By 1907 his system was available to the public as a transatlantic radio telegram service. Marconi was awarded the Nobel physics prize for 1909. In his later life he continued to experiment with short waves and microwaves. Marconi also briefly served as a statesman. He was sent as a delegate to the Peace Conference in Paris after World War 1 where he signed the peace treaties with Austria and Bulgaria. He died in 1937.

Radio changes history

Until radios were put on ships, radio communication didn't make much difference to the course of history. Radio telegrams sent across the ocean or between cities were competing with undersea and overland cable telegrams. Ordinary hard-wired telegraph was just as fast as radio but was not vulnerable to atmospheric conditions. However, once radio transmitters were placed on ships, it was only a matter of time before radio was used to rescue the passengers and crew from a sinking ship. This first happened during the sinking of the RMS Republic.



At 5:40 AM, Saturday January 24, 1909, the 15,000 ton passenger steamship RMS Republic was steaming off Nantucket, Massachusetts through thick fog. The Republic was outbound from New York. This ship had a lot in common with the later Titanic. The Republic was owned by the same British White Star Line and was considered “unsinkable.” Its hull was divided into multiple compartments by watertight bulkheads so that several compartments would have to flood before the ship could sink. Also like the Titanic, the Republic carried only half as many lifeboats as needed for her 800 passengers and crew.

As the Republic motored through the fog she sounded her foghorn periodically and ship's lookouts listened for other foghorns. The crew heard a foghorn from another ship and responded by sounding a steam whistle. It was the convention at that time that, when ships exchanged whistles, both ships would turn right and thereby avoid the collision. There is some evidence that the Italian passenger ship “Florida” turned left instead. The Florida suddenly appeared out of the fog and crashed into the Republic amidships. Seven people were killed outright by the collision. The Florida struck the bulkhead between the two engine rooms on the Republic, thereby flooding the two largest compartments below the waterline. The engines had to be shut down which also terminated the electricity needed to run the pumps and the radio.

Jack Binns saves the day

The Republic's radio shack was a wooden cabin that had been tacked onto the upper deck. It was located where it was easy to connect to the antennas that were strung up in the ship's rigging. With amazing bad luck, the bow of the Florida sliced part way through the radio cabin pushing equipment aside and disabling the radio. The operator John (Jack) R. Binns was

13. Chapter 1, Harris

sleeping on a bunk next to his operating station. He said later that if he had been still working at his radio he would have been gravely injured. Binns managed to piece his transmitter back together, but his little cabin was now open to the cold and fog. Because the ship's electricity was off, Binns had to rummage around in the dark below decks to find batteries to run his radio. Without the ship's electricity, Binn's transmitter range was limited to about 75 miles. His best hope was to reach a station on Cape Cod, 65 miles away. Even Binn's telegraph key was broken. He had to hold it together with one hand while he used his other hand to send out history's first emergency SOS.

Actually, the official distress call at that time was not SOS but "CQD." "CQ" meant calling any station, just as it still does today on the ham bands. CQ was supposed to be short for "Seeking You." "D" of course meant danger or distress. Binns managed to contact the station on Cape Cod. Through them, he continued to call for help and talked to rescue ships for 12 hours while the Republic slowly settled into the sea.

Since the Florida was in no danger of sinking, the Republic crew transferred the Republic passengers to the Florida by lifeboat. Meanwhile rescue ships criss-crossed the fog trying to find them. In addition to foghorns, ships of that era were equipped with "submarine bells" which had a greater range underwater than sound from horns was able to travel through air. The submarine bell of the Republic was heard by the liner Baltic and used its sound to guide it the final few miles to the Republic.

In another account of the rescue there was no submarine bell and the contact was made when the Baltic shot off "its very last aerial rocket bomb." The crew of the Republic heard the explosion and gave them the correct bearing by radio. When the Baltic arrived, the remaining crew on the Republic were rescued, then all 2,494 passengers from both the Republic and Florida were transferred by lifeboat to the Baltic. 39 hours after the collision the Republic sank. Meanwhile rescue ships managed to tow the Florida to New York City.

The success of the Republic rescue was a huge news story. Jack Binns was an overnight national celebrity. Radiotelegraph operators were instantly transformed from curiosities into heroes. It's bizarre and even criminal that the White Star Line didn't seem to learn anything from the sinking of the RMS Republic. However, in 1912 the Titanic sinking and the partial success of the Titanic's SOS emergency call further elevated the status of radio communications. The steamship Carpathian sailed 300 miles to rescue the Titanic survivors the morning after the sinking. Another freighter, the Californian, lay at sea anchor just 10 miles away. The captain of the Californian didn't want to risk steaming at night through the icebergs - smart man! The Californian radio operator sent an iceberg warning to Titanic, but the Titanic radio operator told the Californian to get off the frequency because he was handling telegrams for the passengers. The Californian radio operator shut down his radio and went to bed. The night crew on the Californian could plainly see the Titanic but didn't realize the Titanic was in trouble. When the Titanic shot red emergency rockets into the air, the Californian crew thought the rockets were fireworks to amuse the wealthy passengers.

The dawn of amateur radio

In the early days of radio anyone who wanted to get on the air could build his own transmitter and just do it. Frequency assignments were based on whoever was on the air first with the biggest transmitter and the best antenna. Basement inventors began building their own

14. Chapter 1, Harris

radio equipment and amateur radio was born. In those days there were no licenses so amateurs at first just gave themselves call letters. All radio communications in the beginning were low frequency, 200 meters wavelength and longer. This meant that all communications were happening at what is today AM radio (1,700,000 Hz to 550,000 Hz) and below. Higher frequencies were inefficient to generate and it was believed that higher frequencies were only good for local communication.

When modern amateur radio operators read descriptions of early radio transmitters and antennas, we are impressed by the industrial scale of the commercial equipment. For example, the rotary spark gap transmitter on the Titanic was rated at 5,000 watts. It was so huge and made so much noise and ozone stink, it was installed in a separate room from the receiver. With all that power and size, its reliable range during the day was only 250 miles. At night the range could be as far as a thousand miles. From our modern viewpoint, it's apparent that the biggest weakness of early day equipment was the insensitivity of their receivers. Back then amateur receivers were just as bad and probably worse. Moreover, amateurs were unable to compete with the power used by commercial stations. Consequently, hams were lucky to talk to the next county, let alone any significant distance.

Because early ham radios were limited to short range, radio amateurs banded together to form "relay nets" so that messages could be relayed to destinations many hundreds of miles away. This organization became formalized as the American Radio Relay League in 1914. During World War I the US government banned amateur radio as a national security measure. After the war in 1919 the American Radio Relay League under the leadership of Maxim Percy lobbied the government to allow hams back on the air. The government, especially the military, was unsympathetic. To placate them, the government eventually gave the hams all the "worthless" frequencies above 200 meters. That was roughly everything above present day AM radio.

Flemming develops the vacuum tube diode detector

The vacuum tube diode had actually first been built by Edison. During Edison's work on the electric light, he perfected the technology to put electrodes and filaments in evacuated glass bulbs. Edison was also the first to notice that electrons can flow from a hot filament across empty vacuum toward a positively charged electrode called a "*plate*." However, the electrons could not flow from the plate back to the filament. As a result, the diode behaved as a one-way check valve. Edison experimented with this and wrote about it. This effect became known as the "Edison effect."

Flemming was a British inventor who was intrigued with Edison's discovery and applied it to the detection of radio signals. He worked with Edison who shared his data on the Edison effect. A radio signal received on an antenna consists of a high frequency sinewave voltage that switches from positive to negative and back again hundreds of thousands (or millions) of times per second. These rapid alternating (AC) currents can't power a headphone until they are converted to lower frequency bursts of DC. By passing radio signals through a vacuum diode, one polarity of the signal is "sheared off" leaving just the polarity of the flowing negative electrons. When Morse code signals are received, this results in bursts of DC current that can be used to power a sounder, headphones, or other kind of transducer.

Flemming's detectors became known as the "Flemming Valve." In England thereafter,

all vacuum tubes became known as “valves.” In terms of sensitivity, the vacuum tube detector was not more sensitive than a crystal detector, but it was far more rugged, reliable, and versatile. Later on, when it was combined with the vacuum tube amplifier, its sensitivity was vastly improved.

Lee DeForest launches modern electronics

Tesla was not the only radio pioneer with an ego problem. In many ways DeForest had a personality similar to Tesla’s. DeForest was industrious and gifted. While he was a young man he developed several important inventions. One of his cleverest was a telegraph multiplex system that allowed one wire to carry up to six telegraph messages simultaneously. It’s hard to imagine how it could have worked. All he had to work with were switches, relays, transformers, and motors. Synchronizing such a signal separation system is easy with a microcomputer, but doing it with whirring motors and switches is amazing. De Forest’s most important invention was the triode vacuum tube, which he called an “audion.” The audion was the functional equivalent of the modern transistor. DeForest’s triode vacuum tube was essentially a "Fleming valve" with a grid placed between the filament and the plate. DeForest used the audion to make receivers more sensitive by amplifying weak audio and radio signals.

Actually Edison built the first triode while he was studying “the Edison Effect.” Edison added a grid-like electrode between the filament and the plate of his diode to learn more about the flow of electrons across a vacuum. Although Edison made his measurements, he didn’t notice that the grid was like a sensitive “gate” that could control the current flow to the plate.

The grid can be compared to a matador’s one-pound red cape steering a 2,000 pound bull. When little currents are able to control big currents, the device is said to “amplify.” Little signals coming into the grid can modulate the big current into a larger, “amplified” version of the original signal. Notice that the original signal is not “inflated” in some way, but rather, the amplifier just directs the generation of a larger copy of the original signal. Notice that the copy may or may not be a good likeness of the original.

DeForest successfully applied his triode vacuum tube to radio receivers. The triode meant that weak signals could be amplified to a level high enough so that after detection they could drive a loudspeaker. Once amplifiers became available, nearly every kind electronic device known today became at least theoretically possible. Eventually even television was implemented with the descendants of the audion vacuum tube. During World War II the first computers were built using vacuum tubes.

The vacuum tube oscillator cleans up radio transmissions

A few early high power systems used alternators to generate low frequency radio signals. However, the frequency of an alternator is limited by the speed of a mechanical, rotating magnet. In practice, alternators couldn’t get much higher than audio frequencies, 20 to 50 KHz. An advantage of an alternator was that it generated a pure sinewave signal. Unfortunately it could only cover the very bottom of the radio spectrum.

In contrast, the vacuum tube amplifier could amplify its own output, causing a self-sustained oscillation at any frequency up to hundreds of MegaHertz. Like an alternator, a vacuum tube oscillator could generate clean sinewave signals that were confined to a single frequency. Up until that time, radio transmissions from all high frequency transmitters were

generated by discharging electric sparks, then letting the radio frequency signal components ring in a tuned circuit. "Spark gap" transmitters made a noisy, hissing signal that splattered energy all over the band.

Have you ever heard the clicking static in an AM radio from a passing automobile ignition? Similarly, lightning causes a pop or crash of static that can be heard over the entire radio spectrum. Other than having a filter to limit the noise to one band, early radio transmitters were like little lightning radio noise generators. These early sparkgap transmitters wasted power and frequency space. Because of the availability of vacuum tube oscillators, spark gaps became unusual in the early 1920's and were totally banned in the United States in 1927.

If an inventor is persistent, it's sometimes possible to invent wonderful things without really understanding why they work. This was the case with DeForest's audion. In the short run, ignorance can be OK, but in the long run the inventor had better figure out exactly what he has developed. Specifically, he must be able to explain how it works in his patent application.

Unfortunately, DeForest blew it. His patents failed to give valid explanations of how his vacuum tube devices worked. A dozen years after the invention of the audion, DeForest's patents came into conflict with later patents that were accurately explained. In court DeForest was literally unable to explain how a triode amplified. It is completely understandable how he might have been naive at the time of his inventions. But considering that the vacuum triode was his crowning achievement, it isn't flattering that he never bothered to keep in touch with the field of electronics well enough to find out how his own invention worked. Forty-five years after his invention of the audion, De Forest was still strutting around in formal clothes grandly referring to himself as "The Father of Television."

Reginald Fessenden transmits speech

Professor Reginald Fessenden is an almost unknown hero of radio development. He is truly one of the most remarkable radio pioneers. Although Marconi first demonstrated transatlantic communication, Fessenden was the first to offer it as a regular service in 1906. Fessenden's most amazing accomplishment was the transmission of speech. He is not remarkable so much for what he did, but rather when he did it. In December 1900 he transmitted a voice signal to his assistant Alfred Thiessen over a distance of one mile from his laboratory on Cobb Island in the Potomac River. "One-two-three-four ... Is it snowing where you are, Mr. Thiessen? Telegraph back if it is."

"Yes, it is!" tapped out Thiessen over a telegraph. From a modern perspective Fessenden's invention came at least 15 or 20 years before the parts were available to do it gracefully. What Fessenden needed was high power audion tubes. However, he didn't know that. So he transmitted AM modulated voice transmission using spark gap transmitters. That sounds impossible. And perhaps because spark gaps were "dead end technology," it isn't totally surprising that Fessenden has been largely forgotten. The only articles on Fessenden that I have ever read don't describe his apparatus clearly. However, he seems to have succeeded by means of three major breakthroughs and many minor ones.

Fessenden smooths out the sparks

A smooth, pure carrier wave is needed to produce clear AM modulation, but there is nothing smooth about static from a spark gap. Fessenden reasoned that, if the static crashes

occurred often enough, the frequency of the buzzing racket would be too high an audio frequency for human ears to hear. So instead of sparking a few dozen or a hundred times a second, Fessenden's generator sparked 10,000 times per second. Then (apparently) he filtered the heck out of the signal using inductor/ capacitor resonant circuits. The transmitter had its own steam engine power plant and was probably quite powerful. The steam engine had to be running at full speed before the speech became intelligible.

Using high frequency noise to get rid of low frequency noise is reminiscent of the modern "Dolby sound" noise canceling principle. Rather than fight the noise inherent in any analog recording system, the Dolby system deliberately modulates the music with a high frequency sine wave at about 25,000 Hz to obliterate the noise.

I read another account of Fessenden's work in which his voice transmitter was described as a high-speed alternator. Oh, well. Transmitting speech with a high-speed alternator also sounds difficult. Garbled technical descriptions are a serious problem when studying the history of radio. It is hard to figure out exactly what they did.

Fessenden invents the barretter

Fessenden also invented a sensitive new detector that he called a *barretter*. "Barrette" means "a small bar" in French. Modern barretters consist of a microscopic platinum wire that heats and cools rapidly when bursts of tiny radio frequency currents pass through the wire. As the wire changes temperature, its resistance changes rapidly and this can be used to modulate a DC current passing through a sensitive telephone earphone. Barretters are still used today as microwave detectors.

What I don't understand is how the professor got enough signal strength out of a 1900-era telephone microphone to modulate a powerful transmitter. In my opinion that would have been his third amazing breakthrough. In a commercial amplitude modulated (plate modulated) transmitter from the 1930s and later, the audio sound from the microphone had to be amplified up to half the power output of radio transmitter. For example, for a 1,000 watt transmitter, a 500 watt audio amplifier was needed. There was no way to build such a thing in 1900.

Perhaps he invented the "magnetic modulator." In the 1920s some phone transmitters used a transformer to impress amplitude modulation directly onto the RF signal. The microphone modulated a DC current on the transformer primary while the transmitter ground for the antenna went through the transformer secondary. By saturating the iron in the transformer, the current flowing through the secondary can be radically changed with a small signal, thereby providing the needed amplification. Fessenden must have been an obsessed genius to broadcast speech successfully with steam engines, iron bars, copper wire, and spark gaps.

At the time Fessenden's achievement didn't go unnoticed and he was able to raise money to start a broadcast company. His first public demonstration consisted of speaking and playing "Oh Holy Night" on the violin on Christmas Eve in 1906. However, his commercial progress was slow and by the time AM broadcast was beginning to work well, nearly everyone was stealing his ideas. The Marconi Company eventually licensed his patents in 1914. From a modern perspective, Fessenden's biggest problem was his lack of viable business plans. He invented neat stuff, but had difficulty getting paid for his work.

Edwin Howard Armstrong

Another engineer who understood his own inventions was Edwin Armstrong. He studied electrical engineering during World War One, then, right after graduation, he produced the first of his three great inventions, *the super-regenerative receiver*. In the early days of radio, it was too expensive to build receivers with large numbers of large, costly, power-hungry vacuum tubes.

Armstrong invented a way to use feedback on a vacuum tube amplifier to increase the sensitivity of the receiver by an order of magnitude. Super-regenerative receivers were crude and had to be adjusted just right to avoid an unpleasant squealing noise on top of the stations you were trying to hear. However, when super-regenerative receivers began to be used, the range of radio broadcasts soared to a thousand miles and more.

In spite of their severe limitations, ham radio operators commonly made homemade super-regenerative receivers as late as 1960. "Super-regens" were primitive, but they were a stepping-stone to the next generation of receivers. In the 1920s Armstrong developed *the super-hetrodyne receiver*. This is the basic design used today in most modern receivers, from television to cell phones. When I was a young ham, I built a Knight "Ocean Hopper" super-regenerative receiver from a kit. I only bought it because it was cheap. The high-pitched noise of the super-regen was so obnoxious, I couldn't wait to replace it with a high quality super-hetrodyne communications receiver.

The TRF receiver didn't cut it

To achieve the required amplification without super-regeneration, the obvious solution was to put several radio frequency tube amplifiers in series. These radios were called *tuned radio frequency (TRF) receivers* but they were never very popular. Each amplifier in the string had to be tuned separately to the desired station. This meant that the first TRF radios literally had three or four station tuning knobs that all had to be tweaked independently. Alternatively, in the best TRF radios the tuning capacitors were ganged together with gears and shafts so that they always tuned to the same station simultaneously. This method was extremely hard to synchronize and calibrate so that each tuned coil would track precisely over the entire frequency band. Another problem was that they were inherently "low Q" and tended to receive more than one station at once. The only practical TRF receivers were either extremely expensive or were designed to receive just one frequency.

The super-hetrodyne receiver

Armstrong's solution to the gain problem was to convert the incoming radio signals to a constant *intermediate frequency*, an *IF*. The IF frequency remains the same no matter what station the radio was tuned to. In other words, *a superhetrodyne is a single-frequency TRF receiver with a tunable frequency converter on the front end*. The IF strip is tuned up just once at the factory. It never needs to be tweaked again. Another important advantage was that the signal on the IF strip could be filtered so that it would only admit a bandpass equal to the actual width of the signal. For example, an AM radio receiver might have an IF bandpass of 20,000 cycles per second (one cps = one Hertz). However, a Morse code signal only needs 100 Hz of bandwidth or less. So when a narrow bandwidth filter is used in the IF, the receiver can select just one signal out of many that may be crowding the band. In contrast, a TRF receiver or even a super-regenerative receiver or may force you to listen to 50,000 Hz of bandwidth at once.

The super-hetrodyne generates the IF by means of a *local RF oscillator, an "LO."* The principle can be illustrated with audible sound. When two different frequencies of sound are

mixed together, the sound waves cancel and reinforce each other generating frequency components that are the sum and difference of the two signals. For example, if you hit two adjacent keys on a piano simultaneously, the sound is discordant. That's because you're hearing those sum and difference frequencies. In another example, twin-engine, propeller-driven airplanes are equipped with engine speed synchronizers so that the engines don't make an obnoxious "WAH -WAH- WAH" beat frequency sound. This sound is the difference in frequency between the two speeds of the engines. The same principle works with electrical sinewaves at radio frequencies. Unlike the annoying audible examples, in radio the beat frequency is the desired product and that was Armstrong's invention.

A super-hetrodyne is tuned, not by tuning a sharp filter on the antenna, but rather by tuning a sinewave oscillator that is offset from the signal you wish to hear. The amount of offset frequency is equal to the IF frequency. For example, in a household FM radio, if you wish to tune to a station broadcasting on 100 MHz, then the local tuning oscillator is tuned to 110.7 MHz. The difference between the two frequencies is 10.7 MHz which is the IF commonly used in FM radios. Because the tuning oscillator generates only one precise frequency, and because the IF filtering can be quite narrow, the tuning of a superhetrodyne receiver can be extremely selective. The superhetrodyne is made sensitive by putting several IF amplifiers in series. Or, as explained earlier, you can think of the IF amplifiers as a single frequency TRF receiver.

By the late 1920s spark gap transmitters were banned and replaced by vacuum tube sinewave oscillators. The sinewave oscillators generate just one, discrete frequency. After this improvement hundreds of Morse code signals could share a band without interfering with each other. And using Armstrong's superhetrodyne, the receiver could select just one of these Morse code signals.

Beat Frequency Oscillators – where the musical Morse code tone comes from

Although a simple superhetrodyne receives AM broadcasts beautifully, Morse code is essentially inaudible because a pure sinewave signal is unmodulated. During the 1920s Morse code transmitters were often modulated with a mechanical motor driven switch device that made the Morse sound like a buzz and more like an old spark gap. Alternatively, they sometimes deliberately ran the transmitter on unfiltered DC from a rectifier so that the signal was modulated with AC hum from the power line.

To hear Morse code with a superhetrodyne, another oscillator in the receiver called a ***Beat Frequency Oscillator (BFO)*** is needed to produce the musical sound. For example, my first short wave receiver was one of those ancient all-band radios often found in living rooms in the 1940s. The receiver worked fine for receiving foreign AM radio stations like Radio Moscow. However, when I tuned to the ham bands, the Morse code signals were inaudible or just thumping noises. To receive Morse code I had to place a small table radio on top of the big shortwave radio. I used to tune the little radio until I could hear a harmonic of the table radio's tuning oscillator (local oscillator) in the big receiver. This signal beat with Morse code signals and made them audible. This was extremely finicky to adjust and barely practical. A communications receiver of course has a built-in BFO that typically oscillates at an RF frequency 500 to 700 Hz away from the IF. This produces the clear Morse code whistle we are accustomed to hearing, no matter what frequency the local tuning oscillator is tuned to.

Getting rid of the atmospheric static

Radio communication was essentially 100% Morse code until after World War I. Suddenly it became common to hear voices over the radio. In 1921 the first commercially successful Amplitude Modulated voice broadcasts began. With AM broadcasts, the transmitter was not turned on and off like Morse code, but rather the transmitter was left on continuously. The transmitter power was raised and lowered in time with the music or voice audio frequency. This process impressed or “modulated” voice and music onto the signal. In other words, with AM modulation the information content is proportional to the momentary strength of the signal.

So long as the strength of the signal is high and there is no interference from lightning storms, big DC motors, or nearby automobile ignitions, amplitude modulation (AM) radio works quite well. By 1930 AM radio was a standard appliance in American households. But with all that crackling and popping noise on weak signals, AM radio is never really high fidelity except when tuned to strong, local stations.

Atmospheric static is a natural noise signal that has the same amplitude modulated form as man-made AM signals. Therefore it is impossible to get rid of the static without changing the method of modulation. Edwin Armstrong secluded himself in his laboratory in the Empire State Building in New York City and worked to find a way to eliminate the static in voice broadcasts. Armstrong needed to create an audio modulation that could be impressed on a transmitter signal without imitating the natural noise modulation produced by lightning and static discharge.

Armstrong eventually hit upon the idea of modulating the frequency of the signal rather than the intensity of the signal. In other words, as the announcer talks, the frequency of the transmitter moves up and down in time with the audio frequency and amplitude of the sound. The signal amplitude never changes. *Frequency Modulation* solved most of the noise problem and was the origin of the FM broadcasts we listen to today. Armstrong had been working for the Radio Corporation of America that manufactured superheterodynes. Because of the superheterodyne, RCA with its subsidiary, the National Broadcast Company, dominated AM radio for as long as that patent lasted. RCA was run by David Sarnoff who failed to reward Armstrong’s contribution to the company. Armstrong left RCA and started his own FM radio broadcast network.

Sarnoff needed FM radio to transmit the audio signal with television so he simply stole the invention from Armstrong. Sarnoff, being able to hire more lawyers, was able to play the patent war two ways in his favor. His lawyers persuaded the court that RCA had invented FM, not Armstrong. Sarnoff also persuaded the FCC to force FM stations to broadcast on VHF frequencies at low power that restricted them to local broadcast. This prevented FM from ever being used by long-range stations like the 50,000 watt “clear channel” AM stations that are still scattered around the U.S. Ultimately Sarnoff won all the battles and ruined Armstrong. Armstrong, who loved to climb on high radio towers, ended his life by jumping out of a 13 story window in 1954.

The transistor miniaturizes electronics

The bipolar transistor was invented in 1947 by Shockley and Bardeen while working at Bell Laboratories. In function, the transistor can be thought of as a “miniature triode vacuum tube.” Unlike a tube, a transistor consists of a tiny lump of semiconductor crystal with three wires attached. Like a triode, a control gate called the “*base*” allows a small current to control a much larger current that flows from the “*emitter*” wire to the “*collector*” wire. Unlike tubes,

there is no vacuum chamber, no heated filament, no relatively high voltage, and no separate power supply needed to light the filament.

In vacuum tubes, the control grid of a vacuum tube must always be referenced to the negative pole of the circuit. That is, the grid is always operated at just a few volts different from the voltage on the filament (cathode). The vacuum tube plate potential is usually quite high, typically hundreds of volts, and is always positive polarity. In contrast, transistors can run on as little as one or two volts and can be built in two polarities. The control base can be referenced to either the negative pole, (*NPN transistors*) or the positive pole, (*PNP transistors*.) Because they are available in complementary designs, the two types can be used together to form compact, high gain circuits with fewer additional components such as resistors and transformers.

The first transistors were fragile devices called *point contact transistors* that never appeared in consumer products. (A homebrew attempt to build point contact transistors is described in chapter 4.) The first widely used transistors were made from germanium and not silicon. Early germanium transistors could only tolerate tiny power levels. For example, the 2N35 transistor would burn out if it dissipated more than 35 thousandths of a watt. In the 1950s they were sold to amateurs for experimentation, but it was difficult to get them to work before they burned up. I bought one for \$5 and promptly ruined it. Today that amount of money would be like \$50 each. Then in 1960 the Texas Instruments Company perfected silicon transistors and the dominance of the vacuum tube was doomed.

Radio covers the globe

The Sony Company in Japan realized that silicon transistors presented a unique opportunity. They jumped on it and revolutionized AM radio. They made tiny battery powered “transistor radios” that cost a few dollars and fit in a shirt pocket. Because they didn’t need power from the wall and the batteries were small and cheap, suddenly even the poorest people on Earth could afford transistor radios.

In the 1960s another type of silicon transistor, the Field Effect Transistor (FET) appeared. FETs are also three wire devices. The control gate of an FET is actually called the “*gate*” and the gate uses tiny voltages, rather than tiny currents, to control the big current flowing from the “*source*” lead to the “*drain*” lead. Like bipolar transistors, FETs come in two polarities called “*N-channel*” and “*P-channel*.” Today FETs are the basis of most integrated circuits used in computers and, as we’ll see later, they are also valuable in radio circuits.

Becoming a ham radio operator

My serious shortwave listening began during the cold war. My big “all band radio” allowed me to tune the shortwave bands. This radio was three feet high, two feet wide and packaged in a beautiful wooden cabinet. But compared with a real communications receiver, this living room radio was extremely limited. It had poor selectivity and only covered a few ham bands. It had no “band spread” control so the hambands were only about 1/8 inch wide on 4 inches of dial. On the other hand, it wasn’t worthless. I was able to hear occasional AM phone conversations between hams. Later I bought a World War II surplus “morale radio.” These were shortwave receivers that were issued to the American troops so they could listen to broadcasts from home, Tokyo Rose, or other AM modulated stations. Morale radios also had no “beat frequency oscillator” and I could not receive Morse code without resorting to the second-radio-

trick described earlier.

I learned Morse code in the Boy Scouts. One requirement for our Boy Scout First Class badge was to send and receive Morse Code using a signal flag. The flag was waved over one's head to the left for "dash" and to the right for "dot." Our Boy Scout manual admonished us to remember what the Dutchman said, "Dots right!" Today's Boy Scouts don't have to learn Morse code. That's a shame. In an emergency, the ability to communicate by tapping through a wall or waving across a canyon might not be a trivial skill. Prisoners throughout the world often communicate by tapping messages through walls using a universal code. The prisoners' code translates the alphabet into tapping in which the letter "A" equals one tap, "B" equals two taps and of course "Z" equals 26 taps. Good Grief! I guess prisoners have lots of time on their hands.

Several of my friends were also interested in shortwave and we started a shortwave listening (SWL) club. For code practice my buddy Eric Raimy (soon to be KØDUA), rigged up a telegraph system of buzzers that communicated between his bedroom, the downstairs hall closet, and the basement. We three middle school students sat at our posts and talked with our slow Morse code until we got our speed up to 5 words a minute and could pass the Novice class ham radio test. A local school principal, Glenn Johnson, WØFQK, taught us about ham radio administered the tests to us.

If you wish to get a ham license, you need to find a local ham radio club in your area. In America ham clubs generally conduct classes for new hams and give the license exams. Check the Internet for local clubs. Failing that, if you live in the USA, check the American Radio Relay League website, www.arrl.org or call (888) 277-5289. The ARRL will help you in many ways. They can provide you with study materials, magazines, books, and hams to contact in your area.

Ham radio in the last 80 years

Like electronics in general, amateur radio has exploded into many different facets since World War II. From a hobby that was originally just Morse code, it has exploded into a long list of capabilities and activities. Each decade has added more and more variations in the ways and methods for amateurs to use radio technology. As a rule, new technologies were first demonstrated ten years before they became commonplace. Of all the ham modalities that have ever been used, only spark gap transmitters are completely extinct. However, hams rarely use AM phone today.

1920s Continuous wave Morse code and early AM radio. (Vacuum tubes and the end of the spark gap transmitter.)

1930s AM phone, Very High Frequency (VHF) 54 MHz and above.

1940s Radio Teletype (RTTY), VHF FM communication, 2-way ham radios in cars.

1950s Single Side Band Phone (SSB), amateur television, slow scan television (a kind of radio Fax), UHF communication, 220 MHz and above, Directional Beam Antennas, radio transmitter hunts.

1960s Amateur microwave communication. Easy-to-use SSB HF transceivers. Moon bounce and meteor bounce communication.

1970s Amateur Satellite communication, VHF/ UHF relay stations.

1980s hand-held transceivers, computerized station log keeping, AMTOR packet message

handling (a sort of radio e-mail)

1990s Spread Spectrum communication, radio control, robot beacon stations, PSK-31 messages (computer instant e-mail), IRLP (Internet-connected VHF relay stations), QRP (low power) stations, and amateur radio radio-controlled models, TV on small rockets.

2000s Software controlled radio receivers, complex digital signal processing, remote internet controlled stations, GPS locating for mobile transmitters (APRS) and, in general, the application of all the technologies found in cell phones and computers.

From the point of view of variety of new equipment, amateur radio is booming. On the other hand, thanks to the Internet, fax machines, and cellphones, much of this technology can now be used by people who have no license and no interest in how the equipment works. On the other hand, some aspects of ham radio remain unique to this hobby and haven't changed. These are:

1. Morse code.
2. Exchanging QSL (contact confirmation) cards,
3. Homebuilding equipment.
4. Mastering new or exotic modes of communication, such as satellite relay or unusual signal propagation modes like moon bounce.

The future of ham radio frequency bands

The existence of ham radio as a hobby is totally dependent on our governments allowing us to transmit. For this we need allocations of the frequency spectrum. But every day there are more and more commercial uses for wireless communication. These applications fall into two categories. Short-range communications, so called "Part 15 applications," transmit less than 100 feet. They link printers to computers, support cordless phones, open garage doors, and unlock automobiles. Suitable frequencies can be low, say 1 Megahertz and below. Or they can use very high frequencies, 40 MHz and above. The high frequency (HF) range in between 1 and 40 MHz is not desirable for these applications because, when atmospheric conditions are right, signals from great distances, even the other side of the world, can trigger a local device.

For example, when the first Soviet Sputnik satellite was launched in 1957, it broadcast on 20 MHz. Every time the satellite went over the United States, many homeowners discovered their garage doors mysteriously cycling up and down. Through the use of selective receivers and digital coding, most of this kind of radio interference has been eliminated. But when the frequency bands become crowded with signals, even a sophisticated receiver will eventually be paralyzed by the interference and won't respond to the correct code.

Cell phones, global positioning, and Internet links transmit over distances of a few miles or up to satellites to provide reliable communications. The best frequencies for these applications are above 40 MHz because random signals from the rest of the world usually won't interfere. At 500 MHz and above, signals from over the horizon will almost never interfere. These frequencies can be relied upon day and night for dependable communication. In the modern era it's these UHF and microwave frequencies that have the most commercial value.

Hams have a few frequency bands in this high-value part of the spectrum. So far we have been allowed to keep them by sharing them with the military.

Thank goodness for the erratic nature of HF

Since the 1920s the most important ham bands have been the HF frequencies between 1.8 and 29.7 MHz. The good news for amateurs is that it is the unreliability of these bands that makes them attractive to us and unappealing for commercial users. When we hams turn on our receivers, we really don't know what we're going to hear. There may be just static or there may be two local guys discussing their golf game. Or we might hear a ham in Mongolia looking for a chat. It's like going fishing. That's the fun of it.

Bad signs for the future

As ham radio equipment becomes more complex, fewer and fewer hams understand how it works. It's fair to say that the vast majority of hams today are overwhelmed by the complexity of the equipment they use and no longer make a serious attempt to understand it. As a result only a tiny minority attempt to build their own. American FCC licensing for hams reflects this trend. As fewer hams build their own equipment, ham radios have become just another form of consumer electronics. The FCC has become more concerned about manufacturers building fool-proof equipment than it is about hams understanding their radios.

Forty years ago, ham radio license exams in America were administered directly by the Federal Communications Commission in somber and intimidating government offices. The tests were devoted to the technical details needed to be sure hams knew how to keep their homemade transmitters operating within assigned bands. Typical questions included calculations on crystal specifications to determine whether a given crystal could be relied upon to stay within a particular ham band. The privilege of using all the ham frequencies was only granted to the best-trained hams. They had to demonstrate 20 words per minute Morse code speed and take a complex test that included drawing circuit diagrams of various kinds of transmitters and calculating design parameters. Today the Morse code requirement has been eliminated altogether. The tests are now multiple-choice exams given by ham volunteers. In preparation for the exams, modern hams study the actual tests, rather than the material covered by the tests. In terms of engineering knowledge, the modern ham is a lightweight compared with hams 50 years ago.

Another alarming sign is that the number of ham radio operators is relatively fixed and the average age of hams continues to rise. It's a logical conclusion that eventually our frequencies will be taken away for lack of interest. Ham radio will have become another historical pastime in the same category with quilting-bees and buffalo hunting.

A recent threat to ham radio is the broadband power line initiative (BPL). Power companies wish to make money by using their power lines as Internet connection conduits into every house that receives electricity. Unfortunately the power lines leak this radio noise into the sky and produce a strong buzz of noise that would obliterate all weak to moderate radio signals between 2.0 and 80 MHz. This radio noise obliterates all but the most powerful ham radio and shortwave signals. So far, BPL installations are limited to just a few cities and the ARRL has been fighting the FCC to make the government enforce their own regulations on interference to FCC licensed stations. As of 2010, the hams seem to be winning this battle. Similarly, the radio

racket from plasma TVs and other modern sources increases the background static and makes ham bands less usable than they used to be. The difference in static between the city and living out in the country is dramatic.

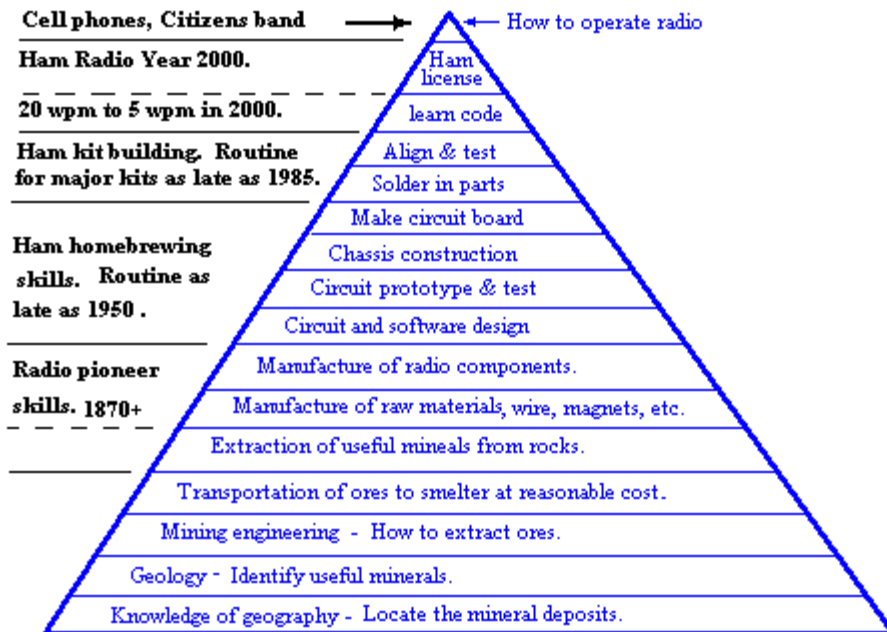
Mastering the technology

As civilization's technology becomes more sophisticated, the knowledge base among our population becomes more and more fractured. Although the amount of knowledge that individual educated people have in their heads may be the same, each citizen knows more and more about less and less. Operating modern ham radio transceivers resembles operating a complex VCR. Yes, the equipment can handle all the modern modes and frequencies. But first you must read the manual and push 48 buttons to select all the right menus and options. It's not easy to operate one of these do-everything wonders. But when you've succeeded, you really haven't learned much about electronics.

Modern radio transceivers remind me of integrated circuits. Transceivers are packed with dozens (or hundreds) of integrated circuits. Some of these contain literally millions of transistors. Like the transceiver as a whole, an integrated circuit cannot be fixed, its contents are mystery, and it is usually a black, rectangular solid with "feet" or leads. Even with the service manual of a modern radio transceiver in front of you, it's hard to get more than a general idea of its block diagram and how it works.

But surely the engineers who designed these wondrous modern radios know how they work! No, not really. Perhaps there are a handful of engineers in the world who have a good grasp of most the technologies in a modern transceiver. But I wouldn't bet on it! Each engineer specializes in assembling or programming modules that are bought from other factories. The modules are sealed and can't be repaired. Exactly what's inside those modules is probably as much a mystery to them as it is to the rest of us.

Over the last century, a radio operator's span of knowledge has continued to shrink. A hundred years ago, the early radio pioneers were not only on the air testing radios, they were also working on the materials to build the components for their radios.



This trend can be illustrated by a “technology pyramid” for ham radio technology. At the very top of the pyramid is the knowledge of how to operate a two-way radio. At the bottom of the pyramid is the prospector who explores the wilderness and first finds the raw materials needed to make a radio and every other modern technology. In the middle are the skills needed to build your own radio equipment.

One way to look at the change is that ham radio has slowly retreated up the pyramid to become just another consumer product like TVs and cellphones. Most hams argue that ham radio can do more things than ever and is therefore more interesting. We can transmit live amateur television, e-mail message nets, and faxes. Fortunately or unfortunately, the same technologies are becoming available to ordinary folks without licenses. Why bother with ham radio?

Homebuilt ham radio and the “QRP”

Building your own radios is commonly known as *homebrewing*. Up until World War II, ham radio was homebrewing. In the early days decent commercial radio equipment was barely available and during the depression it was unaffordable to average people. If you couldn’t build your own equipment, you probably couldn’t afford to get on the air. In this respect a little poverty isn’t always a bad thing. When life is too easy, it becomes boring.

After 1950 building transmitters at home remained common only among the young and impoverished. Good communications receivers were the hardest to build, so homemade receivers were the first to go. In the 1950s and 1960s pre-fabricated, well-designed kits from companies like Heath and Allied Radio replaced the homebuilt equipment. To have good, usable equipment, all you had to do was solder it together. Finally in the 1980s the kits became so complex, the kit companies couldn’t trust us to do more than solder prefabricated assemblies

together. When that happened, the kits became so boring that they disappeared altogether.

Today there is a growing interest in building low power QRP transmitters. These are transmitters with less than 5 watts output. "**QRP**" is an abbreviated way of saying, "please reduce power" in Morse code. The majority of QRP hams are once again building kits. A few modern pioneers are building them from discrete parts. One branch of this hobby builds transmitters in sardine cans to emphasize the small size of the transmitter. Another group uses metal "Altoid" candy boxes that are even smaller. In any case, QRP is the brightest hope our hobby has in remaining technically competent and attractive to young people.

(1) Wizard, The Life and Times of Nikola Tesla, by Marc J. Seifer, Carol Publishing Group, Secaucus, New Jersey, 1996.

CRYSTAL SETS TO SIDEBAND
© Frank W. Harris 2010, Revision 12

CHAPTER 2

HOME-BUILDING AMATEUR RADIO EQUIPMENT

What qualifies as “homebuilding?”

The ultimate homebrewer would be a guy that walks off into the wilderness stark naked. Then, using rocks and sticks, he builds a high tech communications system. Hey, don't laugh! Our ancestors did it. Of course, they had to stay out in the woods for thousands of years to finish the job. Our ancestors were smart, hard-working folks. From our lofty position today it's easy to look down on them as some sort of blue-collar, country bumpkins. Ironically, country bumpkins are often more than they appear. In my opinion, today's family farmers are masters of a wider range of technology than any other group of people in our society. Farmers today can't afford to hire others to repair their old equipment, so they have mastered skills from electrician to biologist. Most farmers today have talents and knowledge that make the rest of us look like specialized robots on an assembly line.

Building your own radio equipment is fun and gives you the satisfaction that comes from mastering knowledge. Homebuilding doesn't need a precise definition. If you're having fun and learning something, do it! You should feel free to invent your own definition. However, the more levels of the technology pyramid you master, the bigger your achievement. Besides, buying ham equipment is like skipping school and buying a diploma. You may get the same privileges, but the result will be empty in many ways. My personal definition of “homebuilding” is that I build my own equipment starting from simple components that (I hope) I understand.

I try never to buy equipment or subassemblies specifically designed for amateur radio. I am proud to be the bane of most of the advertisers in ham radio magazines. I still buy individual electrical components, of course. I just pretend that the electronics industry never got around to inventing radio communications.

An irony of our hobby is that, when the few remaining homebrewers retire from their day jobs, they often build and sell ham radio equipment. These industrious guys manufacture and sell every imaginable ham gizmo. I doubt any of them have noticed that, by making everything readily available, they have discouraged homebuilding.

When is homebrewing NOT appropriate?

Homebuilding should not be done as a way to save money or procure modern equipment. Modern multiband, HF ham transceivers are amazingly cheap. You should be able to buy a quality, used, high frequency SSB transceiver for as little as \$500 - \$1000. The good news is that many people in our society are so prosperous that parents can afford to give kids toys costing hundreds or even thousands of dollars. The bad news is that the economic incentive for young hams to build something has almost vanished. Also, if you do build your own, even the most skilled homebuilder will not have enough years to build a truly equivalent, modern amateur radio station. The commercial units contain custom integrated circuits, custom cabinets, and are the end result of multiple prototypes and exhaustive testing.

Homebuilding with vacuum tubes

50 years ago hams built reasonably good transmitters and receivers in their basements. A well-built homebrew could cover all the high frequency (HF) bands (1.8 to 30 MHz). Best of all, its signal didn't embarrass you on the air. Homebrew CW and AM phone were routine. On the other hand, homebrew single sideband phone (SSB voice transmission) has always been rare because SSB is complex, or at least finicky, to generate.

Circumstances have changed. If you could examine the complete schematic of a modern ICOM, Kenwood, or Yaesu transceiver, you will need a microscope to read it. Of course if it's an "F" size engineering drawing, you might be able to read it OK, but the schematic wouldn't fit on your living room floor. In contrast, the schematic for a 1970 all-band, CW/ AM phone ham transmitter, complete with parts list, fits comfortably on one page of a ham radio magazine. In short, modern stuff is complicated. If they were just made of "little vacuum tubes," it would still take hundreds of times longer to build them. But there are more differences.

Frequency stability

Nearly all hams today are using transceivers designed around precise, digital frequency synthesizers. The frequency is digitally displayed on a little LCD screen to precision as close as 0.1 Hz. The numbers on the readouts may not be that accurate, but the average guy believes his dial is accurate because he hasn't read the specifications. For example, stability might typically be specified to 1 part in a million. So on the 10 meter band, 28 Megahertz, the *precision* of the display might be "0.1 Hz," but the guaranteed *accuracy* might be +/- 28 Hz. However, if the commercial equipment is reading an error of 28 Hz, it is still probably much more stable than a typical homebuilt oscillator. Consequently, when a homebuilt transmitter goes on the air and drifts more than about 20 Hz, it isn't long before the criticism begins.

Today if a homemade transmitter frequency drifts like *typical* rigs of 40 years ago, the complaints will probably drive that ham off the air. In my limited experience, typical vintage ham transmitters from 35 or 40 years ago are likely to transmit poor quality signals that will provoke lots of complaints. On the other hand, if you are using top-of-the-line, best-quality, 40 year old equipment, then the signal quality is likely to be acceptable. Chapter 14 illustrates the effort needed to build old-fashioned equipment suitable for use on the air today. Yes, it can be done. But with such high standards, it's a challenge to make those old parts perform like modern equipment.

Lead Inductance

Another barrier to homebuilding transmitters today is *lead inductance*. The problem is that simple wires act like coils at high frequency. They resist radio frequency currents in proportion to the frequency - the higher the frequency, the greater the "*impedance*" to current flow. When the currents are tiny, like those used in 1960-era ham vacuum tube transmitters, this problem isn't severe. In an old tube transmitter, the plate voltage ranged from 500 to 2000 volts or even more. In accord with Ohm's law, small currents multiplied times the inductance times frequency = small voltage loss. And as you can see, starting with 500 volts, there was a lot of voltage to lose.

In contrast, most modern transistorized transmitters run on 12 volts. Since 12 volts eliminates much of the power supply complexity, this sounds safe and easy. For operation in a

vehicle, you don't even need a power supply, you just run it directly off the battery using the cigarette lighter outlet. 12 volts DC supplies are safer and sound like good news.

Unfortunately, if your power supply is only 12 volts, the currents in your transmitter will be 50 times higher for the same amount of power. Therefore the voltage drop across lead inductances will be 50 times higher and, starting with 12 volts, you don't have much voltage to lose. Suddenly each component in your circuit acts as if it has an inductor in series with it. These unwanted inductors cause the transistor stages to self-oscillate, or simply to produce no power gain. The bottom line is that it's much harder to build transistorized transmitters.

The solution to the inductance problem is *printed circuit boards* and very short leads between the components. This means that the craftsmanship needed to build a transistorized transmitter is higher than we needed with vacuum tubes. If you don't carefully limit your goals and work within your knowledge and time constraints, the decision to homebrew your station can lead down a long road of frustration.

BASIC ELECTRICAL KNOWLEDGE

The first challenge in building radio equipment is acquiring the technical know-how. There are many ways to learn basic electronics. The American Radio Relay League (ARRL) Amateur Radio Handbook is published every year and has (nearly) everything you need to know. This large volume covers all aspects of the hobby. Unfortunately, its size is overwhelming for many readers. Also, so few hams build their own equipment today that serious homebuilding has been de-emphasized in the Handbook. In fact, if all you had were the handbook, you would probably conclude that building your own equipment is impractical. A goal of what you are now reading is to help restore homebuilding to some of the importance it once held in Amateur Radio.

This chapter introduces the minimum knowledge you need to get started. If you have trouble grasping the perhaps overly simplified explanations in this book, read about the same topics in the ARRL manual and other texts.

Much of the following is written in a "Dick and Jane" fashion that ignores many of the fine points. For example, if I say, "*all circuits are complete loops*," a purist might bring up unusual situations in which this doesn't appear to be true. However, it's important to have some simple, bedrock concepts to fall back on which will usually serve you well. "Rules of thumb" are essential to keep your reasoning organized. However, keep your mind open to exceptions, because you'll encounter lots of them. When you do find exceptions, don't throw out the basic rules of thumb. They usually work well and will keep you sane.

I only use math when it is essential to do the job. A serious problem with engineering schools is that engineering professors are selected from the 2% of the students who naturally think in terms of math. So after graduation, the math geeks are the guys who hang around to educate the next generation. The students who think like "normal people," go out in the real world to build things that work. Actually, the majority of engineers are so disenchanted by the obsessive/compulsive math-squiggles that they go into management or sales.

Learn a qualitative understanding first

By concentrating on math, professors often fail to teach the basic concepts of how

electricity works. A friend of mine, John Anderson, taught third year electronics engineering. He was discouraged to discover that most of his students could cover a blackboard with equations, but couldn't bias a light emitting diode or predict the voltage on the collector of a saturated transistor. Any good technician or experienced ham can do these tasks with hardly a thought.

As John told me, "Engineering is like learning to paint a picture. First you need the skill to paint a horse so it looks like a horse and not a house. It's not important for most artists to be able to calculate the physical chemistry of paint pigments. Those skills are only important to a few specialized members of the art community."

Personally, I worked for decades as a real engineer, but my methods are primarily qualitative. I only use simple math that I completely trust. One day I was working on a project with John Anderson when he turned to me and said, "You spent four years in engineering school and all you learned was that math doesn't work and shouldn't be trusted." I am ashamed to admit he's right. Once I got into the real world, I spent too many months calculating random, useless numbers on paper. Eventually I learned to work primarily from experience and intuition. In other words, I work like a radio ham! I'm making this confession to emphasize that when I use formulas and math, it is important stuff and you won't be able to avoid using it.

In case you believe that building radios in your basement is just idle entertainment, consider this: During my four years in the Air Force my job title was "electronics engineer." I did my technical work entirely with my ham skills. No one ever asked me to write equations. All they wanted from me was a working power supply by Thursday, a working radio control link, an electronic timer, a static electricity protection circuit, or whatever. If I had not been a ham, I suppose the Air Force would have found some paperwork for me to do, but I would not have been able to complete the tasks I was originally assigned.

**

MAGNETIC AND ELECTRIC FIELDS

Magnets - an everyday force field generator

I never get tired of playing with magnets. Other than Earth's gravity, magnets are the most common devices in our everyday world that allow us to experiment with a physical field. An invisible force from the magnet reaches out and grabs paper clips or thumbtacks from a quarter inch away or more. Playing with two magnets is even more interesting. One magnet can attract another, the same way a magnet attracts steel. But when you reverse the direction of one of the magnets, the magnetic force acts as a "repeller" pushing the other magnet away or causing it to spin 180 degrees to the opposite polarity. After it has been reoriented, the second magnet jumps toward the first magnet.

Playing with magnets gets us accustomed to the idea that a magnetic field may be generated by a physical device. We also observe that *a magnet field is a short-range phenomenon*. With small magnets the field only seems to be effective for a quarter of an inch or less. With such short range, refrigerator magnets don't seem promising as a starting point for long-range communication.

The magnetic field from a permanent magnet arises from the individual atoms that make up the magnet. Each atom has electrons that orbit around the nucleus. These electrons resemble electrons passing around the coils of an inductor. Unlike the electrons in ordinary atoms, the electrons of iron and other magnetic atoms orbit the atoms aligned to at least a small degree. In contrast, ordinary atoms have electron orbits that race around the entire atom in perfectly spherical shells. Ordinary atoms generate magnetic fields too, but there is no alignment and the fields cancel.

Electric fields are also common in our everyday world, but the effects are usually subtle. During the winter at northern latitudes the humidity in our houses drops and static electricity discharge often startles us when we grab a metal doorknob. Like the magnet, static electricity can move lightweight objects a short distance. It can make non-conductors stick together, or even repel them. Unlike magnets, the objects affected by household electric fields must be featherweight items, like lint or hairs. Static cling in our clothes is an example of oppositely charged materials attracting each other, just like the magnets. In contrast, petting the cat may make the cat's hair stand on end. When hair stands on end, each hair is repelling the hairs around it. Moreover, a bit of humidity makes the phenomenon vanish. Because the affected objects are so lightweight, static electricity seems pretty minor. For both magnetic and electric fields these routine phenomena seem to be strictly short range.

WHAT IS ELECTRICITY?

Electricity consists of electrons flowing through conductive materials. Some physicists might jump in now and start lecturing about holes flowing through P-type semiconductor or chemical ions migrating through electrolytic solutions. But let's forget about exceptions for now. It's easier to visualize current flow as electrons.

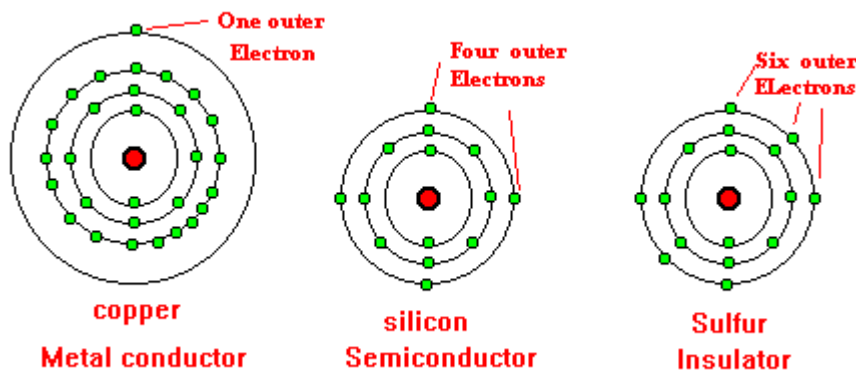
Electrons are a form of "charge." "Charge" just means an excess or lack of electrons that gives rise to an electric field. When charge is gathered together in one place, it establishes an electric field with respect to nearby objects that have an opposite charge, or simply have less of the same charge. If a conduction path is established between the two objects, the electric field becomes a **voltage**. **Voltage is the force that pushes a current flow** from one object to the other until the charges are equal.

Electric field force can be startlingly powerful. For example, suppose a copper penny were floating in the vacuum of deep space. Now suppose it were possible to strip all the electrons from the penny and move them in a glass bottle some distance away from the penny. Obviously electric force will try to reunite the penny with its electrons. How far apart would these two objects have to be moved in order for the force driving them together to decrease to one pound of force? Believe it or not, according to my college physics book, the answer is 3.6 million miles. (2) This tells us that, in the real world, gigantic voltages are needed to remove more than just an occasional electron from an object. Electronics merely dabbles with the surface of an immense ocean of power and energy. Removing all the electrons requires converting the penny into pure energy - in other words, $E = mc^2$.

Electrons have a **negative** charge. Benjamin Franklin coined the word "negative" based on a static electricity experiment in which electric charge was transferred from a person to a glass tube. That is, the person had loss or "negative" amount of charge. Whereas when the glass

transferred charge to a person, the person gained a "positive" or increased amount of charge. (1)

“Negative” is just a word and could just as well have been called “George” or “Napolean.” The opposite of negative charge occurs when an object has lost electrons and needs to replace them. An object with a dearth of electrons is said to have a “*positive charge.*” When the electrons are given the opportunity to travel, they will flow from a negatively charged region to a positively charged region at (nearly) the speed of light. “*Positive current flow*” is usually taken to mean current flow from positive to negative. In other words, positive current flow is the direction opposite to the flow of electrons.



Metal Conductors

Materials that allow electrons to travel are called “electrical conductors.” Electrical conductors are usually metals. If you remember your chemistry, metals are on the left side of the periodic table. Metals have an outer electron shell with 1, 2, 3, or 4 electrons. As you may recall, 8 electrons are needed to complete a stable outer electron shell in most elements. The outer electrons orbiting metals are not tightly bound to their atom and these electrons can be easily lured away. In a piece of metal the outer electrons wander away from their home atoms and move over to neighboring metal atoms. These roaming electrons form an electric current. For example, copper has just one outer electron. When one considers price, weight, conductivity, ductility, and corrosion characteristics, copper is the best available metal for making wires.

A copper penny weighs 3.1 grams. If it were possible to remove all of its electrons instead of just a scattering from the outer shells of atoms, how many electrons would you have and what could you do with that many electrons? The answer is 5×10^{29} electrons. This is the number of electrons that pass through a 100 watt incandescent light bulb in 40 hours of operation - all from one penny! (2)

Insulators

The atoms on the right side of the periodic table have their electron shells filled with 8 electrons or are nearly filled with 5, 6, or, 7 electrons. These atoms do not have loose electrons, but they easily accept loose electrons to complete their shells. In this way, insulators take free electrons out of circulation and prevent current flow. These elements are inert gases and materials like sulfur and phosphorous which are extremely poor conductors. Non-conductors are

called *insulators* and are vital in electronic circuits to confine the electric currents to the intended pathways. For example, sulfur has six electrons in the outer shell and is a crystalline electric insulator. All the lighter elements with 7 and 8 outer electrons are gases. In practice insulators are usually compounds made from two or more atoms with four or more outer electrons. For example, ordinary silicon-dioxide glass is made from silicon with 4 outer electrons and oxygen with 6 outer electrons.

Semiconductors

Just to the right of center in the periodic table are the *semiconductors*. Semiconductors, such as silicon, germanium, and carbon have a valence of 4. That is, they have half-stable outer electron shells. If enough voltage is applied, electrons can be forced to leave a semiconductor atom and the semiconductor can act like a conductor. Or, if the missing 4 electrons are supplied to the atom, it can become a temporary insulator. This ambivalent nature is exploited in semiconductors to make electronic switches and diodes that can be turned on or off. In addition, combinations of semiconductor elements have other surprising properties. Silicon solar cells turn sunlight into electricity. Light emitting diodes turn electricity into light. Other types of simple semiconductor devices detect magnetic fields, detect gamma radiation, regulate voltage, and serve as reset-able circuit breakers. Needless to say, complex matrix arrays of semiconductors are also manufactured into entire computers on a chip or visual displays.

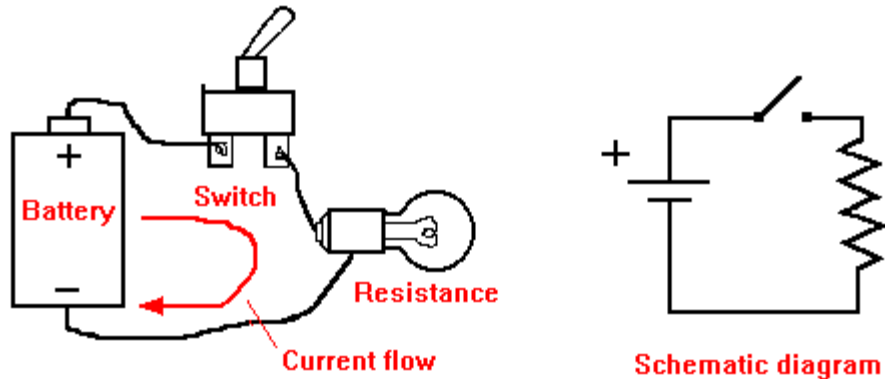
Ordinary amorphous carbon, such as charcoal, is a poor conductor, not a semiconductor. But when carbon is crystallized into graphite it becomes a semiconductor. Unfortunately, graphite is too heat sensitive to be used for transistors. Mixtures of silicon and carbon are used successfully in blue LEDs. In theory, carbon in the form of diamonds might make superb high performance semiconductors. In practice, this has been difficult and hasn't happened yet.

Some semiconductors are made from mixtures of lightweight elements with valences of 3 and 5 that give an average valence of about 4. For example, all light emitting diodes are made of mixtures like this and use a wide variety of elements. As examples, LEDs are made from silicon carbide, indium phosphide, gallium-aluminum-arsenide and aluminum-indium-gallium-phosphide. These produce red, green, yellow, blue, and even infra-red "colors."

High atomic weight elements make poor semiconductors and insulators

The neat relationship for properties of elements breaks down at the bottom of the periodic table. Heavy elements like lead and tin have 4 electrons in the outer shells. Their location in the table suggests that they should be semiconductors. However, when they react chemically, they usually just lose 2 electrons, not 4. They are good electrical conductors and their physical properties resemble zinc or copper, rather than carbon or silicon.

Arsenic, antimony, and bismuth should be insulators since they have 5 electrons in their outer shell. But as the atomic weight rises, they look and act less and less like crystalline insulators and more and more like heavy metals. Bismuth is a good electrical conductor that closely resembles lead. It wasn't fully recognized as being different from lead until 1735. All the elements heavier than the inert gas radon are conductive metals, regardless of their outer shells.



Circuit Loops

All circuits are in complete loops. Electrons must flow in complete circles or no work is accomplished. *Voltage is the force that pushes electrons around a circuit.* Voltage by itself does nothing. Only when voltage is able to push electrons through a complete circuit, does anything happen. For example, unscrew a light bulb while it's glowing. The light is extinguished because the current no longer passes through the bulb. That was obvious, but notice that current doesn't jump across the terminals inside the bulb socket and it doesn't leak out into the room. There's still plenty of voltage across the light socket terminals. You could put your finger in the socket to test it, but current would flow through your finger and, with household voltage, that is a very bad idea.

Voltage = Electrical Pressure

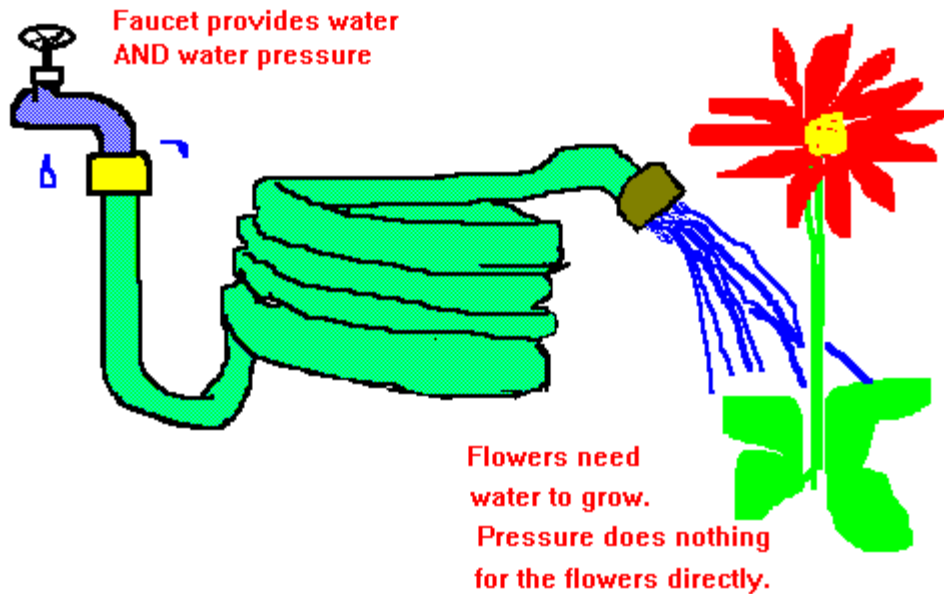
Voltage, electrical pressure, is measured in **VOLTS**. As you know, an ordinary flashlight battery has about 1.5 volts of electrical pressure. Household power in North America has about 120 volts pressure. You already know that handling 1.5 volts is harmless to people, while handling a hundred times that much is dangerous. Sticking your fingers in light sockets can be fatal. If there is enough voltage present, voltage can push an electric arc right through thin air. This feat requires about 30,000 volts per inch of air. If you're interested, you may calculate the voltage needed to generate a typical thunderbolt during a thunderstorm. Hint: This will be a really big number.

Current = The Flow of Electric Charge

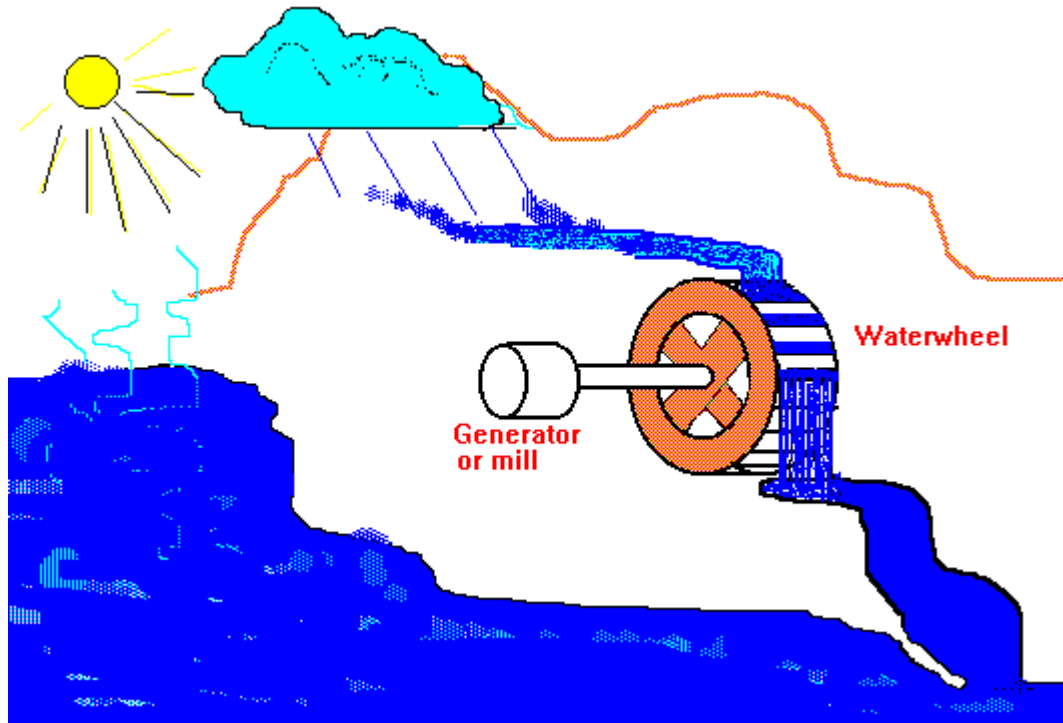
Current could be measured in terms of electrons flowing through a circuit per second but that would be unwieldy. Instead, current is measured in **AMPERES**. An ampere is defined as a coulomb of electrons flowing through a wire in one second. One coulomb equals 6.242 billion-billion electrons. Enough. Let's use amperes! In ham radio, currents larger than an ampere are only common in transmitters. The currents delivered by 12 volt power supplies usually get up into the amperes. However, most ham circuits found in receivers or signal processing deal with currents measured in milliamperes and microamperes.

One milliampere = 1/ 1000 of one ampere. (one thousandth of an ampere.)

One microampere = 1/ 1,000,000 of one ampere. (one millionth of an ampere.)

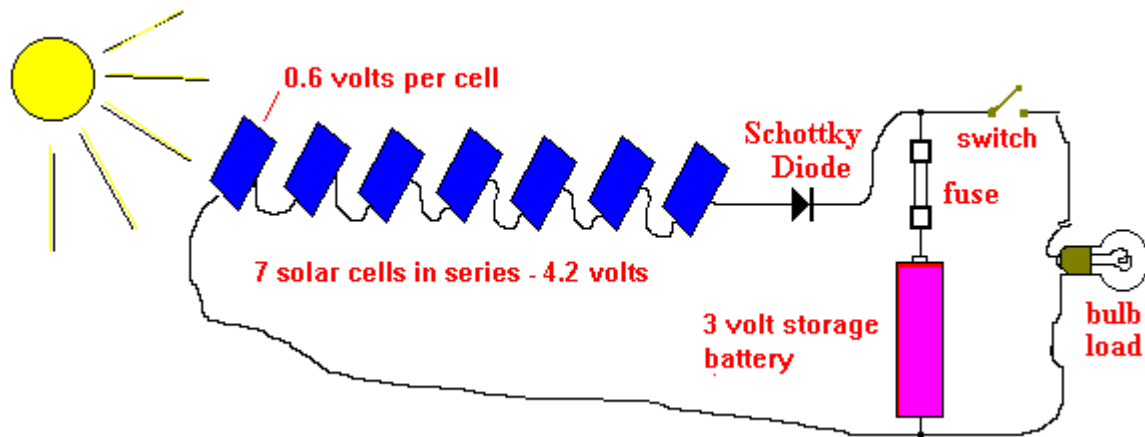


Many people have trouble keeping voltage and current straight in their minds. To the average guy electricity is zappy-shocking stuff. Maybe the following will help. Voltage is analogous to water pressure while electric current is analogous to water. A simple way to remember this is that you can't water flowers with water pressure. Alternatively, there can be lots of water in the reservoir, but pressure is needed to push it through the hose to the flowers.



Water falling as rain and flowing from the mountains down the rivers produces a cycle that is reminiscent of a complete electrical circuit loop. Sun shining on the ocean causes

evaporation that raises the water up above the mountains where it again falls as rain. In other words, the sun's energy is the "battery" that keeps the cycle going. Lifting the water into the air literally raises the potential energy of the water. Rain gathers as mountain streams and rivers that can flow through dams on the way back to the ocean. The falling water imparts its gravitational energy to the water wheel in the dam, thereby doing useful work. In other words gravity provides the water pressure.



Solar cells are devices that are the electrical equivalent of sunshine raising water vapor to high potential energy through evaporation. In a solar cell, sunshine provides the energy to "boost" electrons up to a higher energy level. In practice, each solar cell generates just 0.6 volt of potential. So, in order to charge a 12 volt car battery, at least 20 solar cells must be placed in series so that the electrons can be boosted up to 12 volts.

Power = the rate of doing work

The rate at which the water wheel does work is its "power." ***Power is defined as energy produced or expended per second.*** In ham applications power is usually measured in watts. Watts are defined as joules of energy per second. ***Joules*** are occasionally used in ham work when designing coils or figuring out how big a capacitor should be. However, you won't need them very often and they aren't needed to get through this book.

The amount of energy that can be extracted from falling water equals the volume of water times the height it falls. Notice in the water wheel above, the water is only pushing the wheel around for the upper half of the diameter of the wheel. The rest of the descent is wasted - not very efficient as drawn.

$$\text{Power} = \text{Height of fall (water pressure)} \times \text{amount of water falling (current)}$$

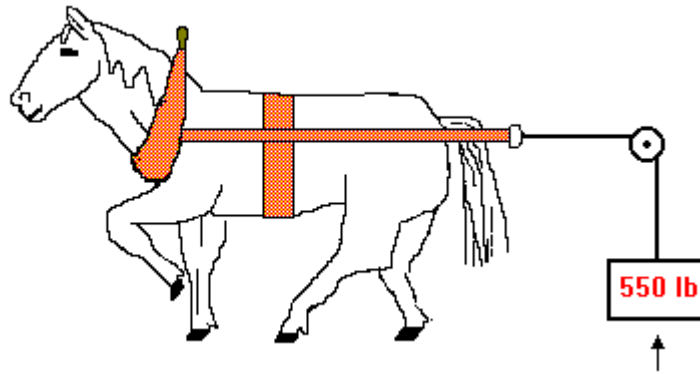
In electricity the relationship is the same:

$$\text{Power} = \text{Voltage (electrical pressure)} \times \text{Current (electrons doing work)}$$

$$\mathbf{P = V \times I}$$

Where "I" is electrical current. "I" is the letter used by engineers to represent current. No, I don't know why. Maybe it's because "C" usually stands for electrical capacitance or the

speed of light.

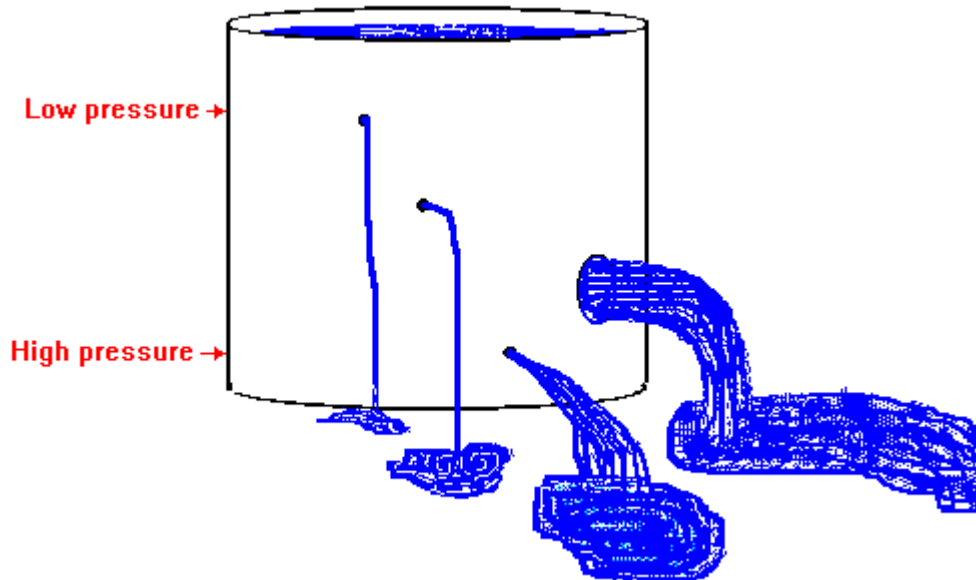


To put watts in familiar terms, power was probably first described in terms of equivalent working horses. For example, horses were formerly used to lift coal or metal ore up a mineshaft. Pulling on a pulley mine hoist, a strong horse might lift 550 pounds up one foot in one second. This was defined as one horsepower. It turns out that:

$$746 \text{ watts} = 1 \text{ horsepower} = 550 \text{ pounds lifted one foot each second.}$$

Resistance

In the water cycle analogy above, the rain falls in the mountains then makes a long journey of days back to the sea. This long journey is analogous to a high electrical resistance. In contrast, if the rain fell directly into the sea, the journey would take only a few minutes. This “short circuit” journey would be analogous to a LOW electrical resistance.



Good water analogies for electrical resistances are narrow water pipes and wide water pipes. For example, suppose a large water tank is suddenly punctured by small bullet holes and a large hole the size of a melon. Obviously the water rapidly flows out of the tank, especially the water coming out of the big hole. The speed at which the water leaves depends on the size of the

hole and the water pressure. Because of the weight of the water higher than a hole in the tank, the water pressure is much higher at the bottom of the tank than it is at the top. Therefore, water leaving from a hole at the bottom of the tank squirts out at considerable pressure, while at the top of the tank it just dribbles out slowly.

Ohm's law

Resistance is measured in ohms. The ohm is named after Georg Simon Ohm. The relationship between voltage, current, and resistance is described by Mr. Ohm's law, which says that one volt will drive one ampere through one ohm resistance.

$$\text{Voltage} = (\text{current}) \times (\text{resistance})$$

In electrical formulas V = voltage and R = resistance. Ohm's law is written as

$$\mathbf{V = I \times R}$$

If you know any two of the three parameters, you can find the missing value with algebra. Rearranging the letters we can have:

$$\mathbf{V = IR \quad \text{or} \quad I = V/R \quad \text{or} \quad R = V/I}$$

Sorry about the math, but this relationship is unavoidable for anyone who wants to succeed with electricity.

For example: You know that household electric current operates at 120 volts. Suppose that you measure the current through a 100 watt light bulb and find it to be 0.833 amperes. What is the resistance of the light bulb?

$$120 \text{ volts} = (0.833 \text{ amperes}) \times \text{Resistance}$$

$$\text{Resistance} = \text{Voltage} / \text{Current.}$$

$$\text{Resistance} = 120 \text{ volts} / 0.833 \text{ amperes} = 144 \text{ ohms}$$

The symbol for ohms is usually the capital Greek letter Omega, Ω . For example, 144 ohms might be written as "144 Ω ."

Resistors in series

When current must pass through two or more resistors in series, the total resistance is equal to sum of the resistors. For example, two 100 watt light bulbs in series will present twice as much resistance as a single bulb:

$$\text{Voltage} = 120 \text{ volts} = 0.417 \text{ ampere} \times (144 \text{ ohms} + 144 \text{ ohms})$$

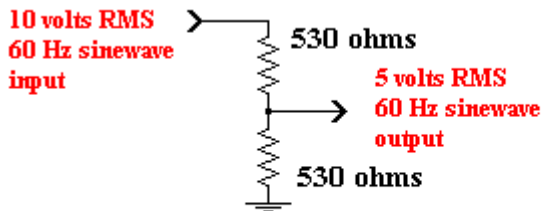
Because the current must pass through twice as many obstacles, the current flow is half and the bulbs will only burn dimly, if they light at all.

A voltage divider made from resistors

A common use for resistors is to reduce DC or AC voltages. Two resistors in series make a voltage divider. This is analogous to the remaining potential energy of the rainwater after it has returned halfway back to the ocean. In the light bulb example above, the voltage across one of the two light bulbs in series will be 50% of the total. In other words, the voltage will be reduced to 60 volts AC. In the DC electronic circuitry it is common to reduce a voltage to bias a

transistor or to control the voltage across a light or other application. The more current required at the lower voltage tap point, the lower the resistances must be to support the extra load at the reduced voltage.

In the example below 10 volts AC is divided to produce 5 volts AC. This same resistive divider could just as well divide 10 volts DC down to 5 volts DC. You'll see shortly that there are other ways to make AC voltage dividers and that is why the odd value of "530 ohms" was used in this drawing.



A Voltage Divider Made from Resistors

Resistors in parallel

When two equal resistors are placed in parallel, the resistance seen by the voltage source will be half as much as if there were one resistor. This causes twice as much current to flow. In the case of light bulbs, when you turn on twice as many lights, the current flow doubles, all bulbs burn equally brightly, and your electricity bill doubles.

When the parallel resistors are equal in size, the current they will draw is intuitively obvious. That is, each resistor receives the same current. But when the resistors in parallel are all different, then you will need to calculate the equivalent resistance using the formula:

$$\text{Resistance equivalent} = 1 / (1/R_1 + 1/R_2 + 1/R_3 + \dots \text{etc.})$$

The equivalent resistance is the inverse of the sum of the inverses of the resistances.

If there are just two resistors, then the formula is slightly less ungainly, but probably harder to remember:

$$\text{Resistance equivalent} = R_1 \times R_2 / (R_1 + R_2)$$

For example, suppose a 50 watt light bulb with a resistance of 288 ohms is in parallel with a 100 watt light bulb with 144 ohms resistance. The equivalent resistance would be:

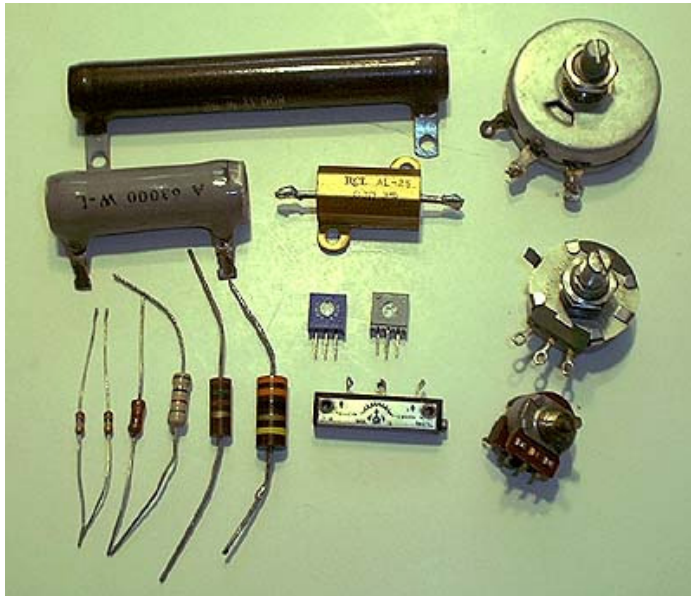
$$\text{Resistance equivalent} = (288 \text{ ohms} \times 144 \text{ ohms}) / (288 \text{ ohms} + 144 \text{ ohms})$$

$$\text{Resistance} = 96 \text{ ohms}$$

Real world resistors

The photo below shows some actual resistors. 95% of the time you will be soldering in those tiny little ¼ watt guys at the lower left. The blue and gray square plastic devices in the center are trim pots that allow you to adjust a voltage or resistance to your exact needs. The biggest resistors and the pot at the upper right are wire wound devices that can handle 5 or more watts. The controls at the lower right are the sort of potentiometers used to adjust the volume on

a receiver or stereo.



The small radial lead tubular resistors are usually marked with a 3 digit color code starting from the left. For example, at the lower center above there is a big 2 watt, 33 ohm carbon composition resistor whose resistance is labeled orange, orange, black. Orange means "3" and black means "0." The third digit tells you how many zeros to add after the two-digit number, zero zeroes in this case.

RESISTOR COLOR CODE

0 = BLACK	
1 = BROWN	
2 = RED	
3 = ORANGE	
4 = YELLOW	
5 = GREEN	
6 = BLUE	
7 = VIOLET	
8 = GRAY	
9 = WHITE	

If the THIRD band is silver or gold, it means the decimal multiplier is fractional.

SILVER = 0.1
GOLD = 0.01

When silver and gold appear as the 4th band, this is the precision of resistor value.

SILVER = 10% Tolerance
GOLD = 5% Tolerance

The fourth colored bar is "gold" which means the resistance value is guaranteed to be within 5% of the above value. If the color were silver, the tolerance would be 10% and no color would mean 20%. These days resistors more imprecise than 5% are rarely encountered.

On the other hand, *if the 3rd band is silver or gold, the decimal multiplier is less than one, 0.1 or 0.01 respectively.* I suggest you check these with a ohm meter before you use them. 1% precision resistors have another bar for a third significant digit. Occasionally another colored bar, usually yellow like the 33 ohm resistor above, is at the opposite end of the unit. This means that the resistance will not drift significantly after thousands of hours of use. When in doubt, use your ohm-meter!

Batteries

A battery is a voltage source that delivers electrical current as a result of a chemical reaction. The battery contains two chemicals that react together to produce a third chemical compound. Nearly all of the energy released by the reaction takes the form of electricity. When

the supply of the original two chemicals is exhausted, the reaction and the electricity stop. The battery is then “dead.” But as you know, some types of batteries can be recharged. This is done by applying a voltage higher than the nominal battery voltage to the same battery terminals. Current flows back into the cell, reverses the original chemical reaction, and restores the original charged state. For example, lead-acid car batteries are designed to be recharged. Others, such as alkaline batteries, can only be recharged with difficulty and may leak or burst. Lithium batteries are tricky to recharge and this may even cause them to catch fire. For example, the Tesla electric car uses rechargeable lithium batteries, however the batteries are immersed in cold freon to dissipate the heat and avoid a fire. The radiator under the hood cools the freon, not the motor.

The voltage and capacity of batteries can be compared to pressure and volume of water tanks. A really large battery, such as a single battery cell in the bank of batteries in a submarine, can have a huge capacity and may be able to supply hundreds of amperes for hours. But in spite of its great size, it might only be able to supply two volts of electrical pressure. In a submarine there might be a hundred or more of these huge cells in series to supply 200 volts to the electric motors. In terms of analogous water tanks, a large low voltage battery is comparable to a large cattle watering tank, perhaps twenty feet wide but only one foot deep.

A car battery is the biggest battery most people ever see. In order to start a car on cold mornings, the car battery must deliver hundreds of amperes for several seconds. It does this through LARGE copper wire cables. These are the thickest electrical wires under the hood. If you tried to use thin wires for this load, the wires would melt in seconds. How much power does it take to start your car in January?

$$\text{Power} = 12 \text{ volts} \times 200 \text{ amperes} = 2,400 \text{ watts}$$

or, $\text{Power} = 2,400 \text{ watts} / 746 \text{ watts/ hp} = 3.2 \text{ Horsepower.}$

In contrast, an ordinary 9 volt alkaline transistor battery has six tiny 1.5 volt cells in series for a total of 9 volts. Each cell is only rated at delivering about 1/2 ampere (550 milliamperes) for one hour. In terms of power, this is about 4.5 watts.

$$\text{Power} = 9 \text{ volts} \times .55 \text{ amperes} = 4.5 \text{ watts}$$

Notice that a little battery with several cells in series would be analogous to a tall water tank with low volume. For example, suppose a pump is located at the bottom of a well one hundred feet down. The pipe might be only an inch in diameter. Therefore a hundred feet of this pipe will only contain a few gallons. But the pressure at the bottom of the pipe will be huge, 123 pounds per square inch. In municipal water systems the water is stored in big tanks up on towers to provide both water pressure and a significant reserve of potential water flow.

Electrical conductors are comparable to holes punched in the water tank. Fine wires have higher resistance than fat wires made of the same material. Metals like copper and silver have such inherently low resistance that the difference in conductivity may not be obvious. But in a conductor like carbon, a fat stick of carbon will have far less resistance than a thin fiber of carbon such as the carbon fibers Edison used in his first commercial light bulbs.

Electrical Power

What is the power consumed by the light bulb? Or more familiarly, what is the light bulb “wattage?”

$$\text{Power} = \text{Volts} \times \text{Current}$$

$$\text{Power} = (120 \text{ volts}) \times (0.8333 \text{ amperes}) = 100 \text{ watts.}$$

Another way to calculate power is often useful when the voltage isn't known:

$$\text{Power} = \text{Resistance} \times (\text{Current})^2$$

$$\mathbf{P = I^2 \times R}$$

Substituting for voltage from above,

$$\text{Power} = (\text{Current} \times \text{Resistance}) \times \text{Current}$$

$$\text{Power} = \text{Resistance} \times (\text{Current})^2$$

Or, if you only have voltage and resistance,

$$\text{Power} = (\text{Voltage})^2 / (\text{Resistance})$$

$$\mathbf{P = V^2 / R}$$

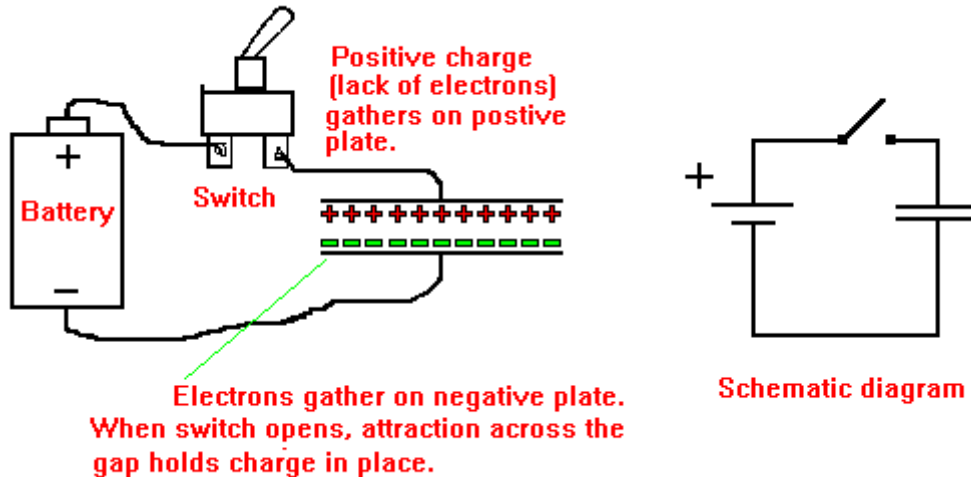
For example, $100 \text{ watts} = (120 \text{ volts})^2 / 144 \text{ ohms}$

Capacitors

Capacitors are devices that store electric charge, much like a rechargeable battery. Capacitors are usually made from two parallel plates of conductive metal separated from each other by a thin layer of insulation. The insulation can be air, paper, plastic, mica, or even vacuum. When the two plates are connected to the poles of a battery, charge rushes into the capacitor by means of wires. Since positive charge is attractive to negative charge, the charge gathers on the plates as if it were "trying" to jump across the gap. Because the voltage from the battery has established the same uniform voltage across the plates, the charge gathered on the plates of the capacitor will maintain that voltage, even after the battery is disconnected from the battery. The charge is held on the plates by the force of attraction from the opposite plate.

The amount of charge a capacitor can store is directly proportional to the area of the plates and how little insulation separates the plates. The less distance between the plates, the more charge it can store. Of course the more thin the insulation, the more likely it is to break down with high voltages. So voltage rating and capacitance are opposing characteristics.

If a charged capacitor has high quality insulation that doesn't leak charge across the gap, the capacitor will store energy in the form of trapped charge indefinitely. For example, large, low voltage capacitors are sometimes used to maintain computer RAM memory when the rest of the computer is turned off. However, with present technology capacitors rarely seriously rival electrochemical batteries as a long-term energy source.



In a capacitor the electrons gathered on the plates establish an electric field across the gap. Another way to look at a charged capacitor is that the electric field across the insulation stores energy, just as a magnet stores energy in the magnetic field in and around the body of the magnet.

The Voltage Across a Capacitor Can't Change Instantly.

In electronics, the single most important property of capacitors is that ***the voltage across a capacitor can't change instantly***. The current flowing into or out of a capacitor can change immediately, but the voltage can't change until more charge has been stored or charge has been removed. In other words, current must flow into or out of a capacitor before its voltage can change. In contrast with a capacitor, the voltage across a resistor and the current flowing through it are proportional and change instantly. With resistors, voltage and current are always strictly related by Ohm's law. Ohm's law works with capacitors only when the driving voltage is a continuous sinewave operating at a constant frequency.

Capacitors are commonly used in circuits in four different ways:

1. They store energy for short periods of time.
2. Because capacitor voltage can't change instantly, capacitors are used to smooth out or regulate voltages and hold them constant. For example, direct current (DC) power supplies use large capacitors to hold the direct current at a constant voltage.
3. Capacitors are used to separate AC signals from DC. Capacitors "conduct" alternating current much like resistors, but because of the insulation layer, capacitors block the flow of direct current. When alternating polarity voltage is applied, current rushes in and out of the capacitor. The alternating current *appears* to be flowing through the capacitor.
4. Capacitors are used with inductors to form resonant circuits. Capacitor/ inductor resonant circuits are the core of radio technology and will be discussed in detail later.

Farads

The storage capacity of capacitors is called "***capacitance***" and is measured in **FARADS**.

One farad of capacitance is a huge capacitor. Although you can buy such a novelty, the insulation between the plates is generally very thin and will only tolerate low voltage, usually just a few volts. In low frequency audio electronics and power supplies the capacitors used are usually measured in MICROFARADS, one millionth of a farad.

Microfarads are sometimes written as " μF " where the Greek letter μ is short for "micro." For example, a large 10,000 microfarad capacitor might be labeled "10,000 μF ."

Capacitors store electrical charge, which is measured in **COULOMBS**. A coulomb of electrons is 6.242 billion-billion electrons. A common electronics laboratory practical joke involves charging up a large capacitor say, 10,000 microfarads, to greater than 20 volts. The capacitor is then tossed to a victim. "Hey, Joe, catch!" Joe grabs it and receives a big jolt as it discharges through his fingers.

A defibrillator for restoring normal heart rhythm works on this principle. A large capacitor is typically charged to about 400 joules of energy - that is, 400 watts for one second. The capacitor is then discharged through large paddles placed across the victim's chest. Being defibrillated is a horrific jolt and can be fatal if misapplied.

Notice that any conductive object isolated from a second conductor by an insulator comprises a capacitor. For example, your saltwater-filled body is a conductive object. If you're wearing insulating rubber soled shoes and standing on a metal floor, you are now a capacitor with respect to the floor. Your body capacitance might typically be, say 50 picofarads. A picofarad is one millionth of a millionth of a Farad. This sounds trivial, but it is not.

If the humidity is low and your body becomes charged as you scuff your feet on the wool carpet, your body can be charged up to thousands of volts potential. Fortunately only a tiny amount of charge gathers on your body, typically far less than 1 microcoulomb. Otherwise you might be electrocuted instead of just jolted when you touch a metal object. This phenomenon becomes important when handling integrated circuits and transistors. Discharging your body capacitance into an integrated circuit can instantly ruin it. ***Always ground your body before touching chips and transistors, especially chips made from field effect transistors.***

Capacitors in parallel are calculated like resistors in series

If two capacitors are placed in **parallel**, the storage capacity of the pair is the sum of the two. This is easy to visualize. If the capacitors are equal, then the size of the parallel plates doubles while everything else remains the same.

$$\text{Total capacitance} = C_1 + C_2 + C_3 + \dots \text{etc.}$$

When capacitors are in series, the calculation resembles resistors in parallel. Capacitors in series have less ability to store charge, but they gain extra insulation and can withstand higher voltage. The voltage rating of a capacitor is called its **working voltage** or "**WV**."

$$\text{Equivalent Capacitance} = 1 / (1/C_1 + 1/C_2 + 1/C_3 + \dots \text{etc.})$$

If you have just two capacitors in **series** they may be calculated like resistors in parallel

$$\text{Equivalent Capacitance} = C_1 \times C_2 / (C_1 + C_2)$$

The current that flows into a capacitor moment to moment while the capacitor is charging can be calculated using relationships that are based on Ohm's law. Unfortunately, to express a

formula that will work in all cases of changing voltages requires a differential equation. In general,

$$I = (dV/dt) / C$$

Where t stands for time and C = the capacitance in farads. "dV" means "the differential of voltage and dt means the differential of time.

Life is too short for hams to get too far into calculus, unless of course it happens to fascinate you. Fortunately for most of us we rarely need it. There are special cases in which we can do simpler calculations to get what we need. For example, from the point of view of an AC sinewave current, capacitors look like resistors. That is, the capacitor takes a finite amount of time to charge and discharge. Therefore, when a sinewave voltage is applied to a capacitor, the current flowing in and out of the capacitor will be limited by how much voltage is already charged across the capacitor.

At one extreme when the frequency is infinitely high, the capacitor has an equivalent resistance of zero – a short circuit. At the opposite end of the spectrum, to a DC current, the capacitor just looks like an open circuit. That is, it will have infinite resistance. After all, the capacitor is just an insulator separating two conductors. And if the charging voltage hasn't changed in ages, no current will be flowing into or out of the capacitor.

Capacitive reactance

At frequencies between zero and infinity a capacitor resists sinewave current flow as if it were a resistor. You can calculate the equivalent resistance or *capacitive reactance* as follows:

Reactance in ohms = $1 / [2 \pi (\text{Frequency}) (\text{Capacitance in Farads})]$

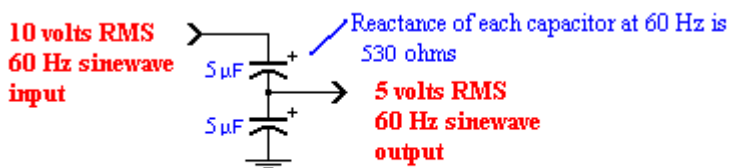
$$X_C = 1 / (2 \pi f C)$$

Where π is "pi" or 3.1416

For example, the reactance of a 5 μ Farad capacitor at 60 Hz is:

$$X_C = 1 / [2 \pi (60 \text{ Hz}) (5 \mu \text{ F})] = 530 \text{ ohms}$$

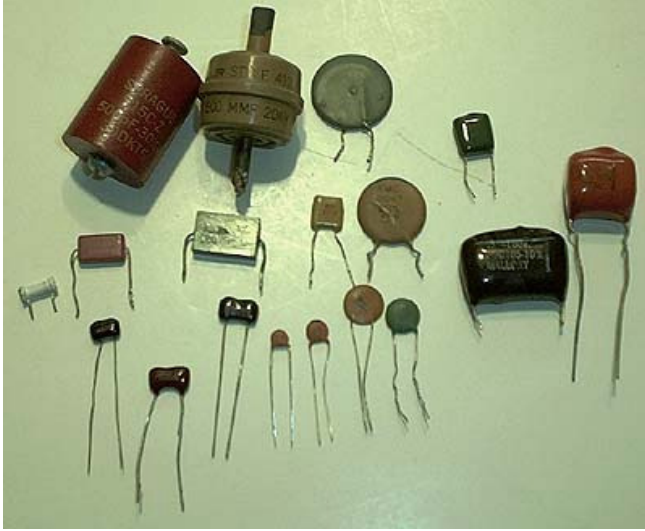
We can use this resistance-like property to attenuate sinewave signals or make voltage dividers. For example, two 5-microfarad capacitors in series can divide the voltage of a sinewave in half.



A Voltage Divider Made from Capacitors

Unlike a comparable divider made from 530 ohm resistors, no energy would be dissipated in the capacitors, so they don't get hot and they don't waste energy.

Real world capacitors



On the left is an assortment of fixed capacitors that have ceramic or mica insulation. Large capacitors either have high capacitance, high voltage ratings, or both. The "door knob" capacitors at the top are rated for 30,000 and 20,000 volts and are used in picture tube power supplies. Mostly you will be using the small mica and ceramic capacitors in the lower row. In ham equipment they typically range from 2 pico-farads (2 micro-micro-farads) up to about 0.5 microfarads.

The material used as insulation also partly determines the capacitance. If a vacuum is used as an insulator, it has a *dielectric constant* defined as 1.000. All other materials produce more capacitance, assuming that the area and thickness are equal. Mica, plastics, and various oils all have constants ranging between 2 and 10. Different dielectrics vary in cost and temperature stability. In general, for radio applications, mica and low dielectric constant ceramics have the best temperature stability and the least energy dissipation. There are many kinds of high dielectric constant ceramic capacitor types, but the penalties are always heat and temperature instability. Pure water is a poor to fair insulator, dissipates a great deal of heat, but it has a high dielectric constant of 80.

Electrolytic capacitors

Capacitors larger than roughly 1 microfarad are nearly always *electrolytic capacitors*. In the capacitive voltage divider shown earlier, the little + signs over the 5 μF capacitor symbols mean they are electrolytic capacitors. It also means that, when you wire them into a circuit, you must wire them so that the + mark is oriented to line up with the polarity of any average DC voltage that might be applied to the capacitor. In the example above, the polarity would not matter because the capacitors are only exposed to AC voltage.

An electrolytic capacitor achieves high capacitance by means of two tricks: First, the insulator is an oxide layer electrochemically plated onto a thin sheet of aluminum or tantalum metal. The oxide layer serves as the insulator and can be microscopically thin. Capacitance is inversely proportional to the distance between the plates, so the thinner the insulator, the higher the capacitance. Because the insulation is chemically bonded to the metal, there are no gaps between the metal and insulation and the contact is as intimate as possible.

The second trick is that, although one pole of the capacitor is the metal sheet, the other pole is an electrolytic solution, a salt bath. The fluid is in extremely intimate contact with the insulation, so that the effective gap between the two conductive bodies is truly tiny, just a few molecules thick. Aluminum oxide and tantalum pentoxide insulation have dielectric constants of 8.4 and 28, which also explains their high capacitance. I was intrigued by a list of dielectric constants in the ARRL handbook that gave the dielectric constant for titanium dioxide as 80. Unfortunately I've never seen any titanium oxide capacitors in catalogs. No doubt they have some severe practical disadvantage - probably the usual heat and low breakdown voltage

problems.

Electrolytic capacitors must be wired with the correct polarity

Now the bad news: *Electrolytic capacitors are polarized*. In other words, if they are used in a circuit with a DC voltage, they must be oriented in the circuit so that one pole is always positive and the other is always negative. If the electrolytic is wired backwards, the DC current will corrode the insulating layer of oxide and the capacitor will eventually short out. When the short occurs, the aluminum capacitor usually makes a loud bang and vents a cloud of foul smelling steam. A shorted tantalum capacitor may even burst into flames. *It is extremely exciting to have an electrolytic go off in your face*. There are homebrewers who *have had* this experience and the rest who eventually *will have* this experience. Always make an extra effort to be sure the polarity is correct. This is especially vital in DC power supplies where the capacitor is continuously subjected to the same polarity.

Fortunately, in low frequency circuits it's OK if the polarity is briefly reversed. For example, if an electrolytic capacitor is used to drive a high power HI-FI speaker, the audio signal voltage is both positive and negative as the music current signal goes through it. But when there is no sound present, the capacitor must be oriented so that the local DC voltage has the correct polarity across the capacitor. There are also special capacitors called *non-polar electrolytics*. They are made from two electrolytic capacitors back to back. They are generally more than twice as large as a polarized electrolytic capacitor of the same capacitance.

Real Electrolytic capacitors

An assortment of electrolytic capacitors is shown below. The tiny ones on the left are all tantalums. Tantalums are generally less than 100 microfarads and have working voltages less than 35 volts. The modern ones are all encapsulated in plastic or epoxy while the older tantalums often have metal cases. The big capacitors on the right are aluminum electrolytics. The largest is rated at 120,000 μF at 10 volts DC WV.



INDUCTORS

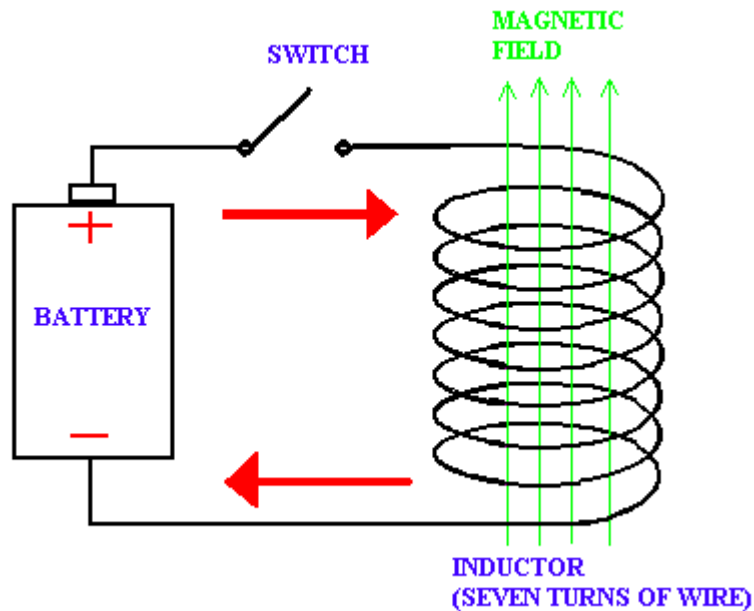
Inductors are the functional opposite of capacitors. Remember that the voltage across a

capacitor cannot change instantly. In contrast, *the current through an inductor cannot change instantly*. Whenever electrons flow through a wire, a magnetic field appears in the space surrounding the wire. This energy floats in the space surrounding the wire. Since the energy is real, it doesn't appear without a cost. The price paid for establishing the field is that energy must be expended in the wire to "charge up" the magnetic field before the electrons can pass through. When the current first begins to flow, the wire appears as a "resistance" for a moment. Then, after the field has been established, this pseudo-resistance drops to zero and the direct current flows through unimpeded.

This property of wires is called "*inductance*." The longer the wire, the more inductance it has. Inductance is measured in **Henries**. It is named after Joseph Henry, an English Physicist who first described this phenomenon. In equations, inductance is usually represented by "**L**," which doesn't make much sense.

Inductor design

The picture below shows several turns of wire wound into an "*inductor*." A coil of wire like this has more inductance than would be expected from a straight length of the same wire. The magnetic fields from each turn overlap, reinforce each other, and gather in the center of the coil.



The more turns in a coil, the more inductance it generates. In fact, the inductance is proportional to the square of the number of turns. Therefore a seven-turn coil like the one above has 7^2 or 49 times more inductance than a single turn coil would have. Notice that the magnetic field produced by this coil is a genuine magnet. In fact, it will lift iron filings. Heck, big electromagnets like this are used in junkyards to lift cars! Unlike a refrigerator magnet, this magnet can be turned on and off using the switch.

If you wanted to build a big electromagnet of the junkyard variety, an air-core coil like the one above would be impractical. By the time you had wound enough turns to generate a field

strong enough to lift a car, you would need miles of wire. Miles of fine wire would have a huge electrical resistance. This is not the kind of resistance called “impedance” or “reactance”, but just the resistance of the copper metal that makes up ordinary wires. To push big currents through a high resistance takes a high voltage, high current power source. If you actually did that, all those turns of fine wire packed together in a coil would get hotter than blazes. As we saw above, power = current times voltage. A high resistance coil would be in danger of melting because the energy dissipated in it would be so high.

As permanent magnets demonstrate, magnetic fields require no power consumption at all once the field has been established. A current is only needed to generate a magnet field. In a permanent magnet, the electrons orbiting around the iron or other magnetic atoms provide the current. No outside power is needed to keep those electrons orbiting, so a permanent magnet can generate the field forever. In theory, superconducting wire can be wound in a closed loop to produce a permanent magnet by having a current circulating through the loop endlessly without loss to form a permanent magnet. In practice, the unavailability of high current, high temperature superconducting wire makes this dream impractical.

Instead, ordinary iron can be “recruited” to form a magnet even when it is not already crystallized with all the magnetic atoms lined up in the same direction. *Electro-magnets are constructed by winding a coil around a piece of iron.*

The Current Through An Inductor Cannot Change Instantly

In electronics, the single most important property of inductors is that *the current through an inductor can't change instantly*. The voltage across an inductor can change immediately, but the current can't change until the magnetic field surrounding the inductor has been augmented or decreased. In other words, voltage must change across the inductor to force a change in the current and its corresponding magnetic field. In summary, inductors are the opposite of capacitors. As with capacitors, Ohm's law works with inductors only when the driving voltage is a continuous sinewave operating at a constant frequency.

Inductors are used commonly in electronic circuits in four ways:

1. Inductors are used to prolong the flow of current into a resistance and hold the current constant. This prevents surges of currents that might otherwise damage other components. They are used in filters of various kinds to regulate voltage and currents.
2. Inductors generate magnetic fields that attract iron and produce motion. Consequently, inductors are a component of relays, solenoids, motors, and loudspeakers.
3. Inductors, as part of transformers or acting alone, are used to change voltage levels up or down.
4. Inductors are used with capacitors to form resonant circuits. Capacitor/ inductor resonant circuits are the core of radio technology and will be discussed in detail later.

Inductance is measured in Henries

The unit of inductance is the *Henry*. A Henry is a relatively large inductor. An inductor that large nearly always has an iron core and is often used in low frequency applications like power supplies. At radio frequencies a microhenry is a significant inductance. As you will see,

most radio circuits use inductors in the range of 1 to 100 microhenries. The energy handling ability of inductor is rated in *amperes*. For example, suppose a small inductor is rated at 1 millihenry at 100 milliamperes. If you put more than 100 mA through it, the wire might burn up or, if it has an iron core, the iron might saturate and the inductance will drop dramatically to much less than its 1 mH rating. Iron cores and saturation will be discussed in more detail shortly.

Inductors in series

When current must pass through two or more inductors in series, the total inductance will be equal to the sum of the inductors. When two equal inductors are placed in series, the current must pass through twice as many obstacles, the current flow will charge up the inductors half as rapidly, but twice as much magnetic field energy will be stored.

To calculate the equivalent inductance of several inductors in **series**, just add up the separate inductances, just like series resistors.

$$\text{Inductance equivalent} = L_1 + L_2 + L_3 + L_4 + \dots \text{ etc.}$$

Inductors in parallel

When two equal inductors are placed in **parallel**, the inductance seen by the voltage source will be half as much as if there were one inductor. This causes twice as much AC current to flow and the magnetic field energy will charge twice as fast and be half as large.

When the inductors are equal in size, the AC current they will draw when in parallel is intuitively obvious. But when the inductors in parallel have different inductances, then you will need to calculate the equivalent inductance using the formula:

$$\text{Inductance equivalent} = 1 / (1/L_1 + 1/L_2 + 1/L_3 + \dots \text{etc.})$$

That is, the equivalent inductance is the inverse of the sum of the inverses of the inductances. If there are just two inductors, then the formula reduces to the same as it did with resistors:

$$\text{Inductance equivalent} = L_1 \times L_2 / (L_1 + L_2)$$

Calculating sinewave current flow through inductors and the voltage across them can be done using Ohm's law. Unfortunately, just like capacitors, when the current is not a constant sinewave, the calculations are tricky because the current flow is time dependent. To do it correctly in a way that works under all circumstances requires a differential equation, the inverse of the differential equation for capacitance. Specifically,

$$\text{Voltage (t)} = L \, di/dt$$

Where t is for time and L = inductance in Henries. Why "L"? Inductance could have been "I," but that stands for current. Fortunately, hams hardly ever need to make these calculations. However, when the changing current is a sinewave, the voltage or equivalent resistance (*inductive reactance*) of an inductor is easy to calculate.

Inductive reactance

From the point of view of a constant AC sinewave current, inductors look like resistors. At one extreme, if the frequency is infinitely high, the equivalent AC resistance is infinite. At the opposite end of the frequency spectrum, to a DC current the inductor just looks like a long piece of copper wire. In other words, at DC a perfect inductor would have zero resistance.

At frequencies between zero and infinity an inductor resists sinewave current flow as if it were a resistor. You can calculate the equivalent resistance or *inductive reactance* as follows:

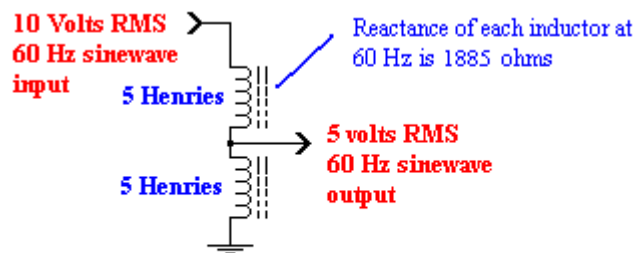
Reactance in ohms = 2π (frequency) (Inductance in Henries)

$$X_L = 2 \pi f L$$

For example, the reactance of a 5 Henry inductor at 60 Hz is:

$$X_L = 2 \pi (60 \text{ Hz}) (5 \text{ H}) = 1885 \text{ ohms}$$

Like capacitors, inductors can be used like resistors to attenuate currents or divide voltages. For example, two 5-Henry inductors in series can divide the voltage of a sinewave in half. Unlike a comparable divider made from 1885 ohm resistors, virtually no energy is dissipated in the inductors.

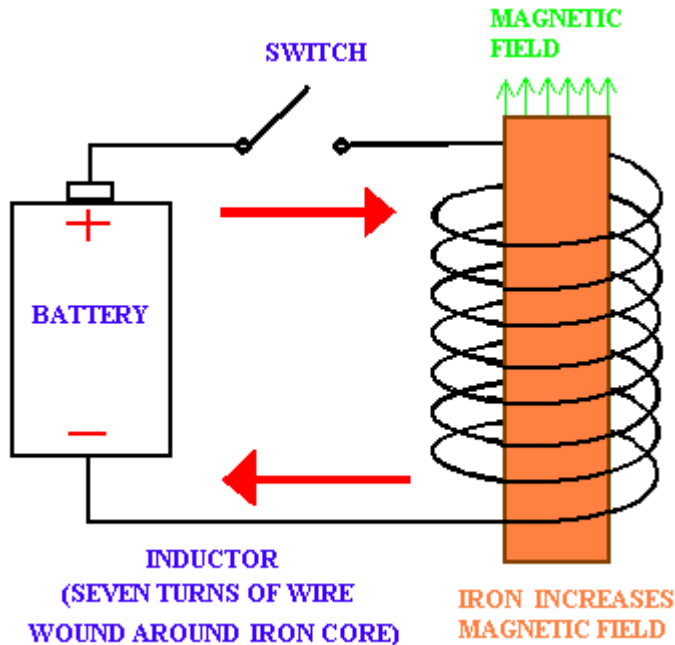


Voltage Divider Made From Inductors

If you wanted 530 ohms reactance like the previous voltage dividers, then you can solve for the inductance starting with 530 ohms. As you can see, smaller reactance means a smaller inductance.

$$530 \text{ ohms} = 2 \pi (60 \text{ Hz})(L), L = 1.4 \text{ Henries}$$

Iron core inductors

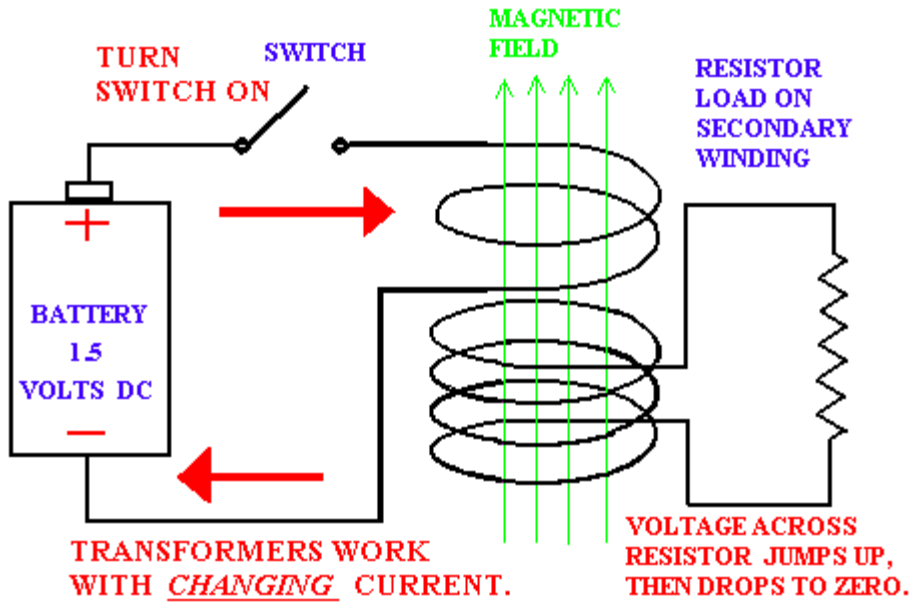


An iron bar placed inside a coil of wire greatly increases the inductance and the magnetic field energy by orders of magnitude. This is how high-force electromagnets are made. In the divider circuit above the dashed lines next to the inductor symbols means that the inductor has an iron core. In practice, any inductor larger than about 0.1 Henry will nearly always have an iron core to achieve such high inductance. If room temperature superconductors ever become practical, this may change. But for now, large inductance means iron core.

Transformers

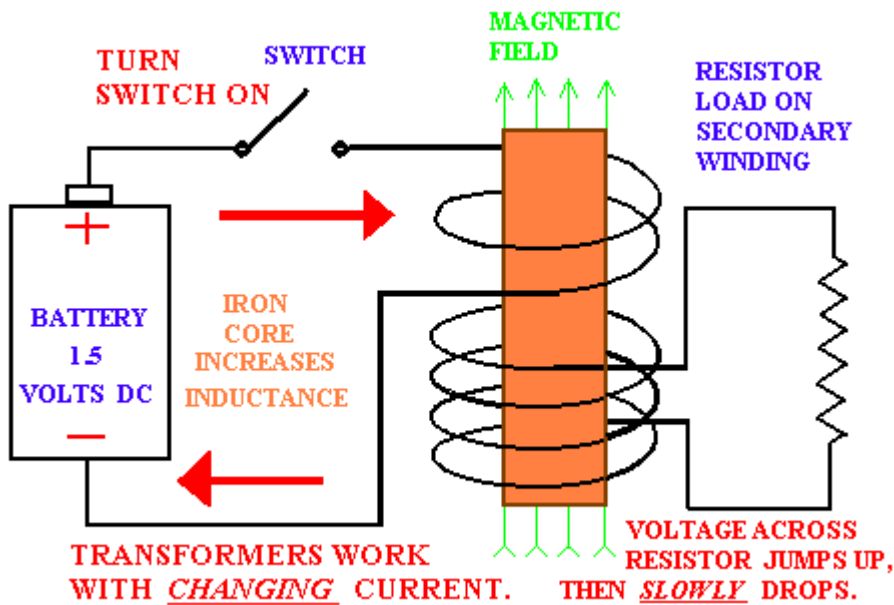
Transformers are devices consisting of two or more inductors that share the same magnetic field. Suppose the two coils are placed next to each other so that the magnetic field from one coil will pass through the other:

A changing magnetic field couples energy from one coil to another. If we put a voltmeter or oscilloscope across the resistor on the secondary coil, we will see a voltage jump up from zero, then immediately fade back down to zero as the magnetic field in the coils is being established. Once a static magnetic field is established in the primary winding, there will be no voltage across the secondary winding and resistor.



Iron core transformers

Putting an iron core inside a transformer vastly increases the inductance of the windings. This greatly enlarges the size and duration of the voltage spike observed across the secondary coil.



Unfortunately, ordinary iron not only generates magnetic fields, it is also a conductor of electricity. As you know, the copper windings are loops of conductive metal. Similarly the iron core is a solid mass of conductive metal. Consequently, the iron acts like a array of shorted loops competing with the copper windings for current flow. As a result a simple iron transformer like the one above works poorly unless the changes in the current are very slow. That is, so long as

the current changes take place slowly, like manually turning an electro-magnet on and off, then it works OK. But as the switch is thrown faster and faster, more and more energy is wasted in circulating currents inside the iron.

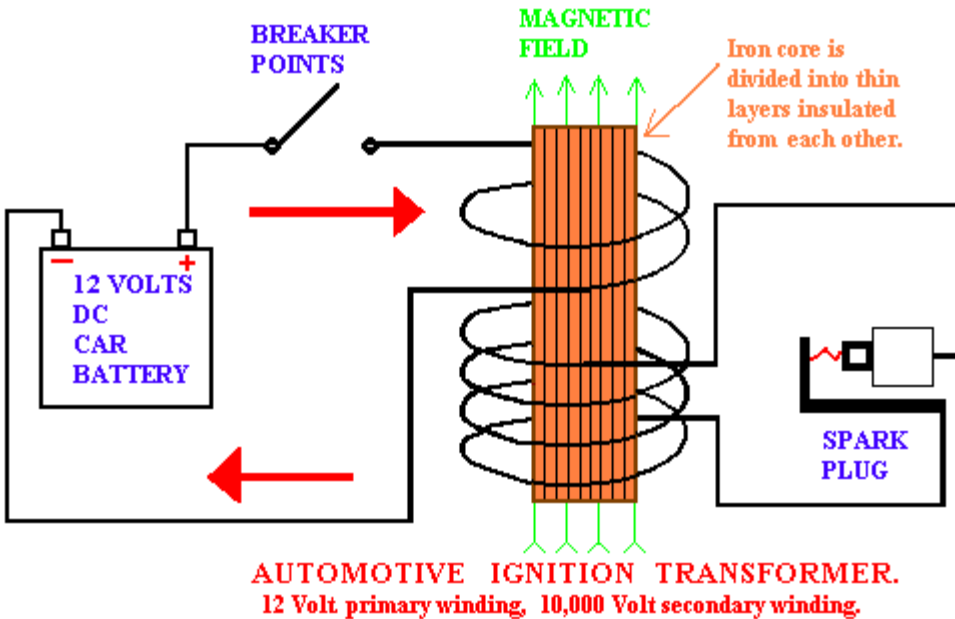
Real inductors



An assortment of inductors is shown on the left. The kinds usually used in modern homebrew ham equipment are in the bottom row. The tiny metal cans are shielded miniature IF transformers used in superhetrodyne receivers. The tiny chokes at the lower left resemble resistors and use the same color codes. I used lots of these in the designs in this book. The big coils, "chokes," and iron transformers were common in vacuum tube transmitters 50 years ago.

An automobile spark coil

Subdividing the iron core into vertical slats of iron (or better yet, silicon steel) ameliorates the problem of circulating currents. This forces the currents to circulate into tiny loops that don't waste so much energy. The figure directly below shows a simplified ignition system for an automobile. The switch in this case is the breaker points in the distributor. In modern cars, the switch is actually a transistor, but the function is the same as the old-fashioned mechanical breaker points. Since the engine can fire many thousands of times per second, the rates of change of the currents in the primary are fairly high.



Voltage step up and current step down

A vital characteristic of an automobile ignition transformer is that the voltage across the secondary must be extremely high. Without the high voltage, the spark would not jump across the spark plug gap. *Voltage is raised by having far more winding turns on the secondary than there are on the primary.* An important use for transformers is to change varying (AC) voltage up or down by increasing or decreasing the number of turns on the secondary.

Ignition systems are an unusual circuit in that the secondary is an open circuit, a spark plug. When the breaker points suddenly *open*, the inductor current must remain constant. The result is that the voltage soars to an extreme level – theoretically an infinite voltage - causing the spark to jump the gap. In practice, a capacitor across the breaker points is needed to force the energy over to the secondary winding. Unlike the inductor, the capacitor can't change its voltage suddenly and this prevents sparks from occurring at the breaker points as well as the spark gap.

Power out of the secondary (nearly) equals the power into the primary winding

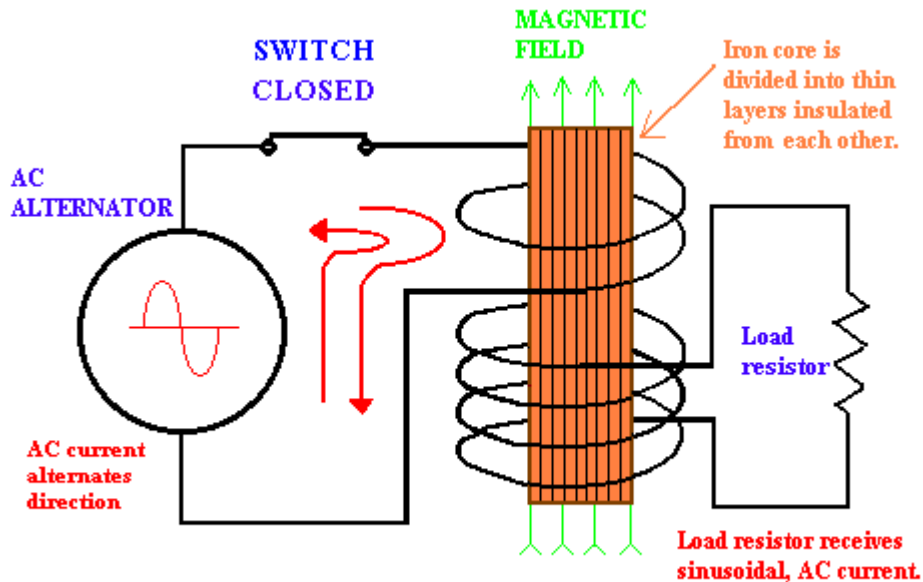
A transformer “transforms” the ratio of current to voltage for AC currents. In other words, if the voltage is stepped up, the current in the secondary will be proportionately stepped down. The power into and out of the transformer remains the same.

$$\text{Power in} = (\text{Voltage in}) \times (\text{Current in}) = \text{Power out} = (\text{Voltage out}) \times (\text{Current out})$$

Generation of sinewave currents

An *alternator* is a device that generates low frequency AC current. How it works will be discussed in detail shortly. But for now let's just use it to deliver an AC voltage to the primary of a transformer. In contrast to a simple switch and battery, the alternator generates alternating sinewave current. When the sinewave from the alternator is fed into the primary winding of a transformer, the secondary winding will have a continuous sinewave on it, just like the primary. The voltage that appears across the secondary will be proportional to the ratio of the numbers of

turns on the primary and secondary. For example, as drawn below, there are twice as many turns on the secondary as on the primary. Therefore the secondary voltage will be twice as high as the primary voltage. Similarly, the secondary current will be half as great as the primary current.

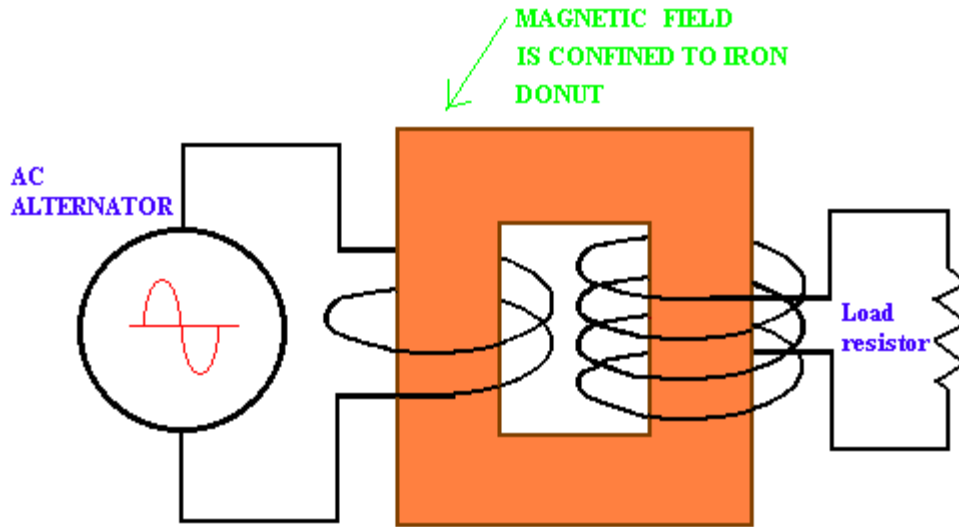


For example, if we wish to step up 12 volts AC to 120 volts AC with a sine wave, the secondary must have $120 \div 12$ or ten times more turns.

Earlier I explained the voltage-boosting phenomenon of open circuit inductors. Now suppose we were going to use AC to generate 10,000 volts for an ignition system. If ignitions ran on AC sinewaves, instead of using DC and breaker points, then the secondary winding would have to have 833 time more turns than the secondary, $10,000 \text{ volts} \div 12 \text{ volts} = 833$.

Toroidal or closed loop transformer cores

The best coupling efficiency is achieved when the magnetic field is confined to the iron core and is not allowed to fill the space around the transformer. Also, the amount of inductance per turn of wire that can be achieved is the highest when the iron core is a closed loop. In the drawing below, the thin donut-like, iron plates making up the core are stacked going away from the observer and so they are not shown.

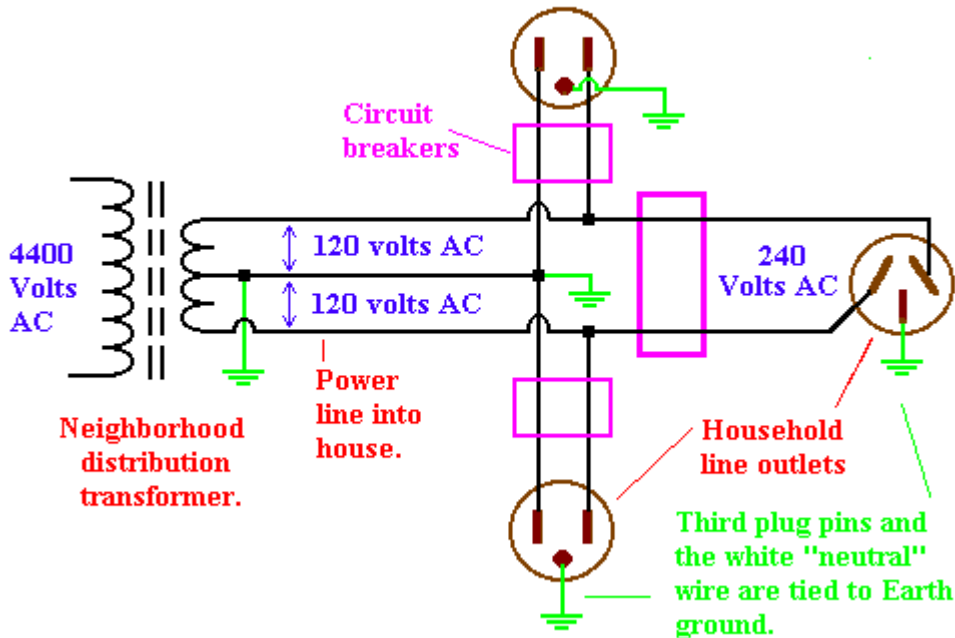


TYPICAL 60 HZ IRON TRANSFORMER
Iron core made from laminated sheets of silicon steel.

Household power distribution

In North America electric power comes into our homes in the form of 240 volts alternating current on THREE wires. This power source is referenced to ground. The reference point is not one of the two hot wires, but is ground located halfway in voltage between the two live wires. We use the two 240 volt AC wires for our 240 volt stoves and electric clothes driers.

HOUSEHOLD POWER DISTRIBUTION



Most of our lights and appliances in the U.S.A. are powered with 120 volts AC. This

voltage is obtained by tapping between one of the “hot” 240 volt wires and ground. Inside your circuit breaker box there are two **buss bars**. These are the 240 volt terminals to which all the circuit breaker units are attached. A third buss located between the first two is the ground terminal. The big 240 volt breakers snap onto the outer terminals. The smaller 120 volt breakers clamp onto the center ground and either one of the two 240 volt side rails. Clever, huh? Now you can obtain two different AC voltages from the two 240 volt AC wires.

Electric power comes into our neighborhoods at very high voltages, 4400 volts AC or more. Large transformers out in the alley convert this power down to 240 volts for several houses in the neighborhood. These step-down transformers are those large, black “pole pigs” up at the top of power poles. Why not just generate electricity at the power plant at 240 volts AC and be done with it? Because copper wire has a significant resistance. If large currents travel through miles of wire, the energy will be dissipated by heating the copper instead of being delivered to the customers. By using very high AC voltages, high power can be delivered with small currents and low losses. For long cross-country power lines the AC voltage is usually hundreds of thousands of volts.

Low frequency transformers at home

120 volt 60 Hz power line transformers are common around the house. Most appliances that contain electronics have a transformer to drop the voltage level down to 12 volts or less. The closed loop iron transformer above is the basic design. Usually, the windings are placed on top of each other rather than on opposite sides of the donut. Also, there are usually two holes in the “donut” with the coils wound on the center post between the two holes.

Safety is an important advantage of transformers. Transformers are often used to isolate AC voltages from ground. For example, if the input current on the primary is referenced to ground, the two secondary wires will only be referenced to each other. Well, OK. Depending on the quality of the transformer design, there may be as much as one milliamperes of leakage current if one of the wires were touched to ground. In a well-designed transformer, the leakage can be just a few microamperes. But for all practical purposes the AC voltage on the secondary winding has no relationship to ground.

As was just discussed, our household AC line voltage is referenced to “ground.” Ground is literally the wet dirt in your backyard. This means that if you grasp a grounded water pipe with one hand and stick a finger in a light socket with the other, a large current will pass through your body and you will experience **electrocution**. This should be avoided unless you are tired of living. We ham radio operators have many opportunities to be shocked, burned, or killed by high voltage. In practice, the most common serious accident for hams is falling from roofs and high towers. We need to be far more concerned about safety than ordinary citizens. Isolation transformers are one way we hams make accidents less likely.

Compared to capacitors, inductors are relatively “imperfect”

In electronics capacitors are used far more often than inductors. One reason is that inductors are more expensive than capacitors. It’s hard for a machine to wind wire around tiny cores, especially a closed loop iron-containing core. Another problem with inductors is that significant lengths of copper wire must be used to build them. This wire inevitably has a significant resistance. This means that every inductor is actually two components; an inductor

and an unintentional resistor. In contrast, capacitors, especially small capacitors, can approach perfection. Capacitors have essentially no resistance, no inductance, and their properties are constant over their operating range.

The other limitations of inductors are the limitations of the iron cores. As pointed out earlier, circulating currents in the iron dissipate energy. This loss appears as a warm iron core and wastes energy as if they were yet another resistor in series with the inductor.

Inductor saturation

As current flows through the windings, the magnetic field “recruits” the magnetic fields of the iron atoms to generate a much larger magnetic field than the coil would otherwise generate. This works well until all the iron has been recruited. At this point the iron “saturates” and the coil abruptly returns to being able to generate no more additional magnetic field than its copper windings can produce. As a result, iron core inductors have a limited operating range.

Little bitty inductors made from extremely fine wire wound on iron cores the size of a raisin can have impressive inductances. The catch is that these tiny coils saturate almost immediately and the inductance is only valid at essentially zero current. Seriously, a tiny inductor might be labeled, 100 millihenries @ zero milliamperes. Needless to say, components like this have limited usefulness! Small, low inductance coils with heavy wire and with no iron core are closer to perfect inductors, but without the iron, the magnetic fields surround the coils. These stray fields induce currents in nearby components. Again, if an inductor couples unwanted signals into neighboring circuits, it is not an ideal component.

Inductor core hysteresis

Another problem with iron is *hysteresis*. When the current in the coil shuts off, some of the magnetism in the iron remains. Then, when the iron is magnetized in the opposite polarity, energy must be wasted to first restore the magnetism to zero before it is magnetized in the new direction. Again, this is a big departure from an ideal component.

Inductors at radio frequencies

Inductors and transformers are vital to radio circuits. In radio circuits AC currents alternate not at 60 Hz or a thousand Hz, but at millions of Hz. The principles are identical to those explained above, but there are differences that may surprise you. First, in general, the more power an inductor or transformer must handle, the bigger it must be. However, the size of a required inductor varies with the frequency. At low frequencies, like 60 Hz, a transformer is comparable to bailing water with a really big bucket. Since it only delivers “water” 60 times a second, the bucket must be large to deliver a lot of water. Now suppose the same water is delivered with thimbles instead of buckets. If the thimbles are filled and emptied millions of times per second, the same amount of water could be delivered as with the bucket. *At high frequencies high power can be handled by tiny transformers.*

Powdered iron cores

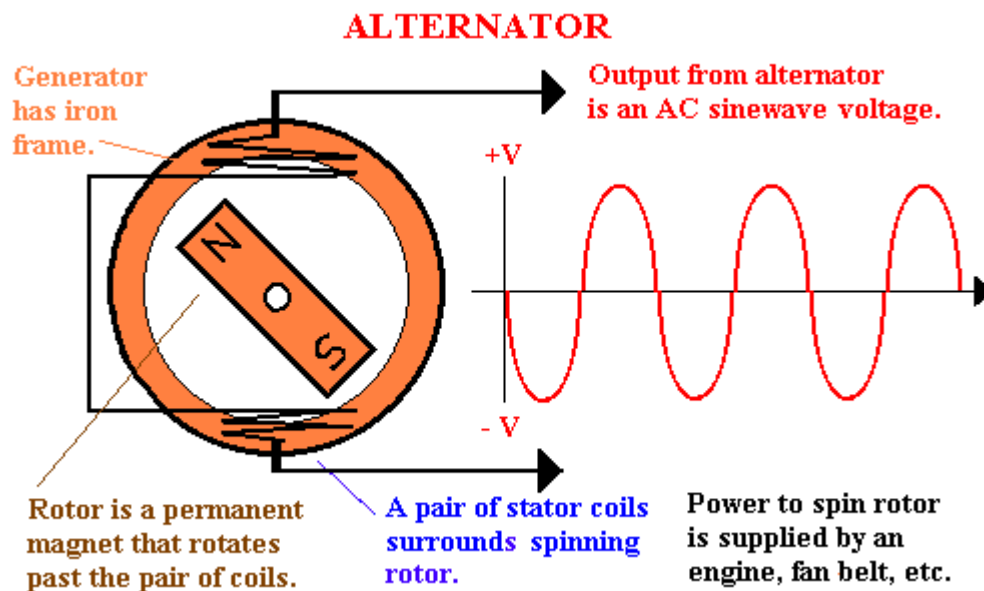
Unfortunately, many transformer problems are accentuated with high frequencies. For example, it is no longer sufficient to build iron core transformers with sheets of steel. For high radio frequencies the iron must be ground into a fine powder and dispersed in ceramic. There are two kinds of powdered iron cores used at high frequencies. Ordinary *powdered iron cores* have

a high percentage of ceramic and relatively little iron. This insures low loss in the cores and prevents abrupt saturation at high peak current level. **Ferrites** are a sophisticated type of powdered iron core that looks more like black glass but has more iron and much less ceramic content. In spite of having little ceramic in the mixture, ferrites manage to insulate neighboring granules of iron from each other. Ferrites allow much higher inductances to be used at radio frequencies than would otherwise be practical.

Ferrites and powdered iron cores are usually in the form of toroids – donut shaped rings. This is the modern way to build radio frequency inductors and transformers. At lower frequencies ferrites are often formed into “pot cores” which totally enclose and shield an inductor with ferrite. This almost totally confines the magnetic fields so they cannot interfere with neighboring circuits.

Sinewaves – “Pure alternating current”

The origin of household AC sinewave current is a gigantic alternator at your local power plant. Alternators are a kind of AC generator that can be thought of as a modified transformer in which one of the windings is mechanically rotated by an engine or other mechanical power source. An alternator produces a pure sinewave output simply from the natural rotation of its input shaft. The **stator** is the stationary part of the alternator. It consists of the iron frame that surrounds the rotating shaft. The stator has a pair of coils mounted on it on opposite sides of the central chamber. These coils are hooked up in series so that the voltages generated at any moment are added together.



The **rotor** is the central part that spins. As drawn here, the rotor consists of a simple bar magnet. Actually, the rotor is usually an electro-magnet, but I'm trying to keep it simple. As the north and south poles of the magnet sweep past the coils, they generate voltages of opposite polarity. That is, the negative voltage appears on the bottom terminal while the positive voltage appears on the top terminal. When the rotor spins around to the opposite alignment, the voltage polarity reverses. The sinewave comes about from the changing angle of the magnet with respect

to the stator coils. To express it mathematically, the voltage output equals the sine of the angle plus ninety degrees.

$$\text{Voltage at any given moment} = (\text{Peak voltage}) \text{ Sine} (\text{Angle} + 90^\circ)$$

Because of the 90 degree offset, this waveform is actually a cosine wave, but nobody calls it that.

When viewed abstractly, alternators closely resemble AC transformers as described above. Although there is a small air gap between the rotor and stator iron, the magnetic field travels in essentially a closed loop. The rotor is analogous to the primary winding. Instead of the energy coming in on wires, the energy enters the system mechanically. The moving magnetic field then creates the sinewave as it zooms past the stator coils.

Automobile alternators

Most alternators, such as the one in your car, are more complicated. They have three sets of stator windings crammed into the same frame. These three windings generate three separate, out-of-phase sinewaves. In your car these three outputs are rectified (converted to DC) by an array of six semiconductor diodes to produce 12 volts DC. (We'll describe diodes in chapter 4.) The DC is then used to charge the car battery. Alternator rotors are nearly always made from electro-magnets. They are powered by *slip rings* (moving spring contacts) that bring DC current in from outside to the moving rotor. Using an electro-magnet for a rotor allows the output voltage from the alternator to be controlled by varying the strength of the current that maintains the magnetic field. This is how the voltage regulator in your car keeps the battery charged, but not over-charged.

A sinewave voltage from an alternator obviously has a frequency determined by the speed of the input shaft. And because of the direct way the waveform is generated, the sinewave is as natural as the mathematical formula that expresses it. In contrast, modern digital electronics often generate "artificial" sinewaves by reproducing voltages dictated by a series of numbers that represent a sinewave. The end product is a complex "stair step" waveform that resembles a sinewave.

RF sinewaves

In radio technology natural sinewaves are universal in every circuit. For example, the voltages on transmitting or receiving antennas are sinewaves. Radio Frequency AC voltages are called *RF voltages*. They are generated by transistor oscillators as pure sinewaves. But unlike the output from an alternator, in radio circuits there are often multiple sinewaves riding on the same wire. For example, a receiving antenna carries sinewaves from ALL of the different radio waves impinging on it. Much of radio technology concerns ways to select and filter one sine wave from among a crowd of sinewaves.

So far we have introduced low frequency electrical theory. Radio frequencies are the same thing, but as we have seen, different aspects of the theory become more important as the frequency goes up. In the next chapter we'll put together a basement radio lab and get ready to build radios.

(1) Chaplin, J. E., *The First Scientific American*, Basic Books (Perseus Books Group), New York, 2006, p109.

36. Chapter 2, Harris

(2) Halliday & Resnick, *Physics for Students of Science and Engineering*, John Wiley & Sons; New York, 1960, pp. 558-560.

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, Rev 12

CHAPTER 3

SETTING UP AN ELECTRONICS WORKSHOP

Research and Development as Recreation

Building an amateur radio transmitter and receiver from the component level up is true research and development. That's why it's fun. Sure, it's much easier than developing products that have never existed before, but conquering the details will be hard and you'll find it plenty satisfying. When you're done, you can brag about your rig to your ham buddies. These days, if you have a 100% homebuilt station, you'll find you are almost unique among other hams.

We can learn how to do R & D by studying the methods of the master inventors. We Americans would probably nominate Thomas Edison as our single most famous inventor. Edison is not credited with the invention of radio, but he did develop many of the components used in 20th century radios. Also many of the techniques to build those components were first developed in Edison's laboratory. Edison fabricated the first vacuum tube diode, the loudspeaker, and the triode vacuum tube, but he never applied them to radio. Edison is best known for a handful of his most important inventions. However, *Edison's greatest contribution may have been his methods of inventing.*

Persistence

A reporter asked Edison why he had often succeeded in perfecting inventions, while other experimenters who started down the same path were never able to build a practical device. Edison replied, "Most inventors will have a good idea and try out one or two versions of their concept. When it doesn't work, they declare it hopeless and give up. The difference is, I never give up."

Try everything and keep careful notes

The most well-known story about Edison's persistence was his legendary search for the ideal material to make light bulb filaments. Edison was asked if he was discouraged by his failure to find a suitable material after trying hundreds of substances. He replied that it hadn't been a failure. He now knew hundreds of materials that didn't work.

The corollary to Edison's method is that it's essential to write everything down in detail. It's not fun writing the details of experiments that failed. But a year later, any researcher can tell you they have had that "deja vu" sensation halfway through an experiment only to find in their notes that they had tried this before. At the moment when you discover "a pearl of wisdom," it seems so profound that you believe you will never forget it. Wrong! Unless your memory is much better than mine, a year later an old laboratory notebook can be re-read almost as if someone else had written it.

Lots of junk

2. Chapter 3, Harris

Edison was asked what a fellow needed to become an inventor. He said, “First you need a large pile of junk. You can’t afford the time and money to run down to the store every time you need something. Often the junk pile will supply the parts to try out an idea right away. If you order parts from hundreds of miles away, you may waste weeks just to find out that your idea didn’t work.”

Subdivide the problem and build for modification

A complex invention like the light bulb consists of many parts. Light bulbs only look simple. What kind of glass can stand the heat of the filament? What kind of wire has the same coefficient of thermal expansion as that of glass? What kind of filament material is optimum? Will the filament leads bond to the glass and keep out the air? What should the resistance of the filament be in order to be compatible with the electric power source? How does the resistance change with temperature? What is the trade off between operating life and brightness? How good a vacuum is needed and how can it be produced? Once the air is pumped out of the glass, how can the bulb be sealed? Answers to all of these questions had to be found and tested one at a time before Edison could make a practical light bulb.

Have you seen the movie Gizmo? Gizmo is a collection of film clips of early 20th century inventors showing off their inventions for the first time. The movie is hilarious because again and again the inventors make the same mistake. They start with ideas that are often fundamentally sound and then they build an entire, polished, beautiful prototype without ever testing the pieces. They make the first test run of their airplane, jet boat, etc. in front of a movie camera. Sometimes they apparently even called in news reporters just to make sure the test would be as humiliating as possible.

My favorite relatively recent invention was McCready’s human-powered airplane. In 1965 an English sponsor named Cramer offered a \$100,000 prize to the first fellow who could fly over a 20 foot obstacle, fly over a half mile course, fly over a second 20 foot obstacle, then turn around and return to fly over the first obstacle again. The plane had to be 100% powered by muscle power. For 20 years many smart people tried to build the pedal-powered plane. Again and again they made the same error. They worked for months building handsome, handcrafted balsa wood airplanes. Then on the first flight the plane would crash and be smashed beyond repair. After two or three attempted flights, the inventors had spent months or years and were out of money and enthusiasm. In contrast, McCready designed his aircraft out of aluminum poles, piano wire, adhesive tape, and mylar. He designed his plane to be flown, crashed, repaired, and modified. McCready was able to crash and redesign his plane once or twice a day until he got it right. And he made sure there were no cameras around until it was tested and working.

Build for function, not beauty

First and foremost, your equipment should work well. It is natural to feel embarrassed by its crude, homemade appearance. Don’t be! Commercial ham equipment has been designed and redesigned several times before you ever see it. Moreover, commercial equipment is packed with custom displays, custom heat sinks, custom cabinets, and even unique integrated circuits. You can’t compete with that, so don’t try. Instead take pride in your crude prototype.

When you see designs for homebuilt equipment in the ARRL handbook or in ham magazines, the equipment is usually quite attractive. But if you read carefully, you will find that

3. Chapter 3, Harris

the unit in the picture is prototype number five or even number one hundred. You probably don't have time to rebuild your station five times just to achieve beauty. Also, if you attempt to duplicate one of those units, you'll find you must use exactly the same parts and circuit board the author did. This means buying a custom circuit board and perhaps a complete parts kit from some manufacturer. If you try to substitute parts, I can almost guarantee it won't work.

Get smart guys to help you

This piece of wisdom from Edison may be limited in usefulness to the basement ham, but it's still interesting. Edison was the first fellow to industrialize the process of research and development. Once he acquired financial backing, he hired a whole team to work on his projects. He didn't try to do everything himself. The quantity of Edison's inventions can be partly explained by the number of competent guys he had working for him. Edison and his lab were credited with inventions that represent the work of many lifetimes. Even for a guy who works day and night, there are limits on what one fellow can do. If you're a one-man show, it's important to limit yourself to projects you can complete. Be sure to use the library to find previous work in your area. Although real ham homebuilders are rare, homebuilding is the most fun if you can find someone in your area to share your triumphs and problems.

Assume as little as possible

Edison looked for guys who had the right attitude about R & D. Many job applicants have a knack for sounding good in an interview, but they turn out to be more glib than useful. Edison's interviews began with asking the applicant dozens of practical questions about ordinary objects such as, "What is asphalt made of?" Another of his tricks was to take potential employees out to lunch. If they put salt and pepper on their food without tasting it first, they were in big trouble with Edison. Edison's selection method is probably extreme, but it does illustrate a cardinal rule of research. *Never assume anything about the project without good data to back up your starting assumption.*

For example, I had known for forty years that resistance in series with a transistor emitter was important for the thermal stability of an RF amplifier. However, I believed that any emitter resistance would inevitably reduce the signal output from that stage. In other words, I thought stability and gain were a tradeoff. Recently I took the time to try different values of emitter resistance over the entire range of possibilities. I was amazed to find that maximum output occurred not at zero ohms, but at a certain significant value, 300 ohms in my specific amplifier. When you do experiments like this, write down the details! You'll want them later.

Many inventions are frustrated by assumptions that turn out to be limiting. For example, weapons inventors were limited for centuries by the concept that firearms had to be ignited by flintlocks. When you consider the practical difficulties of inventing a waterproof, rapid-firing, breech-loading flintlock rifle, it's no wonder that firearms were essentially unchanged for 200 years. Millions of lives were probably saved by this fixation on flintlocks. Narrow-mindedness in inventors isn't always bad for society, but it sure restricts innovation.

The genius of trying

Magic happens when you actually sit down at your workbench and try to do something. You may have thought about the problem in spare moments for weeks, but when you actually have the work in front of your face, ideas pop into your head as if by magic. For this reason,

4. Chapter 3, Harris

many people, like Edison for example, were well known for working non-stop all night. Once you get the momentum going, it can be wasteful to stop. Otherwise you may not remember all the details when you get back to work hours or days later.

I used to work with a patent attorney, Robert E. Harris, who always put everything off until the last minute. I kidded him about his procrastination. He answered me seriously with an explanation that went something like this: “I do it deliberately,” Bob said. “I find that in order to write a patent application, I need complete concentration and nothing gives me that intensity like an approaching deadline. In order to write a good patent, I must have all of the prior inventions in my head at the same time. If I just put in just a few hours, by the next day I will have forgotten important details. For that reason, the day before the deadline I go into seclusion and work all night if necessary.”

When you get stuck, do something else for a while

Unfortunately non-stop work slows to a crawl when you run out of significant new ideas to try. As long as you keep sitting in front of the problem, you will keep finding little variations to try, but as the hours go by, you will become more and more tired and your ideas will become less and less creative. To escape from this trap, get up from the workbench and do something else. Take a walk, take a shower, or go to dinner. When you're not in front of the work, you can't do anything with your hands. Since you've been concentrating so long on the problem, your brain will continue to work on the problem long after you leave the workbench. Because you can no longer try out small, uninspired ideas, your mind must wander farther and you'll find you are thinking seriously about radically new concepts.

For example, when Edison was searching for his light bulb filament material, he was stuck on the idea of using an inert metal filament. An inert metal would not react with oxygen or with residual gasses that might remain in the light bulb. If Edison had been able to carry through his “try everything” philosophy, he would have ultimately tested every metal. Therefore, he would have eventually tried tungsten and that's what filaments are made of today. But perhaps tungsten wasn't available 130 years ago.

Edison was particularly stuck on platinum as a filament material. Yes, it was expensive, but it seemed to work beautifully and gave a bright yellow-white light for a few hours. Unfortunately, after a while a segment of the platinum wire would become thin and abruptly melt, thereby ruining the bulb. A related problem was that the resistance of platinum was too low. This meant that a long, very thin platinum wire had to be used to make the filament compatible with his 100 volt power source.

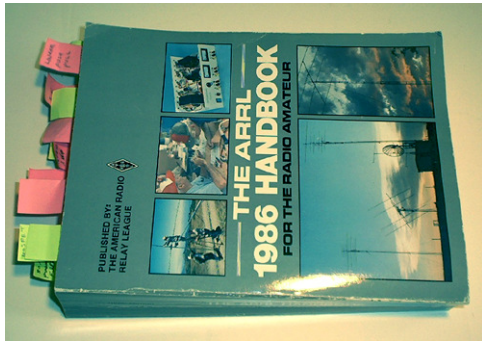
Edison and his team realized that, if they could detect the sudden resistance rise of the filament as it started to fail, they could turn down the current and keep the filament intact. In theory, a temperature/ current regulator could allow the bulb to last indefinitely and would make it almost immune to power surges. The team expended a great deal of effort to invent the regulator, but it never worked well enough. Finally while away from work, Edison thought that the whole idea of a metal filament should be reconsidered. From metals he turned to carbon filaments. Carbon was cheap, had an inherently high resistance, and it didn't melt. Carbon turned out to be a practical answer he could use and in the end carbonized cotton thread became the filaments in his first commercial bulbs.

Developing your own basement electronics laboratory

Before you can begin building ham equipment you will need some basic tools and materials. Notice that, in addition to books, you will need both heavy-duty tools and light-duty ones. If you use tools that are too fragile, you may ruin the tool. If you use tools that are too heavy, you may ruin your project. The following list is incomplete, but it will get you started.

1. Buy an ARRL Amateur Radio Handbook

An R&D hobbyist can't hire a staff of underlings and consultants, but he can get advice from guys who have done it all before. *The first investment a new American ham should make is The ARRL Handbook for the Radio Amateur.* This handbook is as big as a phone book. It's published every year and the latest edition has all you need to understand the breadth of our hobby. It will also give you a good background in basic electrical principles and some detailed descriptions of do-it-yourself construction projects. I presume (hope) that similar texts are available in other countries and languages, but I'm not familiar with them.



The ARRL Handbook , 1986 edition

Yes, the above handbook is way out of date. I also have a brand new edition, but I have two criticisms of modern ARRL handbooks. First, they are so huge, they discourage most people from sitting down and reading them. The second limitation is that modern hams no longer build complex receivers and transmitters. So projects like this are no longer described in detail. In fact, reading my up-to-date handbook I got the impression that building complex transmitters and receivers is impossible for amateurs. That's not true and that's why I'm writing this book.

Other than that, the latest edition handbook is a great reference to own. It covers all the latest exotic technology and you can use it like an encyclopedia. For actual homebuilding I recommend a handbook from the 1980s. During that decade hams were still building good equipment from discrete transistors. Handbooks from the 1970s and earlier usually describe projects that are unnecessarily primitive. The projects in the Handbooks from the 1990s and later usually contain integrated circuits which don't teach you anything about how your project works. The authors of the present day handbook don't expect anyone to build serious receivers and transmitters. Therefore the projects tend to be "toys" with many limitations. You should be able to find a handbook from the 1980s at a ham radio swap fest. Or maybe you can buy one from a ham in your neighborhood who has no interest in homebuilding.

2. A heavy duty, 100 watt soldering gun and a fine pointed small 25 watt pencil or gun

You need both. The big soldering iron is important for soldering antenna wires and heavy work. A fine pencil is essential to solder the leads on fragile components like transistors and

integrated circuits.

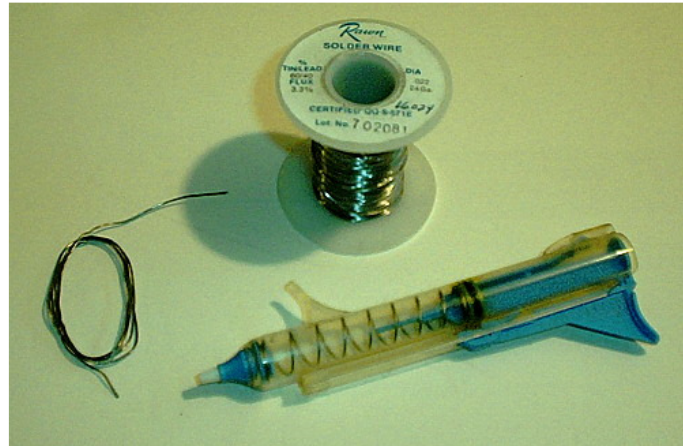


3. 60/40 Rosin core solder, fine and coarse sizes

Rosin core solder (60% tin/ 40% lead) is used for joining wires whenever reliable electrical conduction is the primary goal. The rosin flux is built into the wire-like solder, so you never have to apply solder flux. Acid core solder is used for structural purposes. It is not usually recommended for electrical use because the acid continues to corrode the metal for years afterwards. Eventually residual acid may result in a poor electrical connection. However, *a roll of plumber's acid core solder is nice to have around*. Sooner or later you will be building an antenna or other project that forces you to solder copper wires to steel. Since nothing else works, a bit of acid core solder or acid solder flux can be a lifesaver.

4. Solder Wick and Alcohol

You'll also need some *Solder Wick*® for sopping up excess solder. Solder Wick® is just a small coil of fine, multi-strand copper wire specifically made for removing solder from circuit boards. The free end of your roll of wick is placed on top of the excess solder. The wick and solder are then heated with your soldering iron. The wick sucks up the excess solder. Before you can use it again, you must clip off the used end of the wick with clippers. This sounds clumsy, but it works well. There are also pneumatic pump-like devices called *solder suckers* that suck up surplus molten solder. They're OK, but I prefer solder wick.



Rosin core solder and solder sucker

Iso-propyl alcohol (rubbing alcohol) is useful for cleaning the excess rosin flux off circuit boards. I put a few drops of alcohol on the board, then use a small plastic brush to scrub off the rosin deposits. Denatured ethyl alcohol also works, but not as well. There are also commercial flux cleaners, but the ones I have used are a bit harsh and tend to dissolve paint.

5. Fine needle nose pliers and diagonal cutters for bending and clipping tiny leads

These should be high quality and your best pairs should be almost small enough to fix watches. In fact, if you use modern “surface mount” electronic components, you will also need fine pointed tweezers to manipulate the parts. ***A cardinal rule about delicate tools is NEVER use them on large wires and parts.*** These fragile tools will be ruined instantly if you try to cut steel wire with the small diagonal cutters or use the needle nose pliers as a wrench. A hemostat can be useful for holding small parts in place while you solder. A non-conductive plastic screwdriver is helpful for adjusting trimmer capacitors in situations where the adjustment screw is floating above ground.



The yellow-handled tool in the collection below is a wire stripper for removing plastic insulation from wires. A pocket knife is also nice to have for stripping insulation off the ends of enameled and Teflon insulated wire. These kinds of insulation cannot be removed gracefully with a wire stripper and must be scraped and carved off with a knife blade. A set of tiny jeweler’s screwdrivers is also useful.

6. Heavy needle nose pliers, heavy-duty diagonal cutters and small wrenches

You will often need large versions of the delicate tools. Use them when appropriate.

You will also need a vise, assorted files, a hacksaw, and hole reamers for shaping and mounting PC boards and heat sinks.

7. Microscopes & reading glasses

Even if your eyes are much better than mine, you'll need a strong magnifying glass to inspect your solder connections. Often tiny whiskers of solder or bits of thin wire short out connections. Other times a solder joint looks OK from a distance, but under extreme magnification, the piece is not actually making contact with the desired terminal. These problems usually can't be seen with the naked eye and you might spend hours looking for a problem you could have noticed immediately with a glass. *I routinely examine each solder connection with my lens before moving on to solder the next component.* I use pocket microscopes, a strong magnifying lens, and over-the-counter, strong (+3.50) reading glasses for this purpose.



8. A set of wood carving gouges

“A set of what?” you ask. Wood carving gouges are a kind of delicate wood chisel with a cupped end. I use them for cutting traces on blank printed circuit boards. You will find they work well for making one-of-a-kind prototype printed circuit boards. In my opinion, carving a circuit board is superior to any other method I have seen for homebuilt radio frequency circuit boards. (Other folks prefer the Superglue and disk method described in chapter 6.)



9. An electric drill

An electric drill is used to make holes in PC boards and heat sinks.



10. Male Thread taps



Rather than assemble your entire project with machine screws and nuts, you'll find it's often simpler and more professional to tap threads into the aluminum heat sinks and brackets. I find 4-40 and 6-32 threads to be the most useful sizes.

11. Freeze spray



One of the frustrations of electronics is finding intermittent connections. One minute your device works, the next it doesn't. You open up the cover, expose the circuitry and ... it starts working again. It's hard to fix something that's working! Spraying refrigerant on suspicious solder joints can often reveal which connection is at fault. Sometimes a heat gun (or hair dryer) can be used the same way, but they are not so focused. Heat guns are useful for mounting heat shrink insulation on terminals.

12. A high quality multimeter

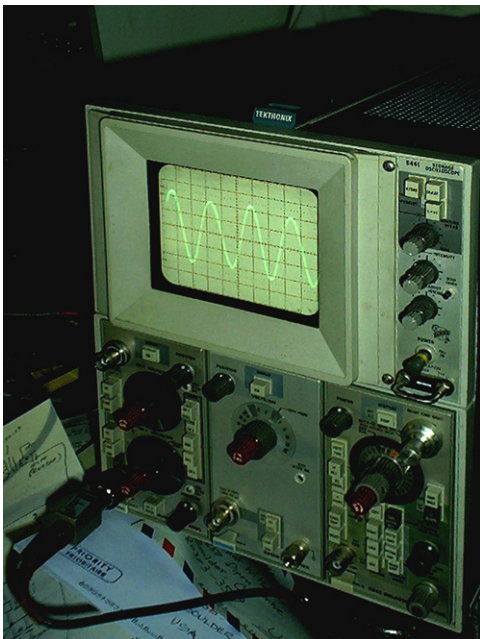


Modern digital “multimeters” measure voltage, current, and resistance. Fancy ones may also measure frequency, conductance, capacitance, decibels, temperature, and other parameters. All multimeters are based on a high input impedance voltmeter. A quality modern meter has an input resistance (impedance) of 10 million ohms. High impedance is needed so that the measurement doesn’t load down the circuit and alter what you are trying to measure. Old-fashioned electro-mechanical meters have impedances as low as a few thousand ohms.

A quality meter is also extremely accurate. Measurements of a voltage or resistance will be correct to several decimal points. ***Don’t be cheap with this item.*** It is the core of your electronic measurement capability. If you expect to take the meter outdoors to work on the car or up onto the roof to do antenna work, then maybe you should also buy a cheap multimeter that you can afford to break.

13. A high quality oscilloscope

The oscilloscope is another foundation of your laboratory. The traces on the screen tell whether your device is working and how well. Without a scope, you are almost blind. Perhaps the most amazing achievement of people like Edwin Armstrong is that they were able to do their work by inferring the function of circuits from secondary measurements. For example, the DC plate current of an RF amplifier tube dips when resonance is achieved. However, it’s so much easier to just look at the signal with a scope and WATCH the actual sinewave while the circuit is tuned.



A first rate oscilloscope might cost \$10,000 brand new. But there are advantages to living in the 21st century. One of them is that 20-year old \$10,000 oscilloscopes are all transistorized, still first-rate quality, and you can buy a used one for \$300 or \$400 dollars. The prime consideration is that the scope must have a frequency rating higher than the frequencies you will be working with. For HF ham radio, 50 MHz is enough, but you can find used scopes that will go as high as 1,000 MHz.

The oscilloscope is connected to your project by a ***probe***. A probe is a 3 to 6 foot long

11. Chapter 3, Harris

coaxial cable with a ground wire clip and a little “grabber” at the end that hooks onto the wires carrying the voltage waveforms you want to look at. Probes usually have a 10:1 voltage divider that protects the oscilloscope from high voltages you may be measuring. Not all probes are created equal. *For high frequency radio work you need a short probe with minimum capacitance.* If you buy a probe, look at the specifications to see what kind of capacitive load you are putting on your circuit.

For example, if your circuit is tuned by a variable capacitor that ranges from 5 to 60 pF capacitance and your probe has 50 pF of capacitance, the probe will totally dominate the circuit tuning. In general, a good RF probe has a short cable and a short ground lead. Of course even 5 pF is a significant load. So when I’m tuning a circuit, I try to tune one stage of an amplifier while I use the scope to monitor the signal in the following stage. That way, the tuning of the first stage will not be affected by the probe.

14. A frequency counter



As soon as you build your first ham transmitter, you will need to prove that your transmitter is operating inside the ham band. Also, we hams are supposed to limit our transmissions to one frequency and not splatter all over the band. By definition, a pure sinewave is a single frequency. My solution is to routinely monitor the frequency and shape of my RF sinewave right at the base of the antenna. If it looks like a good sinewave on the scope, the signal is almost certainly clean.

You can estimate the frequency of the sinewave by using the horizontal marks on the oscilloscope screen to measure how long it takes to complete a complete sinewave. If you count grid squares on the screen, you can measure the frequency of a sinewave to about 10 or 20% accuracy. Unfortunately, that isn’t nearly good enough. For example, if your transmitter frequency is 7.05 MHz, one complete sine wave will take 0.142 microseconds. You won’t be able to read it closely enough to be sure it isn’t really 0.143 microseconds and just outside the 40 meter band. You really need a frequency counter.

Some sophisticated oscilloscopes have built-in frequency counters to measure the exact frequency of a signal. Almost certainly, you will have to buy a separate frequency counter to tell you exactly where you are to the nearest Hz. You can buy a new, quality counter for \$2,000 or more. Or you can get a new, cheap frequency counter for \$200. The best bargains are first-rate used frequency counters. When start-up electronics companies go bankrupt they are often forced to liquidate their equipment at bargain prices. You may be able to buy a good one for under \$100.

15. A quality short wave receiver

Aside from using it to hear other hams, a good quality, commercially manufactured shortwave receiver can serve as a laboratory instrument. A modern receiver is so well calibrated that it may be used as a substitute for a frequency counter. Also, it’s important to be able to listen to your own signal in a receiver to be sure that it doesn’t have subtle defects that may be

hard to see on an oscilloscope. Ideally, you should have both a counter and a calibrated receiver.

16. A laboratory power supply

A laboratory power supply allows you to apply voltage to a circuit cautiously. This will usually prevent component damage due to wiring errors or other problems. Meters tell you how much current is being drawn and the voltage applied. The voltage is adjusted with a control pot. You can start with one volt then gradually turn it up if the current flow isn't excessive. This particular old power supply is actually three separate supplies. For example, you might use the 5 volt supply to power a microprocessor, while the other two variable supplies could be set up to deliver + 12 volts and - 12 volts for operational amplifier circuits.



17. An RF frequency generator

This is a tool you will eventually want. But if you have everything above, it isn't essential. The RF frequency generator allows you to inject a sinewave of known amplitude and frequency into an amplifier so that you can align it. When aligning a homebuilt receiver, it is nice to have a known test signal you can listen to any time you want.

18. A capacitance meter



While not essential, you can use a battery-powered capacitance meter to sort out your junk drawer and give a reliable indication of capacitor sizes. I find it extremely useful for determining the maximum and minimum set points on trimmer capacitors.

19. Catalogs of electronics parts suppliers

You will need at least 3 or 4 catalogs. I like RF Parts Company, Jameco, Digi-Key, Newark, Mouser, and Radio Shack. Hopefully you have a Radio Shack store in your area in case you need some routine part in a hurry.



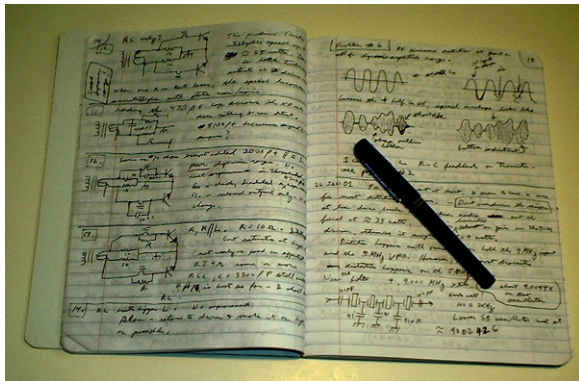
20. Your very own junk collection



As Edison said, it is important to collect junk parts so that you aren't continually waiting for parts to arrive in the mail. Considering that a capacitor or potentiometer costs a few dollars new, it is easy to spend hundreds of dollars on a project. If you are **not** getting most of your parts from old TVs and ham swap-fests, your project will cost a fortune and will proceed slowly. Never throw away an old radio or computer without first cannibalizing it for useful parts. Organize your parts in bins, parts drawers, and labeled boxes so you can find them when you need them. If you can't find a part when you need it, junk is just junk.

21. A laboratory notebook

Your memory isn't half as good as you may think. Write down all your experiments, your triumphs, and especially your failures. The experiment that doesn't work is just as important as the experiment that did.



22. A simple calculator

You probably already own a calculator that will be adequate for the simple component value calculations you must do. Square roots may be the most complex calculation you'll perform on your way to your first two-way ham radio contact.



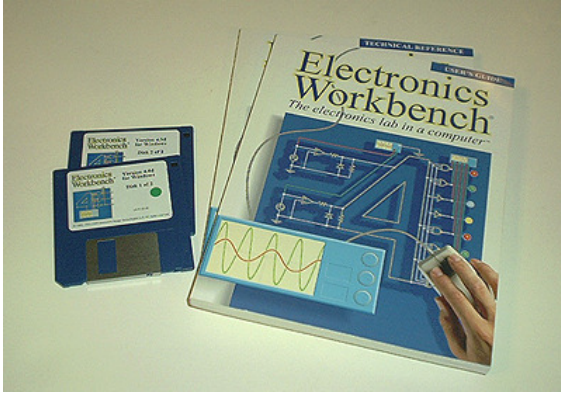
When I was in engineering school, the calculator age had not yet arrived. We young engineers swaggered about carrying big sliderules that hung from our belts like swords. We were very cool. When I sat down in class to take a test, I would ceremoniously draw my sliderule from its sheath and check to see that the upper scale was perfectly aligned with the lower scale. If it wasn't lined up perfectly, I used the blade of my pocketknife as a screwdriver to adjust it. For me this ritual was something like a parachutist checking his harness and D-ring one more time before leaping from the airplane.

For you whippersnappers who haven't used sliderules, these antiques do logarithms, calculate trigonometric functions, take squares and square roots, and do almost everything you can do on a simple "scientific" calculator. The reason for this archaic story is that sliderules don't do decimal points. Therefore, to get the right answer, *we had to have a FEEL for the math*. We had to be able to estimate the answer so that we would know what order of magnitude it would be and where to put the decimal point. In other words, we had to know what we were doing. The sliderule expanded our skills. It did not replace them.

When calculators came out, engineering students suddenly began to fill their test papers with random numbers. Beginners think that, if they push the buttons, the calculator is doing the thinking for them. Wrong. It turns out that calculators really aren't different from sliderules. The students must estimate the answer in their heads so that they will know if they have pushed the right buttons. Once the students mastered the ability to estimate, calculators became a boon to engineering.

23. Software for experimenters

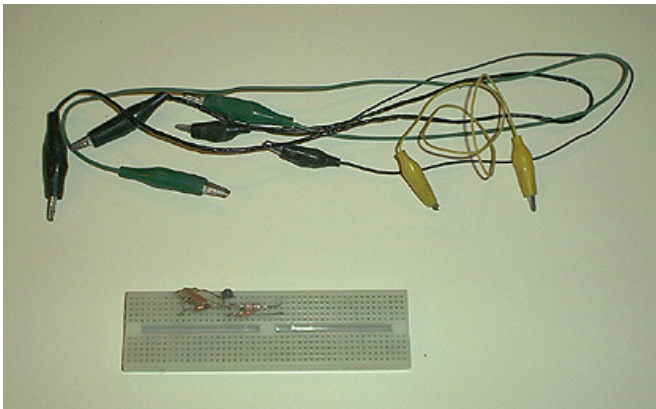
I hesitate to mention circuit simulation software. I am a rebel against the modern age of smug engineers who have never soldered a wire. I don't like the trend of increasing specialization and generalized ignorance that is spreading through the technical industry. Spice programs are much like calculators. They're wonderful if you can estimate what the circuit should do before you activate the simulation. Once you get very far into building ham gear, you will probably get tired to doing everything the hard old way. There are many different simulation programs available that allow you to emulate a circuit on your personal computer before you build a real circuit. I found it particularly useful for designing frequency filters such as those used in chapter 15. Like most modern conveniences, this one is truly marvelous. However, Spice should complement actual circuit testing, not replace it.



I use an old **Electronics Workbench** “Spice” program, but there are probably many newer ones that work as well or better. Mine is a simple program that will not simulate some components, such as crystals or some kinds of circuits like oscillators. I really like it for simulating filters. If I need to build a filter with a certain cut-off frequency, but I don’t have the right parts, I can simulate substituting parts and find out how critical the values are.

Actually, it’s so much fun trying out circuits with so little work, that it’s almost addictive. Also, other problems in my design become obvious that I had never thought of. For example, I built a filter for a ham transmitter that was designed to eliminate interference to the neighbors’ TV reception. (See chapter 9.) Any transmitter signal has minor “impurities” in its frequency spectrum. This means that it can easily be radiating weak signals on the TV channels. A filter will reduce these harmonics. Before I built my filter, I took the time to model it on the Spice and found that, as I had planned, it severely reduced interference on channels 2, 3, and 4. Above those channels, the attenuation of possible harmonics was not nearly as great. For the upper UHF channels, there was hardly any attenuation. Once I saw the problem, it was easy to add a couple more stages of filtering to insure that *all* TV channels were protected.

24. Test leads and experimental “socket” circuit boards



Every electronics lab has handfuls of test leads and a few temporary plug-in circuit boards. Although I routinely use these, I hesitate to recommend them. **ANY ELECTRICAL CONNECTION THAT ISN’T SOLDERED CAN’T BE TRUSTED!** Yes, it’s true that these gizmos often work, but many times I have been led to believe that parts were bad or that circuits didn’t work when they actually worked fine.

Let me illustrate: Once when I was in the Air Force I had to wire some explosive squibs on a 1,500 pound cargo parachute load. The squibs were supposed to explode and deploy the parachute. I passed the bare, scraped copper wires into two tinned metal eyelets, then wound the wire through the eyelets again and again until the eyelet holes were stuffed with clean, bare wire. Then I wrapped the remainder of the bare copper wires tightly around the outside of the metal eyelets and wrapped the whole thing securely in tape. I thought there was no way that the copper wire wasn’t in good contact with the eyelets! The huge box fell 3,000 feet and crashed into the dirt at a couple hundred miles an hour. The squibs never fired. I checked the firing circuit with my meter and found the proper 3 volts across the squibs. I unwrapped the tape from the eyelets. The squibs exploded as soon as I tugged on the bare wire. After that day I soldered my squib

wires and never had another failure.

If you buy a socket board like the one shown above, be aware that the contacts are easily damaged by stuffing component leads into the board that are too big. For example, ½ watt resistors are barely OK, but 1 watt resistor leads will permanently expand the spring contacts.

25. Pliers for crimping connectors and eyelets

What about the special pliers used to crimp connectors and eyelets? Some metal eyelets and lugs are designed to be installed onto wires using special crimping pliers. Yes, crimped connections can be fairly reliable in the short run. However, in my experience crimped wires pull out easily and after several years they often become open circuit. I have seen dozens of failures on old equipment. I still use eyelets on leads, but after I crimp them, I solder them as well. Surprisingly, eyelets that are screwed down to aluminum metal seem to make a reliable contact with the aluminum. However, I still solder the copper wire onto the tinned eyelets.

In conclusion,

The equipment described above should get you started. Everyone has different ideas about what works best and what is essential. For what it's worth, the above list pretty well describes my workshop.

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, REV 12

Chapter 4

HERTZIAN WAVES IN THE BASEMENT

Crystal set radios and ancient spark gap transmitters from the 19th century may seem too simple and too far removed from ham radio to be worth building. If you're already familiar with basic electronics and early radio history, you may not learn anything from this exercise. If you can't wait to build a real ham rig, please skip ahead to the next chapter. On the other hand, if you have little electronics experience, there are worlds of lessons to be learned from old technology. And if you've never built simple radios before, you should find it fun.

The nature of radio waves

Before we build transmitters and receivers, let's review radio waves. When we understand what radio waves are, the technology to generate and receive them becomes more obvious. An electromagnetic wave is an oscillation in free space that radiates out away from its source at the speed of light. It is called *electromagnetic* because it is both electric field energy and magnetic field energy. The wave oscillates or changes back and forth between these two forms of energy as it travels.

Propagating across vacuum

From our experiences with magnets and static electricity, it's hard to visualize how a magnetic or electric field can travel millions of miles across the vacuum of space. In our experience these fields are tightly localized around the device that generated them. How can a magnetic field exist isolated in a vacuum, perhaps even light years away from the nearest atom? Suppose we could somehow magically generate a magnetic or an electric field in space, miles from the nearest object. Would the field just sit in space forever waiting for an object to pass by and be influenced by the field?

Let's suppose there is a refrigerator magnet floating in the void of space. Its magnet field will be at rest in the space surrounding the magnet, just as it does on your refrigerator. As always, the magnetic field will reach out its usual distance of a quarter inch or so. However, if the magnet were to suddenly vanish, the energy in the field would lose its "container" or "anchor" and be loose in the void.

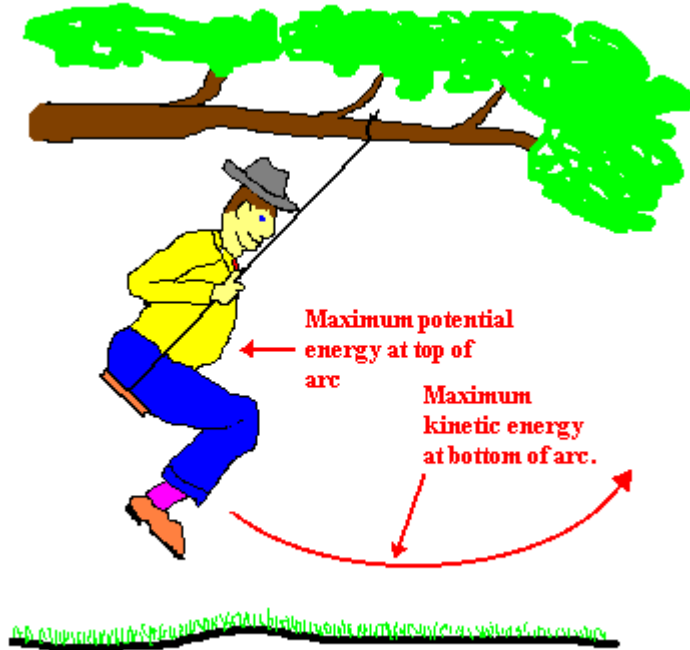
The same scenario can be proposed for an electric field: If a flashlight battery were floating in space, the electric force would extend perhaps an inch out into the space in a halo around the two battery terminals. Again, if the battery suddenly vanished, the electric field energy would lose its generator and be stranded in the void. Without its anchor, it would spill out in all directions.

Oscillation occurs when two form of energy rhythmically change back and forth

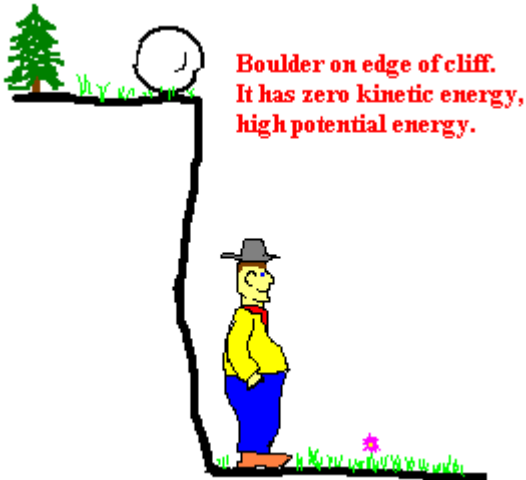
When magnetic and electric fields are turned loose in space, what becomes of them? As James Maxwell first explained over a century ago, electric fields and magnetic fields are intimately related. It turns out that *a changing or moving electric field generates a changing*

magnetic field and vice-versa. As the energy continues to “spill” out in all directions, the energy oscillates back and forth between these two kinds of fields. This connection is not “obvious” or intuitive. If it were, the Greeks, Chinese, or Egyptians would have described and exploited it long ago.

Mechanical oscillators



Many physical devices in our world oscillate, so oscillation between electric and magnetic fields should not be a surprise. An oscillation in nature can be described as energy spontaneously transforming from one form of energy into another then back again. For example, as a clock pendulum swings back and forth, the pendulum acquires the kinetic energy of motion as it swings through the bottom of its arc. Then, when the pendulum swings back uphill, the energy contained in the kinetic energy is returned to gravitational potential energy. When the pendulum reaches the top of its swing, it momentarily comes to a complete halt, turns around and races back downhill. When it is at the top, the energy is all “potential.” A boulder sitting on the lip of a cliff doesn’t seem to have any energy until it is nudged off the cliff. The fellow standing at the bottom of cliff can testify that the rock has plenty of energy when it slams into the foot of the cliff. (That assumes, of course, that he survives.)



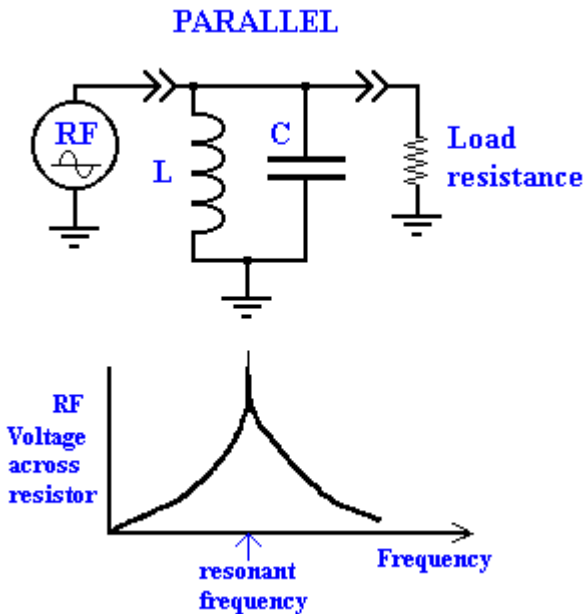
To reiterate, an oscillating pendulum switches its energy back and forth between kinetic energy and potential energy. Notice that the length of the pendulum establishes the frequency of the oscillation of a pendulum. This is because gravity is constant and lightweight objects fall just as fast as heavy objects. If you ignore air resistance, the frequency of the pendulum swing is determined solely by the length of the pendulum arm (and of course the acceleration of gravity). This makes a pendulum good for keeping a mechanical clock running uniformly and accurately. Similarly, once the frequency of a radio wave is established, it doesn't change frequency as it races through space and becomes weaker.

In summary, free space (which is literally "nothing"), can support magnetic or electric field energy, but only temporarily. To be maintained, a magnetic field needs to be generated by a device. ***A magnetic field can be generated temporarily by a nearby collapsing electric field. As the magnetic field collapses, it produces a temporary electric field in the adjacent space.*** This seesaw produces a radio wave traveling outward across the void at the speed of light.

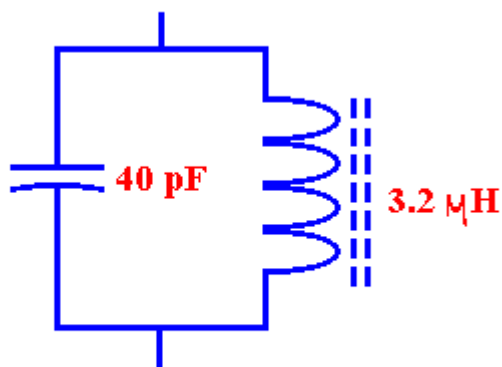
What's special about the speed of light? Good question! Einstein's laws of relativity teach us that time and space are frozen like a 4 dimensional ice cube. Most people are aware that light speed is the ultimate velocity. What is rarely understood is that light speed is really "the speed of time itself." Relativity is almost never studied deeply, even by engineers. This is perhaps because, until the invention of portable atomic clocks, the evidence proving relativity was less than overwhelming. For example, when the first GPS satellite was launched, the software had "switches" that allowed ground engineers to turn off the adjustments for Special and General Relativity in case relativity turned out to be wrong. They weren't. The crazy theories turned out to be laws. Our universe is weird and profound far beyond what 99.9% of humans have the privilege to notice. However, these subjects belong in another book.

Getting back to 20th century radio: Transmitter antennas are designed to generate either a rapidly changing electric field, or alternatively, a rapidly changing magnetic field. The antenna is placed out in the open with free access to the sky. The electric or magnetic fields around the antenna create the opposite kind of field and the result is a free-flying radio wave. The same antennas work well for receivers. As radio waves flash past the metal antenna elements, electric currents are induced into the structure just as if it were temporarily a capacitor or a secondary loop of a transformer.

The LC circuit, the fundamental electronic oscillator



The most fundamental component of all radio transmitters and receivers is the *capacitor/inductor parallel resonant circuit*. This basic circuit consists of an inductor wired in parallel with a capacitor. These are called *LC circuits* where L is the letter used when calculating inductance and C of course stands for capacitance. If a high frequency sinewave voltage is applied across the parallel LC circuit, there is a specific frequency at which the LC circuit resonates and appears to be an open circuit. At all the other frequencies the LC appears as a load or short circuit. The LC circuit attenuates or eliminates the sinewave at every frequency except one. In this way one radio signal can be “tuned in” preferentially over another.



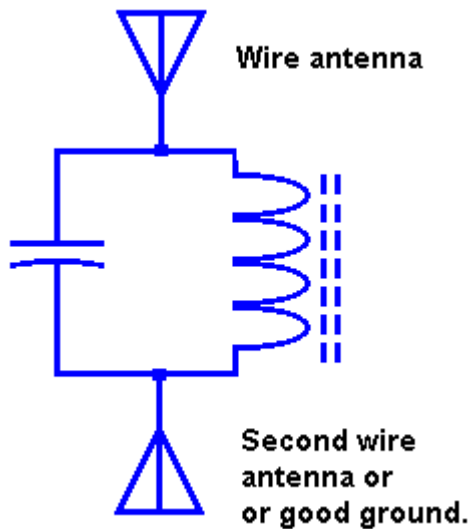
20 Meter RESONANT CIRCUIT

For example, the circuit above resonates at 14 MHz, the 20-meter hamband. The tiny inductor is just 3.2 microHenries. The capacitor is only 40 picoFarads which means 40 millionths-of-a-millionth of a Farad.

The LC circuit is a kind of electric oscillator. It is analogous to a swinging pendulum or a weight bouncing up and down on a mechanical spring. The LC oscillator goes through the same energy cycle as radio waves. First the energy is stored in the magnetic field inside and around the inductor. During the next half cycle, the energy is stored in an electric field between the plates of the capacitor. The energy alternates back and forth between these components until the resistance in the wires dissipates it.

A parallel resonant LC circuit with dual antennas forms a simple transmitter

Significant energy can also be leaked off into the space around the LC circuit as radio waves. Therefore, once we get an LC circuit to oscillate, we are already on our way to generating radio waves. *If we simply add wires to the ends of the parallel LC circuit, these wires form an antenna to couple the electric field to the free space around it.* In other words, the simple circuit shown below is a crude radio transmitter.

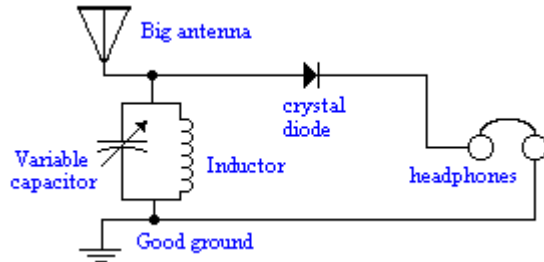


A receiver of radio waves can be built in the same way. Imagine that an identical parallel LC circuit with antennas is tuned to resonate at the same frequency. Now imagine that this second circuit is floating in the void, perhaps miles from the transmitting circuit. When the radio waves radiate past the receiving LC circuit, the electric field component in the radio wave will produce a tiny surge of current in the wires that charge the capacitor. Alternatively, and depending on the orientation of the coil with respect to the radio waves, the magnetic component of the radio wave will induce a tiny voltage to appear across the coil. This is the same as if the inductor were the secondary of a transformer. Once the radio wave has zoomed past, a tiny, miniscule oscillation will remain in the receiving LC circuit, ringing back and forth between the inductor and capacitor.

CRYSTAL SET RADIOS

A crystal set radio is an excellent first radio project. They have few parts and are easy to understand and build. Crystal sets were a common toy when I was a kid and my first electronic project was building one. Although we kids played with crystal sets, we didn't really understand

them. When they didn't work, we had only the haziest notion of how to fix them. If you bought a commercial toy crystal set, I never saw one that had explanations even remotely as complete as what you are now reading. Starting with the crystal set, later on we can build on what we learn to build transmitters and more elaborate receivers.



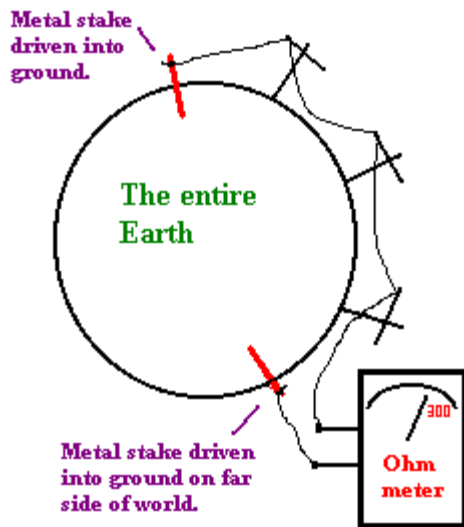
The combination of inductor and capacitor tune in the desired station. That is, the inductor and capacitor oscillate at the frequency of the desired station. The crystal diode rectifies the sinewaves oscillating across the LC circuit. This converts the high frequency sinewaves into low frequency sound frequencies that can be heard in the headphones. Crystal sets have six basic parts. The antenna of course picks up the signal from the air.

The antenna

For crystal sets it is easiest to build an “electric field” antenna. It is usually just a long piece of wire strung out a window or up in a tree. A limitation of a single wire antenna like this is that, when the radio wave generates a voltage on the wire, the current it might produce has nowhere to go. A simple wire antenna is like one terminal of a battery. Yes, the battery has a voltage, but without a connection to the other terminal of the LC circuit, the current has no circuit to flow through. To provide a destination for the current we can add a second antenna. Alternatively we can connect the crystal set to “ground.”

The ground

Electrical “ground” is a word that we learn as youngsters, but most people go through their whole lives without ever understanding it. I suspect that the term arose during the early days of telegraph communication in the 1840s. It turns out that wet earth is a fairly good conductor. If you drive two metal stakes into the ground in your backyard and connect a battery to the two stakes, current will flow from one stake to the other. For two stakes about 100 feet apart, the ground has a resistance of about 100 ohms. If you experiment, you learn that most of the electrical resistance to current flow occurs right around the stakes. Once the current gets launched, the electrical resistance only increases slightly as you increase the distance. A metal stake in a backyard in China and the one in your backyard in the US might only have 300 ohms resistance between them. This was a boon for early telegraphers because it meant they only had to string one wire between cities instead of two wires to complete the circuit loop. In practice, using ground as an intercity “wire” is not as reliable as stringing a second wire, but it illustrates the concept of ground.

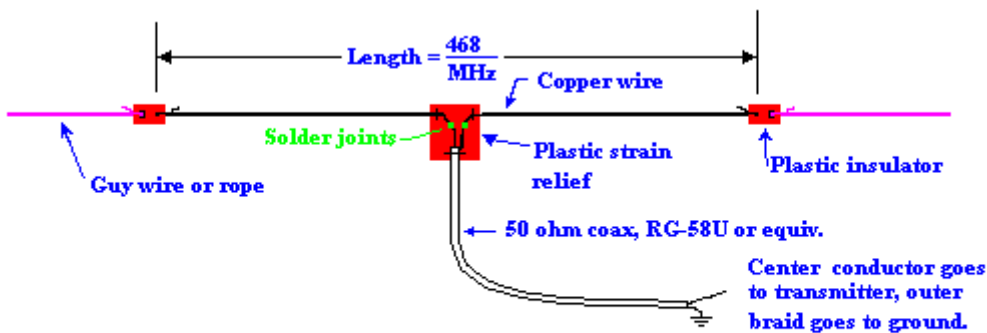


A good electrical connection with ground is an essential component of the crystal set. The most accessible ground for a crystal set or a ham radio station is usually a copper water pipe or a hot water heating pipe. At low frequencies, like standard broadcast AM, ideal electric antennas are very large. Needless to say, being able to use the entire Earth as half of the antenna is often quite convenient.

Dipoles

Unlike low frequencies, at high frequencies, like VHF television or FM radio, the ideal length for an electric antenna is just a meter or so. The higher the frequency, the less distance there is between successive electric and magnetic waves. That is, wavelength decreases with increasing frequency.

Although in theory you could use a stake driven into your lawn for the “ground” path on your TV, it is much simpler to just use a second short antenna oriented 180° away from the “real” antenna. This dual antenna is called a *dipole* and is the most common basic antenna design used in ham radio and TV antennas. Although it isn’t obvious, the arrays of thin metal tubes on rooftops are just refinements of the basic dipole antenna. In general, the lower the frequency, the larger the dipole must be in order to work well. A typical ham radio dipole is shown below.

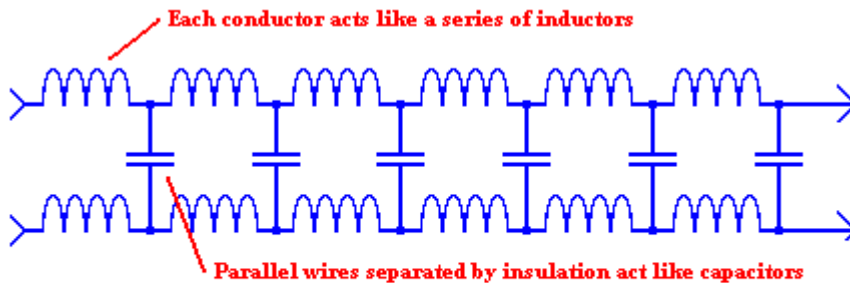


For 40 meters the length is 66 feet. The coax feed line can be any length, but shorter is better.

Transmission lines

In the ham radio dipole antenna above, the “arms” stick out in space in opposite directions and snag the passing electrical field. In general, the higher the dipole is above the local terrain, the better the dipole will receive signals. Unfortunately, you and your radio are down on the ground. Climbing up on the roof to listen to the radio or watch TV is inconvenient, to say the least. The problem of how to move radio frequency signals down to the receiver is solved with a *transmission line*.

A transmission line is a pair of parallel wires separated by insulation. It works very much like a speaking tube in a ship or even the string in a tin can telephone. In all these devices, vibrations are transmitted down a narrow pathway with surprisingly little loss of energy. A terrific example of a mechanical transmission line can be a farmer’s ditch filled with water. Provided the water is flowing slowly, when you throw a big rock into the ditch, the wave from the splash will travel hundreds of yards before it dissipates. A wave in the ditch propagates unchanged for many minutes and travels great distances. In contrast, if you throw the same rock into an open pond, the wave spreads out in all directions and quickly vanishes.



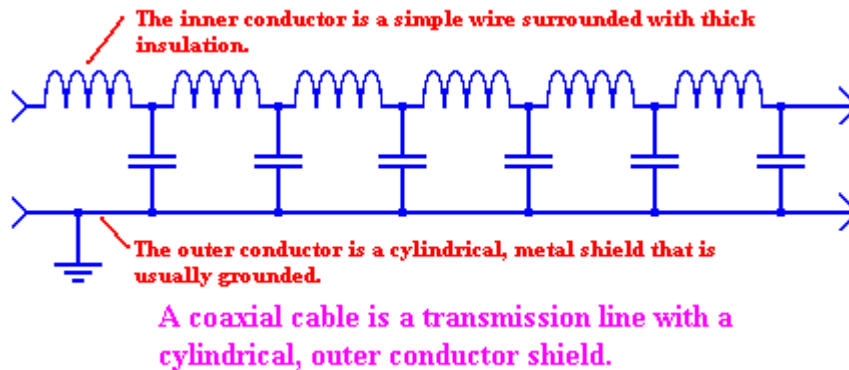
Two parallel wires separated by insulation make up a transmission line.

A radio transmission line is a distributed, LC resonant circuit. We saw in chapter 2 that a simple wire has inductance. Similarly any two wires separated by an insulator comprise a capacitor, whether we planned on making a capacitor or not. Consequently, when we run two parallel, insulated wires over any distance, there will be a measurable capacitance between them and the wires themselves will have a significant amount of inductance. To a radio wave, this construction looks like a long, LC circuit without end. As the capacitance and inductance are charged and discharged, the oscillation doesn’t stand still, but rather moves down the pair of wires at nearly the speed of light. As you can see, propagation down a transmission line is analogous to propagation through free space, but it only propagates in one dimension instead of three dimensions. The electric field or voltage generates a current and magnetic field, which in turn generates a new electric field and so on. An example of a simple transmission line consisting of two parallel wires is the flat wire "300 ohm" TV line used to feed older TVs.

Coaxial cable

The round, shielded transmission line used to feed modern TVs is a *coaxial cable*. Instead of using two separate ordinary wires, the outer conductor of a coaxial cable is a metal cylinder that completely encloses the center conductor. The inductance of the shield conductor is far less than that of a simple wire, but it prevents the radio frequency signals on the inner

conductor from leaking out. Even better, it keeps new signals from leaking into the cable and interfering with TV reception.



The ham radio dipole antenna described earlier uses type RG-58 coaxial cable to transport the radio frequency signals down into the house. You will notice that the outer shield is connected to ground. This is nearly always the case with coax. You could use cheap TV coax cable for your ham transmitter, but you will find it difficult to work with. The outer shield of cheap coax is just aluminum foil and is difficult to connect mechanically and electrically. In contrast, the outer shield of quality coax is braided copper wire that is easy to cut and solder. It also has considerable mechanical strength.

Transmission line impedance

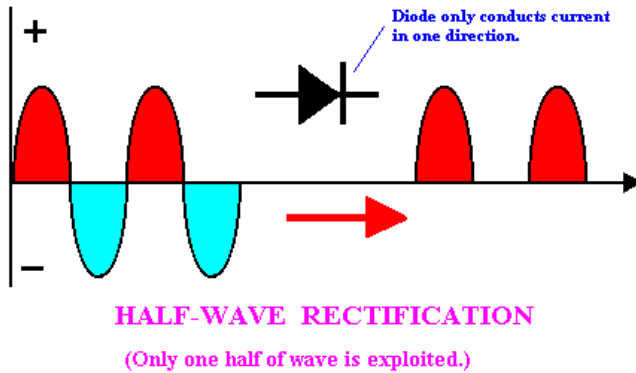
An abstract characteristic of transmission lines is that, from the point of view of a traveling radio signal, the line “looks like” a specific load resistance. For example, RG-58 coax appears to the radio signal to be a 50 ohm resistor. It isn’t, of course, but the voltage and current levels along the wire suggest that it is. In other words, voltage divided by current at points along the line will give 50 ohms. Another reason not to use TV cable is that TV cable is usually designed for 75 ohms, while most ham equipment is designed for 50 ohms. Similarly, the old flat, brown TV lead-in wire had a characteristic impedance of 300 ohms.

In general, the finer the wire and farther apart the two conductors of a transmission line, the higher the characteristic impedance. Sometimes hams use a wide “ladder line” in which bare copper conductors are separated by an inch or more of air and a few ceramic separators. Ladder line often has an impedance of 600 ohms. Ladder line is useful when transmitter power must be transmitted great distances to get to the antenna. Because a ladder line has little or no insulation in contact with the wires, the small dissipation of energy in the insulation is reduced to the absolute minimum. More importantly, the high impedance means that smaller currents will flow in the wire and less energy will be dissipated in the resistance of the copper. Of course, the trade off is that higher voltages are needed to transmit the same power levels. I know a ham who lives at the bottom of a canyon where radio reception is poor. He uses a long ladder line hung in the trees to connect his transmitter to the antenna, which is located hundreds of yards up on the mountainside.

Diode detectors

The diode is the *detector* that converts radio frequency sinewaves into audio frequency

electric waves, ready to be converted into sound. The diode is a “one way electricity valve.” In plumbing terms, it works like a check valve. The schematic symbol for a diode is an arrowhead pointed at a barrier at right angles to the wire.

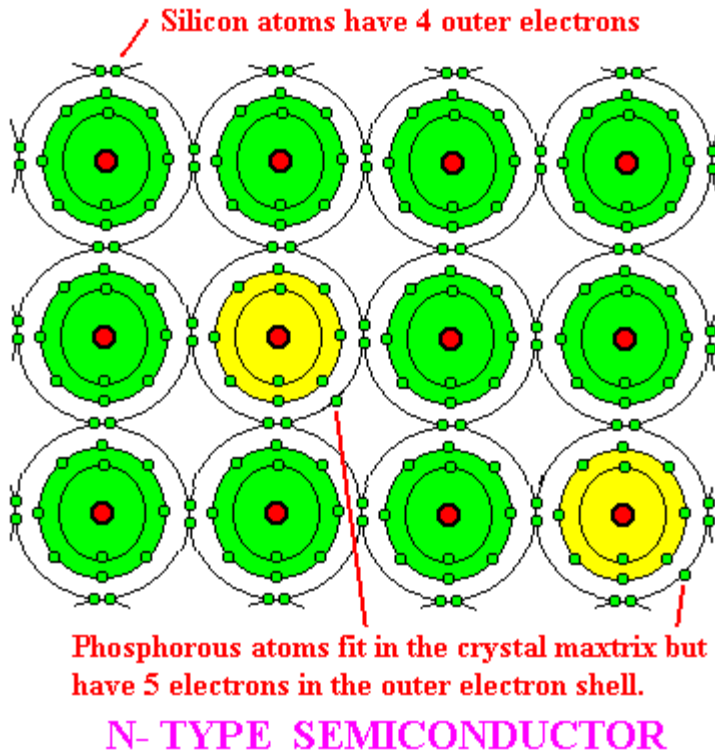


In electronics, the convention for “*positive*” *current flow is from positive to negative*. Unfortunately, the flow of electrons is from negative to positive. So, what is actually “flowing” from positive to negative is the absence of electrons. Confusing, no? I suspect this convention was established before electrons were understood. Referring to the symbol for a diode, positive current is allowed to pass if it flows in the direction of the arrowhead. Positive current will be blocked by the diode if it attempts to enter the diode from the perpendicular “barrier” side.

Semiconductors usually perform the check-valve function of diodes. A semiconductor is a crystal of an element like silicon or germanium that has a chemical valence of 4. That is, during chemical reactions this element can either take up 4 electrons, or give away 4 electrons. As we shall see shortly, semiconductors can also be fashioned by making crystals out of mixed elements with valences of 3 and 5, or even 2 and 6.

N-type semiconductors

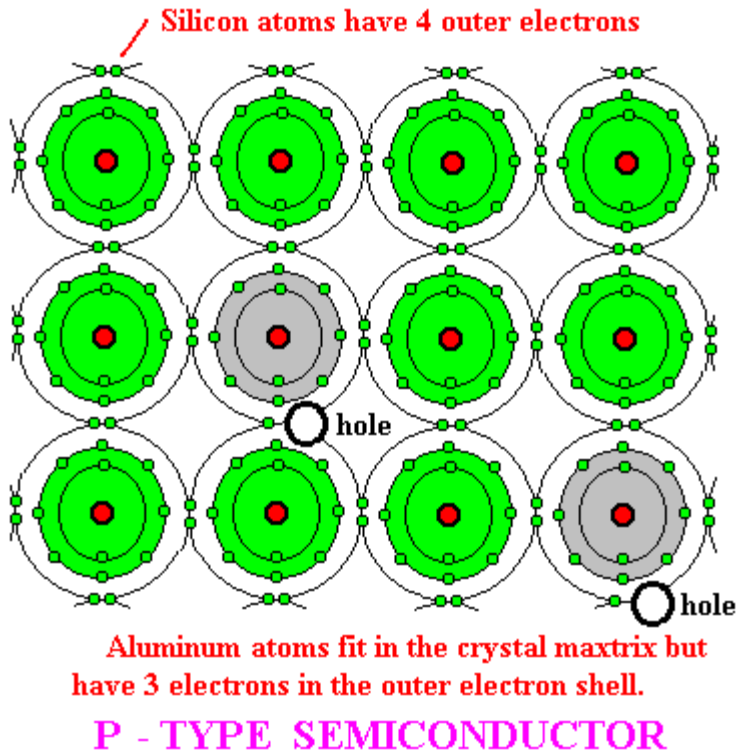
To keep it simple, let’s suppose we have a pure crystal made out of silicon, which has a valence of 4. If we put some multimeter (ohm meter) probes across this pure silicon, it will act like an insulator – there will be no significant current flow. However, if we make a new crystal with just a touch of phosphorus impurity in it, suddenly it becomes a conductor. Phosphorus has a valence 5 and is almost the same as silicon in atomic weight. This means that in chemical reactions it normally accepts 3 electrons to complete an outer shell of 8 electrons. But when silicon crystal is contaminated with phosphorus, lone atoms of phosphorus are trapped among a frozen, rigid crystal of silicon. The phosphorus atom fits in the matrix, but it has an extra electron that is “loose” and free to move around the crystal. The electron can’t move over to silicon atoms because they are joined with neighboring silicon atoms so that each silicon atom has a stable outer shell of eight shared electrons. However, the extra phosphorous electron can move over to other phosphorous atoms that have already lost their 5th electron. In other words, *a silicon crystal with just a touch of valence 5 impurity acts like metal*. It has electrons that are free to migrate through the whole solid. A semiconductor with extra electrons is called an *N-type semiconductor*.



P-type semiconductor

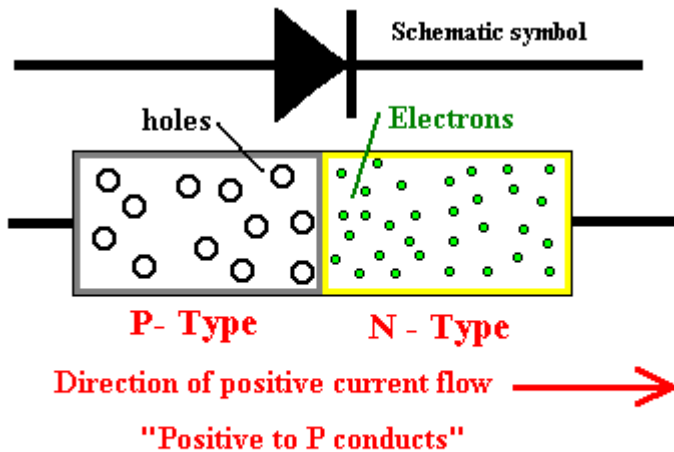
P-type semiconductor is a bit abstract. Instead of making a silicon crystal with valence 5 impurity, now suppose we add an impurity such as aluminum, indium, or gallium with a valence of 3. The impurity fits into the crystal matrix, but it needs one more electron to reach an equilibrium of 8 electrons shared with its neighboring silicon atoms. In other words, this semiconductor has “*holes*” in the crystal matrix that can be filled by electrons passing through. Now when you place multimeter probes across a P-semiconductor, it will conduct just like the N-type semiconductor. However, the conduction mechanism is different. With P-type semiconductor, the negative metal probe touching the crystal supplies all the free electrons flowing through the crystal. These electrons are hopping from hole to hole to cross the crystal.

Like phosphorus, aluminum atoms have almost the same atomic weight and size as silicon. Aluminum atoms fit perfectly in the silicon crystal matrix.



Diodes are P-N junctions

Semiconductor diodes are constructed by placing P- type semiconductor in contact with N-type semiconductor. In other words, for electrons to flow through the diode, the electrons must enter the N-type crystal and then move across the junction into the P-type where they complete the journey by jumping from hole to hole.



P-N SEMICONDUCTOR DIODE

“positive to P conducts”

If we measure the resistance across a diode with an ohmmeter, the resistance is low when we place the positive pole of the meter on the P-type semiconductor and the negative pole on the N-type. OK. Now let's reverse the probes of the ohmmeter. We are placing the positive probe against the N-type semi-conductor and the negative probe against the P-type. Electrons flow off the metal probe and into the P-type semiconductor. No problem so far. On the other side of the diode the extra electrons from the N-type silicon are being attracted or "sucked" into the positive metal probe. Thus the conduction seems to start out all right, but it isn't long before the extra electrons in the N-type silicon along the P-N junction are depleted. All that remains in this region are depleted valence 5 atoms that are now acting like pure silicon. This whole region now acts like pure silicon and the conduction stops.

So why can't the electrons that are migrating through the P-semiconductor holes hop across the P-N barrier and move onto the valence 5 atoms? The reason is the same. The migrating electrons have filled in all the holes in the P-type and the crystal has also become pseudo-pure silicon that is an insulator. When thinking about PN diodes, remember, "**positive to P conducts.**"

Real diodes

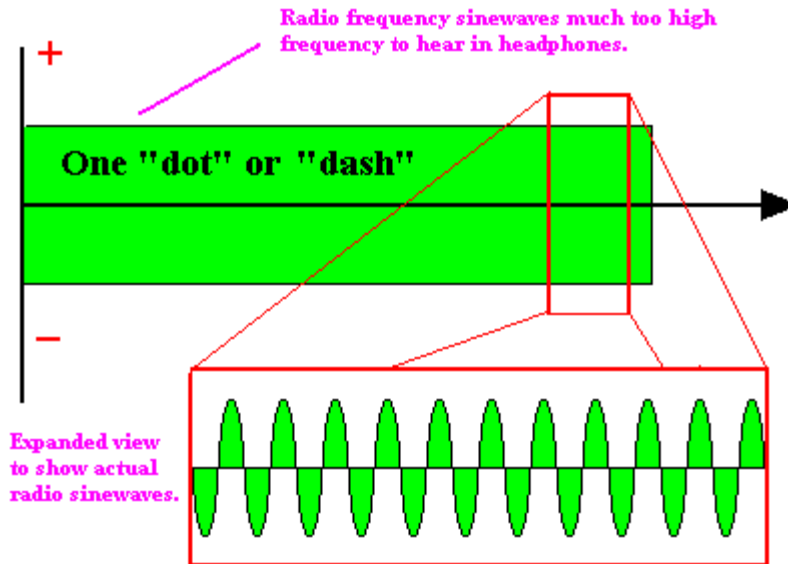


Commercial diodes come in all sizes. The types suitable for detectors in crystal sets are the little bitty guys on the lower left. The big black diodes on the right are rectifier diodes and diode "bridge" arrays for power supplies. The long black diode is rated at 6,000 volts. The two diodes that are built like machine bolts are high speed, high power units that might be used in a large switching power supply or an industrial RF generator.

Detection of AM radio signals with a diode

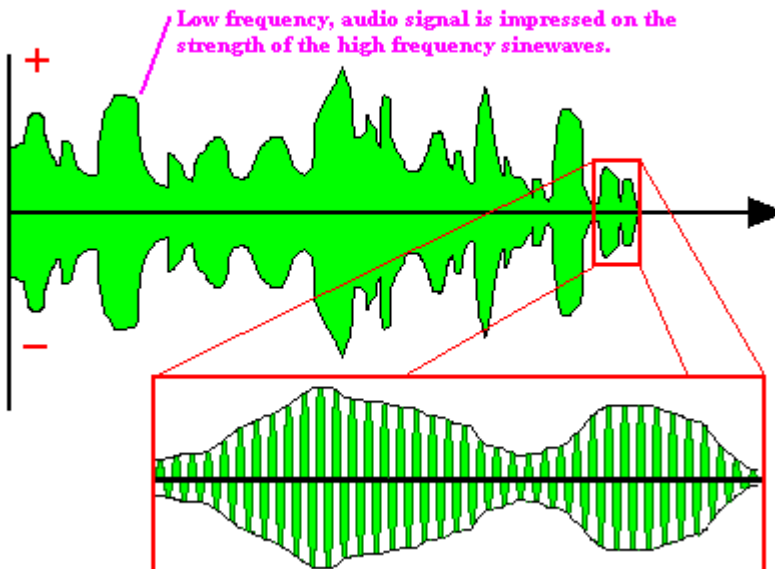
In amplitude modulation, (AM) the audio speech signal is impressed onto the radio signal by varying the AMPLITUDE of the radio signal. An AM transmitter literally increases and decreases the output power of the transmitter in time with the speech and music being broadcast. The drawing below shows an unmodulated radio signal of the sort used to send Morse code. The radio frequency sinewave remains the same amplitude throughout the time that the transmitter is keyed. Because the sinewave maintains its amplitude during the "dots" and "dashes," Morse code signals are known as *continuous wave* or "**CW.**"

Unmodulated Radio Frequency Sinewave used to send Morse Code (CW).



As the name implies, an *amplitude modulated (AM) radio broadcast*, (550 KHz to 1.750 MHz) makes a continuously varying graph of the RF signal that looks like a psychiatrist's Rorschach. But of course the outline of the audio signal is actually made up of hundreds of thousands or millions of RF sinewave cycles.

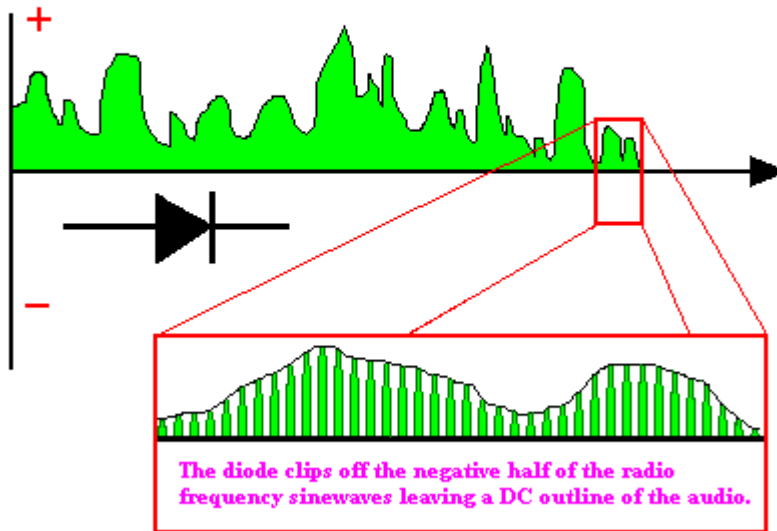
Amplitude Modulation of a Radio Wave



The diode detector recovers the audio signal by "shaving off" one of the two polarities of the RF signal. Sinewave currents have both positive and negative polarity. Diodes only allow conduction in one direction. So, when a radio frequency sinewave current is passed through a

diode, one of those polarities will not pass and will be eliminated. What remains is a series of narrow, direct current pulses, all with the same polarity.

DIODE DETECTION OF AUDIO MODULATION ON A RADIO WAVE



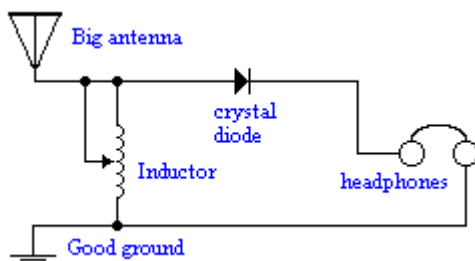
This detection process, which is also called *rectification*, produces a varying DC signal that may be passed through a headphone to convert it into sound. Physically, a modern diode is usually a tiny glass cylinder typically $\frac{1}{4}$ inch long with two wires extending from the ends. It's not much to look at. As will be described below, it's more fun to make a diode out of sulfide ore, or even out of razor blades or safety pins.

Headphones

After the diode has generated the varying DC current representing the audio signal, a device is needed to convert the current into sound. The classic way to do this is to use a magnetic headphone. As we shall describe below, a headphone is an electromagnet that attracts a thin, steel diaphragm and makes it vibrate in time with the speech and music.

A practical crystal set schematic

The crystal set can be extremely simple. A schematic is shown below:



Crystal Set Parts List:

Big antenna – 50 feet of wire strung up in a tree will be ideal. Or, use the 40 meter dipole described above. For this application, use the entire dipole assembly as if it were a single piece of wire. Connect the center conductor and the braided outer shield of the coaxial cable together and fasten the resulting “wire” to the “big antenna” location above.

Good ground – A connection firmly clamped to a household copper water pipe would be ideal. Alternately, you may use a second length of wire strung up in another tree. The second wire should be far away from the first wire. I happen to have a 30 meter ham band dipole in my back yard. I used my 40 meter dipole in my front yard as the “antenna” and the 30 meter as a “ground.” Or, as it would be known in this application, the 30 meter dipole became a “*counterpoise*.”

Inductor Wind about 20 turns of bare copper wire around a large diameter cardboard tube. Cardboard Quaker Oats boxes are the classic coil form for this purpose, but the cardboard cylinder from a toilet roll will work. In general, the larger the diameter coil, the better it works. I believe large coils work better because the coil is acting as a magnetic antenna, as well as a tuned LC circuit. In other words, a large diameter coil snags more magnetic field component from the radio wave. To tune the crystal set, you need to rig up a slider or shorting clip that allows you to short out some of the coil.

Capacitor Where’s the variable capacitor? A capacitor consists of two pieces of metal separated by an insulator. If you wind a big coil of wire around a cardboard tube, then there is capacitance between one loop of wire and all the neighboring loops. “But, hold on! That can’t be! They’re shorted together!” you say. Yes, you’re right. But if you look at an LC circuit as a whole, the inductor is a kind of “short circuit” across the whole capacitor and we know that works OK. The hard part about physics is that you have to learn to think abstractly. A lot of phenomena seem fuzzy and inconsistent. We are forced to “get a feel” for what works and what doesn’t. The coil of wire is said to have *intra-winding capacitance* that acts the same as if it were a separate capacitor across the whole thing, honest.

Crystal diode It’s great fun to build your own diode as described below. However, to get started, you may want to use an ordinary, small silicon diode such as a 1N4148 or a 1N914, which is available at Radio Shack.

Headphones. You may construct a working headphone from ordinary parts as described below. This will be fun and educational, but eventually you will need to buy a good pair. You may buy either old-fashioned high impedance (2000 ohms) headphones or modern low impedance (8 ohms) headphones. The modern ones are extremely efficient, comfortable to wear and have hi-fi sound. The high impedance headphones are historic and little more can be said in their favor.

Homebuilt diode detectors

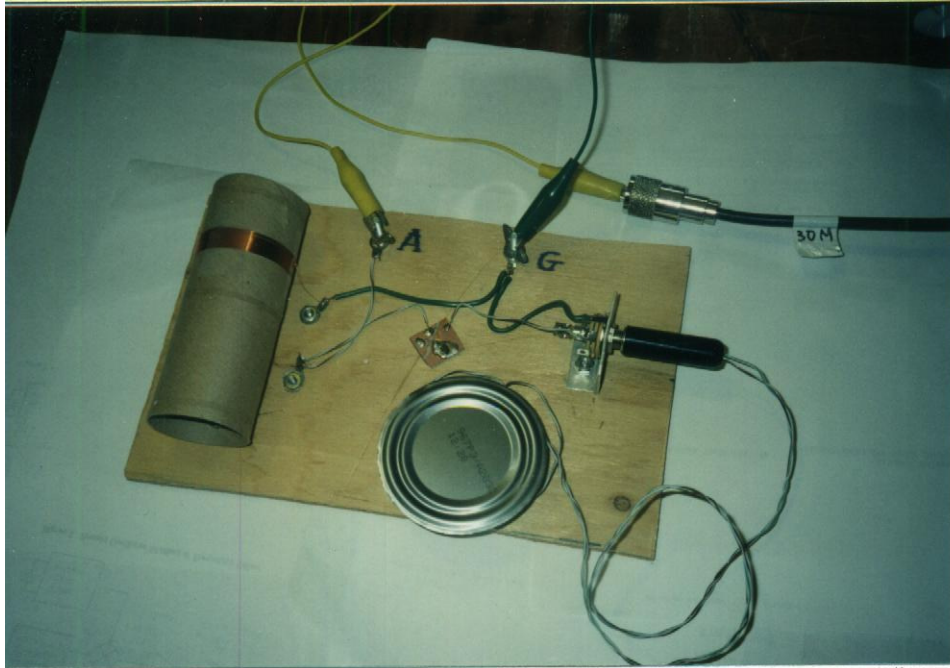
My experimentation with crystal sets as an adult began one day when I was hiking near Jamestown, Colorado. I was scrambling up a yellow-colored abandoned mine dump. Mine tailings up there are mostly yellow, sulfated, powdered rock that consists of broken-down granite or gneiss. Suddenly right in front of my face were chunks of the shiny, black sulfide ore that was the reason for the mine. Without an assay, I don’t know exactly what’s in this ore, but it’s a safe

17. Chapter 4, Harris

bet that it's a mixture of sulfides of silver, lead, and maybe zinc, a dash of arsenic, tin, and copper. There might even be a trace of gold telluride in those crystals. Galena, which is lead sulfide, is the stuff used in old-time crystal sets to make detector diodes. "Gee! I wonder if I can make a crystal set out of this ore?"

It seems to me I once saw a war movie in which a POW in a Nazi Stalag made a radio out of barbed wire, a razor blade, and silver paper from a chewing gum wrapper. Well, that's Hollywood, but maybe a receiver can be built without using parts specifically manufactured for radios. I happened to have a toy crystal set radio dating from about 1950 in my attic, so I hauled it down and checked it out. The "diode" consists of a tiny chunk of gray galena sticking out of a little puddle of solidified solder. The positive pole of the diode is a metal "cat whisker," a piece of thin copper wire poked against the crystal.

My crystal set project was done in two sessions and is written as two separate articles. Before you build the set pictured below, I suggest you read about the second crystal set as described in another article following this one. The second crystal set encountered some abstract mysteries, so while it worked better, it is harder to understand.



The above picture shows my crystal set with all three homemade components. An LC resonant circuit is vital to select the AM radio band (or other band). An actual tuning capacitor isn't really needed at AM radio frequencies. A big coil, at very least two inches in diameter with 20 to 60 turns wound on a cardboard tube, has enough inter-winding capacitance to resonate in the AM band. From a physics point of view, the circuit in the "practical" schematic is functionally the same as the circuit that contains the variable capacitor across the coil.

Without a variable capacitor, you will have no way to tune in particular stations. A tap on the winding can be added for peaking a station. A "tap" is just a way to short out part of the inductor. Using this method you can crudely, very crudely, select the loudest stations at the top or bottom of the AM broadcast band. Tuning a crystal set is (usually) sloppy. However, the

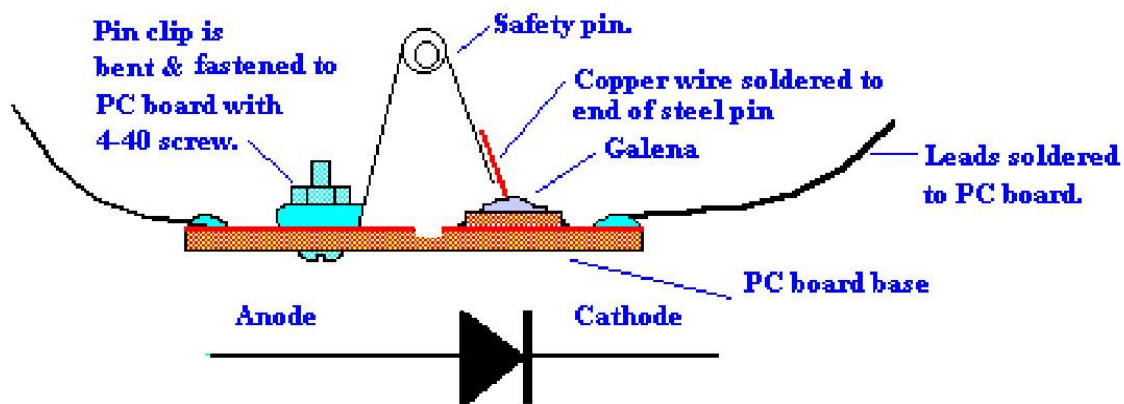
article at the end of this section demonstrates how to accomplish sharp tuning.

The crystal diode rectifies the radio frequency voltage ringing on the LC circuit and the headphones turn it into sound. Some crystal sets also have an audio signal filter or “integrator” capacitor. This capacitor, about 0.01 microfarad, is placed across the headphones. However, in my crystal set, it didn’t do anything useful, so I left it out. Leaving out parts is a good way to find out what they do.

Try leaving out the LC circuit and just connecting the diode and headphone to the antenna and ground. At my house all I could hear was faint static that sounded like power line noise. That implies that power lines generate the biggest AM signals over the entire radio spectrum. In any case, without the LC circuit, I heard no radio stations.

The Jamestown crystal diode

To make my crystal detector out of sulfide ore, I melted a puddle of solder about 3/8 inch wide on a piece of PC board. Then I used tweezers to press a bit of ore into the puddle so that, when it hardened, half of the crystal was exposed. Next I soldered a tiny loop of copper wire onto a pad on the board for a cat whisker. My first diodes used loops of fine copper wire as “cat whiskers.” The copper wasn’t springy enough to poke into the crystal with enough force for reliable performance. It worked well, but with a little vibration, it quickly died.



A safety pin pushes the copper whisker against the galena.

In my next diode I made a copper ring cut from the end of 1/4 inch copper tubing that served as a deep “tub” of molten solder into which I could push the galena. Bob, NØRN, told me that when he was a kid, he used safety pins as cat’s whiskers. Sure enough, the spring-loaded safety pin produced plenty of force and solved the mechanical problem. *Don’t forget to cut the notch or gap in the circuit board between the galena side and safety pin side* – they are two separate circuits!

Carbon steel is a semiconductor

When I first put my diode with the safety pin cat whisker into a crystal set, it was stone silent - nothing. No matter how I moved the sharp steel pin around on the galena, the headphones were dead. The pin happened to strike the solder at the edge of the galena and the

crystal set came to life with music from KBCU, our loudest local AM station. At first I was mystified. The steel pin rectified well against either solder or copper. The signal was perhaps only 2/3 as loud as it had been with the copper-to-galena diode, but it was much easier to adjust.

It turns out that steel is a carbon-iron semiconductor compound called cementite. The surface of hardened steel is a crystal, perhaps not radically different from the galena (lead-sulfide) crystal. Carbon has a valence of four, just like silicon or germanium. So, if you want to build a crystal set for your kids, *you don't have to mine galena. Just use a safety pin pressing against copper or solder.*

Another surprise for me was that copper-to-copper, solder-to-solder, or solder-to-copper junctions also rectify and produce weak signals. The contact between the two metal surfaces must be extremely light - just barely touching. This phenomenon is poor for making crystal sets, but it's a warning about bad contacts in electronic equipment. *Cold solder joints and loose screws can fill your circuit with accidental diodes.*

Copper cat whiskers work best

As shown in the diode construction diagram, I used *acid core* solder to attach a piece of copper wire onto the end of the pin. Now the contact point of my diode is between the semiconductor galena and copper rather than semiconductor steel-to-semiconductor sulfide ore. I connected my crystal set to the center conductor of my 40-meter dipole coax and my station ground. I scratched the copper whisker around on the sulfide crystal and suddenly I was again hearing our local station. Using commercial 8-ohm headphones, it was almost painfully loud. Too bad KBCU is mostly rap music.

Where is the P-N junction in these crude diodes?

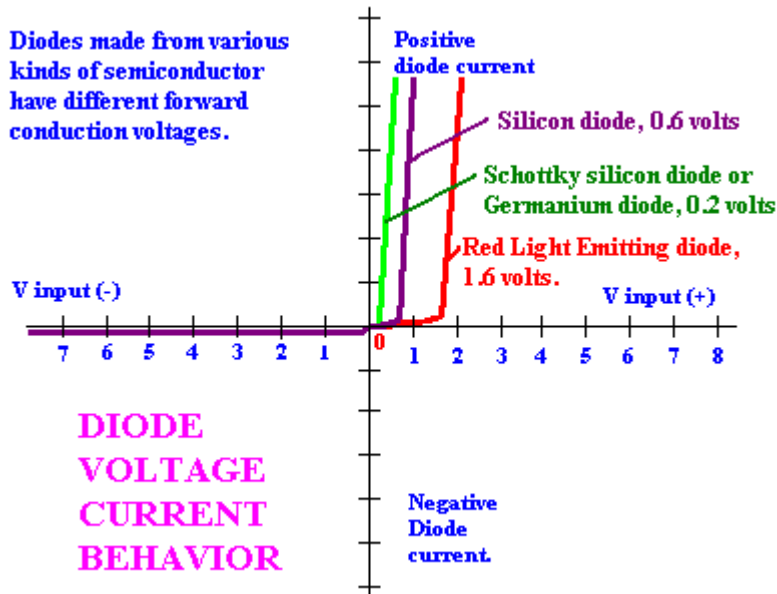
If you are a thoughtful person, you must be asking, "Where is the P-N junction with the impurities imbedded in the pure semiconductor and all that?" It turns out that you can make crude diodes by throwing together pretty inferior materials. For example, pure galena crystal consists of lead and sulfur that have valences of 2 and 6, that sort of average to 4. But there are also all those other atoms in typical galena ore. These impurities, like silver or copper, have valences like plus 1, while other transition metals like tin have valences of 2 or 4. Let's just assume that because of sulfide (valence 6) and arsenic (valence 5) salts, my ore is a N-type semiconductor. So where is the P-type semiconductor? It turns out that if you press a metal against N-type semiconductor, metal ions will migrate a few microns into the N-type crystal and make a tiny P-type region surrounding the contact point of the "cat whisker."

As you might expect, the disadvantage of such crude diodes is that P-N junction is quite fragile. That is, the check valve function only works with very low voltages and extremely small currents. The P-N junction is easily destroyed if you put large reverse voltage across it or try to pass large currents through it.

I tried measuring the volt/ ampere characteristic of a steel/ copper diode. It was no surprise that it looked like a short circuit on an ohm-meter. I studied it carefully with a high impedance multimeter and 10 megohm series resistors, but it still looked like a short circuit. I believe I just learned that *the world of RF detection is quite subtle*. At least the legend about POWs in WWII making radios out of barbed wire and razor blades is starting to make sense. The razor blade must have been the semiconductor.

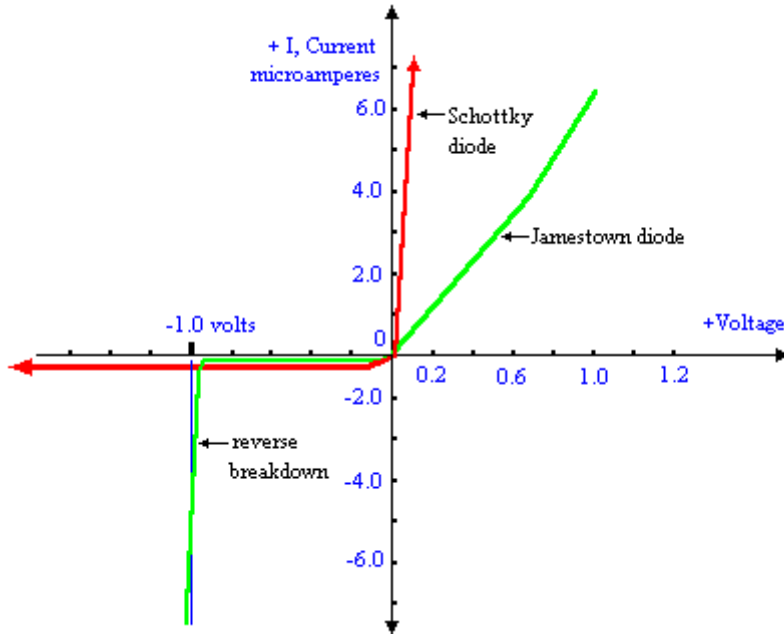
Commercial diodes

A perfect diode would have zero resistance in the forward direction and infinite resistance in the reverse direction. As you can see in the graph below, no real diode is perfect and all diode types have different forward voltage characteristics, depending on the semiconductors used to make them. The reverse characteristics of commercial diodes are all excellent and similar, but each type of semiconductor diode needs a certain level of forward voltage before it will begin to conduct. In the graph below relative current is plotted on the vertical axis. Commercial diodes handle hundreds of milliamperes or even hundreds of amperes. As you'll see below, homemade diodes can barely handle microamperes of current before they fail.



Volt – ampere characteristics of homemade diodes

Once I had my cat whisker adjusted, the Jamestown diode was just as loud as the 1950 crystal set diode. I tried substituting a modern, hot-carrier Schottky diode for the crystal. In theory, a Schottky should be comparable to a point-contact diode. Schottky diodes are commonly used as detectors in relatively modern equipment. I was surprised to discover that the modern Schottky produced as big a signal as the crystal diodes, but no better. If these diodes perform the same, how do their volt/ ampere characteristics compare?



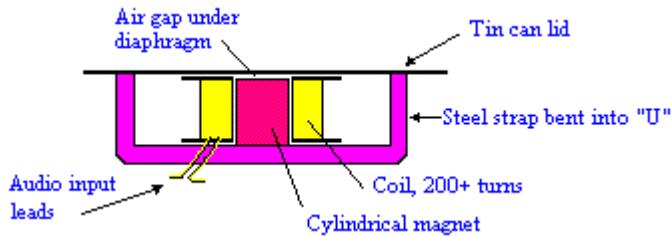
Volt / Ampere curves for the Jamestown diode and a commercial Schottky diode

At big voltages and currents, (milliamperes), the Schottky diode acted as you would expect: It passed big currents (milliamps) above 0.2 volts forward voltage and leaked only 100 nanoamperes with reverse voltage. Notice that if the Schottky were “perfect,” the red line would be directly on top of the vertical axis upward, and directly on top of the horizontal axis to the left. However at very low currents, microamperes, the commercial Schottky was pretty nearly perfect with a transition right at zero volts.

In contrast, with big currents the Jamestown diode behaved like a resistor in both directions. At first it wasn’t obvious to me that it could rectify anything. The curves above show the behavior of both diodes at tiny current levels, microamperes, using a 1 megohm (one million ohms) load. For tiny currents, the Schottky and Jamestown diodes were both strongly non-linear at the zero current, zero voltage point. The surprise for me was that, for reverse voltages, the Jamestown diode broke down abruptly at minus one volt. It’s no wonder it conducted so well in both directions with a “low” resistance 10K ohm load. This abrupt, reverse breakdown is called *avalanche breakdown*. When it occurs with big currents it usually destroys the diode. As we’ll see in chapter 8, some diodes called *Zener diodes* are designed to breakdown at specific voltages without being destroyed.

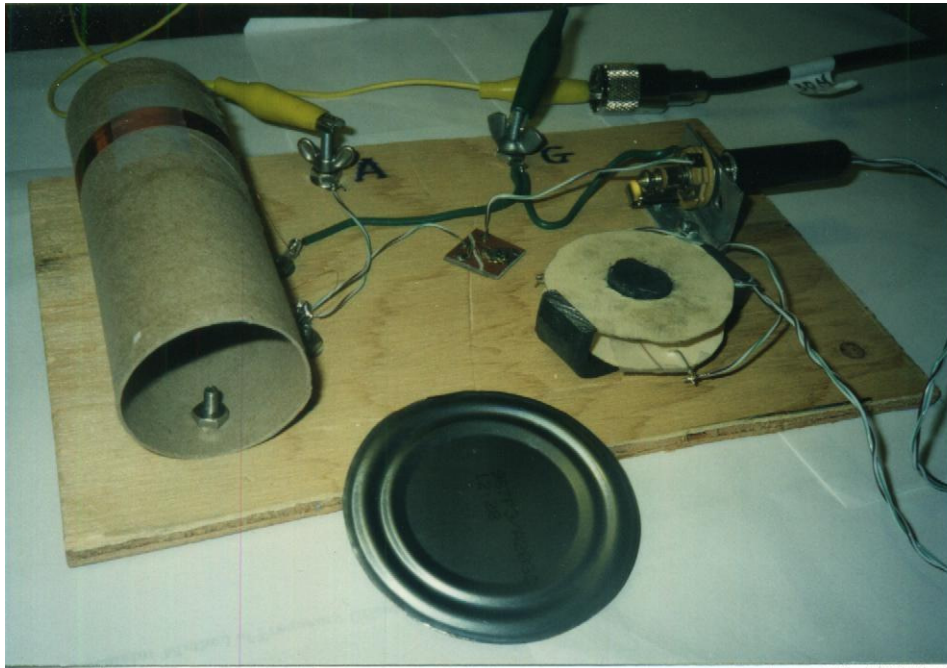
A homemade headphone

Building my own headphone was the hardest part of my crystal set. A headphone uses a high impedance coil of wire to make a magnetic field proportional to the audio signal. The changing field pushes and pulls against a thin steel diaphragm to produce sound vibrations. Even if you decide to build one of these headphones, I strongly suggest you buy a good pair of headphones so you will have them for your ham rig. Also, with commercial headphones the speech and music will be perfectly clear and loud, even with a safety pin diode.



The Caribou headphone

A cross section of my homemade headphone is diagramed above. Its construction is basically the same as old-fashioned high impedance headphones. Yes, the sound is tinny. What did you expect from a headphone diaphragm made from a tin can lid? The coil is hundreds of turns of #36 wire wound on a paper coil form. Inside the coil is a cylindrical magnet I took out of an old loudspeaker. A piece of steel strap conducts the magnetic flux around to the edges of the lid. The magnetic force holds the lid on. By completing the magnetic circuit, the magnetic force is concentrated in the gap between the tin-plated steel and the magnet.



Crystal set showing homemade headphone. The tin can lid diaphragm has been removed.

I started out using a small magnet from an old loudspeaker, but that felt like cheating. Would Heinrich Hertz have been able to use a loudspeaker magnet? Anyway, it seemed to me that the magnet wasn't essential. Why couldn't the coil just magnetize ordinary iron? I tried substituting a big steel nut of the same size. Sure enough, it worked, but the sound was too faint to be audible in the crystal set. However, when I plugged the homemade headphone with the steel nut into my shortwave radio, it was surprisingly loud. Not Hi-fi, mind you, but loud. No, for a sensitive headphone a magnet is needed to overcome the hysteresis.

Hysteresis

What's hysteresis, you ask? Whenever iron is magnetized with a DC coil, the tiny

“magnetic domains” in the iron line up to make a big magnetic field. But when the DC current is shut off, some of the magnetic domains remain aligned and leave a residual field. To magnetize the iron in the opposite direction, a current of the opposite polarity must first overcome the residual field. This means that hysteresis interferes with the sensitivity to weak signals. Since crystal sets are powered by the radio waves themselves, sensitivity is vital. A magnet is needed to overcome the hysteresis and “bias” the magnetic field so that it always operates in one direction. I could magnetize iron with a DC powered coil, but then to be a purist, I would need to build a homemade battery. And I would need to smelt and extrude my own copper wires. (Forget I said that.)

I had a sudden inspiration. I dug around in my rock collection and found a piece of magnetite ore from a mine dump at Caribou, Colorado. Magnetite is a specific iron oxide, Fe_2O_4 , that retains a magnetic field. I machined the magnetite with my bench grinder into a small cylindrical magnet. Unfortunately, the grinding and heat ruined the magnetism. However, fixing it to a big, heavy permanent magnet, I was able to put my magnetite in a strong magnetic field. Then I banged on it firmly against my anvil. Believe it or not, that abuse restored the magnetic field. Behold! - The completed Boulder County rock and toilet roll radio!

How does it perform? Well, frankly the homemade headphone is pathetic and needs lots of R&D. The sound is plenty loud when plugged into a real radio, but installed in the crystal set, I can just barely hear the rap music. Perhaps if I had a thinner steel diaphragm, a headphone for each ear, optimum impedance matching, better craftsmanship, and other refinements, it might approach a commercial headphone. In other words, for serious listening, buy a decent headphone! And, after your done playing with homemade crystals, I suggest you buy some silicon diodes. Type 1N914 or 1N4148 diodes work great in this radio. *They don't work better than the diode made from sulfide ore*, but they are smaller, more rugged, and don't need to be carefully adjusted.

This crystal set article was first written in 2002. I revisited crystal sets in 2006 and discovered some surprises.

CRYSTAL SETS REVISITED

Or, electronics makes us humble

A friend of mine, Jack Ciaccia, WMØG, suggested to his grandson, Rutger Koch, that a broadcast band crystal set like the one described above would be a good science project. Rutger did a terrific job of duplicating the set and the homemade diode. The only obvious difference I could see was that he had used the 5-inch cardboard oatmeal box coil form that I had recommended. But when Rutger put it together, it was totally inert - no sound.

Rutger consulted his granddad who also couldn't find anything wrong. Jack brought the crystal set over to my house and we two old hams scratched our heads and still couldn't find the problem. After five minutes of swapping parts, I dug out my prototype crystal set from the closet and there was the answer: If you go back to the drawing of the homemade diode made out of the piece of PC board and a safety pin, you will see that there is a notch carved in the PC board between the anode and cathode. Rutger had forgotten to cut the copper sheet between the anode and cathode so they were shorted together. We cut the copper sheet and it worked perfectly.

Our eyes only see what they expect to see! Don't take the obvious stuff for granted. By the way, Rutger's science teacher refused to believe rocks could serve as diodes until he put on the headphones. This ancient technology is all new information for whippersnappers.

Does a bigger diameter coil work better?

When I first built my AM broadcast band crystal set described earlier, a toilet paper roll was the largest diameter cardboard form I could find around the house. Although I hadn't noticed any obvious superiority in Rutger's crystal set over mine, I decided to wind a big coil like his and see if my magnetic antenna theory had any validity. That is, the big coil might pick up the magnetic wave components and produce a bigger signal. Perhaps it would be directional like an AM band ferrite core antenna. Since my crystal set had previously been converted to 10 meters (see the next article, below), I just took off the loop antenna and left the 140 pF variable capacitor on the set. Then I installed the oatmeal box coil with about 20 turns on it. Since I already knew that ordinary silicon diodes have the same sensitivity as the rock diodes, I used a 1N4148 diode and my large, low impedance headphone.



Oatmeal box crystal set - operating without a ground or counterpoise

I hooked up the 40-meter dipole antenna, "A" above, and used the 30-meter dipole as a counterpoise connected to the ground post, "G" above, just as I had before. This was the same way Jack and I had hooked up his grandson's set. The silence was deafening. Good grief! Now what?

After some flailing about, I accidentally disconnected the counterpoise wire as shown above, just leaving the antenna wire connected. Voila! It not only worked well, the tuning was precise enough to tune in my local NPR station at 1490 KHz with excellent selectivity and signal strength. By "excellent" I mean, it was not only loud and clear, I could only hear the one station. Precise tuning with a crystal set! How is this possible? When I padded the relatively small 140

pF variable capacitor with 100 pF fixed capacitors, I was able to tune down the AM broadcast band and uniquely select other stations. The farther down the band I went, the less precise the tuning. I believe the loss of precision at the low end of the band is related to the relative signal strength of the stations. Also, I obviously needed more turns on my coil. If I were starting over, I would use a larger variable capacitor, e.g., 365 pF.

How does this work?

The selectively tuned crystal set seems to be an example of a circuit that doesn't seem to have a complete circuit loop. Without a ground or a counterpoise, where does the current go? I assume that there is some form of capacitive coupling that completes the loop, but I must say this coupling isn't obvious. As you can see, RF sometimes makes current loops that are hard to identify.

Using the backyard antenna as a counterpoise didn't work with the big coil, but I found that clipping the ground terminal, "G" to my station ground did improve signal strength. However, it ruined the precision of the tuning. Hooking the station ground and the counterpoise antenna together still worked, but was weaker and produced poor tuning. Using the backyard 30-meter antenna as the sole antenna, worked just as well as the 40-meter antenna.

I probed with my oscilloscope at various places on the circuit to get some answers. As soon as I attached the oscilloscope probe ground wire, it behaved just like the grounded hook up, just as you would expect. The signal strengths across the coil were on the order of 0.40 volts peak. The power delivered to the 8-ohm headphones was about 20 milliwatts peak. The most surprising observation was that, when I just left the scope probe and its ground wire lying six inches away from the crystal set, I could see the modulation on the screen appear and disappear as I selected specific stations. The voltage signal was only slightly less than when it was directly connected. Apparently there is a large electric field surrounding the crystal set.

As for the magnetic antenna effect, when tuned into a specific station, there was no hint of directionality as I rotated the coil from north to south. In conclusion, the advantage of the big coil seems to be a dramatically higher Q (higher quality resonance). But to observe this advantage, the headphone must be powered exclusively by the signal ringing across the coil. If the current is passing from antenna to ground, the L-C circuit has much less effect on the tuning. And finally, (apparently) when the ends of a high Q coil are connected to two equal antennas, the signals cancel each other.

Perhaps you have your own theories about these phenomena. Feel free to pontificate. Obviously we old hams don't know everything, even about the simple stuff! Keep your brain engaged and question authority.

**

RECREATING HERTZ'S RADIO EQUIPMENT

Most of what I've read about the history of radio was written by non-engineers. They describe the revolutionary apparatus invented by our heroes using old-time radio terms like "earth resonances," "aether," and "coherers." They tell us how far it transmitted, but they give us only the faintest clues about how the gizmo actually worked. Was it a spark gap transmitter? A

high-speed alternator? What the heck was a “Tesla oscillator” anyway?

In 1884 James Maxwell published four equations that quantified and connected magnetism with electric phenomena. These equations also predicted the existence of radio waves. The changing magnetic and electric fields related to each other with sine functions. So, once physicists had the equations to stare at, it wasn't too huge a leap to conclude that sinewave-shaped electric and magnetic fields would generate each other in an oscillation and radio energy would propagate through space.

In 1889 Heinrich Hertz, a physics professor at the University of Bonn, Germany, was the first to demonstrate radio waves in the laboratory. Of course he might have done this in 1884, or 1887, depending on which website you visit. Ah, the glorious information age!

That's fascinating, but **HOW** did he demonstrate radio waves? Using 1880 technology, that could not have been easy. How did he know he was detecting waves and not just magnetic coupling from one coil to another? Or if his antenna was capacitive, how did he know he wasn't observing capacitive coupling? *If I were skeptical about the existence of radio waves, but I understood the full implications of Maxwell's equations, I would be convinced if I could see communication across a distance greater than one wavelength.* A minimum of one wavelength means that “the alleged electromagnetic wave” would change from magnetic to electric field energy then back again at least once. *Of course, I would also want to see evidence of standing waves and a way to measure frequency.*

Demonstrating Hertzian waves

Suppose you were living in the year 1884 and Maxwell had just predicted the existence of radio waves. Using components available in your time, how would you generate Hertzian waves and get those waves named after you instead of Hertz? If you are able to generate radio waves, how could you prove to a skeptic that you had actually done it? Hertz managed this feat and apparently his demonstration was convincing. Otherwise the unit of measurement for frequency would not be the *Hertz*. One Hertz (Hz) equals one cycle (one complete oscillation) per second.

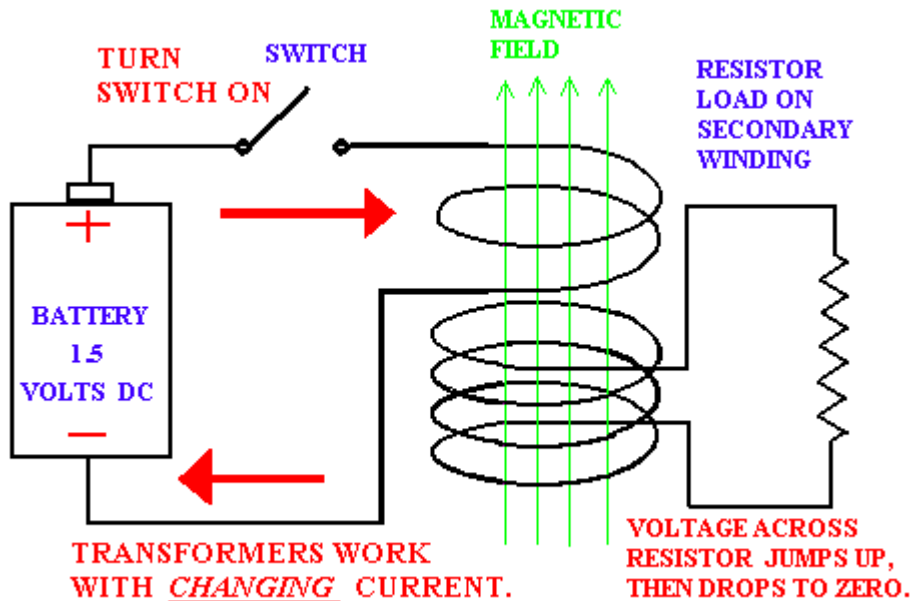
When I first had the idea of pretending to be Dr. Hertz, I was not able to find a description of his apparatus. That was a good thing because it forced me to invent my own method to demonstrate Hertzian waves. If you already know enough about electricity to be able to handle the challenge, then get out your 1880 hardware and build a transmitter and receiver that will transmit at least one wavelength. If you don't know how to begin, keep reading.

Transmitting and receiving as simply as possible

The only detail of Hertz's apparatus I found described was that he detected his waves by means of a loop of wire. The wire had such a large current and voltage induced into it by the radio waves that a visible spark jumped across a gap in the circle of wire. Wow! It must have been a big radio signal that would induce that much energy into a loop of wire. And if the signal was that big, how far away from the transmitter had the loop been? I suspect the signal strength had to be high and the loop had to be very close, like a foot or two away.

If were a skeptic who already knew about Faraday's transformers, this demonstration would not convince me. How would I know that radio waves had propagated across the one foot distance to the loop? Maybe all I was seeing was a big magnetic field that reached from one coil

to another.



Maybe Hertz's demonstrator was just a transformer?

A transformer is a *magnetic* device that works by transmitting a changing magnetic field from one coil to another. Coils (inductors), convert the energy of an electric current moving through a wire into magnetic field energy that hovers in a cloud like region around the coil. If a second coil is close enough to the first coil to be inside the magnetic "cloud," then if the magnetic field is changed, then an electric force, a voltage, will be generated in the second coil. Transformers and the above diagram were discussed in chapter 2.

Inductors store magnetic energy in the space around them so long as current is passing through the coil. The energy will remain in space so long as the current keeps flowing in the same direction through the coil. But when the current stops flowing, the magnetic energy becomes "stranded" in space. The magnetic energy then returns to the coil and induces a voltage in that coil in a direction that would force the current to continue flowing. That is, the induced voltage will try to keep the status of the magnetic field and coil the same. If the current is gone for good, then the magnetic field will collapse completely and the energy will dissipate into the coil and any circuit connected to it. But if the first coil is open circuit and even high voltages cannot restore current flow, then the field will collapse into the second coil. If the induced voltage is able, it will cause current to flow in the second coil to maintain the field. Or, as in the case of Hertz's loop detector, the induced voltage caused a big spark to jump across a gap where the resistor is located in the illustration above.

But I thought transformers were always made from iron

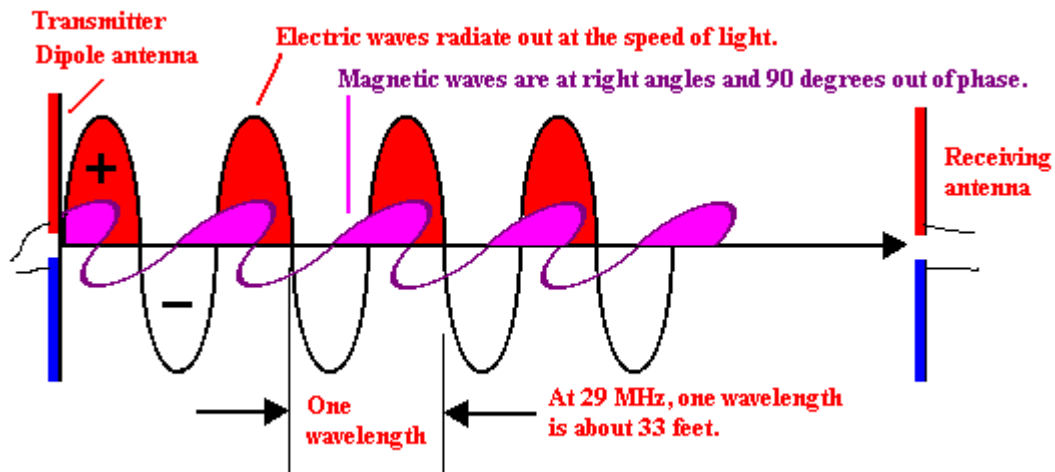
You may be thinking that transformers are not air-filled flimsy coils but rather large iron things like the big steel cylinder on the power pole in the alley behind your house. Yes, those big iron things are transformers but they are designed for low frequency power lines. An AM radio frequency is on the order of a million Hz frequency, while the power company supplies current at

60 Hz. Therefore, instead of having air between the two coils, power transformers have iron. The magnetic field from the coil magnetizes the iron temporarily. Recruiting iron and turning it into a magnet increases the magnetic field a thousand times or more. With a huge magnetic field stored in the iron, the power transformer can transmit big amounts of energy with only 60 direction changes per second. A similar transformer without an iron core could transmit the same amount of energy, but would have to repeat the magnetic field cycle perhaps a thousand times more often to transfer the same amount of total energy.

Why do you suppose the power company doesn't use 1million Hertz and do away with all that iron? After all, at one million Hertz the RF voltage would still be a burn hazard, but it could not electrocute anyone and would be considerably safer. Unfortunately, at one million Hz the power lines would act like antennas and radiate the energy into the sky instead of delivering it to your house. This is the same reason hams object to using the power lines to distribute high-speed Internet connections (BPL). BPL broadcasts noise all over the shortwave bands and makes them nearly unusable.

How far should it transmit to demonstrate the existence of Hertzian waves?

To be sure that the waves are Hertzian and not just magnetic fields, I would be impressed by the demonstration if the detector (the receiver) were more than one wavelength away. A wavelength is the distance that a radio wave travels during the time it cycles from magnetic field, to electric field, and back to magnetic field.



The speed of light is 186,000 miles per hour, or 300,000,000 meters per second. (A meter is about 39 inches) A wavelength is the distance a wave travels while going through one cycle of magnetic to electric energy conversion. The wavelength of the forty-meter amateur radio band (7 MHz) is obviously 40 meters. It turns out that typical, (total) antenna lengths for radio transmitters are either one half wavelength or one quarter wavelength. On 40 meters, a typical vertical pole antenna is one quarter wavelength or 10 meters (33 feet) tall. The 10 meter ham band extends from 28.0 MHz to 29.7 MHz.

What exactly is the frequency in Hertz of the 10 meter ham band? To convert wavelength to frequency, divide meters per second of light speed by the wavelength:

$$f = c / \lambda$$

Where f represents frequency, c represents the speed of light and λ represents wavelength

Speed of light/ wavelength = Frequency in Hz.

300,000,000 meters/ second / Ten meters = 30 Million Hz (30 MHz) frequency

Remember that the AM radio band extends from 550,000 Hz to 1.7 MHz. The old analog channel 2 television started at 54 MHz . So the 10 meter ham band is roughly halfway between AM Radio and TV.

Getting back to the Hertzian demonstration, if I wish to transmit one wavelength, on 40 meters, my loop would have to be 132 feet away from my transmitter. Frankly, I don't think Hertz's loop detector will work at that range. And if it did, I would be arrested for using a transmitter that powerful. As a rule of thumb, the American FCC will not object to experiments like this if the radio waves don't go past 50 feet at easily detected signal strengths. On the other hand, maybe I could use a higher ham band like 10 meters. Now I only have to go 33 feet. If I go up to UHF frequencies, the wavelength could a foot or less, but those frequencies would be hard to generate and harder to measure with 1884 technology. I have since been told that Hertz actually used 4 meters wavelength for his demonstrations.

Designing the 10 meter transmitter

For the sake of symmetry I used two identical LC circuits for my transmitter and receiver. To imitate what little I knew about Hertz's apparatus, I used one loop of wire about a foot in diameter. I knew from experience that seeing sparks on the receiver side was hopeless, so I also made the receiver an LC circuit that I knew would trap an oscillation from the transmitter.

At this point, you may want to depart from the year 1880. It all depends on how pure you wish to be playing the historical game. For a capacitor I used a modern 140 pF variable capacitor. That way, I could adjust the capacitance and tune the oscillation to a particular frequency. If I wanted to be a purist, it would not be hard to make a homemade capacitor made from sheets of metal with paper for insulation between the plates. Personally, I was confident that such a capacitor would work. I just didn't want to spend hours to make one.

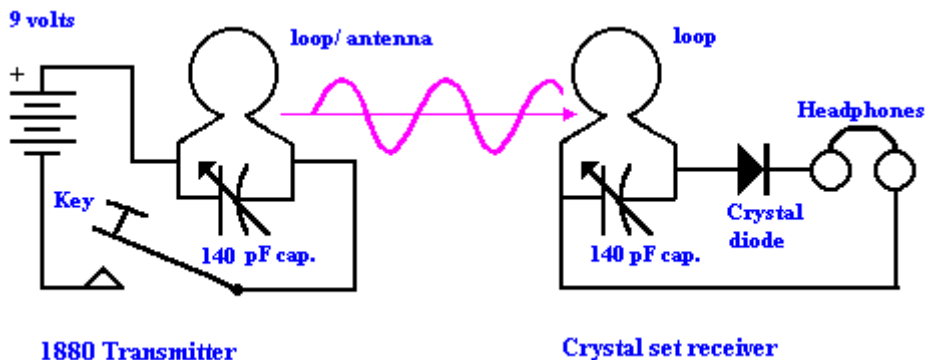
My first problem was how to start the oscillation in the transmitter LC. In theory, by shorting a battery across the loop, it will charge the loop with a big current limited only by the internal resistance of the battery. Then when the battery is removed, the coil's magnetic field will discharge forcing a voltage to appear across the capacitor. The loop will then be shorting out the capacitor and the oscillation will begin.

Like the variable capacitor, this project will go faster if you use modern tools to make sure your components are working. For example, to see if my transmitter was really transmitting, I used a ham band receiver tuned to ten meters. Sure enough, when I clicked the battery on the capacitor terminals, I could hear a click in the receiver loudspeaker. And when I tuned the capacitor, I could get the sound to reach a sharp maximum volume at a specific setting of the capacitor. Of course, if this were 1880, I would have to do everything by guess, trial, and error. Those old guys were darn sharp.

Designing the receiver

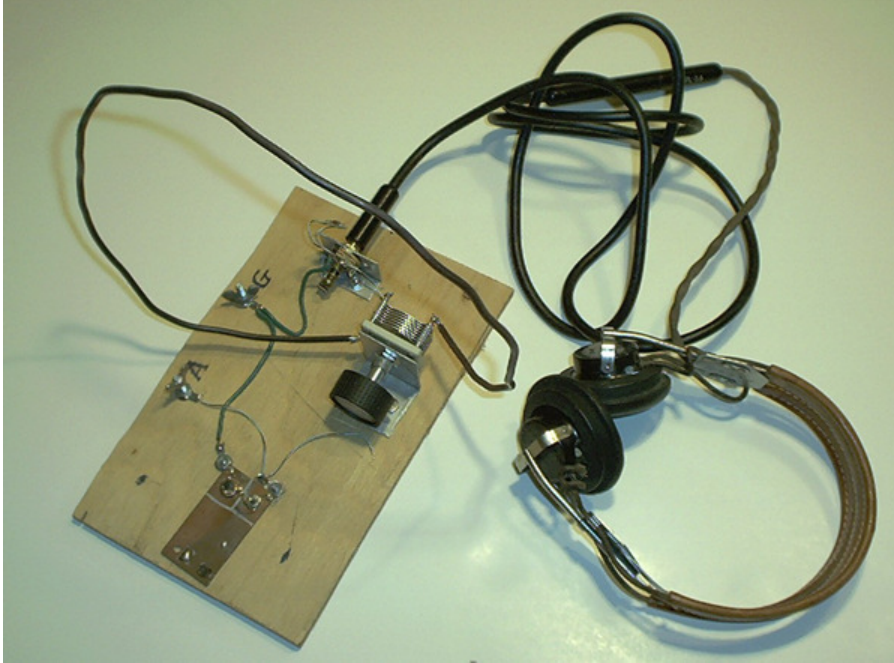
The next problem was how to detect when the receiver loop was oscillating due to waves from the transmitter. What to use for a detector? The 1880 solution would be to use a detector called a *coherer*. Coherer detectors were developed for the wire telegraph. By the time a signal had propagated miles down a telegraph wire, the signal was often too weak to close a mechanical relay. Coherers were used to “amplify” a weak Morse code signal. They were described in chapter 1, page 10. Unfortunately, coherers are a low frequency device, under 20 Hz. They are suitable for detecting a weak DC Morse code signal on a cross-country telegraph wire, but will not respond to the modulation in the audible range. I doubted that they would be useful for tiny radio frequency signals. Being lazy, I didn’t build one to find out. Besides, my crystal detector made out of local rocks certainly fit the 1880 criterion. I decided to build a 10 meter crystal set.

Are headphones 1880 technology? Yes, just barely. Alexander Bell built his first telephone in 1879. He used a headphone designed like the homemade device described earlier. Actually, for my 10-meter receiver I used old commercial high impedance headphones instead of the homemade earphone. I couldn’t afford to waste any sensitivity.



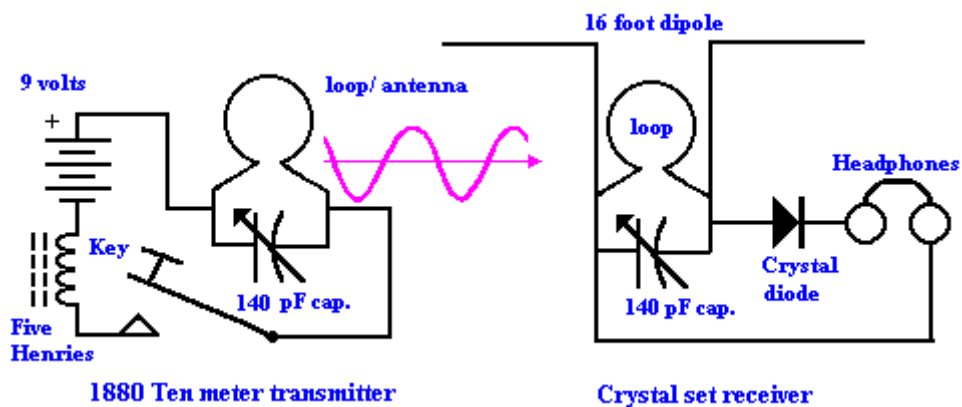
The simplest 10-meter communicator

I began with identical loop antenna/ inductors about 1 foot diameter for both receiver and transmitter. Instead of Hertz’s spark gap, I put 140 pF variable capacitors across both loops to give me tunable LC circuits.



10-meter crystal set receiver

To charge the LC circuit, I used a crude *spark gap*. I just touched battery terminals across the LC circuit while listening to the crystal set. I positioned the crystal set a foot away from the transmitter loop. It wouldn't be "radio" communication, but it would at least tell me if I was on the right track. I made sparks on the transmitter loop while tuning the capacitor. When tuned to just the right spot, I could suddenly hear obvious clicking in the headphones. I was surprised how sharp the tuning had to be. The big loop had relatively low inductance, so the capacitor had a tuning range of over 30 MHz. Tuning was probably not sharp by modern standards, but the adjustment was critical. In any case I achieved a range of 12 inches from the transmitting loop. Progress! Well, it's much farther than the obvious range of a refrigerator magnet.

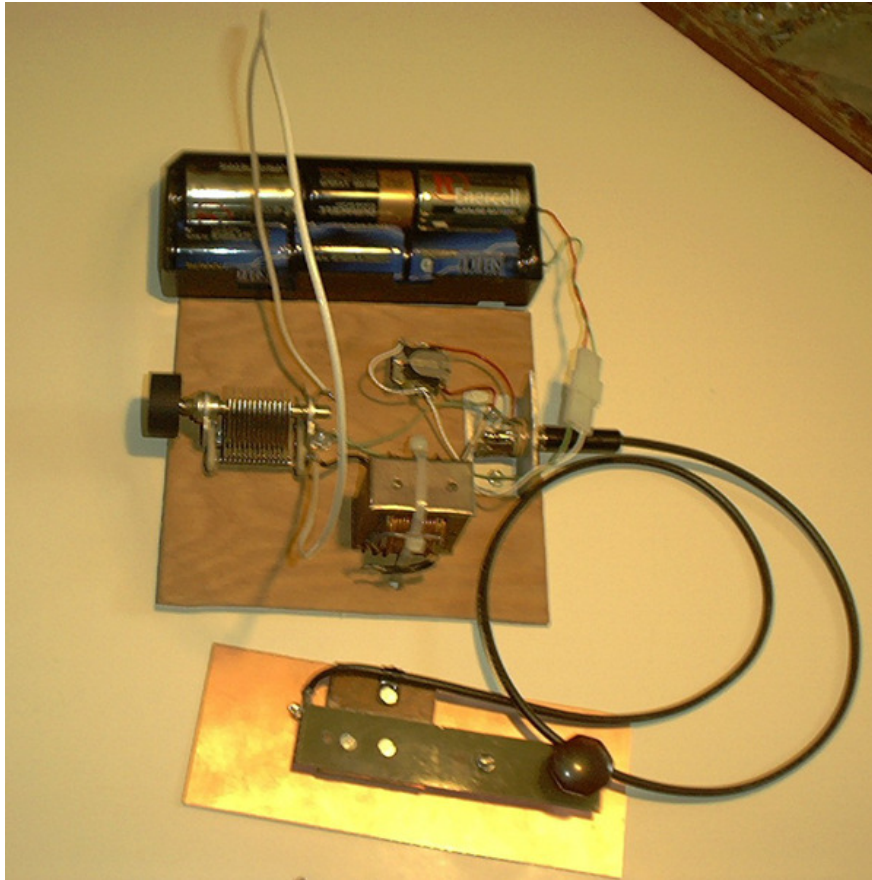


Improved spark gap transmitter & receiver

By adding a big iron core inductor in series with the battery, I got a much bigger, more sustained spark and a much louder signal in the crystal set. The inductor was the primary of an iron core filament transformer that I had in my junk box. The secondary of the transformer was

left open circuit. Actually, I tried several transformer windings and inductors until I found one that gave me the biggest visible spark. The battery was six D-cell alkaline batteries in a plastic battery holder from Radio Shack. My telegraph key was made out of two pieces of printed circuit board separated from each other by a piece of wood. (See Chapter 9.)

Using an extra inductor in this way is analogous to the automobile ignition system described in chapter 2. Without the big inductor, the only inductance to store energy was the single loop of wire. So when I tapped the battery wire on the LC circuit, very little energy was stored in the capacitor and inductance. The spark in a spark gap transmitter happens when the wire charging the inductor is broken, just like opening the breaker points in a car ignition. The more energy stored in the system, the bigger the spark when the connection is opened.



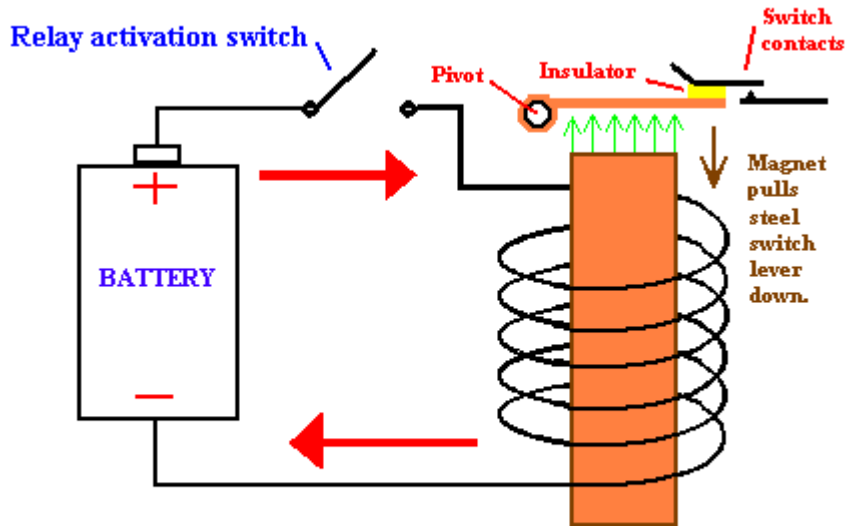
10 meter sparkgap transmitter

I enlisted my XYL to listen to the headphones while I moved the transmitter across the room. (Wives are known as “XYL” in Morse code. XYL stands for “former young lady.”) Now that I had the inductor and a larger spark, I got clear out to a range of 10 feet! I explained to Katie that she was doing the same job as Marconi’s assistant, Mignani. When Mignani heard the repeated “S” in Morse, he fired a rifle into the air. “Don’t I get a rifle?” Katie asked.

A relay for automatic keying

Unfortunately, a wavelength at 29 MHz is 33 feet and I was still short. Hmmmm ... How to get the last 23 feet of range? First I added a relay to key the inductor. Yes, they had relays in

1880. The relay had nothing to do with extending the range, but it did enable me to continue doing experiments without having a Mignani to do the listening for me. You know, fire the rifle and all that.



RELAY CONSTRUCTION

A relay is an inductor/ electromagnet wound around an iron core. A hinged piece of steel is suspended by a spring near the iron core. When current passes through the electromagnet, the steel hinge is attracted to the iron with an audible “clunk.” The hinge, in turn, mechanically closes a switch that can be entirely independent of the electromagnet circuit. In this way, one current can control an independent circuit. In my transmitter the switch contacts on the relay became my “spark gap.” Every time the switch opened, a big spark jumped across the switch contacts, not unlike the spark in an automobile ignition spark plug.

Using a relay, I could use my electronic telegraph key, a “bug” set on “dots,” to key the transmitter automatically. This homemade bug is described in Chapter 9. If you don’t have one of those, you’ll have to have your “Mignani” key the transmitter for you. With the transmitter making a continuous buzzing signal, I could move the receiver around my house. The signal sounded just like the automobile ignition noise that you sometimes hear in your AM radio.

More range = bigger, higher antennas plus bigger batteries

I could easily increase the range of the transmitter by using more and bigger batteries and a larger series inductor. If I really wanted to extend the range, I could add a dipole designed for 10 meters and put it up in the air about 50 feet. In fact, this is exactly what the early guys did – they made bigger and bigger transmitters and antennas. However this was 2002, not 1880. The trouble with using a wavelength of 10 meters is that, if I were to increase the effectiveness of my transmitter, I might easily hear it with my crystal set 33 feet away. Unfortunately, someone else might also hear it in Australia. That would be bad since sparkgap transmitters have been banned since 1927.

The simplest improvement I could make to the receiver was to add a 16-foot dipole

antenna. The dipole consisted simply of two eight-foot wires soldered onto the sides of the receiver tuning capacitor. The dipole was oriented at right angles to the direct path to the transmitter. That did it. Now I could plainly hear the signal from the basement to the other end of the 2nd floor of my house, over 50 feet. That was well beyond one wavelength range. Success!

Looking for standing waves

To measure wavelength, I set up a long wire transmitting “antenna” about 50 feet long across the floor and upstairs. I reduced the transmitter batteries from 9 volts down to 3 volts. Then I turned on the transmitter. I took the dipole off the receiver and then used the receiver loop as a “probe.” Walking along the wire, I was able to hear peaks and dips in reception every 6 feet or so along the wire. What I was hearing was “standing waves.” When the RF current reaches the end of an open wire, it bounces back along the wire. The returning waves cancel and reinforce the outgoing waves making the peaks and nulls I was hearing. A large number of peaks means the wire length is different than one wavelength and the standing waves are complicated. If the wire was exactly one wavelength, I would hear just two peaks – they would be the two humps of a single sinewave.

Next I cheated. Since I already knew the frequency was 29 MHz, I calculated what the wire length should be for one wavelength. I trimmed the wire to exactly that distance and tried again. As expected, there was a single pronounced dip in the center of the wire. The sinewave signal was reflecting back and forth from one end of the wire to the other, with a dip, the zero crossing, in the middle. When the reflections don’t come out even, you get many multiple dips and peaks.

Of course, knowing the answer before you start is not what Hertz experienced. He had to figure out all the details the hard way. Also, knowing the answer ahead of time biases the result. The exact alignment and distance of the receiver loop with respect to the wire were critical, so there’s a chance I was just hearing what I wanted to hear. Craftsmanship and scrupulous honesty are essential when doing science. My frequency measurement obviously more needs work.

**

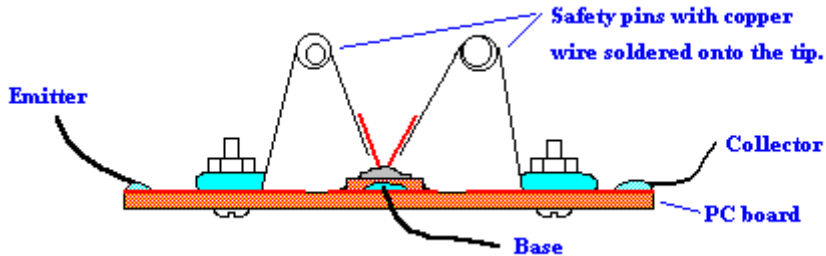
HOME BREW TRANSISTORS

Here is another project you may enjoy. It will also introduce you to the basic principles of bipolar transistors. Schockley and Bardeen first invented bipolar transistors while working for the Bell Laboratories in 1947. Actually, I’ve read that the basic principles for field effect transistors were described in German patents from the 1930s. However, field effect transistors (FETs) were not developed into useful components until the 1970s. We shall first use an FET in chapter 6, so FETs are discussed there.

The purpose of transistors is to “amplify” small signals. Saying it another way, transistors control big currents or voltages using tiny control signals. Transistors can amplify a tiny signal that is audible only with sensitive headphones. They can make it strong enough to run a loudspeaker or even deafen a stadium during a rock concert. Alternatively, a transistor can be used to allow a little control signal to turn on a huge current and voltage. For example, an

engineer at a power plant might push a keypad on a computer with a fraction of a milliampere of current flowing through the switch. This action is amplified and results in megawatts of power at hundreds of thousands of volts flowing toward a city.

The homebrew transistor

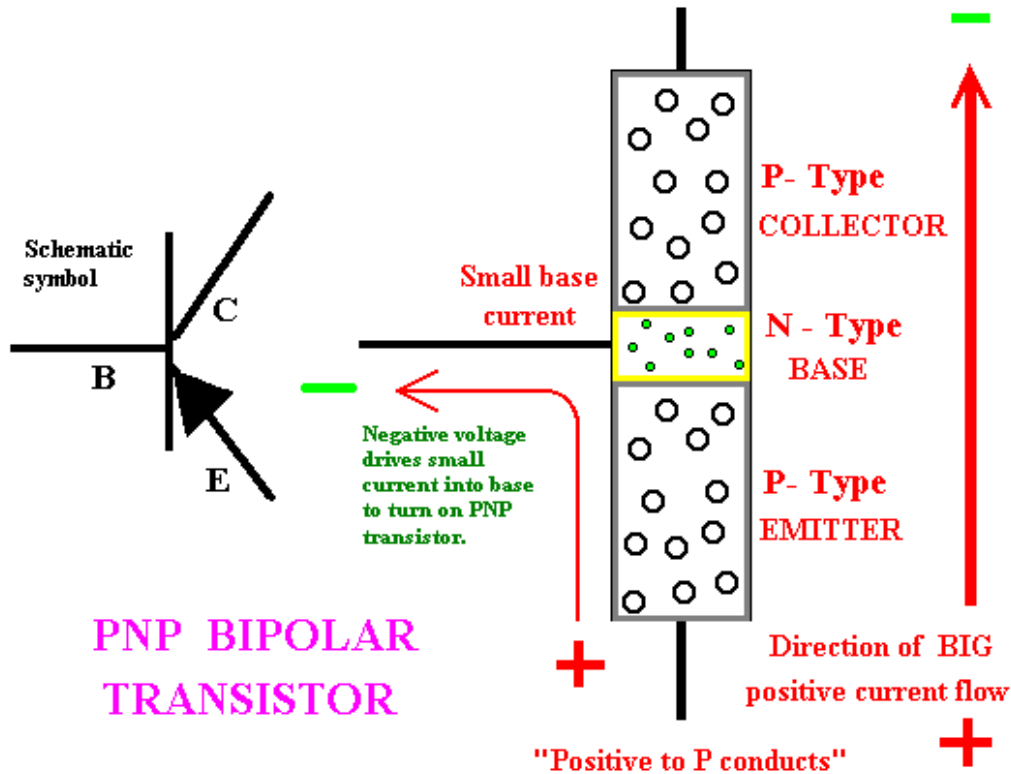


A point contact transistor

The first bipolar transistors were the “point contact” type. They were much like the galena diode described earlier. After my diodes worked so well, I wondered if I could make a transistor.

Idealized construction of a PNP bipolar transistor

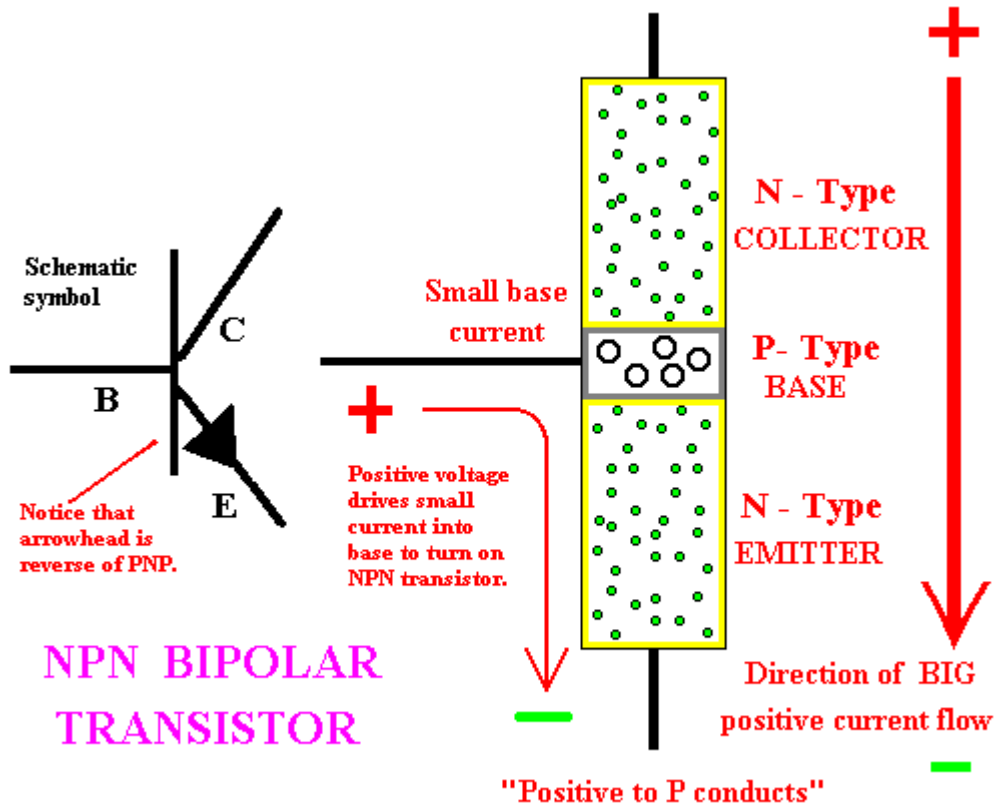
A *bipolar* junction transistor consists of two diodes made on the same semiconductor crystal. In the experiment above, I am attempting to use galena as the N-type semiconductor. The diodes are connected back-to-back so that it will look like an open circuit from the terminals called “emitter” and “collector.” The two copper points are supposed to touch the galena so close together that the tiny semiconductor region between the two points can be biased by the base current. The bias current is supposed to electrically convert the semiconductor region into a “conductor” and thus turn the two back biased diodes “ON.” Don't forget to cut notches in the copper sheet to separate the three terminals.



In theory, the metal from the copper points diffuses into the surface of the crystal and makes a tiny region of P-type semiconductor where the copper touches the semiconductor. Unfortunately the “emitter” and “collector” are identical and aren’t optimized for their different roles as they are in commercial bipolar transistors. I also tried making a copper/steel/copper transistor, but without any measurable breakdown voltage, it just acted like a short circuit.

NPN transistors

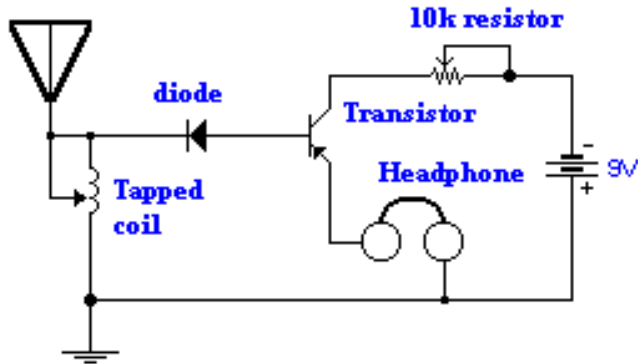
A nifty advantage of bipolar transistors is that they can be built two ways. By reversing the P-type and N-type semiconductors, an NPN transistor can be built that operates exactly like a PNP transistor, except all the polarities and current directions are reversed. The advantage of having two polarities is that the circuits can often be simplified by using both kinds in the same circuit. In practice, NPN transistors are usually slightly more robust and less likely to fail at high power loads. For this reason, the power amplifier stages in modern transmitters are almost always N-channel devices. On the other hand making an NPN transistor out of crude crystals and safety pins is inherently difficult!



Proving the homebuilt PNP transistor has gain

I measured the static volt/ ampere characteristics of my galena, point-contact transistor but couldn't show any gain with static DC currents even in the microampere range. Before I gave up, I thought I would try it as an amplifier in the crystal set. Maybe I could demonstrate gain in the subtle world of RF detection.

I decided my "transistor" was most likely to work as an *emitter follower*. In an emitter follower, there is no voltage gain, only current amplification. The load, the headphones, would be located between the emitter and the positive side of the battery. That would match the impedance between the high impedance detector and my low impedance (8 ohm) commercial headphones. Because galena diodes break down with typically 1 volt of reverse bias, I used a 9 volt battery with a 10K pot in series so I could limit the voltage on the collector to less than 1 volt.



Rock radio schematic

As I moved the emitter pin around on the crystal, a loud radio station abruptly appeared in the headphones. I disconnected the battery. Sure enough, the music was much louder with the battery connected.

An accidental crystal microphone

With the battery in place, but the signal diode disconnected, I heard a faint “sea shell” roaring sound - you know, like a live microphone. Tapping on the transistor assembly, I heard the scratching sound greatly amplified in the headphones. I seemed to have built a “crystal microphone”! I replaced the homebrew transistor with a real PNP transistor, a 2N3906, which amplified just as well but had no microphone-like characteristic.

Commercial crystal microphones consist of a lump of Rochelle salt held between two electrodes. When exposed to sound, mechanical vibrations cause the salt to generate a tiny audio frequency electric voltage. Crystals like this are called piezoelectric crystals and perhaps I had just built one. Piezoelectric quartz crystals are used to regulate frequency and are discussed in chapter 6.

Repairable transistors

While listening to a radio station, I slowly increased the battery voltage by lowering the resistance of the 10K pot. As the collector-to-emitter DC voltage rose higher, the volume increased higher and higher. I monitored the average collector to emitter DC voltage with a high impedance voltmeter. Then suddenly the voltage and sound crashed. I lowered the voltage again, but the sound didn't return. Good grief! I blew my transistor! No sweat. I just scratched the collector pin around on the crystal until I found a new “sweet spot” and I was back in business. Repairable transistors! Now there's a concept. After several trials I found sweet spots as high as 5 volts before the transistor died.

Now that I had an amplifier on my crystal set, I replaced the commercial headphone with the homebuilt “Caribou headphone” which I described earlier. You may remember that this headphone was made from a piece of magnetite ore and a tin can lid for a diaphragm. Sure enough, the sound was loud enough to understand actual words, rather than just distant music. More progress!

Is this gain or what?

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, REV 12

CHAPTER 5

GETTING ON THE AIR

Deciding what to do first

Earn an amateur license!

If you're going to build your own ham station, you will need a national government radio station license to transmit. In the US the Federal Communications Commission issues ham licenses. In this country committees of senior hams in our local areas give the tests rather than government officials. The simplest first step is to contact a ham in your area. He or she will tell you what to do. Failing that, if you are an American, contact the American Radio Relay League, www.arrl.org. Most other countries have similar organizations of radio operators. They will fix you up with study guides and point you to the nearest ham radio club where you can meet other hams and take your test. Working on a license can be an interesting side project while you build your receiver and transmitter.

Learning Morse code

If you're going to build and operate a homebuilt transmitter, it will have to be a CW (Morse Code) transmitter. Building a single sideband (voice) transmitter is too difficult for beginners. Even for experienced guys that takes hundreds of hours of effort. Until recently, all nations required Morse code at least 5 words per minute (WPM) speed to earn a license for operating between 1.8 MHz and 30 MHz. That has changed and many countries including the US now issue licenses without Morse code skill. Fortunately Morse code is not hard to learn for most people - besides, it's fun! The average conversation on the air takes place at roughly 10 to 15 WPM, but there are usually a few beginners poking along at 5 WPM. The senior hams at the bottom of the CW bands zoom along at 25 or 30 WPM. Don't feel bad if you can't do that. I can't either.

To practice code, you can listen to it with a shortwave receiver and you will also need to practice sending with a key. During the evenings in the US the ARRL station W1AW broadcasts code practice sessions. These sessions start at 5 words a minute then gradually increase the speed. Scheduled times for the almost daily broadcasts can be found in the QST magazine. If I haven't been on the air for a while, I tune in the low ends of 40 meters or 20 meters and copy a few CW (code) stations to restore my speed and confidence before I start sending. I write down each letter as I receive it. The really good operators hear entire words and don't have to write down anything! I've never been that good. I spend too much time soldering.

Planning your station

Most hams are content to buy one of those marvelous commercial transceivers. They plug it into the wall, put up an antenna, and start talking. In contrast, a growing number of hams are building small, low power transmitters called *QRP transmitters*. QRP is an old Morse code abbreviation meaning "turn down the power." In modern usage QRP means a transmitter delivering less than 5 watts of RF power. QRP guys are usually fellows who have been using

2. Chapter 5, Harris

commercial rigs for years and want to try something more adventurous and primitive.

Most QRP enthusiasts buy tiny transmitter kits with pre-printed and pre-drilled circuit boards. The assembly procedure consists of following a picture, plugging components into the correct holes, and soldering the leads. These kits teach soldering technique and you will learn what the components look like. Unfortunately, if the kit is well designed, it offers little chance to learn how the circuits work.

A few hams start with a circuit from the ARRL handbook or QST magazine. Following the circuit diagram, they build their own version of the circuit out of individual components. Their components are bought or scrounged one at a time and rarely exactly match the components used by the author of the article. A QRP like this usually doesn't work properly without sweat and rebuilding. This sounds like frustration, but the compensation is that now you're learning something! This kind of project is educational whether we planned to learn anything or not. Frustration, persistence, and triumph is what ham radio used to be.

Rules of the game

Scratch-building your own station is a kind of game. *Our chief opponents are the amount of free time we have and the modern frequency stability standards.* In my fantasy it would be neat to build all the components from raw materials and invent and design totally new circuits from scratch. Unfortunately, these tasks are too much for me. Rather, I use discrete parts I scrounge from junk and components I buy through catalogs or local stores. For circuit design I borrow circuit blocks from examples in the ARRL handbook and other sources. Then I assemble the circuit blocks into my project.

After I retired and had plenty of time, I got out my ARRL handbooks and studied plans for homebuilt receivers and transmitters. I quickly encountered my other nemesis, *integrated circuits:* Tracing the circuit diagram of a typical modern receiver, one finds that the antenna is connected to a chip marked "RF amplifier." Then the signal goes to another chip labeled "mixer." The mixer receives a local oscillator signal from a large chip called "frequency synthesizer." The output from the mixer goes to a "crystal filter" sealed in a tiny metal can. Well, you get the idea. *Modern radios are just block diagrams soldered onto printed circuit boards.*

I find that 1980 technology is usually a good compromise. Few integrated circuits appear in the parts lists from that era. And if you're a purist, most of the integrated circuits can be replaced with discrete components. In summary, I try to use individual transistors and passive components exclusively. This teaches me how the circuit works and I can still build equipment that's reasonably modern. One compromise I have had to make was integrated circuit voltage regulators. In order to hold the frequency constant, the voltage supplied to the oscillators must be more stable than I know how to build using discrete parts.

Another compromise I've made is the use of integrated circuit operational amplifiers. An operational amplifier is an array of transistors that functions as though it were a "perfect transistor." It is usually easy to substitute real transistors, but you need to use many more of them to get the same performance. After a while I became bored making the same complex circuit again and again using discrete transistors. So, my rule is that, if I have proved I can build the equivalent of an integrated circuit with discrete parts, I feel I have "earned the right" to use

3. Chapter 5, Harris

certain kinds of integrated circuit.

My rules have taught me how the circuits work. I've learned plenty. And by golly, when I'm done, I really feel that I built it myself! Because I have struggled to understand it and make it work, I rarely have the feeling I am using "magic." You don't have to use my rules. Make up your own. If you're having fun, those are the right rules.

Planning your station

A simple receiver and a QRP transmitter are a great start on a homebuilt station. (See Chapters 6 and 7) However, before you can go on the air with your transmitter, you will also need:

- A ham radio license. Contact local hams in your area or, in the US, the American Radio Relay League in Newington, Connecticut. (888) 277-5289.
- A 12 volt DC power supply for the QRP. (Chapter 8.)
- An antenna (See end of this chapter, Chapter 5)
- An antenna tuner (Chapter 9)
- A telegraph key for Morse code. (Chapter 9)
- Basic test equipment to ensure that your transmitter is operating correctly. (Chapter 9).

Equipment for later on:

- A selective, sensitive, all-band hamband receiver (Chapter 13)
- A Class B or linear amplifier. (Chapter 12) Although QRP is fun, you will probably eventually wish your signal were more powerful. With a loud signal more stations will hear you without a struggle and your contacts won't say "73" (good bye) so quickly. There are two ways to achieve a bigger signal. Build a better, high gain (directional) antenna, higher above the ground. The other way is to build a linear (or Class B) amplifier to raise the QRP power from 5 watts up to 50 or more watts.
- **A lowpass filter.** (Chapter 9) If you have a high power Class B amplifier, it is a good idea to build a low pass filter to make sure that harmonics of your signal are not interfering with the neighbors' cellphones and television.
- **VFO.** As you'll soon learn, being restricted in frequency mobility by crystal control is awkward and you will eventually want to build a variable frequency oscillator to replace those clumsy and expensive crystals. (Chapters 10 and 11)
- **Single Side Band Generator.** (Chapter 15) After you have been a ham for a few years, you will sooner or later want to get on phone (voice) so you can talk to the majority of hams. Otherwise you'll be stuck just talking to funny old Morse code geezers like me. Almost no one ever builds their own SSB. So if you get that far, you will have joined an extremely exclusive club of homebuilding hams.

Divide and conquer

Building an entire ham radio station from discrete components is a huge project. The secret to having fun is to build it in carefully planned pieces that can be used and enjoyed right

4. Chapter 5, Harris

away. How big the challenge becomes depends on where you start. If you're a retired electrical engineer like me, the project begins by wandering down to the basement, dusting off the workbench and getting started. If you are still working for a living, your free time for this effort may be just a few hours a week. If you have never worked as an electronics technician or as an engineer and you have no formal electronics training, your road to homebuilt ham radio will be lengthy. If you have no electronic experience at all and little free time, then maybe buying a receiver and a QRP kit may be the best way for you to begin.



The author's 100% homebuilt station. It isn't flawless and it isn't the latest technology, but it talks around the world and sure has been fun. Oh, by the way, the oscilloscope and frequency counter are *NOT* homebuilt.

Many guys try to do too much too soon. This can easily result in many hours invested in useless junk that does nothing except get hot and generate acrid smoke. A better plan is to focus on small projects that can make you proud as soon as possible. Try to decide what it is about ham radio that turns you on and then zero in on those aspects. Your ambitions will always be greater than the time you have to achieve your dreams. Plan carefully.

Pick an HF band

50 years ago it was practical to build simple ham transmitters that tuned several bands. Unfortunately today a ham transmitter must meet strict frequency stability standards. Actually, your government is only interested in having you stay inside the hamband and radiate a reasonably narrowband signal. However, other hams will almost always complain about your signal if you drift more than about 50 Hertz per minute. This degree of precision can be hard to achieve, but it's easiest if you start with crystal frequency control and just build for one hamband at a time. Later you may expand your capability as your time, knowledge, and enthusiasm permit.

5. Chapter 5, Harris

There are ten different HF bands and seventeen VHF, UHF, and microwave ham bands. In addition, a ham is free to operate anywhere he likes above 300,000 MHz, provided output power is limited. As the frequency goes up, the basic principles are the same, but the construction methods change radically and the precision and craftsmanship needed soar with the frequency. This book only considers the HF bands because scratch building equipment for VHF and higher frequencies needs expensive test equipment and a good understanding of HF building principles. In other words, walk before you run.

40, 30, and 20 meters

In my experience, the easiest and most versatile frequencies to build for are the 40, 30 and 20 meter hambands. (7 MHz, 10 MHz, and 14 MHz.) The signals on these bands are strong and these bands are usually “open” throughout the year. For Americans it’s easy to talk to hams all across North America on all three bands. Talking around the world is relatively easy on 30 and 20 meters. Optimal antennas are relatively small. On 40 meters (7 MHz) a dipole is 66 feet long while on 20 meters (14 MHz) a dipole is only 33 feet long. A vertical antenna on 20 meters is only 16.5 feet high. A typical suburban house is about 50 feet long so it’s usually possible to put up a 40 meter dipole somewhere on the property.

40 meters (7.000 to 7.300 MHz)

This is a great band for CW contacts within about 2,000 miles. However, for us Americans, often only the bottom 50 KHz is usable. Yes, we’re allowed to operate from 7.00 MHz to 7.30 MHz. Unfortunately, foreign broadcast stations often obliterate the upper half of the band. On the other side of the world most of this band is available for commercial shortwave broadcasts. Also, from 7.05 to 7.10 the band is filled with foreign hams talking on single side band phone (SSB, voice transmission). We Americans can’t use phone below 7.150 MHz, so we can’t join in. Consequently, most of the time American hams just use the bottom 50 KHz for CW. 40 meters can be useful for local sideband phone contacts during the daytime. For example, in my state there is a noon SSB net where guys around the state chat with each other. However at night most of 40 is unusable.

30 meters (10.10 to 10.15 MHz)

Thirty meters resembles the CW band on 40. It’s only 50 KHz wide and no phone is allowed. Typically there are only 4 or 5 CW stations on the air. It’s a terrific band for homebuilders. The power output on this band is limited to 200 watts worldwide, so it is a good band for talking to DX (foreign stations). Nearly everyone on 30 is using comparable equipment, so you won’t have to compete with kilowatt stations using giant, multi-element beam antennas. Another advantage is that contesting isn’t allowed on 30. Ham organizations often hold weekend contests to see how many stations one can talk to in a 24 hour period. All the bands except 30, 17, and 12 meters become packed with guys just exchanging call letters. It’s pretty boring if you aren’t competing in the contest.

20 meters (14.000 to 14.350 MHz)

Twenty meters is the single most popular band. It is large and, depending on the 11 year sunspot cycle, usually usable 24 hours a day and “open” year round. It normally has hundreds of stations. In fact, 20 meters is often so crowded, you will need a receiver with great selectivity to carry on a conversation. If you can copy fast Morse code, foreign CW stations are easily heard at

the bottom of the band. Because of the crowds and high speed, talking to them isn't so easy. Most of the band is filled with powerful stations on single side band phone. It is hard to build a homebuilt station that will compete on the 20 meter phone band.

17 meters (18.068 to 18.168 MHz)

Seventeen meters is a fine little CW and phone band. It's mostly inhabited by single side band phone stations. However, there are usually a couple CW stations at the bottom of the band. When conditions are good, many of these stations are DX on the other side of the world. It isn't my first choice for a QRP CW transmitter, but other than scarce CW stations, there's nothing wrong with 17 meters.

15 meters (21.000 to 21.450 MHz)

Fifteen meters is slightly harder to build for than 20 meters, but it's an excellent band for beginners. 15 meters is a large band, 450 KHz wide. It's not crowded but there are plenty of stations. 21.150 MHz is a great place to meet beginner CW operators. 21.040 to 21.060 MHz is where most of the QRP CW guys hang out. 15 meter QRP transmitters are crystal controlled and are usually locked into that frequency range. After your code speed gets up over 20 WPM, you can move down to the bottom of the band where the DX (foreign) stations and high-speed, old-time CW operators hang out. On the other hand, every now and then a station on the other side of the world will answer your slow speed CQ. Actually, these are usually the best DX QSOs because the other fellow obviously is no hurry to talk to anyone else.

Extra care in construction and antenna tuning are needed as the frequency goes up. You may find that your homemade receiver is slightly less sensitive than it was on 20 Meters and your transmitter probably won't produce as clean an output waveform as it did on 20 meters. On the other hand, a 15 meter vertical antenna is only 11 feet tall and a dipole is only 22 feet long. Another reason for selecting 15 meters is that ***a 40 meter dipole (or 40 meter vertical) will work well on both 40 meters and 15 meters.*** This simple antenna is ideally matched to both bands.

Some hams successfully string 15 meter antennas in their attics or along the ceiling of a large second story room. When I was in high school, a friend of mine, Al Beezer, KØKZL, had his 15 meter antenna strung across his second floor bedroom. He attached florescent light bulbs at each end of his dipole. The bulbs flashed every time he pushed the telegraph key. Great show biz! Yes, Al's signal would have been stronger if his antenna had been 10 feet higher outside in a tree, but his indoor antenna was adequate to make contacts all over the U.S.

Open bands and sunspots

The disadvantage of 17 meters and higher bands is that these bands are often not "open." When the sunspots are few, the Earth's upper atmosphere is minimally ionized. When the band is "dead" the radio signals are passing through the ionosphere right out into space. The sunspots occur in an 11-year cycle and 2008 happened to be one of those years when the upper bands are quiet. As of 2010, the high bands are just now beginning to be active again. 15 meters is often closed for months at a time, especially in the summer. During these times all you'll hear is the hiss of static. On the other hand, 15 meters can still be used for local communications during these periods. The higher the frequency, the less often the bands are open. Ten and 12 meters are even more erratic.

10 and 12 meters

I found building receiver converters for 10 and 12 meters was as easy as it was for 15 meters. However, building the transmitters was more difficult. My final amplifiers and antennas were hard to tune. It took me several attempts and many modifications before I got more than a few watts of power output on 10 meters. For example, my transmit-receive antenna relay had too much reflection (high SWR) to work properly on those bands. I had to bypass the relay and use a separate antenna for the receiver. However, once I was able to transmit just two watts on 10 meters, I could easily talk to other continents. In that sense, I believe 10 meters is the best QRP band. But as I said, sadly, months often go by when there is nothing to hear on 10 meters but static.

When I was in high school, several of my friends and I built handheld 10 meter walkie-talkies. They put out 1/4 watt into a 2-foot long antenna with a loading coil. One of my biggest thrills in ham radio was standing on my chimney in Colorado and talking to a guy in New Jersey - 3,000 kilometers away. That was nothing. My friend, Bob (KØIYF, now NØRN), was walking down the street and talked to a fellow in Morocco. Fifty years later he still remembers the call letters, CN8NN.

6 meters

Six meters is a huge band, 50 to 54 MHz . It closely resembles 10 meters in that a few watts will talk around the world using high ionospheric propagation. Some years, on ham field day at least, (the last weekend in June) it is crowded with signals from all over the world. The catch is that 6 meter propagation is rarely “open.” You might have to listen for many months before you hear stations. With good craftsmanship, it’s possible to build homebrew equipment for 6 meters using the technology discussed in this book. However, I don’t recommend it until you have become bored with 10 meters.

80 and 160 meters

80 meters (3.5 to 4.0 MHz) and 160 meters (1.8 to 2.0 MHz) are large, lightly used bands. Of all the ham bands, transmitters are most easily built for these bands. There are plenty of SSB phone stations on 80 meters at night, but relatively few CW stations on these bands. Good receivers are hard to build for these bands because the atmospheric noise is so heavy that it takes a sophisticated receiver to pull signals out of the static. Noise from lightning is especially bad in the summer. Also, if your homebuilt receiver isn’t well filtered, it may be overwhelmed by your local standard broadcast AM stations, which are located just below 160 meters. A modern commercial high-end transceiver can often hear dozens of stations while a simple homebuilt receiver might only hear a few. During the day, these bands buzz with noise and are usually only good for across town. Sometimes at night, if the thunderstorm noise isn’t too bad, there are lots of stations from all over the continent. It also helps to live out in the country far from power lines, plasma TVs, auto ignitions and heaven only knows what else is in city background static.

Another barrier to 80 and 160 meters is that large antennas are needed for good performance. On 80 meters a vertical antenna must be about 66 feet high and a dipole antenna is 135 feet long. For 160 meters, ideal antennas are twice those sizes. In my opinion 160 is the noisiest and least popular band. Yes, you can get on 80 and 160 with small antennas equipped with “loading coils” and antenna tuners. Unfortunately, in my experience, if you don't have a big

antenna, you will rarely get out of town. On the other hand, once you have a full size antenna, I was surprised to discover that QRP transmitters can talk all across the continent on 80 meters.

60 meters

Since July 4, 2003 American hams have been allowed to transmit single sideband phone (USB SSB) on five discrete channels, 5.332, 5.348, 5.368, 5.372, and 5.405 MHz. This band is noisy and is shared by several services. Each channel is like an old time party-line phone on which everybody tries to talk at once. Moreover, at any one time, you will find that two or three of the channels are occupied by commercial teletype (RTTY) stations. It's interesting, but frankly it isn't worth the trouble for a beginning ham.

In summary, I recommend starting off with CW on 40 and/ or 15 meters. A 40 meter dipole works well on both bands and the equipment is relatively easy to build. Both bands will let you talk all over your local continent with ease. On 15 meters you will have the chance to work foreign stations even with simple equipment and minimal code skill.

Phone (voice) transmissions

For a homebrewer in the modern world, building an SSB phone transmitter is a difficult project. Actually, amplitude modulation (AM) voice transmitters, like those used on standard broadcast radio, are relatively easy to build and are still legal for ham radio. To convert a CW transmitter into an AM transmitter, all you have to do is impress an audio voice signal onto the power supply line of the transmitter's last stage of amplification. Occasionally you can still hear AM stations on 10 meters, 80 meters, and 160 meters. But in general, AM is rarely used today by hams.

The modern replacement for AM is *single sideband (SSB) phone*. SSB is similar in principle to AM phone, but it takes up about a third of the bandwidth of an AM signal. Sideband can be thought of as AM radio with half of the signal plus the carrier wave removed with precise filters. This allows more stations to share the band and makes your transmitted power three times more effective. The SSB signal must be generated at a fixed frequency then translated up or down to the desired frequency using mixer technology. To maintain the purity of the signal, all of the amplifiers along the chain must operate perfectly in linear mode so that the speech is not distorted.

A sideband generator is described in chapter 15 of this book. Scratch-built sideband phone is definitely an advanced project. To be honest, I found mine hard to get working and spent many months on the project. I rebuilt some stages of the transmitter several times. Perhaps homebuilt single sideband should be something to look forward to when you have loads of free time. After you have worked on an SSB transmitter for a while, you may decide that good old Morse code isn't so bad after all!

On the other hand, receiving single sideband is easy. A filter made from a single, off-the-shelf, microprocessor crystal is all you need to receive clear, interference-free speech. The homemade receiver described in chapter 13 works great for SSB.

Instant high quality communications

Perhaps you have read all of the above and decided that your primary goal is to talk to people by radio as soon as possible. For you, building equipment is a secondary interest. If that

describes you, you should probably buy a modern high frequency (HF) transceiver then begin work on your ham license as soon as possible. Modern commercial ham stations are usually “transceivers” that combine the transmitter and receiver in one unit. Many of the circuit blocks in transmitters and receivers are almost identical. Logically enough, the transceivers use the same circuits for both send and receive.



A modern, top-of-the-line HF transceiver – the Yaesu Mark V Field, FT1000MP

I recommend buying a transceiver that can tune all ten high frequency bands. If you buy a modern, quality **used** transceiver, the price can be well under \$1,000. This will give you a (nearly) complete station that is more sophisticated than you or I could build with years of effort. Even if you don't have your license yet and can't transmit legally, you should buy or borrow some kind of receiver as soon as you can. That way, you can at least listen to shortwave radio. Really, listening is more than half the fun. Many commercial transceivers or receivers can receive the entire shortwave spectrum from 1.8 to 30 MHz. This includes all the commercial broadcast, foreign stations, and time and weather stations. Listening will make studying for your ham license much less theoretical. If you want to experiment with the built-in transmitter, you may not transmit on the air without a license. However, you can practice loading a “dummy load” instead of an antenna. If you have an antenna tuner, it's fun to load up an ordinary filament lightbulb as a dummy antenna and watch the light pulsate as you talk or send Morse code. See Chapter 9.

Occasionally I consider buying a modern transceiver like the one above. These transceivers are “easy” in the sense that they can instantly perform virtually every feature and communication method you have ever heard of. For example, when the new 60 meter band opened, it was possible to reprogram the Yaesu FT1000MP to cover 60 meters just by pushing the right combination of buttons. And, as you might expect, practically everyone on 60 meters was using an FT1000MP. The bad news is that the instruction manuals make operating your VCR look like child's play. All those buttons, menus, and operating modes are enough to drive you to drink.

Yes, I occasionally think about buying one, but for me, it wouldn't be satisfying. As soon as I had read the manual and tried out the features I was interested in, the transceiver would become boring. I can name several hams who have superb transceivers gathering dust in their home stations. They haven't turned them on in months or even years. On the other hand, if your ham radio bliss is working all the 335 odd call signs in the world, then you will need the best possible equipment. Building your rig yourself is going to slow you down for many years or decades. Maybe that's a good thing. You decide!

Pursuing a dream

When I was in high school 50 years ago, television was “exotic.” Although black and white TV receivers were common in our living rooms, almost no one could afford a TV camera. Because I couldn’t afford a camera, their unavailability made them fascinating. I spent hundreds of hours building and experimenting with TV cameras. Only one of my five camera projects actually worked properly. (See chapter 16.) Later when I was grown, my wife bought me a fantastic TV camcorder which today is a big yawn. Because camcorders are routine today, to me the camcorder was just another way to take baby pictures. I have hardly done a thing with it.

Familiarity and ease of acquisition produce boredom.

VHF/ UHF Hand-helds

The simplest and cheapest kinds of commercial ham transceivers are VHF hand-held walkie-talkies for 2 meters (144 MHz) and/or 70 centimeters (420 MHz .) These walkie-talkies are slightly more adventurous than a cellphone, but in my opinion they aren’t as useful or interesting unless you are using IRLP, described below. Hand-helds also require a ham license, but in the US at least, a VHF "technician" ham license has the easiest test. Another limitation of hand-helds is that the communication is basically line-of-sight. In other words, if you are behind a mountain and want to talk to the other side of the mountain, you need a relay station (a repeater) that just happens to be on top of the mountain or in some location that is visible to both you and the guy you’re talking to.

The best feature of hand-helds is **IRLP**. This is an Internet-connected network of VHF and UHF repeater relay stations or "nodes." The idea is that you use your handheld transceiver to key in codes into your local repeater node. The repeater uses the codes to connect you via the Internet with other nodes anywhere in the world. The repeater node in Boston, Australia, or Berlin then rebroadcasts your VHF signal as if it were local. Guys in those distant cities hear you and reply as if you were located in their own town. This system is mostly used for rag-chewing and isn't burdened with contests and guys who are just interested in collecting call letters and QSL cards.



A 2 meter hand held transceiver (walkie-talkie) with a spare battery pack.

Personally, I use my 2 meter walkie-talkie as an emergency radio for hiking. Honestly, I

think a cellphone would probably serve me better in an emergency, but I've been too cheap to buy one. Most owners of VHF walkie-talkies use them like citizens band radios to talk around town. In general, the quality and range of the commercial amateur radio hand-helds is far superior to citizens band radios. On the other hand, citizens band and the "Family Radio Service" (FRS) are other "quick and dirty" ways to get on the air without a license.

If you buy a hand-held, be sure to buy an extra battery pack or two. To make mine reliable in an emergency, I replaced the rechargeable batteries inside the battery packs with alkaline batteries. Although they aren't rechargeable, alkalines store several times more energy and tolerate cold temperature much better than rechargeables. I found that the original NiCads went dead almost immediately when I was out skiing.

HF versus VHF and UHF ham radio

Among serious hams, the spectrum is generally divided into two halves, "High Frequency" (HF = 1.8 to 30 MHz) and "Very High Frequency" (VHF = 30 MHz to 300 MHz) extending up to Ultra High Frequency (UHF = 300 MHz and above). Above UHF are the microwave bands with frequencies measured in gigahertz and wavelengths in centimeters. Most HF hams like long distance communication with either CW or voice. There are also HF packet-radio modes and slow speed picture transmission which resembles e-mail with a very slow modem. RTTY and PSK-31 are modes that resemble instant e-mail messaging on the Internet.

There are two kinds of VHF/UHF guys. The vast majority of them just own hand-helds, but a few UHF hams are extremely technical and do high tech experimentation. This can be ham-television, exotic voice modulation like spread-spectrum and transmissions using satellites. One way the microwave guys have fun is trying to see how far they can communicate between mountain tops.

Much like my effort to build a TV camera, what you do with great effort is more rewarding than buying a gadget and copying the crowd. So it shouldn't be a surprise that, for the technical UHF guys, a lot of the fun is organized around trying to talk to distant stations using ionosphere substitutes like satellites, or bouncing radio waves off the moon or even the aurora and falling meteors. Instead of using repeater relay stations, these guys get their kicks by using these exotic substitutes.

**

BUILDING AN ANTENNA

Every shortwave radio station needs an antenna and building one should be your first project. Shortwave reception with a modern receiver can be adequate with as little as a few feet of wire dangling off the antenna connector. Many commercial short wave receivers built for non-hams have coil antennas (magnetic antennas) built inside the receiver case. Tiny antennas like this are adequate for hearing powerful stations such as Voice of America, Deutsche Welle, (Radio Germany), Radio Moscow, or the BBC (British Broadcasting Corporation).

Amateur radio stations, by law, are limited to 1,500 watts Peak Envelope Power (PEP) and most of them run 100 watts or less. This means that hams are hundreds of times weaker than the commercial stations mentioned above and a big antenna is important to hear them. The lower

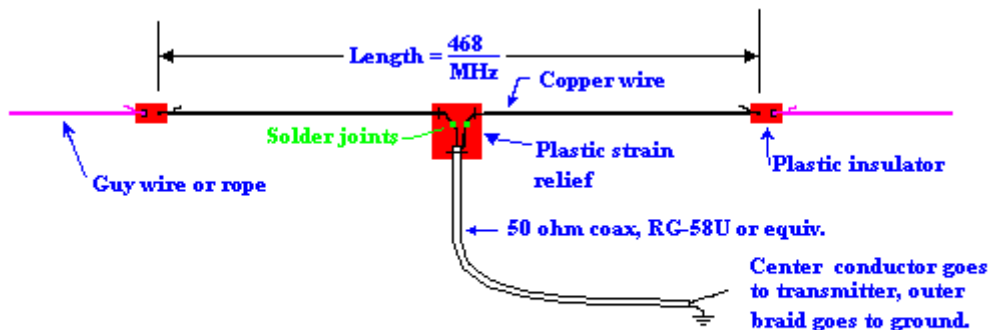
the frequency, the bigger the antenna you will need. A good transmitting antenna needs to be at least $\frac{1}{4}$ wavelength long. A good transmitting antenna for shortwave radio signals must be high enough to send signals toward the horizon with as few obstructions as possible. Although an adequate receiving antenna can often be small and close to the ground, a large, high wire antenna works well for both jobs.

The long wire

The simplest, most versatile antenna is a “long wire.” It is literally a long piece of wire, ideally $\frac{1}{4}$ wavelength long or larger. For example, for 40 meters, it must be at least 33 feet long and should be strung up in a tree or other place as high as possible. In general, if you connect a random length of long wire to a transmitter, it will not be resonant with your hamband and you must “match it” with an impedance transformer called a *transmatch* or *antenna tuner*. Fortunately, an antenna tuner can be quite simple and can be put together in a couple hours. An example is described in Chapter 9.

The 40 meter dipole

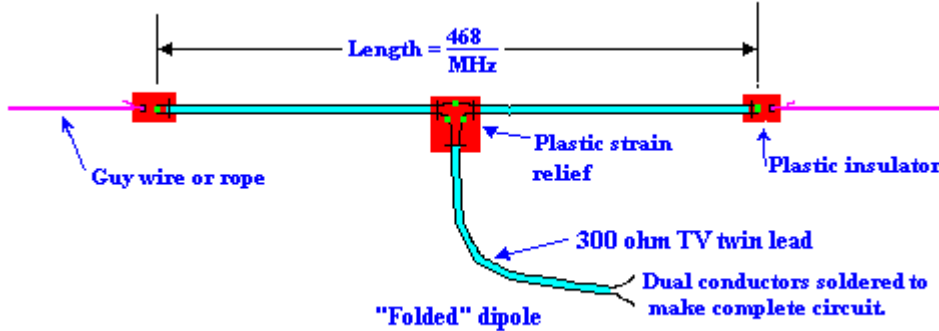
If I could only have one antenna, this is the one I would build. This simple antenna works well for both 40 meters and 15 meters (7 MHz and 21 MHz). As will be explained later, extra antenna arms can be added so it will work on most of the other hambands. The advantage of a dipole antenna is that they have an impedance of roughly 50 ohms that is easily loaded by a ham transmitter. So, although an antenna tuner is still helpful, this antenna will transmit quite efficiently without much tuning.



For 40 meters the length is 66 feet. The coax feed line can be any length, but shorter is better.

Where do I get antenna materials?

Radio Shack stocks RG-58U coax, insulators, and heavy, multistrand copper wire that are perfect for dipoles. I usually make my insulators out of plastic scrap from a local plastic fabrication shop or I use ABS plastic pipe sections from the hardware store. The total length of a dipole in feet is easily calculated. Divide the constant number 468 by the frequency in megahertz. For 40 meters, $468 / 7.05 \text{ MHz}$ is 66 feet long. If you have trees, a roof, or other tall objects on which you can mount an antenna, you're in business. Hang it as high as you can. I use relatively light nylon rope to secure the ends to trees. The nylon stretches as the wind blows and prevents the antenna from breaking. Steel or aluminum guy wires don't stretch and are more likely to break although I suppose stiff springs could also be used to take up the slack.



The folded dipole

Homebrew dipoles come in two basic flavors, “regular” and “folded.” Back when I was young and impoverished, my favorite dipole was “folded” and made entirely from 300 ohm TV twin lead. The dual conductors of all three arms of the “T” are soldered together to complete the circuit in a “loop.” I had one antenna cut for 40 meters that I used primarily for 40 and 15. It even worked OK on 75 meters for the local AM phone round tables our club used to hold. Aside from being made from cheap wire, another advantage of the folded dipole is that flat 300 ohm twin lead can slip through a slightly open window without mashing a fat, round cable or without drilling holes in the window sash.

Yeah, I know. 300 ohm balanced folded antennas need a *balun coil* and a transmatch to match the transmitter. When I was a happy, dumb novice, I just loaded it directly with my unbalanced π (pi) output class C vacuum tube transmitter and it worked very well, thank you. Then, when I learned how balanced antennas are supposed to be driven, I bought some fancy balun coils. I was disgusted when I observed no difference in performance.

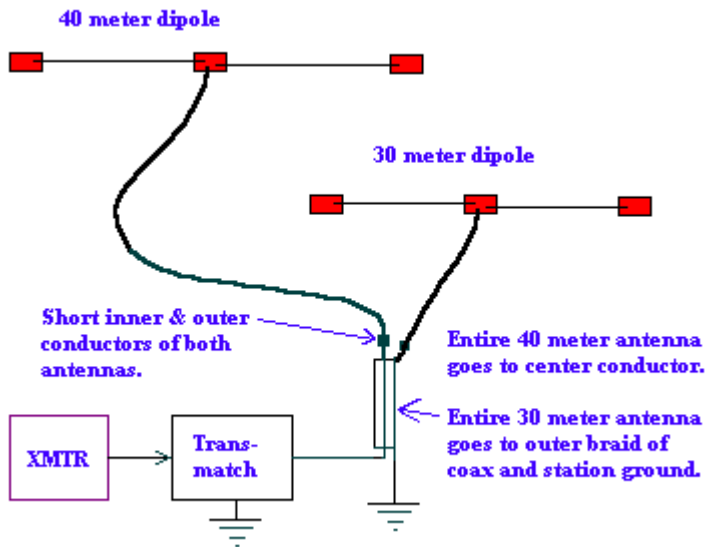
Multi-band Dipoles

Today we have four more HF bands than 40 years ago and I can’t resist trying them all. Any band I can’t work MUST be wonderful, right? I have a “regular” 40 meter dipole in the front yard and a 30 meter one in the back yard. I guess I have room for an 80 meter Zepp, but I’ve been too lazy to build one. Jack Ciaccia, WMØG, uses the gutters and drainpipes on his house as an 80 meter “longwire.” This sounded like a terrific solution. Unfortunately, my laziness soared when he began talking about “the buried radial ground field.” In other words, I was supposed to dig long ditches across the lawn in several directions and bury multiple ground wires. My wife would be thrilled with that.

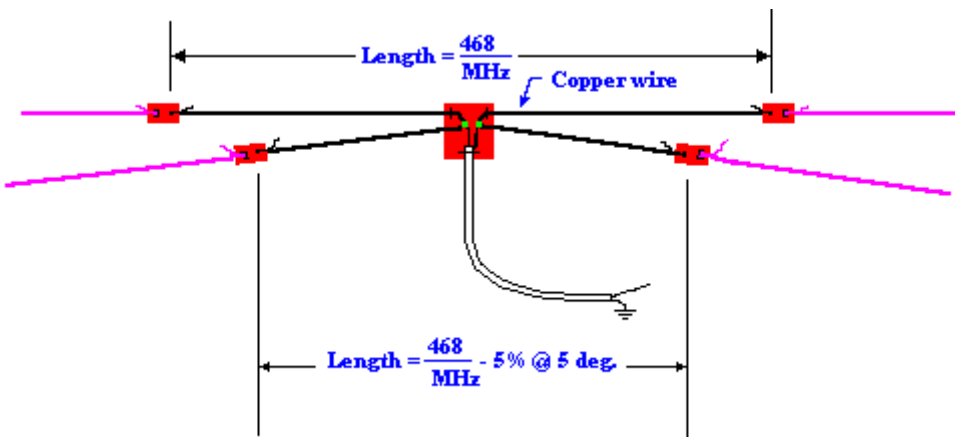
A year later Jack told me that deep heroic ditches are unnecessary. He waters his lawn to soften the dirt and roots. Then he digs his “ditches” with a large pizza roller cutter. He cuts a slit in the turf a couple inches deep. He slips the radial wires into the slits and, when the turf grows back, the wires are sealed under the grass.

Several years ago the 80 meter band was exceptionally “hot” with dozens of CW stations on every night. I was eager to get on the air. I tried loading my 40 meter dipole on 80. I managed to do it, but there were hundreds of volts at the station end of the coax. (With a 40

meter antenna, the transmitting impedance is a tad high on 80 meters.) After a couple hours of calling and tweaking, no one answered me. It seemed clear that I wasn't getting out and I needed a better plan.



Then the cerebral lightbulb dawned! Why not use the entire 40 meter dipole, coax and all, as a longwire? For a counterpoise I first used my station ground, which is heavy copper wire connected to a water pipe. This loaded better than the 40 meter dipole but still didn't work very well. Next I connected the entire 30 meter dipole, coax and all, to the station ground. My 30-meter dipole is in the back yard and well separated from the 40 meter dipole. Presto! I suddenly had a low impedance 80 meter antenna that loaded beautifully. There was one little glitch: My wife stormed downstairs and told me that I was obliterating the TV pretty much on all channels. Oh well, after that experience I got on 80 after she went to bed. I think (pray) the TVI is limited to inside my house. My theory is that I'm loading up the house wiring and the TV is immersed in the antenna near field. More recently we bought a much more modern TV. It seems to be immune to not only my 80 meter signal, but my signals on all the HF bands.



The multi-band dipole

15. Chapter 5, Harris

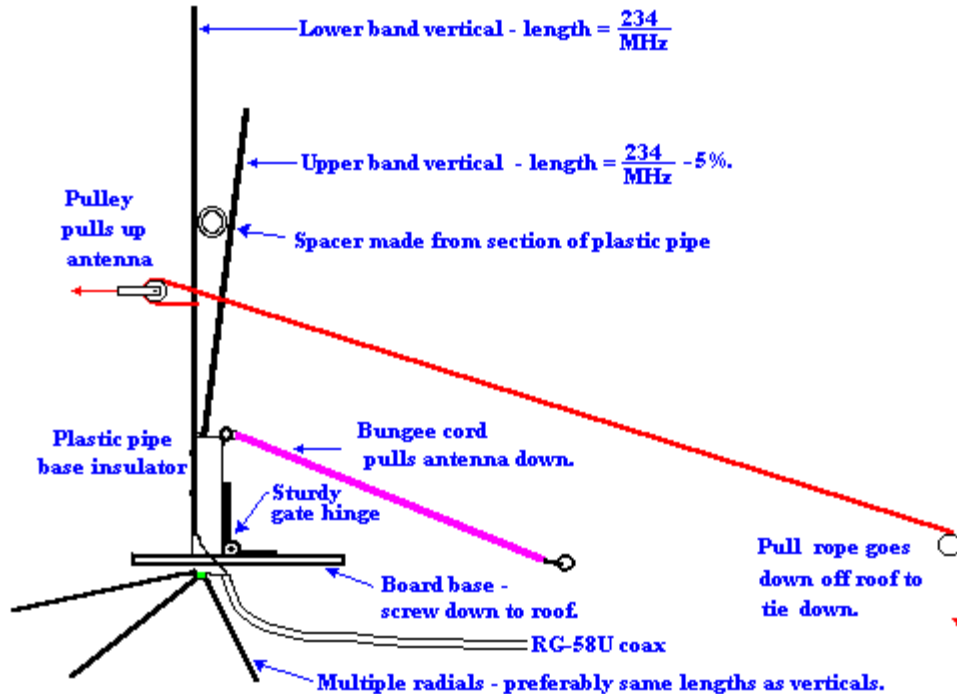
When I tried to get on 20 meters with my 40 meter dipole, I had a high impedance problem similar to using the 40 meter dipole on 80. However, using the antenna tuner described in chapter 9, I still managed to work folks. Consulting the ARRL handbook, I added 20 meter elements to my 40 meter dipole to turn it into a two-band dipole. A simple formula for the length in feet of both of the secondary elements taken together is $468 / \text{frequency in MHz} - 5\%$. Each arm of the dipole is offset from its neighbor by about 5 degrees. This lowered the impedance on 20 meters to something near 50 ohms and has been quite successful.

Now suppose you want to add elements to the 40/20 meter dual band dipole to cover other bands, such as 30, 17, 12, and 10. Yes, it's possible to do this. Steve, WØSGC, built a five-band dipole just like this. The ARRL handbook doesn't recommend this because such an all-band array tends to radiate every stray harmonic your transmitter may generate. In other words, it works too well! On the other hand, three-banders, such as 30/17/12 meters or 40/20/10 meters are recommended. Notice that you don't need to add an element for 15 meters because the 40 meter elements already work well on 15 meters. Therefore a tri-bander built for 40, 20, and 10 is actually a four-band antenna.

The length of the third dipole is calculated just like the second dipole. Suppose you already have the 40 and 20 meter dual band dipole and want to add another dipole for 10 meters (28.1 MHz). The length would be $468 / 28.1 \text{ MHz} - 5\%$ or 15.82 feet. (15 feet 9.8 inches). The third antenna would also be offset from the center (20 meter) dipole by 5 degrees. Do *NOT* decrease the length by 5% a second time.

A limitation, or possibly an advantage, of a dipole is that it transmits the most energy perpendicular to the wire. It also radiates significant power in line with the dipole. That is, dipoles are somewhat directional. Therefore, if you wish to talk to South America or over the North Pole to Russia, ideally in the US your dipole should be oriented east to west. Conversely, if you wish to talk across the US to the east and west coasts, the dipole should be oriented north and south. This isn't a big deal in performance, but if you have your choice in places to string the antenna, it is something to consider.

The curtain rod vertical



A dual band, dual vertical, hinged for lightning protection

I wanted antennas for 10 and 15 meters that would be higher off the ground and less directional than my dipoles. Vertical antennas are simply metal poles $\frac{1}{4}$ wavelength long sticking straight up. They are really just dipoles standing on end. Therefore, although we talk about the vertical part, we also need the counterpoise portion connected to the coax cable outer shield. The counterpoise consists of "radials" preferably the same length as the vertical extending out along the roof or ground in all directions. In theory, like a dipole, a single radial will work, but in practice multiple radials equal or longer than the vertical work best.

I started with a 15 meter vertical consisting of an 11 foot curtain rod lashed to my chimney. (234 divided by 21.1 MHz) Four thin wire radials fanned out down the roof in four directions. It worked well the first time I loaded it. The fun of using a real curtain rod is that, when you tell someone your antenna is "a vertical made from a curtain rod," they usually comment on it as if you had built a nuclear reactor out of a washing machine. Interesting psychology. Obviously these guys have never built anything themselves.

Trap antennas

Next I tried to add 10 meter capability by adding a parallel LC resonant trap tuned to 10 meters about 8 feet up the vertical. The idea is that, if a tuned LC resonant circuit is added at the right distance up the antenna, the trap will prevent RF current from traveling up the antenna past the trap. In other words, for higher frequency bands the trap makes the antenna appear shorter than it really is. In this way a long antenna can also work well for a frequency much higher than its length would suggest. After I built a trap resonant for 10 meters, I adjusted the distances above and below the trap dozens of times. But even with an antenna tuner, I could never get it to load well on either band. It turns out that homemade trap antennas are hard to build.

You may have noticed that in an LC resonant circuit, the sizes of the L and the sizes of the C are not fixed. In other words, the LC circuit will be resonant at the desired frequency so long as:

$$\omega = 1 / (LC)^{1/2}$$

or, $\omega^2 = 1 / (LC)$

where $\omega = (2 \times \pi \times \text{Frequency})$

$\pi = \text{Pi}, 3.1416.$

L = inductance

and, C = capacitance

(an exponent of $\frac{1}{2}$ means the square root)

$$2 \times \pi \times \text{Frequency} = 1 / (LC)^{1/2}$$

Unfortunately, the sizes of the L or C do matter in a trap. This is because a capacitor or an inductor shift the phases of the current and voltage and affect the reflections of the waves along the wires. To design a trap properly, the distances above and below the LC as well as the sizes of the L and the C all have to work together to make the whole apparatus look like a 50 ohm resistor as seen by a radio wave. Good luck!

It turns out that this is a problem for Smith charts. These are a way of mapping out inductive reactances, that is, current phasing, so that they cancel and the antenna will look resistive. I haven't figured out a practical way to do this and the handbooks don't help, unless you copy their trap antenna designs precisely. In the end, I just applied the same dual-dipole principle as the multi-band dipoles discussed earlier. I added a second vertical to the first, separated by about 5° degrees and about 5% shorter than it would have been if it were standing alone. I added two more radial wires cut for 10 meters, but I'm not convinced they were essential. Once again, it worked perfectly on both bands the first time I loaded it.

Caution: ***Remember that "the vertical antenna" begins at the exact inch where the coax inner conductor first separates from the outer braid.*** A common mistake is to ignore an extra 6 inches of inner conductor that may be adding to the effective length of the driven element. The dual band vertical has worked beautifully. I've also used it on 12 meters successfully. Much to my surprise, it also worked on 17 meters, although the SWR (Standing Wave Ratio) isn't great. In other words, when there are standing waves on the antenna because the length is wrong, it takes extra voltage to drive it. I was probably losing some power on 12 and 17 meters.

Two years later, 10 and 15 meters were no long open but 17 meters was still active. To make the 15 meter vertical work well on 17, I tacked on an additional 1.9 feet in length and added some 16 foot long radial wires which are suitable for 20 meters. After this modification the antenna loaded easily on 17 meters and I got good signal reports. I can summarize verticals by saying that all you need to do is calculate the length in feet using the formula $234 / \text{frequency}$ and it will work well the first time you try it.

Kaboom! What about lightning?

Looking up at the metal poles on my roof, they looked more like lightning rods than curtain rods. I'm probably more paranoid than necessary, but I've had bad experiences with lightning. When I was a novice, fuses blew in my rig during a thunderstorm. A buddy of mine had his oscilloscope fried and a hole blown in his roof. On mountaintops I've felt my hair stand on end and heard my ice axe hiss as we galloped down the mountain in terror. Once I had the grim duty of carrying three deceased lightning victims down from Arapaho Glacier. Lightning scares the heck out of me and that vertical looked like a disaster waiting to happen.

My solution was the base hinge and bungee cord shown above. During the summer I raise the antenna by tugging on the rope whenever I need it, then lower the vertical when I'm done. The hinge also has stealth advantages. One important point is that the rope pulls the antenna *UP*, while the bungee makes sure it folds back *DOWN*. I tried to have the bungee pull it up, but that worked poorly. There was too much torque on the vertical and the bungee wouldn't let the antenna fold flat against the roof.

How lightning forms and how likely it is to occur

According to the National Lightning Safety Institute of Louisville, Colorado, lightning begins with "leaders" of corona coming down from the clouds. These leaders of charged air produce high voltage with respect to the ground. In response "streamers" of charge rise up from the ground and are most easily launched skyward by sharp conductive objects. When the streamers meet the leaders the ion path from cloud to ground is complete and the current flow enters a brief "spark phase" when small currents begin to flow. This can easily transition into "arc phase" in which the air becomes fully ionized and large currents are free to flow. Once the path is complete, a lightning bolt begins. Lightning can be postponed or even prevented if the streamer paths can be suppressed and streamers don't merge with the leaders. *Fortunately, except for the highest peaks and tall metal towers, lightning strikes are rare and capricious.* Your best bet for safety, (but not for DX), is to keep your antennas no higher than the local trees and buildings.

Fuzzy metal brushes on an antenna are controversial

A relatively new approach to lightning prevention is to bleed the excess local charge off a vulnerable metal tower with metal brushes before it can attract a full-fledged lightning bolt. In contrast, *the National Lightning Safety Institute (www.lightningsafety.com) strongly condemns using lightning rods of any sort.* They say that lightning rods are allowing the streamer to begin earlier and are therefore attracting lightning. The fact that this is controversial demonstrates that lightning really is capricious. After 200 years of research it still isn't obvious whether lightning rods are good or bad! This tells us that, statistically speaking, lightning is not a big risk.

The Lightning Safety Institute had a research project up on a bare, rocky ridge high above timberline at 11,500 feet above sea level near Nederland, Colorado. The location looks like a good place to avoid during a lightning storm. I have been up there three times and examined their array of various lightning rods. They have pointed ones, square ones, and round ones. The rods are connected to ground through fuses. The first time I was up there, they were using 20 ampere fuses but none of them had blown. The next year they were using 2 ampere fuses and still none of them had blown. That must have been frustrating!

On the other hand I have encountered two 60 foot high spruce trees that were struck by lightning. The trees were literally exploded into giant chunks of log weighing hundreds of pounds. These trees were located among thousands of other 60 foot high trees in relatively flat high altitude forests. What was special about those trees? Apparently nothing. Those trees were just unlucky. In summary, *lightning is extremely random and difficult to predict.*

The 2005 ARRL Handbook doesn't discuss antennas as lightning rods. Instead ARRL stresses grounding antenna towers and placing lightning arrestors on lead-in coax and wires. They don't even mention using spiky points on antennas. ARRL emphasizes that *it is difficult or impossible for a ham to protect from DIRECT strikes.* This is because the spike of current produced by a lightning bolt is so huge and so sudden that, lightning not only delivers thousands of amperes, the abrupt rise in current means that any wire or metal conductor we could install will have too much inductance to ground to shunt the whole pulse away. The current pulse and big voltages will divide and jump to other objects. The best we can do is protect our house and equipment from surges due to *nearby* strikes. For example, instead of having tall, grounded spiky metal poles projecting from the roof ridge, it would be better to simply put a grounded wire along the ridge of the roof.

ARRL recommends surge protectors on power cords to prevent damage to line powered equipment. Battery powered ham stations obviously don't need surge protectors and battery-power has other advantages as described in chapter 8.

In summary, unless you live on a mountaintop or have a huge metal tower, lightning is not an imminent threat and you don't have to be paranoid. If you're like me, your antennas are no higher than the local power lines and trees. I haven't had any incidents since 1960. However, I still crank my vertical antenna down in the summer whenever I'm not on the air and I unplug my antennas from my rig.

CRYSTAL SETS TO SIDEBAND

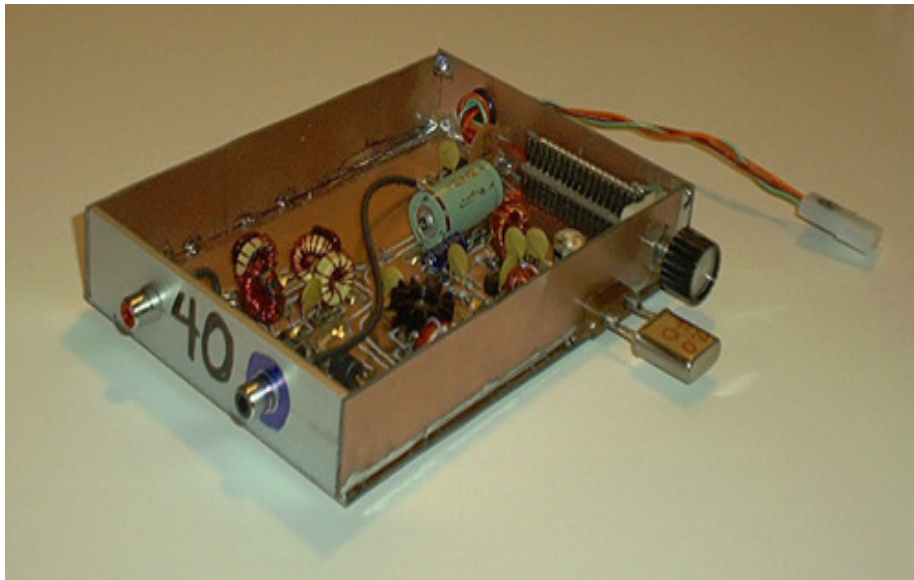
© Frank W. Harris 2010, REV 12

Chapter 6

BUILDING A HOMEBREW QRP

Among the guys I work, QRPs seem to be the most common homebrew project, second only to building antennas. Therefore this chapter describes a simple QRP design I have settled on. I use my QRPs as stand-alone transmitters or I use them to drive a final amplifier to produce higher power, 25 to 100 watts.

It's true that before you build a transmitter you'll need a receiver. Unfortunately, a good selective, all-band ham receiver is complicated to build and most guys don't have the time and enthusiasm to do it. (See chapter 13.) On the other hand, chapter 7 describes building a simple, 5-transistor 40 meter receiver that I have used with the QRP below to talk to other hams. This simple receiver will work best during off hours when 40 meters isn't crowded. It can also be used to receive Morse code for code practice.



The QRP transmitter shown on the left is designed exclusively for 40 meters, (7.000 to 7.300 MHz.) The twelve volt power supply comes in through the pig-tail wire on the right. The telegraph key plugs into the blue-marked phono-plug socket on the right of the aluminum heat sink. The antenna output is the red-colored socket on the left end of the heat sink.

A 40 meter QRP module.

The transmitting frequency of the QRP module is controlled by a quartz crystal. That's the silver rectangular can plugged into the box on the right front. The knob on the far right is a variable capacitor for adjusting or "pulling" the crystal frequency over a range of about 3 KHz. As we shall explain in chapter 10, a variable frequency VFO that can cover the entire band is hard to build. I don't recommend starting out with a VFO. You need success, not frustration.

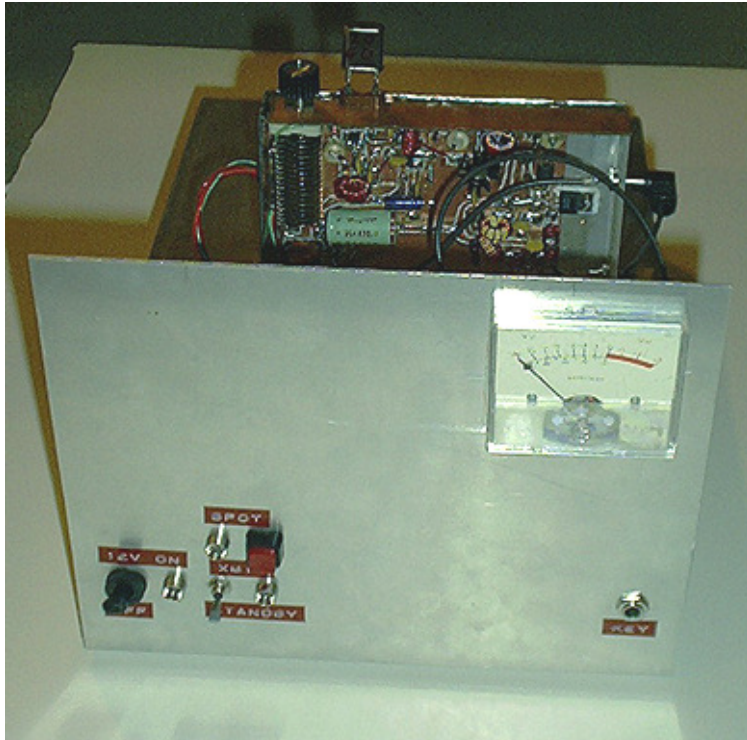
Start simple

The easiest QRP is just a crystal-controlled oscillator. It usually has one to three amplifier stages to raise the power to between 1/2 to 5 watts. This will get you on the air quickly.

Unfortunately crystal control means you must order \$18 custom crystals for your favorite frequencies in each band. Because the oscillator only has a very narrow tuning range, you can usually only call CQ (calling any station). As luck would have it, it always seems as though the other fellow calling CQ is just out of your crystal range.

The transmitter “mainframe”

You could use this bare-board little transmitter just as shown above. However, it will be more convenient to mount it in a larger chassis equipped with an ON/OFF switch, pilot lights, an antenna relay, and other niceties. My whole transmitter assembly is shown below.



The transmitter “mainframe” is a box to contain your transmitter modules. The large meter at the upper right indicates the current drawn by the final amplifier. It's helpful to know how much power the transmitter is consuming. The switches and lights on the lower left are the main power switch and the transmit/ receive switches. There are also LED lights to indicate which switches are active. The large red button is a “spot” switch. With the spot switch engaged, the QRP oscillator may be tuned to another station without actually transmitting. How big you make your mainframe depends on your plans and ambitions. As you can see, I had

Transmitter mainframe

really big plans. By the time you add multi-band capability, a VFO, power supplies, and single-sideband capability, even a large box may be too small. My previous mainframe was too small so I made this one extra large to eliminate crowding.

HF construction methods – building your own circuit boards

Back in the vacuum tube days we built hand-wired HF transmitters. Inside they had long skinny wires running every which way. However, transistors generate high power with low voltage and big currents. As a result, the inductance of the wiring must be kept as low as possible. This means you must build with printed circuit boards or the transmitter simply won't work.

For example, once I connected an output lead from a 21 MHz (15 meter band) transistor power amplifier to the base of the next stage with a bare wire 4 inches long. If this had been a vacuum tube circuit, this wire coupling would have worked well. But with high current transistors, the wire acted like an RF choke. That is, the wire blocked current flow as if it were

an inductor. Sliding an oscilloscope probe along the wire, I could see an 80% drop in drive voltage from the output of the first amplifier to the input of the next stage. In contrast, a wide circuit trace printed on a circuit board acts like a coaxial cable and has very low inductance. With a PC board the same drive to the next stage can be nearly 100%, not 20%.

If you have already developed your own method of making printed circuit boards, you may skip ahead. But if you have never done this before, read on.

MAKING PROTOTYPE RF CIRCUIT BOARDS

PC board tools and materials

I usually use double-sided printed circuit (PC) board material such as Radio Shack part # 276-1499A. This board has layers of thin copper bonded to both sides of a 1/16th inch fiberglass sheet. I only solder components onto the surface of one side. The solid surface of grounded copper on the opposite side provides distributed capacitance over the whole circuit. I believe this gives extra stability and works as a grounded shield to prevent radiating signals to whatever circuits might be adjacent to the bottom of the board.

Traces on a PC board act like transmission lines

A transmission line, such as the coaxial cable that delivers your TV signals, is remarkably efficient. As explained in chapter 4, the wire in the center of the coax acts like a distributed inductance that rings with the distributed capacitance between the center wire and the outside insulation. In other words, a coaxial cable is a distributed LC circuit and does not dissipate voltage and energy as you would otherwise expect. In fact, the energy losses that do occur are only the heating losses in the insulation and the simple resistance losses that happen in copper wire.

A two-sided circuit board can be designed to act like a circuit wired with pieces of coax. The circuitry is mounted on one side of the board while the other side is ground. Each trace has a small amount of inductance and each trace has a proportional amount of capacitance with the grounded copper sheet on the far side of the board. The result is that signals are almost unchanged as they travel along the traces of a circuit board. It would be interesting to build the exact same RF power amplifier on single-sided and double-sided boards and compare the difference in performance at HF frequencies. I'm convinced double-sided is far better, but I've never done a controlled experiment.

In microwave printed circuit boards the traces are deliberately designed to act like transmission lines for the particular frequency that is being used. The precise, optimum dimensions for these "microstrip" traces can be calculated for maximum performance. Fortunately for us, high frequency circuit boards like ours don't have to be designed with so much care.

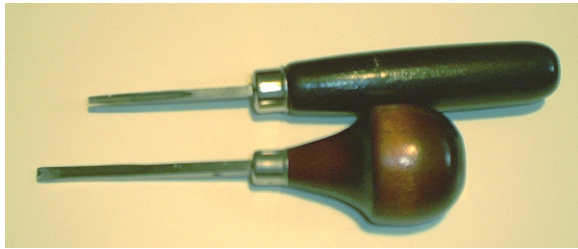
Etched circuit boards

There are at least four ways to make homebrew RF boards. Originally I tried etching "real" printed circuit boards with ferric-chloride solution. It's slow, messy, and lots of work. Etching boards is an art that isn't easy to master. You may under-etch or you may over-etch, often on the same board! If you succeed, you'll have a result close to a commercial product.

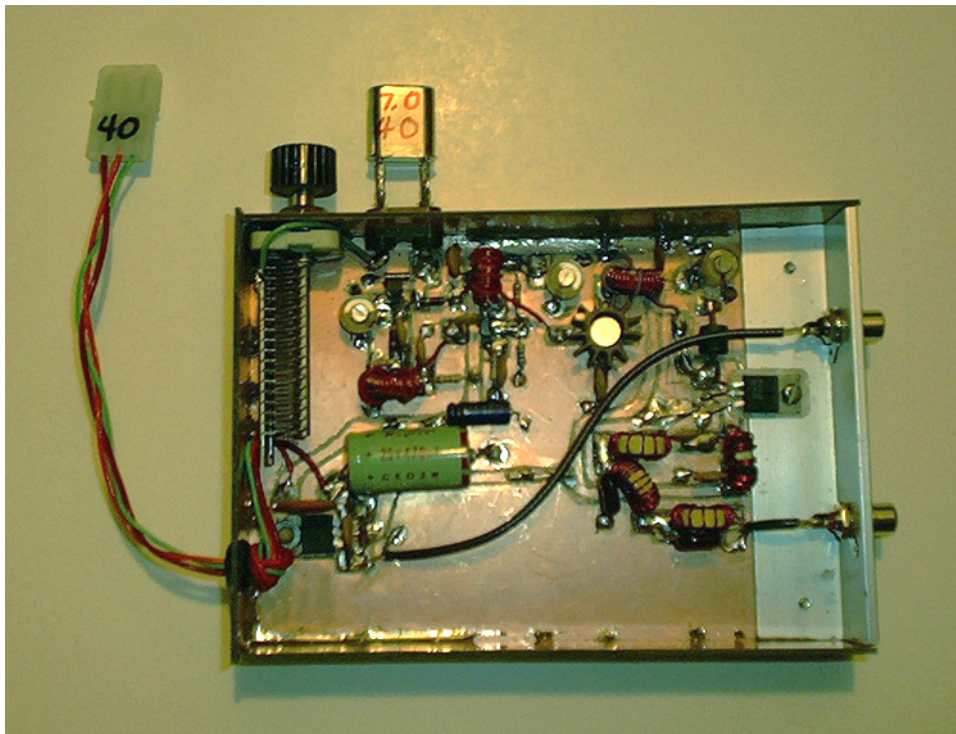
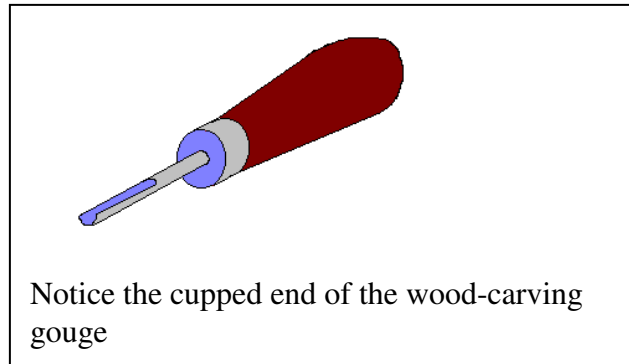
Unfortunately, when you use a circuit layout from an ARRL handbook or QEX magazine, you are making the assumption that you can buy all the exact parts the author used. Good luck! The parts you can actually buy may not fit on the board. I found that the worst limitation of etched PC boards was that I couldn't build and test my circuits one transistor stage at a time. If I needed to add another component or add another amplifier stage, I had no room for it. *The key to success in homebuilding is building AND TESTING one small circuit at a time.*

Gouged PC boards

My favorite method for making RF boards is carving them into a bare, two-sided PC board with a small wood-carving gouge. The gouge is a chisel with a cupped end, about 0.5 to 3 mm across. I have several, but my favorite is about 1 mm across. I got it from the Traditional Woodworker Co., (www.traditionalwoodworker.com)



Two small wood-carving gouges



This QRP board was made with "gouged board" construction. Nearly all of the visible copper is "ground." The aluminum angle on the right serves as a heat sink for the output transistor.

When you push the gouge along the board at a high angle and twist your wrist back and forth, the gouge carves out a little trench through the copper. Hint: Keep your elbow high and the gouge won't skate across the surface and into your hand. Ouch! Obviously two "trenches" can isolate a strip of copper that serves as wire or "trace." Often I just isolate little islands of PC trace onto which I solder short component leads. I usually solder components to the surface, rather than drilling mounting holes for each lead.

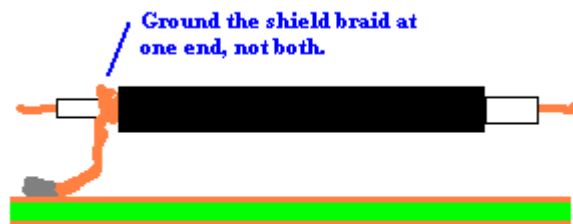
PC boards for integrated circuits

A wood-carving gouge works fine for RF circuits made from discrete transistors, but is impractical for integrated circuits. For through-hole ICs I use 0.1 inch center punch-boards and wire-wrap methods. There is an example of this construction method in chapter 7. Another method of working with integrated circuits is to etch (or buy) tiny boards for mounting each type of IC. That is, you make 8 pin boards, 14 or 16 pin boards, etc. These little boards have big pads connecting each pin so that you can solder jumpers down onto your relatively crude handmade board. Isolated little IC boards are especially good for working with "surface mount" ICs which are otherwise too tiny to handle.

Coax jumpers

If you need to, it is still possible to run long wires from point to point. But instead of wire, you must use shielded coax. Sometimes I "pipe" an RF signal from one end of a PC board to the other without significant loss of voltage or power. If there's no room for a wide trace, I use a piece of skinny RG-174 coax transmission line for this purpose.

Another application for a coax jumper is to shield an audio or DC signal from the RF. If you run a bare wire across a PC board full of RF currents, the low frequency signal will be contaminated with RF signals by the time it arrives at the other end. For example, in the QRP board above, my DC (Morse code) keying signal is transported across the board with a length of coax. Because of the way my mainframe transmitter chassis was wired, my QRP board plugs into the mainframe with the telegraph key input at the wrong end of the board. The telegraph key must switch the 12 volt power MOSFET transistor on an off, but unfortunately it was located on the opposite end of the board from the key input. To shield this low power DC line, I used a coax jumper as shown in the photo.



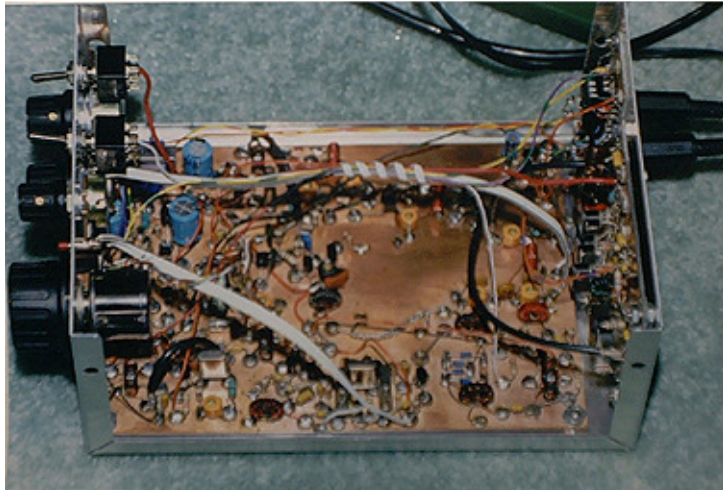
COAX JUMPER CABLE

Just ground the coaxial shield at one end. The most common error when using coax jumpers on a board is to ground both ends of the shield. This introduces a "current loop" that can act something like a turn of a winding on a transformer. This current loop may pick up stray currents and the coax might do more harm than good.

Disk and Super-glue boards

Another practical RF PC construction method is the "disk and Super-glue" method. Small disks or strips are punched or cut out of PC board material. The disks and strips are glued

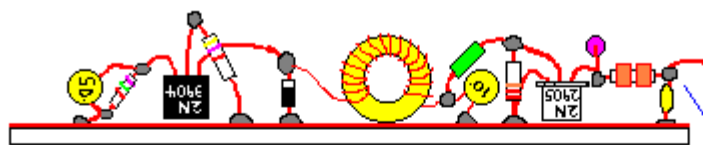
onto the PC board using superglue to form contact nodes and traces. An advantage of this method over gouged board is that the ground sheet is unbroken. That is, when you solder a component lead to ground, you will know that the entire PC board is "ground," and not just areas or strips of "ground." A continuous sheet of copper means that there will be virtually no voltage differences between one region of the board and another. The higher the frequency or the higher the power levels, the more important this advantage becomes.



Mike Fitzgibbon, NØMF, built the homebrew QRP transceiver shown on the left using the super-glue technique. I met Mike on the air while he was using this transceiver. The transceiver puts out about a watt and uses a super-regenerative receiver. We communicated easily across 1,400 miles so apparently it works very well.

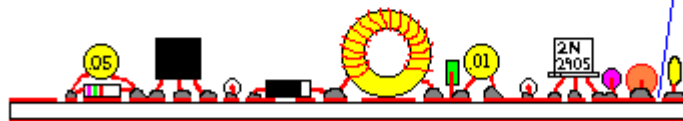
Dead Bug construction

“Dead bug” construction resembles super-glue boards in that the PC board is used as an unbroken sheet of grounded copper metal. Traces are not cut or etched into metal. Instead of using disks glued to the board, the ungrounded component leads are soldered together up above the board as needed. Since the ICs and transistors are upside down, they resemble "deceased insects" with their feet in the air. Of course you must keep the leads as short as possible. When currents are low, lead inductance isn't a problem. For the low power stages (less than 100 milliwatts) I have found “dead bug” construction OK, but I don't recommend it for RF power amplifiers.



"Dead Bug" - Parts soldered to p.c. board ground plane.

Every ungrounded connection is made above the board.



"Gouged Board" - Parts soldered to islands and traces on 2-sided p.c. board.

Channels carved out to make circuit traces.

“Dead Bug” versus “Gouged Board” construction.

When you get into “high power,” greater than 100 milliwatts, you should minimize the lead inductance by using wide traces on a PC board. Once I built a 10 meter power gain amplifier stage using extremely compact dead-bug construction. It worked well and gave me about 0.5 watts output. Since the stage was a success, I rebuilt it using gouged board construction. Using carved traces, the same circuit and components gave me 1.0 watt, a 100% improvement. When I have to connect an RF power lead across the board for a half an inch or more, I cut a wide trace on the board or I use a short piece of coax. For big, 10 ampere RF currents in a power amplifier my traces might be ½ inch wide or more. If I’m short of space, sometimes I use a wide rectangle of PC board material standing on edge as a wide, low inductance “wire.” The antenna relay shown in chapter 9 uses this technique for the transmit circuit.

Boxes out of PC boards

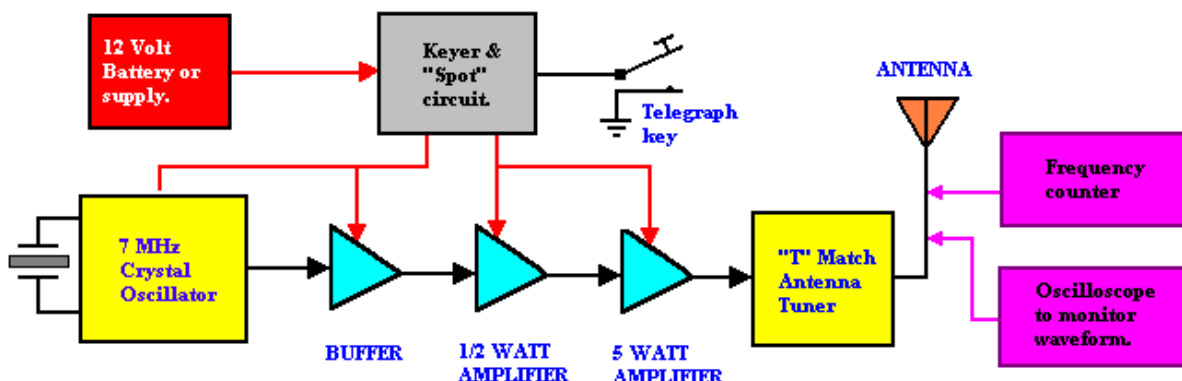
It’s often necessary to shield circuit boards from other circuits. That is, the circuit needs to be completely enclosed in a metal box so that it does not radiate or receive radio signals to or from nearby circuit boards. A gouged board circuit can be shielded by building up the edges into a box. Solder inch-high strips of PC board material around the periphery of the board. Since the copper surface solders nicely, it’s easy to build up a board into a sturdy open-top box. And because a gouge-board doesn’t need to have through-hole components, the circuit inside is completely isolated from the grounded outside of the box and is enclosed on five sides.

To make a lid for the box, fold a flat piece of thin aluminum or copper sheet into a mating shallow box that fits over the top. The top just needs to be snug enough to hold it in place. This technique is essential for receivers and SSB transmitters as illustrated in chapters 13 and 15.

**

The complete crystal controlled QRP transmitter

The block diagram below shows the basic modules of the completed QRP transmitter from battery to antenna.



40 Meter 5 Watt QRP Transmitter Block Diagram

The bad news is that there are lots of circuit blocks. Two of the modules on the right, the

oscilloscope and frequency counter, are test instruments you need to be sure you are operating on the correct band. These are items you will almost certainly buy. The power supply that I prefer is a simple car battery or a 12 volt deep-discharge marine battery. It's desirable, but not essential, to regulate the battery power to about 11 volts. In this way, the transmitter always has the same supply voltage, whether the battery is being charged or nearly dead. You can also build a power supply that plugs into the wall or buy a supply. Building a ten-watt, 12 volt AC plug in power supply for your QRP is fairly easy. But later, when you get into high power amplifiers needing 100 or 200 watts, building high power AC line-powered supplies is much harder and you may want to return to a battery. Power supplies are discussed in chapter 8.

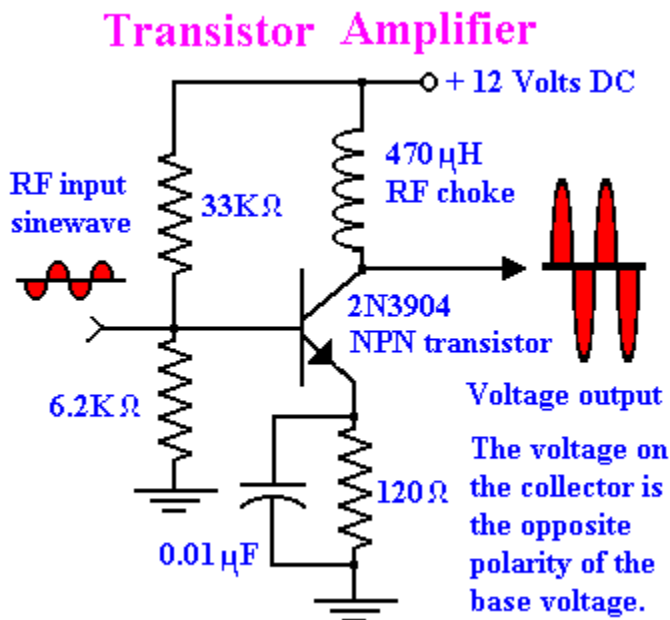
The oscillator, buffer, and amplifiers will be discussed next. The keyer circuit is discussed at the end of this chapter. A receiver is not shown above and is assumed to use a separate antenna. If you hook your antenna to the transmitter and receiver simultaneously, the receiver is likely to be damaged. Suitable antennas are discussed in chapter 5. Accessories like the telegraph key and the T-match antenna tuner are discussed in chapter 9.

Amplifiers and oscillators

In order to generate a radio signal, we first need to make an oscillator. A spark gap generates radiowaves by the electronic equivalent of banging on a bell. On the modern ham bands we need continuous, pure sinewaves. Think of it as the radio equivalent of an electronic organ. You hold down a key and a pure tone never stops. In fact, that's the origin of the term "continuous wave" or CW for radiotelegraphy. You may have already asked yourself, "If I'm pounding on a telegraph key, what's continuous about that?"

Continuous waves at Megahertz frequencies are most easily generated using electronic oscillators. A continuous wave oscillator is an amplifier that amplifies feedback from its own

output. Before we can understand an oscillator, we need to cover bipolar transistor amplifiers.



What is a linear amplifier?

The circuit at the left is a simple transistor RF (radio frequency) amplifier made from an NPN transistor. If you prefer, you could reverse all the polarities and use a PNP transistor and it will work just as well. The above amplifier is designed to be *linear*. Linear means that it can amplify big signals or tiny signals equally well over a wide range of frequencies. In other words, although designed for radio frequencies, this amplifier is "hi-fidelity" and is analogous to the audio frequency amplifiers

found in your stereo. Another name for a linear amplifier like this is *Class A amplifier*.

As we saw in chapter 4, a bipolar transistor can be thought of as a structure made by merging two PN junction diodes. When a silicon diode is forward biased, (positive to P conducts) relatively large currents, (milliamperes), can pass through the diode. However, current will flow only when the forward offset voltage, (about 0.6 volts) is exceeded. Just like a diode, when a silicon NPN transistor is used, nothing significant will happen until the base voltage rises above positive 0.6 volt. When this occurs, a relatively small base current will “convert” the tiny region of P type semiconductor into a conductor. Big currents are then free to flow from collector to emitter. In the 2N3904 transistor used above, the transistor “gain” causes a big current to flow that is 100 times larger than the base current.

Suppose that we want to amplify a sinewave that has both positive and negative polarities. A transistor amplifier with a minimum of parts would be just a base connected to the input. That amplifier would only amplify the upper part of the positive half of the sinewave, above 0.6 volts. All the rest of the sinewave would be below the turn-on threshold. The purpose of the 33K ohm resistor in the above circuit is to turn the transistor “halfway on,” like a faucet. Now when a sinewave current comes in on the base, the negative portion of the sinewave will turn the transistor *LESS ON*. And when the positive half of the sinewave arrives, it will turn the transistor *MORE ON*.

What does the 470 microhenry inductor “choke” do?

The choke produces a voltage output without wasting energy. We could use a resistor instead, but a resistor would waste energy and become hot. This amplifier is designed to generate a big RF voltage. The output is the voltage that rides on the transistor collector. The current flowing through the inductor isn’t really doing anything useful besides dropping the voltage between the 12 volts supply and the collector. Therefore, we use a large inductor relative to ham band frequencies. RF cannot pass through the choke, but DC current can. Remember that *the current through an inductor cannot change instantly*. The inductance is high enough so that, during each half-sinewave cycle, the inductor is too large to charge significantly with current. Consequently, a big RF voltage appears on the collector and little energy is wasted.

Stabilizing the transistor operating point

The **33K ohm resistor** is the component that turns the transistor “half-on.” It *biases* the transistor on by injecting a small current into the base. The **120 ohm resistor** serves to add a small amount of negative feedback so that the transistor will not turn on too hard when the transistor becomes warm. As big DC currents flow through the 120 ohm resistor, a DC voltage will appear across it. This voltage “raises” the emitter voltage off ground, thereby decreasing the base to emitter voltage. When this voltage difference drops, the current flowing into the base decreases, thereby turning the transistor a bit less on. So long as this resistor isn’t too large, it just serves to bias the transistor and make it more stable with temperature changes.

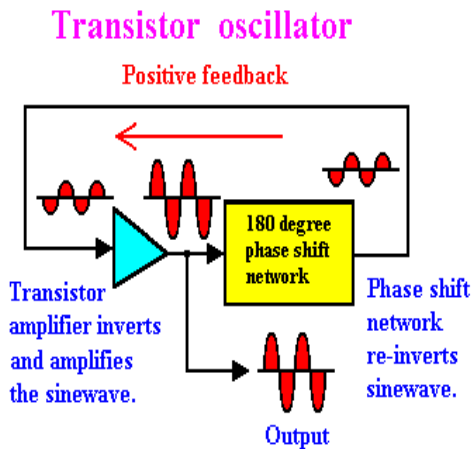
If you replace the 120 ohm resistor with a short circuit, you’ll find that the amplifier still works, but the transistor will run hot to the touch. The **6.2K ohm resistor** makes sure that the charge in the base of the transistor always has a way to leave and turn off the transistor. The 6.2K resistor also stabilizes the operating point and insures that the circuit will work every time you build it.

Bypass capacitors

So what's the 0.01 microfarad capacitor across the emitter resistor for? This is a *bypass* capacitor. An RF amplifier can be thought of as two circuits superimposed on each other. One circuit establishes the static DC voltages and currents needed for stable, linear operation. The other circuit handles the transient RF sinewaves that modulate the static voltages and currents. As explained above, DC current passing through the 120 ohm resistor causes a DC voltage drop from emitter to ground. Radio frequency current passing through the resistor would also cause an RF sinewave to appear on the emitter. This voltage would be subtracted from the voltage on the collector and therefore would decrease the output. You may remember that *the voltage across a capacitor can't change instantly*. The bypass capacitance is chosen so that, although it will charge up to some DC voltage, at ham band frequencies the capacitor voltage will not change significantly. For a capacitor this large, the fractions of a microsecond that the RF voltage oscillates up and down are not important. The result is that emitter will have zero RF voltage on it and all the RF voltage will appear on the collector. Another way to look at bypass capacitors is that they "shunt" RF to ground, but don't affect the DC.

How an amplifier becomes an oscillator

You already know that a public address system turns into an audio frequency oscillator when you place the microphone close to the loudspeaker. This results in an ear-splitting, screaming oscillation. Electronic oscillators work by feeding the output back into the input.

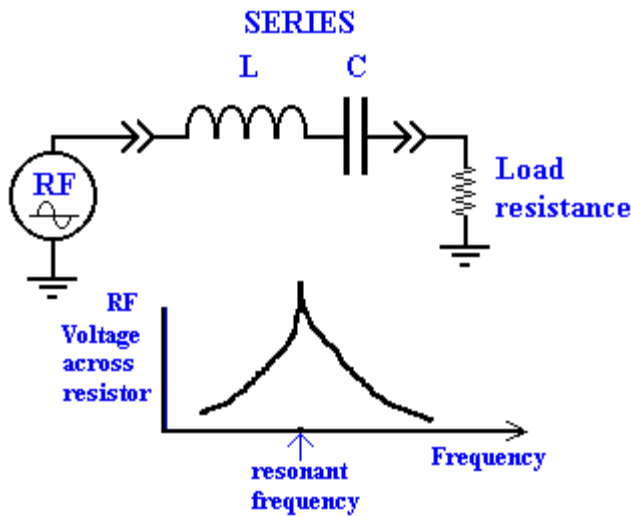


Notice that a one-stage transistor amplifier inverts the polarity of the input waveform. Rising voltage on the base causes the voltage on the collector to fall. In theory at least, if you were to feed the output of this amplifier back to the base circuit, the opposite polarity of the output would cancel out any signal that begins

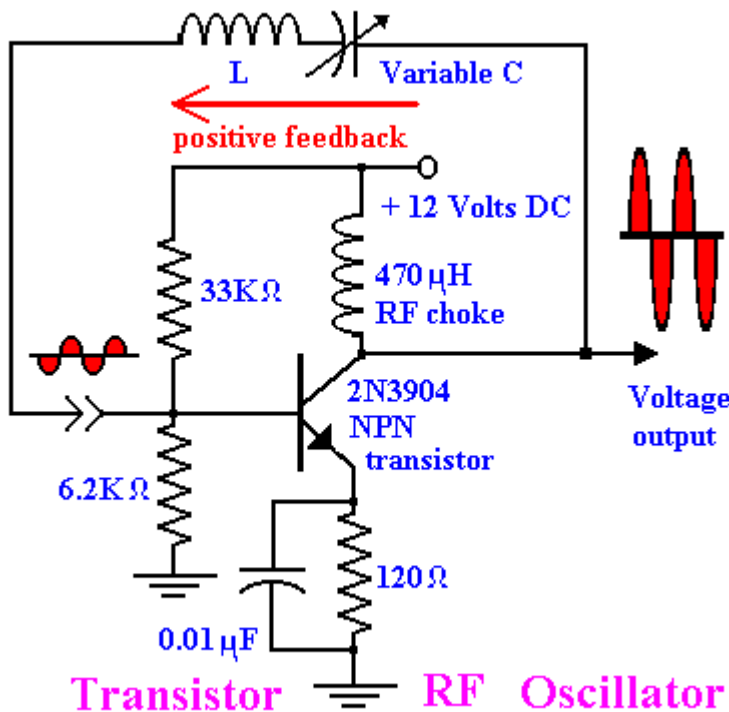
to form on the input. For this reason, if you wish to make an oscillator, the waveform needs to be turned up side down or *phase inverted* before the feedback is introduced to the transistor base.

The need for a phase inverter circuit gives us the opportunity to use this inverter circuit as a filter that also restricts the oscillation to just one frequency. You have already met parallel L-C resonant circuits. A series L-C circuit will attenuate every frequency except its resonant frequency. A series L-C circuit located between the collector and base of a transistor amplifier will oscillate on a specific frequency determined by the series inductance and capacitance.

Series LC resonant circuit



In chapter 4 you were introduced to the parallel resonant circuit. The series resonant circuit also resonates at a specific frequency and can be used in much the same way. The parallel resonant circuit appears as an *infinite resistance* or *infinite “impedance”* at a specific frequency while shorting out RF voltage at all non-resonant frequencies applied across it. In contrast, the series resonant circuit looks like *zero resistance* at the resonate frequency. As shown above, it only passes one RF frequency current efficiently to the load resistor. To all other frequencies, it appears as a large inductance or as a tiny capacitance.



A working transistor oscillator

The circuit on the left oscillates in the range of 1 to 30 MHz, depending on the sizes of the inductor L and capacitor C. Unfortunately, if you build it, you’ll find this oscillator too unstable for use in ham radio. However, it does produce a strong oscillation. Once you get it running, you can illustrate the importance of the 33K forward bias resistor. When you disconnect this resistor, the oscillator will continue to oscillate as

though nothing happened. Well, almost nothing. If you look closely on your oscilloscope, you'll see that the bottom loops of the output sinewave are severely distorted. Without the 33K, the transistor turns off whenever the input drops below 0.6 volts.

Now turn off the power supply for a moment. Turn the supply back on and the oscillator will be "dead." The output will be just a straight line on your oscilloscope. Without this 33K forward bias, the amplifier cannot "see" its own tiny random noise output and the oscillation never begins. That is, the random noise is way below the 0.6 volt threshold. Restore the 33K and the oscillation will restart immediately.

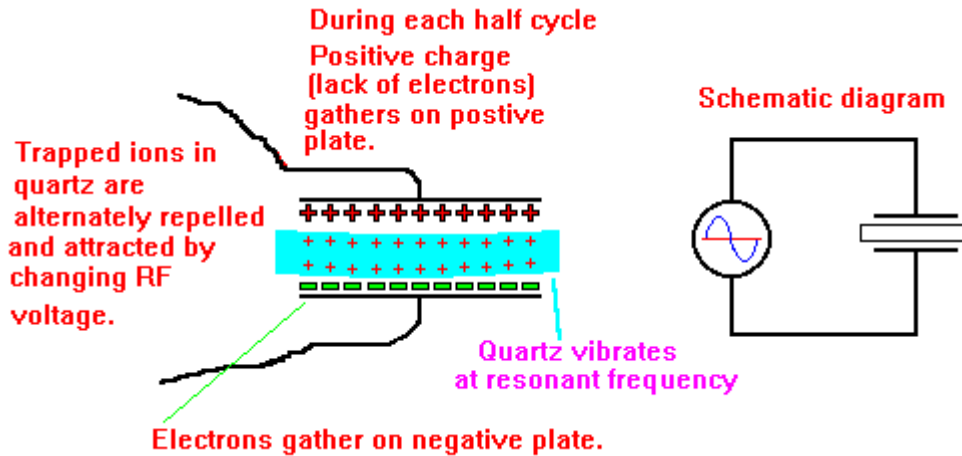
A non-linear amplifier with no forward bias is called a *Class C amplifier*. They are useful for amplifying CW signals that are greater than the forward base drop. That is, the drive for a Class C amplifier must be greater than 0.6 volt, otherwise there will be no output. Class C is not useful for amplifying voice or music signals because the 0.6 volt threshold cuts off much of the waveform and distorts it severely. The good news about class C amplifiers is that they run at higher energy efficiency than a class A. 65% versus 30% is typical.

Quartz crystal oscillators - the key to modern frequency stability

Electronic wrist watches today use quartz crystals as the frequency standard that gives cheap everyday watches precision that rivals the old time mechanical chronometers that once were vital for navigation. Analog color TVs use crystals as a time standard so that the color separation can accurately separate red, blue, and green. Computers use crystals as clock standards so that modems will run accurately and remain in step with the sending station.

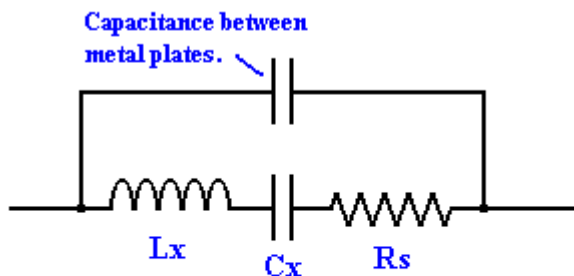
Quartz is a type of natural, crystalline, silicon dioxide glass. It is an extremely good insulator. Household glass is also mostly silicon dioxide, but the atoms are arranged in an amorphous structure, something like a random pile of bricks dumped from a truck. In contrast, quartz has a regular crystalline structure as though the bricks were neatly stacked in layers. The quartz is not perfectly pure, but contains ionized, contaminant atoms that are trapped in the crystal lattice. Notice that contaminant ions *do NOT* convert the quartz into a semi-conductor. Natural quartz from Brazil and a few other places occurs as large, clear crystals with sharp flat faces and uniform structure. This material can be cut and polished into thin, flat sheets that are cut up into tiny squares. Each square is then mounted between two metal plates as if they were building a simple capacitor with quartz glass as the insulator. Since WWII quartz for crystals is manufactured artificially in ovens.

When voltage is applied across the quartz, the charged metal ions contaminating the quartz are physically attracted to the charged plates as shown below. The thin quartz sheet literally bends back and forth as the voltage changes polarity. If the voltage is an RF voltage, the polarity changes back and forth millions of times per second and the crystal vibrates at that frequency.



When AC voltage is applied to a crystal, it vibrates most easily at a frequency proportional to the mass and physical dimensions of the quartz. In other words, each crystal can be fashioned to vibrate at a specific frequency. As you would expect, big thick crystals vibrate at low frequencies. Thin tiny quartz chips vibrate at high frequencies. Even though crystals oscillate at millions of vibrations per second, the vibration is mechanical and they resemble musical instruments. Just like musical instruments, crystals also have overtones or higher harmonic frequencies. Some crystals are designed to operate at the 3rd or 5th overtones, rather than the fundamental frequency. Overtone crystals can oscillate at frequencies as high as 100 MHz or more.

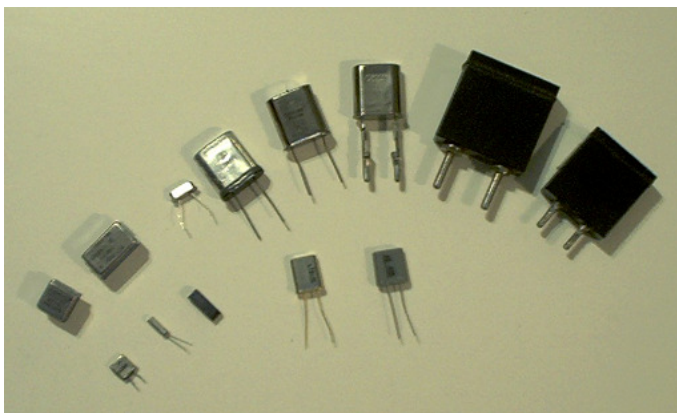
Although the oscillation is mechanical, it also acts as though it were oscillating electrically. Quartz crystals act like a series L-C circuit. They are equivalent to the L-C components we used to tune the crude oscillator above. The equivalent capacitance C_x and L_x



Series "equivalent" components are determined by the mechanical properties of the crystal.

Equivalent circuit of a crystal.

are completely dependent on the physical dimensions of the crystal wafer. Think of a quartz crystal as an extremely stable, L-C circuit. Since the crystal is constructed from two metal plates applied across the quartz, one can also say that the crystal has an element of parallel resonance as well as series resonance. The resistor R_s represents mechanical heating.



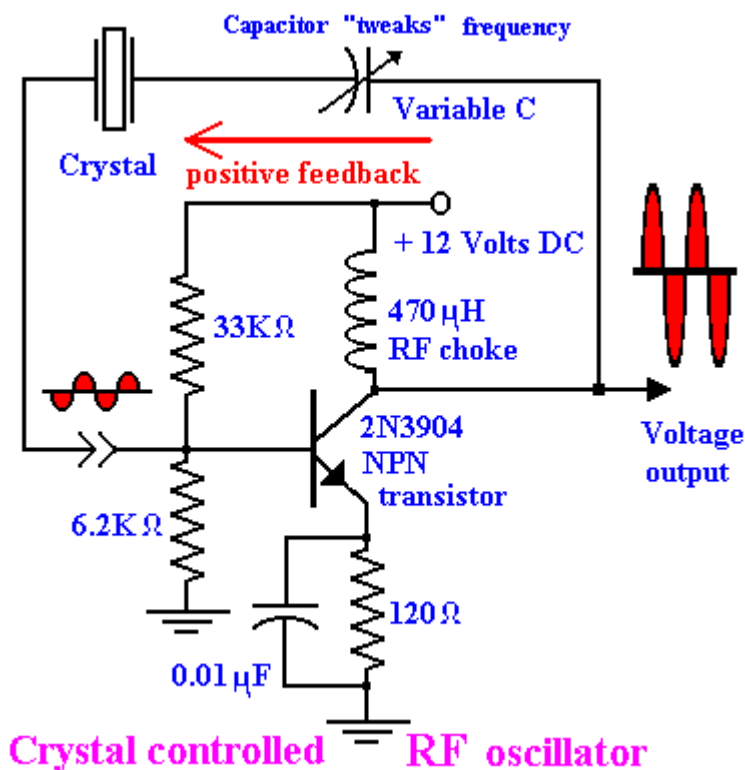
Typical crystals are shown below. Two large ancient, ham crystals are shown at the upper right. These can be good parts, provided they are still working after 50 or more years. Sometimes dead, ancient crystals in FT-243 holders can be taken

apart, cleaned with alcohol, and made to work again. Careful! The bare quartz wafer is quite fragile. But if the crystal was already inert, breaking it isn't a loss.

An assortment of quartz frequency control crystals

The three big silver-colored crystals in center rear are size HC-33 and are modern-manufactured, first-rate parts. The two medium size HC-49 crystals in the front center are microprocessor crystals. They are good parts, but often they aren't available for the exact frequency you happen to need. Sometimes it's necessary to order custom HC-49s from companies like International Crystal Manufacturing, Inc. (ICM) for about \$18 each. The little bitty crystals at the left front should be used with caution. Little crystals get warm easily and their frequencies drift. The square and rectangular "crystal blocks" at the extreme left are complete crystal controlled oscillators packaged in little cans. These are intended for computer work, not RF frequency control. So far, I have never encountered a crystal block oscillator that didn't run hot as a pistol and drift like crazy. Unless you've checked it out, **don't use an oscillator block!**

Common Crystal Oscillator Circuits



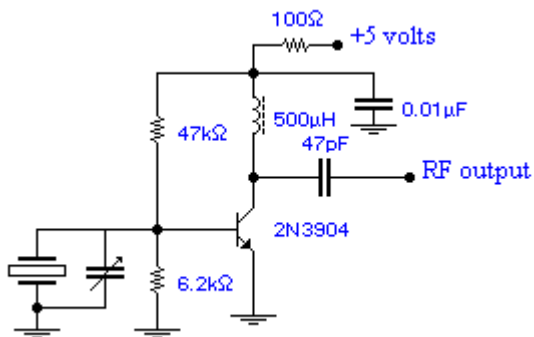
There must be a dozen or more transistor crystal oscillator circuits. The circuit on the left is practically the same as the crude LC oscillator illustrated earlier. The variable capacitor allows you to "tweak" the frequency a kilohertz or more above, on, or below the nominal frequency printed on the crystal case. The circuit above is useful and you will occasionally see it used in homebuilding projects. Yes, if you like, you can leave out the variable capacitor. However, it is not a good idea to put big sinewave voltages directly

on the crystal. For example, if you leave out the variable capacitor, the collector voltage will be directly on the crystal. Too much RF voltage on a crystal can heat it and cause frequency drift. Crystal heating will cause the oscillation frequency to begin dropping the moment you turn on the oscillator. In extreme cases, such as exposing the crystal to big voltages in a vacuum tube

oscillator, the voltage will literally crack it and ruin it. For these reasons, although this circuit is easy to explain, I rarely use it.

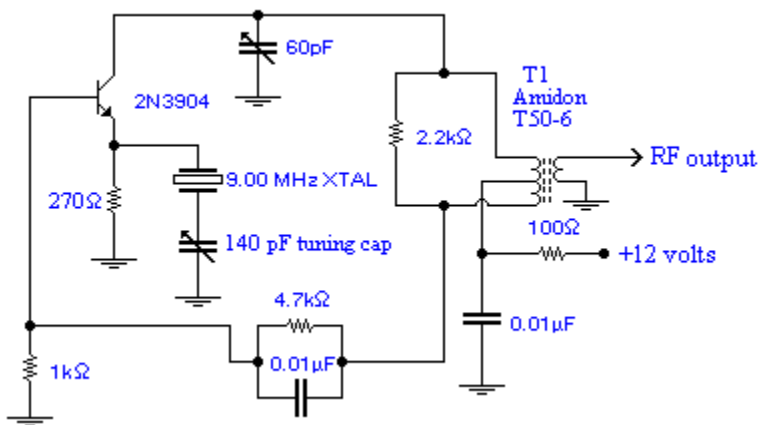
Series-cut and parallel-cut crystals

So called *series cut* crystals are designed for use with a capacitor in series with the crystal as shown above. This means that when the series-cut crystal has a specified size of capacitor in series, the crystal will oscillate at the exact frequency on the label. Otherwise, it might be a kilohertz off or more. Similarly, *parallel-cut* crystals are labeled to operate with a specific parallel capacitance as shown below.



The oscillator shown on the left has the crystal connected to the base of the transistor. A variable capacitor is connected in parallel with the crystal. Again, when you first turn on the oscillator, the exact oscillator frequency may be hundreds or even thousands of Hertz off the nominal frequency. By adjusting the capacitor, the oscillation can be the exact frequency you need.

Butler is better



I checked out every oscillator in my receiver and transmitter and discovered that some of them didn't have the warm-up drift when turned on. The stable ones were Butler oscillators as shown on the left. Notice that *the crystal and its capacitor are in parallel with the emitter resistor*. I don't really know why, but this circuit is stable the moment it is turned on.

A Butler crystal oscillator

Maybe it's because the crystal just shunts the emitter resistor so the crystal voltage is low and it receives little heat energy. Anyway, Butlers typically drift no more than a hertz or two per minute. Two of my oscillators showed zero Hertz drift during the first minute. One of them, my receiver BFO shown above, was on the same Hertz a half hour later!! Now that's what crystal control is supposed to be like. Also, it wasn't necessary to put these oscillators in heavy-walled, sealed metal boxes. Even built on an exposed board out in the breezes, they are impressively stable.

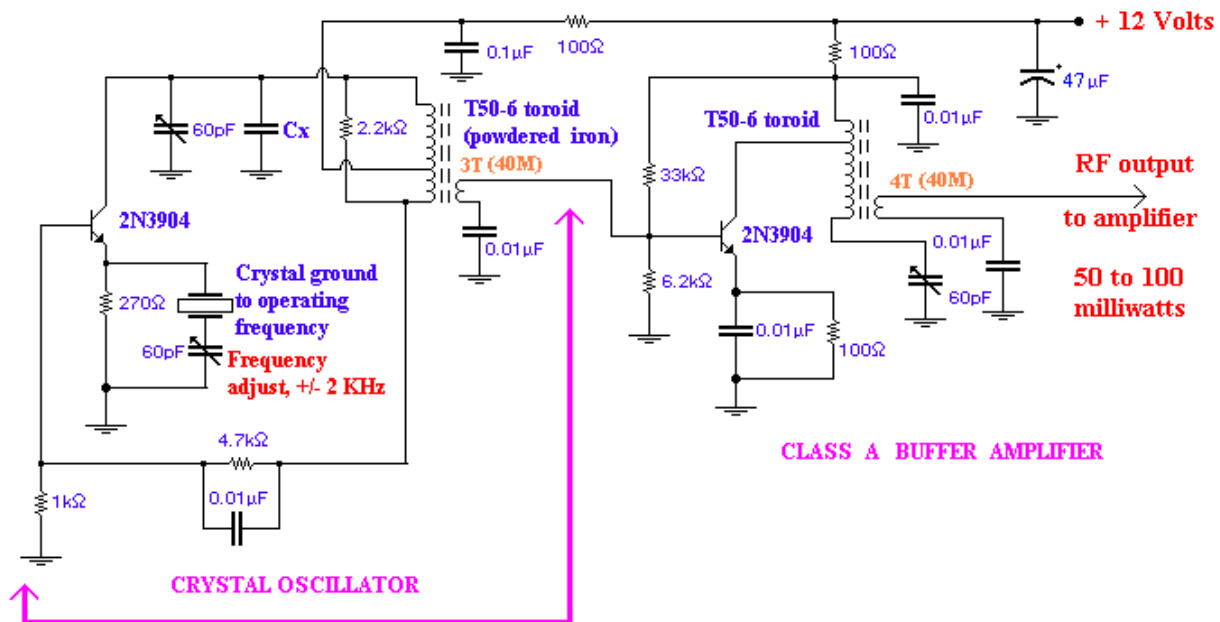
On high frequencies, like 30 MHz, the circuit as shown above may not oscillate right away. If you're sure it's wired right and has 12 volts applied to it, then try increasing the 270 ohm resistor to 470 ohms. If the output is too weak, sometimes it can be increased by lowering the same 270 ohm resistor to say, 150 ohms. Also, big crystals tend to put out much larger signals than small ones.

Depending on your application, the Butler also has the advantage that the auxiliary tuning capacitor can pull the frequency lower than the base-connected oscillator shown earlier. I studied the oscillator circuits in my ARRL annual handbooks. In one of the examples of a modern commercial transceiver in the 1998 handbook there was a version of the Butler oscillator. These oscillators were touted as "low phase noise" but the low initial drift advantage wasn't mentioned.

Most modern equipment use anonymous integrated circuit (IC) oscillators, like "NE602." Among other circuit blocks, these ICs contain oscillators. To wire it, the crystal is just connected to pins on the little square package. Heaven only knows what's in there! I guess only we homebrewers care.

The 40 meter QRP circuit

The circuit shown below is the core of the QRP transmitter. The crystal oscillator on the left is a butler oscillator. The transistor RF amplifier on the right is similar to the example shown earlier, but is tuned with an L-C circuit for a specific band. Also, its output is a transformer winding that "matches" the high impedance output (roughly 600 ohms) to a 50 ohm dipole antenna.



The Crystal Oscillator and Buffer

The diagram above shows oscillator and buffer stages for the QRP. This circuit puts out

about 1/8 watt and could be used directly. Of course, you'd have to have a terrific antenna for anyone to hear you. How much power you get from this circuit depends on the crystal you use. I used a big, new, size HC-33 that worked so well, that instead of 5 watts, my QRP (including the final amplifiers described below) put out 15 watts with 12 volts on the power supply. Oops! When I run it on 6 fresh flashlight batteries (9 volts) it puts out about 7 watts.

The Butler oscillator circuit comes from a receiver project in the 1986 ARRL handbook and I've used it successfully many times. The tuned amplifier-buffer is part of a QRP design in the 1979 handbook. This basic amplifier circuit gives high voltage gain and can also serve as a tuned, active filter. Or, when it's coupled to a low impedance secondary, as it is here, it works as a power gain stage.

Building this QRP is really several small projects. Build the oscillator and get it working before you build the buffer amplifier. The important thing is that it works, not beauty or compact size. When building a project, use circuits you understand and parts you can get.

The diagram above doesn't include a detailed parts list. Parts lists are nice, but only if you can actually buy those exact parts. Manufacturers and distributors change every year and listing specific manufacturers will only frustrate you. The inductor cores are the only critical part. They should be powdered iron and designed for approximately the right frequency range. To work with a brand like Amidon (CWS Bytemark), Micrometals, or Fairrite, you need the A_L inductance value so you may calculate the number of turns. This process is explained later in this chapter.

Inductor specifications for the QRP oscillator

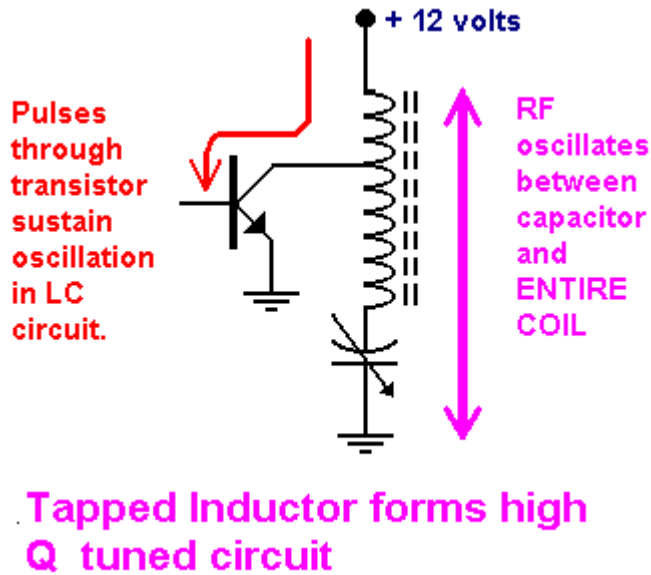
Band	Toroid type	Primary turns	Secondary turns
80 Meters	T50- 15	41 turns, tapped 1/3	4 turns & 5 turns
40 Meters	T50- 15	30 turns, tapped 1/3	3 turns & 4 turns as shown.
	Or, T50- 2	51 turns, tapped 1/3	5 turns & 7 turns
30 Meters	T50- 6	36 turns, tapped 1/3	7 turns & 9 turns
20 Meters	T50- 6	28 turns, tapped 1/3	3 turns & 4 turns
17 Meters	T50- 6	22 turns, tapped 1/3	3 turns & 5 turns
15 Meters	T50- 6	22 turns, tapped 1/3	3 turns & 4 turns
12 Meters	T50- 6	16 turns, tapped 1/3	3 turns & 3 turns
10 Meters	T50- 6	16 turns, tapped 1/3	3 turns & 3 turns

Turns are NOT critical – if it tunes up well in the center of the variable capacitor range, that's the right number. (The toroids are CWS Bytemark, formerly Amidon)

Tapped toroid inductors

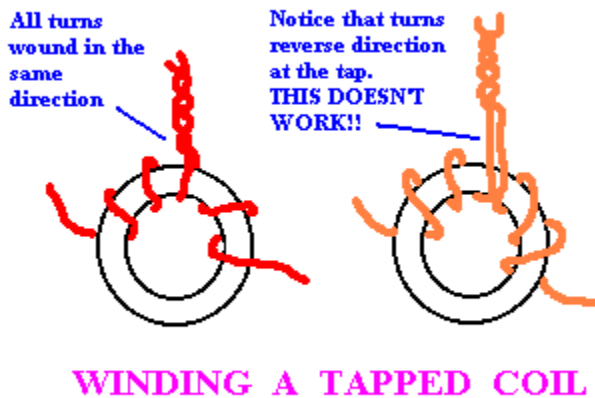
The crystal oscillator and following tuned amplifier stages of this QRP transmitter use tapped coils for the primary windings of the output transformers. The tap is 1/3 of the way from the power supply end of the coil. The DC current from the 12 volt source flows into the primary

winding, then after 1/3 of coils, it leaves through the tap and enters the transistor which turns on every half cycle and shunts the current to ground. The opposite end of the primary winding is connected to the variable capacitor making a resonant LC circuit. At this end of the winding there is no exit for DC current. So 2/3 of the coil is only used for resonant “ringing” of RF currents. That is, most of the inductor is devoted to oscillating at a tuned frequency.



Short pulses of DC current through the 1/3 end of the coil serve to prime the oscillation and keep it going. It is comparable to an adult pushing a child on a swing. The adult only pushes briefly at one end of the arc of the swing. The pendulum system of the swing does most of the oscillating, not the adult. This tapped coil makes the oscillations much larger than they would be if the winding weren't tapped. Also, the oscillation is much more confined to a specific frequency. In other words, the “Q” or quality of the resonant circuit is higher.

A mistake you might make



The drawing on the left shows the right way and wrong way to wind a tapped inductor. A tapped inductor is supposed to be a single coil that has an external wire connected to some spot along the coil. In other words, the coil must be wound from beginning to end in the same direction. In the drawing above, the correct tapped coil has three turns wound in one direction, then three more turns wound in the same direction. If the coil winding direction reverses at the tap, the inductance of the first half of the

coil will cancel out by the inductance of the second half. In other words, the device on the right has no inductance at all! The device on the right isn't even an inductor, it is just a “wire.”

Q = equals quality

Inductors and capacitors have a quality factor called “Q.” It is defined as the reactance of the device, X, divided by the resistance of the device, R. *Reactance is the property of capacitors and inductors that resists the flow of AC current and acts like a resistor.* Inductors are made

from lengths of copper wire wound into a coil. Because of the resistance of the copper metal, the resistance of inductors wound with fine wire and many turns can be significant, even without the reactance component. Therefore, inductors are sometimes “low Q.” In contrast, the resistance of the short wires in capacitors is rarely significant, so capacitors are almost always “high Q.” In large capacitors that have dielectric plastic (or electrolytic) insulation between the plates, this insulation dissipates energy and appears as a “resistance” and lowers the Q.

Frequency multipliers

By the way, the tapped coil amplifier can also be used as a frequency multiplier. Frequency multipliers can be explained by the adult-pushing-the-kid-on-the-swing analogy. Instead of the adult giving the swing a push with every cycle, suppose the adult only pushes every other cycle or every 3rd or 4th cycle. In this way the frequency of the pushes can be some fraction of the natural frequency of the swing. Notice that the frequency of the kid's motion on the swing depends on the length of the swinging pendulum and has little to do with the frequency of the adult pushing. In other words, the length of the pendulum must be "tuned" to the frequency of the pushes. Or, the push frequency can be tuned to the swing frequency or an even fraction of the swing frequency.

For example, let's apply a 7 MHz sinewave to the input. Now suppose the LC circuit is tuned to 14 or 21 MHz. While the amplifier is running, your scope will reveal a 7 MHz sinewave on the transistor collector. Meanwhile, the whole coil and capacitor will be oscillating at the multiple of the frequency of the input determined by the LC circuit. To make use of the higher frequency, tap into it with a tiny capacitor, like 2 pF, between the coil and the trimmer capacitor. A bigger capacitor will tend to load the ringing LC circuit too much and kill the oscillation. Alternatively, the higher frequency oscillation can be sampled with a one or two turn secondary winding wrapped around the primary coil.

If inductive and capacitive resistance is called “reactance,” what’s impedance?

Impedance is the sum or total result of all the reactances and resistances in a circuit. When we say a circuit has an impedance of “100 ohms,” we are saying that every component in the circuit works together to behave like a 100 ohm resistor *at that particular frequency*. For example, as mentioned earlier, most ham antennas, receivers, and transmitters are designed to work with 50 ohm impedance loads.

Impedance matching

If you wish to transfer power from one circuit to another and you don't have a perfect voltage source, then you can transmit the most power if you “match” the impedance of the load with the internal impedance of the voltage source. In other words, real voltage sources always have internal resistance that limits how much energy you can suck out of the source. For example, a fresh battery has low internal impedance. In contrast, a dead battery (usually) has the same chemically generated voltage, but when the battery is exhausted, there is now a huge resistance in series with the voltage. This limits you to very little power that can be drawn out of the battery. However, even with a nearly dead battery, you can always maximize the power transfer by matching the load resistance to the internal resistance, no matter how high it may be.

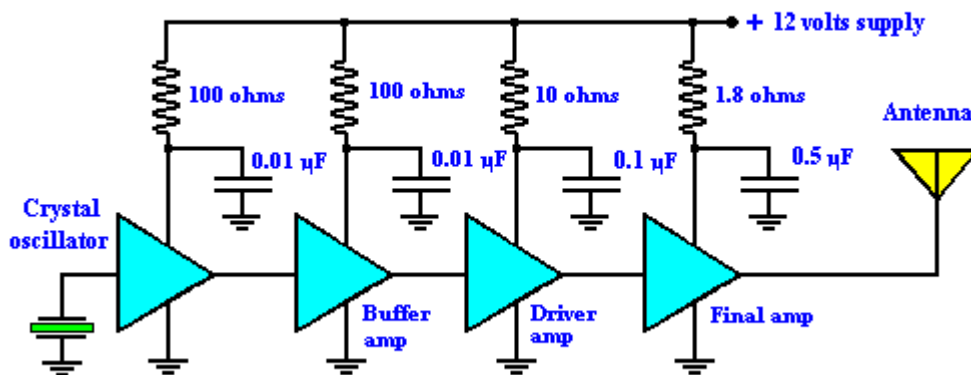
The buffer stage and power supply decoupling

A **buffer amplifier** follows the oscillator. The purpose of a buffer is to isolate the oscillator from the final amplifier(s) as well as amplify the oscillator signal. Although it makes no intuitive sense, changes on the output load of an amplifier can couple back to the input of the amplifier and affect the oscillator. This feedback makes subtle changes in the frequency of the oscillator and contributes to **chirp**. Chirp is a change in tone of the Morse code that makes it sound like a bird. One way to decrease chirp is to add a buffer amplifier between the oscillator and final amplifiers.

Ideally, all “communication” between one amplifier and the next is through the intended path between the output transformer and the base of the next stage. Unfortunately, other ways amplifiers “talk” to each other can be through the power supply or even through skinny ground traces. You can minimize the ground communication by using large ground traces or by soldering feed-through ground points through the PC board to the unbroken grounded copper sheet on the far side.

Power supply communication is more difficult. Suppose a big sinewave signal is being generated in a final amplifier. As the current rises through the large output transistor, this big current loads down the power supply voltage and can cause it to drop. The amplifier driving the final then loses some of its supply voltage, just when it needs to supply the rising current. The result of this interaction is that the sinewave can jitter and become unstable. On an oscilloscope the sinewave loses its focus and becomes blurry. A frequency counter will usually read below the crystal frequency and will be unstable. This instability can be greatly improved by decoupling each stage as shown below:

RC Power Supply Decoupling



The resistor / capacitor feeding each stage slows the changes in the power supply voltage, RF cycle by cycle. That is, the R-C time constant of each network should be much longer than the variations in the power supply voltage.

R-C time constant is just **resistance times capacitance = time constant in seconds**

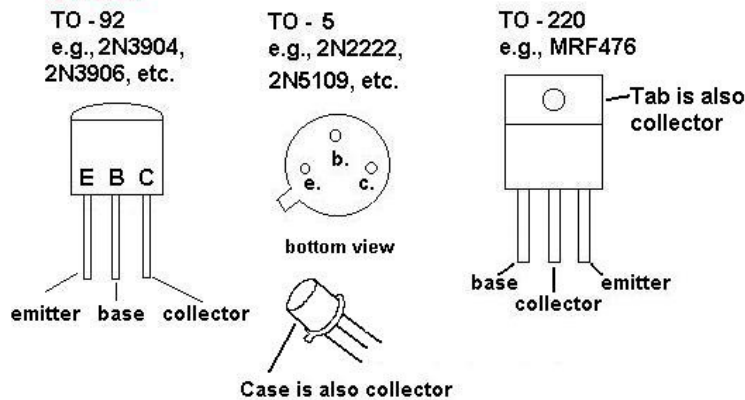
e.g., 1.8 ohms X 0.5×10^{-6} farads = 0.9 microseconds

This limits the voltage change to the output stage much slower than an RF cycle. That is, $1/0.9 \mu \text{ sec} = 1.1 \text{ MHz}$

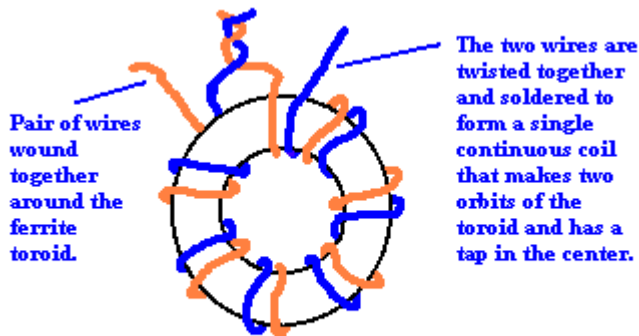
with 27 turns on the primary, you can (barely) cover 20 to 10 meters. Make the tap about 1/3 of the total number of turns, or about 9 turns in this case. The secondary would be about 6 turns. The input of a transistor amplifier is usually a low impedance. Therefore the transformer lowers the voltage and raises the current to “match” the impedance.

The buffer that follows the oscillator circuit is **Class A** because it’s biased “on” with the 33K resistor. The emitter R-C circuit keeps the class A amplifier stable so it won’t run away when the temperature rises. Class A is best when the signal levels are small. In the two amplifiers above, the first (tuned) amplifier runs **Class C**. This means that the input voltage swing must be far larger than the base offset voltage, 0.6 volts. This Class C runs at relatively high power levels, so you’ll need a bigger transistor, 2N3053, 2N2222 or equivalent. This moderate power transistor has a metal case like a tiny tin can to help conduct away the heat. Moreover, a “top hat” heatsink should be clipped onto this transistor to help radiate the heat. Look in your catalogs under heatsinks and you should find a large assortment.

COMMON BIPOLAR TRANSISTOR CASES



Bifilar wound transformers



BIFILAR WOUND TRANSFORMER

The transformer for the broadband final amplifier stage is a “bifilar wound” transformer. This broadband transformer is untuned and will work on ANY HF hamband. The toroid core is an Amidon T50-61 ferrite instead of powdered iron. The ferrite provides much higher inductance than you would obtain if the same coil were wound on powdered iron cores, such as the T50-6. That is, the A_L factor is much larger for a

ferrite core. The high inductance means that the input signal to the transformer will be passed along to the output before the inductor has a chance to charge. There is nothing resonant about

this transformer.

Although the transformer is wound with two parallel wires, the two wires are soldered together to make one winding that orbits the toroid twice. Bifilar wound transformers are a kind of tapped coil. As a result, the impedance (voltage) can be stepped up or down by connecting the output to either all of the coil for high voltage, or just half of the coil to step down.

Before you wind one of these coils, examine the drawing extremely carefully. It works only when wound exactly as drawn. This is really easy to screw up! *If you connect one of the wires to itself, that wire becomes a shorted turn that will dissipate most of your RF energy.* Before you solder your bifilar into a circuit, use an ohmmeter to confirm that all three terminals have zero ohms between them. If you find that the "centertap" is an open circuit with respect to the other two wires, you have connected it wrong. I have made this error twice and wasted considerable time finding it.

Tuned amplifiers versus broadband amplifiers

The QRP described above uses two amplifier stages that are tuned by trimmer capacitors and a broadband final amplifier that needs no tuning. Tuned amplifiers almost always work – that's a big advantage! A disadvantage of tuned amplifiers is that the tuning can be critical and may not cover the entire band. Tuning all the stages in a transmitter turns out to be a bad idea. As my car battery power supply discharged, sometimes my signal would "crash" halfway through a QSO. On the scope I could see a sudden loss of amplitude on the output and distortion would appear in the sinewave. My contact would say, "You're signal is breaking up."

Another advantage of tuned stages is that, when you tune up one stage, by subtle shift in the sinewave phase, you're also adjusting impedance matches in the following stages. It works much like an antenna coupler matching an antenna. I confess I don't fully understand this, but the phenomenon is real and useful.

Noise mode

In contrast, broadband amplifiers just pass along whatever signal they receive. So, if you build all your stages as broadband amplifiers wired in series, they won't work unless you've done a wonderful job of matching impedances at every stage. When a broadband amplifier is mismatched, it goes into "noise mode." That is, you put a sinewave into the input and the amplifier puts out a blast of noise that contains only a ghost of the sinewave you hoped to amplify. If you don't have at least one tuned stage in your QRP, you'll have nothing to adjust when the final goes into noise mode.

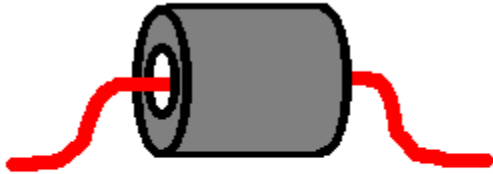
The output stage in the QRP is a broadband amplifier that uses a five-element Chebyshev filter to suppress high frequency harmonics in the output. Chebyshevs are described in detail below. The filter component values can be found in tables and formulas in an ARRL Handbook, e.g., 1986 or later. This broadband amplifier is a universal circuit you may add to your bag of tricks. For example, in my ten meter QRP board I used two broadband stages in series to increase power from 2 to 9 watts. The first broadband stage used a 2N3053 and it didn't need its own Chebyshev filter.

Expensive RF transistors

The final amplifier uses a Motorola MRF-476 transistor. They are pricey, \$13 or more.

According to the RF Parts Co. 2006 catalog, the type 2CS2166 is direct replacement for the MRF-476 and costs only \$1.95. I haven't tried any, so I can't vouch for this. There must be hundreds of cheap transistors that can put out 5 or 10 watts at HF frequencies. Unfortunately, the cheap transistors I have actually tried needed 24 to 80 volts collector supply voltage to deliver the same power. The virtue of Motorola "MRFs" for HF seems to be that they deliver big power with a 12 volt supply. To me it was worth the cost.

Ferrite bead RF chokes



FERRITE BEAD RF CHOKE

Notice the bead RF choke on the MRF-476 base. It's just a short piece of wire through a big ferrite iron bead. This eliminates low frequencies from the output and turns a "roller coaster," chaotic output waveform into a clean sinewave. This simple component looks as though it would act as a short circuit to ground. But even if you run the amplifier on a low frequency like 80 meters, the bead is vital and doesn't reduce output power. If this sounds illogical

to you, unsolder the choke and look at your waveform.

**

CAPACITORS

Capacitors are rarely a problem

In contrast to inductors, capacitors are rarely a problem. If the label on the capacitor says 330 picofards, that's probably what it is. Small mica capacitors are often labeled with 3 numbers. The last number is the number of zeros following the first two digits. For example, a 330 picofarad capacitor would be labeled "331." 33 picofarads has no zeros so it would be "330" which is confusing. If the label is puzzling, a capacitance meter usually tells you everything you need to know about the unlabeled capacitor in your junk box.

Electrolytic capacitors can be a little tricky. Those are the caps with the plus and minus labels on the leads. You have to orient them with the correct polarity. The positive end must be aligned with the positive voltage in your circuit. Also, there are a few rules about what kind to use where. Aluminum electrolytics have large capacitances and are often used to stabilize power supplies. They are packaged in little plastic-coated aluminum cans and have + marked on the positive lead. They do not conduct RF particularly well so it may sometimes be advisable to shunt an aluminum electrolytic cap with a ceramic or mica RF bypass.

Tantalum electrolytics have the largest capacitances relative to their small physical size. They are usually packaged in tiny plastic rectangular blocks or blobs of colored epoxy. Again, they have plus and minus lines on them to indicate polarity. Sometimes the positive is just marked with a dot of colored paint. They conduct RF well. That is, they make good RF bypass capacitors as well as low frequency ripple stabilizers. On the other hand, tantalums have low

voltage ratings and you should not place them directly across a battery. Sudden rises in voltage across a tantalum can cause it to break down and burst into flames. For example, I once designed a battery-powered circuit with a 10 volt rated tantalum wired across a 9 volt battery. It wasn't long before I had a charred capacitor and circuit board.

CONQUERING INDUCTORS

Inductors are often the problem

As you gather parts for the above QRP transmitter or any typical ham project, you may discover that the hardest parts to locate are the inductors. “Where do I buy a Miller # 233 anyway?” Or, maybe the parts list says, “6 turns on a Stackpole 4-12 toroid core.” Who sells Stackpole cores? Where do I get a catalog? Then you think, “I know what to do! I’ve got an iron core-thing that LOOKS just like the picture. I’ll use that!” With this optimism you are well on your way to building a useless piece of junk destined for your attic. All of us who have wound inductors have wished our multimeters had “inductance scales.” Sorry. Handheld inductance meters barely exist. And if you have one, it probably won’t tell you much about core losses, leakage inductance, saturation, and winding resistance.

A little math is as good as an inductance meter

Normal humans hate mathematics. However, simple calculations and toroid cores with known characteristics are a tool that let you wind the exact inductor you need. Your LC circuits will resonate in the right band, your filters will attenuate and pass the right frequencies, and your equipment will work! The ability to wind the right inductance is a vital skill.

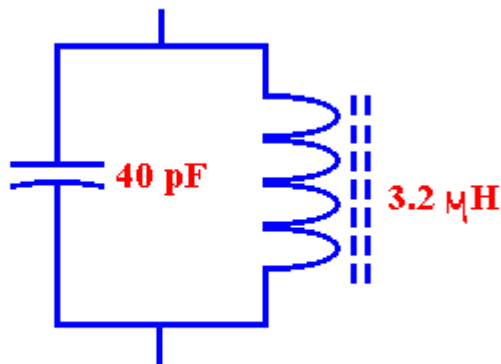
LC circuits. What size inductor do I need?

Radio technology is based on LC circuits. Sure, some circuits use piezo devices like crystals and “SAWs” that only *act* like LC circuits. But they are LC circuits none-the-less. The C part is easy enough. Just pick a capacitor value. But how big does the inductor need to be?

$$\omega^2 = 1/LC \quad \text{where } \omega = 2\pi \text{ (frequency in Hertz)}$$

L = inductance in Henries.

C = capacitance in Farads.



20 Meter RESONANT CIRCUIT

Suppose you’re building a transistor amplifier stage that has an LC resonant tank circuit. Your trimmer capacitor has a range of 5 to 60 picofarads. You need an inductor that resonates with that capacitor. Let’s say the band is 20 meters, 14.1 MHz. We’ll design the inductor to resonate with say, 40 pF. That way, you can tweak the frequency if necessary.

Using the above formula:

$$[2 \times 3.1416 \times 14.1 \times 10^6 \text{ MHz}]^2 = 1 / (40 \times 10^{-12} \text{ Farads})(L)$$

Solving for L, $L = 3.18 \times 10^{-6}$ Henry or 3.18 microhenries.

Now that we know how big the inductor must be, we need to wind a coil on a toroid core.

Using CWS (Amidon) powdered iron cores

There are many quality brands of ferrite and powdered iron core toroids. I like CWS Bytemark cores (Formerly Amidon) simply because I know where to buy them. Go to www.bytemark.com or www.coilws.com. The important issue is that *the cores must have a known inductance factor, A_L* . A_L allows you can calculate how many turns you need for a given inductance.

Ferrite vs. powdered iron

Ferrite cores have high iron content and produce high inductance for a given number of turns. In ham projects, ferrite is usually used for inductors that are too large to charge significantly for several cycles of the design frequency. In other words, ferrites are used for RF chokes and waveform transformers. For example, the output transformers of *WIDEBAND* linear amplifiers are usually ferrites. The final amplifier of the QRP circuit above uses a T50-61 ferrite toroid. Ferrites are rarely if ever used for resonant, tuned LC circuits.

In contrast, powdered iron cores contain far less iron and more ceramic. They are used

for high-Q resonant circuits and filters. Notice the powdered iron cores are color coded for their permeability. In contrast, all the ferrites are just plain black, semi-shiny toroid cores.



First: Select the type and size of toroid core appropriate for the frequency and power level. There are several grades of powdered iron and ferrite cores that are designed for different frequency ranges. For resonant circuits or filters on the upper HF hambands, I usually *use type 6 powdered iron (color code yellow and black)*. For the lowest

HF hambands 80 and 160, I sometimes use type 2 (red/black) or type 15 (red/white). These give me more inductance for the same number of turns and allow me to use heavier gauge (lower resistance) wire. Type 17 powdered iron (yellow-blue) is useful for 30 MHz and above. Type 26 (yellow-white) cores are most useful for frequencies well below the ham bands. They are often found in switching power supplies.

The power level is proportional to the size of the toroid core. I've had bad luck with

little bitty size T-37 cores. They produce low gain and are hard to wind. Don't use them unless you are pressed for space. On the other hand, type T-50 works fine from receiver circuits up to a few watts in a QRP. Type T-68 is good for 10 watts or more. Type T106 and T200 handle 200 watts or more and are used for output filters in high power linear amplifiers.

Second: Calculate the number of turns needed for a given inductance. The wire size is simply the largest gauge that will fit conveniently in the toroid. Don't go nuts with thick wires. On the other hand, for low frequency, high inductance usually means many turns of wire. The coil will work best when you use the highest diameter wire that will fit in the core without overlapping the turns. For each core type, there is a constant, "A_L," that is proportional to the square of the number of turns.

The number of turns = 100 (Inductance in microhenries)/ A_L)^{1/2}

Suppose we are using a T-50 type 6 powdered iron core to design a 3.18 microhenry inductor:

The T-50-6 core has an inductance constant, A_L, equal to 40. Note that when calculating, the "micro" part isn't in the calculation. 3.18 microhenries is just "3.18."

$$\text{Number of turns} = 100 (3.18 / 40)^{1/2} = 28 \text{ turns.}$$

Note: a bracketed number to the power 1/2 is another way of writing "the square root of."

You should be able to get 28 turns of # 30 enameled magnet wire onto the core. If not, use a finer wire, say # 34. If the wire doesn't cover up most of the core, use a fatter wire, say # 26.

**

Calibrating the trimmer capacitors

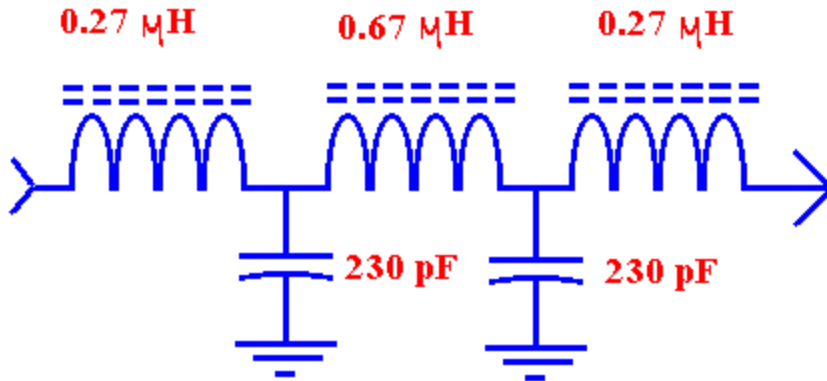
I used small, cylindrical variable "trimmer" capacitors to tune the first three stages of my QRP module. They are about the size of a grape and are adjusted with a small screwdriver. A problem with these devices is that you can't tell what capacitance they are set to by just looking at them. Since the adjustment screw goes around and around without stops, there is no way to know when they are at maximum or minimum.

Suppose you tune up an amplifier stage and you find that it produces the maximum signal at a certain setting. If you knew that this set point were the maximum capacitance point, you could guess that probably you need more capacitance to get the best performance. You could fix this by soldering a small capacitor, say 30 pF in parallel with the trimmer. Alternatively, you could add a few more turns to the inductor. On the other hand, if you knew that the best performance set point happened coincide with the minimum capacitance point, then you could conclude that the primary winding of the transformer probably has too many turns and needs to be reduced.

My solution is to measure the capacitor with a capacitance meter, then mark the minimum and maximum set points. With my ceramic trimmers, the maximum is 60 pF and minimum is about 7 pF. I use a fine felt-tip marker pen to indicate the maximum capacitance point. Minimum capacitance is 180 degrees from maximum. Ideally, when I have the amplifier tuned up for maximum signal, I will find that the screw is adjusted to roughly half of the capacitor's range. This means I have a good working amplifier stage and can't improve the LC circuit

further.

Chebyshev filters



20 Meter CHEBYSHEV FILTER

LC circuits are vital to *tuned* amplifier stages. But many modern amplifiers are *untuned* or *linear* and just need a filter to prevent harmonics above the transmitting frequency. The output stage of nearly every transistorized linear transmitter final has a 5-element filter to

prevent harmonics above the operating ham band. Your ARRL handbook has long, long, detailed explanations about designing different kinds of Chebyshevs. Most guys look at all those pages and think, “Like heck I’m going to figure out all that!” On the other hand, you usually just need a 5 element low pass and here is how you design it:

First: What operating impedance do you need? Let’s assume 50 ohms. That’s the most common.

Second: What frequency is it for? Let’s assume we want to attenuate everything above the 20-meter band. That is, 14.35 MHz.

Third: Calculate the “normalized” capacitance and inductance for the filter:

$$C_s = 1 / 2 \pi (Z) f$$

where $\pi = \text{pi}$, 3.1416, $Z = \text{impedance in ohms}$ and $f = \text{frequency}$

$$\text{Capacitance, } C_s = 1 / 2 \pi (50 \text{ ohms}) (14.35 \text{ MHz}) = 222 \text{ pF}$$

The normalized inductance is defined as:

$$L_s = Z / 2 \pi f$$

$$\text{Inductance, } L_s = 50 \text{ ohms} / 2 \pi (14.35 \text{ MHz}) = 0.55 \text{ microhenries } (\mu\text{H})$$

Fourth: Multiply the normalized C and L by the *design factors* for each of the five elements.

The values of the five elements are:

$$L1 = \mathbf{0.4869} L_s = (.4869) (0.55 \mu\text{H}) = 0.27 \mu\text{H}$$

$$C2 = \mathbf{1.05} C_s = 1.05 (222 \text{ pF}) = 230 \text{ pF}$$

$$L3 = \mathbf{1.226} \quad L_s = 1.226 (0.55 \mu\text{H}) = 0.67 \mu\text{H}$$

$$C4 = \mathbf{1.05} \quad C_s = 1.05 (222 \text{ pF}) = 230 \text{ pF}$$

$$L5 = \mathbf{0.4869} \quad L_s = (.4869) (0.55 \mu\text{H}) = 0.27 \mu\text{H}$$

For the capacitors, 220 pF (a standard value) will work just fine.

Heat sink for the output transistor

Use a big metal heat sink on your MRF-476 and keep it cool. I haven't damaged any, even with as much as 15 watts RF CW output. Notice that a bare MRF-476 is only rated at 3 watts dissipation. I use large aluminum heat-sinks made from 1" aluminum angle from the hardware store. The metal tab on the MRF-476 is the transistor collector and must be kept insulated from the grounded heat sink. I insulate the transistors from the aluminum with mica insulators. I use a film of silicon grease on the mica to improve heat conduction. Look for "transistor mounting kits" in your parts catalog index. The mounting hole for the MRF-476 is tapped into the aluminum with 4-40 thread so that no nut is needed.

Zener over-voltage protection for the output transistor

The 30 volt Zener helps protect your MRF-476 from open circuit operation. The Zener doesn't seem to be vital, but it doesn't hurt performance either. With these precautions I have found these transistors extremely hard to damage. However, the book does say 3 watts only, so try not to run them so hard or so continuously that they become too hot to touch.

Connectors for your QRP module

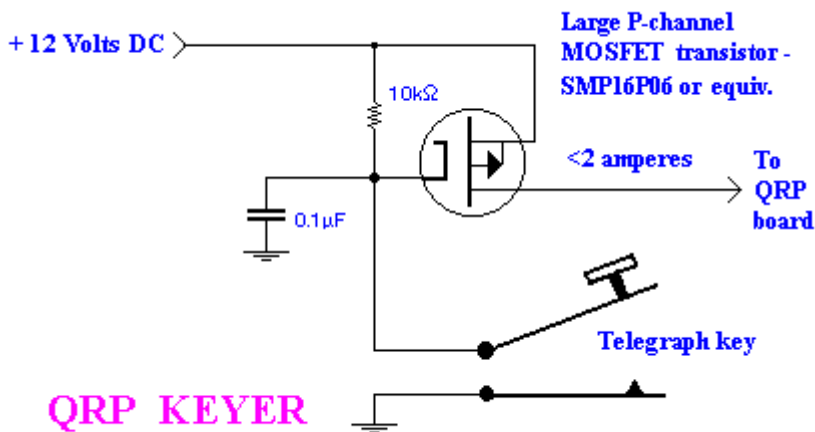
I use "RCA" audio phono plugs and coax for RF connections between HF modules. Yes, I should be using BNC or other connectors designed specifically for RF. However, phono plugs are cheap, easier to wire, and there seems to be no difference in performance, so long as the power level (current level) is under roughly 10 watts and frequency is below 30 MHz. After all, phono plugs only have twice as much capacitance (4 pF more) than an equal length of coax. 30 MHz is probably as high as one should go with phono jacks, especially at high power levels. Small card edge connectors are another way to snap PC board modules together. For example, I use PC board card edge connectors for plug-in Chebyshev filters so I can change bands easily. You don't need gold-plated card edge fingers. However, you should use wide traces and connect several pins in parallel wherever you're worried about keeping inductance or contact resistance low.

Keying CW Transmitters

Some QRP designs put the telegraph key in series with the emitter of a transistor amplifier stage just before the final amplifier. To transmit, the key is pressed connecting the emitter to ground. When the operator wants to "spot" his signal to find out where the transmitter is with respect to a station, he or she turns on the power supply, but doesn't key the transmitter. Without drive to the final, the oscillator and first buffer stage deliver a loud (but not overwhelming) signal to the receiver.

Supposedly, an amplifier with no emitter current or no base drive won't produce a signal. That sounds right and in the old days it worked OK with tubes. Unfortunately, in my basement the transistors don't care and deliver RF anyway. The capacitor across the key and even the capacitance in the coax going to the key provide enough AC current to produce drive through the emitter to deliver drive to the output stage. All I ever achieved with emitter keying was to lower the signal amplitude between the dots and dashes. If you just key the oscillator and leave the other stages active, that works fine as long as the oscillator is completely controlling them. Unfortunately, when you let up the key, the following stages will often self-oscillate at whatever frequency they please.

A P-Channel MOSFET Keys the DC Power Supply



I like to key the transmitter by keying the entire power supply on and off. This circuit is not elegant, but it works. For micropower QRPs, like homebrew transmitters in Altoids boxes and sardine cans, I notice they just put the key in series with the supply. Keying the battery directly works, but for keying 5 or more watts

of DC power, it's better for the key contacts to switch the current with a solid-state (transistor) switch. I use a P-Channel power MOSFET as shown above. The resistor and capacitor in the gate circuit soften (extend) the turn-off time to prevent key click.

David, VK6DI, pointed out to me that my circuit shorts out the charge in the capacitor thereby turning the 12 volt signal on abruptly. I agree with him when he says this *should* cause key clicks. As he points out, I could slow the turn-on by putting a small resistor in series with the key. It must be small, like less than 1K so the gate turn on voltage will charge to be nearly 12 volts. Or better yet, we could put another cap across the 10 K resistor. These steps may be "gilding the lily." The above circuit has worked well for me. Perhaps it is the relatively slowly charging capacitors in the rest of the transmitter circuitry that soften the turn-on time and prevent key clicks. He also suggested keying with an operational amplifier to turn the transistor on and off gradually. He also suggest saving money by using bipolar transistors instead of MOSFET. Those ideas all sound good to me, but I haven't tried them.

One of the mysteries of CW transmitters is that producing good-sounding CW with a vacuum tube circuit is harder than with transistors. I had lots complaints about my vacuum tube key clicks and chirp. (See chapter 14.) But in my experience, avoiding clicks and chirps with transistors has been much easier.

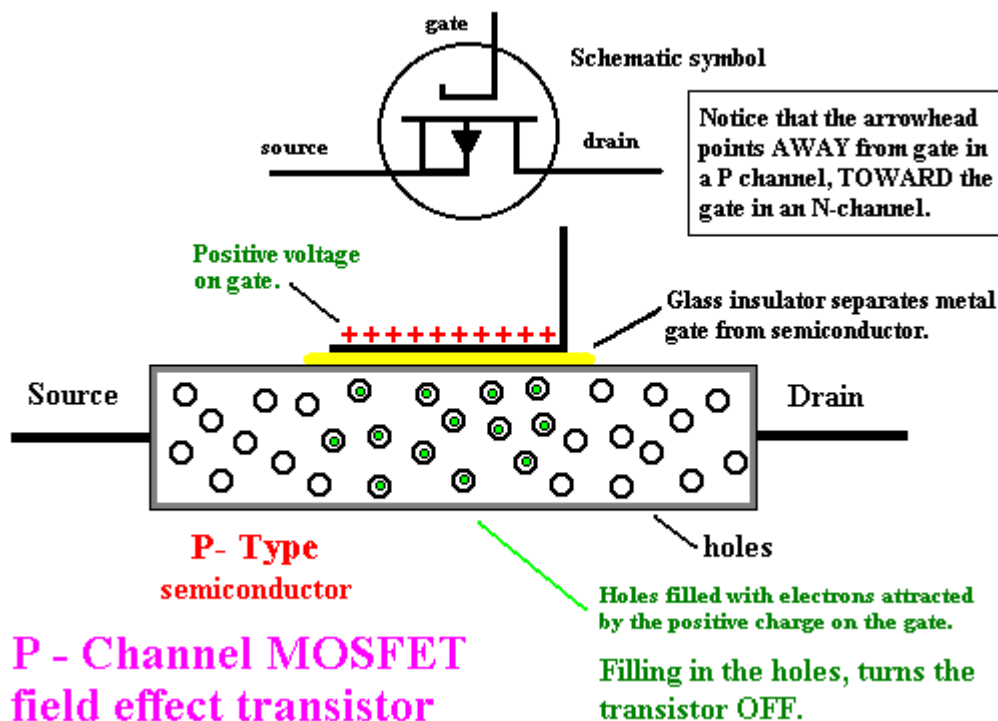
If you have any doubts about the sound of your signal, listen to it in a quality receiver

with the receiver antenna input shorted and the RF gain turned way down. This will simulate how your signal will sound from hundreds or thousands of miles away. Chirps, clicks or power supply noise on your signal will be obvious.

**

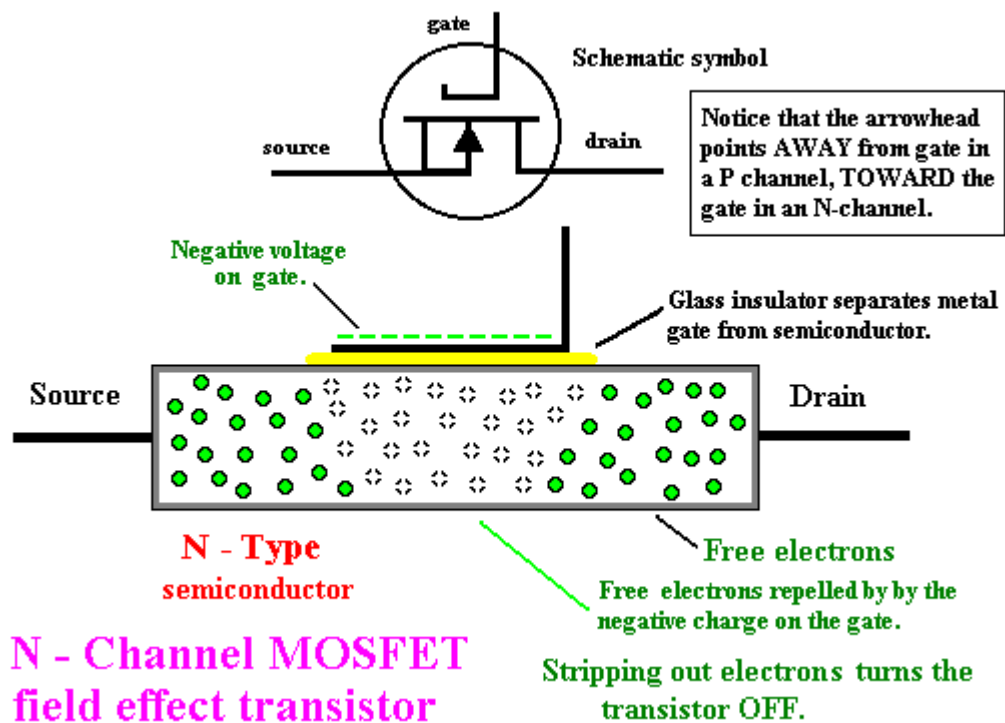
MOSFET field effect transistors

What is that weird transistor called “MOSFET,” you ask? Metal Oxide Semiconductor Field Effect Transistors work differently than the bipolar transistor you met in chapter 4. Fortunately, they are easy to understand. A MOSFET transistor consists of a piece of either P or N-type semiconductor mated to a capacitor. The semiconductor strip or layer is necked down in the middle so that the center is very narrow. The narrow region also serves as one of the two conductive plates that make up the capacitor. The other plate of the capacitor is the metal control gate. The gate is insulated from the transistor by a thin film of glass. The control gate is analogous to the base of a bipolar transistor. When voltage is applied to the capacitor, (that is, applied between the control gate and the piece of semiconductor), charge gathers on the conductive surfaces around the gate insulator. When charge gathers in the semiconductor, it changes the ion density in the semiconductor and changes its conductivity.



N-channel MOSFET

Just like bipolar transistors, a complementary version that works with the opposite polarities can be made by replacing the P-type semiconductor with N-type.



Depletion-type and Enhancement-type MOSFETs

A simple MOSFET, like the one diagrammed above, is normally turned about half on. That is, when the gate voltage is zero, the transistor has a significant resistance, perhaps 300 ohms. This type of MOSFET is called a *depletion-type*. When one polarity of gate voltage is applied, the transistor turns full on. When the other polarity is applied, all the holes are filled in or all the free electrons are drawn out and the transistor becomes an insulator. That is, if the semiconductor is N-type, the extra electrons are pulled out of the crystal and the crystal becomes an insulator. Depletion MOSFETs are usually used in low power receiver applications.

Enhancement type MOSFETs

Enhancement type MOSFETs have been cleverly designed to be more convenient for typical power applications. When the gate voltage is zero with respect to the lead attached to the transistor semiconductor called “the source,” the enhancement MOSFET is turned off. The SMP16P06 or the IRF9541 P-channel MOSFETs used in this book are enhancement types. This means that when the telegraph key is open, the QRP is fully off. Then when the key is depressed, the MOSFET turns full on and turns on the QRP. Power MOSFETs like these are also equipped with an internal diode to protect the transistor from being used with the wrong polarity. When the MOSFET is correctly biased, the protection diode looks like an open circuit and doesn’t interfere. But if the polarity is reversed, such as when it is exposed to a ringing inductor, the diode turns on and shorts out the piece of semiconductor and protects it from being fried.

Compared to bipolar transistors, MOSFETs have two major advantages:

1. There are no PN junctions in a MOSFET. This means that there is no PN junction to breakdown and no PN junction to cause temperature sensitivity. Because big MOSFET

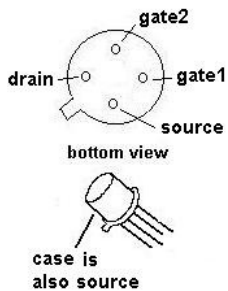
transistors are hard to break, they are often the best choice in high power applications.

2. MOSFETs are a voltage-controlled device. Once a voltage is established on the gate, no current is required to maintain the ON state of the transistor. MOSFETs are often ideal for power supply applications and switching big DC currents. And, they can be used for high powered audio amplifiers. Power MOSFETs, like the P-channel used to key the QRP transmitter, aren't so well suited for use as a high frequency (RF) power amplifier. The capacitor input means that every time the input voltage changes, the capacitor input must be charged or discharged. For very high frequencies, the driving circuit needs to stuff current into the gate and pull it out tens of millions times per second. This makes driving a power MOSFET like the one above impractical for high power radio frequency transmitters.

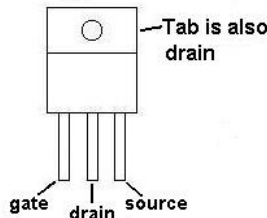
For example, from time to time QST ham magazine has had transmitter plans using high power MOSFETs for 20 to 50 watt transmitters. The catch was, they didn't recommend them for hambands higher than about 40 meters. Above that frequency, the power needed to develop the drive current had to be so high, that the driver power began to be similar to the output power. In recent years however, special RF MOSFETs have been developed that can be used for transmitters running at hundreds of megahertz. However they are quite pricey and I haven't seen hamband transmitter designs using them.

MOSFET TRANSISTOR CASES

DUAL GATE MOSFET
TO - 72 CASE
e.g., NTE454, NTE 221, etc.



MOSFET POWER SWITCH
TO - 220 CASE
e.g., IRF9140, SMP20P10,
MTH25P05, etc.



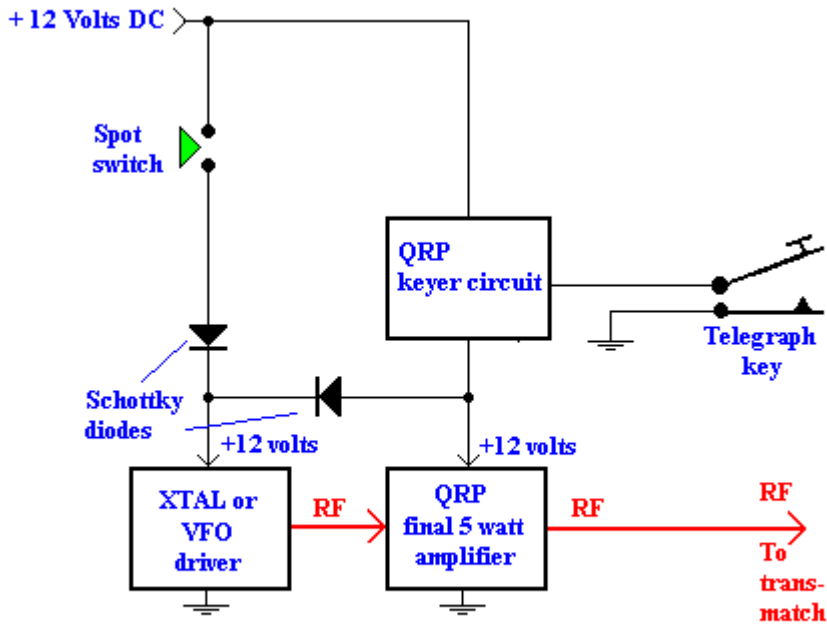
Power enhancement MOSFETs made by different companies have various designs that make them more rugged, handle larger currents, work at high frequencies, and dissipate more waste heat. Names like HEXFETs and V-MOS are examples of sophisticated power MOSFET designs. Dual gate MOSFETs are used to make mixers, product-detectors and RF amplifiers in receivers. As the name implies, they have two control gates instead of one. They will be discussed in chapters 7 and 13.

*

SPOT SWITCHES

Suppose you hear another ham calling CQ and you'd like to answer him. How can you tell whether your crystal and variable capacitor can reach his frequency? The answer is a "spot switch." The idea is to turn on the oscillator so you can hear your own transmitter in the receiver, but your signal will not be broadcast until you are ready to call the station. Using the spot switch, you turn on the oscillator and maybe the buffer, but not the amplifiers. This is done by separating the +12 volt power into the QRP into two wires, one for the oscillator and a second for the amplifiers.

In the circuit below, diodes are used to power the oscillator from either wire under the appropriate circumstances. Strictly speaking, the diode in series with the spot switch isn't really needed, because the open spot switch will turn the oscillator off while the transmitter is in stand by. However, the voltage supplied to the oscillator will be more equal if diodes are in both supply lines.



QRP KEYER WITH "SPOT" BUTTON

The "spot" momentary contact button turns on the oscillator and buffer stages with power through a Schottky power diode capable of handling 100 milliamperes or more. Then, when the telegraph key activates the final amplifier, the oscillator gets its power from a second Schottky diode connected to the P-channel MOSFET keyer.

I have spent hours trying to accomplish these functions without big MOSFETs and diodes, but I have yet to succeed. Have a go at it! Maybe you can be more clever than I was.

Building accessories and checking out your QRP

Building power supplies for your QRP module is explained in chapter 8. Other important accessories, such as a telegraph code key and an antenna coupler are discussed in Chapter 9. Checking out your QRP is also covered in chapter 9.

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, REV 12

Chapter 7

A CODE PRACTICE RECEIVER

This chapter describes how to build a simple *direct conversion* ham receiver for the 40-meter CW band. This receiver can be used to listen to CW ham stations for code practice. It will also receive ham single sideband (SSB, voice) stations and foreign shortwave broadcasts. When combined with the CW QRP transmitter described in chapter 6, you could even use it to talk to other hams.

The main virtue of this receiver is its simplicity. The basic design has only 5 transistors and is an excellent first project for a new ham. It can be powered with a 9 volt battery. However a 12 volt battery made from small AA flashlight batteries will last much longer and provide more volume in your headphones.

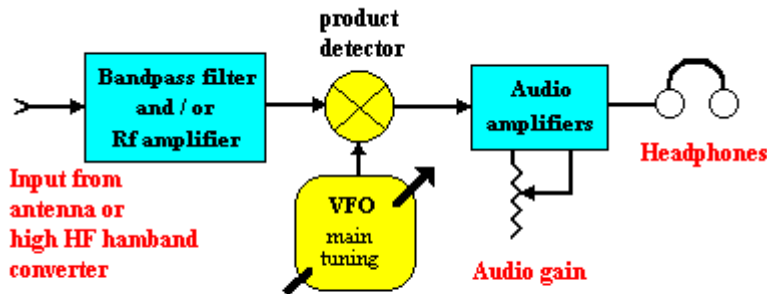


This receiver has good sensitivity and good stability. Unfortunately, by modern standards the selectivity of the basic receiver is poor for receiving CW. On many evenings the 40 meter CW band will be too crowded to listen to a single station easily. Adding the 700 Hz audio filter described later in the chapter will improve it greatly. Also, if you have a powerful AM broadcast station in your neighborhood, you may need to build a high pass filter to get rid of that interference. The broadcast filter is the little box shown to the right of the receiver.

When you're ready for a first rate receiver with selectivity as well as sensitivity, you may want to buy a commercial receiver or begin work on a superhetrodyne receiver as described in chapter 13. It is possible to get the same performance out of a direct conversion receiver, but that will require super-selective audio filters, image-canceling, and other R&D that I've never attempted. If you're interested, go for it!

Direct conversion receivers

A direct conversion receiver (DCR) has 4 basic circuit blocks. They are a band-pass filter, a variable frequency oscillator (VFO), a mixer or "product detector," and an audio amplifier.



Direct Conversion Receiver

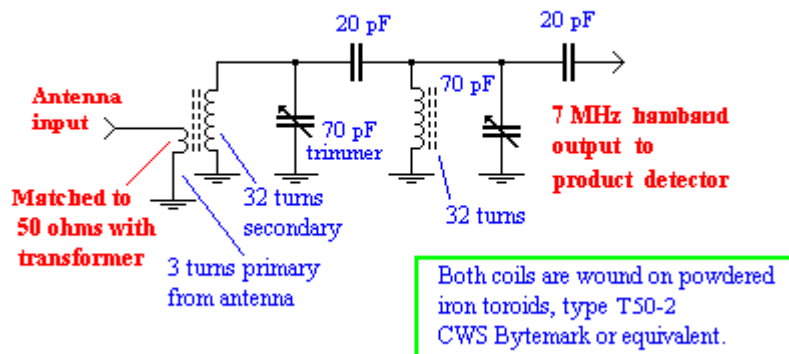
The frequency tuning of a DCR is accomplished with an adjustable frequency oscillator called a VFO (variable frequency oscillator). This sinewave signal is mixed with the incoming radio signals in a special amplifier called a *product detector*. The signals heard in the headphones are those that differ from the VFO frequency by a difference within the audio range, say 20 Hz to 2.5 KHz. For example, suppose you are listening to a Morse code station on 7.100,000 MHz. You might tune the VFO to 7.100,700 MHz. That is, you tune 700 Hz above the actual transmitting frequency. The frequency difference will be heard as an audible, musical, 700 Hz Morse code tone.

The difference frequency is filtered, amplified, and passed on to the earphones - pretty simple radio! Considering how few parts it has, it's amazing how sensitive it is. I measured the performance of mine and found it could easily detect a 0.5 microvolt signal on 40 meters.

The input filter

The product detector has a weak diode-like characteristic. That means it is prone to act like a crystal set and detect strong signals present on the antenna that are not near the VFO frequency. Consequently, the signals coming in from the antenna should first be filtered to restrict signals to approximately 7 MHz. As you may recall from your experience with crystal sets, the tuning selectivity of a simple input LC filter is usually limited. However, a simple filter can get rid of background low frequency AM broadcast signals or strong foreign AM shortwave broadcast stations operating near 7 MHz.

40 Meter Hamband Passband Filter



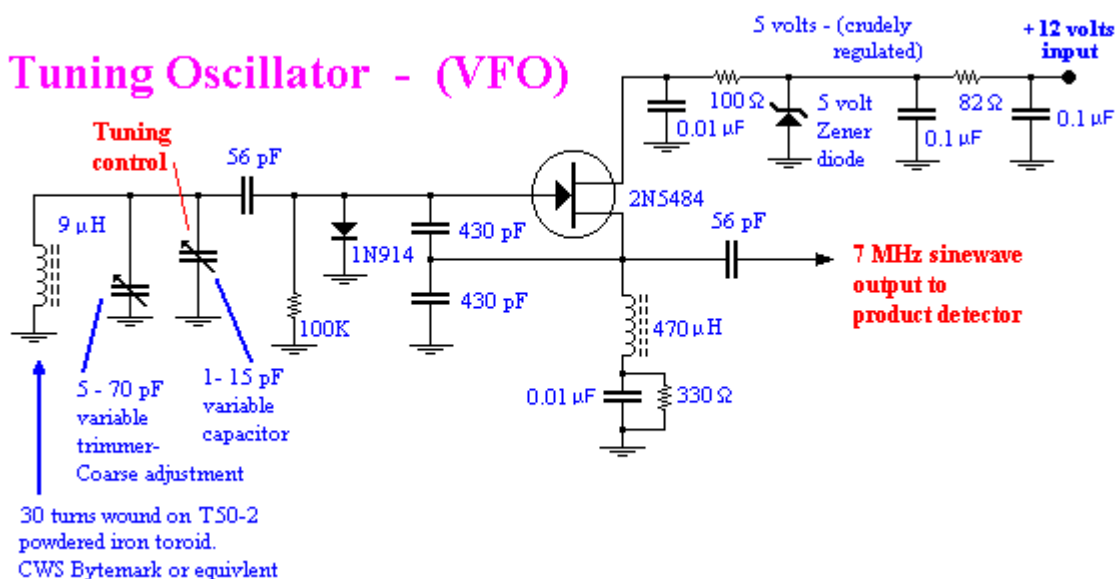
The input filter consists of two tuned LC circuits. The input from the antenna is wired as an RF transformer that matches the high impedance filter and high impedance product detector with a low impedance antenna. In other words, the antenna is assumed to be approximately 50 ohms, like a typical ham dipole with a coax lead wire. The transformer steps up the RF voltage about ten times using the 1:10 turns ratio. If the receiver will be used with a high impedance long wire or whip antenna, the input lead should simply connect to the top of the trimmer capacitor through a small blocking capacitor.

While listening to CW signals on 40 meters, tune the trimmer capacitors until the signals are as loud as possible and any background voice stations disappear. If this filter is insufficient to get rid of local AM broadcast signals, a 1.8 MHz high pass filter is described later in this chapter. Also, you might try reducing the 20 pF coupling capacitors between the LC stages to 5 pF or less.

This input filter section could also include an RF amplifier stage. However, this would probably not be useful on 40 meters because atmospheric noise is relatively high below about 20 meters. On the other hand, if you would rather build this receiver for 20 meters or above, an RF amplifier will be a great help to sensitivity. RF input amplifiers are discussed in chapter 13.

The RF tuning oscillator (VFO)

The circuit below shows the VFO tuning oscillator. As shown, the inductor and capacitor values will tune the 40 meter ham band and the shortwave broadcast bands just above and below 7 MHz. The circuit is a tunable oscillator comparable in function to the crystal-controlled oscillator used in the QRP transmitter in chapter 6. Instead of a quartz crystal, the frequency control is a tunable LC circuit that has a range of hundreds of KHz. This VFO is too crude to control the frequency of a transmitter. It would drift too much and the guys you are talking to would complain about your unstable signal. However, because you will be listening to a KHz of audio at once, a drift of 50 Hz per minute will be scarcely noticeable. Building a first rate VFO for a transmitter is described in chapter 10.



JFET TRANSISTORS

This tuning oscillator uses a Junction Field Effect Transistor, (JFET). They are ideal for building VFOs. Unlike bipolar transistors, the main current from the JFET drain to the source does not pass through any PN junctions. PN junctions change their characteristics with temperature. Therefore VFOs made from bipolar transistors tend to drift more than JFETs. JFETs work on the same principle as a MOSFET transistor, but the control gate is a P-N junction diode rather than a tiny capacitor. Power MOSFETs were introduced in chapter 6 as a way to key the QRP power supply on and off.

P-N junctions

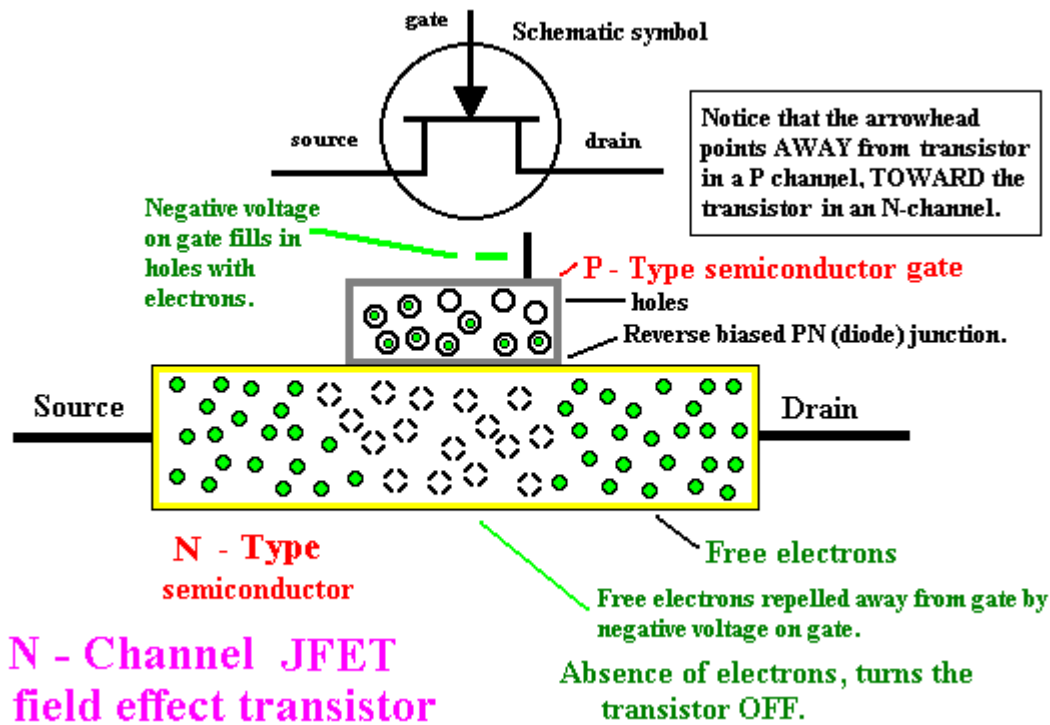
As you learned in chapter 4, *a semiconductor P-N junction conducts when positive voltage is applied to the P-type semiconductor*. Conversely, it does not conduct when positive is applied to the N-type semiconductor side. In the crystal set, we were dealing with such tiny currents (microamperes) that the transition at zero volts was plainly visible. Commercial diodes handle much larger currents, milliamperes or even amperes. With commercial diodes the forward conduction doesn't fully start until a forward offset is reached. For an ordinary P-N junction silicon diode, this is around 0.6 volts. For a commercial Schottky diode, this offset is around 0.2 volts. This threshold means that if we apply a positive voltage to the P-type semiconductor side below the threshold, say, 0.1 volts, the current will be far less than a milliampere. Since very little current flows, the diode is still essentially "OFF."

P-N junctions can work like capacitors

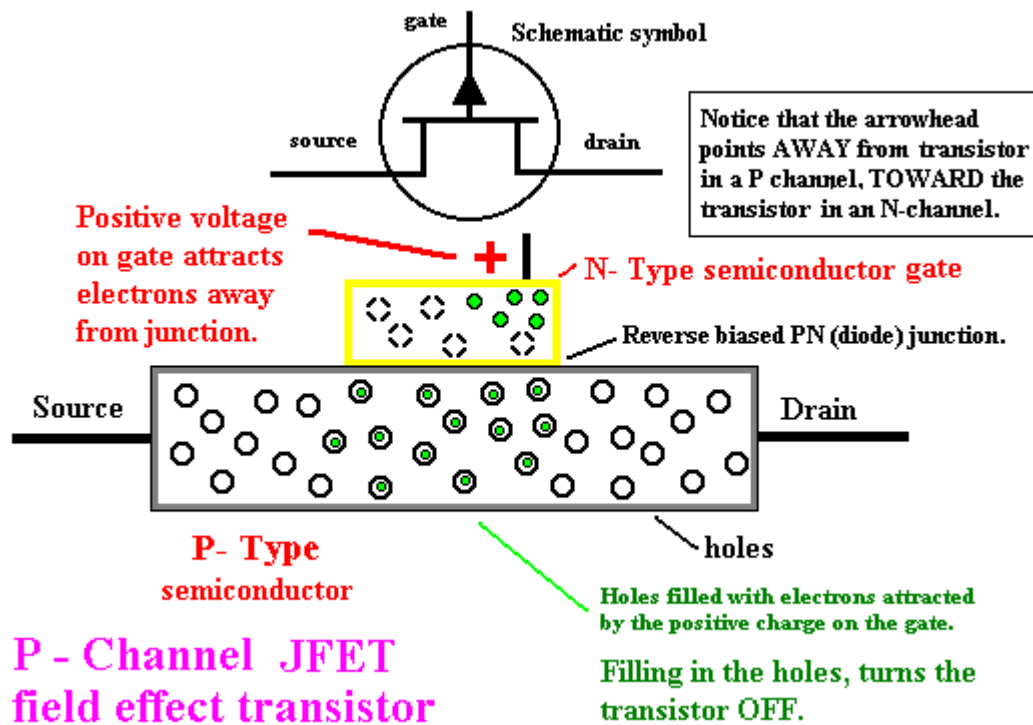
In a MOSFET, gate current is prevented from flowing into the main channel by means of a layer of glass insulation. In a JFET, the gate appears to be a forward biased diode but doesn't conduct much current unless the drive exceeds the forward breakdown voltage, about 0.6 volts DC. *With zero volts input on the gate, the JFET is already partly turned on*. In other words, with zero volts on the gate the transistor is already operating as a Class A amplifier and, unlike a bipolar transistor, no bias resistor from the drain supply is needed.

JFETs operate at input voltages less than 0.6 volts

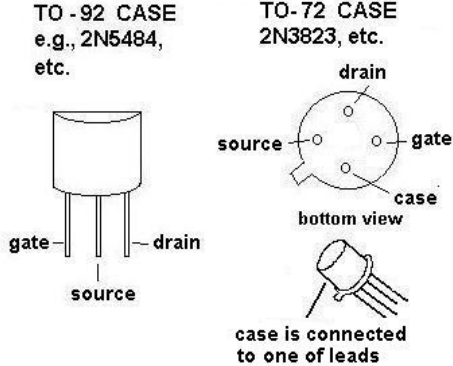
The JFET turns full on, (that is, it saturates) when the gate voltage approaches or exceeds 0.6 volts. Notice the diode clamp that prevents the gate voltage from ever exceeding 0.6 volts. To turn the JFET completely off, reverse voltage must be applied to the gate so that the charge carriers, holes and electrons, are completely depleted. For example, in the N-channel JFET shown below, the transistor turns completely OFF when the gate goes negative with respect to the source lead of the transistor.



As you would expect, P-channel JFETs are mirror images of N-channel JFETs with respect to construction and polarity. To turn a P-channel fully off, its diode gate is back biased with positive voltage as shown below.



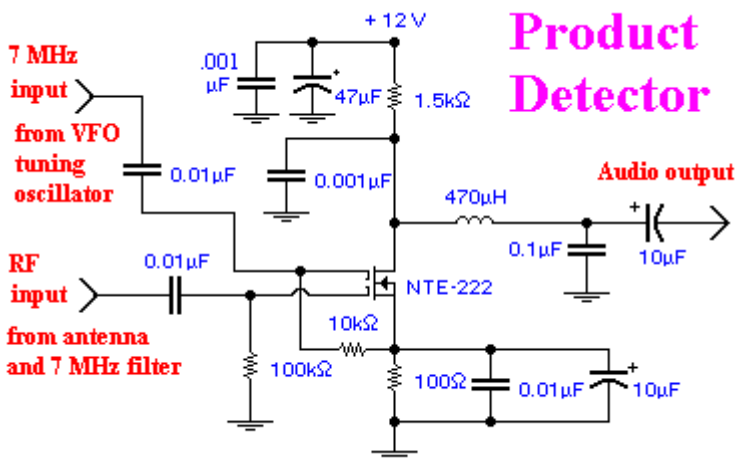
COMMON JFET TRANSISTOR CASES



The product detector

This receiver project uses a *product detector*. The product detector amplifies and mixes the VFO signal with the signal coming in from the antenna. The resultant mixture of radio signals is amplified and sent to an audio amplifier. Since the only audio component present is the *DIFFERENCE* between the two radio signals, that's what the audio amplifier passes on to the earphones.

The product detector circuit described here uses a dual gate N-channel MOSFET transistor. A dual gate MOSFET works like a single gate MOSFET (or JFET). But as the name implies, it has two control gates modulating the drain-to-source current instead of just one gate. With two gates this MOSFET is convenient for mixing two separate signals because the output of the amplifier is an amplified mixture of the two inputs. Mixers and product detectors can be built with single gate MOSFETs and JFETs, but with a dual gate MOSFET, both inputs are amplified in one stage.



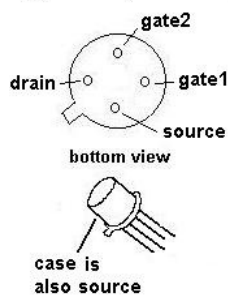
The gates of the MOSFET are tiny capacitors and therefore have extremely high impedance. The amplifier design is a *common source* design, which implies that the source is essentially at ground. This also means the load resistance, 1.5 K ohms, is on the drain side (+12 volt side) of the transistor. Because the desired output is an audio frequency signal, the load impedance is a resistor, not an inductor. In order to work at audio frequencies, an inductor would

have to be huge and for this application would have little advantage over a resistor. The 470 microhenry RF choke (inductor) and the 0.001 and 0.1 microfarad capacitors serve as a filter to remove the RF from the audio output. Without the filter, the audio amplifier would be more likely to rectify, (i.e. detect), strong RF signals that are able to get into the product detector and are not within the desired audio frequency difference from the VFO.

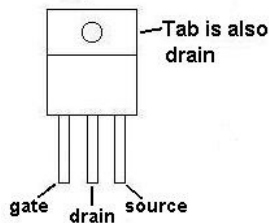
Modern designs often use integrated circuit mixer modules for product detectors. Personally, I prefer the dual gate MOSFET design simply because I know what's in there. It isn't just another mysterious integrated circuit. In this application any of the following dual gate MOSFET transistor types will work fine. I have successfully used the NTE221, NTE222, NTE454, or NTE 455. These are all "replacement" transistor types. So far as I know, any of the original 3N-series dual gates such as the 3N140 will also work. The 40763 by RCA is available from RF Parts Co. or from Mouser Electronics and should also work. I haven't personally tried it but I've seen it used in similar circuits.

MOSFET TRANSISTOR CASES

DUAL GATE MOSFET
TO - 72 CASE
e.g., NTE454, NTE 221, etc.

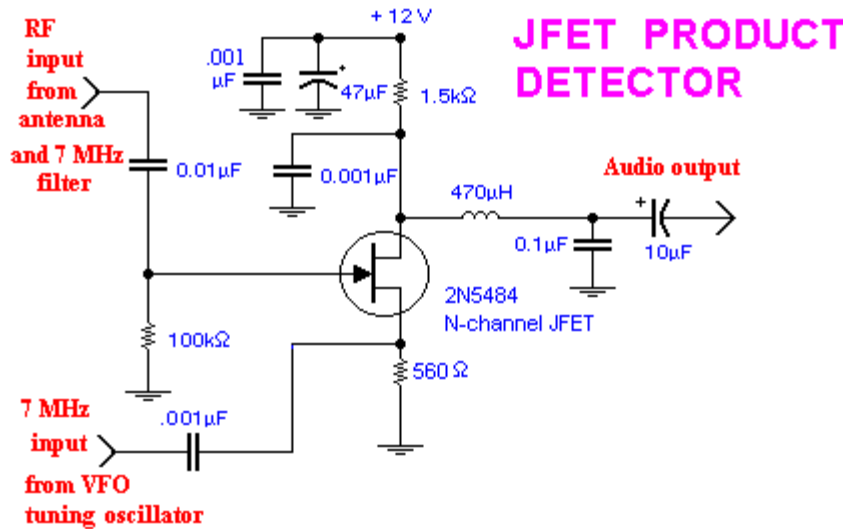


MOSFET POWER SWITCH
TO - 220 CASE
e.g., IRF9140, SMP20P10,
MTH25P05, etc.



A JFET product detector

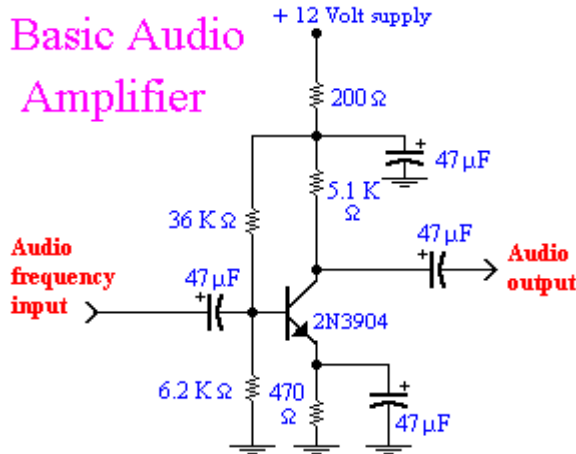
Since this book was first written, dual gate MOSFETs have become increasingly expensive and hard to find, at least in my neighborhood. In the event that you need a substitute, here is a JFET circuit that works but, in my opinion, isn't quite as sensitive. It is practically the same circuit but instead of introducing the local oscillator signal into a separate gate, it is introduced across the source resistor.



An article in the May 2008 issue of World Radio News describes a DCR similar to mine designed by Wayne McFee, NB6M. The interesting difference is that the JFET product detector was implemented with two JFETs in series. In that way both inputs, the VFO and the antenna as well, both go to gates and the output signals are added together, literally one on top of the other. The antenna amplifier JFET takes the place of the 560 ohm source resistor above. Since the McFee design has often been copied, I gather it works well, but I haven't tried it as a product detector. I did try to use it as a mixer in a superhetrodyne, but its performance was not significantly different than a single JFET mixer.

A generic R-C coupled audio amplifier

The output from the product detector is an audio signal that needs to be amplified before it goes to the earphones or speaker. Once again, most designs seen in ham magazines use integrated circuits marked "audio amplifier." For example, the LM386 is a typical one-chip audio amplifier. I've used these and they usually work well. Of course I didn't learn anything from the experience.

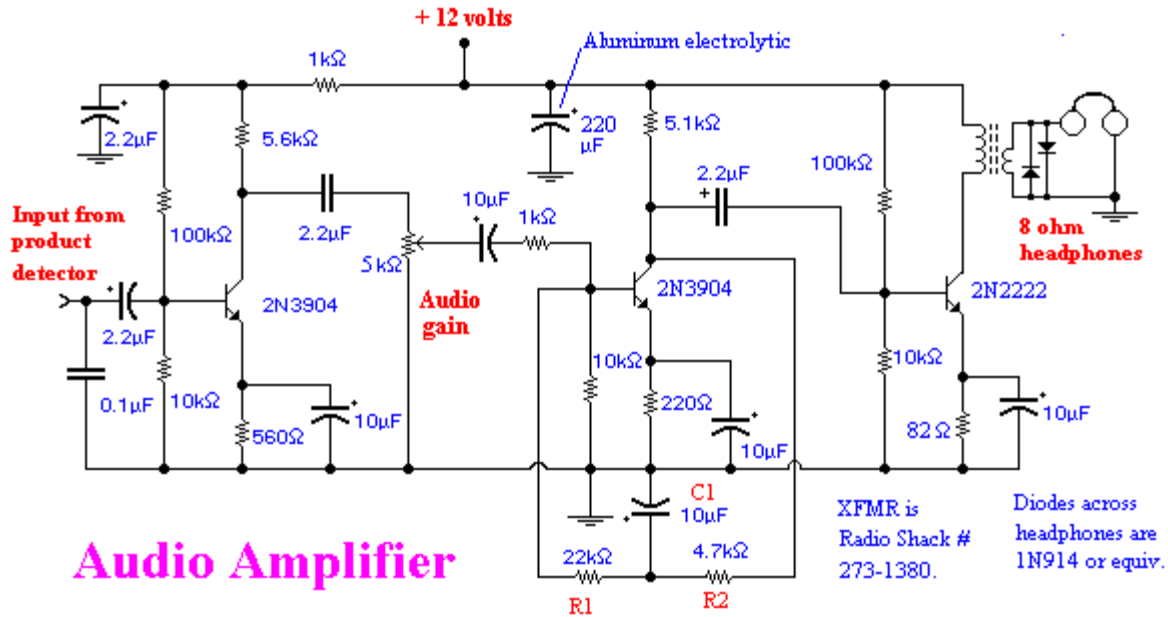


The diagram above shows a basic audio frequency *RC coupled* linear amplifier. If you look closely at the component values, you'll see it is similar to the class A RF amplifier we used as a buffer amplifier in the QRP transmitter in chapter 6. The differences are the large sizes of the capacitors and the absence of inductors. A 5.1 K Ω resistor is used as a load where you would expect to find an inductor in an RF amplifier. You could use an inductor here, but at audio frequencies it would have to be huge and expensive. Notice that the 36 K Ω resistor turns the amplifier partly on so that an audio sinewave will "fit" between zero volts and 12 volts. Otherwise the amplifier would only amplify positive signals larger than about 0.6 volts. Without the forward bias, the negative half of the sinewaves would be clipped off and the sound would be distorted. Because of the 0.6 volt base voltage offset, small signals wouldn't be heard at all.

The 470 ohm resistor biases the transistor, giving it a small amount of DC negative feedback. When the transistor conducts DC voltage, the voltage across this resistor in effect decreases the voltage on the base, thereby turning the transistor more off. This reduces the amplifier gain slightly, but makes the amplifier less likely to oscillate or run hot. The adjacent 47 μF capacitor allows the AC audio signal to go to ground without passing through the resistor. This allows us to have it both ways: The amplifier is more stable and the audio amplification is essentially unchanged.

The DCR audio amplifier

My complete audio amplifier is an extensively modified version of an example in the ARRL 1986 handbook. It is the same circuit used in the receiver in chapter 13. It looks like three straight-forward R-C coupled amplifiers in series. But the original design had extra filter components I didn't quite understand. Every part that I didn't understand, I left out. That's how I learn how circuits work. The audio amplifier was dead as a doornail when I first turned it on.



An audio Automatic Gain Control (AGC)

I was particularly puzzled by the low frequency feedback link, R1, R2, and C1. I couldn't understand what sort of "low frequency filtering" the designer was trying to accomplish. But, when I turned it on, the amplifier seemed completely dead. I put those mysterious components back in the circuit and ... voila! The earphones came to life. It turns out that this loop biases the amplifier "on" for weak signals and biases it "off" for loud signals. It's a kind of audio Automatic Gain Control (AGC) circuit.

Remember that for a bipolar transistor to turn on, the input signal must be greater than 0.6 volts or no current will flow into the base. In a "Class A" amplifier a small DC current is injected into the base. This increases the base voltage above 0.6 volts so that it's always turned on. The low frequency feedback adjusts the bias for weak and strong signals. When the signals are weak, the middle transistor is turned off, so it's collector voltage is high (+12 volts) and unchanging. This big collector voltage is leaked into C1 through R2. The voltage on C1 then biases the base through R1 to provide a forward bias for the transistor, turning it on and raising its sensitivity. Conversely, when the signals are strong, the collector has a big current flowing but a low average voltage from the collector to ground. This lower voltage biases the transistor more "off."

Protecting your ears from strong signals

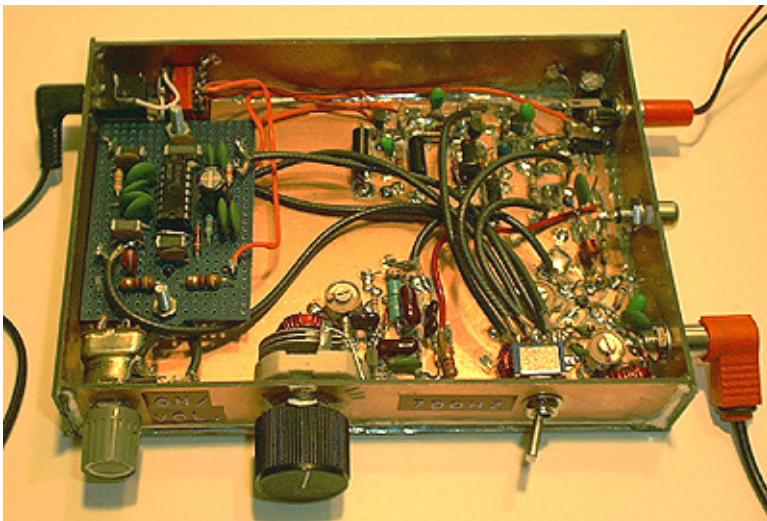
This triple amplifier has enough gain to almost deafen you when you encounter a strong signal. Therefore it's essential to add a clamp circuit to limit the voltage to the headphones to less than about one volt. In practice, with sensitive, modern 8 ohm headphones, I found that less than one volt peak is plenty of volume for me. Eventually I put in two ordinary silicon 1N914 diodes "shorted" with opposite polarities across the headphones. This limits the positive and negative sound peaks to just 0.6 volts and my ears have been adequately protected.

How Hi-Fi should it be?

11. Chapter 7, Harris

The original circuit was also sprinkled with 0.1 microfarad bypass capacitors as if the designer were trying to kill all higher frequency sounds and shunt most of the audio to ground. Since I was worried about having enough gain, I left out the bypasses. The amplifier worked well without them, but the sound of the static had an obnoxious, piercing high pitch that irritated my ears. I put the bypass on the input back in and, as I expected, the audio sounded more “bass” and became somewhat weaker. However, getting rid of that piercing, hissing static was well worth the loss of gain. Experiment!

The original design also had no emitter bypass capacitor. That's the 10 μF capacitor across the 220 ohm resistor. Not having this bypass capacitor reduces the gain because some of the audio voltage signal is wasted across the 220 ohm emitter resistor. Since I didn't want to waste any gain, I put in the capacitor and my gain jumped up noticeably. This bypass has no disadvantage that I could detect.



Mechanical construction

I built my receiver in a box made from soldering pieces of two-sided PC board together. This is the same construction described for the QRP transmitter described in chapter 6. The black coax RG-174 cables running around the inside of the box connect the optional 700 Hz filter module described later in this chapter. The coax shields the wires from stray RF that might be present. Only one end of the coax should be grounded.

The tuning knob ideally should be a mechanical, vernier, planetary-gear device to spread out the 40 meter CW band and make the signals easier to tune. Alternatively, one can use two capacitors in parallel with a smaller variable capacitor, say 3 to 15 picofarads (pF), for fine tuning. In this way, out of the 180 degrees of useful knob rotation, more degrees can be devoted to the CW band and less to the nearby broadcast stations. A 70 pF trimmer capacitor tunes the whole frequency spectrum around 40 meters to align the small capacitor to the ham band. The low capacitance variable capacitor is called an *electrical bandspread*. In my receiver the 15 pF fine-tuning capacitor has the big black knob, while the physically tiny 70 pF ceramic screw adjust trimmer is directly behind it.

The receiver power supply

The receiver will work well on 9 volts at about 10 milliamperes. However, when the

voltage drops below about 8 volts, the volume and sensitivity will fall off dramatically. So, if you use a small alkaline 9 volt "transistor radio" battery, it will only work well for about 1/3 of the energy stored in the battery. ***To get the most from alkaline batteries, you need to be able to run them down to 2/3 of their original voltage.*** In this case the receiver would have to work well down to 6 volts. I recommend making up a 12 volt battery out of AA cells. Radio Shack and other companies sell battery holders that carry 6 or 8 cells to give you 9 or 12 volts. Or if you are using the receiver with the QRP transmitter described in the last chapter, the receiver can share the QRP power supply.

Hearing the transmitter VFO

When I was trying to use the DCR with my QRP transmitter, I found I couldn't hear my own transmitter VFO (crystal oscillator) over the stations I wanted to call. To fix that, I ran a coax cable over to the QRP and imported a weakly-coupled transmitter crystal oscillator signal into the receiver box. The center connector on the right side of the receiver is for that purpose. The receiver has no direct connection to the transmitter oscillator. The connector merely projects a small piece of wire into the receiver box like an antenna to broadcast the weak oscillator signal.

**

FIXING THE LIMITATIONS OF DIRECT CONVERSION

One of the DCR limitations I had read about did not need to be fixed. Because a DCR has nearly all its gain in the audio amplifiers, these amplifiers are supposed to be prone to ***microphonics***. In other words, DC receivers are supposed to be sensitive to vibration. When you touch a knob or bump the table, you are likely to hear that sound amplified in the earphones. I observed no microphonics at all. I suspect microphonics may have been a common problem when using vacuum tube amplifiers.

A DCR detects both sidebands at once

Unfortunately, the product detector mixer detects both the upper and lower sidebands simultaneously. This is OK for listening to AM radio stations that broadcast both sidebands, but it has poor selectivity on a crowded CW band. A good CW receiver can select a bandwidth as small as 500 Hz or less. A simple direct conversion receiver will have a bandwidth of 10,000 Hz or more, depending on the audio filtering.

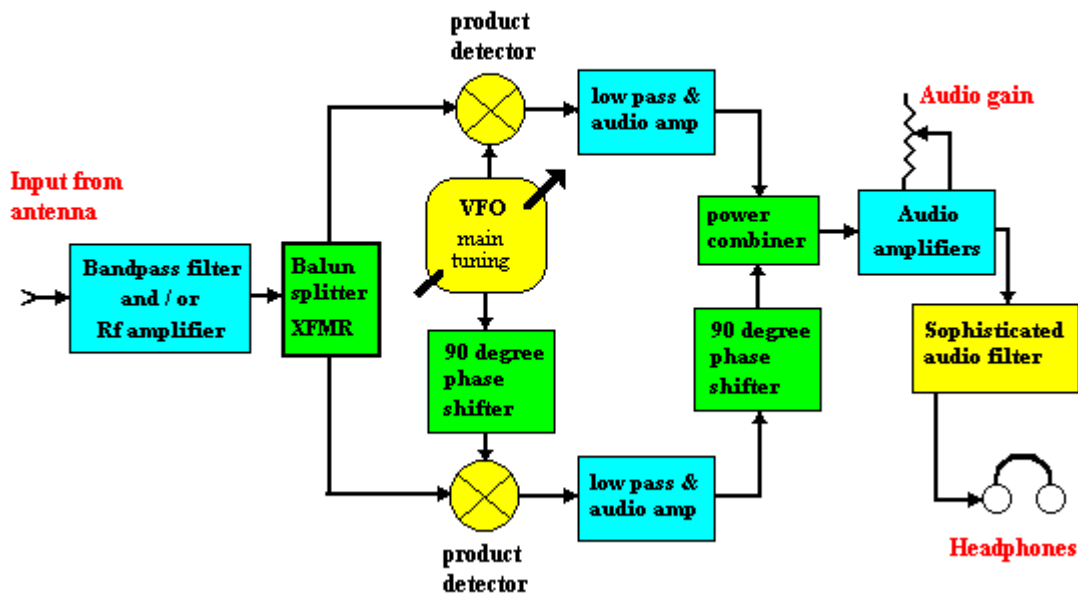
Although audio filtering is helpful for a DCR, the big problem is that you'll still be listening to audio from both "sidebands" at once. CW by definition is extremely narrowband. It covers a few Hz at most. Therefore, CW doesn't really have sidebands. However, to hear the signal as a musical tone, a receiver must be tuned either above or below the actual frequency by an amount equal to the frequency of the desired musical tone. Most modern hams are using transceivers that automatically listen about 700 Hz above or below their transmitting frequency. This offset frequency is adjustable, but is nearly always set between 500 to 1000 Hz. By convention, ***On 40 meters and below, they are listening BELOW the transmitting frequency.*** On HF bands 30 meters and above hams listen ABOVE the transmitting frequency. This convention has its origin in the method for generating single sideband phone that was formerly common 40 years ago. The old SSB design isn't used anymore, but the convention lives on. The

new 60 meter band is specified for upper sideband only and is an exception. The result is that if you answer a station on the upper sideband side while the station is listening on the lower sideband, he will never hear you because modern equipment only hears one sideband at a time.

Sharp audio filters aren't enough

A sharp audio filter on the DCR output does not correct this problem. For example, suppose you build a sharp audio filter to select 700 Hz audio tones only. Yes, you'll hear your 700 Hz offset CW station just fine. But you're likely to be confused by an *image* signal that you can also hear 1.4 KHz away on the opposite sideband. That is, $2 \times 700 \text{ Hz} = 1.4 \text{ KHz}$. When you answer a CQ, this confusion will make it hard for you to know where your contact will be listening. Remember, when he switched his commercial transceiver to that band, he selected upper or lower sideband and didn't have to worry about this effect.

Modern Image-Rejecting Direct Conversion Receiver



A sophisticated direct conversion (DC) receiver eliminates one sideband by essentially building two DC receivers. One sideband is cancelled out by phase shifting the input VFO RF signal and also phase shifting the resulting audio signal to remove one sideband. So, although a DCR is “simple,” you might need to build two of them, plus a sophisticated audio filter. Personally, I decided that a dual conversion superhetrodyne was the best way to go.

AM broadcast interference

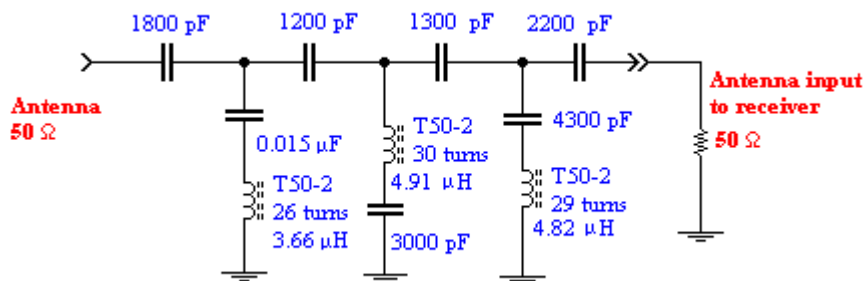
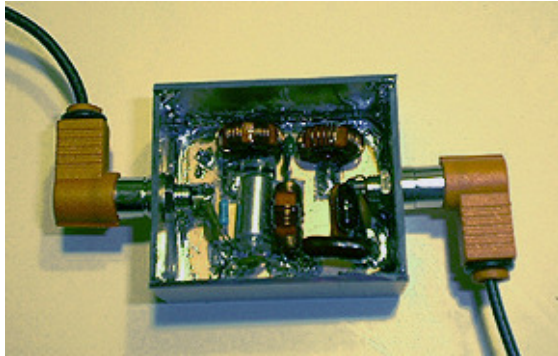
In my city there is a powerful AM radio station that broadcasts at high power during the day. When I put an oscilloscope on my 40 meter dipole lead wire, I see a 1.75 peak volts RF signal on the wire even with a 50 ohm resistor connected to the antenna. This represents 31 milliwatts of power! No wonder my crystal set was so loud.

$$\text{Power} = \text{Voltage (RMS)}^2 \div \text{load resistance} = V_{\text{RMS}}^2 / R$$

RMS voltage = Voltage peak x (0.707)

Power = [(1.75 volts peak) x (0.707)]² ÷ 50 ohms = 31 milliwatts

The ham signals I was trying to listen to were buried in the voltage storms from the local AM rap-music station. The input filter for the DC receiver described earlier in this chapter was apparently inadequate to get rid of such a large signal. So, although I could hear ham stations, in the background I could always hear the rap music leaking through like a crystal set. I needed a better filter. The good old '86 ARRL handbook had such a filter design. It worked the first time without tweaking and reduced the RF voltage coming in on my antenna down to about 0.15 volts peak without affecting the strength of the 40 meter signals.



An AM broadcast filter

A 700 Hz audio filter – why you need one

As described earlier, if you intend to answer a fellow calling CQ, you must be sure you are listening on the same side of his transmitter frequency that he is. Because your direct conversion receiver has no image canceling, you will hear his Morse code both above and below his actual transmitting frequency. If you zero in your transmitter on the wrong side of his signal, your transmitter will be 1.4 KHz (2 X 700 Hz) away from where he is listening and he'll never hear you. Unless of course, his receiver is as primitive as yours.

For example, on 40 meters, as you tune *UP* the band you'll first hear his Morse code on the low side of his actual frequency. That is the lower sideband. If you continue tuning *VERY* carefully, the tone you hear will fall to a low pitch, then disappear, then rise back up to the same musical tone again. That is the upper sideband.

If you wish to answer the fellow's CQ, listen on the fellow's lower sideband on 40 meters. Now set your transmitter to "spot" and tune your transmitter's crystal-pulling capacitor **DOWN**-frequency until you first hear an equal tone. If you have a little musical talent, you should be able to match the tones pretty well. ***In summary, when listening for CQs, tune UP the 40 meter band. When spotting your transmitter oscillator on top of the station you wish to call, tune the transmitter DOWN the band.*** If you were on 30 meters or above you would reverse these instructions, because upper sideband is the convention up there.

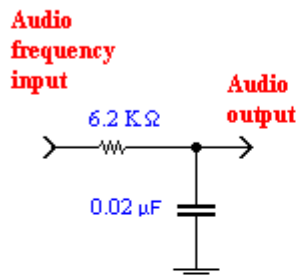
Those darn modern hams are listening with exquisitely narrow audio filters. They will usually only hear you if your signal is making a tone within a couple hundred Hz above or below their listening frequency. When they switch in the really sharp digital filters, they only hear stations within a few Hz of their listening frequency.

An analog audio filter

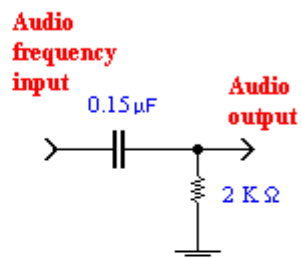
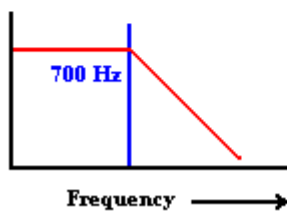
If we had ideal, small cheap components, the easy way to build analog audio filters would be to use inductors and capacitors the same way we build radio frequency filters. We might even imagine that there would be audio frequency quartz crystals for building super precise audio filters.

Unfortunately, in the real world those parts don't exist. In order to work at such low frequencies, the inductors would have to be gigantic and expensive. Since that approach isn't practical, we use resistor/ capacitor networks. ***These RC networks don't resonate, but rather they just attenuate some frequencies more than others.*** A large capacitor charges more slowly than a small one. When combined with a resistor, the frequency of the sinewave across either the capacitor or the resistor will be attenuated at either the high frequencies or the low frequencies, respectively.

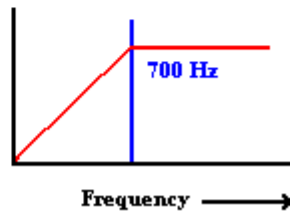
700 Hz Low Pass & High Pass Filters



Low pass filter



High pass filter



Low pass filter

As shown above, a simple resistor and capacitor makes a low pass filter when the output is taken off the capacitor. If the capacitor is large, relatively high frequency sinewaves will be "shorted" to ground. Remember, *the voltage across a capacitor can't change instantly*. In contrast, the effect of smaller capacitors will be negligible to low frequency sinewaves that have time to charge the capacitor during each half cycle. The resistor loads down the circuit and draws current into the capacitor. Similarly, during the next half cycle, the resistor has sufficiently low resistance to fully discharge the charged capacitor and get ready for the next half cycle.

High pass filter

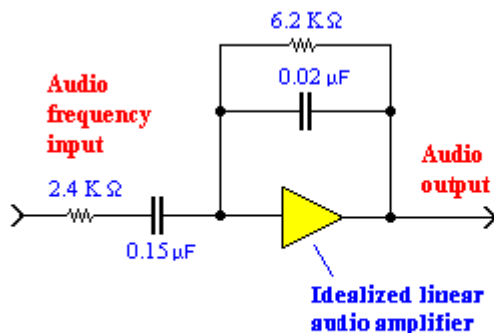
When the R and C are reversed and the output is taken off the resistor, then the RC filter becomes a high pass filter. High frequencies pass right through a capacitor to the output as if it weren't even there. Remember, *the voltage across a capacitor cannot change instantly*. Therefore, to high frequencies the capacitor looks like a wire with zero AC voltage drop across it. At high frequencies there isn't time to charge. At low frequencies, the capacitor charges up completely and the AC voltage drop across the capacitor approaches the entire voltage of the input sinewave. These *RC coupled filters* all have a particular frequency called the *break point* where the capacitor becomes relatively insignificant in the circuit. A simple RC filter attenuates the sinewave voltage ten times (20 decibels) for a tenfold change in frequency away from its break point.

Compensating for attenuation

A problem with RC filters is that the resistors attenuate ALL the frequencies to some degree, not just the ones we don't want. Fortunately if an RC network is combined with an audio frequency linear amplifier, we can compensate for the attenuation. By amplifying the output, we can restore the signal strength of the desired frequencies back to its original strength.

Bandpass filter = RC networks plus amplifier

To make a bandpass filter we need to combine a low pass filter with a high pass filter and then amplify the result. The circuit below is a one-stage R-C (resistor/ capacitor) audio filter/ amplifier that accentuates 700 Hz tones and attenuates tones above and below roughly 600 and 800 Hz.



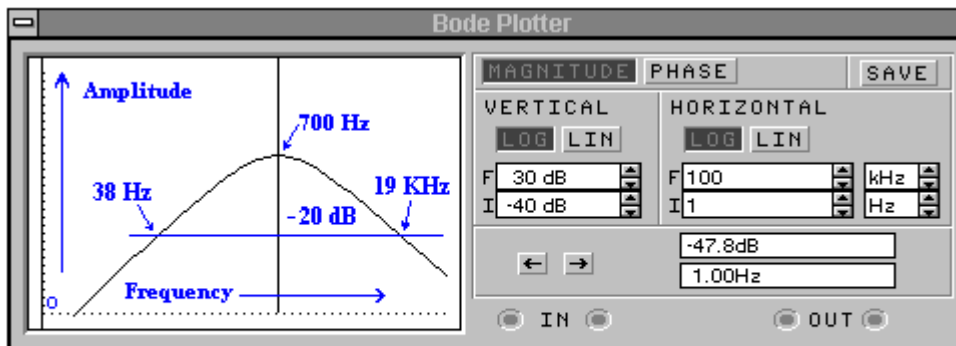
Single Stage 700 Hz Bandpass Filter

In this filter the Rs and Cs are not arranged as you might expect. However, if you

carefully analyze how they affect signals passing through the circuit, they work the same as the separate circuits described earlier. That is, low frequencies and high frequencies are attenuated and the desired 700 Hz frequency range is relatively unaffected. The input RC, the 2K Ω and 0.15 μF capacitor, attenuate low frequencies because low frequencies, (for example, 60 Hz and direct current), can't get through the capacitor. Therefore the input network is a high pass filter.

Note that the 6.2K Ω ohm and 0.02 μF capacitors are wired between the input and output of the linear amplifier. This negative feedback network is the low pass filter. This combination of components tends to "short out" the amplifier and attenuate everything above about 700 Hz. Note that the small 0.02 μF capacitor has little effect on low frequencies because it charges essentially immediately. Because the capacitor charges almost instantly, its voltage follows the low frequency sinewave curve without significantly attenuating it. However, at high frequencies a 0.02 μF capacitor becomes charged more slowly than the high frequency sinewave is changing. Between half cycles, the 6.2K Ω ohm resistor has low enough resistance to be able to discharge the 0.02 μF capacitor significantly so that the network is restored to block the next half cycle.

The two resistors, the 2.4 K Ω and 6.2 K Ω , also control the gain in this circuit. The triangle amplifier symbol is assumed to have infinite gain. It doesn't of course, but this symbol generally means an operational amplifier, which is supposed to act like a perfect transistor with unlimited gain. The gain is set by the external resistors. There's no need to go into the details, but, the ratio of the feedback resistor to the input resistor is 6.2 K / 2.4 K = 2.5 times. That means, the gain is approximately 2.5. To say it another way, the voltage lost across the 2.4 K resistor while entering the amplifier is compensated by the much larger voltage gain across the 6.2 K. This more than makes up for the signal voltage lost in the filtering process.



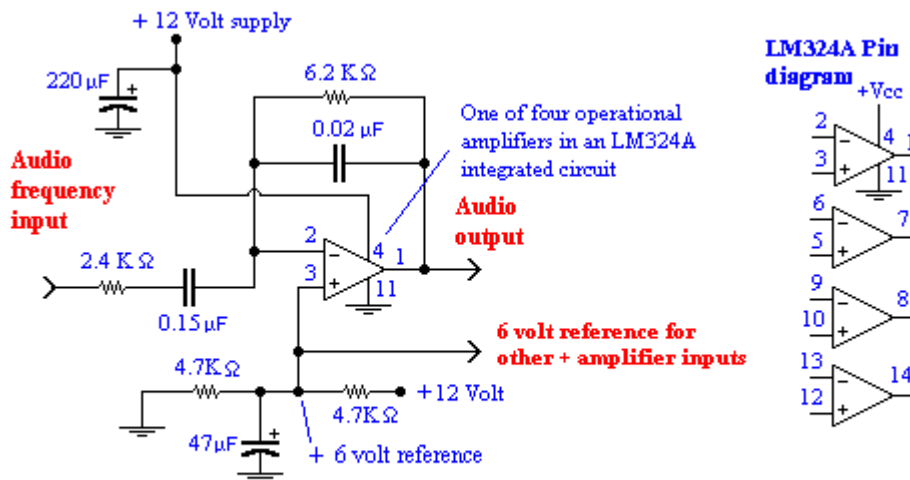
Single Stage 700 Hz Audio Filter

The frequency plot above shows the response of the single stage filter. As you can see, this filter is pretty crude. In order for the voltage of a sinewave to be attenuated more than 10 times (20 decibels), the frequency must be below 38 Hz or above 19 KHz. To be blunt, this won't help much. It will decrease some of the unpleasant high frequency noise from static, but won't be particularly helpful in relieving the QRM (interference from other stations).

More precise filtering can be achieved by putting multiple audio filters in series. The plot below shows four of the same filters in series. This is a big improvement and makes it easier to listen to just one station at a time. It also eliminates the high frequency noise and makes listening less tiring.

Typically there are two or four operational amplifiers on a single chip. The symbol for an operational amplifier is a triangle. The typical op-amp has an output pin and two input pins. For example, look at pins #1, #2, and #3 below. A **positive** voltage on the **positive input** pin makes the output pin voltage rise, that is, go positive. In contrast a **positive** voltage on the **negative** input pin makes the output pin go down. **Because of the feedback, the op-amp will "attempt" to drive its output pin up or down until feedback from the external circuit components cause the two inputs to be equal in voltage.** If the feedback is insufficient to produce equilibrium, the output will bump into either ground or the voltage supply, whichever happens first.

To bias an operational amplifier so that a large sinewave will "fit" between zero volts and 12 volts output, the amplifier must have a baseline about halfway between the supply voltage and zero. In this case the resting level will be about 6 volts. In the filter below, the positive input is connected to a 6 volt reference level made from a voltage divider connected between 12 volts and ground.



Single Stage 700 Hz Bandpass Filter

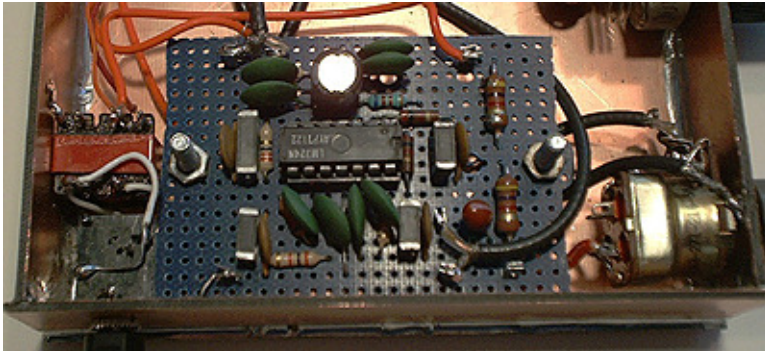
Homebrewing with integrated circuits

Homemade "gouge boards" described in chapter 6 are usually much too crude to use with integrated circuits. Therefore when I build with ICs, I use "perf-boards." These are plain, 1/16 inch thick fiberglass boards. They have no copper layers but have a grid of tiny holes drilled on 1/10 inch centers. The older ICs have their pins spaced 1/10 inch apart and the two rows of pins are spaced apart in even multiples of one-tenth inch. Modern ICs are often available either as old-style, through-hole or modern surface-mount. To use through-hole, you could just push them through the perf-board and then solder your components and wiring on the pins on the other side.

I prefer to **use IC sockets** rather than hard solder them on. If you accidentally damage an IC and it is installed with an IC socket, it can be instantly replaced. Without a socket, you'll seriously damage your wiring when you tear it apart to solder in a new one. The IC socket also has pins lined up just like an IC, so you push it through the board and solder your wires to the socket pins on the bottom.

For homebrew work you need the big, old time ICs with 1/10 inch spacing. Modern

surface mount ICs have pin spacing as tiny as 20 thousands of an inch. They are designed to be installed with mass production robots and are extremely tricky to solder in your basement. One practical (but extremely time-consuming) home-brew approach is to make little etched circuit boards that accept the surface mount ICs. The little adapter boards have traces that serve to expand the pin lead spacing radially out to large pads that human fingers can work with directly. Using hemostat clamps, tweezers, and a microscope, you solder the IC onto the miniature board. After you have inspected your pin connections under a microscope, you can then solder these adapter boards onto a normal size perf-board.



A four-stage 700 Hz bandpass filter built on a perf-board.

Using the diagram for the single stage filter shown earlier, simply feed one output into the next input until you have four stages in series. All four op-amps can share the same 6 volt resting level reference.

Label your pins!

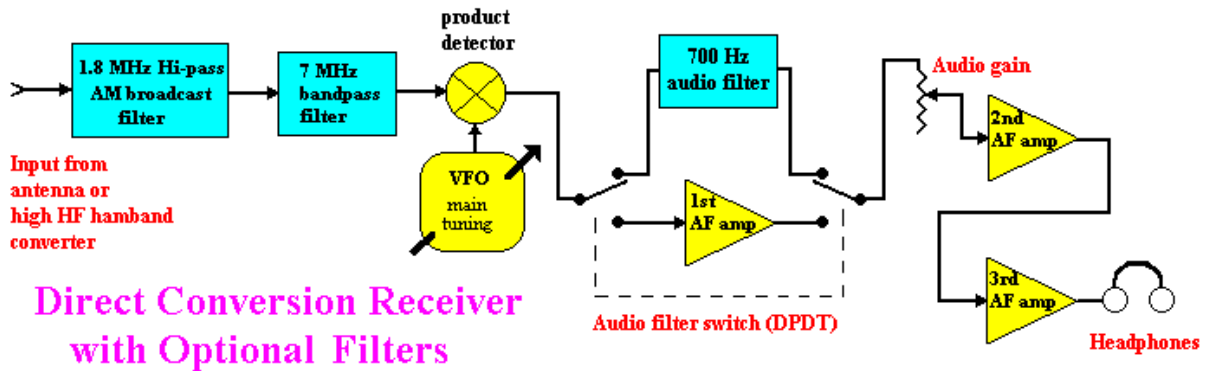
Keeping track of the pin numbers isn't easy unless you label them. I like to cut out a narrow strip of sticky white label paper and paste it between the pins. I write the pin numbers on the paper with a fine felt-tip pen adjacent to the respective pins. ***Pin # 1 is at the end of the integrated circuit that has the notch.*** Sometimes pin # 1 is indicated with a little number or a round indentation in the black plastic. The notch and indentation may be seen in the above photo. In any case, the pin numbers seen from the top are numbered counterclockwise. However, as seen from the bottom of the IC socket where you do your soldering, the pin numbers go around clockwise starting from the end with the notch in the plastic case.

There are two kinds of IC sockets suitable for ham work - ***solder tail*** and ***wire wrap***. Wire wrap sockets have big tall pins that allow thin wires to be wrapped around them with a special tool. I prefer the solder-tail type. They are harder to work with, but aren't so tall, are less messy and don't take up so much room. Just to cover the subject of IC sockets, large complex computer ICs use "grid sockets" and "solderball sockets" with hundreds of contact points. Unfortunately, working with these is nearly impossible at home because that would require extreme precision and building multi-layer PC boards.

Wiring the 700 Hz filter into the circuit

I designed the op-amp filter to have a slight amount of amplification. Unfortunately, by the time I put four in series, I had as much gain as one of the audio amplifier stages. Therefore, the output of my filter goes to the input of the second AF amplifier stage and bypasses the first stage. When I returned the signal to the input of the 1st stage, it was much too loud and unstable.

You could bypass the 2nd stage, but you would lose your AGC. A block diagram of my receiver is shown below. A double-pole, double-throw DPDT switch substitutes the filter for the 1st stage AF amplifier.



The digital solution to audio filtering

Actually, op-amp filters are also old-fashioned. The modern way to build audio filters is to use digital filtering. Basically, a microcomputer program measures the width of individual sinewaves with a counter-like algorithm. For example, a 700 Hz sinewave cycle is 1.43 milliseconds long. The digital filter measures the height and widths of the sinewave humps. If the widths are the desired frequency, then it just recreates waveforms of that length and amplitude. Sinewaves that are longer or shorter are ignored. Averaging and integrating math algorithms are used to massage the data and arrive at the most accurate and useful representation of the original spectral content of the signal. In practice, a digitally filtered passband of just one Hz is easy to build but is very hard to tune in with your VFO tuning knob. Therefore the passband of a digital filter is usually adjustable. When the passband is fairly wide, say 200 Hz, tuning isn't so difficult.

In conclusion,

The block diagram above shows the receiver I built. I packaged the AM broadcast band filter outside the receiver so I could use it with other receivers. A switch allows me to put in the 700 Hz filter when I need it. If you use it with single sideband phone, it will get rid of much of the noise, but voice quality will be poor. To tune in single sideband, you have to turn off the filter and tune your VFO to exactly the right spot to make the modulation intelligible. AM voice stations must also be tuned in perfectly, otherwise they make an obnoxious whistle. The whistle occurs because the AM broadcast includes a fixed carrier wave that is comparable to a Morse code signal with the key held down. To get rid of the whistle, you must "zero beat" the VFO so that there is no audio frequency difference between the carrier wave and your local VFO. When you do that, the whistle vanishes and you will just hear the audio sidebands.

So? How well does the direct conversion receiver work? If this were the year 1935, all your ham friends would probably be insanely jealous of its terrific performance. Unfortunately, by modern standards it is a bit of a toy. It's adequate for shortwave listening and an experienced CW operator can use it to talk to people. I managed to use it in conjunction with the QRP transmitter in chapter 6 to talk to hams in other states. I guess that makes me an experienced operator. Novice hams could easily use it for communications when the band isn't crowded. It

22. Chapter 7, Harris

has plenty of sensitivity, just not much selectivity.

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, REV 12

Chapter 8

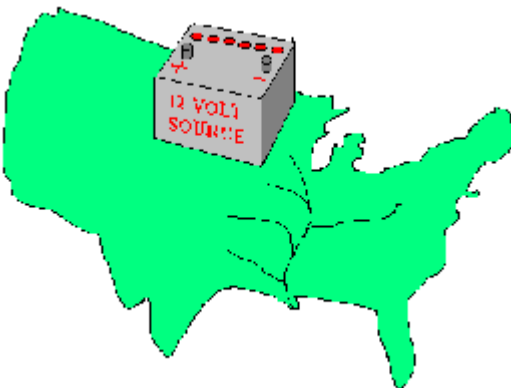
POWER SUPPLIES

Once you progress past crystal sets, electronic projects almost always need a power supply. Low power projects, like a small receiver, can be powered with flashlight batteries or even a little 9 volt “transistor” battery. Other convenient sources of low power DC are *adapter plugs*. These are the black cubes a few inches square that plug into the wall and have a long, skinny cord that plugs into your recorder or small appliance. They deliver 6, 12, or other DC voltage at a few watts. Adapter plugs have the safety of a battery with the convenience of wall power. On the other hand, their voltage may have high AC ripple noise and need to be filtered.

If you plan to power your QRP with household power, you’ll need more than a few watts. A 5-watt transmitter needs at least 10 watts of power with good voltage regulation. Otherwise AC ripple on the DC will go right out over the air as a hum or buzz. When you decide to plug a homebuilt circuit into the wall, you must confront some significant safety issues. Line-powered power supplies convert 120 volts AC into DC voltage at the required levels of voltage and current. Actually, a transmitter can also be thought of as an energy conversion device. It converts direct current into radio frequency current. In this chapter I’ll describe some power supplies you could use for your QRP transmitter.

Line-powered power supplies

The ideal power supply is called a *voltage source*. A voltage source is a power supply that can supply infinite amounts of current without the slightest waver in the voltage. For example: As every northern resident knows, starting a car can be difficult when it’s below zero. A cold battery does not supply as much current as a warm battery. So, when you turn the ignition key on a frigid morning, the battery voltage crashes.



On the other hand, if you had a battery the size of North Dakota, the voltage would not drop a microvolt when you started the engine. Moreover, you could start all the other cars in Minnesota simultaneously without voltage drop. Of course, there are also other practical issues here. For example, your battery would need zero resistance battery cables, zero resistance

connectors, etc. Well, you get the idea: The ideal voltage source should not lose any voltage, no matter how much power it supplies. Using ham radio vernacular, a good power supply is a “stiff” supply.

Lab power supplies

A reliable, line-powered laboratory power supply is useful for checking circuit boards. No lab should be without one. A big advantage of commercial lab supplies is that the voltage is adjustable from zero to some high level like 20 volts. Meters show you the current and voltage at every moment, so you know what is happening. Variable voltage allows you to power up a new circuit *CAREFULLY*. You can start with a few tenths of a volt and see what happens. If the circuit is shorted, you can find out with one volt applied to the circuit board, rather than blasting it with 12 volts right away. This helps you avoid burning up expensive transistors. Many lab supplies put out two or even three separate supply voltages at once. Another feature of some lab power supplies is that they automatically limit the available current to some maximum that you select.

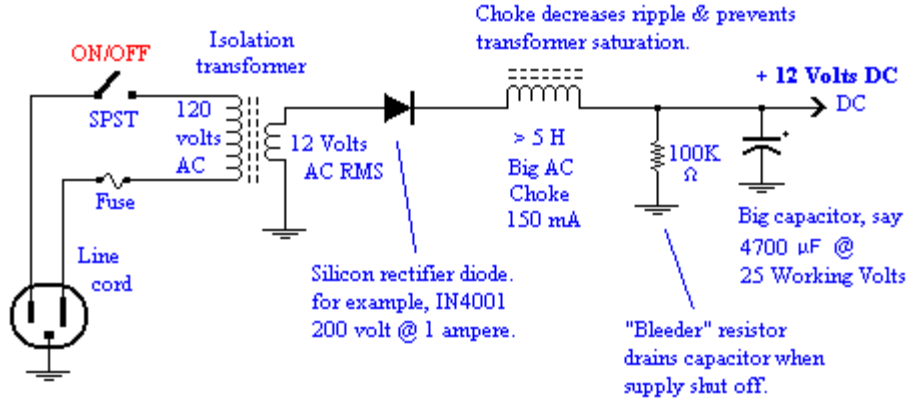


Bench power supplies are quite generic and there are many modern ones that will serve you well. Remember, to power your QRP you need about 1.0 ampere at 12 volts DC. A typical modern, transistor QRP transmitter runs on a 12 volt power supply but its efficiency is only about 50%. Therefore,

$$10 \text{ watts} = 12 \text{ volts} \times 800 \text{ milliamperes}$$

Homebuilt power supplies for use with rechargeable batteries or line power are described below. If you aren't familiar with power supply design, a discussion of the basic principles follows.

Simple wall-powered supplies for 120 Volts AC



SIMPLE LINE-POWERED 12 VOLT POWER SUPPLY. (NOT SUFFICIENT FOR QRP)

The diagram above illustrates the simplest, safe, generic, line-powered power supply you can build. Unfortunately, this supply is too poorly regulated to power a transmitter. However, it illustrates the minimum safety features and it's easy to explain.

The following discussion assumes that the reader lives in North America where the standard household line voltage is 120 volts AC RMS @ 60 Hz. The safety issues explained here are applicable to other regions of the world. However, voltages, connector types, wire color codes, and ground configurations are often different. For example, in Europe the standard is 220 volts AC RMS @ 50 Hz.

Power supply safety

Metal enclosures. The supply should be enclosed in a box to insure that children (and you) won't get fingers across the 120 volts AC. Ideally the box should be made of metal so that, in case of a short circuit, a fire is highly unlikely.

Another safety design philosophy is called **double insulation**. In this scheme the electronics are housed in a plastic box and extra effort is made to insure that the internal wires are properly protected so that shorts and loose wires are highly unlikely. A double insulated plastic box does not necessarily need a ground wire in the line cord. However, in ham work, metal boxes shield circuitry from stray radio waves and are usually the best choice.

Line cord. The line cord should be the modern, three-wire type with the (green) ground wire securely connected to the metal box. In case a loose wire in the box causes the hot side of the AC line to touch the metal box, the ground wire will safely shunt the AC current to ground.

The line cord should pass into the metal box through a **rubber grommet** so that the metal edge can't cut through the insulation on the wire and cause a short circuit. Once inside the box, the cord should be held captive by a clamp, properly known as a **strain relief**. The strain relief insures that if the power supply is ever yanked by its cord, the live wires will not be ripped loose and short out.

The wires in a line cord are usually color-coded. The “hot” wire usually has **black** insulation while the “neutral” or return wire is **white**. The third **green** safety wire is connected to power line ground. It should be connected directly to the metal chassis. The neutral wire is also supposed to be connected to the house ground buss out in the circuit breaker box. Looking at a North American household three-prong socket, the round pin is the “ground” and is connected to the green wire. The wider, flat pin is the hot side and the narrower flat pin is neutral. Unfortunately, sometimes wall sockets are wired wrong, so it’s better not to bet your life on the orientation of the flat pins.

Fuse. The first destination of one of the two power wires, preferably the “hot” black lead, should be a **fuse**. As you probably know, fuses are little pieces of solder-like lead mounted in a glass case. When the current exceeds some calibrated level, like one ampere, the lead melts and the circuit opens. Fuses, of course, can only be blown once and can’t be reused. A fuse is represented on the diagram by the squiggle in the diagram labeled “1A,” meaning “one ampere.” The electrical standards allow a fuse to be considerably larger than necessary, like 5 amperes and still give adequate protection against shorts. Small **circuit breakers** serve as reset-able fuses and are available in low current levels such as 3 or 5 amperes.

Switch. The power switch can switch just one side of the line, such as the single-pole, single-throw (SPST) switch shown above. Or, it is even safer to switch both sides of the power line at once using a double-pole, single-throw switch (DPST). The switch should be rated for at least 125 volts AC and 3 amperes.

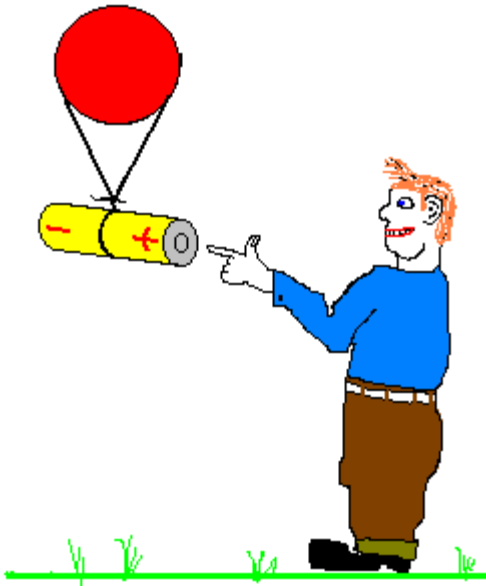
The transformer

After the power switch, the line current usually goes to the primary winding of a transformer. The transformer has two functions: first, it **isolates your power supply from the household supply** and from ground. This makes electrocuting yourself much less likely. As explained earlier, the AC lines supply 120 volts AC referenced to ground. The transformer secondary delivers AC power that has no relation to ground at all.

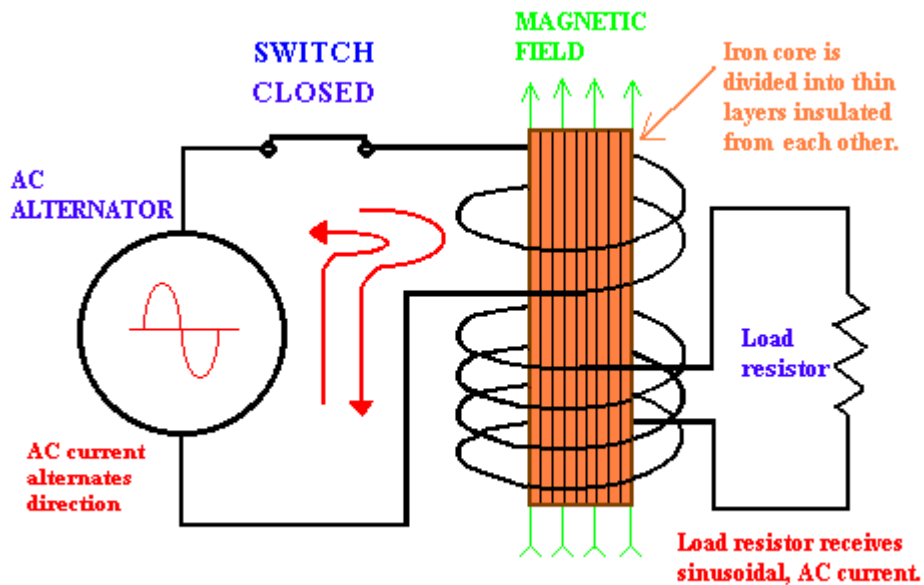
For example, I don’t recommend actually trying this, but suppose you were to plug a well-designed transformer into a wall socket. And suppose that this transformer has high voltage secondary wires left dangling open circuit: Because of the isolation, you could touch either secondary wire without being shocked, even if your other hand were hanging onto a grounded water pipe. Of course if you touch both high voltage wires simultaneously, they will blast you.

A secondary winding is isolated from ground - like a battery floating in mid-air

Think of isolation as a battery hanging from a balloon. Electric circuits require a closed loop in order for current to flow. For the dangling battery, the current can only flow from one end of the battery to the other. There is no relationship to ground. If a person standing on the ground reaches up and touches the battery, no circuit loops are completed, so no current flows.

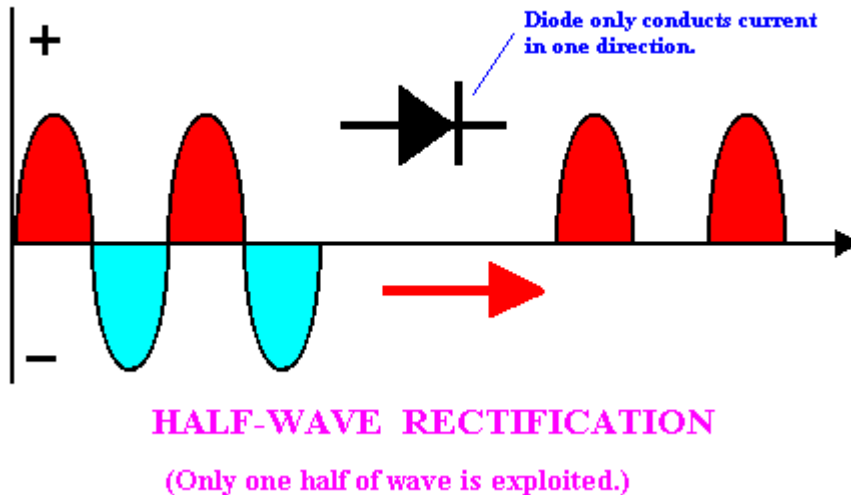


As explained in Chapter 2, transformers can change the ratio of current to voltage in proportion to the number of turns of wire around the core. To convert 120 volts AC to 12 volts AC, the turns ratio between primary and secondary coils would be 10:1. Or, if you needed to generate 1200 volts AC for an oscilloscope cathode ray tube (**CRT**), the turns ratio would be 1:10.



Transformers are not 100 % efficient. They are made from copper wire that has a significant resistance and iron that dissipates a small amount of energy as heat every time a magnetic field is generated or its polarity is reversed. In general, the larger the transformer, the larger the diameter wire used on the windings, the higher the efficiency will be.

Iron has a definite and abrupt limit on how much magnetic field it can support. Once all the iron has been magnetized, the iron will contribute no more magnetic field, no matter how much more current flows through the primary. Obviously, the larger the iron core, the more energy the iron can pass on to the secondary before the iron saturates. As a general rule, the larger the transformer, the more power it can pass through its windings.



Rectification

Most electronic devices require DC voltage to work properly. AC is converted to DC by means of rectifier diodes. Rectifiers are high-power, high-current, high-voltage versions of the diodes used in crystal sets. Referring to the simple power supply shown earlier, the transformer is followed by a rectifier diode. *The diode only passes positive current flow in the direction of the arrow.* This means that current leaving the diode is in the form of “humps,” or half sine waves. Only half of the sine wave is passed through, so a single diode rectifier is called a *half-wave rectifier*. By definition these humps are “DC” since they have only one polarity. Unfortunately, for most electronics applications bumpy, intermittent sine-wave halves are grossly inadequate. For example, if you use them to power a CW transmitter, your signal will sound like an unpleasant buzz and it will take up 120 Hertz of bandwidth. In the 1920s this was often done deliberately to modulate Morse code and make it audible in a receiver without a BFO. If you tried to run a computer microprocessor on these humps without filtering, the processor would reset 60 times per second.

Peak Volts, RMS volts, and DC volts

Obviously sinewaves don’t stand still at any one voltage, so how are they measured? If the sine wave reaches peaks of plus 12 volts and minus 12 volts, then most of the time the output from the rectifier will be much less than 12 volts. Also, the positive voltage seems to cancel the negative voltage so that the arithmetic average of any sine wave voltage is zero. Obviously that measurement isn’t useful either.

Rules are needed to name sine wave voltage and current. As you might expect, *peak voltage* is the voltage difference between zero and the most positive extreme of the waveform.

Peak-to-peak or **PP** voltage means the voltage difference between the most negative peak and the highest positive peak.

As you may know, the voltage that comes out of North American wall sockets is officially named **120 volts AC RMS**. During my lifetime American line voltage has also been nominally called “110 volts AC,” “115 volts AC,” “117 volts AC,” and now it is called “120 volts AC.” Confusing, no? Anyway, the two power wires coming into your house from the power pole out in the alley nominally have 240 volts AC across them. Of course it was formerly called two times 110 volts AC or 220 volts AC. Some people still call it 220 volts. Line voltage is designed so that each of the two wires from the power pole is at 120 volts AC with respect to ground.

As explained in chapter 2, inside your circuit breaker box these two wires are connected to two big metal “buss” bars. There is a third, grounded metal bar that runs down between the two active buss bars. The individual circuit breakers snap onto these bars like cars on a railroad track. Heavy power circuits for your electric stove and clothes drier clip clear across the ground buss to engage both hot lines for a total of 240 volts. Small circuit breakers just clip from one side to the ground bar to obtain 120 volts for ordinary low-power circuits.

The **RMS** or **Root Mean Square** of a sinewave voltage is the peak voltage divided by the square root of two. RMS voltage can be thought of as “the effective average voltage.” It can be used to calculate AC RMS current, power, and AC resistance and impedance. For example, 120 volts RMS is a sinewave with a peak voltage of 1.414 times the RMS voltage. In other words,

$120 \text{ V RMS} \times \sqrt{2} = 120 \times 1.414 = 169.7 \text{ Volts Peak}$. Therefore, ordinary household line voltage could be expressed as **120 Volts RMS, 170 Volts Peak** or **340 Volts Peak-to-Peak**.

Filter capacitors - filtering out the ripple

The half sinewave bumps, which are properly known as “ripple,” must be smoothed out into a continuous DC voltage. This is accomplished by means of a **low pass filter**. In this case low pass means that the filter only passes frequencies well below 60 Hz. DC is of course zero Hertz, which is the lowest frequency possible. The half-wave rectified supply illustrated earlier is equipped with an L-C “L” filter. L-filters are simply two-element filters that represent the two legs of the letter “L.”

Capacitors conduct AC and prevent the flow of DC. Inductors conduct DC but resist the flow of AC current. In an effective DC filter, the component values will be huge, like 10 henries and 5,000 microfarads. This is because the frequency we want to filter out, 60 Hz, is extremely low and big components are needed to have an effect on such a slowly changing sinewave.

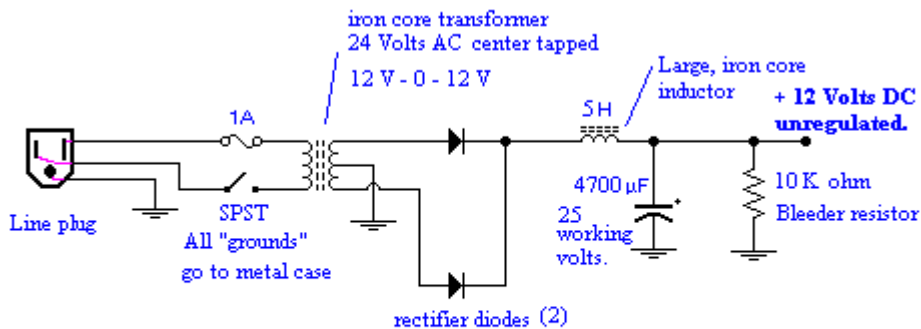
Bleeder resistor across the capacitor

The purpose of the bleeder resistor across the filter capacitor is to discharge it when the supply is not in use. Remember that high quality capacitors will hold their charge for many hours, sometimes days. Bleeders usually aren’t important with a low voltage supply like 12 volts. But if this were a 500 volt supply, a person could get a nasty jolt or burn if they were to touch the capacitor. This could happen even though the supply is no longer turned on or plugged in.

If you were to build the half-wave supply shown earlier and put a 10 watt load on it, with

an excellent transformer and a really huge capacitor, perhaps the DC voltage will at least be continuous. However, there will still be a 60 Hz sinewave ripple or waves impressed on top of it. If you used it to power a transmitter, the tone of the Morse code would have a distinct rough sound as the DC level varies at 60 times per second. When hams gave you a signal report they would say that your signal tone was a number much less than 9. For example, they might send “UR RST 593.” (RST means Readability, Strength and Tone. Hams use a scale of 1 to 5 for readability, and 1 to 9 for both strength and tone.) Because of the harsh note of your tone, you might only rate a “3.” For this reason, transmitter power supplies always use dual rectifiers to produce *full-wave rectification*.

Full-wave rectifiers

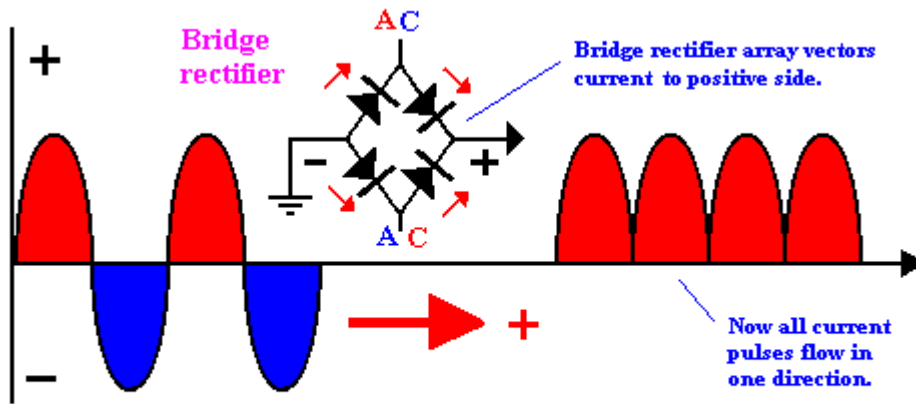


FULL - WAVE RECTIFICATION USING A TAPPED POWER TRANSFORMER

Full-wave rectifiers convert both halves of the sinewave into useful DC current. The DC voltage is now a succession of “humps” with no “off” intervals. With twice as many “humps” per second, the voltage is much easier to filter. Full-wave rectification is a big step toward producing a DC source that resembles the smooth continuous voltage available from a battery.

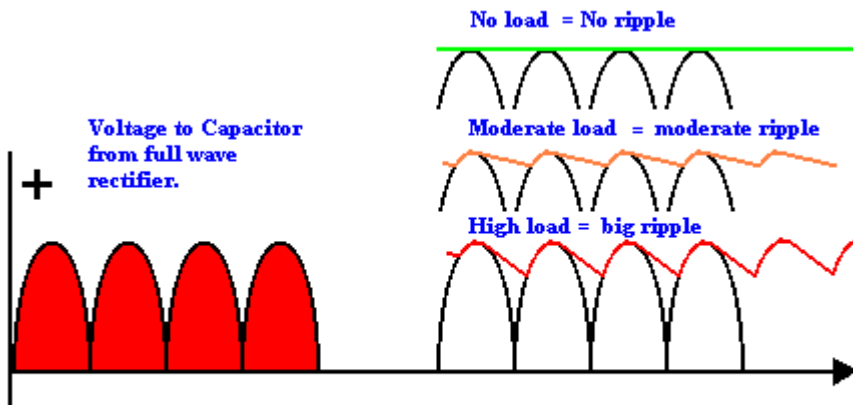
There are two ways to achieve full wave rectification. The circuit above uses two diodes. What you probably didn’t notice at first is that the secondary of the transformer has *TWO* 12 volt RMS AC windings. By having two separate windings, and wiring them in series, one of the windings can be positive at all times. This allows positive current to flow through one of the two diodes at all times and greatly decreases the ripple. Notice that, if we wanted, we could reverse the polarity of the diodes and produce the same waveform with the opposite polarity. That is, if we wanted a *NEGATIVE voltage source* referenced to ground, reversing the diodes would do that.

Bridge rectifiers



FULL WAVE RECTIFICATION
(Both polarities of sinewave are exploited.)

The second way to achieve full wave rectification is to use a bridge rectifier made from four individual diodes. This configuration allows us to get full wave rectification from a single secondary winding. The four diodes are soldered in a diamond pattern as shown above. The AC voltage source is applied across the top and bottom of the diamond. The two diodes on the right are pointed so that the positive current will always flow to the positive side. The left side is wired to ground and the diodes point in such a way the negative current is always vectored toward ground. To say it another way, the positive current always flows “UP” from ground.



Effect of Load Current on Power Supply Ripple.

Ripple

Because the rectifier is supplying current in the form of “humps,” the voltage output across the capacitor will also vary up and down. If the capacitance is large the voltage doesn’t drop to zero during the “valleys,” but it can drop fairly low if the current drain from the supply is large. The more current that is sucked out of the capacitor, the lower the voltage “valleys.” This is illustrated in the drawing above. If the choke is large enough, it will work with the capacitor to smooth out the height of the voltage peaks and raise the level of the valleys dramatically.

With no load current, output voltage charges to the peak voltage

Notice that, if the power supply is not connected to an external load, the output voltage will rise up to the maximum voltage that comes through the rectifiers. For a 12 volt RMS transformer output winding, this is approximately the square root of two (1.414) multiplied times 12 volt RMS volts, or about 18 volts. Referring to the diagram, with no external load the only load on the capacitor is the tiny one milliamperere current passing through the bleeder resistor. This means that the variation in voltage between the humps will be extremely small. In summary, if there is no load on the power supply, to a voltmeter it looks like a “regulated” 18 volt power supply with essentially no ripple. If your 12 volt circuit might be damaged by 18 volts, you must not connect a supply like this to your circuit.

When you first turn it on, the voltage will be 18 volts for a moment before the load current flow is established and the choke and capacitor pull the peak voltage down. RMS (Root Mean Square) refers to the *AVERAGE* voltage of the rectified sine wave “humps.” If the output from the big capacitor were fed directly into your QRP without a regulator, the capacitor would charge toward the peak voltage of the “humps.” Depending on how much current your QRP was drawing, 18 volts might destroy some of the components in your QRP. As the load on the power supply is increased, the output voltage would drop down toward the rated RMS voltage, 12 volts. As the rated transformer load, say 3 amps, is exceeded, the DC voltage will probably drop below 12 volts.

Power transformer saturation

A second purpose of the choke (series inductor) is to prevent the peak current from the transformer from exceeding the current rating of the transformer. If the choke were not located between the rectifier and the capacitor, the current from the “humps” would only flow into the capacitor when the voltage from the rectifiers is higher than the voltage already stored in the capacitor. It is like a tidal pool alongside the ocean. The pool can only fill with water when the tide rises higher than the level of the pool. The result of these pulses of charging current is that the power transformer must provide much more peak current than it may be rated for. If a transformer is rated for, say 10 amperes RMS, and these surges of current are drawn in bursts just a few microseconds long, then the peak current might be 100 amperes. Since the transformer doesn't have enough iron for that, the iron saturates and the transformer inductance momentarily collapses. Suddenly, the transformer will act like a few turns of copper wire shorting out the AC source. Saturation causes the windings and the transformer to heat rapidly and perform poorly.

Substituting big chokes with small, cheap resistors

In the real world, most low voltage power supplies like this solve the problem with a cheap resistor instead of a large, expensive iron core inductor. Resistors waste energy, but what the heck! You can use the resistor with an extra-large filter capacitor that costs less and weighs less than a choke with equivalent filter value. Or, as we'll see shortly, a linear voltage regulator can put a load on the capacitor all the time so that the current flow is not just in short bursts.

Regulators

To provide pure DC at a constant voltage over a wide range of load current, you need a regulated power supply. The regulator's first task is to “trim off” unwanted peak voltage and provide a DC voltage equal to (or similar to) the transformer rated RMS voltage. Regulators

solve the 18 volt over-voltage problem described above. Its second purpose is to maintain constant voltage even when the load resistance is changing continuously or during a line voltage brown out. A regulator circuit is usually added to a power supply like the one above. There are two basic designs for regulators, *linear regulators* and *switching regulators*.

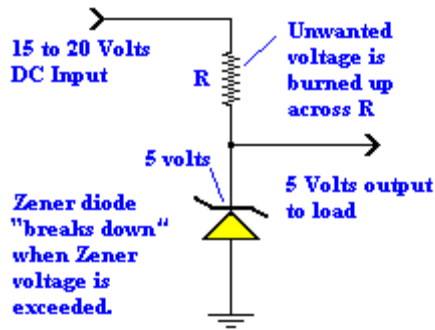
Linear regulators are a sort of automatic variable resistor placed in series with the output of a simple supply like the ones we have been discussing. The regulator uses feedback from the load voltage to change the size of the “automatic resistor” and hold the load voltage constant. For example, in the above power supply the regulator input voltage might vary from say 15 to 18 volts, but the regulator would change its resistance to hold the output constant at 12 volts DC. *A linear regulator not only insures that the load voltage is always the same, it also “trims” off the ripple.*

Switching regulators are more complex circuits that usually involve inductors (or transformers) and switching transistors. They start with unregulated DC and turn it back into AC power. This AC power is then passed through a transformer to generate whatever voltage is needed above or below the original DC voltage. In an equivalent method, the unregulated DC is pulsed through an inductor to generate higher or lower voltages. Some switching regulators work directly off the household line. In other words, the 120 volts AC is rectified without a transformer and results in roughly 120 volts DC that is then converted into AC to drive a small, high frequency transformer or a step-down inductor. For amateur radio work, switchers usually make radio noise that you will hear in your receiver. Yes, commercial radio equipment often use switchers in their designs, but in my experience, getting rid of the switching noise is extremely difficult.

In contrast to switching regulators, some switchers just boost the voltage, but don't regulate the output voltage. These are often called *charge pumps*. The noise from these unregulated charge pumps can be insignificant because they only switch at one frequency and they don't “dither” back and forth trying to hold the output voltage constant. To summarize, *regulated switchers are noisy* and I have pretty well given up trying to use them inside ham equipment.

Zener diode regulators

The simplest regulator is made from a *Zener diode*. It is a “*linear regulator*” because there are no abrupt pulsed signals involved and it works entirely with DC. It dissipates the unwanted voltage as heat. A Zener diode is a modified silicon diode subtly different from the rectifiers used in the power supplies above. Zener diodes are made from silicon that has been doped (contaminated) with extra ions. The extra ions cause the diode to break down at a specific lower reverse voltage when a high reverse voltage is applied. Zener diodes are deliberately manufactured to be inferior rectifiers, but when used as regulators, they are quite useful.



Why ordinary rectifiers don't behave like Zeners

Diodes rectify because the reverse voltage is insufficient to force electrons through the P-side of the P-N junction that has no free electrons. However, when enough voltage or “electrical force” is applied, the P-N barrier breaks down in an *avalanche breakdown*. When this breakdown happens at high voltage and high current, the sudden heat generated often ruins the diode (or bipolar transistor). You may remember the homemade crystal diode discussed in chapter 4. When this crude diode was reversed biased, it broke down abruptly at about one volt. At any voltage above 1 volt, it acted like a short circuit and regulated the load voltage to one volt. At low voltage levels, such a breakdown doesn't necessarily destroy the diode if the diode doesn't overheat. This *Zener voltage* level can also be used as a voltage reference.

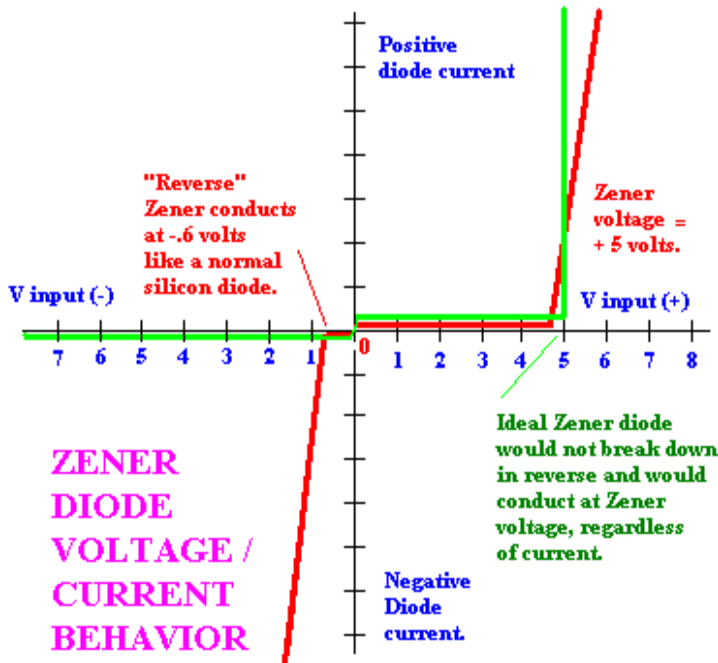
Doping silicon diodes makes Zeners

When big, tough, modern 400 volt silicon diodes are “doped” with extra ions mixed into the semiconductor, the avalanche can happen at lower voltages anywhere below 400 down to as little as 3 volts. Because the load voltage is low, and the load resistance presumably limits the current to a safe level, the heating in the silicon is mild enough that the diode survives the breakdown. In practice, Zener diodes are available from about 3 to 50 volts. 100 volt Zeners would have to be capable of dissipating a great deal of heat or they would be easily destroyed.

In the circuit above the Zener diode breaks down at 5 volts. If one of these diodes is placed across a load, the Zener diode will clamp the voltage to 5 volts so the voltage across the load never rises above 5 volts. Of course the input voltage must always be higher than 5 volts and the unwanted voltage will be dissipated across the resistor in series with the power supply. Ohm's law tells us that at least half of the resistor current must pass through the Zener on its way to ground. So the Zener diode itself is dissipating as much energy as the intended load. As you can see, Zener diode regulators have poor energy efficiency.

Real versus ideal Zeners

If a Zener diode behaved “perfectly,” the voltage across it would be the Zener voltage, no matter how many amperes flowed through the diode. This is illustrated by the **green** curve in the graph below. Unfortunately, the Zener voltage rises with large currents as shown below on the **red** curve. Notice that when the Zener diode is wired backwards, it acts like a normal, forward-biased silicon diode. Conduction starts at about 0.6 volts. What is called “forward” conduction for a normal diode is called reverse conduction for a Zener diode.

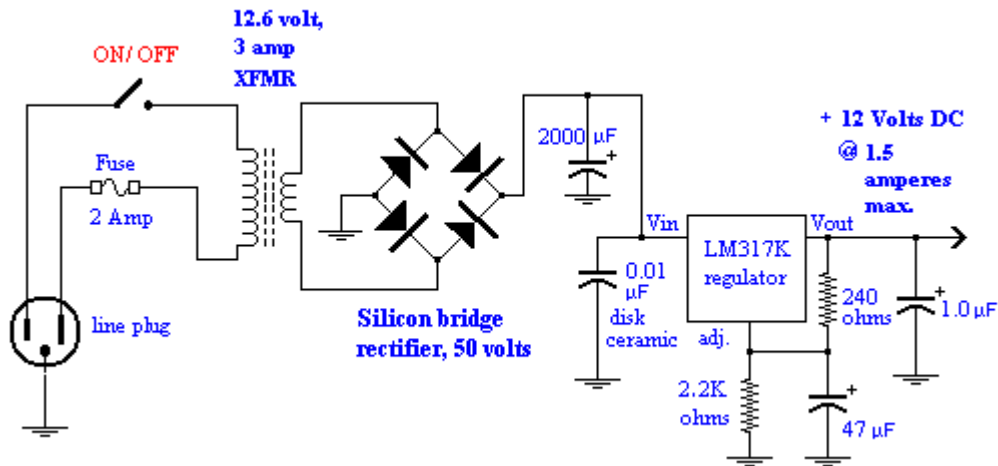


Zener diodes are impractical for heavy current regulation. They not only dissipate energy in the series resistor R, they also burn up energy in the diode. Moreover, as the diode current rises, the Zener voltage can be significantly different from its nominal value. In practice Zener regulation is used for light loads over a narrow range of input voltage. As you will see later, Zeners can be used as **VOLTAGE REFERENCES** to run a transistor regulator. In this way, the regulation can be fairly good and energy isn't wasted.

This will be illustrated in an application later in this chapter.

A homebuilt, line-powered power supply for a QRP

Now let's be practical: The 12 volt supply below worked well for me and can be assembled entirely from parts at your local Radio Shack.



This 18 watt regulated line-powered supply should be built in a metal chassis. The round ground pin from the line cord should be connected to the chassis. In that way, if the "hot" black wire should break and touch the chassis, the metal would not become dangerous to touch. A 2 to 5 ampere fuse in series with the line input protects the supply. The ON/OFF switch should be rated for 250 volts DC and at least 1 ampere. The line cord should pass through a rubber grommet on the way into the chassis. Once inside, the line cord should be clamped to the chassis

so that, if someone picks up the power supply by the cord, the force will be on the clamp and not on the solder joint where the line cord is fastened to the fuse and switch.



The transformer is rated at 12.6 volts RMS at 3 amperes. I used Radio Shack part # 273-1511. The rectifier is a generic silicon bridge rectifier rated for at least 50 volts @ 3 amperes. Alternatively you could use 4 individual rectifiers arranged as shown above. The filter capacitor following the rectifier just needs to be large and greater than about 25 working volts. The other three capacitors serve to stabilize the output and prevent oscillations and ripple. Adding a 12 volt dial light so you will know when it is on is a nice touch.

The LM317K programmable voltage regulator

The LM317K regulator chip is packaged in a TO-204 (formerly known as TO-3) metal case and can deliver 1.5 amperes. To dissipate the heat, the TO-204 case should be bolted to the metal chassis and insulated by means of a mica washer and silicone grease. Mounting kits for this purpose are also available at Radio Shack. This regulator chip works by regulating the voltage between the V_{out} terminal and the "adjustment" lead on the regulator. The regulator regulates this voltage difference to 1.2 volts. This low voltage allows the designer to regulate voltages equal to or higher than 1.2 volts. In this 12 volt application, the regulator passes current through a 240 ohm resistor and regulates the voltage across the 240 ohm resistor to 1.2 volts. This results in a "current source" that drives a constant current through the 2.2K resistor to ground. This increases the total regulated output voltage from 1.2 up to 12 volts. In other words, 240 ohms is about 10% of the sum of 240 ohms plus 2200 ohms. Because you can "program" the total regulated voltage, this same regulator can be used to regulate voltages from 1.2 volts up to about 20 volts.

Another reason you need good voltage regulation is that the tuned stages in your QRP don't take kindly to changing the supply voltage. If you tune up the antenna using 12 volts, and the voltage later goes up or down, the tuning of some stages may change slightly and your signal might crash in the middle of a QSO (conversation).

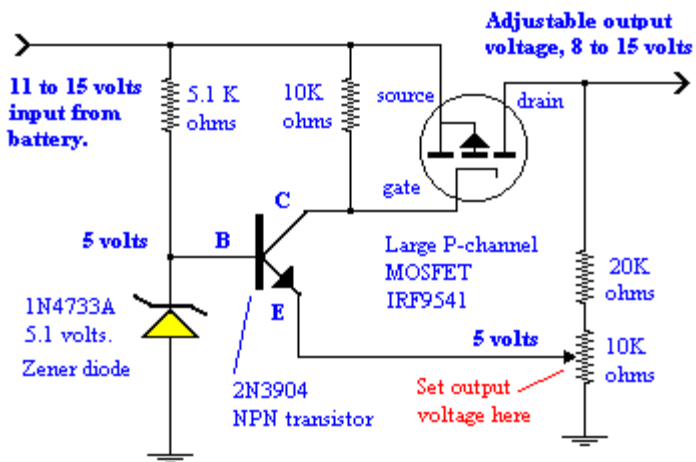
The LM317K "clips off" any voltage above 12 volts so your QRP will never see a higher voltage. Notice that the LM317K is a ***linear regulator***. This means that it turns any input voltage that is above the regulation voltage into heat. This seems wasteful, but linear regulation makes no radio noise and produces a flat output voltage with practically no ripple. Notice that the choke (or a resistor) is not necessary here because the regulator is drawing current from the

capacitor nearly all the time. This means that the current is flowing from the transformer nearly all of the time and will not be saturated by high current pulses.

This power supply violates my goal to never use integrated circuits. If there are purists who share my aversion to integrated circuits, the “low dropout” regulator shown below can be substituted for the LM317K regulator. A larger power supply than this would be more versatile and could power a bigger transmitter. Obviously, the higher the power level, the more cumbersome the regulation becomes. Running a 100 watt transmitter requires a 300 watt regulated power supply. I sidestepped this project by running my entire ham station on a solar-charged 12 volt battery which is described later in this chapter.

A low dropout voltage regulator for use with a battery

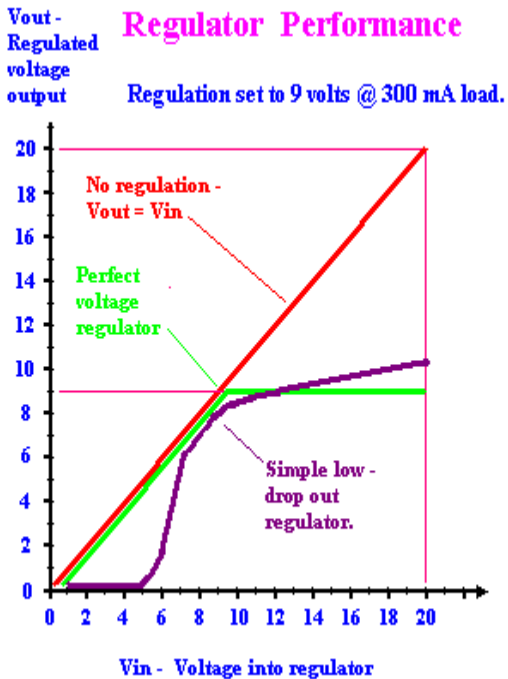
As you will read shortly, two 6-volt lead-acid golf-cart batteries make a fine, high-current 12 volt power supply. Unfortunately, running your transmitter on batteries means that, when the battery is ready to be recharged, its voltage will drop down to 11 or even 10.5 volts. This means that (ideally) your QRP must be tuned up to run on 10.5 or 11 volts and then regulated to that level. Remember that *a linear regulator can only deliver LESS than its input voltage*. So if you’re running on a 12 volt battery, you need a regulator that wastes as little voltage as possible. This waste voltage is called *dropout*. The regulator shown below receives nominal 12 volts from a battery. The active regulation element is a big P-channel MOSFET transistor. This transistor can be arbitrarily large. The bigger it is, the less voltage it will waste across its internal resistance and the lower the “drop out.”



The P-channel MOSFET transistor turns on (conducts current) when its gate voltage is pulled downward toward ground. So when the battery voltage drops, the gate voltage must be pulled down (toward zero volts) to turn the MOSFET more on. When the battery input voltage rises, the gate voltage must be raised to turn the transistor more off and restore the output to the set voltage.

Low Dropout 12 Volt Power Supply

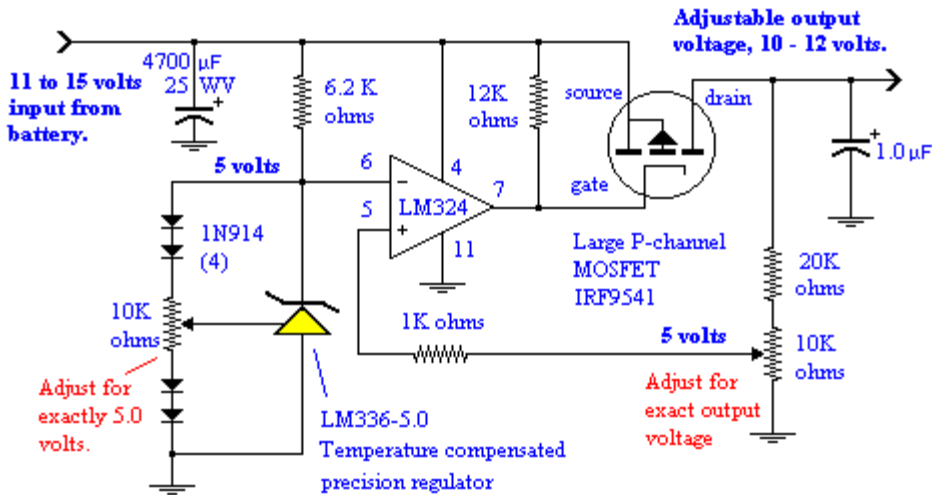
The gate voltage control is done with an NPN bipolar transistor. The transistor compares the reference voltage across a 5 volt Zener with a fraction of the output voltage across the sense resistor pot on the lower right. The slider on the sense resistor contacts the resistance at a level that produces about 0.6 volts less than 5 volts. As the output voltage rises, the voltage on the sense resistor rises. This in turn increases the 2N3904 emitter voltage. The difference in voltage between the base and emitter drops, causing the drive to the NPN transistor to drop. As the NPN transistor turns more off, the gate voltage on the MOSFET rises toward the battery voltage and turns the MOSFET more off and lowers the regulated output voltage.



The **purple** plot on the left shows the performance of this simple power supply when it has been set to 9 volts with a 300 milliamperere load. The **red** line shows the voltage the load would receive if there were no regulation. That is, $V_{in} = V_{out}$. The **green** line illustrates the performance of an ideal or perfect linear regulator. If the transistors had infinite gain and the Zener diode always produced precisely the same reference output voltage, then the green curve is what you would get. As soon as the regulator is given 9 volts input, it would deliver exactly nine volts, no matter what the load was. As you can see, the simple regulator isn't radically different from the ideal, but it is far from perfect.

A precision, temperature-compensated, low-dropout regulator

More nearly perfect regulation can be achieved by replacing the NPN transistor with an operational amplifier. Operational amplifiers, "op-amps," are integrated circuits composed of many or even dozens of transistors. Op-amps perform as though they were nearly perfect transistors. Similarly the LM336 voltage reference is an integrated circuit made from bunches of transistors that perform as though they were a nearly "perfect" Zener diode. As the voltage across the regulator is varied, the voltage across the Zener remains constant within a couple thousandths of a volt.



Low Dropout 12 Volt Power Supply with Precision Regulator

The op-amp is the triangle in the center. This op-amp has 14 pins and the numbers shown are the pin numbers. This particular chip contains four op-amps. Only one is used in this circuit. Pins 6 and 5 are the inputs. The input pins function in such a way that the op-amp changes the output voltage (pin 7) to “try” to keep the two input pins at the same voltage. That is, so long as the voltage on pin 6 is identical to the voltage on pin 5, the output remains constant. When the **positive** pin 5 has a higher voltage than the **negative** pin 6, the output pin will shoot positive as high as it can go. When the negative pin 6 is higher than pin 5, the output pin will zoom negative as low as it can go.

Unlike simple transistors, the op-amp has nearly infinite voltage and current gain. Gains like 100,000 or a million are common. Also, the inputs draw essentially no current. They have nearly infinitely high input resistance. This means that op-amps are ideal to “monitor” some condition, such as the output voltage from the power supply, and then change the OP-AMP output pin voltage in order to restore the supply to equilibrium. Looking at the diagram, pin 6, the negative input, always rests at 5.00 volts, so long as the battery voltage input is above 5 volts. The output voltage pot at the lower right is adjusted to produce the desired output voltage. The big MOSFET transistor will remain turned on to the exact degree to deliver the voltage you set. This set point is the place where 5 volts appears on the pot. As soon as the op-amp “sees” that pins 5 and 6 have the same voltage, the output voltage on pin 7 holds still and stops changing.

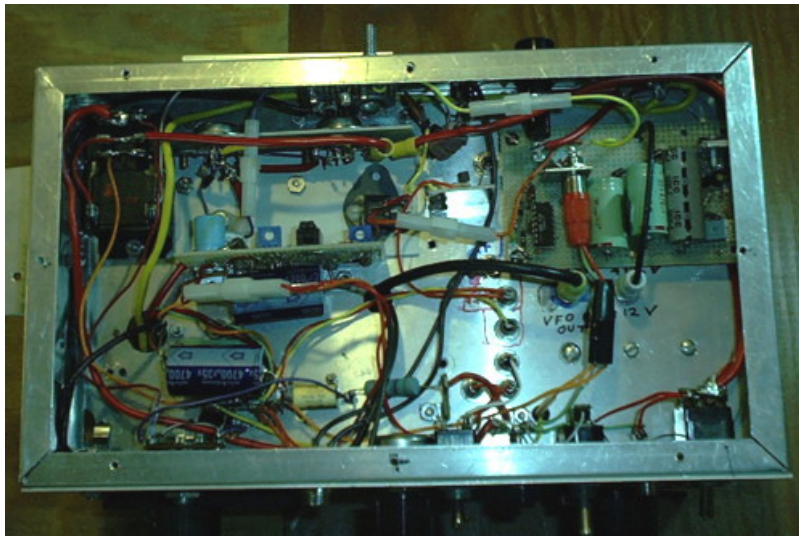
A precision Zener diode

The LM336 precision Zener diode is not only extremely accurate, it will maintain its accuracy over a wide temperature range. Speaking of temperature change, don’t forget to bolt your MOSFET to a big heat sink. At high input voltages and big load currents, you may expect the MOSFET to get boiling hot without a heat sink. Keeping it cool keeps its internal resistance low and improves the regulation. The metal flange on the transistor should be insulated from the heat sink and metal chassis with a mica insulator and silicone grease.

As we shall see in chapter 10, building a variable frequency oscillator that reaches modern standards of frequency drift requires the use of a super-regulated power supply. This in turn will require you to use regulators made from integrated circuits. Sigh. Of course you could prove me wrong by building one with discrete parts.

Packaging power supplies

The photo below shows the underside of my all transistor CW transmitter. It is based on the modules described in chapters 6, 10, 11 and 12. The low dropout 12V QRP power supply is located just to the left of the center. The circuitry is mounted on a commercial perforated circuit board. This circuit board is standing on edge but the blue trim pots that adjust the LM336 and output voltage can be seen. The P-channel power MOSFET that controls the output is just above the board. The transistor is insulated from the chassis with a plastic screw and a gray silicon pad.



The perf-board circuit at the upper right with the three large capacitors is the precision supply for the VFO. The two large TO-204 transistors mounted vertically are the CW keying transistors for the 100 watt linear amplifier. The black relay at upper left is the main DC relay that engages the 12 volt battery during transmit.

Each module is mounted to the chassis with Molex or other connectors so that it may be easily repaired or replaced. Phono plug connectors are used as feed-through connectors wherever needed.

**

BATTERIES AS A POWER SUPPLY

The beauty of batteries

As I mentioned earlier, I run my whole station on solar power stored in a 12 volt battery. Now I know this sounds like tree-hugging, liberal silliness, but my solar powered station came about quite logically and has many advantages for a homebuilt station. There are lots of hams that do this - and no wonder! A lead acid storage battery is a wonderful power supply. It puts out huge currents whenever you need them and the voltage regulation is excellent. The best advantages are that batteries make no switching power supply RF noise and there's no waste heat from a big linear regulator.

My return to ham radio began in 1997 when I hauled my 1967 homebuilt mobile ham rig

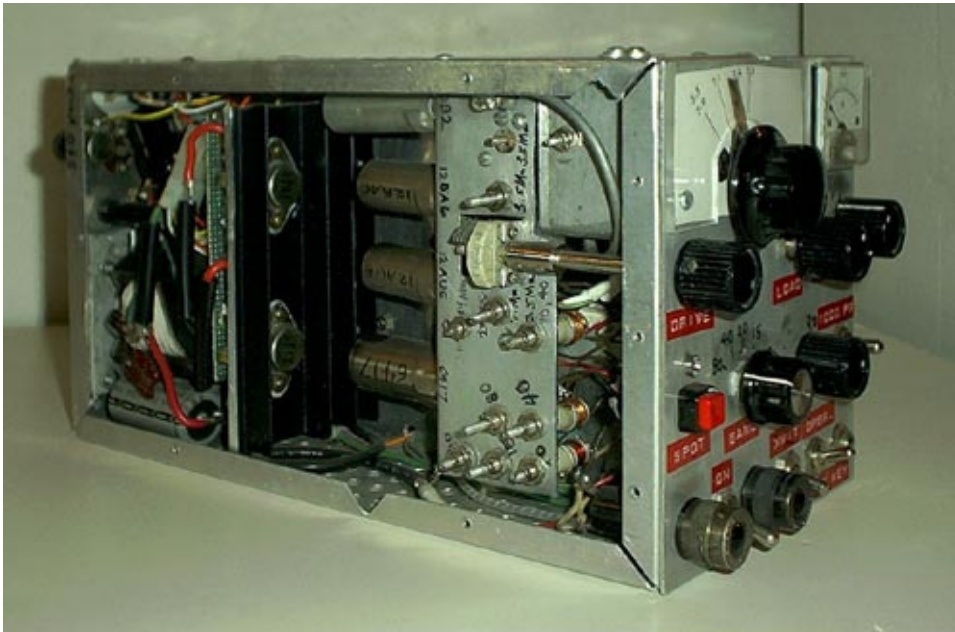
down from the attic and blew off the dust. Since my old mobile rig runs on 12 volts, I couldn't even try out the receiver without a heavy-duty 12 volt power supply. I considered building or buying a supply but after 10 seconds I decided that was ridiculous. I happened to have some 6 volt golf cart batteries in the garage. I hauled two of them down to the basement and put on an automotive 12 volt trickle charger. After a day, the batteries recovered and I could fire up the rig. AM phone was extinct, but there was nothing to stop me from getting on CW, which I did with good success. Well, that's not quite true. My adventures included a drifting VFO and a blown 200 watt charge-pump switcher, but those problems had nothing to do with the power source.

My old vacuum tube rig was a power hog. The receiver drew 3.5 amperes at 12 volts. That's 42 watts just to listen! The transmitter was much worse, of course, but it wasn't dramatically worse than a transistorized rig. After all, a transmitter can't radiate big power if it doesn't draw big power. Moreover, a modern, linear, class A transistor rig can be even more inefficient than an old Class C vacuum tube transmitter. Either way, my transmitters draw 6 to 20 amperes.

Compared to a golf cart or an automobile starter motor, a ham rig is a low power device. 20 amperes should be plenty of current. A deep-discharge storage battery is best, but there's no reason you can't use an old car battery. Those of us who live in snow country routinely discard car batteries when they can no longer supply 400 amperes on a frigid January morning. But even an old car battery will usually supply 20 amperes for five minutes without appreciable voltage drop. All you need to do is keep a small, one-ampere charger on it continuously. For anyone on a budget, a free used battery is a darn cheap high current regulated supply.

Requirements of a line-powered 20 ampere, 12 volt supply

I don't plan to build an equivalent line-powered power supply. But if I did, I wouldn't build a switching power supply. I've had zero luck running ham equipment on switchers. If the switcher is more than just an asynchronous charge pump and actually regulates the output voltage, then it will make RF noise which you'll hear in your receiver.



A 1967 homebrew all-band transmitter with a switching power supply running on 12 volts DC

The 150 watt switching supply is at the left rear. Originally the supply was a simple charge pump that used germanium power transistors. It consisted of a free-running multivibrator (square wave oscillator) circuit that drove a step-up transformer with no feedback. The supply worked well and didn't produce audible hash in my receiver. Then one day a germanium transistor blew and I was unable to find a suitable replacement. Germanium transistors seem to be extinct in the modern world – they can't really compete with MOSFETs. I rebuilt the supply using a modern pulse width modulator regulation system and MOSFET power transistors. An elegant feature of the new switcher was that the output voltage was adjustable. Just by turning a knob I could vary the transmitter output power from 20 to 80 watts.

Unfortunately, the switcher and the RF amplifier stages “talked to each other.” That is, when the load increased, the supply increased the pulse width modulation to compensate, but not without a slight delay. This subtle ripple or “jitter” was hard to see on a scope, but no matter how much I filtered the DC high voltage, the jitter appeared as a slightly rough note on the CW signal. In practical terms, I kept getting 598 RST reports.

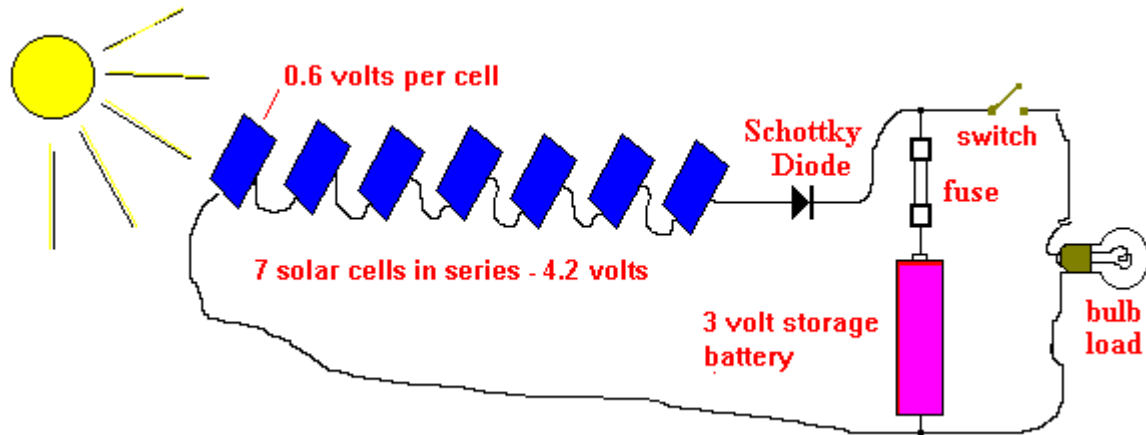
There was an elaborate 12 volt switcher in QEX magazine a few years ago that solved the jitter noise problem. I was delighted to see that I wasn't the only one who noticed “jitter noise.” The problem is real, but after seeing the complicated Rube Goldberg solutions, my desire to build one vanished.

If I had to build such a supply again, one method would be to build a charge pump or other unregulated switched system that boosted (or lowered) the input voltage to just above the desired voltage. Then I could use a linear voltage regulator to accomplish the regulation function with a minimum of waste heat generated. This is the low noise approach I used to power my super-regulated miniature VFO power supplies described in chapter 10.

One idea I've had for a high power charge pump would be to use a manually adjusted pulse width for the AC generation. This way the output voltage could be manually set so that the linear regulator would waste as little energy as possible. This regulation margin would depend on how consistent my line voltage was and how stiff the charge pump conversion system was. For example, starting with 120 volts AC, the charge pump might lower the voltage to say, 18 volts DC. Then the linear could reduce the 18 volts DC down to 12 volts.

Going solar

Because my automotive trickle charger was feeble, I was charging non-stop. Even then, I was having trouble keeping the battery charged for a couple hours of daily operating. However, I already owned a 12 watt, 12 volt solar panel which I installed on the roof.



A simple solar charger circuit

Solar cells are a kind of silicon diode. They are arranged in series so that the forward voltage drop of each diode adds up to some voltage greater than the voltage of the storage battery. For example, at 0.6 volts per solar cell, we need at least 20 cells in series to raise the panel voltage higher than the 12 volt battery. Typically, an open circuited panel puts out 20 volts in bright sunshine. This extra capability insures that it will continue to charge a 12 volt battery all day and implies that there are roughly thirty 0.6 volt cells in series. Solar cells are interesting to play with. I was surprised to discover that if you put your hand over just one of the series cells, it turns off the whole string, something like Christmas tree lights wired in series. This means that just one wet leaf stuck on your panel can turn off the whole array.

The panel output current is proportional to the sine of the angle the sunlight makes with the panel. If your object is to produce the maximum kilowatt-hours during the entire year, then the angle should equal the latitude. I mounted my panel at 45° , which at 40° latitude, gives me better performance during the winter. Optimizing for winter is smart because the days are short and the panel is often covered with snow. Actually 50° may be better here in Colorado. Snow slides off a steep incline and higher angles are more resistant to hail damage. On the other hand, mounting them on a steep frame may make them subject to wind damage. There is no way to win. Many people just mount the panels flat on whatever roof they happen to have. If you wish to sacrifice some percentage of the output for beauty or mounting convenience, that's your decision.

The "lunar discharger"

It's bad form to connect a solar panel directly to a storage battery. The solar cells are forward biased diodes with respect to the battery. Therefore, whenever the sunlight quits, the panel voltage may drop below the battery voltage and a small battery current will reverse and flow through the solar panel. In other words, at night, the solar charger becomes a "lunar discharger." (Never mind. That was a silly joke.) If there are enough extra solar cells, then the night-time voltage drop may still exceed the battery voltage. In any case, the discharge problem is typically prevented by a silicon diode in series with the panel to insure that current is never allowed to flow from the battery back into the panel. Since this check valve diode has a forward voltage drop that wastes energy, you may as well use a big Schottky diode that will only penalize

you with 0.2 volts instead of 0.6 volts loss.

Another small issue is lightning protection. My panel is on the roof where, in theory, it might attract a lightning bolt. I'm not really worried, but I have a connector on the lead from the panel so I can disconnect it from my shack when I go away on trips or whenever a storm is particularly frightening. If I lived on a mountaintop or if my house were higher than the other houses in my neighborhood, I would be more concerned.



Solar panel on the roof

I built my panel frame out of varnished wood. The wooden boards screwed down to the roof retained water against the shingles and rapidly rotted. I replaced the boards with 2 inch aluminum angle stock which seems to be a more permanent fix.

Conservation helps

My solar panel charges about as much as the line-powered trickle charger, about 1 ampere. Consequently I still had to use line power to charge occasionally whenever I stayed on the air too long. A breakthrough came when I built my new transistorized receiver, the one described in Chapter 13. The new receiver draws 120 mA. That sure beats 3,500 mA. Since then, I haven't needed my line-powered charger.

12 Volt power distribution

A storage battery can deliver hundreds of amperes, so it's wise to isolate the battery from your rig and solar panel with an appropriate fuse. A 30 ampere fuse should be about right. I have a master switch to isolate the battery from the ham rig when I'm not using it. A little LED pilot light tells me when it's connected and a voltmeter warns me if the battery is not fit for use. I also have charging and discharging ammeters (ampere meters) so I know the status of my supply at all times. I find the discharge meter helpful for monitoring my transmitters. You can even tune the antenna while watching the battery current. The wire in front of the charge meter goes to my 12 volt desk lamp.



Battery charge monitor

Maintaining clean battery contacts is critical to keeping the supply voltage constant under load. Every few months, I clean the contacts using baking powder and water. I know the battery contacts need cleaning when the pilot light on my transmitter begins to flicker noticeably while I'm transmitting. I top off the batteries as needed with distilled water to keep plates in the cells from being exposed to the air. A gel-cell battery shouldn't have these corrosion and fluid loss problems. However, if you overcharge a sealed gel-cell, the water cannot be replaced and the battery will be permanently damaged.



The 12 volt storage battery power system

The storage batteries are shown above. The transistorized inverter to the left of the batteries converts 12 volts DC to 120 volts AC for those rare times when a storm knocks out our commercial electricity. On those occasions I have simply strung an extension cord upstairs to power the TV and few lights. The glass and rubber device is a *hydrometer* for measuring the specific density of the battery acid. When the glass float rides high in the green zone, the battery is fully charged.

Storage battery safety

My power system is small and I rarely have to add distilled water to my batteries. This tells me that my use of stored energy and the output of my small solar panel are well-matched. If I were having to add water constantly it would mean that I was wasting energy and converting the water into gaseous hydrogen and oxygen. This situation could be potentially dangerous. If I had

a large system powering more of our household needs, the likelihood an explosion would be serious. Therefore, a large storage battery array should be located out in a well-ventilated place like a garage. Moreover, the state of the batteries should be continuously monitored with an electronic regulator to be sure that the batteries are not overcharged and generating significant amounts of hydrogen. Charge control regulators are mandatory in any large system.

I once read an article written by a fellow who was in charge of maintaining remote microwave relay stations. Wind turbines powered the stations, but the power systems were not equipped with any means to turn off the charging current to the batteries during windstorms. The results were catastrophic explosions inside the stations. Eventually, the phone company realized the problem and put in charge control regulators.

In summary, I get a kick out of operating like a fully solar-powered Field Day station. Because the whole station runs on 12 volts, in theory I'm always ready for Field Day and there's nothing to stop me from going mobile. One of my back-to-nature dreams is that, during a power failure, I can go right on operating and thumb my nose at the evil corporate power monopoly. Twice during power failures I have galloped downstairs in the dark to make my first 100% truly independent radio contact. But before I could even tune the transmitter, the *#@%!\$ lights came back on. Oh, curse those efficient fellows at Xcel Energy Company!

**

LED THERE BE LIGHT

Emergency Station Lighting

As explained above, I run my whole station on solar energy stored in a 12 volt battery. An advantage of battery power is that I operate free from the power grid. This saves very little money, but it's quite romantic. Of course at night, even on batteries I need to keep a log and throw the correct switches. Using candles or a flashlight clenched in my teeth didn't seem very sophisticated.

My first idea was to dangle a 12 volt automotive light bulb over my shack. My buddy Bob, NØRN, uses such a light in his tent on Field Day. This solution is completely practical, but it seemed old-tech and boring. It also draws about 10 watts of power. If I am going to all the trouble to build a custom 12 volt light, I figured it should at least be *an interesting light*. Modern lighting methods produce more light per watt than tungsten bulbs. Also, energy conservation is important when your station is powered by a battery charged with a small solar panel.

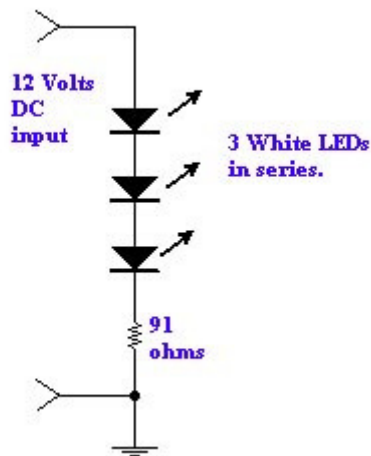


A homebrew LED and fluorescent station lamp

White LEDs – a modern marvel.

I happened to notice some “white LEDs” for sale down at Radio Shack. (Part # 276-320) I thought cynically that they were probably really dim and not really white. I bought one and hooked it to a variable power supply. I slowly turned up the voltage until I obtained the rated 20 mA DC current. Hey! Not bad! The beam of white light has a slightly bluish cast, but otherwise, it throws a spot of light out to a couple feet. It’s rated at 1100 mcd. That’s impressive brightness when you consider its beam angle is 100°. One LED makes a perfect key chain light and many LED flashlights are now on the market.

I wrote this section some years ago. Since then, screw-in 12 volt light bulbs consisting of large clusters of white LEDs have become available. I now have one in the shack that draws 3 watts and delivers considerably more light than the two systems below. Even so, there are lessons to be learned from my experimenting below. The switching power supply described for the fluorescent light is a design I have used often for several applications.



I'm told these white LEDs are made from sophisticated layers consisting of yellow and blue LEDs and a phosphorous that glows white. As LEDs go, it has a rather high voltage drop, 3.6 volts. I figured if I put three in series plus a single dropping resistor, it could run on 12 volts. The current is limited with just one 91 ohm resistor. The resulting triple light consumes just 0.25 watts and is adequate for keeping a log and operating the station. That's amazing when you think about it. We routinely squander hundreds of watts to illuminate entire rooms when all we really need is $\frac{1}{4}$ watt to read our newspaper or book.

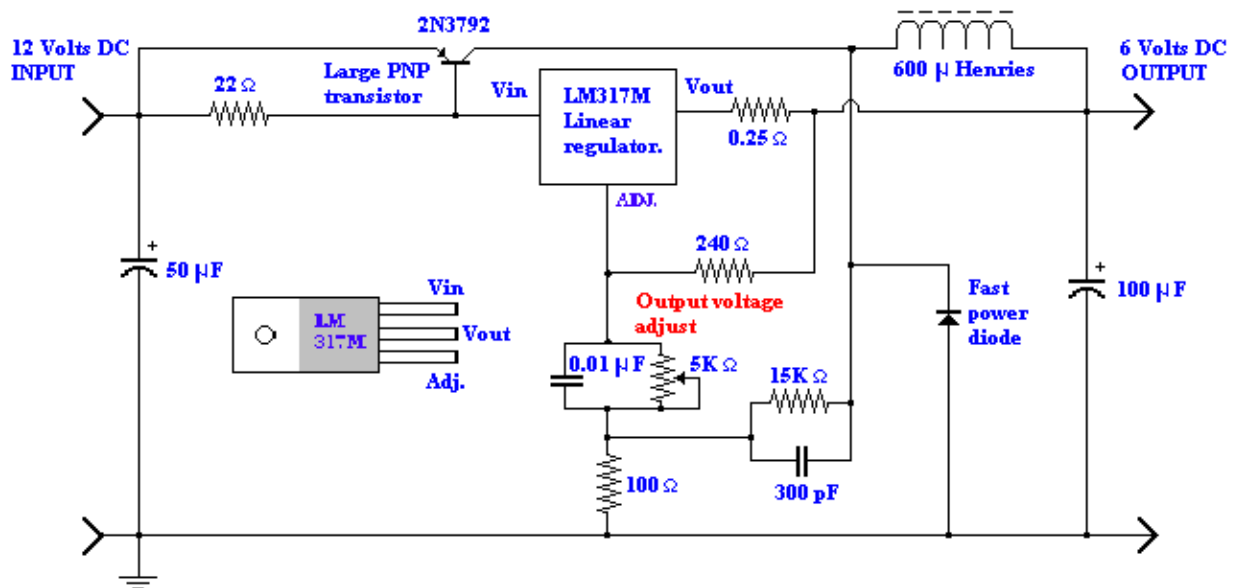
Flourescent lighting

Unfortunately, "adequate" isn't the same as "comfortably bright." So my next project was to build a 12 volt powered compact fluorescent. I fiddled for a couple hours trying to build a power oscillator capable of producing the required 800 Volts AC needed to ignite the miniature fluorescent bulb. I had several transformer and switching transistor problems that I was having trouble solving. I also fried my voltmeter because I forgot to change the range when I put it on the high voltage. There's nothing like dead test gear to make you think differently.

I remembered that I still had a 6 volt fluorescent lamp that I used to use for lighting my pup tent while camping. One day I rolled up the tent while the light was still hanging from the tent ceiling. Oops! The plastic housing was splintered and the remains of the light assembly were still in my junk box. I found the parts of the light and resoldered the broken wires. I connected it to a 6 volt power supply and it still worked fine. Next I built a shiny reflector/lampshade out of sheet aluminum and it produced loads of light. Unfortunately, I need a 12 volt light, not a 6 volt light. I didn't have a second light to put in series with the first, so I used a big dropping resistor to run the light on 12 volts. That worked OK, but it seemed pretty crude. Besides, I was already "cheating" because I hadn't built the fluorescent high voltage supply.

Nifty "buck-type" switching power supply

I replaced the dropping resistor with a switching power supply to reduce 12 volts DC down to 6 volts. I got the design from the National Semiconductor data book. Using the switcher the fluorescent light draws about 2.5 watts at 12 volts. The switcher is about 80% efficient. That is, it dissipates 10% of the total energy. In contrast a resistor would have dissipated 50% of my energy. I have used this little supply design for several home projects so far and found it thoroughly reliable. If you're a homebuilder, this simple, buck-switcher belongs in your bag of tricks. If you're bored with building a 12 volt light, maybe this little switcher will interest you.



STEPDOWN SWITCHING POWER SUPPLY

(12 Volt DC to 6 Volt DC Converter)

Switching power supply made from a linear regulator

How can this work?

This switcher uses a LINEAR regulator to generate the pulsewidth modulation needed to implement a switching power supply. This is essentially the same linear regulator used in the suggested line-powered QRP power supply. But, when you put a scope probe on the inductor, sure enough! The linear regulator is switching full on and off in rectangular pulses. Apparently the 15K Ω resistor and 300 pF capacitor are coupling a feedback pulse from the inductor into the regulator to cause it to switch full on and full off. The pulse width varies with load and responds just like a real switcher. Aside from my amazement that linear regulators can work as switchers, I was also surprised that I hear very little switcher noise in my receiver. The RF noise it produces is apparently sufficiently isolated from the receiver that I rarely hear hash competing with the ham signals. On the rare occasions when I do hear it, I simply turn off the fluorescent.

Subjectively, the fluorescent produces roughly twice as much light as the LEDs. In other words, for ten times as much power the light seems to be twice as bright. On the other hand, it illuminates a much wider area than the LEDs, so I just run both of them simultaneously. The LEDs illuminate my log and scratch pad while the fluorescent lights up the station as a whole. I've used this light for hours at a time. It's bright enough that I'm content with it and I don't think about running across the room to turn on "the real lights." In summary, battery power and energy conservation are entertaining games. And, if we're really unlucky, someday our hobbies might even be useful in a community crisis.

CRYSTAL SETS TO SIDEBAND

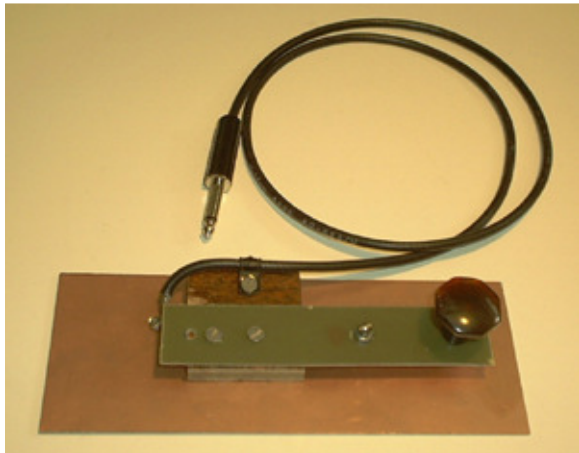
© Frank W. Harris 2010, REV 12

Chapter 9

ACCESSORIES & SKILLS

A MORSE CODE KEY

“Straight keys”



A simple telegraph key

A telegraph key for sending Morse code is an easy mechanical project. All that's needed is a reliable spring-loaded switch. The fingers contact a simple knob on a lever. The operator rests his wrist and forearm on the table and grips the knob with two fingers and a thumb. The operator pushes down on the knob, closing the switch contacts. A “straight” key like this is used to send both dots and dashes. The timing of the dots and dashes is totally dependent on the operator.

Commercial straight keys, especially the old ones, are made from elegant machined brass parts and springs on engraved Bakelite plates. The exact tension and gap width can be adjusted to each operator's preference. This sophistication is nice, but not essential for a beginner sending at low speeds. A straight key is good for code speed up to about 15 words per minute. Faster speeds are tiring and hard to send well.

The straight key shown above was made from two pieces of single-sided printed circuit board. The upper sender lever board serves as the spring and its underside is the conductive surface. The switch contact consists of a machine screw that touches the grounded lower board when the lever is pushed down. Two nuts on the screw adjust the contact distance. Most operators like to adjust the switch contacts so that the travel is about 1/32 inch. The spring action of the lever should be strong enough so that it breaks the contact sharply when the lever is released, but not so much force that it is tiring to use. The two pieces of circuit board are insulated from each other by a small block of plywood. The knob is a plastic pull handle from a drawer.

Several articles in QST have appeared in recent years describing how to make keys out of household junk. Most of these keys are really “paddles,” rather than straight keys. Paddles are keys that are pressed side-to-side instead of just downward. Paddles have two switch contacts and are used to control automatic “keyers” of the kind found in modern transceivers. When the paddle is pushed to the left, the keyer automatically generates perfect dashes. When the paddle is pushed to the right, the keyer pauses the exact length of time and then automatically makes

perfect dots. It would not be hard to adapt the mechanisms described in those magazine articles to make a “straight,” up-and-down key.

Mechanical bugs

No, we’re not talking about a mechanical glitch, we’re talking about a type of telegraph key. The next step up in sophistication from a straight key is a mechanical “*bug*.” This telegraph key is activated with a paddle. When pushed to the right, it automatically makes dots, so long as the operator deflects the paddle. Mechanical bugs make the dots with a weighted beam that swings back and forth propelled by a weak spring. A dot occurs whenever the swinging lever closes the “dot switch.” When the bug paddle is pushed to the left, it closes the “dash switch.” The operator must make each dash manually. So unlike a modern keyer, the operator provides the timing for dashes. Mechanical bugs like this were standard among commercial radio-telegraph operators and hams for many years. Railroad telegraph operators also used them.

You can still buy commercial mechanical bugs. At one time there were even complex versions that generated both dots and dashes automatically. A mechanical bug is a difficult basement project without a machine shop. It would require a great deal of patience to make a reliable mechanical bug, but it can be done.

Homebrew electronic keyers with automatic dots and dashes are a common homebrew project. Most hams just buy a keyer kit that has a tiny, pre-programmed “PIC” microcomputer chip that does all the difficult timing chores. Since a pre-programmed chip didn’t fit my rules for “homebuilt,” I built a homebuilt electronic bug that makes automatic dots but requires manual dashes.

**

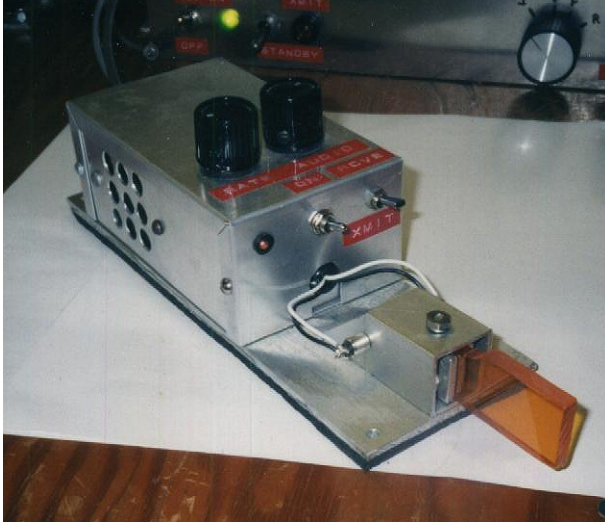
A HOMEBREW ELECTRONIC BUG

No matter how I adjusted the screws and cleaned the burned contacts on my 45 year old mechanical bug, the dots sounded more like static. Of course, if I had bought a quality bug in the first place, it would still be working. While I was trying to get the old bug working properly, it occurred to me that my key was the only part of my rig that wasn’t homebrew. Ah ha! - a challenge!

I didn’t see how I could build a decent mechanical bug with my limited tools. However, I figured that an all-electronic key that generated both dots and dashes automatically couldn’t be too hard. I began prototyping a logic circuit based key on a large plug-in board. I quickly discovered that implementing automatic dashes wasn’t so simple. The dashes had to be timed with respect to the dots and there could be no overlap. Moreover, the spaces between dots and dashes should be enforced regardless of how inept the operator might be. I soon had about 20 CMOS ICs wired in a complex mess of logic circuits that nearly worked. But no matter how many more gates I added, I always seemed to have glitches. This was becoming frustrating. Also, my new key was going to end up as a foot-long circuit board. I lowered my sights to building a simple electronic bug built with op-amp oscillators. The new key would have automatic dots, but manual dashes. In other words, it would be the electronic equivalent of a

mechanical bug.

A homebrew electronic bug



The mechanical parts

The mechanical requirement was to make two momentary-contact, spring-loaded switches controlled by a single paddle. I suppose I could have used printed circuit board switches like the straight key discussed earlier. However, my solution was to use two miniature, push-button momentary switches. The switches can provide both the switching and spring action. I mounted them on opposite sides of a piece of square aluminum channel so that the buttons face each other. The back of the plastic paddle arm rests between the two buttons and pushes one or the other as needed. I cut out the paddle from a plastic sheet that I bought at a local plastics

shop. By the way, scrap plastic is a great resource for material to make antenna insulators, stand-offs, boxes, etc. The bug is packaged in a commercial aluminum box and screwed onto a thick aluminum plate. I glued a piece of sticky rubber from an old mouse pad onto the bottom to prevent sliding from side to side.

After I got my bug working, I had trouble sending accurately. That is, I kept sending extra dots or half-formed dots. The biggest problem turned out to be insufficient return spring force. I supplemented the spring force of my button switches with coil springs that I stuffed into the aluminum channel on both sides of the plastic paddle. Afterwards I was surprised how much easier it was to send good code.

Another annoyance was that the key kept sliding on the table, so I screwed metal “railings” onto my tabletop to confine the key. The key continued to creep away from me so I finally just screwed it down to the table. Now I can bang away and the key stays put. Good sending is just plain hard. Any advantage you can give yourself is worth doing.

The electronic parts

red LED that lights on just one milliampere reminds me to turn it off. When it's time to change the battery, a 5 volt Zener diode in series with the LED makes the LED dim when the voltage gets down to about 6 volts. When not sending, the bug draws 1.2 milliamperes. This means the 550 milliampere-hour alkaline 9 volt battery will last over two weeks if I forget to turn it off.

All oscillators in the circuit are implemented with an LM324 quad op-amp. Op-amps were discussed in more detail in chapter 7. The LM324 is a great old component. It doesn't work at high frequencies like modern op-amps, but that can be a good thing because it doesn't oscillate unexpectedly. And unlike nearly all the old op-amps, such as LM458, LM741 or LM301, the LM324 almost always acts like an "ideal op-amp." It only needs one supply voltage and it rarely surprises you with "practical limitations."

The other component I haven't discussed before are the CMOS logic circuits, specifically the CD4001 NOR logic chip. Logic circuits consist of small arrays of transistors used for making simple binary decisions. For example, if you have two binary (high or low) inputs and you wish to know when either or both of the two inputs is high (a "one"), then these two input lines can be connected to the inputs of a two input "**OR gate**." When either or both lines go high, the output gate of an OR gate will switch from low to high. In this circuit we are using a "**NOR gate**" which is also known as a "NOT OR gate." These work the same as an OR gate except that when either or both the inputs go high, the output will switch in the opposite way. That is, the output line will drop from high to low. "**AND gates**" and "**NAND gates**" are similar except that the output changes only when both inputs go high simultaneously.

The 4000 series CMOS logic gates are also old-tech and quite slow relative to modern CMOS logic chips. The "CD" part just identifies the particular brand of gate. The 4000 number identifies the particular construction technology of the logic gate. These 1970s era parts are immune to interference from RF and tolerate up to 18 volts peak. Modern CMOS gates are limited to lower voltages and are designed for performing logic at high speed. High speed isn't needed here and just makes the chips vulnerable to interference and self-oscillation.

It's necessary to "debounce" the dot key. First I just tried turning on the dot-generating oscillator with the dot switch. Because my timing wasn't always matched to the oscillator speed, and because the contacts didn't always close solidly, the dots often sputtered like my old bug. Referring to the circuit diagram, the dot switch now keys a multivibrator (U1-A). This generates a narrow, repeating pulse that sets the maximum dot rate. The actual dots are formed by a second op-amp multivibrator, (U1-B). The pulses from (U1-A) start a new dot, provided that the second oscillator, (U1-B), is ready to start one. The dot rate is adjustable over a wide range using the 100K pot.

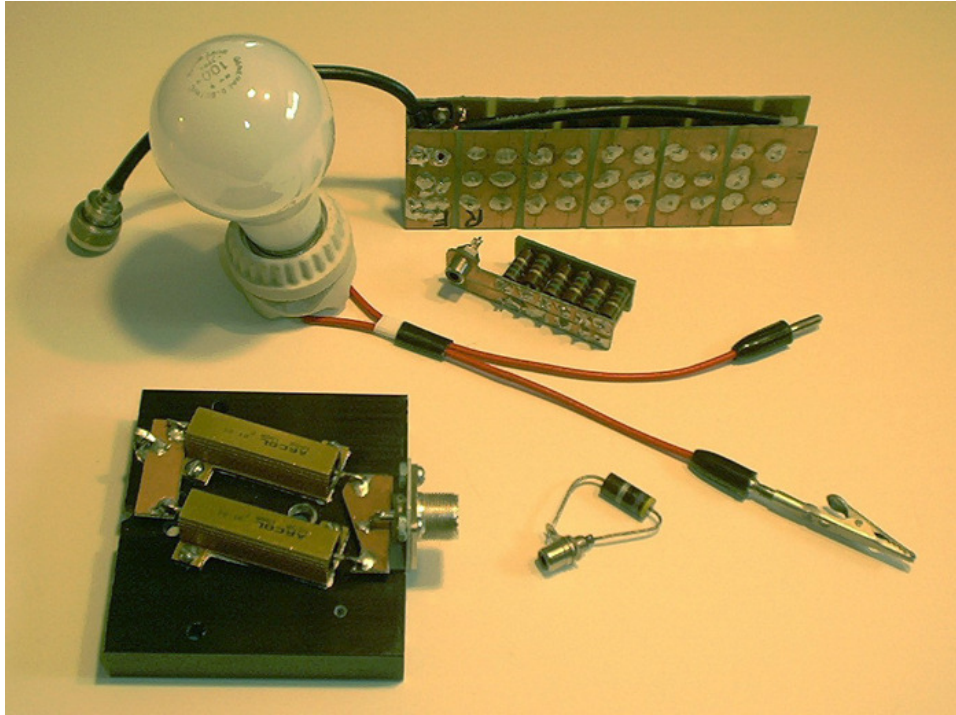
The dots and dashes are combined with a CMOS 4001 NOR gate to make a single keying signal. That is, the NOR gate puts out an output if either a "dot" or a "dash" is present. Two more NOR gates serve as a signal polarity inverter and driver for the keying transistor and for the audio oscillator. The NOR gate output turns on the audio oscillator (U1-C) by pulling up the hysteresis 100K feedback resistor. The audio oscillator in turn drives an op-amp voltage follower (U1-D) and the 2N2222 speaker driver. The audio volume control is simply a 100 ohm pot in series with the 8 ohm speaker.

I've used my bug for three years. I've had hundreds of QSOs with it and replaced the battery about twice a year. Once the paddle began to stick "on," so I had to oil the machine

screw pivot on the paddle. Otherwise, the bug has given me good service and little trouble. This is an easy home project because it doesn't involve RF and is almost guaranteed to work.

DUMMY LOADS

A checkout of a homebrew transmitter begins with a low inductance dummy load. Once you are able to deliver a pure, stable sinewave into your dummy load, then you may graduate to an antenna.



Homebrew dummy loads ranging from 2 to 100 watts.

A dummy load is just a big resistor that can stand the power from your transmitter without smoking or catching fire. In order that it resembles a well-designed antenna, the dummy load should be a pure resistance with little accidental inductance or capacitance. Big, non-inductive resistors are pricey and must be specially ordered. That's why most hams buy commercial dummy loads rated for power equal or greater than their transmitter's maximum power. Dummy loads are almost always designed for 50 ohms because that is the standard design impedance for most transmitter amplifiers and many antennas.

For a QRP, a dummy load can be as simple as a 47 or 51 ohm 2 watt carbon composition resistor. Single, 50 ohm resistors are rare items because the standard resistor values are set up logarithmically. If you don't drive it continuously, five watts won't hurt it. Be careful, though. The heat may not damage the resistor, but it can melt oscilloscope probe tips clipped onto the hot metal resistor leads. For higher powers, you can build a good dummy load out of arrays of carbon composition or other low inductance resistors.

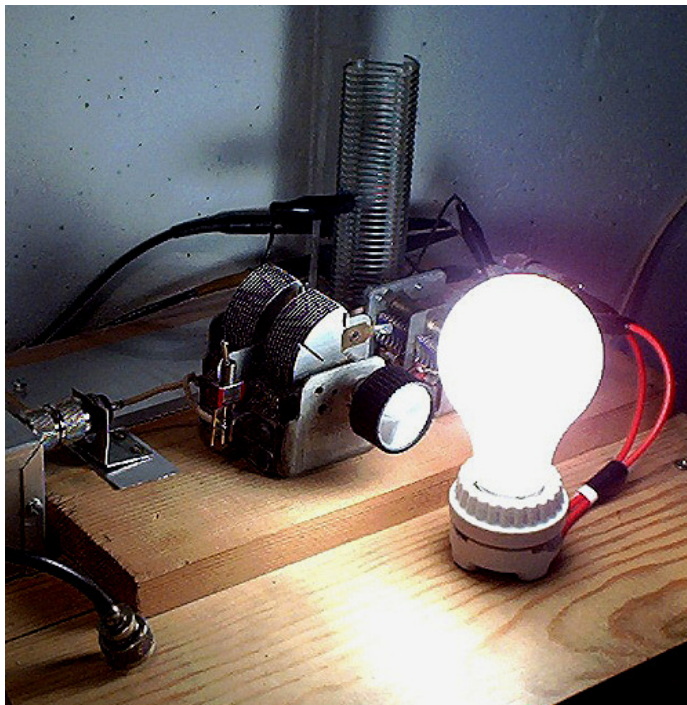
A dummy load is one of the few simple quality homebrew test instruments that a guy can

make for himself in a few hours. A big dummy load resistor can be made from an array of low power, low inductance resistors. Metal film resistors and carbon composition resistors usually have low inductance and make good loads. For example, I happened to have a whole package of old 1 watt, 150 ohm carbon composition resistors. By placing them in the appropriate series/parallel arrangement I made a 10 watt, 50 ohm dummy load. If you need a 50 watt dummy load, it can be made from an array of 25 two watt resistors. You will have to be clever selecting the resistance and arranging them so that the final resistance is 50 ohms.

For high frequencies, like the 10 meter band and above, it is important to use a low inductance connection with the resistance. Therefore, the leads into the dummy load should be coaxial cable. I used circuit boards with wide traces to connect the individual resistors in an array. In the large load it was also necessary to connect one end of the array to the other internally. I first used a simple wire for this and it had significant inductance. I replaced the wire with a piece of coax grounded at one end and the inductance disappeared.

Beware of high power, "low inductance" resistors

I bought a pair of supposedly "low inductance" 100 ohm, 50 watt resistors. I put them in parallel and mounted them on an aluminum heat sink. They should have made a terrific high power dummy load. Alas, there was considerable inductance in these resistors and, even in parallel, at 14 MHz they had twice the impedance I expected. In summary, this big dummy load is useful, but it isn't 50 ohms.



Light bulbs as dummy loads

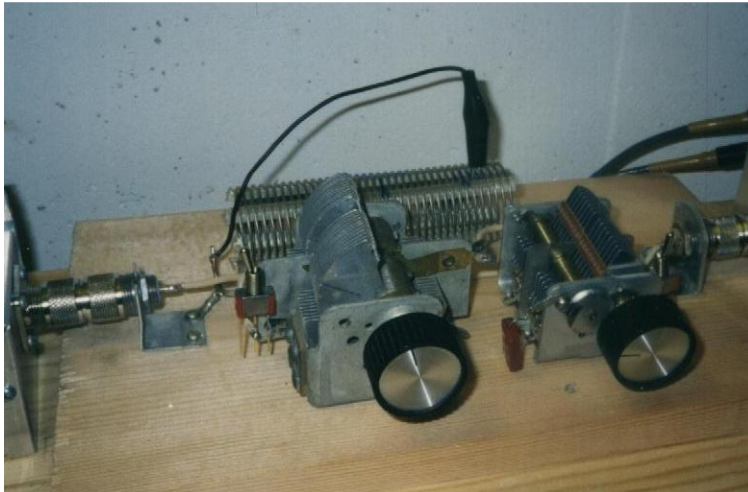
An ordinary filament light bulb can work as dummy load. They are far from ideal and should not be your only dummy load. However, they do have advantages: They are fun to use and great show-and-tell devices. However, at less than 100 watts, their impedances are much higher than 50 ohms and the impedance rises as they get hot. On the other hand, if you need a dummy load that simulates a high impedance antenna, then a light bulb is useful. Also, if you're checking out a power meter, a light bulb gives an obvious indication of when the power output is maximum. Also, when a 40 watt bulb shines at full brilliance, obviously it is dissipating about 40 watts.

Similarly, small Christmas tree light bulbs can be useful for checking out QRP transmitters.

BUILDING A "T- MATCH" ANTENNA COUPLER

Modern transmitters are usually designed for 50 ohm antennas. The Chebyshev output

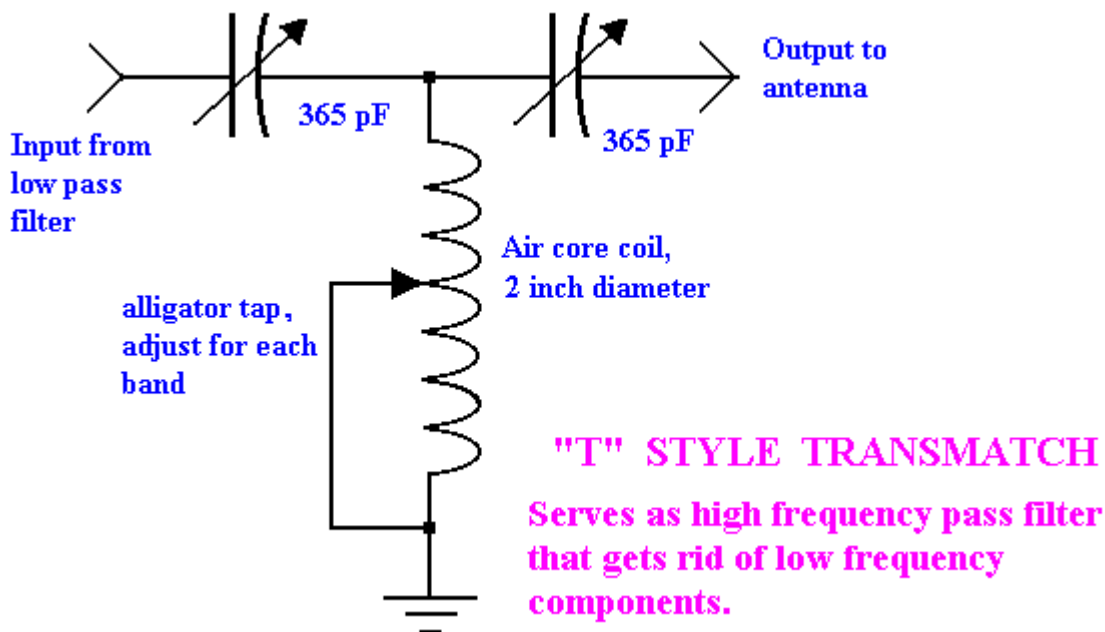
filters found in modern transmitters only work at this design impedance. When you load them with a mismatch, you won't believe the scrambled waveform that comes out. In other words, they only filter properly at 50 ohms. Unfortunately, real antennas are usually higher or lower impedance and need some form of impedance transformer to make them appear as a 50 ohm load to the transmitter.



Old vacuum tube "Pi output" transmitters had built-in antenna couplers, but none of the transistorized designs in the ARRL annual handbooks have couplers. So after I built a transistorized transmitter, I needed an antenna coupler. The coupler designs in the handbooks were complicated with all-band capability and built-in power / SWR meters. They're nice, but I wanted to get on the air quickly. I consulted Bob, NØRN, for advice. Bob had built several couplers and he thought a simple

T-Match was best. It just consists of two variable capacitors and a variable inductor.

A Simple T-Match Antenna Coupler



How it works

The idea behind the T-Match is to resonate the variable capacitor on the left with the inductor to ground. When tuned to resonance the oscillation produces sinewave voltages across

the L and C that can be much larger (or smaller) than the sinewave voltage that arrives on the input. Because the voltage across the inductor can be huge, the coupler can “match” the impedance of a high impedance antenna. The oscillating L and C work like a transformer, stepping the voltage up or down. For example, to drive a 300 ohm antenna, the impedance of a 50 ohm transmitter output will have to be made to “look like” it's six times higher in order deliver the same power. For this to be true, the voltage across the antenna will have to be 2.5 times higher.

The variable capacitor on the right is not nearly so critical. You will find that for most situations keeping the capacitor at full capacitance, 365 pF, produces the best signal. Sometimes I can get a little better sinewave output or slightly more amplitude by adjusting this capacitor. But usually, I just leave it alone. For the lower bands, 80 and 160 meters, you may need to add more capacitance in parallel with both variable capacitors using switches. My variable capacitors are dual-section types from old broadcast radios. I use small toggle switches to add the capacitance from the second sections. In addition, the right hand capacitor has a fixed 1000 volt, 200 pF mica capacitor across the second section so I have plenty of coupling capacitance for 160 meters.

Packaging

My friend Bob showed me a T-Match he had built in a wood and plastic box.

“Why didn’t you use a metal box?” I asked.

“Oh, wood was easier and it doesn’t matter,” explained Bob. “Maybe I get more RF radiation here in the shack, but otherwise, there’s no need for a metal cabinet.”

I was anxious to get on the air, so I rummaged through my junk and came up with two dual section 365 pF broadcast radio variable capacitors. One of them was out of a 1935 radio. I thought using an ancient component had nostalgic charm. I also found a big piece of open “Air Dux” coil I could use for the inductor. I made the inductor “variable” by using an alligator clip to short out the unwanted length of coil. For RF connectors, I used SO-239 UHF connectors from Radio Shack. After an hour’s work I had screwed all the parts down onto a pine board and I had a T- match.

Improving performance on the higher bands

I originally used a simple 12 gauge wire connecting the grounds on the input and output connectors. This simple wire looks like a significant inductor on 17 meters and above. This small inductance can occasionally make loading difficult or impossible with some antennas. I replaced the wire with a low inductance, 3 inch wide sheet of metal and the difficulty largely disappeared. Try to maintain at least a half an inch of spacing between this ground sheet and your coil. Another modification that was helpful was mounting the coil vertically. This minimized the capacitive coupling between the coil and the sheet metal ground plane. I used clear plastic and epoxy to build brackets and insulate the bottom of the coil.

I tested the coupler by using a few ordinary light bulbs as dummy loads. Bulbs have a wide range of resistance, depending on the wattage and how hot the filament happens to be. The T-Match worked great and the bulbs burned brightly. It worked just as well on my real antennas, so I went on the air and began working folks right and left. So, if you just want a coupler that

works, the story is now over. If you like, you may stop reading.

The T-Match as an aid for receiving on 80 and 160 meters

One surprise from this project was that my T-Match has become vital for receiving weak signals on 80 and 160 meter ham bands. These lower bands are quite close to the standard broadcast AM band, (550 – 1700 KHz). As you know, these stations are extremely powerful – as much as 50,000 watts. If you have such a station within 50 miles, or a less powerful station close to your house, there will be big RF voltages riding on your antenna at all times.

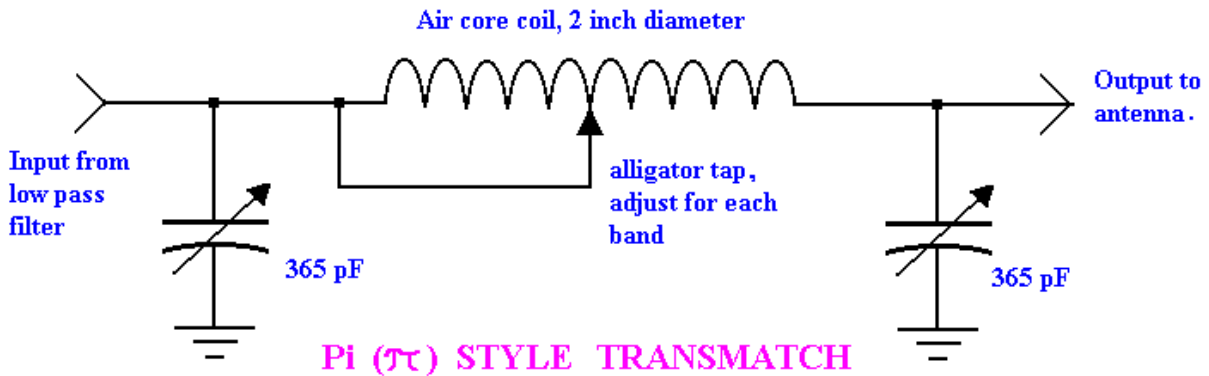
With these AM elephants bellowing in my neighborhood, my home-built receiver had trouble filtering them out and hearing the low power ham stations hundreds of miles away. The front end of a receiver can be easily overwhelmed and this problem may not be obvious. I couldn't hear the AM broadcasts in my headphones but the ham bands were mostly static and I didn't know there were any ham signals present. But when my receiver shared the antenna with the transmitter, the signal strength of the weak signals on the low bands peaked dramatically when the T-Match was properly tuned for the transmitter. The T-Match serves as a “high pass” filter that reduces the signal strength of the broadcast stations dramatically. Not only was I suddenly hearing dozens of CW stations on 80 meters, I found myself working QRP stations halfway across the country. I didn't know that was even practical.

Using the T-Match on receive has another benefit. Since my receiver is designed for a 50 ohm input, when I peak the received signal strength using the T-Match, the 50 ohm transmitter is also (nearly) perfectly matched. So on any band, before I try to load the antenna with my transmitter, I peak the received signals with the T-Match.

Adding the whistles and bells

The interesting part of the T-Match story is what happens when you add the refinements - you know, the metal case, the power meter, and all that. After I had used my primitive coupler for a while, I wanted something more impressive. I already owned a metal enclosure that was about the right size. It took me considerably longer than an hour to build another coupler, but eventually I had a professional-looking T-Match in a metal box. I tried it out and ... it didn't work worth a darn. It couldn't match much of anything. It seemed to be a wonderful standing wave generator, but a poor antenna coupler.

I consulted Bob about my problem. He nodded knowingly. “Oh, yeah. It doesn't work in metal cabinets. That's why I used wood and plastic.” Now he tells me. “However,” he went on, “you could convert the coupler to a ‘ π match.’ That should work in a metal box since the capacitors go directly to ground and the accidental capacitance to the metal case will become part of the circuit. Also, you could use a powdered iron core inductor. The magnetic flux is confined to the core, so powdered iron cores work well in small metal enclosures.”



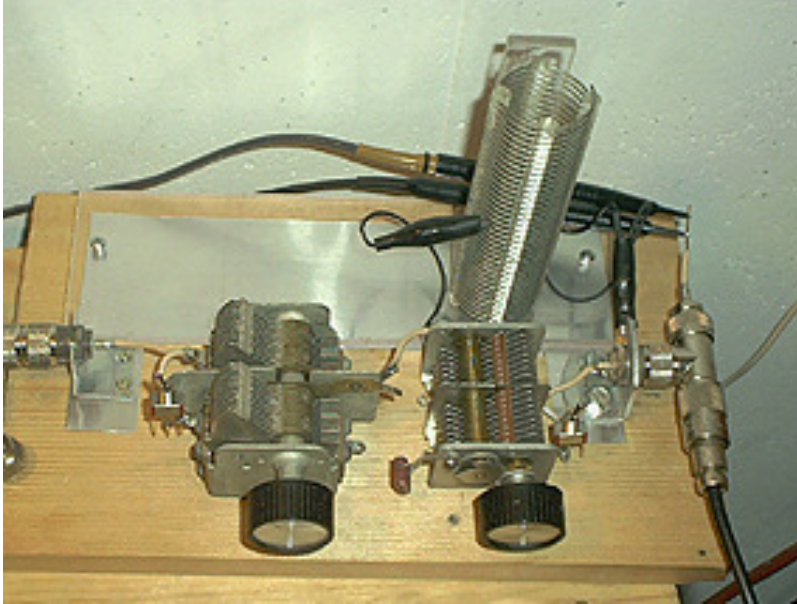
The π - Match

I tried out these ideas. Yes, I got the π to work, but I learned that the T-Match was better. If you examine the π -Match circuit, you'll see it is a low pass filter. That is, the high frequency noise gets shunted to ground through the capacitors, while low frequency components pass through the inductor. I was already using a low pass filter to suppress TVI, so the π -Match was redundant. When I used the π -Match I noticed the output waveform usually had low frequency, "roller coaster" distortion and sub-harmonic modulation on it that resembled AM modulation. In contrast, the T-Match serves as a high pass filter that removes these distortions. It turned out that the low pass TVI filter and the T-Match work together as a band pass filter to maintain a pure sinewave.

I found a powdered iron core in my junk box large enough to handle 100 watts and I wound a multiple tap winding on it. Yes, the powdered iron core inductor worked, but it became hot and was clearly inferior to the air core. Since I didn't have any data on the core I was using, I ordered a big new core from CWS Bytemark with known properties. I bought a CWS (Amidon) T200-6. Sure enough, it heated up too. Long live air-core inductors!

My other experiment was built-in power meters. I installed dual meters for forward and reverse power. Cool, huh? Too bad they worked so poorly. The meters were voltage sensitive rather than power sensitive. For example, they read twice as much "power" into a 100 ohm load as into a 50 ohm load. I knew the meters weren't correct because all the other data I had from my oscilloscope, DC power input to the final, etc., all told me that the power into 50 ohms and 100 ohms should have been equal. I discovered I could compensate for this error by placing the power meters on the transmitter side, the 50 ohm side, of the antenna coupler. That way the voltage was constant for the same power level.

I soon retired the fancy coupler to the junk pile and I'm still using the piece of wood with the 1935 capacitor. (Now you know why I have so much junk.) In order to monitor my output power and frequency purity, I monitor the input to the antenna with scope probes going to a frequency counter and to an oscilloscope. The scope and the frequency counter readout are far more sensitive to the problems of a homebrew rig than an SWR meter will ever be.



The T-Match monitored by oscilloscope and counter probes. The low pass filter is on the left. The antenna coaxial cable exits on the right. Note the flat sheet of aluminum that serves as a low inductance ground plane. It's covered with plastic to help isolate it from the coil.

BUILDING A LOWPASS FILTER

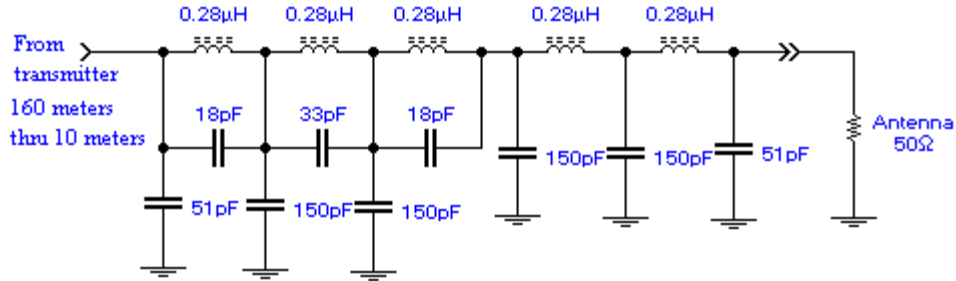
Back in 1997 I carried my old vacuum tube HF transmitters down from the attic and looked at them critically. Hmm ... Class C output stages. Class C produces distorted sinewaves and distortion causes harmonics. I hadn't been on the air in 30 years, but I knew from studying for my new license that spectral purity standards were higher than they used to be. At the very least, if I used my ancient transmitters, I would be risking TV interference (*TVI*) complaints from the neighbors. Consequently a transmitter lowpass filter became my first project.

I'm told that today hardly anyone with a modern transceiver needs or uses lowpass filters. However, if you do any homebrewing, especially with Class C or Class B output stages, a lowpass is a good idea. When placed directly on the transmitter output, I've found that the filter doesn't reduce power output and it doesn't make the antenna hard to tune, even when operating QRP. I think of my lowpass filter as "insurance" against angry neighbors and pink slips. So why not use one?

Your first question probably is, "Do I need one for my little 5 watt QRP?" The answer is, "Probably not." However, as soon as you get complaints, your neighbors will eternally label you as the cause of every bit of snow on their TV screens or virtually any problem with their sets. Once the complaint syndrome begins, being "legal" and "meeting FCC requirements" aren't enough. It is much better to do everything you can to be sure the neighbors never realize that you might interfere with their TVs.

Electrical Design of the Filter

13. Chapter 9, Harris

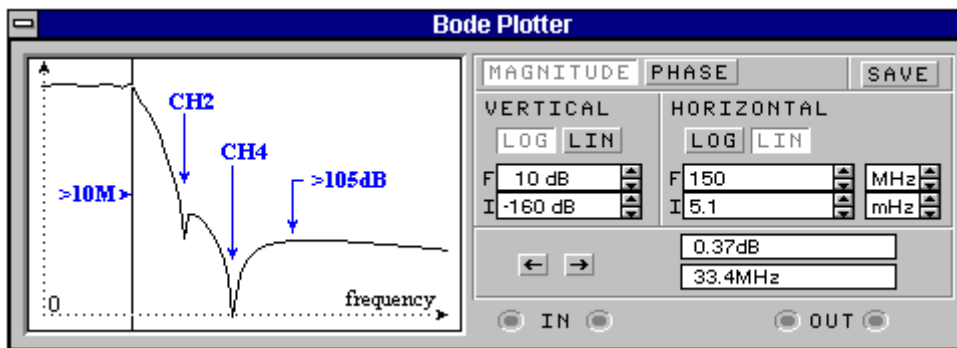


A five-stage lowpass filter

I started with a three stage elliptic lowpass filter from the good-ol' ARRL handbook. Later I acquired a "Spice" program for analyzing circuits, [Electronics Workbench](#). I turned it loose on my lowpass and settled on the circuit shown above. The capacitors to ground tell us this is a lowpass filter. In other words, the capacitors shunt high frequencies to ground that might otherwise radiate in the TV bands, while lower HF frequencies will pass through the filter via the inductors. This filter is designed to pass all the ham HF bands from 10 meters (30 MHz) and below. As you will see shortly, it attenuates all frequencies above 10 meters.

Notice that there are 33 pF and 18 pF capacitors across three of the inductors. Each inductor is part of an LC resonant trap that appears as high series impedances to TV channels 2 and 4. However, the higher channels are also attenuated at least 105 dB. The main lesson I learned from Spice was that component values are surprisingly tolerant. I had used Chebyshev filter tables that have values to 4 decimal points and sophisticated "bell curves" for the different component values. That elegance made me think filters had to be precise. Wrong! Well, that's what Spice and my experience tells me. Notice that I made all the inductors identical and use only two values of capacitors to ground.

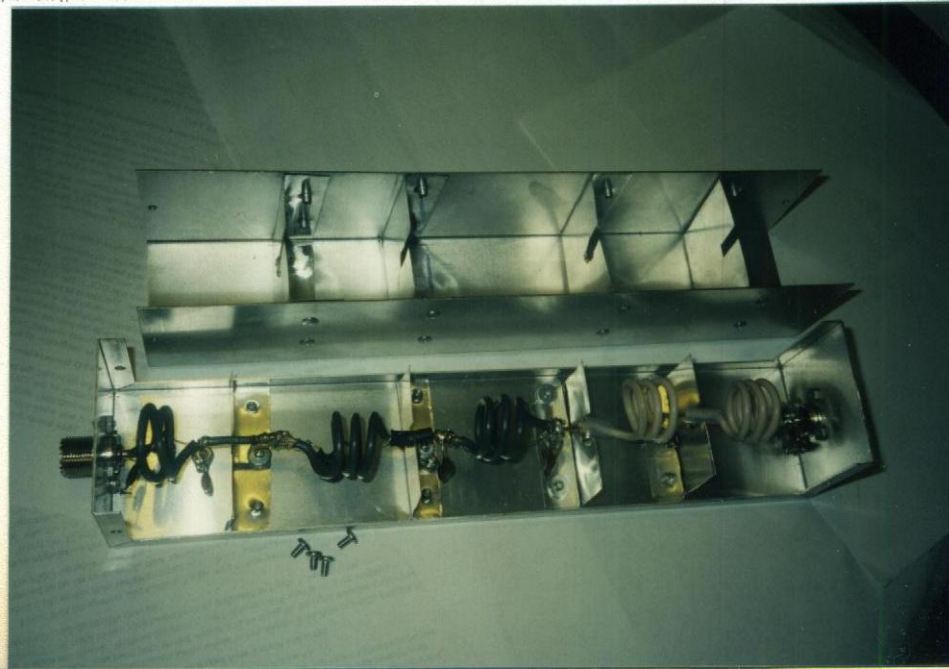
Like all complex reactive filters, this one is designed for specific impedances, in this case 50 ohms. That means that the filter only works correctly when the input and output impedances are 50 ohms. For that reason, it's inserted into the antenna line right after the transmitter and just before the antenna coupler. If you are using a power meter designed for 50 ohms, it would go between the low pass and the antenna coupler. The antenna can have any impedance from near zero to hundreds of ohms, so the coupler serves as a transformer to match 50 ohms to whatever is needed.



Lowpass filter Bode plot

Construction Details

The filter is housed in a long, skinny aluminum box. Capacitance to ground is part of the design. Therefore, provided the leakage capacitance between the coils and the metal box isn't extreme, this stray capacitance won't degrade the performance. Just keep the coils at least 1/2 inch away from the grounded metal walls and the filter will work well. I used air core inductors, which meant that I had to rivet four pairs of overlapping metal partitions into my box to prevent coupling between the five coils. Without the metal shields, air core inductors would couple to each other like transformer windings. I prefer air core because simple coils don't dissipate significant energy. I'm also cheap.



Inside view of the filter. Each coil is isolated from its neighbors by notched partitions.

I wound my coils out of 12 gauge insulated copper wire stripped from Romex household three-conductor wiring cable. If you follow the dimensions in Table 1 exactly, you should get about the same resonant frequencies I did. Depending on the shape of your box, you may use either large coils with 2 turns or smaller diameter coils with 3 turns. The inductance will be about the same. The important issues are that the three LC traps should resonate well above the 10 meter band and there should be no significant attenuation below 30 MHz.

Table 1. **Air core inductor specifications.**

	turns	diameter	length	inductance
	2 turns	1.25 inches	0.5 inch	0.28 microhenries
or,	3 turns	1 inch	0.75 inch	0.28 microhenries.

How to measure air core inductance

How did I know when I had 0.28 microhenries? I calculated what the resonant frequency should be for 0.28 microhenries and a convenient fixed capacitor. I wound a coil, put the capacitor in parallel, and put the LC circuit across a frequency generator output. Using an oscilloscope to watch the voltage, I adjusted the frequency to find the resonant peak and then rewound the coil until it peaked at the calculated frequency.

The inductors could also be wound on powdered iron cores. An advantage of powdered iron is that the magnetic flux is confined in the cores and you can cram the filter into a smaller metal box without metal shields between filter sections. However, powdered iron core inductors will still have stray capacitance to ground.

All capacitors should be mica and capable of handling voltages consistent with your power level. If you're running more than 100 watts, it would be prudent to use capacitors with working voltages of 1,000 volts or more. I used 500 volt caps with my 100 watts and so far haven't had any capacitor failures. Two identical 500 volt caps in series will give a working voltage approaching 1,000 volts, but of course the effective capacitance will be half the value of each. Use real RF connectors on your filter, UHF SO-239 or equivalent.

Testing the filter

I tested my filter by terminating it with a 50 ohm load and then running an RF signal generator through it. There was no significant attenuation or distortion of the sinewave from 160 to 10 meters. Above 10 meters the output signal dropped to almost nothing. Similarly, when I loaded lightbulbs and 50 ohm dummy loads on all HF bands, 80 through 10 meters, I could see no differences with or without the filter.

So far, my only TVI complaints have been from my own family. On 15 meters, they see minor flickering on the picture. Not surprisingly, 17 Meters bothers channel 4 ($4 \times 18 \text{ MHz} = 72 \text{ MHz}$) and 30 meters tears up channel 6 ($8 \times 10.1 \text{ MHz} = 80.8 \text{ MHz}$.) I believe my biggest remaining TVI problem is my open-chassis transmitter with the PC boards exposed to the breezes. Obviously I need a cabinet.

When we bought a modern TV, all my interference problems vanished. Fortunately, digital TV and the increasing use of cable TV, Direct TV satellites, and 2.4 gigahertz digital cell phones, makes annoying the neighbors less and less likely. In February 2009 in the United States UHF digital television replaced all analog channels 2 through 13. In other words, the need for a low pass is rapidly passing. Considering that we are living in "The Wireless Age," the future of our TVI problems is surprisingly bright.

**

STAYING LEGAL WITH HOMEBREW TRANSMITTERS

On Field Day I watched while up-to-date hams tuned up their rigs. I was amazed by how casually they assumed their signals were matched to the antennas and not suffering from rough CW tone, harmonics, or drifting frequency. They plugged beam antennas and dipoles directly into sophisticated transceivers and were instantly in business. I didn't see any antenna couplers, power meters, low pass filters, dummy loads, oscilloscopes, frequency counters, or any of the tools we homebuilders use to stay legal.

Investigate before you radiate

Many hams these days are building QRP transmitters. Before they go on the air with a homebrew transmitter, they should learn how to check it out. Out there on the bands are Official Observers (OOs) who send out little white SWL (Short Wave Listener) cards. Ten years ago when I got back on the air with my homebrew, vacuum tube antique, I quickly got an OO card from New Jersey. OO cards are *NOT* suitable for framing. The card informed me that my CW signal was drifting and had an obnoxious tone. Very embarrassing! Don't just go on the air and hope everything is OK. *Investigate before you radiate!*

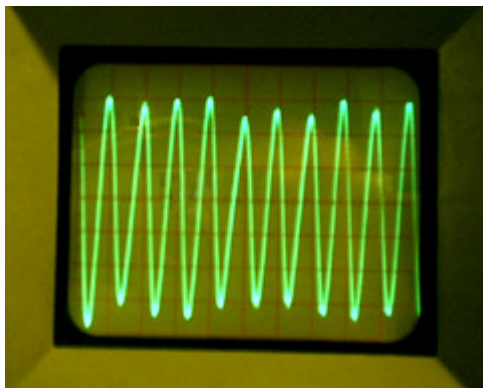
Listen to your own signal

A good way to find out how your signal would sound to another station is to load a dummy load then listen to it with your receiver. I routinely use an old Collins receiver for this purpose. The tricky part is desensitizing the receiver so that the signal strength simulates a signal on the air. I did this by shorting a coax connector and plugging it into the antenna jack on the back of the receiver. I also clamped ferrite blocks on the line cord and speaker wires to help keep RF out of the receiver cabinet. After I made these changes, the signal was sufficiently weak that I was able to hear key-clicks, rough note, or "warble" instabilities. Now I could understand what my contacts were complaining about.

My 1967 homebrew transmitter was a mobile unit with a switching power supply. No matter how I filtered the supply output, I couldn't get rid of the switching hash. The hash was extremely hard to see on the oscilloscope, but in the receiver, I could hear a distinctly rough note. No wonder I kept getting those 598 reports!

Oscilloscopes

In my opinion, an HF transmitter would be hard to build without a quality RF oscilloscope. Looking at the waveforms on a scope makes it easy to tune up a stage, or at least to get the tuning approximately right. When I operate, I keep a 10:1 scope probe right on the antenna feedline. That way, there's no question about what's being transmitted. A typical probe is rated for several hundred volts and has one megohm load resistance and five picofarads capacitance. This shouldn't bother your tuning and your transmatch can compensate for any slight mismatch.

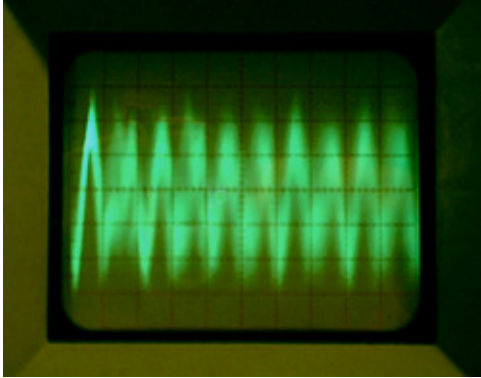


Usually on the lowest HF bands, like 80 and 40, you'll see a truly perfect sinewave on your antenna. But the higher the frequency, the less perfect the waveform will probably be. The 30 meter signal on the left is sharply focused, but it has a bit of low frequency modulation. This is quite all right.

A well-tuned 30 meter CW signal on the antenna lead

Beware of blurs

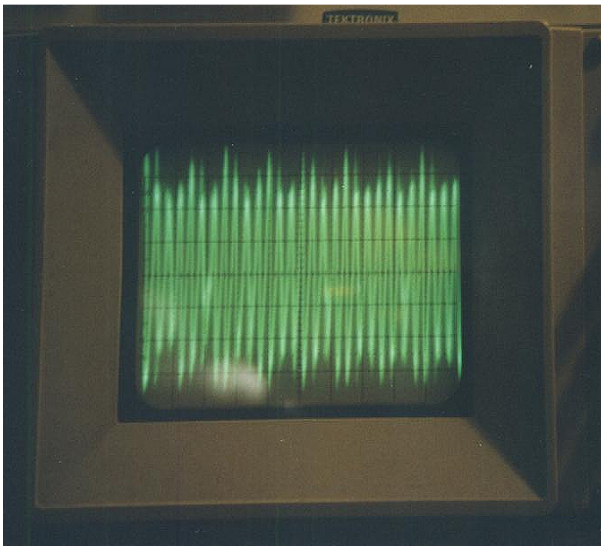
On the other hand, the 30 meter signal shown below is mistuned. Notice how only the first half sinewave is synchronized. After that, the waves are a blur of different, overlapping frequencies. Also, the reading on your frequency counter will be low and out of the desired band. Usually tuning the transmatch instantly corrects this.



A poorly tuned 30 meter CW signal

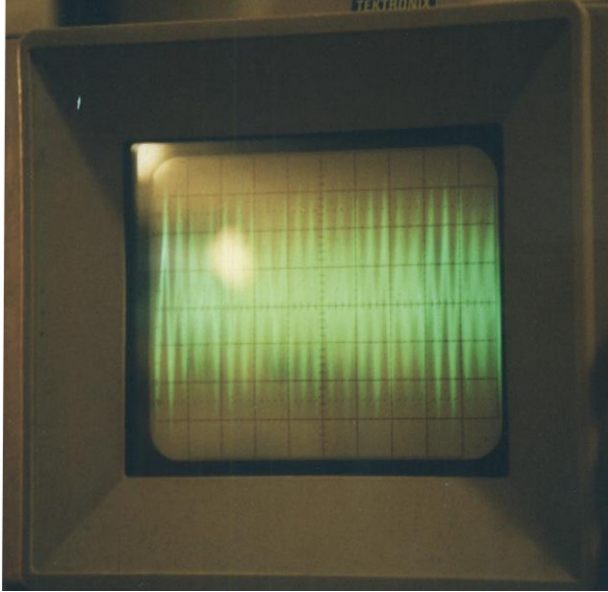
Look for the zero crossings

At even higher frequencies, like 15 and 10 meters, your sinewave may have more low frequency modulation and be slightly blurry as illustrated below. The higher the frequency, the more difficult purity becomes. Also, above 20 meters it becomes increasingly hard to know what's artifact from the oscilloscope and probe and what's actually going out the antenna. *A reliable indication that all is well is when the picture focuses sharply enough to see the zero crossings clearly.*



An adequate signal on 10 meters

In contrast, the 10 meter signal shown below is too blurry. Tune your transmatch!



Tuning for maximum power out

I tune my transmatch for maximum amplitude of a sharply focused sinewave at my antenna lead. This gives me an approximate measurement of antenna impedance. For example, suppose I first I load my 50 ohm dummy load on 80 meters and get about 50 watts. In other words, the scope shows a 70 volt peak sinewave. Next I try to load my 40 meter dipole on 80 meters. Using the transmatch, it loads up and produces a sharp 300 volt peak sinewave. Unfortunately, the 300 volts peak on the coax with a 50-watt signal suggests really high antenna impedance, about 900 ohms. If the antenna looked like 50 ohms, I would see about 70 volts peak, just like the dummy load. In my experience, with a match that poor, it may be safe for the transmitter, but nobody will hear me. Let's look at the calculations:

Measuring transmitter power with an oscilloscope

To measure the power output of your transmitter into an antenna or a dummy load, you can look at the RF voltage across the load with an oscilloscope. RMS power is the heating value of the electric current. That is, one watt RMS equals one joule of energy per second. Hams usually use RMS power instead of peak power or other possibilities. To find the power we first need to measure the RMS voltage of a sinewave. You can measure the peak voltage by counting the grid squares on the screen. Then, to get the RMS voltage, you divide the peak voltage by the square root of two. For example, suppose the RF sinewave on the screen is 100 volts peak:

$$100 \text{ volts Peak} / \sqrt{2} = 100 \text{ volts} / 1.414 = 100 \text{ volts} \times 0.707 = 70.7 \text{ volts RMS} .$$

Rather than calculating the square root of 2 or its inverse every time, you can proceed more quickly by remembering the factors 1.414 and 0.707. For example, suppose the RF voltage seen on the oscilloscope screen is 100 volts peak, then the RF power delivered to a 50 ohm antenna or dummy load resistor would be:

$$\text{Power} = I_{\text{RMS}} \times V_{\text{RMS}} = (V_{\text{RMS}} / \text{Resistance}) \times V_{\text{RMS}} = (V_{\text{RMS}})^2 / \text{Resistance}.$$

$$\text{In this case, Power output} = (70.7 \text{ volts RMS})^2 / 50 \text{ ohms} = 100 \text{ watts}.$$

I remember my electrical engineering professor turning purple in the face when a student

used the V^2/R formula for power during class. “You must be a ham! You guys are always using that formula, but we never teach it because it assumes that the current and voltage in phase.” He was absolutely right on both accounts. That is why the power is first measured on a resistive dummy load. Dummy loads have no capacitive or inductive components to make the current and voltage components out of phase. Then, logically, if the transmitter is drawing the same current from the 12 volt battery, the power input must be the same. Therefore we can assume that the antenna is receiving the same power as the dummy load did we are justified in calculating the power to the antenna.

Peak Envelope Power (PEP)

The U.S. government regulations for ham radio operators limit the power we can use to a specified amount of "*Peak Envelope Power*." This varies with different hambands and class of license. As examples, on 30 meters we are only allowed to use 200 watts PEP, but on 20 meters, 1,500 watts PEP is permitted.

PEP is defined as "the average power supplied to the antenna transmission line by a transmitter during one RF cycle at the crest of the modulation envelope taken under normal operating conditions." In other words, it is the peak RMS power for the highest part of a modulated waveform. So, if you were operating with single sideband phone, the measurement with an oscilloscope would measure the highest peak voltage seen on the scope multiplied by 0.707. Then, just as we did above, we would square this RMS voltage value and divide by the impedance of the antenna, e.g. 50 ohms. A CW transmitter output is measured the same way.

An oscilloscope for HF ham work should be rated for at least 50 MHz. A brand new oscilloscope like this will cost at least \$2,000, but is not a good value. My Tektronics 5441 scope originally sold for \$11,000 in 1976. Today that scope or equivalent ones can be found used in electronic surplus stores or mail-order catalogs for \$400 or less.

An FM radio will detect serious frequency impurity

A serious splatter problem (noise mode) will make a roar of static in your FM radio. On the other hand, sometimes the FM radio just cuts out and goes silent. That may not be a transmitter problem. It could be that the radio's IF is just overwhelmed by your signal. Alternatively a harmonic of your transmitter frequency might happen to line up with your FM station and obliterate it. Again, the FM radio just goes silent.

DC power supply ampere meter

It is always nice to know how much current the transmitter is drawing. Linear amplifier stages run at roughly 50% efficiency, while the transmitter circuitry as a whole will be somewhat less than that, say 40%. DC current is another indication of the SWR (Standing Wave Ratio). That is, SWR describes how well your antenna is tuned. When operating correctly, 50 watts output should draw about 8 to 10 amperes at 12 volts. If it reads 15 or 20 amperes, it means you are way out of tune and the final amplifier is heating rapidly.

Frequency counters

The most persistent problem a homebrewer faces is frequency drift. Commercial transceivers use frequency synthesizer chips slaved to unusually stable crystal oscillators. They also have built-in displays that read frequency to a fraction of a Hertz. This amount of precision is almost never justified by the specifications. But hey! The guy you're talking to hasn't read the specs on his transceiver and he believes his readout is gospel. Since we



A typical HF frequency counter

When I operate, I have two scope probes on the antenna line. One goes to the scope and the other goes to a frequency counter. A good counter is vital because most of the frequencies you must measure are too close to the edge of the ham band to simply count squares on the oscilloscope screen. When the transmitter is operating properly, the counter display is solid to within 10 Hz and doesn't dance around. The same conditions that cause blurry sinewaves on the scope cause the counter to read low and jump about. For example, if you are loading up on 15 meters and the counter reads something like "20.6XXXX" with the last few digits changing every second, you are mistuned. Don't be satisfied until the counter reads what it should and stays there. That is, you should see a relatively solid reading of a legal frequency, like "21.120XX." Counters can be a bargain if you buy them used. My used Hewlett-Packard counter originally sold for about \$2000, but I paid \$60 for it.

Lowpass filters

When operating homebrew equipment it's a safe bet you will occasionally generate out-of-band harmonics, especially while loading your antenna. A lowpass filter is simple insurance against generating interference above some design frequency. Another way I minimize the out-of-band noise problem is to keep a chart of the transmatch settings for each band tacked up on the wall. So when I switch bands, the transmatch is already fairly well adjusted before I key the transmitter.

Not so useful instruments

Power meters I have not found power meters particularly useful. I have a commercial one that gives readings that correspond well with the light produced by a light bulb dummy load. My homemade power meters aren't that good. The difficulty is that power meters only tell you the total power delivered to the antenna. I need to know much more than that to avoid bad signal reports and OO cards.

Grid dip meters In the old days we used "grid dip meters" for frequency measurement. A grid dip meter measures the frequency of a resonating coil by placing a secondary coil next to the target coil. RF currents induced into the coil produce a drop or "dip" in the meter reading when the tuning knob on the meter is tuned to the resonating frequency. The approximate frequency is then read off the dial. Grid dip meters aren't at all accurate, but they got us onto the right ham

band. Today's inductors are usually wound on powdered iron toroids. Grid dip meters don't work well on toroids because the magnetic field is trapped inside the closed iron loop. There is practically no leakage outside the toroid for the grid dip meter to tap into.

Spectrum analyzers A spectrum analyzer would be great for homebuilders. They measure the purity of transmitter signals by graphing all the frequency components. Pictures of analyzer displays are often shown in homebrew transmitter articles. Unfortunately, even a used spectrum analyzer with sufficient precision is pricey - many thousands. Since I can't afford one, they don't do me a bit of good. Without this tool, I have to "interpret" what I see on the oscilloscope and the frequency counter. Fortunately, that isn't hard.

ANTENNA RELAYS

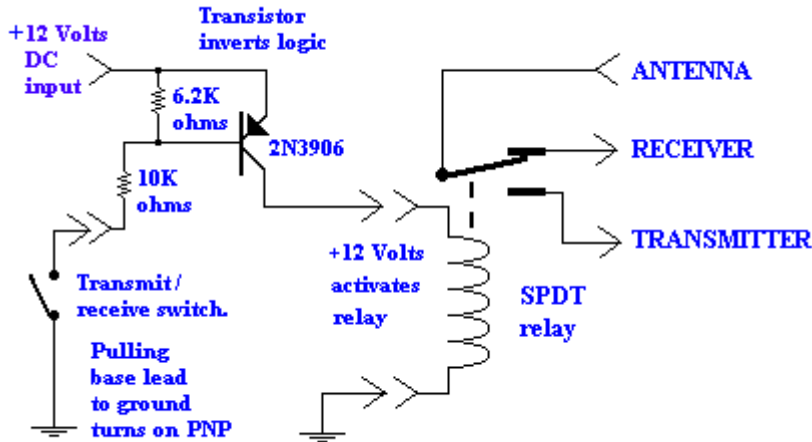
Switching from transmit to receive

If you simultaneously connect both your receiver and your transmitter to the antenna, you may burn up the front-end stages of your receiver when you transmit. When you first go on the air with your QRP transmitter, you will no doubt be irritated by the need to use a separate antenna for the receiver. A clumsy solution would be to rig up a manual switch to move the antenna back and forth from transmitter to receiver every time you stop sending. That's inefficient, to say the least. If you have to throw more than one switch to go between send and receive, you will be at a huge disadvantage when trying to work DX or in contests. Actually, even one switch is not up to modern standards.

Modern transceivers have "break-in keying." When they stop sending, the receiver instantly comes back on automatically. Non-homebuilders aren't even aware that switching antennas is a problem. I haven't yet mastered building break-in keying and still use one switch to go from send to receive. Even so, by the time my receiver comes back up after transmitting, I usually only hear the last three or four characters of my call sign from my contact, "...IYE". The other guy has already switched over and sent "KØ" before my receiver was back on the air. As you can see, one switch operation is the bare minimum.

Requirements for an antenna relay

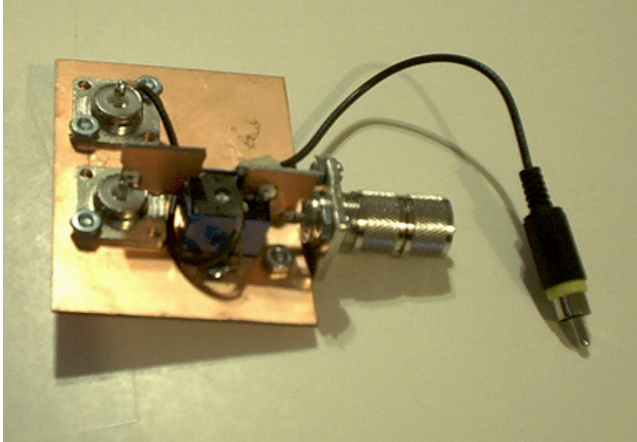
An antenna relay is usually a *single-pole, double-throw* switch, sometimes called *SPDT*. The external antenna line is connected to the moving contact. This contact is normally resting against the receiver contact. When the relay is activated, the moving contact switches over to the transmitter contact.



Schematic of antenna relay The optional transistor inverter turns on the relay with a high impedance line switched to ground.

Unfortunately, ordinary relays have too much inductance on 10 meters. Inside the relay RF current must travel through a length of wire perhaps one or two inches long. This wire is not a coaxial transmission line or a wide, low inductance strip. The result is that ordinary relays often work poorly on 10, 12, and 15 meters. By “poor” I mean that no matter how you adjust the antenna coupler, you can’t quite deliver a sharply focused sinewave to the antenna. (See the above article on checking out homebrew transmitters.) In fact, the final amplifier may remain in “noise mode” and not produce a sinewave at all. You can demonstrate that the problem is the relay by bypassing it and connecting the final amplifier directly to the lowpass or to the antenna coupler. Once the relay is out of the circuit, you will often find that the problem is cured and the antenna coupler will load the antenna just fine.

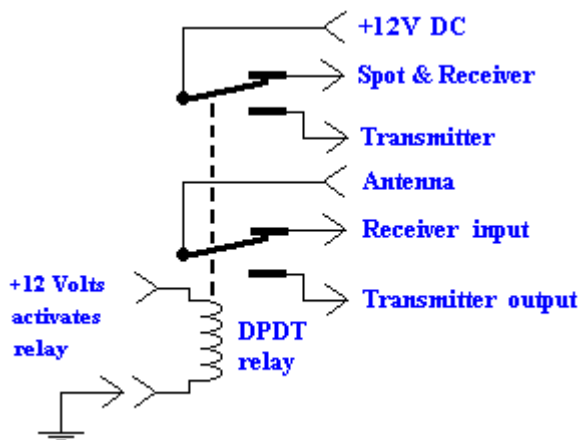
There are, of course, commercial coaxial cable relays to solve this problem. I built a usable antenna relay out of a *TINY* 10 amp relay rated at 120 volts AC (Radio Shack Part # 275-248A). The important specification is the “tiny” part. Since the relay is miniature, the wires inside the relay are very short. I kept the external transmitter RF leads as short as possible by implementing the “wires” with little, low-impedance rectangles of PC board. The connections only have to travel about 5/8 inch from the center conductors of the SO-239 RF connectors to the relay pins.



Homebuilt antenna relay

The receiver antenna connection is not nearly so critical. Therefore it was implemented with a three-inch length of RG-174 coaxial cable. The cable shield is only grounded at one end. These precautions reduced the inductance of the relay leads sufficiently. Now when I load my 10 meter vertical antenna, it works as well with or without the relay in the pathway. The relay coil was energized with another short length of RG-174 going to the phono plug on the right. I shielded the 12 volt signal wire because I was trying to keep RF out of my power supply. This goal was easier for me using the logic inverter to drive the relay coil. Don't bother building the inverter if you don't need it.

Turning on the transmitter power supply



In many homebuilt transmitter designs the antenna relay has another set of contacts to turn on the DC power supply for the transmitter. A VFO-controlled transmitter is much more complex than a crystal controlled QRP. There are usually one or more oscillators running during transmit that must be turned off during receive. Otherwise you will hear them as whistles in the receiver. The “double” relay above in older ham transmitters is usually a *Double Pole, Double Throw*, a *DPDT*. The DC supply line goes to a moving contact.

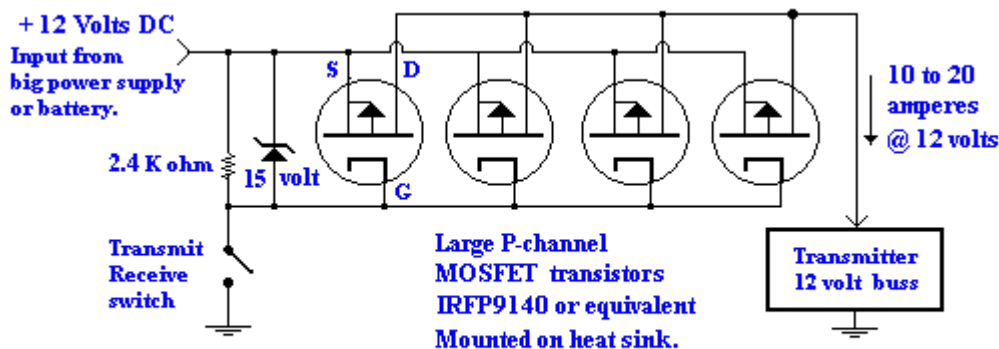
At rest this contact energizes the “spot” circuit and perhaps also the receiver. The “spot switch” allows you to turn on the transmitter crystal oscillator or VFO to figure out where your signal will be in relation to the fellow you’re listening to.

Grounding one side of the relay coil activates both the antenna relay and the DC supply relay. In other words, this control line always has 12 volts on it. When the line is grounded by means of the send-receive switch, this line activates the transmitter. This same signal can also be used to “mute” or inactivate the receiver. Alternatively, the DC supply relay in the transmitter could turn the power to the receiver off and transfer it to the transmitter.

I have built three transmitters that used a DPDT relay to perform both the antenna switching and the DC power switching. Except for the 10 meter problem explained earlier, these big relays all worked well ... at first. But eventually, the DC power side always became intermittent. For this reason, if you are going to run a 50 or 100 watt transmitter, plan on switching at least 20 amperes. I recommend using a 30 ampere relay and maybe yours won't become intermittent. Of course, the bigger the relay, the more difficult it will be to use one section of the relay as an antenna relay. I finally gave up and used separate relays for the power and antenna. When I push the little send / receive toggle switch on my electronic key "bug" box, it activates the coils of both relays.

Avoid power relays

Yet another problem with relays is that, the larger the relay, the more DC current it takes to activate it. A big 20 or 30 ampere relay coil can draw 100 to 200 milliamperes of current just to turn it on. Better yet, don't use a DC power relay. Using the QRP keyer described in Chapter 6 as a model to follow, you may use P-channel MOSFET power transistors to turn on the transmitter and/ or receiver. A heavy duty P-channel MOSFET power switch is illustrated below.



TRANSMITTER POWER SWITCH

The MOSFET power switch above uses four P-channel MOSFETs in parallel. When they are turned on, MOSFETs look like low resistances, 0.15 ohms or less. This means that little voltage is wasted across the switch. The larger the MOSFET, the lower the resistance. By putting several in parallel, the resistance can be lower still. Large TO-204 package MOSFETs can be bolted to a heat sink to keep the transistor temperature as low as possible. Otherwise, as the temperature rises, the internal resistance of the transistors will also rise.

P-channel MOSFETs are the easiest to use because you can turn them on by pulling their gates down to ground. In my first transmitter I used two big TO-204 case MOSFETs. Their heating was negligible when bolted to a large heat sink. In my second transmitter I used four smaller TO-220 case MOSFETS, type RFP30P05 p-channel MOSFETS. (Notice that you can decode the type number: 30 = 30 amperes, P = p-channel and 05 stands for 50 volts.)

Actually, for a given size and voltage rating of a transistor, N-channels are superior to P-channels. N-channels usually have about 1/3 of the on-resistance and are more difficult to damage. Unfortunately, to turn on N-channel MOSFETs, you would need a 24 volt power

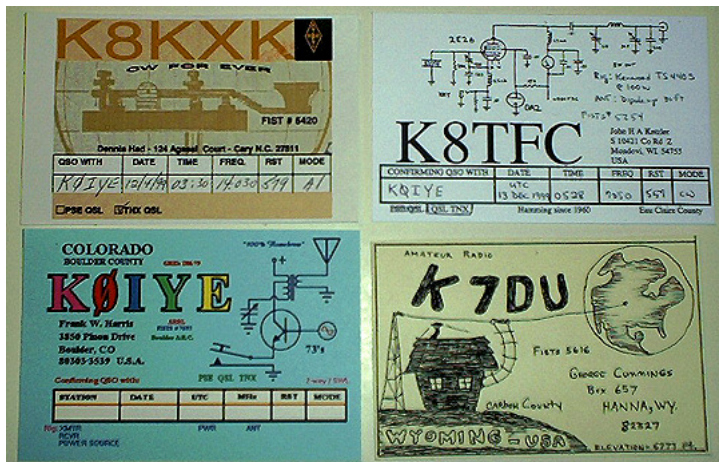
supply to pull the gates *up* to about 12 volts above 12 volts. However, if you have built a VFO like the one described in chapter 10, you already have a 22 volt power source you can use.

The 2.4 K ohm gate-to-source resistor insures that the transistors turn off when the switch opens. The 15 volt Zener diode on the gates is advisable because, in my transmitter, the gates of the transistor are in parallel with the antenna relay coil. When the transmit/ receive switch is opened, a big voltage can appear across the coil and may damage the transistor gates.

HOMEMADE QSL CARDS

I do not miss the QSL cards from the old days. Fifty years ago the most common American QSL cards were bought from World Radio Labs. They had a map of the US with one's call letters printed in red. It seemed as though everyone who didn't send out World Radio cards was sending Allied Radio cards. Allied cards were just glossy white cards with big orange call letters and a couple of orange stripes. These designs were quite attractive, but since they were the vast majority of what you received, QSL cards were pretty monotonous. Back then, if you had bought QSL cards that would have been competitive with today's commercial cards, they would have cost a fortune. Hand-drawing my own cards was fun, but only for the first 2 or 3 cards. After that, it was far too time consuming to be practical. I managed to make a crude template and print some rough black and white cards that were barely acceptable, but they sure looked primitive.

Since the age of Xerox, computers, digital cameras, and the color printers, making your own color QSLs has become a breeze. Other than knowing how to run a computer, it is totally non-technical. I dare say that typical 12 year olds can make great cards, even if their parents can't. Considering how easy it is, I'm disappointed that so few guys make their own cards. These cards have much more "soul" than mass-produced commercial cards.



Here are a few examples of homebrew cards. The two on the left were made using Microsoft Paint, Mac Draw or a similar, standard drawing program. The ones on the right were made using hand drawings that were later Xeroxed. They were printed onto plain 5 by 8 inch index cards and then trimmed to postcard size. Not much to it, really!

My buddy Jack, KØHEH, used his digital camera to take a picture of a nearby mountain. Then he used a free QSL software program to overlay his call letters on the scenery and ended up with a beautiful card. The cards can be printed on a color printer using photo quality paper. The result is very classy.



Four more examples are shown above. The Boulder Amateur Radio Club card at the upper left, WØDK, could be made with a digital camera as was just described. Alternatively, one could begin with a regular color photo and a scanner. The photo card on the lower left, is from Paul, WAØNXZ. This card could have been done with a scanner or digital camera, but this particular card happens to be a commercial postcard with hand-lettered call sign at the top. It's a beautiful card but buying postcards is pretty expensive.

The guy with the surfboard holding the walkie-talkie at the upper right, is Tom, KQ6DV. He used his own photo but kept the cost down by not using color and photo quality paper. The card at the lower right, is from John, KB2JKS. He made a complex hand-drawing and then Xeroxed it onto cards.

There are loads of ways to make QSL cards today. And all of these cards are more interesting than commercial ones. Yes, printing cards a few at a time is expensive. But most of us don't send out zillions of cards anyway. Making them yourself lets you modify them as often as you like. You aren't stuck with some error on the card for the next two hundred copies. Even if it's just QSL cards, homebrew is more fun!

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, REV 12

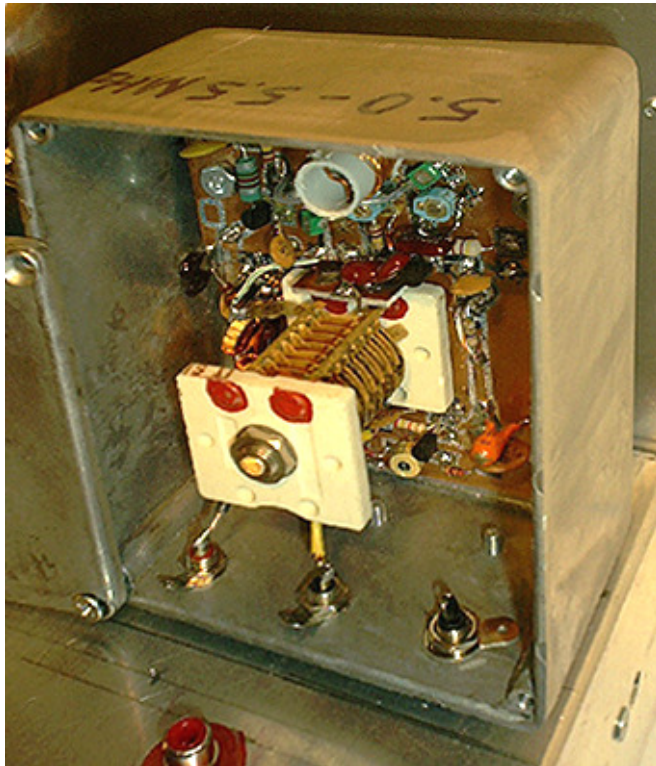
Chapter 10

Variable Frequency Oscillators (VFOs)

Sooner or later you'll become frustrated with being stuck on a few crystal-controlled frequencies. You would like to have a frequency-tuning knob that covers the entire band and not just a few kilohertz. This sounds simple, but isn't. It's difficult because, without the stability of a crystal, an ordinary RF oscillator will drift hundreds of hertz while you're sending. The fellow you're talking to probably has a modern transceiver with a narrow, stable passband. From his perspective your signal quickly drifts out of his passband. His digital readout may be calibrated to tenths of a Hertz and he will take great delight in telling you about *YOUR PROBLEM*.

Drift is a big deal today

In the old days, like 1950, receiver passbands were usually huge, like 10 or 20 kilohertz. So you could drift quite a distance before your contact even noticed, let alone could no longer hear you. Besides, everyone drifted a little back then, so it wasn't worth mentioning. In the really old days, like 1930, the signals drifted so much, that hams often tuned their receivers with one hand while they copied down the Morse code with the other.



A stable variable frequency oscillator can replace a crystal oscillator. This chapter summarizes what I learned in my odyssey through six VFO prototypes. My early VFOs drifted hundreds of Hz and I got loads of complaints. After I added temperature compensation, I got the instability down to 20 Hz drift per minute. Some stations notice 20 Hz drift and a few even told me about it. Eventually I built a super-regulated power supply for the VFO and got the drift down to about 5 Hz. I suggest you avoid embarrassment and work directly toward 5 Hz. According to the ARRL handbook, +/- 5 Hz is about as stable as you can achieve without phase lock loop technology.

A 5 MHz VFO tuned by a mechanical variable capacitor

2. Chapter 10, Harris

I was recently talking to a brand new local ham on 40 meters CW. We were chatting at a leisurely 5 words per minute. He, of course, was using a wondrous modern transceiver. It took us an hour to communicate very little information. Finally he tired of the strain and called me on the phone. "By the way," he said, "were you aware that you drifted over 50 Hz during our QSO?" He thought he was informing me of a grievous defect in my rig. Less than 1 Hz per minute? I was delighted that the drift was so low.

The test equipment needed to build a VFO are a precision multimeter for measuring voltage down to millivolts and a frequency standard. A super-accurate, modern receiver is OK, but a frequency counter is better for this application. The hardest part about building a stable VFO is following all the detailed instructions on how to do it. If you're like me, you'll have trouble believing that all that trivia is really necessary. Yes, you can cut a few corners, but the more compromises you make, the more your VFO will drift.

Low frequency VFOs drift less than high frequency VFOs

It's practical to build a VFO that operates directly on 160 meters (1.8 to 2.0 MHz) or on 80 meters (3.5 to 4.0 MHz). This makes transmitter design simple. For these bands you just amplify the VFO signal directly. For example, if you had a crystal-controlled QRP designed for 80 meters, an 80 meter VFO could be plugged directly into the crystal socket. You might want to attenuate the signal somewhat before directly substituting a crystal, but the VFO can replace the crystal and allow you to tune all over the band. If you can build a really first rate VFO for 40 meters, that band would also be practical. Unfortunately, for a given level of sophistication and precision, frequency drift is directly proportional to frequency. You will probably find that somewhere above 5 MHz, there is too much instability to keep the drift under 5 Hz per minute. In order to build a low drift VFO for 40 meters or above, a low frequency VFO can be "converted" up to the desired high frequency. Conversion means adding the VFO to a high frequency crystal oscillator signal and then extracting the sum frequency with a filter. Frequency conversion is covered in chapter 11.

Considering the size of most HF ham bands, a VFO needs a tuning range of at least 0.5 MHz. The higher the basic frequency of the VFO, the wider the tuning range you can achieve. ARRL handbook VFO projects have various frequencies ranging from 1.75 to 9 MHz. My CW transmitter VFO ranges from 3.5 to 4.0 MHz. My receiver and SSB-transmitter VFOs tune from 5.0 to 5.5 MHz. In retrospect, if I were starting over, I would have built the 5 MHz VFO first, since that frequency turns out to be more versatile. The disadvantage of a 5 MHz VFO is that it can't be used on any hamband directly and every hamband needs a frequency converter circuit. (Yes, a 5 MHz VFO can reach 60 meters. But CW isn't permitted on 60 and generating SSB on the same frequency on which you're transmitting requires a phase shift technique that is rarely used today.)

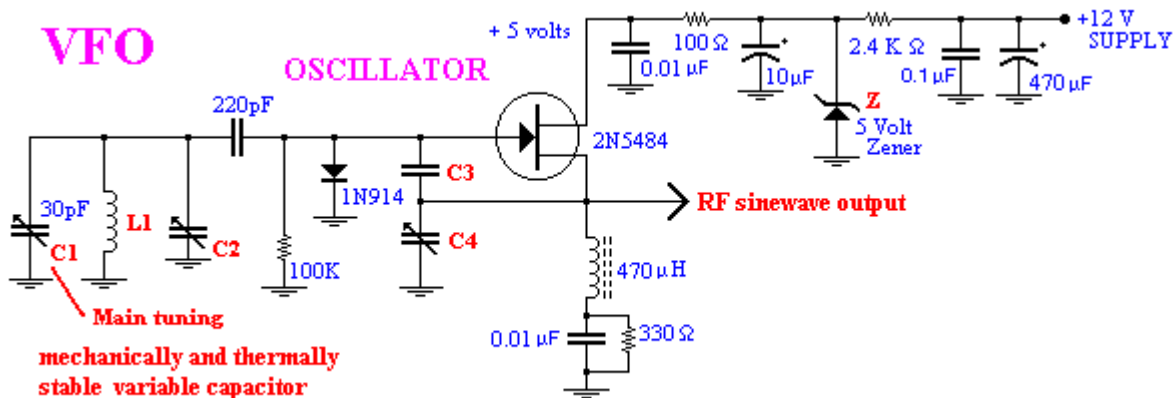
JFET transistors

Junction Field Effect Transistors (JFETs) are ideal for building VFOs. Unlike bipolar transistors, the main current from the drain to the source does not pass through any PN junctions. PN junctions change their characteristics with temperature. Therefore, VFOs made from bipolar transistors tend to drift more than JFETs. JFETs work on the same principle as a MOSFET, but the control gate is a P-N junction diode rather than a capacitor. JFETs were explained and used in the VFO oscillator in the direct conversion receiver in chapter 7.

THE VFO CIRCUIT

The basic oscillator

In principle the VFO is almost the same as a quartz crystal oscillator. The crystal is electrically equivalent to an LC resonant circuit. Therefore, to tune a VFO we use either a variable capacitor or a variable inductor to change the resonant frequency. So far as I know, suitable variable inductors can't be bought or built in a home workshop. That means that the tuning element will have to be a variable capacitor, much like the one you used to adjust the crystal frequency in your QRP.



The circuit above is essentially what you will find in your ARRL handbook. It uses a JFET transistor. The oscillator is a *Colpitts* and can be recognized by the capacitive divider feedback, C3 and C4. Whenever the source voltage goes up, some of this change is coupled to the gate through C3. This turns the JFET more ON. That is, the feedback is positive which sustains the oscillation. The basic LC resonant circuit that determines the frequency is C1 and L1. C2 is a trimmer capacitor to help adjust the desired tuning range.

So what are the values of C1, L1, C2, etc.? The answer isn't simple. We start with a quality variable capacitor for C1 as described below. For various reasons, **C1 will probably be about 30 pF**. Starting with this capacitor and the need for a 0.5 MHz tuning range, the other values must be determined by trial and error. The values are extremely hard to calculate because C3, C4 and even the 1N914 diode are part of the capacitance. Don't try too hard to get the values right until you have studied this entire chapter and formulated a plan for your VFO. As you will see later, C2, C3, and C4 are part of the temperature compensation strategy and will need to be determined by those considerations first. When you have decided what to do about C3 and C4, then you can work on L1 and C2.

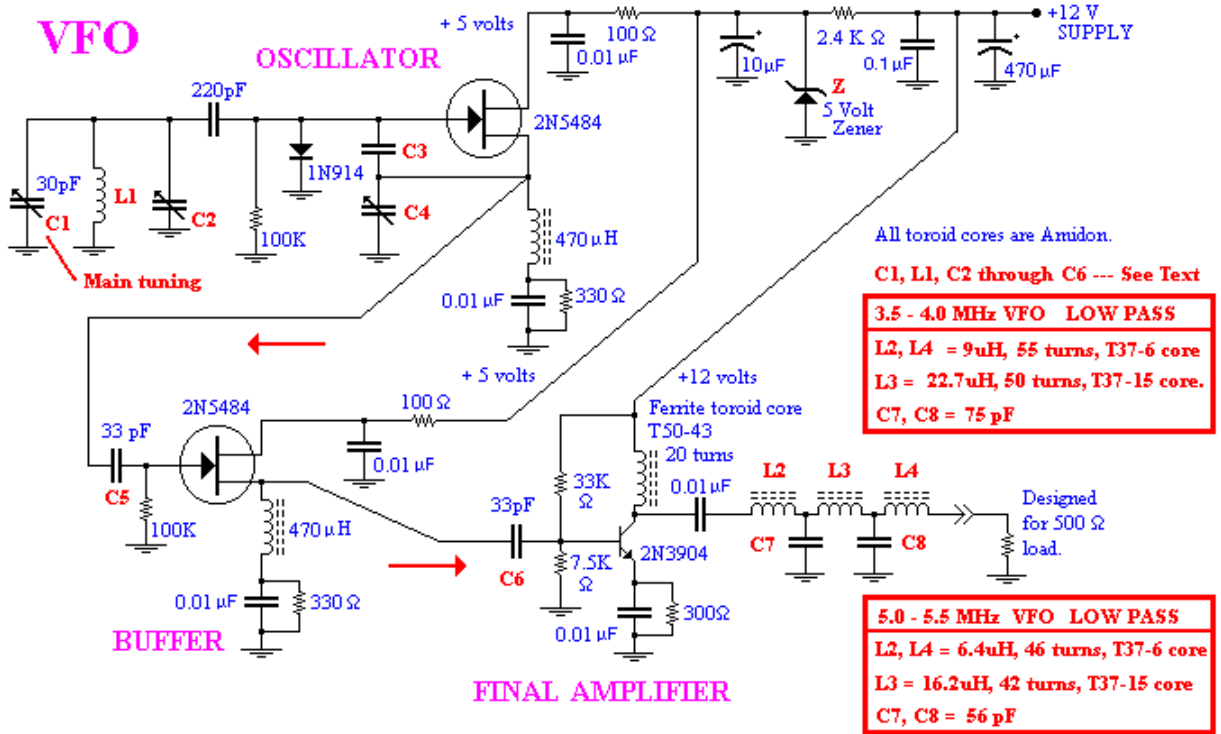
The 470 μHenry choke in the source circuit serves as the load “resistor.” That is, the oscillator sinewave output is locked in between the operating voltage, +5 volts, and ground. Since the sinewave voltage appears across the transistor, the remainder, 5 volts minus the sinewave, must appear across a load of some sort. This choke could be functionally replaced with a resistor, except that a resistor dissipates energy and gets hot. The last thing you need in your VFO is another source of heat. The choke inductance is high enough so that the current through it changes very little during one RF cycle and its effect on the frequency of oscillation is

minimal and unchanging.

While we're on the subject, you might experiment with substituting an LM336-2.5 volt precision Zener diode for the 5 volt diode. This would of course cut the amplitude of the oscillation in half, but it will also decrease the circuit heating to one fourth. It may not work out for you, but anything that reduces heating, increases stability.

The 1N914 diode on the gate seems counter-productive, but it is used as a clamp to keep the base of the JFET transistor out of the forward conduction region. That is, when the oscillation gets too vigorous and the gate P-N junction begins to turn on at 0.6 volts, the diode will help prevent operation in this range. The VFO as a whole is powered by 12 volts. However, 5 volts derived from a Zener diode regulator (Z) power the oscillator stage and its buffer. This is done to dissipate as little energy as possible in the oscillator and prevent the components from heating.

The entire VFO circuit



Here is the entire VFO circuit, excluding the temperature compensation. As you can see, the VFO also contains a buffer stage and a final amplifier. Temperature compensation consists of special circuits that replace either C2 or C4.

Buffer

The buffer stage separates the oscillator from the final amplifier. Otherwise there would be a subtle connection between the load on the VFO output and the oscillator. Believe it or not, without the buffer, if you change the load on the VFO output slightly, the frequency will change too. The buffer is connected to the other stages by C5 and C6. These capacitors should be as small as possible to reduce the connection between the oscillator and final amplifier.

Final amplifier

The final amplifier raises the VFO output up to the level needed to drive the transmitter. The stage being driven in the transmitter is usually a “mixer” which we shall discuss in the next chapter. But, if the VFO is designed for the 80 meter ham band, then the next stage after the VFO could be a string of class C amplifiers to increase the output power to the final level, say 5 or 50 watts. The VFO final stage will need to deliver at least two volts peak sine wave. Since we have deliberately kept the oscillator and buffer signals tiny, the final amplifier must be a linear or Class A amplifier to get the signal level up to 2 to 5 volts peak. The drive to this transistor is biased with a 33K resistor so that this stage is always turned on.

Low pass filter

The drive to the transmitter should be as pure a sinewave as possible to avoid radiating harmonics outside the hamband. A low pass filter on the output attenuates most of the harmonics above the desired frequency range. A Chebyshev low pass filter is shown designed for a 500 ohm load. In Chapter 6 you were introduced to Chebyshev filters designed for 50 ohms. However, here we have no need for power, just voltage. Therefore, the filter is designed for 500 ohms, which is plenty of drive current for this application. Values are given for both a 80 meter VFO (3.5 to 4.0 MHz) or a 5 MHz VFO (5.0 to 5.5 MHz).

**

The 50 secrets of avoiding drift

Suppose you were to build the above VFO without reading the details in the following paragraphs: When you first turn it on, you will be disappointed to find that it drifts a hundred Hz per minute or more. ***The drift is caused by temperature change.*** The components expand and contract with temperature and this causes small changes in the capacitance and inductance of the components. Air wafting across the board doesn't allow the temperature to stabilize. ***Drift is prevented by preventing temperature change and by choosing components that change as little as possible with temperature.***

VFO building is an art form as arcane as Grandma's secret pie crust recipe or the fine points of building Cub Scout Pinewood Derby racers. As you'll see, there must be 50 ways to improve the drift problem. I have never built a VFO that was completely "stable" and probably never will. But perhaps that's because I only know the 14 secrets listed below. If you apply as many of these as possible, you should get within the 20 Hz target - and maybe even under 5 Hz.

Secret # 1. Use Junction Field Effect Transistors (JFETs). The first secret of a stable VFO is using a JFET instead of a bipolar transistor. As described earlier, a field effect transistor is better because it is less sensitive to temperature. I have used 2N3823, 2N5484, and 2N4416 N-channel JFET's for VFO oscillators. My impression is that any small N-channel FET works well.

Secret # 2. Seal the VFO in a cast metal box. Simply protecting the VFO from air currents makes a huge improvement. Use a heavy cast metal box so that the temperature will at least change slowly. In contrast, a flimsy sheet-metal aluminum box will heat and cool relatively rapidly. On the other hand, *ANY* box is a huge improvement over not having the circuit sealed from air currents.

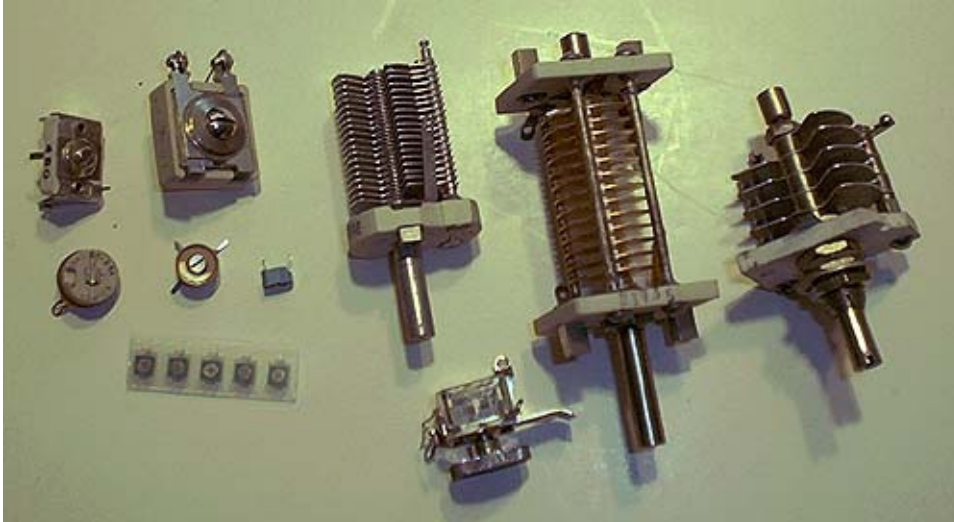
Secret # 3. Use single-sided PC board. A double-sided PC board is constructed like a capacitor. That is, thin metal sheets are bonded to a layer of insulator. Unfortunately, the resulting capacitor has a significant temperature coefficient. As temperature increases, the board material expands (thickens) and the capacitance across the board drops. If the VFO is built on traces and islands that have changing capacitance to ground, the frequency of the oscillator will drift slightly.

Secret #4. Mount the oscillator PC board away from the metal case on standoffs. Following the same principle as above, do not mount the single-sided PC board flush against the metal case. By standing the board up and away from the case, the capacitance between the traces and the metal case can be minimized.

Secret #5. Choose and mount all components affecting the oscillator LC circuit carefully. All the L and C components in the oscillator should be designed for minimum temperature drift. Referring to the diagram, it is not just capacitors C1 and C2 that affect the frequency. Capacitors in series with the 220 pF capacitor, C3, C4, and even C5 affect the frequency. To at least a tiny degree, ALL components in contact with these capacitances can affect frequency drift. These include the diode, the RF choke, the transistor, and the 100 K resistor.

Secret # 6. Mechanical variable capacitors should be chosen carefully. Although appropriate mechanical variable capacitors are hard to find, they may be the best solution for you. Pick a capacitor of about 30 to 60 PF, not larger. High capacitance variable capacitors are too sensitive to temperature change. Smaller ones don't tune far enough. *Don't use a capacitor with aluminum plates* – they warp too much with temperature. *Brass is the best metal. Try to find a capacitor with thick, widely-spaced plates.* Paper-thin plates are compact, but warp too easily.

An assortment of variable caps is shown below. The big brass variable cap just to the right of center is rather big physically. However, out of this group it is the best for a VFO. The capacitor to its right is quite stable, but its capacitance is too small. The tiny green plastic trimmer caps in the clear plastic strip are positive temperature coefficient variables useful for VFO temperature compensation. The round ceramic white and silver trimmer just above them is my favorite 60 pF trimmer. I used dozens of them in the projects of this book. The small variable cap at the bottom center has surprisingly large capacitance, 250 pF. Unfortunately it's too unstable for a VFO.



If the capacitor tuning is linear with degrees of rotation, the frequency it produces will be somewhat non-linear. Ideally, the capacitor plates should have a non-linear shape that allows it to tune an LC resonant circuit so that the frequency will be linear. Rotate the capacitor through its range and you'll see that a compensated capacitor has rotor plates that are not simple half circles. As they rotate, they do not mesh with the stator plates at the same point. The non-linear correction isn't a big deal, but it is something to be aware of. RF Parts Co. sometimes has adequate capacitors in stock. See www.rfparts.com.

Secret # 7. Varactors are the most stable tuning element. It's hard to buy mechanical variable capacitors that are mechanically and thermally stable. Collins Radio formerly tuned their VFOs with special powdered-iron slug-tuned coils, but I've never seen any for sale. A varactor capacitor controlled by a quality pot can be a good solution to these problems. Varactors are a kind of silicon diode biased with DC voltage. In my experience varactors are an order of magnitude more thermally stable than mechanical capacitors. They are at least two orders of magnitude more mechanically stable. You can slap the VFO with your hand and, although other components may vibrate, the varactor will not change its capacitance.

Unfortunately, varactors produce a non-linear scale on the frequency tuning knob. This means that the high frequency end of the VFO range will be extremely detailed while the low end may be compressed into a few degrees of rotation. For this to be usable, ideally the potentiometer should be non-linear to compensate. Varactors are discussed in detail below.

Secret # 8. Use NP0 fixed capacitors. When selecting fixed capacitors, look for type C0G (formerly known as NP0). These are supposed to have minimum temperature change. Use these for *ALL* fixed capacitors affecting the LC circuit.

Secret # 9. Use multiple C0G(NP0) capacitors in parallel to achieve a given value. For example, you might use fixed capacitors for C1 or C2 in the above circuit. For each value needed it is better to use several small ones in parallel rather than one large capacitor. The temperature of a small capacitor stabilizes quickly, whereas heat builds up more slowly in a larger capacitor.

Secret # 10. Temperature compensation for the LC circuit is essential. It took me four prototypes to accept this, but temperature compensation is as important as putting the VFO in a

8. Chapter 10, Harris

box. Lots of guys claim to have succeeded without it, but I never have. Not using temperature compensation implies that every capacitor and inductance in the VFO must have a zero temperature coefficient. Alternatively, all negative coefficients must be balanced precisely with components that have equivalent positive temperature coefficients. Good luck doing that! Compensation circuits are described below.

Secret # 11. Use an air core inductor. As usual, it is most convenient to use a powdered iron toroid core. Unfortunately, powdered iron changes its permeability (magnetism factor) with temperature. Therefore, by not using iron, another variable is eliminated. I have successfully used old plastic ball point pen caps as little coil forms for air-core inductors. I bore little holes in the plastic to accept tiny pieces of stiff copper wires to serve as wiring terminals.

If you do use powdered iron, among the CWS (Amidon) cores, type #7 is supposed to have the best thermal stability. CWS Bytemark (Amidon) #6 cores have worked reasonably well for me but maybe #7 would be a few percent better. If you make a coil out of turns of copper wire on a plastic form, the copper will change its dimensions slightly with temperature too. And because an air core inductor requires more turns of wire, there is more opportunity for the copper to change its dimensions, its interwinding capacitance, and also its resistance. Finally, an air-core coil will couple like a transformer to nearby parts whereas a powdered iron toroid couples far less. Sigh. Nothing is perfect.

After you have your coil wound and working over the right frequency range, epoxy or clamp it to the board. Without the epoxy, the frequency will warble with the slightest vibration. I once tried to use slug-tuned coils. They were convenient to adjust, but were mechanically and thermally unstable.

Secret # 12. Precision voltage regulation for the VFO supply is vital for precision frequency stability. The 12 volt supply for the VFO as whole must be regulated. Ordinary voltage regulators like the LM317 or LM7812 gave me regulation within 0.1 volt. This was OK for frequency stability down to about 20 Hz drift. But to get down to less than 5 Hz, I needed to regulate my VFO power supply to a few millivolts. To achieve this, I built a precision supply that just powers the VFO. The less current the supply has to deliver, the more constant its output voltage will be. The supply is discussed in detail below.

Secret # 13. The VFO should draw as little power as possible. The less power drawn, the less heating that occurs inside the VFO box. Also, the less power drawn, the easier it is to build a precision voltage supply to drive the VFO. That is why the VFO was designed for a 500 ohm load rather than 50 ohms like most ham RF circuits. The VFO as a whole should draw less 20 mA DC. 10 mA would be even better.

My next attempt at a VFO will house the oscillator and buffer inside the cast metal box and I'll put the "high power" final stage outside the box so its heat can't affect the oscillator. Another idea I'm going to try is to run the oscillator on even less voltage, perhaps 1.5 to 2.5 volts.

Secret # 14. Forget tube oscillators. You old timers may be tempted to use a tube oscillator. I first tried to update an old tube VFO, but tubes get hot and make temperature compensation too difficult. You'll have plenty of trouble without this extra burden. You may use bipolar transistors for the final amplifier in your VFO, but not for the oscillator. For good measure you may as well use a JFET for the buffer as well.

Vernier mechanical tuning and frequency indicator

Because a VFO must be tuned precisely to the other fellow's frequency, it is vital to use a vernier tuning gear between the tuning knob and the variable capacitor. In my opinion, the tuning knob should rotate at least three times around for each revolution of the capacitor. Without vernier tuning, it will be exceedingly difficult to tune your receiver or transmitter accurately to the other fellow's frequency. A planetary reduction gear is generally mounted on the front panel. Machine screws clamp it to the 1/4 inch capacitor tuning shaft that protrudes from the VFO box. Tuning gear systems are usually combined with a dial and pointer that you can calibrate. A paper dial can be marked with ink for the calibrations. A plastic cover protects the paper from moisture.



I used a National Company brand vernier dial on one of my VFOs shown at left. Recent interest in QRPs has made these available again after being absent for some years. Look for the ads in ham magazines. Unfortunately, these dials are pretty pricey. For some of my VFOs I used a military surplus reduction gear that had no pointer and dial. I made the pointer out of super-thin PC board painted black. The dial calibrations were on thin white cardboard covered with 1/8 inch Lucite plastic and screwed onto the front panel.

If you use a varactor variable capacitor as described below, you may be able to find a multi-turn potentiometer for your tuning vernier. This solves the vernier problem, but doesn't offer a way to calibrate the dial. Some hams have built elaborate frequency counters or digital voltmeters as solutions for VFO calibration. All I can say is beware of digital circuitry in your ham equipment. Homebuilt digital circuits (in my experience) always generate radio noise that will interfere with hearing weak signals. Commercial manufacturers make digital technology look easy. But so far, all my digital toys have generated a static "hiss" that I have regretted.

**

Varactor Tuning

While building a new receiver, I had to construct another VFO. In this prototype I explored replacing the mechanical tuning capacitor with a varactor. Back-biased P-N junctions

The advantages of varactor tuning are:

- 1. Varactors are mechanically stable.** Assuming the potentiometer driving your varactor is mechanically stable, then the resulting VFO will be mechanically stable. You can bang the table with your fist and the frequency will barely warble in the receiver.
- 2. Varactors are more thermally stable than mechanical capacitors.** When testing a mechanical capacitor VFO circuit with a hair dryer, I found that the blast of hot air on the circuit board caused the frequency to soar or plunge hundreds of Hz, sometimes even KHz. When my varactor VFO is given the same treatment, the frequency change is an order of magnitude less.
- 3. Varactors are available.** Good mechanical tuning capacitors are hard to find. In contrast, varactors can always be purchased from Digi-Key, Mouser, and other companies.
- 4. Varactors are tiny.** Some of the ones I used are the size of a grain of sand. Soldering them on my circuit board required patience, sharp tweezers, and a jeweler's loupe. A VFO module made with a varactor can be much smaller than a VFO made with a mechanical variable capacitor. Also, the varactor can be tuned by a potentiometer located at some distance away on a front panel.
- 5. Varactor VFOs may be tuned by phase-lock loops.** Since the varactor VFO is tuned by a variable DC voltage, it can be part of a modern phase-lock loop design. A homebrew VFO doesn't have to be confined to old technology.

The problem with varactors

Alas, varactor-tuned VFOs are non-linear. However, you can turn this to your advantage. As the DC voltage is changed across the varactor, the frequency change it produces is not linear. When the voltage is first applied, the holes and electrons in the PN junction are filled in readily and decrease the capacitance rapidly. After the first big change, more and more voltage must be applied to fill in more holes and deplete the electrons in the N-type semiconductor. In other words, the wider the tuning range, the more non-linear the relationship between applied voltage and frequency. This exaggerates the tuning of the high-end frequency end of the band. For example, if the varactor is pushed to its maximum capacitance range, then 75% of the voltage tuning range might be needed to cover the upper 25% of your total frequency range.

Suppose you are primarily interested in CW operation. The CW portion of the band is always at the bottom of the hamband with phone at the high frequency end. The linearity problem can become an advantage by designing the VFO frequency converter in your transmitter or receiver so that, for each band, the high frequency end of the VFO range covers the low CW end of the ham band. That is, the VFO frequency should be *subtracted* from a higher crystal controlled converter frequency.

CW signals have little bandwidth, a few Hz, and the CW bands are often crowded. In contrast, although phone bands are sometimes crowded, the phone bands are several times wider and the phone signals themselves each cover 3 KHz. In other words, good bandspread, (small frequency change for big knob rotation), is important for the CW band and not so important for the phone band. Yes, tuning in SSB phone requires fine-tuning. But you may find that tweaking the speech quality is more easily done with the receiver BFO knob than with the VFO tuning.

For example, in a transmitter, the VFO might range from 5.0 to 5.5 MHz. To transmit on

40 meters (7.00 to 7.30 MHz), the transmitter could use a 12.5 MHz crystal controlled local oscillator to cover from 7.0 to 7.5 MHz. That is, 12.5 MHz minus 5.5 MHz = 7.0 MHz. In this way, the high end of the VFO tuning covers the *LOW* end of the ham band. In contrast, if you use a low frequency crystal, 2.0 MHz (e.g., 2.0 MHz + 5.3 MHz = 7.300 MHz), the high frequency end of the VFO will cover the upper end of the phone band where bandwidth isn't important. If you're confused, frequency converters are explained in detail in chapter 11.

Frequency offset on transmit

A transmitter VFO has a problem you may not have thought about. With an old-fashioned, wideband CW receiver, when you tune past a CW signal, you'll hear a whistle that changes from a high pitch to a low pitch or "zero beat," then rises back up to a high pitch as you continue to change frequency. If your receiver were tuned precisely to the other guy's frequency, he would be at the "zero beat." His CW signal would have such a low pitch you wouldn't be able to hear it.

To fix this, modern transceivers automatically add a frequency offset between receive and transmit, usually 700 or 800 Hz. Also, fancy transceivers don't receive the lower half of the signal unless the operator selects LSB on the front panel. In general, the lower sideband (LSB) is used on 160, 80, and 40 meters while the upper sideband, (USB) is used on 60 meters, 30 meters and above. With a modern, narrow bandwidth receiver, modern hams may not even be aware that there are two sidebands. The upshot is that, when you answer a CQ with your homebrew VFO, you must tune in the correct direction about 700 Hz above or below his zero beat point. Otherwise he won't even hear you. Old timers used to tune around, but modern guys don't. I believe I had this problem when I first got on the air with my homebrew rig. Few stations seemed to be able to hear me. Yet, when I did talk to someone, I got good signal reports.

The simplest solution is to use the narrow bandwidth filters on your receiver so that you can only hear the upper or lower sideband at one time. Then when you zero beat your signal on top of the fellow calling CQ, you only hear your VFO when you are on the correct sideband. Narrow passband filters for a homebrew receiver are discussed in chapter 13.

VFOs for transceivers

If you build a VFO for a transceiver, the VFO will be used during both receive and transmit. As explained above, it may be useful to add a varactor tuned offset adjustment to the VFO so that you can send and receive on slightly different frequencies. To do this, add an auxiliary low capacitance varactor adjuster in parallel with the main tuning. The technology is the same as for varactor tuning, but the tuning range will be less than one KHz.

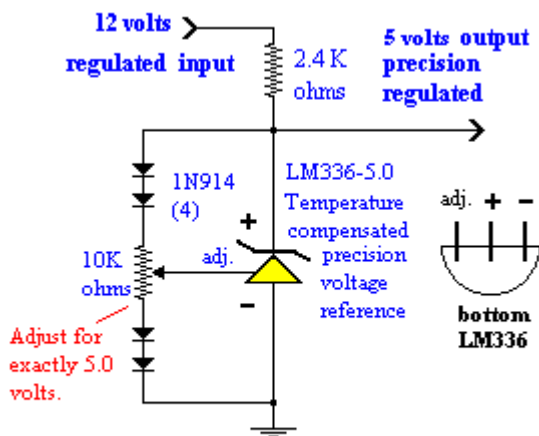
A precision power supply for the VFO

One of my VFOs had a relentless upward drift of 200 Hz per hour. I was puzzled until I noticed that my 12 volt VFO power supply had a subtle downward drift. Ordinary voltage regulators are crude compared to temperature compensated regulator ICs. Regulators like the LM317 or LM7812 drift hundredths of a volt per minute, especially if the load is more than 100 milliamperes. A simple Zener diode regulator can easily allow one or two tenths of a volt change on the oscillator. The solution is to build a precision voltage regulator. This 12 volt regulator

should be located outside the VFO box. So far as possible, *anything that generates heat should be kept outside the VFO box.*

Precision Zener diodes

The trick to building a precision, temperature-compensated power supply is a precision Zener diode reference. Ordinary Zeners vary their regulation voltage with temperature. Precision Zeners are integrated circuits that behave like Zener diodes, but have temperature compensation circuitry and can be adjusted to exactly the rated voltage. The LM336-5.0 Zener diode can be adjusted with a trim pot to precisely 5.000 volts DC. It is designed to have the best temperature compensation at that exact voltage. Other than the pot and the diodes, this part is used like an ordinary Zener.



Precision 5 volt Zener

Yeah, I know. I promised I wouldn't use ICs that I couldn't build myself. I'm afraid precision regulators are beyond me. I've tried, but my attempts never exceeded the precision of the most ordinary IC voltage regulators. I did manage to build a pretty good voltage reference consisting of Zeners regulating other Zeners in a cascade in which some of the resistors were thermistors. Unfortunately, the final output was only stable at tiny voltages and tiny load currents and I couldn't successfully leverage it up to useful voltages and currents.

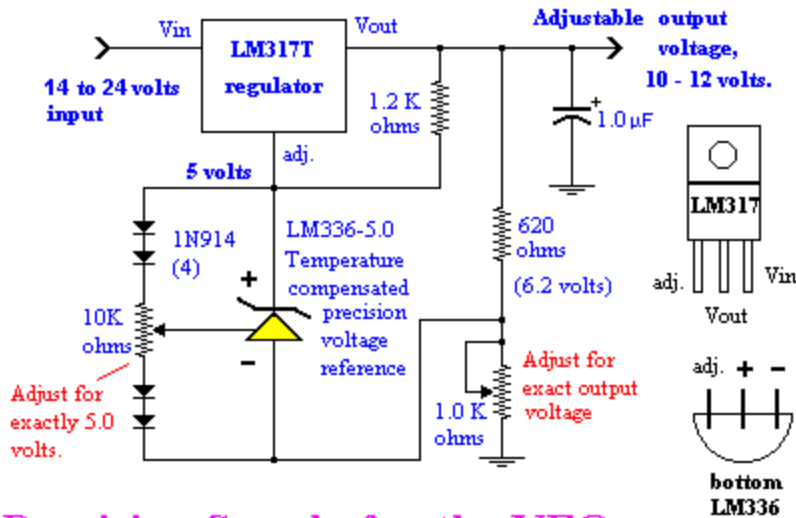
A precision 12 volt power supply

The precision voltage regulator shown below comes from the National Semiconductor Data Book for linear integrated circuits. This regulator will hold the VFO voltage constant to within about 2 millivolts. It uses a programmable LM317T regulator. (The "T" at the end identifies the TO-220 case style.) The output of the big regulator is "modified" with a precision Zener reference regulator to hold the output voltage constant. The LM317 regulates the voltage across the 1.2 K ohm resistor to about 1.2 volts. The precision reference then regulates the voltage across the 620 ohm resistor to exactly 6.2 volts - that is, 1.2 volts plus 5.000 volts. Since the voltage across the 620 ohm resistor is held constant, the current passing through the 1K potentiometer is also held constant. Therefore, adjusting the 1K pot can adjust the total voltage.

In order to maintain this high degree of precision, *the above regulator just powers the VFO.* When I tried to run other transmitter stages with the precision power supply, the load rose to several hundred milliamperes. Although the regulator chips were operating within specifications, the extra load ruined the millivolt precision regulation. I retrofitted my old capacitor-tuned VFO with the same precision regulator and found the frequency stability became as good as my newer varactor VFO.

I try to keep my VFO supply current down to less than 10 milliamperes. If you need more than a 3 volts peak output voltage, you'll probably find this difficult. In the full circuit shown

above, by the time you get a 5 volts peak, pure sinewave, the current drawn from the supply is likely to approach 20 milliamperes. One way to compensate is to adjust the voltage from the precision supply to the bare minimum needed to provide the output waveform you need. That is, instead of using regulated 12 volts, use regulated 8 or 10 volts.



Precision Supply for the VFO

Separate regulation for the VFO oscillator

If your VFO is consuming more than about 10 mA, you may want to compensate for the temperature change inside the box by powering the oscillator inside the VFO box with 5 volts from a separate precision 5 volt or 2.5 volt Zener instead of using an ordinary 5 volt Zener.

A voltage doubler for battery use

If you're line powered, the regulator described above will probably work just fine, unless there is a brown out. On the other hand, if your transmitter is battery powered, its output voltage will fall well below 12 volts as the battery discharges. One solution is to run the VFO on regulated 9 volts. That way, even with 10 volts left on the battery, the regulator will still be providing 9.000 volts. However, if your VFO uses a varactor as the tuning element, you may need at least 10 volts to get the maximum tuning range from the varactor. My solution to this frustration was to first double the unregulated battery voltage. By starting with nominally two times the battery voltage, my VFO will always have at least 12 volts. Because the VFO only draws 10 to 20 mA DC, this DC voltage doubler does not have to be powerful.

**

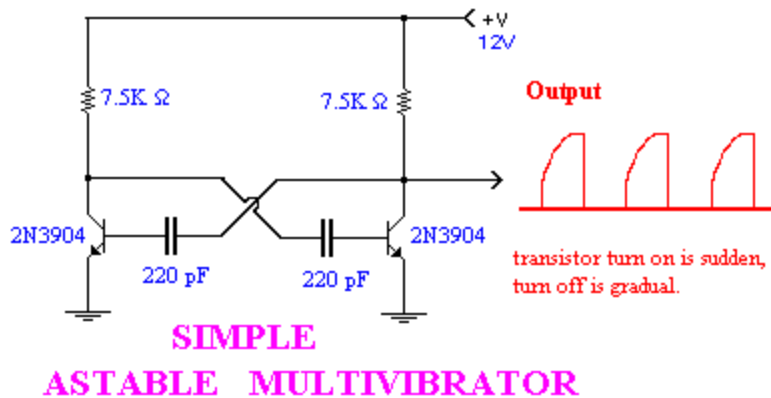
A DC voltage doubler

Square wave generation

Any time you wish to raise a DC voltage, it is necessary to use the existing DC supply to generate a source of AC voltage. For example, the AC voltage could be applied to a transformer

to produce as high an AC voltage as you need. The high AC voltage would then be rectified back into DC at the required high voltage. Instead of using a transformer, the voltage doubler described below uses a capacitive *charge pump* to raise the voltage. As you'll see, this technique is a specialized kind of rectification.

The first task is to convert the DC supply to square wave pulses. It turns out there are many ways to generate square waves using integrated circuits. For example, I used an operational amplifier IC to generate the dots in the electronic bug in chapter 9. You may use an IC if you like, but you might enjoy doing it the hard way. As usual, if you're new to electronics, you'll learn some interesting concepts.



A simplified *astable multivibrator* oscillator is shown to the left. As you can see, this circuit consists of two grounded emitter amplifiers wired so that any change on the collector of one transistor is immediately coupled to the base of the other. Let's assume that the capacitor on the left is charged to a low voltage, say 1 volt. The capacitor on the right is charged to nearly 12 volts.

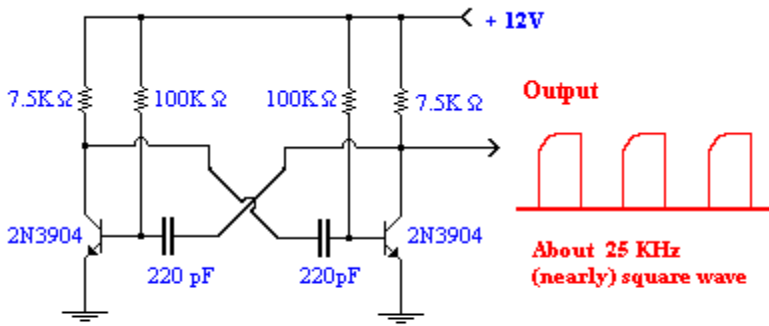
The capacitor on the left is charging toward 12 volts through the 7.5 K resistor on the right. As the positive charge flows out of the capacitor and into the base, the left transistor turns on. This pulls its collector and its respective capacitor toward ground.

Since the voltage across the capacitor on the right can't change instantly, the voltage on the right base is pushed downward to roughly -12 volts. This extreme negative voltage turns off the right hand transistor. The right hand capacitor with its -12 volts will discharge toward zero volts since there is now no source of voltage to maintain negative 12 volts. This discharge takes a significant length of time because the current must bleed into it through the 7.5 K ohm resistor. Eventually, the voltage on the right transistor's base rises above $+0.6$ volts, which will turn that transistor back on. When the right transistor turns on, it pushes the left hand capacitor back down to -12 volts turning off the left transistor.

A practical multivibrator

The simplified multivibrator described above oscillates OK, but it doesn't always start spontaneously. In fact, you will find that it only runs at a specific range of supply voltage and must be turned on abruptly. If you turn up the supply voltage gradually, the multivibrator remains stable with one or both sides turned off and the oscillation never begins.

The unreliability of the simple multivibrator can be fixed by biasing the transistors partly *ON* with the 100K ohm resistors. These resistors insure that the capacitors will always be charging or discharging. Now the circuit will generate square waves even with very low voltages. When the power supply voltage is turned up slowly, the oscillation will always start. Also, the *ON* state of each transistor is maintained longer and a better square wave results.

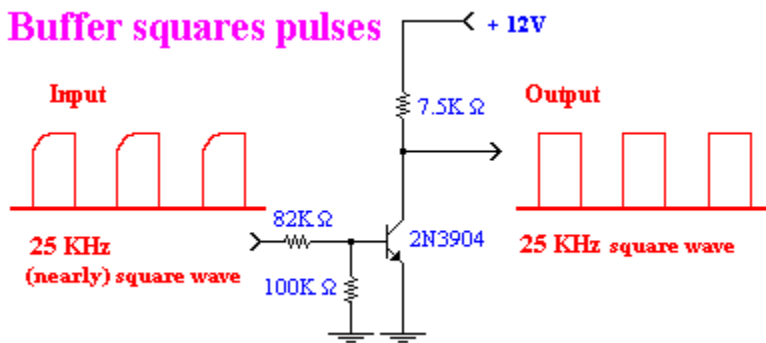


ASTABLE MULTIVIBRATOR

multivibrator. If a pulse is introduced to one transistor or the other, the circuit can be made to “flip-flop” to the opposite stable state in which the *OFF* transistor turns *ON* and the *ON* transistor turns *OFF*. The *flip-flop* circuit is the basis of static RAM memory (SRAM). One flip-flop can store one bit of information. So long as the supply voltage is applied, the circuit will “remember” one bit of information indefinitely. Or, it will remember it until another pulse comes along and resets it to the opposite state. In an integrated circuit SRAM literally millions of flip-flops are printed on a chip storing megabits of information.

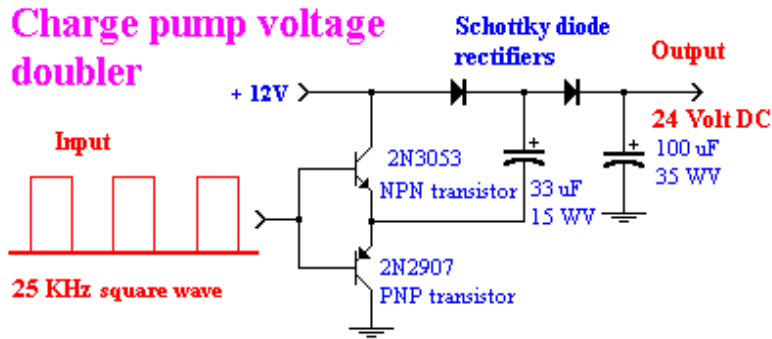
Squaring up the low power square wave to drive a doubler charge pump

Now that we have a low-power, square-wave voltage, we need to clean up the waveform and amplify it so that we can produce about 30 mA squarewave AC for our VFO power supply. This is done with a simple buffer amplifier to make it square. A square waveform is important because the less time that the circuit spends “half turned on,” the more efficient the power supply will be.



This square wave buffer is just a high gain voltage amplifier. During the sloping, rising input voltage, the upward slope of this voltage is exaggerated by 10 or 20 times. This diminishes the rise time until the rise time becomes negligible.

Diode voltage doubler



How can we “double” DC voltage using diodes? The idea is to repeatedly charge the 33 μF capacitor to +12 volts as though that capacitor were a rechargeable battery. Then the capacitor is switched out of its “charging mode” and added like a battery on top of the existing

12 volt supply. In other words, 12 volts plus 12 more volts equals 24 volts. This pulsing, 24 volt signal then charges up the large 100 μF storage capacitor on the right to 24 volts. Provided the current drawn from the 24 volts supply is small, the capacitor on the right can maintain a relatively constant voltage approaching 24 volts.

As shown above, the PNP and NPN transistors work together to pull the left hand capacitor up and push it down. When the PNP transistor is turned on, the bottom end of the capacitor is connected to ground. In this condition the diode on the left charges up the capacitor to 12 volts. When the PNP turns off and the NPN turns on, the bottom end of the capacitor is suddenly shoved “up” and tied to the 12 volt supply line. Since the top of the capacitor is suddenly 12 volts higher than the supply line, the diode on the left is back-biased and can no longer charge it. Instead, the diode on the right is now forward biased and will discharge the 12 volts into the storage capacitor on the right. The capacitor on the right charges toward 24 volts thereby creating twice the original voltage.

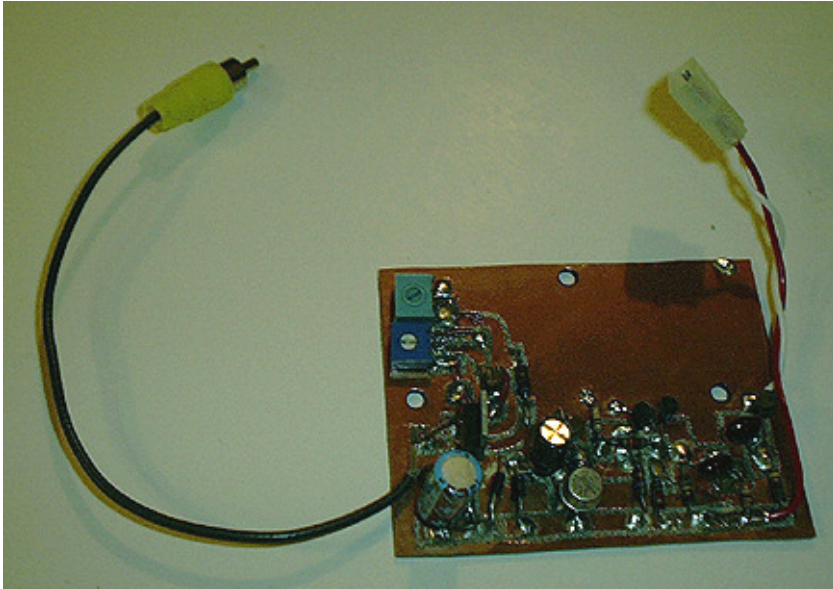
Complementary transistors in action

In chapter four I mentioned that it was often convenient to have transistors that work with opposite polarities. As the drive to one transistor turns it on, the same polarity turns its complement transistor off. The output is taken off the emitters. In effect, the complementary transistors connect the output back and forth between ground and the 12 volt supply without any resistors becoming hot and wasting energy.

By the way, the logic circuits in your personal computer are almost entirely implemented with integrated circuits made from Complementary N-channel and P-channel MOSFET transistors. These ICs are called *CMOS*. By avoiding resistor loads on the FET drains, heating is minimized and switching speed is maximized.

Use Schottky rectifiers for best efficiency

Now we have loads of extra voltage, even when the battery supplying the transmitter is nearly exhausted, so there is still plenty of voltage for the precision regulator to generate 12.000 volts. The supply works best if the two diodes in the voltage doubler are power Schottky diodes. These rectifier diodes only waste about 0.2 volts per diode when conducting current.



The down side of Schottky rectifiers is that they can usually only tolerate about 30 volts maximum, but that's plenty for this application. In the circuit shown on the left I used ordinary 1N4001 silicon rectifier diodes. Each of these wastes about 0.7 volts when turned on. Consequently, my 24 volt supply only delivers about 22 volts when the input is 12 volts.

VFO power supply board. It has a variable battery voltage input, precision regulated 12 volts output.

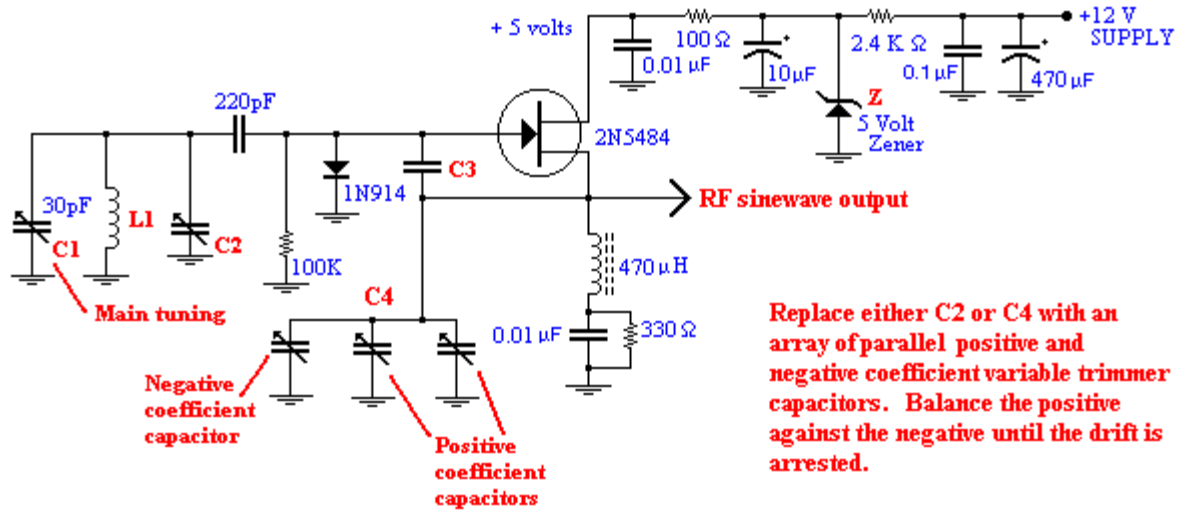
TEMPERATURE COMPENSATION

Supposedly, good VFOs can be built without temperature compensation. Personally, I've never succeeded, but don't let me be a wet blanket! Go ahead and try. Just leave room on the PC board to add compensation later.

The challenge is that most VFO parts such as variable capacitors, PC boards, etc. all have negative temperature coefficients. That is, their capacitance drops as temperature rises. The strategy of compensation is to substitute C2 or C4 with a capacitor that has an adjustable *positive temperature coefficient*. Therefore by paralleling the capacitance with a capacitor that has an equal but opposite positive temperature coefficient, the capacitance change will be cancelled. I suggest you start with this method of temperature compensation since it is the easiest.

Positive coefficient trimmer capacitive compensation

If you look in Digi-Key, Mouser, or other parts catalogs you'll occasionally find trimmer capacitors with positive temperature coefficients. These are capacitors that increase their capacitance with rising temperature. I used 20 to 40 pF variable trimmer capacitors made by Sprague-Goodman, type GCL. I replaced some of the fixed capacitance in the capacitive divider, C2 and C4, with two positive coefficient trimmers in parallel. *The clever part is obtaining both the correct positive coefficient and the correct amount of positively changing capacitance. This is done by using a similar negative coefficient trimmer in parallel with the positive trimmer.* By balancing the positive coefficient trimmer directly against an ordinary negative coefficient trimmer, you can produce a total positive coefficient value that compensates for the actual negative coefficient of the rest of your LC circuit.



POSITIVE TEMPERATURE COEFFICIENT COMPENSATION

Adjusting VFO temperature compensation

Put a 500 ohm load on the VFO output and put probes across the load for your scope and frequency counter. Check that your voltage supply is set where you want it, say 12.000 volts. It should be rock stable within a millivolt or two. If you're using a mechanical variable capacitor, set the capacitor to maximum capacitance. Now adjust the positive and negative coefficient trimmers to midscale at the desired low-end frequency of the VFO. For example, with a 5 to 5.5 MHz VFO, you would set it to 5.000 MHz (or just below). Check that you can still tune up to 5.5 MHz using the main tuning capacitance. If you can't, you may have to change C3, or fiddle with C4 or C2. Remember that C2 can also be a positive or negative coefficient trimmer, depending on what you need.

Now put the lid on the box but don't screw it down. Watch the frequency drift on your frequency counter. You will almost certainly see it *drift relentlessly up or down*. If it is going down, assume this is caused by increasing temperature in the box. Turn a positive trimmer to *LESS* capacitance, then adjust a negative trimmer to restore the frequency back to where you started. Repeat this again and again until the drift direction reverses. Now it should be going relentlessly *UP*. Now take off just a bit of the negative trimmer until the drift comes to a halt. When you get them balanced well, the frequency will still change, but now it will *wander up and down but soon return to the same frequency*. That is, the frequency will no longer march continuously in the same direction. When you get to this point, you have done as well as you can with your present set of components. With luck, during any given minute it won't wander up or down more than 5 Hz.

**

Thermistor temperature compensation

You may find that your positive trimmer capacitance compensator just doesn't give you enough positive compensation to do a good job. A *thermistor* compensation circuit may be just

21. Chapter 10, Harris

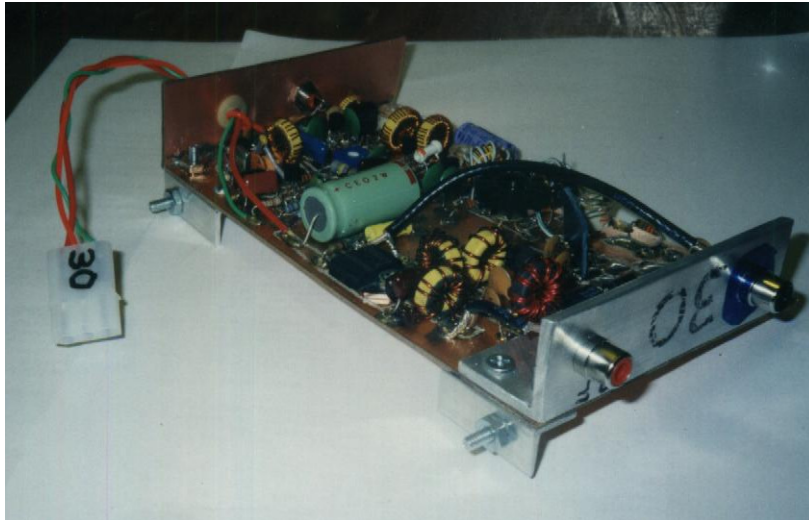
yacked with guys for an hour without any complaints about my drift. This was especially true if I was able to avoid discussing my funky homebrew transmitter. For all they knew, I was using a first rate modern transceiver.

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, REV 12

Chapter 11

Building a VFO for the higher bands (PMOs)



A QRP CW module for 30 meters is shown above. In many ways this module resembles the crystal controlled QRP module described in chapter 6. However, it uses a crystal-controlled premix oscillator (PMO) to convert the low frequency VFO sinewave up to the desired ham band. This particular module receives an 80 meter VFO signal and converts it to cover the 30 meter ham band, 10.100 to 10.150 MHz. The VFO signal and DC power come in at the back. The 5 watts of RF output exits from the red phono jack at the left front on the heat sink. The telegraph key port marked with blue is at the right. The Chebyshev output filters are visible in the foreground. The PMO filter amplifiers are at the rear. It would be more professional if it were enclosed in a metal shield, but I like to see all the components. With a CW QRP, you can get away with not using shielding. Later you will find that shielding is essential for SSB.

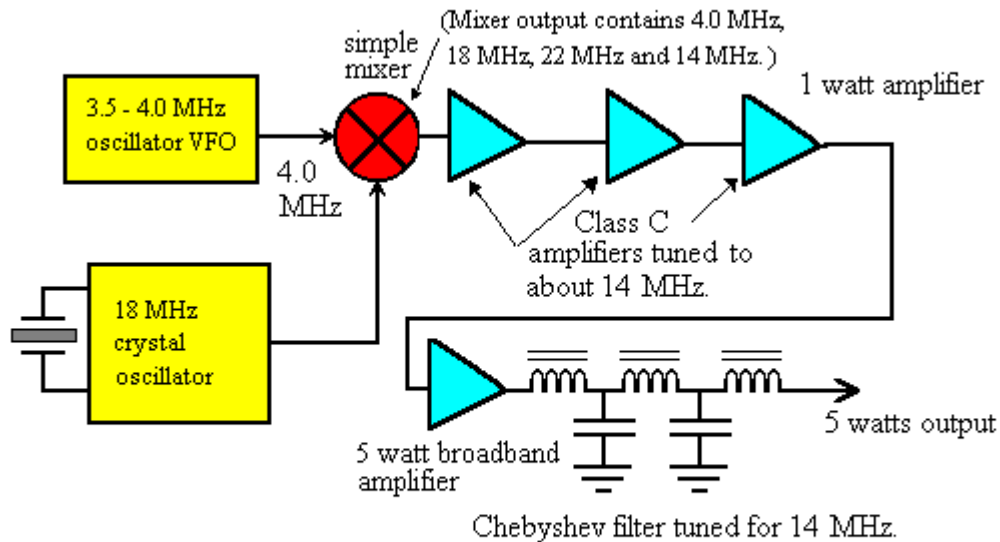
You can't multiply frequency anymore

In the old days, it was customary to build a VFO for 1.8 to 2.0 MHz or 3.5 to 4.0 MHz. Then for higher frequencies, we ran the signal through successive frequency multiplier amplifiers to get 7, 14, 21, and 28 MHz. A frequency multiplier was simply an amplifier tuned to the second or third harmonic of the input frequency. By using an amplifier tuned to multiples of the base frequency, the desired harmonic could be selected. For example, the tapped coil-tuned amplifiers described in chapter 6 work well for this purpose.

If your driving oscillator is crystal-controlled, then frequency multiplication is still practical. However, if your VFO drifts more than about 2 Hz /minute, you may get complaints on the upper bands. For example, if you have an 80 meter VFO you will have to multiply the frequency eight times to raise the frequency up to 28 MHz giving a drift of 16 Hz. But, if your VFO drifts 5 Hz, then the multiplied signal will drift 40 Hz at 28 MHz.

Fortunately, carefully built high frequency crystal oscillators can be quite stable even up

to 30 MHz. The solution to the drift problem is to “add” a low frequency VFO to a stable high frequency crystal oscillator. These crystal oscillators are called *Pre-Mix Oscillators* or *PMOs*. A *mixer* performs the frequency addition by literally combining two sinewave signals. The composite signal contains, not only the original signals, but also signals with frequencies that are the sum and difference of the original frequencies. Filters follow the mixer to extract and amplify the desired frequency component. The process is illustrated by the block diagram of a 20 meter QRP transmitter shown below:



20 Meter 5 Watt QRP Transmitter Block Diagram

PreMix Oscillator method of frequency translation

In the diagram above, an 80 meter VFO is “converted” to 20 meters. The 80 meter sinewave is mixed with the output from an 18.000 MHz crystal oscillator. When the VFO is set to 4.0 MHz, the output from the mixer is a messy looking waveform that contains several frequencies, namely - 4.0 MHz, 18 MHz, 22 MHz, and 14 MHz. By tuning the next three amplifier stages to 14 MHz, the “contamination” goes away and we get a pure 14.0 MHz sinewave tunable up to 14.5 MHz. The crystal oscillator may contribute a Hz or two of drift, but basically, the drift on 20 Meters is the same as it was on 80 Meters. The mixer is comparable in function to those used in superhetrodyne receivers, but PMO mixers are much less critical. Low noise and extreme image canceling aren’t necessary because both input signals can be as large as you like.

**

CRYSTAL OSCILLATORS ARE STABLE, AREN’T THEY?

A few years ago I thought I had the VFO problem conquered. I had just enjoyed a nine-

3. Chapter 11, Harris

month “VFO vacation.” During this time my signal was so stable, that no one ever commented on it. I was quite proud of myself. Then I built QRP modules to get on 17 and 30 meters. Suddenly the complaints started up again and I was mystified. After all, I was using the same VFO. What had changed?

I checked out my VFO. I discovered that, when it was cold, it drifted downward 20 Hz the first minute. Then, after a few more minutes, it stabilized and the drift was plus or minus a 2 or 3 Hertz /minute. Of course, by definition, whenever I start sending the VFO is cold. Therefore, unless I send for minutes on end, it must always be drifting. But even so, that didn't explain the 100 Hertz complaints.

Surely, it couldn't be the frequency converter crystal oscillators, could it? Crystals drifting!!?? Blasphemy! I checked out my 17 and 30 meter crystal oscillators. The 30 meter oscillator drifted downward 50 Hz the first minute, 25 Hz the 2nd minute and eventually stabilized 150 Hz below the starting frequency.

Use HC-49 or larger crystals

The problem with my 30 meter converter turned out to be the crystal. The crystal was a teeny-weeny can, about 1/4” square and a 1/32” thick. It had come from my junk box and I don't know what size number it was. However, I've since concluded that all the tiny ones in my collection aren't as stable as the HC-49 or larger crystals. Little bitty overtone crystals are particularly bad. Yes, eventually they settle down and become reasonably stable. But by then you have switched the QSO over to the other guy. Now your oscillator is cooling off again so it will be ready to drift during your next transmission.

Not all tiny crystals are bad. I have some little half-size 9.00 MHz HC-49 crystals that work extremely well in my receiver BFO and IF filters. I guess the lesson is that you need to check out your oscillator stability during that first critical minute. The drift after 5 minutes is interesting, but not very important for a ham transmitter.

TTL oscillator blocks

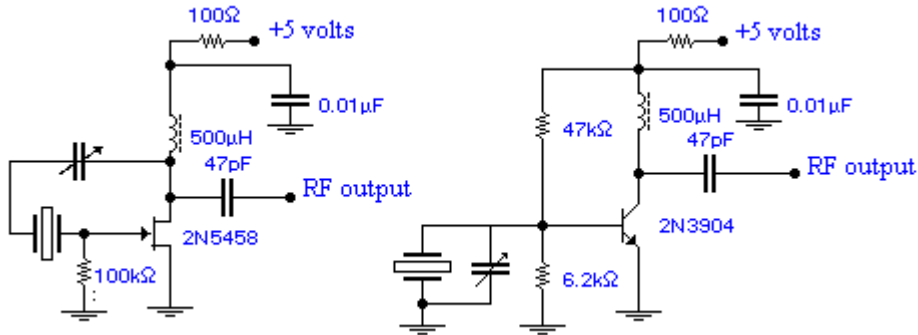
The 17 meter board had one of those sealed-in-a-can, TTL oscillator blocks. They're like an integrated circuit with the crystal and oscillator sealed in the same package. I used one because it was the right frequency and I happened to have it in my famous junk collection. Yes, I remembered to run it at a correct 5 volts TTL voltage, not 12 volts. My oscillator started out at the right frequency, but it ran surprisingly hot. Then it dropped at 25 Hz per minute. Although the drift slowed, the frequency never stopped sinking. I happen to have a big bag of various frequency oscillator blocks and they all did that. Every one I tried was terrible! All except the really high frequency ones - like 50 or 100 MHz. ... Those were really terrible. Some moved as much as 500 Hertz a minute. The only good news is that they're consistent. They all drift downward. It did not occur to me to try running the oscillator blocks at lower voltage, say 3 volts or lower.

Solutions to crystal drift

I could leave the crystal oscillators running continually. That might work with the ones that stabilize, but then I might be forced to listen to a harmonic of the oscillator signal in the receiver. No, thanks. I already have a couple whistling artifacts in my receiver. Notice that

vacuum tube oscillators might actually have an advantage in the warm-up problem. Since the tube filaments run continuously, a vacuum tube oscillator is always hot and a few milliamperes of plate current aren't going to change its temperature much. In the old days, temperature controlled ovens were used to hold crystal oscillators at constant temperature. I don't know how you feel about it, but that's too drastic for me.

All oscillator circuits are not equal



Two common crystal oscillator circuits

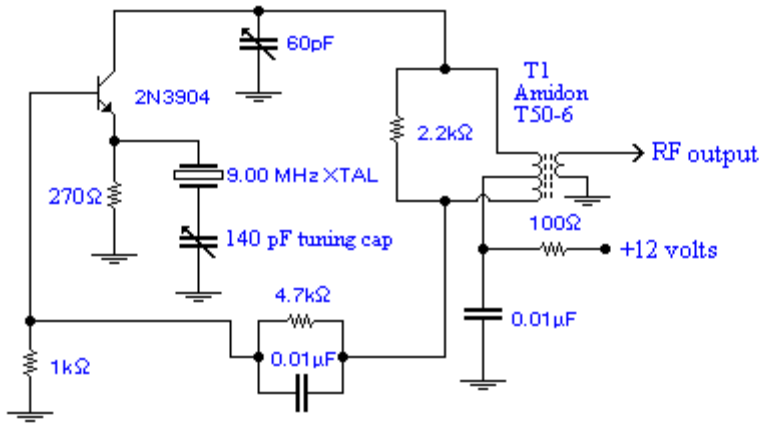
The drawing above shows two common crystal oscillator circuits that I used in some of my first QRP PMO converters. The variable capacitors are used to trim the frequencies to the exact Hertz. **Both oscillators have the crystal connected to the base or gate.** (Remember that feature and you'll know which oscillators to be wary of.) In my experience, these base-connected crystal oscillator circuits drift downward when first turned on. Finally, after a minute or two, they stabilize.

Plan your frequency converters so the drifts cancel.

Suddenly I understood why I received no complaints while using my 40-, 20-, and 15-meter crystal-controlled frequency converters. They used oscillators with the crystals connected to the bases like those above. However, the crystal frequencies were 4 MHz **above** the target band. As the oscillators drifted downward for the first minute, typically at 20 Hertz per minute, my 4 MHz VFO was also drifting downward at the same rate. For example, (25 MHz - 20 Hz crystal drift) minus (4 MHz - 20 Hz VFO drift) = 21.000,000 MHz. The result was a relatively constant frequency and no complaints. After a couple minutes the drifting stopped and the crystal oscillators were slightly more stable than the VFO.

Notice that if these converter crystal oscillators had been **below** the target hamband, then the drifts would have been added instead of subtracted. It turns out that my receiver was designed this way. Oops! Oh well, no ham has ever complained about my receiver during a QSO. And of course receiver oscillators can run non-stop, so initial drift isn't a big deal.

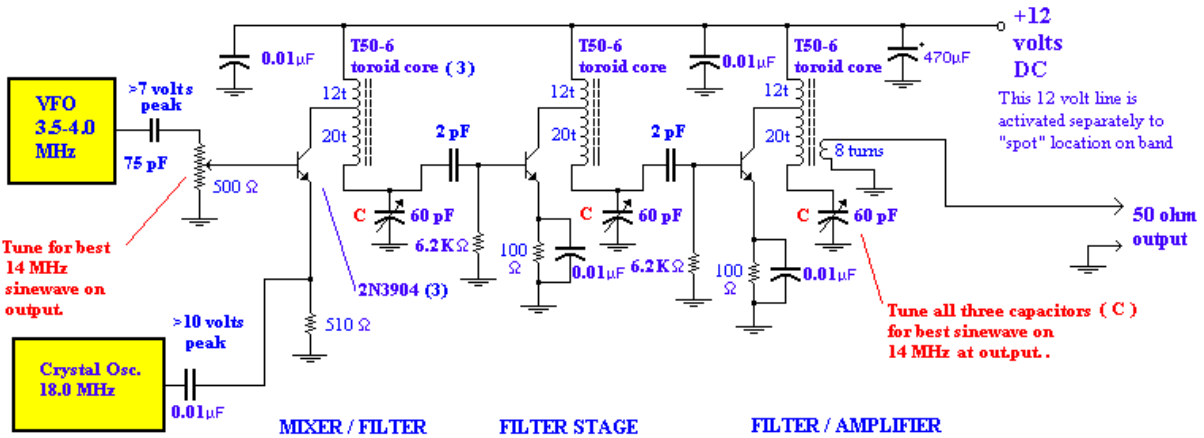
Butler is better



A Butler crystal oscillator

I checked out every oscillator in my rig and discovered that some of them didn't drift when turned on. The stable ones used the Butler crystal oscillator above. Notice that *the crystal and its capacitor are in parallel with the emitter resistor*. The equivalent FET oscillator circuit works as well and maybe better. I don't really know why, but this circuit is stable the moment you turn it on. I suppose it's because the crystal has little voltage across it and receives little power to heat it. Anyway, Butlers typically drift no more than a hertz or two per minute. Two of my oscillators showed zero Hertz drift during the first minute. This is the same oscillator I recommended in chapter 6. Depending on your application, Butler also has the advantage that the series capacitor can pull the frequency lower than the base-connected oscillators above.

A VFO controlled QRP



QRP DRIVER FOR 20 METER CW (14 MHz)

My "standard design" for a CW QRP driver is shown above. Unfortunately each QRP driver covers just one band. However, once it's tuned and working, it covers the entire band without further tuning or fussing. I should mention that the same filter train can be designed so

6. Chapter 11, Harris

that it could be tuned up for several different bands, for example 20 meters through 10 meters. But of course, changing bands would mean changing the crystal oscillator and retuning the entire chain for the new band – not exactly convenient band switching.

So far, I've built seven versions of this design covering 40 through 10 meters. Taken as a whole, the entire circuit shown above can be considered as a 14 MHz VFO. In other words, it took me all those parts to generate a stable sinewave on 14 MHz. A simple crystal oscillator using 14 MHz crystals generates the same result, but of course it will only tune a few KHz at best. Life is hard for us homebuilders in the 21st century.

So why didn't I build one driver that works on every band? Back in the vacuum tube days, that was easy to do. However, the spectral purity and stability of our signals back then was awful. Also tubes are much easier to work with. If you're a lightly-equipped tinkerer like me, you'll find that getting even one band working to modern standards is much harder than it looks. I suspect that's why hardly anyone does this kind of scratch-built homebrewing anymore. I strongly recommend you *start simple*.

Changing the direction of tuning

In the 20 meter QRP driver above, the 80 meter VFO is mixed with an 18 MHz local oscillator. Note that the oscillator could also run at 10.5 MHz. As an experiment I ran my 20-meter QRP with both 18 MHz or 10.5 MHz crystals. All I had to do was change the crystal and it worked well. The 14 MHz filter remained tuned up without any adjustment. The operational difference is that *the direction of the VFO tuning reverses*. As explained in the last chapter, this can be useful if you are using a varactor VFO and need to have the high frequency end of the VFO range tuning the lower end of a ham band.

The mixer needs a big local oscillator drive signal

The mixer stage in the above converter is just an RF amplifier made out of a bipolar 2N3904 transistor, much like the amplifiers in the filter train. This mixer is a class C amplifier stage with a 500 ohm emitter resistor. We can use class C because the input signals are much larger than 0.6 volts. One input, usually the VFO, feeds into the transistor base in the usual fashion. However, this drive level is adjustable with the input pot.

The local oscillator input is applied across the emitter resistor. I usually inject the higher frequency input across the resistor, but I've done it both ways. Unlike the input to the base, the input to the resistor has no amplification gain whatsoever. In order for the emitter signal to produce a big signal on the collector, all of the signal amplitude must be impressed onto the 500 ohm resistor.

What I learned the hard way is that, *the local oscillator drive must be strong enough to turn the mixer stage full on and off like a switch, cycle by cycle*. I use an input sinewave of at least 20 volts peak-to-peak. A wimpy little 2 volt crystal oscillator signal will produce little difference-frequency component in the output and it will take many stages of filtering to extract the desired frequency. To get 20 volts pk-to-pk signal drive, I had to amplify the output of the crystal through an amplifier stage before it went into the mixer. I threw out two boards before I figured this out. (I'm a slow learner.)

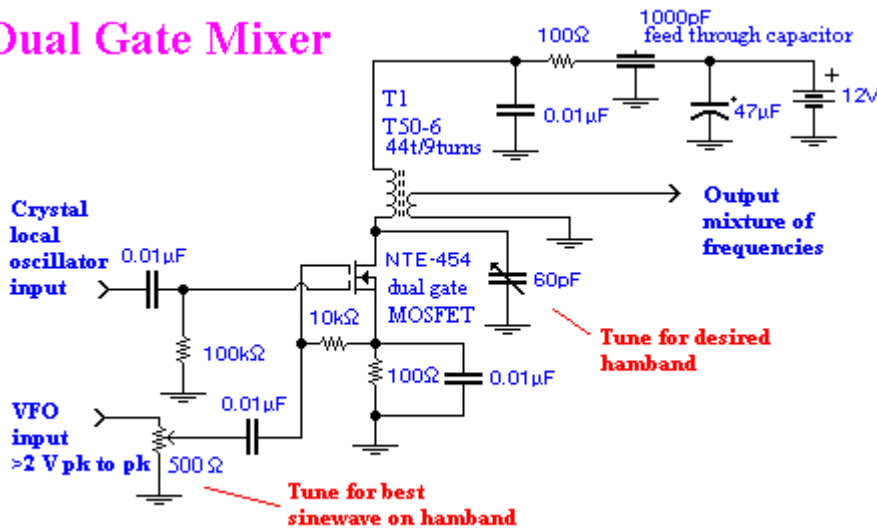
On the other hand, the second input signal, the VFO, can be small because it is amplified

by the transistor. Later, when you're tuning up the whole filter/ amplifier string for best output, you'll find that the maximum output and purity occurs at a specific setting of the input pot. The optimum VFO input level is not simply maximum input.

The LC filter/ tank circuit on the mixer collector is tuned to the desired sum or difference frequency. Using the formulas in your CWS (Amidon) T50-6 core literature, calculate the inductance needed to go with your trimmer cap to resonate at the desired band, just like we did back in chapter 6. I found that T37 cores were too small and didn't produce the gain per stage that I got out of the T50s. In contrast, the T68 cores were unnecessarily large.

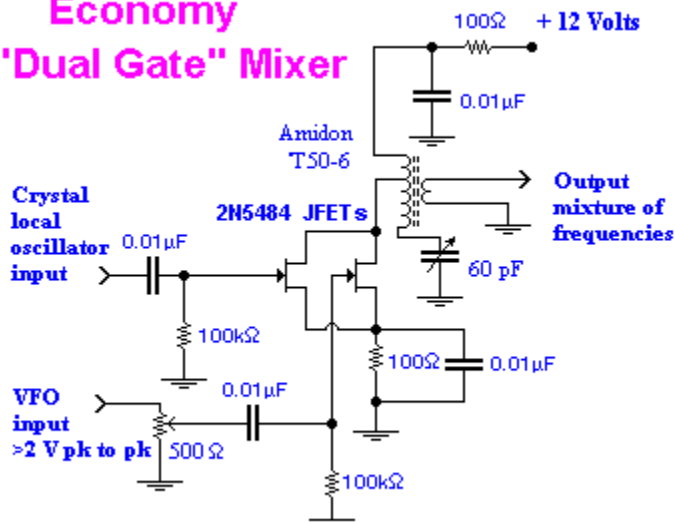
Dual gate MOSFET mixers

Dual Gate Mixer



The principal advantage of the bipolar transistor mixer shown earlier is that *it's cheap*. I began using dual-gate MOSFET transistor mixer stages in a receiver project and found them superior in several ways. A dual gate MOSFET is a small RF transistor with *TWO* input gates. Otherwise, in principle a dual gate works just like the power MOSFETs described in chapter 6. Since both gates have lots of voltage gain, small signals may be used on both inputs. I found that each gate only needs 2 volts peak-to-peak and the output is much easier to tune and filter. Unfortunately dual-gate MOSFETs cost at least \$7 each compared with 20 cents. This saves me some complexity and my later converters usually used the pricey mixer. I have used NTE-221, NTE-222 and NTE454.

Economy "Dual Gate" Mixer

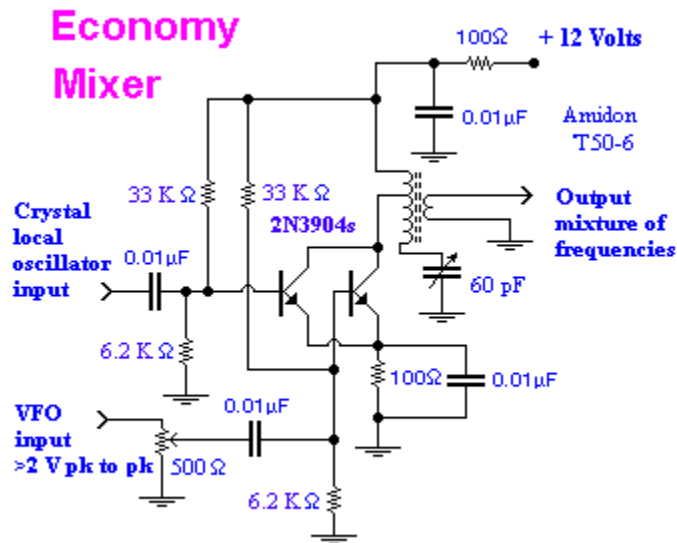


This application is quite uncritical and I believe any dual gate will work well. You will find that mixers in superhetrodyne receivers are not so uncritical.

The economy dual gate mixer

The "dual gate mixer" shown above is made from two paralleled JFETs. Two JFETs are about a tenth the price of the MOSFET and solve the cost and availability problem. Like the dual gate MOSFET, this circuit has the advantage that both inputs have gain. The two circuits are interchangeable for this PMO application. Notice that the VFO input goes to a 500 ohm pot and may be adjusted.

If you are really miserly, you can use the same trick with parallel bipolar transistors. If



both input signals are small, both transistors will need forward bias, the 33K resistors. If one of the inputs is large enough, say 5 volts peak or larger, you won't need the forward bias for that input. This circuit should be plenty sensitive for a receiver mixer. However, because it has PN junctions, it will be noisier than the dual-gate MOSFET mixer and I don't recommend it for receivers.

Tuning the mixer

When you first apply the two input frequencies to the mixer stage, the scope will show a messy, complicated waveform on the collector (or drain). It will be impossible see what setting of the trimmer capacitor on the drain is best. The first step is to disconnect the input frequency that is farthest from the desired output frequency. Now it will be easy to tune the trimmer for maximum gain. For example, in the 20 meter filter train above, tune the first mixer/ amplifier to the crystal frequency of 18 MHz. When it's peaked at 18 MHz, look to see if the trimmer is at or near maximum or minimum capacitance. If it is near minimum capacitance, but not quite there, the mixer stage should tune up well at the lower frequency, 14 MHz. If the gain at 18 MHz is maximum while the capacitance is tuned to either minimum or maximum, then you know that your toroid coil has too many or too few turns.

Later in the receiver chapter (13) and the sideband chapter (15) there are examples of un-tuned, broadband mixers that could also be used. Broadband mixers don't need tuning and they are less likely to self-oscillate. However, they have less gain and you may need more stages to reach the same power level.

Filtering the desired frequency from the mixture

At the mixer drain (or collector) there are four frequency components and you must filter the one you want into a pure sinewave. I first considered using complex Chebyshev filters as described in the Handbook. I was discouraged by the many inductors and capacitors needed to achieve the desired "pure" output. Eventually I realized that Chebyshev filters have the virtue that they can be designed for arbitrarily low impedances, that is, high power signals. In the PMO

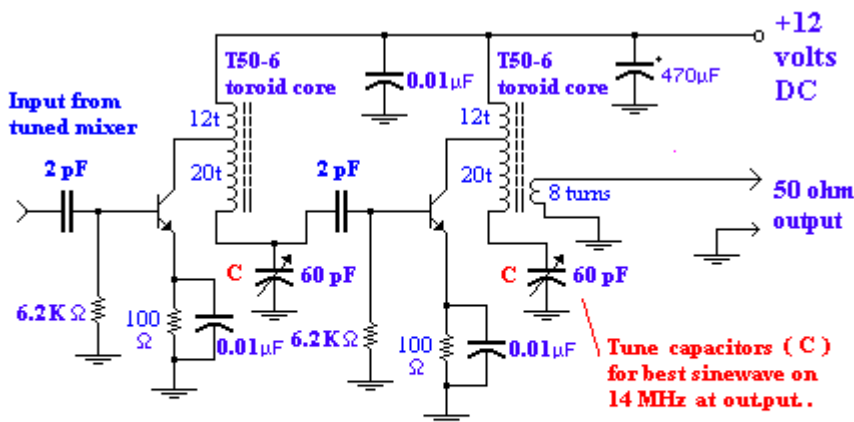
application here the signal is extremely high impedance and some relatively simple parallel LC filters are adequate. Chebyshevs are not needed. This approach is illustrated in the SSB transmitter in chapter 15.

My CW transmitter uses two sharply tuned amplifiers as filters, just like an IF amplifier in a receiver. The ease of filtering depends on how far the desired frequency is from the local oscillator and other mixer products. For example, on 14 MHz, the 4.0 MHz VFO is 28% of the desired frequency. 14 MHz compared with the 18 MHz crystal oscillator is 77% of the desired frequency. This is pretty close but not a problem. Now suppose we use a 32 MHz crystal on 10 meters (that is, 28 MHz). With a 4.0 MHz VFO, the desired frequency is 88% of the crystal frequency. You will find that tuning this is much more "tweaky," but still practical. In general, having the crystal oscillator *BELOW* the desired frequency makes tuning the filters easier.

In summary, the tuned amplifier approach is reliable for CW and is extremely hi-Q. It can separate frequencies that are quite close. However, it is not suitable for use in an SSB transmitter because the hi-Q amplifiers tend to self-oscillate during pauses in the speech signal.

Bandpass "filter amplifiers"

Each amplifier stage is essentially like the bipolar transistor mixer shown earlier. However, the emitter resistor is bypassed with a capacitor so that, from the point of view of the RF, the emitter is connected to ground. The purpose of the RC in series with the emitter is to stabilize the gain and reduce the DC current drawn by the stage. You may use either class A or class C amplifiers. I often use class A amplifiers, meaning the stage is biased "on" at all times with a 33K resistor, just as we did back in chapter 6. Class A amps draw more current than class C amplifiers that are basically the same circuit. However, they handle wave components of any amplitude. Or to say it another way, class As work over a wider range of input amplitudes and don't introduce harmonics that must be filtered out.



FILTER FOR 20 METER CW (14 MHz)

An RF filter/ amplifier stage

Two stages of filter amplifiers are shown above. Including the tuned mixer stage, three

stages of tuned amplifier were enough for any HF band using an 80 meter VFO. However, as explained earlier, when you are trying to separate two frequencies that are only 10% different, using only 3 filter stages is just barely practical. If you are having trouble getting a pure sinewave, just add another tuned stage. As shown above, the above stages are class C. If desired, you could forward bias these amplifiers on with 33K ohm resistors and convert them to class A amplifiers. In this way, they could handle smaller signal levels.

Use tiny interstage coupling capacitors

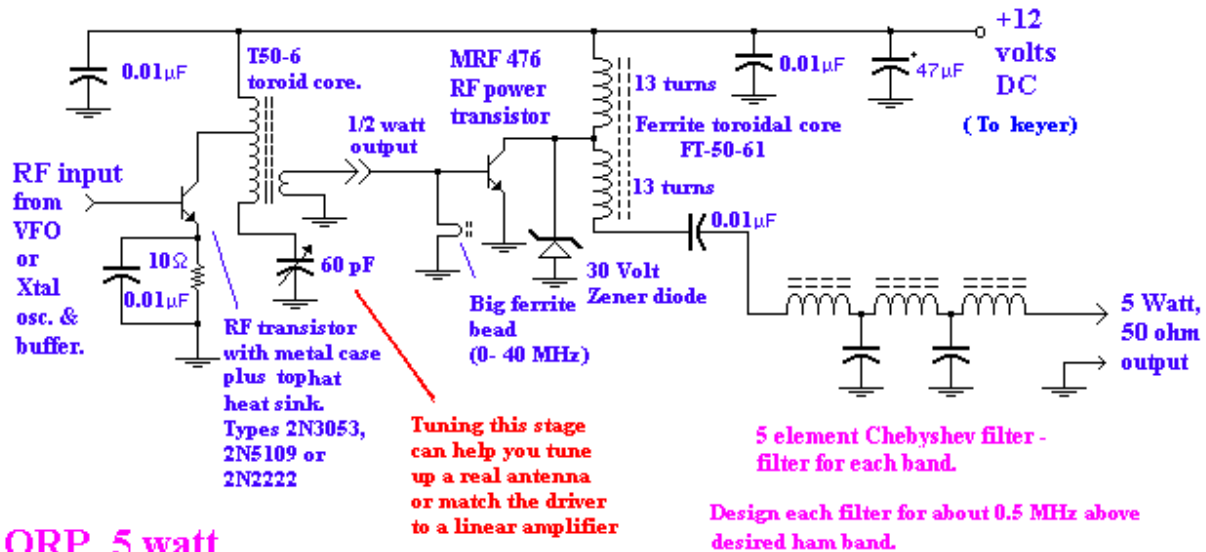
The BIG SECRET in making “filter amplifiers” work is to *use tiny coupling capacitors between amplifier stages*. Notice the 2 PF capacitors between stages in the diagram above. The purpose of these amplifier stages is *filtering, not power gain*. The LC circuit “rings like a bell” when the input contains a frequency that resonates with the LC. This ringing exaggerates the desired frequency component. If you load the LC circuit by trying to couple significant power to the next stage, it’s like putting your hand on a ringing bell - the ringing will be damped and the filter effect dies. *To avoid damping the ringing, use tiny 2 pF capacitors*. OK, on 80 Meters maybe 5 pF is acceptable. And on 10 meters 1 pF would be better. However, 2 pF works over the whole HF spectrum. Notice that if you use large coupling capacitors, say 50 pF, that 50 pF becomes part of the LC resonance and will dominate the tuning and lower the Q. Also remember that your scope probe contributes another 5 pF or so. To make a final adjustment of a filter stage, you must put the probe on the output of the stage *following* the one you are adjusting.

With one stage of filtering after the mixer, the waveform will still look “messy” on the scope. But after two stages of filtering it should be possible for your frequency counter to lock onto the correct frequency. As you tune the VFO, the reading on the counter should track solidly with no drifting and dancing digits. When properly tuned, the sinewave will look nearly perfect on the oscilloscope after two stages of filtering. When you first try to tune up all three stages at once, you may be frustrated, but keep trying. When your counter “locks” onto the desired band, look at the ringing on the trimmer of the last stage with the scope while tweaking all the previous stages for the best sinewave. Notice that perfection occurs when you trim the input level of the VFO on R1. Now you see why the input is applied through a trim pot.

Where to get crystals for your local oscillators

Yes, you need a separate crystal for each band. Fortunately, when using an 80 meter VFO, standard microprocessor frequencies can cover the major ham bands. (e.g., 11 MHz, 18 MHz, 25 MHz, and 32 MHz cover 40, 20, 15, and 10 meters, respectively.) Mouser Electronics and Digi-Key sell these for about \$1 each. For WARC bands and 160 Meters you may have to spend some money or be creative. As explained earlier, don’t use those TTL oscillator blocks. The cheap ceramic resonator “crystals” are also a poor idea. Significant drift is not worth saving a few dollars.

The QRP power amplifier stages



QRP 5 watt amplifier

Your VFO now tunes the HF band of your choice. To increase the gain of this signal up to 3 to 5 watts, you will need two or three stages of power gain as described earlier in chapter 6. My QRP boards use two power amplifier stages. The first is a tuned stage. The second is a broadband amplifier followed by a Chebyshev lowpass filter designed for 50 ohms. This scheme seems to combine the advantages of both systems. For example, suppose I connect the QRP output to a non-inductive 50 ohm dummy load. All seven QRP boards I have built have no trouble delivering a clean sinewave into a dummy load. That is, tuning is easy until you have to connect it to a real antenna or to a final amplifier.

Tuning the QRP output to an antenna or amplifier

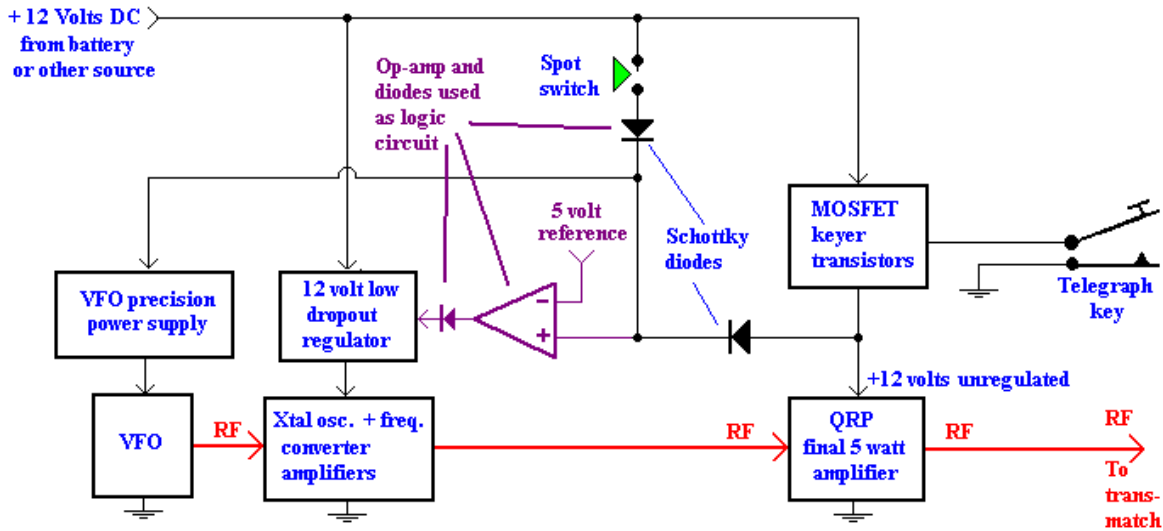
Suppose after tuning it up with a dummy load, I connect the QRP to a high power final amplifier or to an antenna tuner. Suddenly I discover that the QRP output is badly distorted. The output stage broadband amplifier may even go into “noise mode.” If I had designed both stages as broadband, I wouldn’t have anything to adjust. Strange as it seems, tweaking a tuned stage will usually match up the broadband output stage to my final amplifier. In general, the lower the frequency, the easier it is to match stages and the antenna. Matching 80 and 40 meters is as easy as falling off a log. 10 meters is tough and I still haven’t gotten my linear final (described in chapter 12) to put out more than about 20 watts on that band. Needless to say, I am in awe of guys who homebrew transistorized UHF rigs.

In summary, when you build an amplifier input that is nominally designed for “50 ohms resistive,” you may find that it has lots of reactance (inadvertent capacitance and/ or inductance) and is quite different than planned. Notice that Chebyshev filters are designed for specific input and output impedances. In other words, filters don’t filter when they are mismatched.

Spotting with a VFO

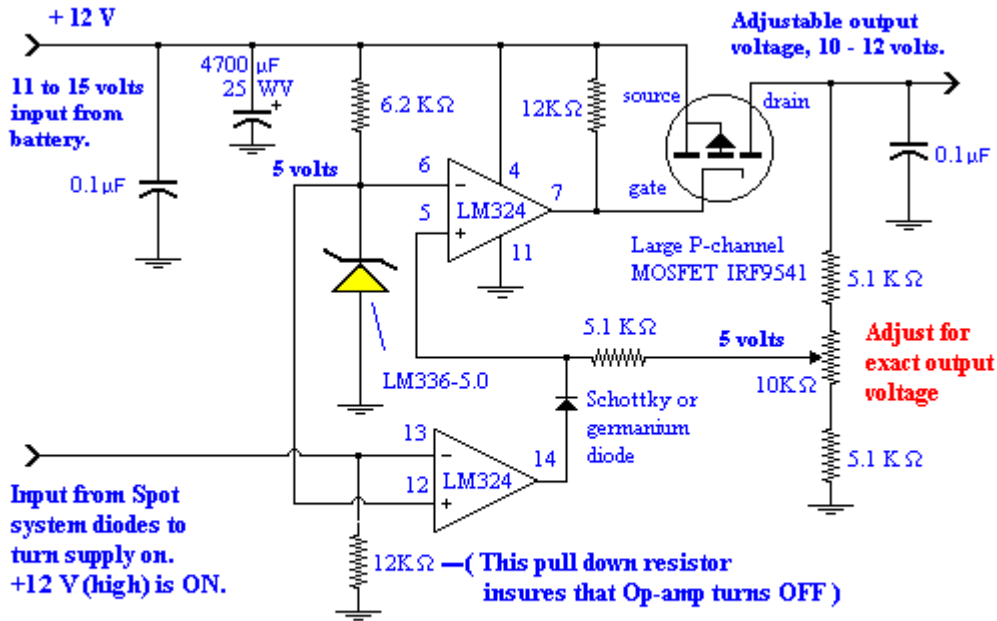
Now suppose you are on an upper band using your new VFO driven QRP. You hear a station calling CQ. But if you key your transmitter and adjust the VFO to the same frequency as

the station, you will be sweeping the band with your transmitter and making yourself unpopular. Besides, you have probably wired the antenna and power supplies so that the receiver shuts off while transmitting. In order to hear your own QRP in the receiver, you need to turn on those parts of the QRP that generate the desired frequency, but not the power amplifiers. You also want the antenna to remain connected to the receiver and you don't want the receiver to shut down. To hear the VFO we need to direct power from the "Spot" switch to the VFO power supply. But we also need to turn on the QRP PMO sections that generate the desired frequency.



QRP KEYER WITH "SPOT" BUTTON

If you are running your transmitter on battery power as I do, then the low dropout supply only has to run the crystal oscillator and the filter/amplifiers. The power amplifier (or amplifiers) can run directly off the battery and that unregulated 12 volt line can be activated by the MOSFET keyer circuit. Now when you push the spot switch, the VFO and the low power sections of QRP will turn on, without shutting down the receiver. Below is the low dropout regulator with the turn-ON control line from the Spot diodes.



Low Dropout 12 Volt Power Supply with Remote

When I began trying to get on the air with my first CW QRP, my goal was simply to reach 15 meters. This chapter summarizes what I learned on that first journey. Since one band was plenty of challenge, I didn't worry about expanding the QRP to cover multiple bands. After a while I began to wish I could operate on 40 meters, so I just built another version of the same QRP design. Because soldering is such fun, I eventually cloned the unit for every HF CW band. This was grossly inefficient and, in retrospect, is a bit embarrassing, especially since I included a separate keyer MOSFET on every band module. Surely you can improve on that!

If you are an experienced builder and want make a single multi-band QRP, then go look at the Single Side Band (SSB) QRP modules in chapter 15. In that system the amplifiers are wide-band/ linear and made separate from the band filters. If everything works as planned, arrays of filters for each band can be switched in with only one set of linear amplifiers. In the CW PMOs described in this chapter, the filters are tuned amplifiers that are easier to make work, but much less versatile. Beginners beware. Multi-band units are like flying submarines – A vehicle that does both is almost certainly a poor airplane and a lousy submarine. It is very difficult to build one machine that performs multiple functions well.

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, REV 12

Chapter 12

SIMPLIFIED QRO AMPLIFIER DESIGNS

When I first got back on the air as a retiree, I built a QRP that put out 4 watts on 15 meters. I spent two days answering CQs and calling CQ. Unfortunately no one heard me. I came to the (incorrect) conclusion that QRP is a hobby for guys with expensive, huge beam antennas, not guys with verticals and dipoles. Without that extra 10 dB of gain, I figured my QRP signal must be down in the noise. The other way to get 10 dB of gain is an amplifier. Transmitting more than 5 watts is called *QRO*. In this chapter I shall describe my efforts to build a good linear amplifier. Having QRO power when I need it has made my transmitter a reliable communications system. With 50 or more watts, your contacts won't have to work so hard to hear you and rag-chewing becomes practical.

Now that I'm older and wiser, I realize that low power and simple antennas weren't my biggest problem. In the old days our receivers had passbands several KHz wide and most beginners were stuck with a couple crystals for each band. After we called CQ, we tuned up and down the entire band looking for replies. In contrast, today guys with modern receivers are usually just listening to a few hundred Hz. When I put my 4 watts on 15 meters, I didn't realize that using the upper sideband is the standard convention for 20 meters and higher. On 15 meters the other stations were tuned to the upper sideband while I was often zeroed in on the lower sideband. My old (1967) homebrew receiver was so wideband, it wasn't obvious to me which sideband I was on. When I answered those CQs, I was usually off their frequencies by about 1.4 KHz.

In this chapter I describe three different final amplifier designs that I used successfully on the air. I don't recommend building the first one. I describe it here because it was educational. It was a *tuned class B amplifier*. It worked, I learned from it, and it covers 20 through 10 meters. Unfortunately, it was too hard to tune. Moreover, you would probably have a hard time finding a dual-section, butterfly variable capacitor like the one I used to tune the output to resonance.

The second amplifier is an *untuned class B* design. It works on all bands and is suitable for CW only. Someday when you graduate to single sideband phone you can upgrade this amplifier to the third design, which is an all band *Class AB linear amplifier*. Rather than just read the descriptions of the finished products, you may gain some insights by reading my odyssey of how I worked my way up to a real linear amplifier.

The quest to build a 50 watt amplifier

I began my QRO project by searching my 1998 ARRL handbook for linear amplifier construction projects. I found three examples of linear amplifiers. One of them, "An HF 50 Watt Linear Amplifier," was a complex schematic that covered two pages. The other two examples were buried in diagrams of elaborate transceivers that seemed to be "illustrative" rather

2. Chapter 12, Harris

than something I was encouraged to build. I could almost hear a deep baritone voice saying, “For your own safety, do not build this at home.”

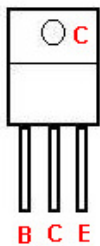
I studied the HF 50 watt linear amplifier project closely. It used a pair of MRF-477 transistors. I looked them up in my RF Parts Company catalog. It said, “call for pricing.” That was ominous. It turned out that a pair of them was \$45. I also worried about all those feedback loops and clamps that protected the transistors from **overdrive**, from **excess SWR**, from **excess collector voltage**, and from **thermal runaway**. In addition, there were at least three kinds of frequency compensation feedback. *In short, the schematic seemed to be telling me that high power RF transistors are extremely fragile.*

The article gave me the impression that, if all those protection circuits didn’t work perfectly the first time I turned it on, my pricey transistors would turn into toast before I could say, “expletive deleted.” I had never built a high power transistorized RF power amplifier before. My only comparable previous projects had been 200 and 300 watt switching power supplies. Until I got those projects working, they had devoured numerous \$20 transistors like popcorn. I was extremely wary of this project.

I retreated to my 1979 handbook and found a more primitive linear transistor amplifier project. This one also had thermal protection, but at least they implied that it didn’t have to work perfectly in concert with a flawlessly adjusted bi-directional power meter. The most reassuring feature was that MRF-454 transistors seemed to be the cheapest power transistors available, about \$13 each. These transistors are big, rugged, and able to dissipate a great deal of heat. Just in case, I bought two extra sets of transistors.

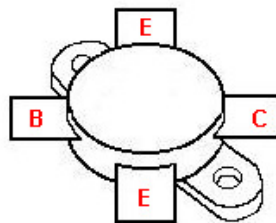
At this point you may be thinking that, even at \$13, those are expensive transistors! Why doesn’t he use a cheaper power transistor that has adequate power and frequency ratings? The answer is that the MRF-454 will produce high power with a 12 volt power supply. Sure, if you’re willing to build a 48 volt, 200 watt DC power supply, you can find dozens of really cheap transistors that will work well.

RF POWER TRANSISTORS



Case T-220

MRF-476, MRF-477,
etc.



Case 211 - 11

MRF-454, MRF-422,
etc.

Notice that there are 2 emitter tabs. The tabs insure low inductance connections to the PC board.

The eyelets must be screwed down to the heat sink.

Basic features of a modern linear amplifier

A typical modern amateur radio linear final amplifier has six basic features:

First, *Two separate power transistors are driven with a center-tapped transformer.* The driver transformer is wired so that it turns on one transistor for half of the sine wave while the other transistor is turned off. During the next half cycle, the first transistor turns off while the second transistor turns on.

Second, *it is a class B design operating in “push pull.”* An advantage of class B is that, when there is no RF on the input, both transistors are nearly completely turned off. This means that they don't get hot and don't waste energy. Even when running with forward bias to make the amplifier linear, very little forward bias is needed and the efficiency approaches 50%. Also, class B tends to cancel out even harmonics.

Third, *the transistors must be cooled with a large heat sink.* Large power transistors are designed to be bolted onto a heat sink. They have metal flanges with mounting holes for this purpose. For a 100 watt amplifier, the heat sink is typically a large, aluminum casting perhaps five or six inches on a side. Heat sinks usually have multiple cooling fins $\frac{3}{4}$ of an inch high.

Fourth, *the output from the two transistors drives a second, center-tapped, untuned high inductance transformer.* Since this output transformer is untuned, it can amplify nearly ANY RF signal over a wide range of frequency. So long as its circuit board is properly designed and the input signal is pure, the output will be a pure sinewave. The tricky part of this design is that, if any noise or “complex waveform” is introduced into the circuit, the amplifier may run away and produce wideband noise - more about this problem later.

Fifth, *a push-pull linear amplifier is not really running “Class B” but rather it runs “Class AB.”* This means that a small amount of forward DC bias is injected into the bases of both transistors to turn them slightly on at all times. By having the transistors already turned on, they respond instantly when a tiny input signal appears on the bases. Without the bias, an input signal would have to exceed some threshold limit before the transistors could turn on. The advantage of matched pairs of transistors is that the forward DC bias for each transistor can be equal and low.

Sixth, *a low pass output filter limits the frequency components in the output waveform.* In other words, the filter suppresses harmonics so that, if you're transmitting on 40 meters, nobody will be able to hear you on 20, 15, or 10 meters. Each band you operate on needs a separate filter that clips off harmonics that would radiate at higher frequencies. You can get by with using the same filters for 12 and 10 meters and for 15 and 17 meters. I built my filters on little circuit boards that I plug into a card edge connector on the main board. I use several connector pins in parallel to keep the inductance of the connection as low as possible.

**

It looked easier in the handbook

When I began my work, I built the linear as close as I could to the drawings in the 1979 handbook, although as usual I had to substitute some parts. After I had carefully tested the forward base bias regulator circuit, I gingerly put 12 volts on the output transistors. Without any

RF input drive, the transistors immediately ran away and drew huge currents. Gee, something must be wrong with the bias circuit! I soon discovered that *ANY* forward bias caused the transistors to run away. Obviously, the guy who designed this amplifier used MRF-454s that behaved differently than mine.

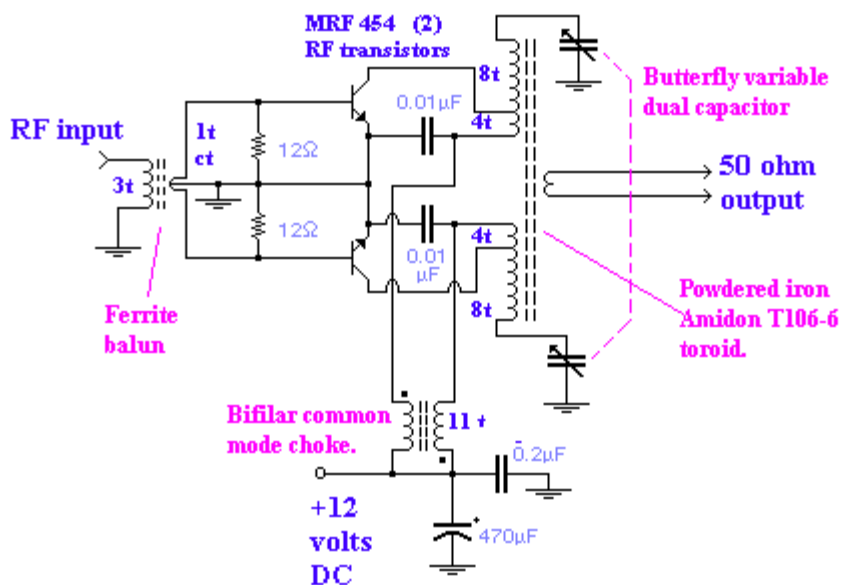
Next I disconnected the bias circuit and powered it up again. In other words, I was hoping it would run as an untuned, push-pull Class B “sort-of-linear” amplifier. This time at least the transistors didn’t run away. I put an RF signal on the input and found that the amplifier was operating in what I call “noise mode.” As you know, linears are supposed to act like hi-fi amplifiers. They uncritically amplify whatever frequency signals you put in. If you put 80 meters or 10 meters in, you are supposed to get amplified 80 meters or 10 meters out.

Noise mode

An unfortunate mode of operation for a linear is “HF broadband noise generator.” I put in a clean, filtered 5 watt sinewave and I got a blast of wideband noise from the output that made my FM radio roar like a waterfall. Using an oscilloscope, the waveform across the dummy load looked like dancing grass in a tornado. My new amplifier had terrific power output into a dummy load. Unfortunately, little if any power was at the desired frequency.

Class Bs are easier

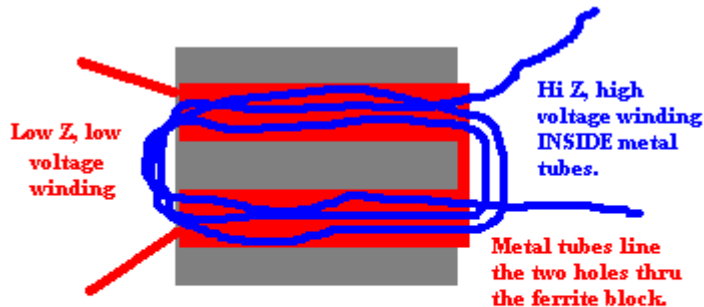
I concluded that my linear had at least two fundamental problems. I had already encountered “noise mode” while I was building my first 15 meter QRP. At that time I hadn’t found many cures for that disease, even at the milliwatt level. So I wasn’t optimistic about fixing it at the 50 watt level. I was tired of not having a working transmitter, so I decided to start over and build a simple class B *TUNED* amplifier. I was almost certain I could get that to work. Of course a tuned class B would only work on two or three bands without changing the output transformer and tuning capacitor. However, that was better than being off the air, possibly for months.



Amplifier # 1. **A simple class B tuned amplifier.** This works, but I don't recommend it.

The tuned class B worked well. The only trouble I encountered was getting the input transformer to match properly and deliver the required big drive currents. After two unsuccessful attempts at winding powdered iron toroid input transformers, I tried the ferrite balun transformer from the linear amplifier. Success! Ferrite balun transformers really are different from powdered iron toroids. They match those low impedance power transistors when nothing else will. At least *SOMETHING* from the linear design worked.

Ferrite balun transformers



BALUN TRANSFORMER

(Cut-away to show construction)

Think of the ferrite balun transformer as two large ferrite beads placed side by side. The beads are simply hollow cylinders made from high A_L ferrite. When a coil is wound around them, the ferrite produces a large inductance with very few turns. Sometimes the two beads are cast as a single block of ferrite with two cylindrical holes side by side through the block. In principle, the transformer is just like the transformers you have met before. That is, it consists of two coils wound on the same iron core. The high impedance, higher voltage winding has the most turns and is just 3 or 4 turns of wire wound through the hollow centers of both beads. So far, this is pretty ordinary.

The tricky, unobvious part is the low voltage, low impedance winding. What I haven't mentioned yet is that the hollow centers of the two beads are lined with non-ferrous metal tubes. The high impedance, high voltage winding is passed through these tubes. At one end of the assembly, the two tubes are connected together electrically so that they form a "U" passing through both beads. This "U" is the entire low impedance winding. Like any transformer winding, it has two output leads and these are the two legs of the "U." The center tap of the low impedance winding is the connection between the two tubes, on the right in the above drawing. That is, the bottom of the "U" is soldered to the PC board ground. The ungrounded ends of the tubes go to the balanced, low impedance transistor inputs.

For the input balun transformer, I made my "U" out of tubular mesh from the outer conductor of a length of RG-174 coax. I forced holes in the sides of the outer braid mesh to bring the insulated secondary winding wire in and out of the braided tubing. This is tricky to make and you may have to try a couple times. Using thin-walled brass or copper tubing would

be easier and more elegant. I used Teflon insulated multi-strand wire for my secondary windings to be sure there would be no short circuits between primary and secondary. I bought the small input balun ferrites from CWS Bytemark. These small ferrites consist of a single, flat block of ferrite with two parallel holes molded through the longest dimension.

Bifilar wound RF choke

The power to the final is delivered by a small bifilar wound choke. Bifilar wound transformers were discussed in chapter 6. Wind about a dozen turns of a pair of #26 wires onto a small ferrite core. The two wires are wound on the core simultaneously as if they were one wire. An FT50-61 CWS toroid ferrite core will work well. The exact type of core or number of turns is not critical. Just be sure that the RF that appears from one winding will generate an opposite voltage in the other winding. If you don't, the two transistor collectors will be effectively shorted together. That's the meaning of the dots next to the coils on the diagram. Yeah, I get as confused as you do about dot marks. Leave the leads on one coil long enough to swap the ends when it doesn't work!

The tuned class B worked, but I don't recommend it

The diagram of the tuned class B was shown earlier. Depending on the range of the ganged, dual tuning capacitor, it can tune between 10 and 20 meters. I got on the air using CW and talked to lots of people with my 50 watt Class B. I was pleased, but whenever I changed frequency more than about 50 KHz, I had to retune the amplifier. Using a scope, my procedure was to tune the amplifier and a "T" type transmatch for maximum amplitude with minimal low frequency artifacts. When tuned, it produced a clean sinewave output and I could see no evidence that the lack of forward bias was distorting the output. Just to be on the safe side, I ran the output through the multistage, TVI low pass filter described in chapter 9. This TVI filter is designed to work with any HF band since it cuts off above 10 meters. The amplifier ran quite cool and I didn't burn up any transistors, even though I had omitted all those exotic feedback safety circuits.

The disadvantages of my tuned class B was that it was a bit tweaky and tended to go out of tune whenever the battery voltage declined. The best reasons for not building one are that the class B untuned amplifier described below works better and doesn't use any hard-to-find parts.

A CLASS B, UNTUNED, SORT-OF-LINEAR AMPLIFIER

Episode two of the power amplifier saga

15 meters was dead in the evenings so I wanted to get on 40 meters. Rather than build a new tuned Class B amplifier just for 40, I went back to work on the linear. First I ordered a data manual for Motorola RF transistors. When I got my manual, I discovered that the MRF-454 was the only transistor in its class that *WASN'T* recommended for linear operation. The manual didn't say why it wasn't, but I thought to myself, "No wonder MRF-454s are so cheap and no wonder they run away with forward bias!" I got out my RF Parts Company catalog and priced all the similar RF transistors that were recommended for linear operation. They were all much more expensive than the MRF-454, but I picked out the cheapest and ordered a matched pair of MRF-422s. The output from the transistors goes to a large balun ferrite transformer. Large balun transformer assemblies are also available from RF Parts Company. I have used the 1 inch and 1.5 inch versions (PN # T1 & T1.5). Both seemed to work fine with no signs of saturation.

When my new transistors arrived, I put them in the linear and ... they ran away, just like the MRF-454s. Each transistor had swamping resistors that connected each base to ground. I lowered the values of these again and again until the transistors stopped running away. Of course by that time I had zero RF output. Apparently forward bias works for everyone else but the laws of physics are different at my house. On the other hand, unless you are planning to go on SSB (voice), you don't really need a linear amplifier. Old fashioned class B or class C amplifiers work fine for CW.

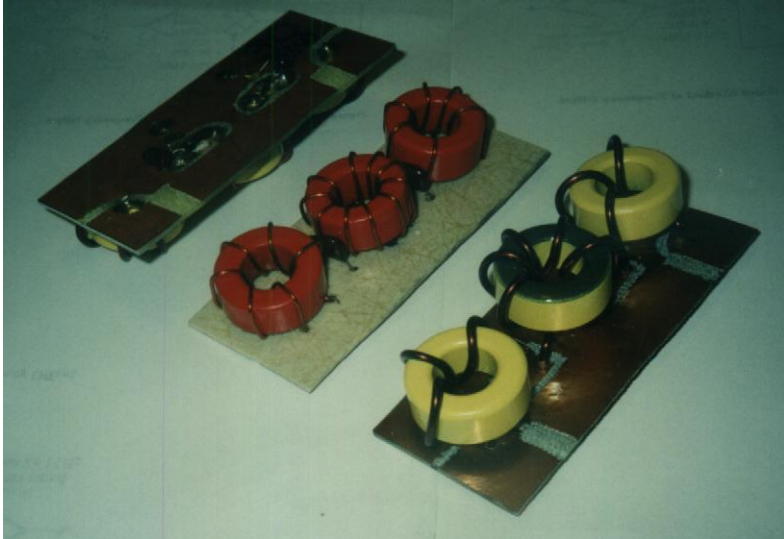
Trouble with Chebyshev output filters

I tried again to run my "linear" amplifier as an untuned class B. As before, it just produced high power noise. I looked more closely at my Chebyshev output filters. Were they defective in some way? I had built them from the 1979 handbook linear amplifier plans. I had followed the winding instructions exactly using identical CWS (Amidon) 106-6 toroid cores. To test the 15 meter Chebyshev filter, I substituted it for the TVI low pass output filter on my working tuned Class B amplifier. It should have worked fine, but instead, the old tuned Class B amplifier went into noise mode, just like the new amplifier. Very little power arrived at the dummy load and the filter cores got quite hot. Something was wrong with the filter.

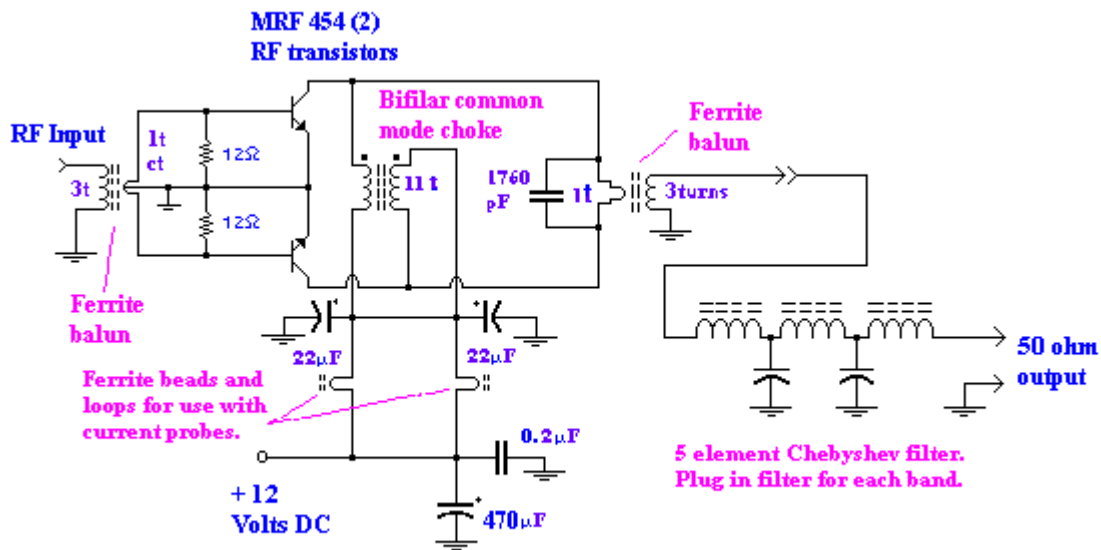
It turned out that the parts list or coil turns listed in the table were just plain wrong. I started over and redesigned my plug-in filters using the Chebyshev design tables from the 1998 ARRL handbook. I used the procedure described for making 5-element low pass Chebyshev filters that I previously explained in chapter 6. The main difference between the QRP filter and the big amplifier filter is that, for 100 watts, you need large powdered iron cores. Instead of T50-6, I used T106-6. For 40 meters and below you might want to use T106-2 cores. T68 cores might be big enough, but I haven't tried them at high power levels.

It turned out that the instructions in the 1979 manual described filters that were more appropriate for several bands below each band listed. For example, the 15 meter filter was designed about right for 160 meters, and so on. The filter for 160 meters would have been correct for low frequency transmissions from submerged nuclear submarines. Something in the T106 core specifications must have changed over the years.

I checked out the redesigned 15 meter filter on my old amplifier and ... it worked perfectly! Progress! Next I put the new filter on my new linear amplifier and held my breath. Behold ... it was still operating in noise mode. Now I was mad. I got out my wood-carving gouge and cut the PC board traces to the transistor bases. Now they were free from all that R-C-L frequency compensation network gobble-de-gook. I wired the bases up just like the tuned Class B linear input above. As far as I can tell, it works perfectly. It puts out 100 watts of lovely sinewave on 40 meters and doesn't blow transistors. I only get 50 watts on 15 meters because my driver isn't as powerful. I soon worked dozens of stations on 15 and 40 and got excellent signal reports.



Chebyshev output low pass filters for an untuned class B. They plug into a card edge connector.

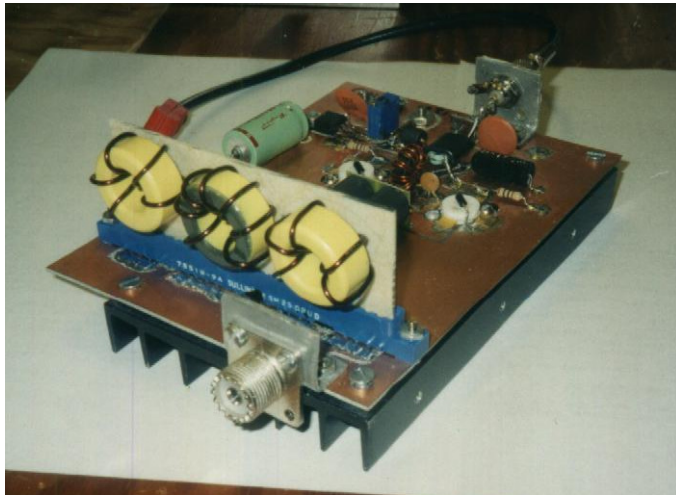


Amplifier # 2. A simplified class B untuned amplifier

Why didn't I need fancy frequency compensation feedback loops? The answer may be that the purpose of the feedback loops was to equalize the outputs on all bands. Also, I am driving the linear with complete QRP transmitter drivers that have their own Chebyshev output filters. In other words, the input signals are quite pure. I have observed that any defect in the input sinewave is faithfully reproduced in the output. Even without forward bias to make it class AB, it is "hi-fi" to a large degree.

After all my worry, I never did ruin any transistors. On one occasion I was testing the linear at 80 watts output. I was happily looking at the scope when I smelled something burning. Oops. I had forgotten to screw the big heat sink back on. I shut off the linear and no harm was

done. RF power transistors aren't so fragile after all.



The completed linear amplifier. A 15 meter low pass filter is plugged into the output.

You may already be using an adequate low pass filter

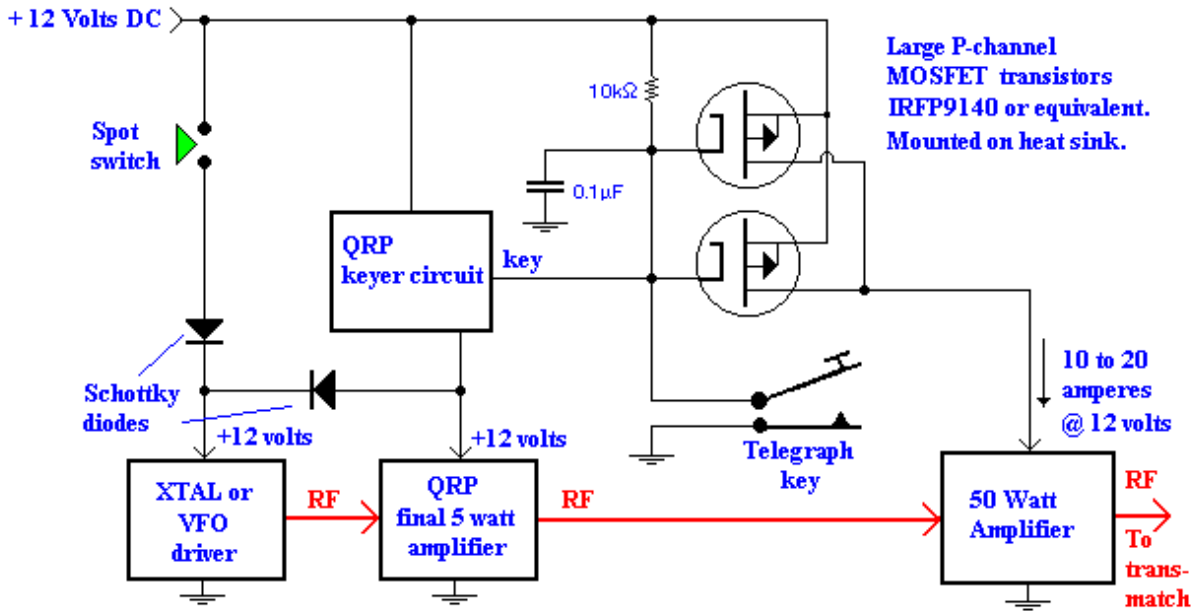
I have occasionally had trouble loading antennas on 17 meters and above. Even with the T-match coupler described in chapter 9, sometimes I couldn't get a good sinewave signal on the antenna lead wire. The waveform was contaminated with low frequency modulation(s) and the frequency counter was usually reading low and wouldn't lock. Sometimes I have been able to correct the problem by using an output filter for the next band higher than the one I was on. For example, if it wouldn't load on the correct 15 meter filter, it would sometimes load well using the 10 meter filter.

Finally it occurred to me that I was already using the multistage 30 MHz cut-off low-pass TVI filter described in chapter 9. Therefore, for those high bands my 10 meter output filter on the final was redundant. I built a "blank" filter that was just a piece of RG-58 coax that shunts from one end to the other of a blank PC board plug. To summarize, using the TVI filter by itself is another alternative for your bag of tricks.

Keying the 50 watt linear amplifier

When I first began using my finals, I kept them turned on all the time. That is, whenever a QRP signal appeared at the input, the final was supposed to amplify it. When there was no input to the amplifier, there should have been no output. This way, I could leave the 12 volt power supply connected all the time. Unfortunately, every so often the final would begin oscillating all by itself at some random frequency outside the ham bands. I often had two or three successful QSOs without trouble. Then suddenly, for no reason that I could determine, the oscillation began.

I have been told that professionals solve this problem by loading down the input of the final amplifier with a resistor, perhaps as low as 100 or even 50 ohms. I haven't experimented much with this approach, but I'm certain that it cuts drive to the final and lowers my output power. If I were you, I'd experiment some more with this cheap approach. However, if you don't like your results, you can always fall back to my keyer circuit shown below.



50 WATT TRANSMITTER KEYS

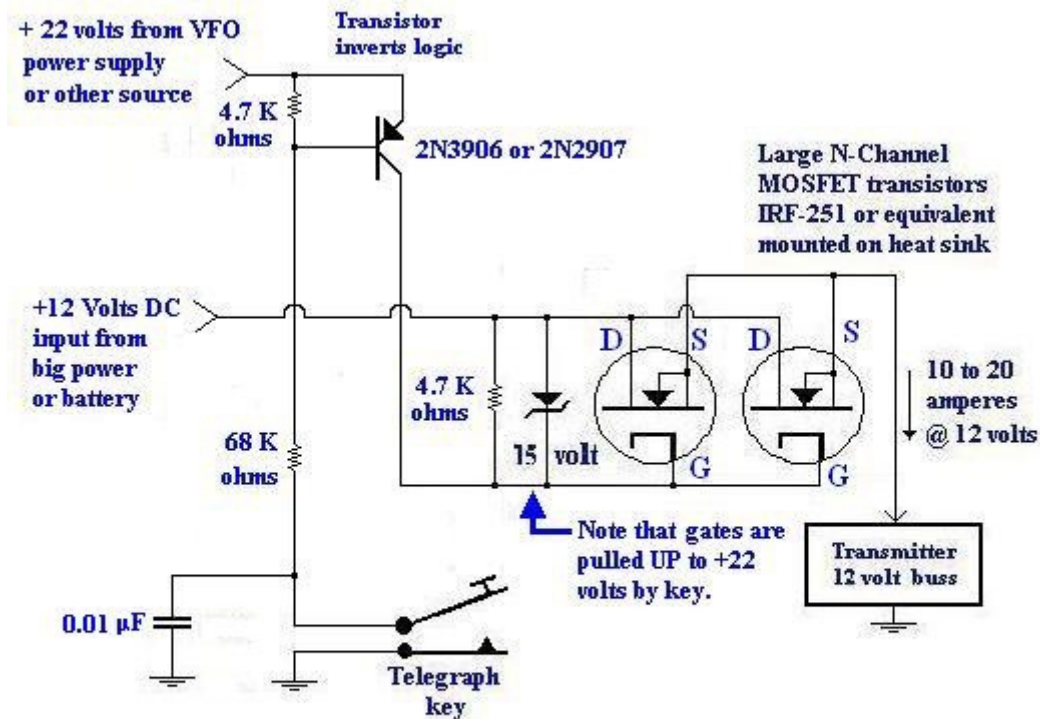
My solution was to build a giant version of the same MOSFET power switch I used to key my QRP modules. Naturally I had to use humongous P-channel MOSFETs with low on-resistance. Referring to the figure above, the telegraph key pulls the MOSFET gates down turning on the MOSFETs and bringing power “down” to the amplifier. The MOSFETs are mounted on a small sheet of 1/8 inch thick aluminum plate which in turn is bolted to the thin aluminum chassis. Even at heavy current loads I haven’t noticed the MOSFET transistors becoming warm to the touch. The cases are the drain connection and must be insulated with mica or equivalent insulators. A light layer of silicon heat sink grease on the mica insulator fills the air gaps and improves heat conduction.



Power bipolar and MOSFET transistors and the necessary size TO-204 mounting kit

As with the QRP module, turning on the power abruptly by shorting out the 0.1 microfarad capacitor with the key looks like a recipe for producing key clicks. I haven't had any trouble yet with this, but I wouldn't be shocked if someone received complaints of key clicks. David, VK6KI, suggests turning the keyer on gradually with an op-amp keyer will prevent any abrupt turn-on and turn-off. He also suggests using cheaper bipolar PNP power transistors. Use whatever works for you. It's your homebrew and it's fun to try different ideas.

N-Channel MOSFETS have much lower ON resistance and are harder to damage. They can also be used as keyers and fewer transistors can do the same job. Of course, the problem is that, instead of pulling the gates down to ground as we did above, now the gates have to be pulled UP to 10 or 12 volts above the 12 volt supply. If you have built the VFO described in chapter 10, then already you have a convenient 22 volt source. This is the keyer in my CW transmitter:



HIGH POWER TRANSMITTER KEYER Using N-Channel MOSFET transistors

What had I learned up to this point?

1. The ARRL Handbooks are excellent but occasionally they print errors. Don't believe everything you read in a parts list.
2. I understand the need for class A forward bias. In practice, for CW use it isn't necessary. However, I was still mystified how the experts do it without a runaway. In my experience, the transistors ran away instantly with the first milliamp of forward bias. This happened even when

the transistors were stone cold. It couldn't have anything to do with temperature feedback being defective because there wasn't time for heating to occur. Moreover, runaway wasn't related to the RF drive, because it happened with or without RF input.

3. Ferrite balun transformers are impressive components. They produce tight coupling at really low impedances and they don't need tuning.

4. If your Chebyshev output filter doesn't work the first time, check it out carefully for solder splash shorts on the PC board. If you're sure it should work, but it doesn't, go to the design table in a recent ARRL handbook and redesign the filter yourself starting from scratch. If it still doesn't work, try a different core size.

5. A Chebyshev filter in a QRP driver worked poorly when I designed it with T68-6 cores. But the same filter worked great when I rebuilt it using smaller T50-6 cores. Sorry, but I have no idea why. Sometimes it helps to be open-minded and try things that may seem silly. Persistence is your ultimate weapon!

6. Finally, it seems to me that much of the complexity in designs in QST and QEX is great in theory, but sometimes unnecessary in practice. The guys who wrote those articles are over-educated. Their sophistication often discourages us. Don't let them rain on your parade! Build it simple and work up from there.

**

A LINEAR AMPLIFIER, THIS TIME FOR SURE

Adding linear bias to the Class B amplifier

As explained above I was able to run my final amplifier as an untuned Class B, but when I applied DC bias to make it "linear," the amplifier "ran away." That is, it drew huge currents and blew fuses. In the end, I left it as a class B broadband amplifier. Class B amplifies both halves of the driving sinewave, so there's only a small cross-over non-linearity. So who cares if it isn't class AB? At the end of my project I was happily working guys on CW and I always used a lowpass filter to suppress harmonics. So what's the fuss over "linear" amplifiers? *I* certainly didn't need one!

Sideband needs a linear

Eventually I got bored with HF CW and built an SSB exciter. I fed SSB English speech into my class B "nearly-linear." All that came through were the voice peaks. It sounded something like African click language. I couldn't understand the speech, but I finally got the message: ***The key virtue of linears for sideband is that they amplify all AMPLITUDES.*** Yes, linears also amplify all *frequencies* equally. They are a sort of "RF Hi-fi," but the broadband part isn't so important. A sideband amplifier only has to amplify a signal 3 KHz wide. In theory at least, a tuned class A amplifier would work fine on sideband, even if you had to retune it every time you QSY a hundred kilohertz. In practice, a tuned amplifier on sideband would tend to self-oscillate every time you stopped talking.

When class C or class B amplifiers are operated CW, a big drive signal comes in on the base(s) of the final amplifier and you get a big, constant output signal with about 10 dB gain over the input. The big drive signal exceeds the base forward voltage drop of the output transistors by

a wide margin. *When operating CW the amplifier only operates at one amplitude*, so the base voltage threshold problem never arises.

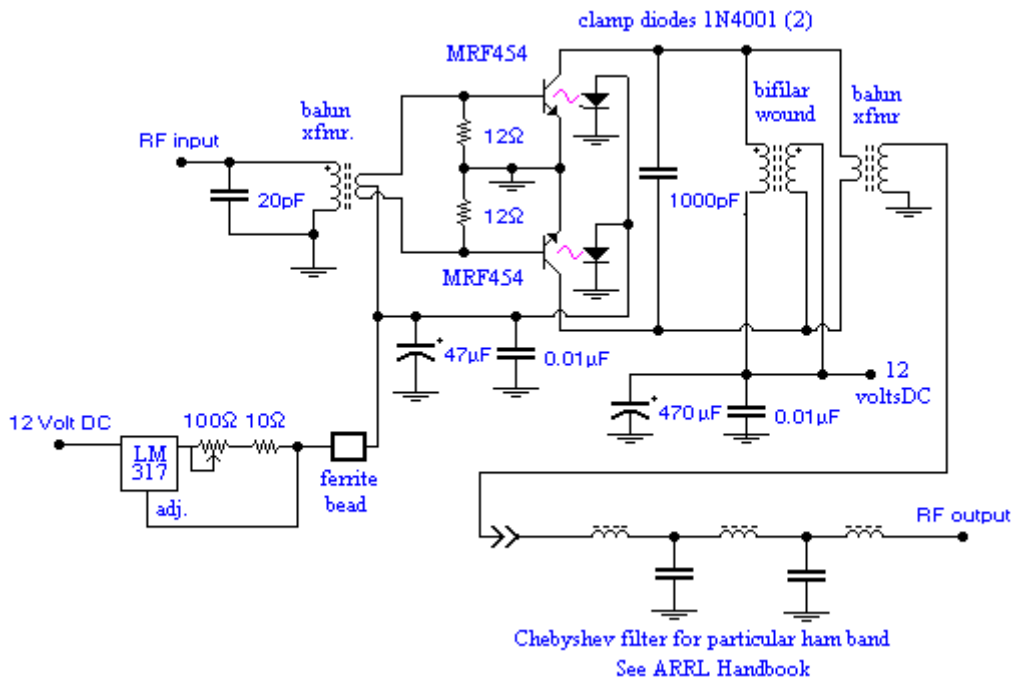
Why does sideband need a linear when AM modulation was so easy?

Sideband is different. The drive from an SSB exciter has a range of amplitudes and all must be amplified equally. Actually, it's useful to amplify the low amplitude signals *more* than the high amplitude voice peaks. This raises the average power and makes the SSB signal better able to compete with noise and QRM.

At first glance SSB doesn't seem so different from AM. So why was AM phone so easy to build back in the old days? Amplitude modulators usually modulated the final, not the driver. For AM we tuned up the tube final on CW, then *we modulated the power supply, or the screen grid, or the cathode of the final tube amplifier with audio frequency*. The final amplifier acted like a mixer that produced sum and difference frequencies. With no conscious engineering effort we produced two audio frequency sidebands in addition to the original RF carrier. Another advantage of an AM transmitter final is that, whenever there is no speech, it is still generating a carrier, just like CW. Therefore it can't self-oscillate.

Guys who could afford big AM modulation transformers modulated the power supply for the final. We cheapskates modulated the screen grid or cathode of our final amplifier tube. Either way, we were modulating the gain of the final amplifier, not the drive signal. Now that I think about it, I guess I knew that some guys used *LINEAR AMPLIFIERS* to boost the power of their low power AM exciters. The fog clears. Yes, you can broadcast AM with class B or even Class C final amplifiers, but you can't amplify a low level AM or SSB drive signal without a linear.

Biasing a linear amplifier without thermal runaway



Amplifier # 3. A push-pull linear amplifier

The entire linear final is shown above. The bias circuit at the lower left solved my run-away problem and gave me the linear amplification I needed. I found the bias circuit lurking in a big schematic describing a commercial transceiver in the 1998 ARRL handbook. This deceptively simple circuit performs three functions:

- * It provides an adjustable, constant DC bias current into the transistor bases.
- * Diodes (1N4002) shunt the bases to ground, limiting how high the base voltages are allowed to rise.
- * The diodes heat up with the transistors and provide temperature compensation.

An LM317 voltage regulator is used as an adjustable current source to feed roughly 100 milliamperes of DC into the bases of the high power output transistors. The LM317 is a three-terminal, 1.2 volt voltage regulator. The regulator output passes through a variable current set-resistor. The voltage drop across the resistor is monitored by the “adjustment” lead of the regulator so that the voltage across the resistor is held constant at 1.2 volts. The regulator is RF-isolated from the amplifier by a big ferrite bead on a short chunk of wire. The rest of the circuit is almost identical to the final in an SSB transceiver in the ARRL 1986 handbook. The 1000 pF capacitor across the collectors is found in all these push-pull circuits. I took mine off and I got a few percent more gain. I don’t know what it’s supposed to do.

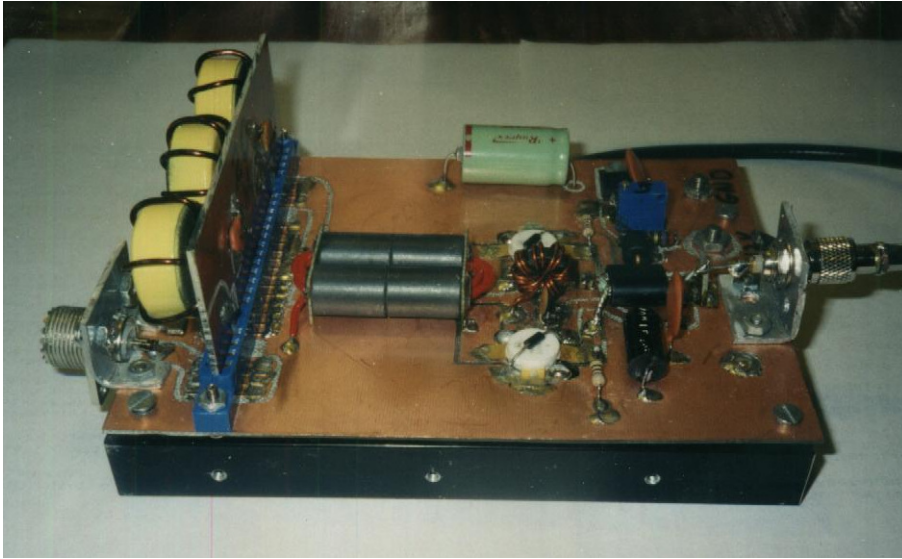
Clamp diodes prevent run-away

The critical parts of the bias circuit are the two rectifier diodes which clamp the base voltage (V_{be}) to ground. Their most important function is that they instantaneously clamp the base voltage to less than roughly 0.8 volts, like a Zener diode. They limit how high the drive voltage to the transistors can rise when the whole assembly gets hot. Hot transistors draw more current, causing more heating. This positive feedback is called thermal runaway. As the input drive to the transistors increases, the DC base-to-emitter voltage of the output transistors rises which causes the collector to draw bigger and bigger currents. For example, while operating sideband, the DC base voltage rises to well over 0.8 volts on voice peaks. If it were allowed to rise to 0.9 or 1.0 volt, runaway might result.

The second function of the diodes is that they also change with temperature and automatically compensate for temperature rise. *They are strapped across their respective transistors so they are in thermal contact with the transistor cases.* As the transistors and piggyback diodes heat up, the forward voltage drop of the diodes *decreases* with increasing temperature. When cold, the V_{be} peaks might start at 0.8 volts, but as the transistors heat up, the V_{be} voice peaks will try to rise higher still. So, under the same bias current level, but at a higher temperature, the diode clamp voltage might typically drop from 0.8 to 0.7 volts or even lower. The decreasing voltage drags the base voltages down, preventing runaway. While holding the telegraph key down, I could watch the DC base voltage slowly sink, while the total DC current drawn by the entire amplifier remained constant.

The difference between this bias circuit and the ones I tried earlier is that there were no clamp diodes. Yes, there was a reference diode mounted on the heat sink for temperature compensation, but my output transistors ran away immediately before the temperature had a chance to rise. A current source with just a temperature compensation circuit has no instantaneous clamping function.

Mechanical construction



The linear 50 watt amplifier. Notice the large ferrite balun output transformer in the center of the assembly. The bias circuit is at the right rear. Also notice how the base clamping diodes are strapped across the output transistors so that any transistor heating will immediately be passed on to the diodes. The holes in the PC board adjacent to the white output transistors are where the machine screws bolt the transistor bodies to the heat sink. A thin layer of silicon grease between the transistors and the heat sink is advisable, but mica insulation is not needed. These mounting tabs are not electrically connected to the transistor leads.

The completed amplifier module is made from a two-sided circuit board screwed down into holes tapped in a large, finned heat sink. The major RF traces are wide, about 3/8 inch or more, to keep the inductance down. This is a simple circuit and all the traces were cut into the board with a small wood-carving gouge. **It is vital to arrange the collector and emitter traces so that they are symmetrical and equal in every way to the other transistor.** Otherwise, one transistor will have more trace capacitance and inductance than the other. The input and output transformers are the balun type which were described earlier.

The input comes in through a mini-UHF connector. Mini-UHF connectors are the only affordable, small RF connectors I have found. At \$5 a mated pair they are expensive compared to phono plugs. But if you must pay \$12 a pair for SMA, SMB, or SMC connectors, \$5 looks cheap. The output connector is a big UHF SO-239 that, strangely enough, has always been affordable. For high power, >5 watts, I suggest avoiding connectors like phono plugs which weren't designed for RF power. You can get away with phono plugs on 20 meters and below, but the standing waves make it difficult or impossible to tune the amplifier on 10 meters. Also, if you plan to amplify sideband with this, it's a good idea to build a shield cover to fit over the top of the board. As you can see, I didn't. However, all commercial transmitters have their linears sealed in extremely tight metal enclosures. In my SSB transmitter all the low level modules are sealed individually in separate metal boxes.

I built my Chebyshev low-pass filters for the linear on separate PC boards that plug into the linear board using a card edge connector. To keep the inductance low, I soldered eight

connector pins in parallel at each end of the card connector and the rest of the pins were used for ground. To change bands, I plug in another low-pass filter. If you like, you can use little RF reed relays to switch in different filters. Personally, I like the old-time flavor of plug-in coils. It is probably practical to use smaller ferrite toroids, such as T68-6, but I haven't tried them at this power level.

Why stop at 100 watts?

I opened up an issue of QST (June 2006) and discovered plans for a homebrew 600 watt linear amplifier. It uses two pairs of MRF-150 transistors to reach this level. It is quite similar to my linear in many respects. I was surprised to see that it's practical to get so much power from so few parts.

I was tempted to build one until I remembered Bob Hamilton's experience with his kilowatt amplifier. Bob, NØRN, used to live in the city like I do. He quickly found that his new kilowatt interfered with the neighbor's TVs and stereos. In contrast, his 100 watt transmitter had never bothered them. Bob fought the problem for several months and even had his station checked out by a government accredited expert. It turned out that his station was operating correctly and in accordance with the law. The difficulties were in the sensitivity of the neighbor's appliances. Bob was "legal" but that didn't really change anything. His neighbors were still mad at him and weren't willing to buy new TVs, cordless phones, etc. In the end, Bob mothballed the linear in a closet and went back to 100 watts. Since then Bob has moved out into the country where his nearest neighbor is hundreds of meters away. He resurrected the kilowatt amplifier and has had no complaints from his neighbors. Signal strength falls off with the square of the distance and 300 meters is vastly different from 30 meters distance.

Surprisingly, in the US the maximum power on most HF bands has been increased. Formerly transmitter power was defined as the DC power input to the final stage. For example, in the old days a "50 watt novice transmitter" might have 500 volts DC on the tube plate and draw 100 milliamperes. That is, 500 volts times 0.1 amps = 50 watts. Since the efficiency of a class C amplifier is no greater than 65%, "50 watts" was really only 32.5 watts PEP. Similarly an old "kilowatt" Class B amplifier, the kind you find at hamfests, is 50% efficient and delivers at most 500 watts to the antenna. But now on many bands we are allowed 1,500 watts PEP measured at the antenna. That can be three times as much power as an old "kilowatt." And, when you consider that SSB concentrates all the power into a single sideband, the modern SSB kilowatt has at least 6 times the effective power as an old AM modulated kilowatt.

In conclusion,

In the end I was able to build a linear using the cheap MRF-454 transistors, just like the handbook said - even if their darn bias circuit didn't work. I talk to guys on sideband and they seem to understand what I'm saying. If my final weren't close to linear, they wouldn't have understood a word.

How much power the linear amplifier delivers depends on how much power I put in and what band I'm on. Not all my QRP drivers are equal. On 10 meters I only get 20 watts, while on 40 or 80 meters I get as much as 120 watts. As usual, lower frequencies are easier. The efficiency is about 50 percent. For example, to get 120 watts output I need 18 amperes input from the battery.

17. Chapter 12, Harris

Hmmmm ... Now that it works, I wonder what would happen if I unsoldered the base clamping diodes? It should run away, of course. After all, these are the same individual transistors I used before. It better run away! So I unsoldered the diodes. It didn't run away. The temperature compensation no longer worked, but it didn't run away. I have no idea why it didn't. Sometimes electronics drives you crazy! Persistence is your only weapon against the innate perversity of inanimate objects.

CRYSTAL SETS TO SIDEBAND
© Frank W. Harris 2010, REV 12

Chapter 13

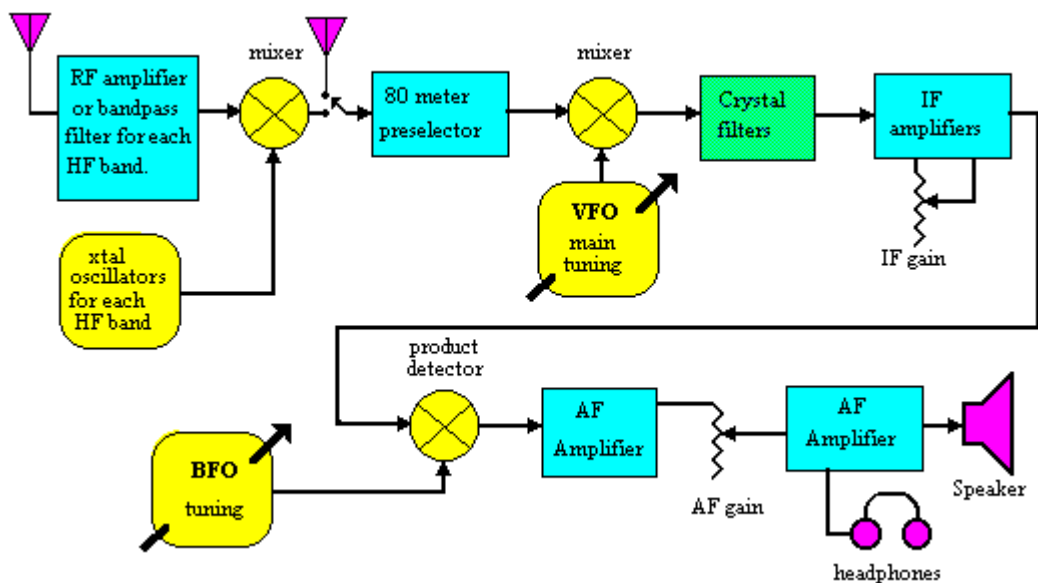
BUILDING A HOMEBREW HF RECEIVER

The Vanishing Art

The 1986 ARRL Amateur Radio Handbook reported that hardly anyone was building homebrew ham receivers. Since then, handbooks have had fewer and fewer practical details on building radios. Out of hundreds of contacts, so far I've only worked three guys, George, K7DU, Mike, NØMF, and Biz, WDØHCO, who were using homebrew receivers for the QSO. Two of these receivers were made from vacuum tubes. The third homebrew receiver that I worked was an old-fashioned super-regenerative design. However, the super-regenerative was implemented with modern FET transistors and integrated circuits. All three of these receivers seemed to have no trouble hearing me on 40 meter CW. I talked to one other fellow, Gil, N1FED who told me he had just finished a vacuum tube receiver. Unfortunately, it was performing so poorly he was still using his modern transceiver on the air. Gil told me he didn't like transistors. I guess he found printed circuit boards and those pesky oscillations too much trouble.

In spite of this pessimism, *you CAN build transistorized receivers that work reasonably well.* I built mine because I was intrigued by mysterious circuits like “balanced mixers,” “product detectors,” “cascode amplifiers,” and “crystal ladder filters.” Before this project, I could recite the purposes of these circuits, but I had no “feel” for how they worked and why receivers are designed the way they are. What better way to learn than to build one?

What's a reasonable goal?



An “adequate performance” communications receiver

2. Chapter 13, Harris

My receiver is based on the “High Performance Communications Receiver” designed by W7ZOI and K5IRK described in most of the annual ARRL Handbooks in the 1980s. In my opinion “High Performance” is optimistic, but certainly “adequate performance” is realistic. I define *adequate sensitivity and noise figure* to mean that I can hear the DX and QRPs that other stations are working. Before I built the receiver described here, I often had the impression I was hearing only the loudest signals. For me, *adequate selectivity* means that it's good enough for CW QSOs in the evening on 20 and 40 Meters. On these bands there are often dozens of narrow CW signals operating within a few hundred Hertz of each other. With a 10 KHz bandpass you may hear many stations simultaneously and not be able to copy any of them.

Adequate sensitivity will allow you to hear most QRP signals. I believe that 45 years ago hardly anyone had receivers that were “adequate” for QRP contacts. When I was a novice, my first transmitter was a 7-watt homebrew for 40 and 80 meters. It was a close copy of a design in the 1957 Handbook. I know it worked OK, because I talked to my novice buddies around town. Unfortunately I hardly worked anyone outside of town. It wasn't until I bought a 50-watt commercial kit, just like all the other novices, that I was able to talk to all the same stations my friends were working. I was still using the same dipole antenna, so I can only assume the improvement was the extra power.

The sensitivity of the receiver described in this chapter is well under 0.5 microvolt on 80 meters and lower bands that have no RF preamplifiers. On the upper bands where the receiver has preamplifiers I could hear a calibrated signal source at 0.02 microvolts. Wow! No wonder I can hear those QRPs. In the old days sensitivity less than 1 microvolt was considered hot stuff.

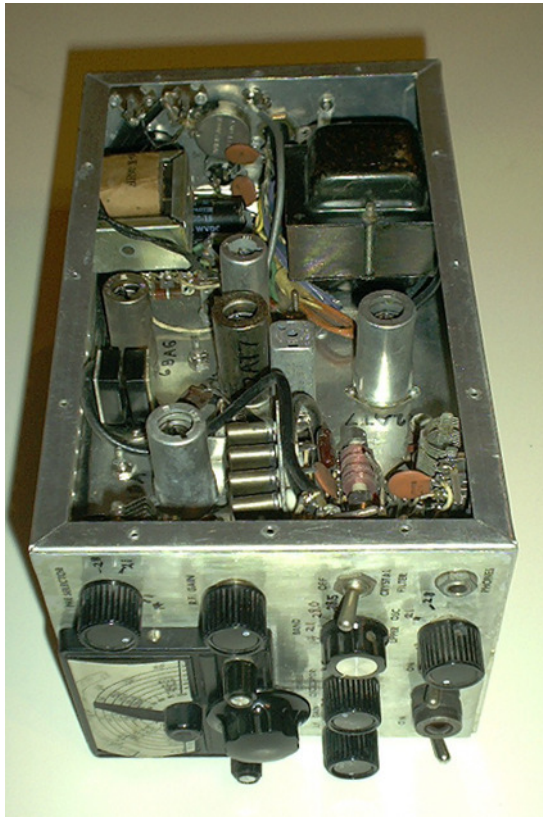
Another issue is *adequate stability*. When your receiver is equipped with sharp crystal filters, it is vital that the VFO and crystal oscillators are stable enough that the signals you're listening to do not drift in and out of your passband. If you build a VFO like the one described in chapter 10, you will have no drift troubles.

Does it have to be so complicated?

Looking at the block diagram above, each one of those blocks represents one to three transistor stages. The front-end converter has three transistor stages for each separate HF band. That means you need to build about 20 transistor amplifier or oscillator stages for the converters to cover all the bands. You're probably wondering if there isn't some simple receiver you can build that will get you on the air rapidly. The best news is that you can build the above receiver in stages. The core of the all-band HF receiver is a quality 80 meter receiver. You can build that first, then at least you'll be in business on 80 meters. In the beginning you can also do without the loudspeaker and multiple crystal filters. After you have a functioning receiver, you can add features and the converters to hear the other ham bands.

Yes, you can build a less complicated receiver, but I doubt it will be “adequate.” My direct conversion receiver in chapter 7 worked well, but was not selective enough. There are modern super-regenerative receiver designs with two or three integrated circuits that *MAY* be pretty good, but I haven't built one, so I'm not convinced. Chapter 14 describes a vacuum tube regenerative receiver that was great fun to build and quite good for listening to foreign short wave broadcast stations. Unfortunately, it was *NOT* selective and sensitive enough for ham communications. In summary, ***YES, a decent ham receiver does have to be complicated.***

A homemade ham receiver built in 1967



A homebuilt ham receiver from 40 years ago is shown above. It has 11 tubes, a simple crystal filter, and covers 80 through 10 meters. It runs on either 12 volts DC or 120 volts AC. It doesn't cover the WARC bands. Yes, it works OK. But compared to the all-transistor receiver described in this chapter, it is insensitive, noisy, and has poor selectivity.

Being realistic, any receiver you build is unlikely to match the performance of high-end commercial rigs. But every time your receiver brings in DX on a new band or whenever you conquer one of the dozens of glitches you will encounter, you'll have a thrill and pride you'll never get from a commercial rig. If you decide to build your own version of the W7ZOI / K5IRK receiver, I recommend you find a copy of an old ARRL Handbook from the 1980s and Xerox their original descriptions. You'll find they built most circuit blocks differently than I did. Going back to the original description may give you some useful ideas. Perhaps their version will work out better for you.

PLANNING YOUR RECEIVER

Superhetrodynes offer crystal filters for CW

A superhetrodyne uses a mixer to produce a constant intermediate radio frequency (IF). This intermediate frequency signal is always at the same frequency so it can be filtered with fixed crystals or mechanical filters to establish bandpass widths for CW and upper and lower SSB. Before you commit to any design, make sure you can buy the critical parts you need, especially the crystal or mechanical filters for your IF. For example, many receiver designs use a 455 KHz IF. Unfortunately, I have yet to find an easy source for 455 KHz crystals for building filters and

4. Chapter 13, Harris

BFOs. Consequently, I have avoided this frequency. Among homebuilt ham receivers the most common IF frequency seems to be 9 MHz.

Why not single conversion?

I had always wondered why homebuilt all-band HF receivers are almost always dual conversion. It turns out that the fundamental challenge of homebuilt receivers and transmitters is building a stable VFO. Yes, you can build a reasonably stable VFO, but homebrew VFOs usually don't have much tuning range. 0.5 MHz is typical. And, in order to drift as few Hertz as possible, the VFO needs to be relatively low frequency. Homebrew VFOs are usually in the range of 2 to 7 MHz. The disadvantage of a low frequency VFO is that its harmonics will appear as one or two loud whistles on some upper HF ham bands.

Compared to the practical VFO range of 2 to 7 MHz, the HF spectrum is huge, 1.8 to 30 MHz. Right away one can see that a homebrew direct conversion 10 meter receiver is difficult because it needs a stable VFO that will tune 28 to 29.7 MHz. This problem can be solved by "converting" the VFO oscillator up to 28 MHz using a crystal controlled oscillator and a mixer plus 28 MHz filter/amplifiers. This complexity ruins the simplicity of direct conversion. If you're going to operate above 40 meters, you may as well build dual conversion like the rest of us.

How do modern receivers do it?

Modern receivers use integrated circuit frequency synthesizers to generate stable VFO signals anywhere they like. Sometimes modern HF receivers escape from artifact images and harmonics by using an IF frequency way up in the VHF range. In addition, after the initial mixer stage, some commercial receivers use multiple conversions to get the signal back down to an audio output. At each conversion stage, different kinds of filtering are applied. For example, the Yaesu FT1000MP has four down-conversions from an 89 MHz IF. (!) This includes the digital signal processor with its 32 KHz input.

In a superhetrodyne the VFO interacts with the incoming RF signals to produce an intermediate (IF) frequency. A 5 MHz VFO implies that the IF is going to be within 5 MHz of the band or bands it covers. Such a receiver might cover 28 MHz, but that would imply an IF of 23 MHz or possibly 33 MHz. The lower bands would be out of range unless the VFO could be tuned over many MHz. Consequently, a single conversion homebrew superhetrodyne can only cover one band well and can't possibly cover the whole spectrum.

In some old ham designs the VFO tuned 5.2 to 5.7 MHz. They used a 1.7 MHz IF and either subtracted or added the IF to the VFO frequency to cover either 80 or 40 Meters. Specifically, 5.7 MHz *minus* 1.7 MHz = 4.0 MHz and 5.3 MHz *plus* 1.7 MHz = 7.00 MHz.)



Homebuilt all-band dual conversion HF ham receiver.

Start with a single band, single conversion superhetrodyne

My "adequate receiver" is shown above. At the upper right is the preselector tuning for peaking or decreasing the sensitivity of the 80 meter IF. This control is useful as an attenuator when tuning in SSB stations. Above the frequency dial is a bargraph S-meter. The S meter is useful for zeroing in my transmitter VFO onto a station I wish to call. Unfortunately, the bargraph produces digital switching noises that often interfere with weak signals. When I substitute the analog meter on the left, the noise vanishes. Difficulties like this are typical of the real world of building your own equipment. Try to learn from these challenges and find pleasure in meeting them. Building perfect equipment is not a practical goal for us homebrewers.

Begin by building the best single-band receiver you can. The core of my receiver tunes 80 Meters. To cover the other eight HF bands, separate crystal controlled converters convert the signals down (or up) to 80 meters. This makes the receiver "dual conversion" on every band except 80 Meters. In the old vacuum tube days each homebuilt amplifier stage was designed to work on several bands. This meant that the front panel of a 1970 homebrew receiver usually had a bunch of tuning knobs to adjust each stage. Today, a transistor amplifier or mixer stage is physically tiny, so it's practical to build a separate converter and amplifier pre-tuned for each band. My experience was that building the converters to translate the bands to 80 meters was relatively easy. Unfortunately, building a decent 80 meter core receiver was much harder. Maybe with the help of this chapter, you'll find the core receiver easier to build than I did.

My 80 meter receiver has a 9 MHz IF. 9.00 MHz crystals are available for less than \$1

from Digi-Key and Mouser. The low price is important because, depending on your filter plans, you may need as many as 11 or more 9 MHz crystals. The downside of 9.00 MHz was that I had to wait months for the crystals to arrive.

An 8 MHz IF wasn't such a good idea

At first I used the more common 8.0 MHz crystals. Unfortunately, to receive 4.0 MHz, the VFO had to tune 4.0 MHz. I expected the 4.0 MHz VFO signal would be “a little birdie” that would mark the high end of the band. I thought this “edge-of-band marker” would be kind of convenient. Instead, the “birdie” was more like a screaming siren that overwhelmed the IF and made the upper end of the 80 meter ham band unusable. So when the 9.0 MHz crystals eventually arrived, I rebuilt everything for 9 MHz. Now the VFO (the big tuning knob on the above receiver) tunes 5.0 to 5.5 MHz to cover 4.0 to 3.5 MHz. That is, 5.0 MHz + 4.0 MHz = 9.0 MHz. Of course the BFO frequency also had to change from 8 MHz to 9 MHz.

An unusual adventure

Once your receiver begins to work, you'll have interesting glitches. Until I got my 80-meter preselector filter working, I usually heard rap music from my local 1190 KHz AM radio. Also, the 31 meter shortwave band is just above the 9 MHz IF. Before it was aligned, I was hearing sermons from HCJB in Quito, Ecuador. Later, my 20 meter converter was overwhelmed by Dr. Scott, a Los Angeles evangelical minister, who preaches on 13.8 MHz. Once I had my modules tuned and sealed, Dr. Scott and his friends were silenced. Actually, I got a kick out of these problems.

Building a receiver revived my interest in shortwave listening. I've had shortwave radios since I was a kid. Some of them, like my Army surplus Collins R-388/URR, were excellent. In spite of this, I rarely listened when I wasn't actively hamming. But once my homebrew receiver(s) began to work, I found myself exploring the bands as never before. For instance, on 80 meters I was amazed to hear hams from all over the continent. I had heard about guys who work DX and earn WAS certificates (Worked All States) on 80 meters, but I never really believed it. I have even worked QRP stations on 80 meters. 80 meters is usually so noisy, I didn't know that was possible. Until I built this receiver, I had never heard “spy code stations” before. Some of them have an announcer reading what sound like random letter groups, but most of them are CW “spy stations” sending Morse code 5 letter groups, just like the WWII Enigma signals. I often hear them on 10 and 30 meters. As I built converters for each of the HF bands, it was like hearing those bands for the first time. The “WARC bands” were interesting because they were near to shortwave broadcast bands I hadn't listened to in years.

Building with modules

Aside from the need to shield circuit blocks from one another, a homebrew receiver with a single big board full of discrete components has another problem. If you build the whole thing at once without buying a kit and pre-cut board, I guarantee it won't work. *To make homebrew stuff that works, you have to develop your own technology based on parts you can get and circuits you understand.* Thinking this way has always been difficult for me. Rather than “building a receiver,” I had to lower my sights and build one circuit at a time, e.g., “an oscillator,” “a mixer,” “an audio amplifier,” etc. Then I put the blocks together to complete my project. Some of these circuit blocks didn't work the first time so I had to build a new block.

7. Chapter 13, Harris

There were various reasons the modules didn't work. Usually, I wasn't able to buy the exact parts used in the circuits I was copying. Or my craftsmanship or shielding wasn't adequate. Sometimes I never did figure out why one version of a circuit block was superior to another. By building my receiver using separate little shielded modules for each circuit block, I could replace a circuit block whenever I managed to build an improved version. Otherwise, I would have ruined the whole big board.

On rare occasions my circuits didn't work because there were errors in circuit diagrams in QST magazine or in the handbooks. I found some serious errors in my 1979 ARRL Handbook and a minor one in my 1998 edition. Perfect editing is not possible, so we shouldn't expect it. If painstaking R & D is new for you, prepare for a long battle. On the other hand, you'll learn a lot and victory will be especially sweet.

Mechanical construction



Homebrew receivers should be built in big cabinets. That way there's lots of room to add features and swap modules. The table in my shack is small, so I shoe-horned my receiver into a fairly compact package. In general, roomy boxes with lots of panel space are a much better idea. For example, when I discovered that my bargraph wasn't practical, there was no room on the panel for an analog meter. My long-range dream is to recycle my receiver modules into a larger cabinet. Eventually I want to add DSP, frequency counters, phase lock loops, and other goodies that intrigue me. With a big enough chassis, a receiver can grow and improve continually.

The receiver modules are interconnected with right-angle phono plugs and skinny coax.

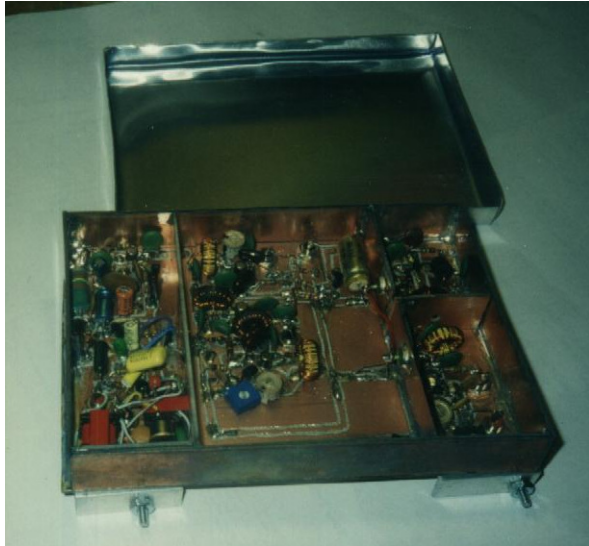
Metal boxes shield each circuit block

A basic reason for building a receiver in metal-shielded modules is that capacitive coupling from one circuit block to the next can degrade performance. For example, my first 80-meter receiver module was built on one board. A crystal filter determined the selectivity. I made two "plug-in" crystal filters so I could use different filters for CW and for SSB. Using my 20 meter converter, I was tuning around 20 meters one day. I could hear lots of hams, but I was bothered by poor sensitivity and poor selectivity. I thought, "What's wrong with this receiver today?" I soon discovered there was no filter at all plugged into the 80 meter receiver board. What I was hearing was just stray coupling between the mixer and the IF amplifier. Amazing! So if you want band-pass filters with 50 dB skirt attenuation, you're going to need at least that much isolation between the stages. That means you need metal shields between all stages, coax interconnects and lots of bypass capacitors.

8. Chapter 13, Harris

The metal-shielded modules could be small circuit boards mounted in commercial boxes. What I usually do is make shallow rectangular boxes out of pieces of two-sided circuit board material soldered together. The circuit is then carved into the floor of the box using small wood-carving chisels. The press-fit lid of the box is made from thin sheet aluminum folded over the corners of the PC board box.

Egg carton construction of the “mother board” of an 80 meter receiver



The compartment on the left is the product detector and audio amplifier. The large area in the center is the IF amplifier and AGC. The two modules on the right are the mixer and an optional RF pre-amplifier for the crystals.

If you plan on having more than one circuit block on the same board, you can isolate circuit blocks from each other using circuit board barriers soldered in place. The result is “egg-carton construction.” Power can be routed between compartments using feed-through capacitors. If you are concerned that a circuit block might not work, you can wire your

circuit on a separate square of PC board and then mount it on the floor of the desired compartment. All of these techniques are illustrated above. I constructed the IF amplifier in the center compartment on a separate PC board.

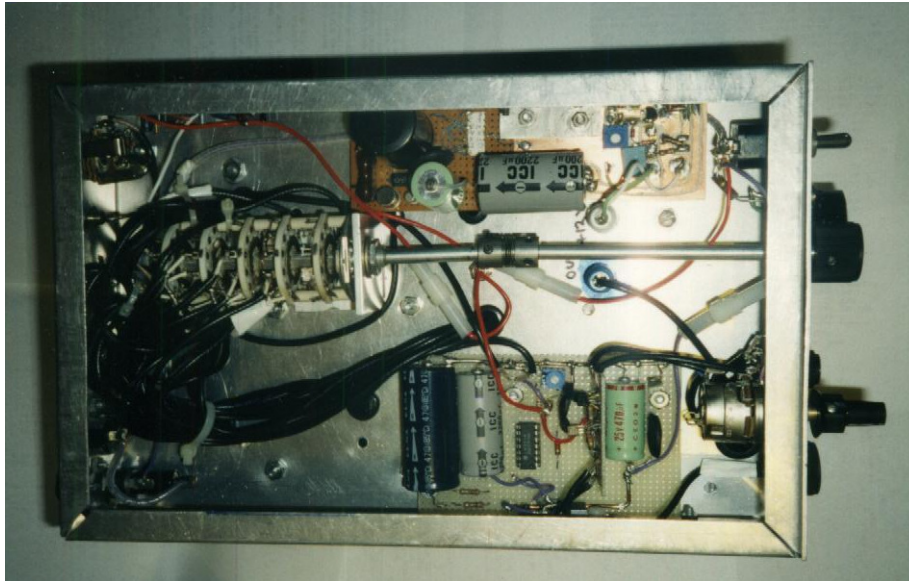
Shielded modules and shielded cable interconnects

For connections between stages I use thin **RG-174 coax and phono plugs**. Right angle phono plugs are not designed for RF and they have too much capacitance, about 4 picofarads. However, they’re cheap, available, easy to wire, and don’t take up too much room. I don’t pretend that phono plugs are OK for 6 meters and VHF. I got some feel for their frequency limit when I discovered that switching from a phono plug to a UHF PL-259 on the input to my 50 watt transmitter amplifier vastly improved its performance on 10 meters. So far, I haven’t seen any problems when working with lower frequencies and far lower power levels. Fortunately, receivers have tiny currents and low voltages. Most phono plugs have plastic bodies. That means that about 3/8 inch of the center conductor is not shielded. For my crystal filter module I used metal-bodied phono plugs that are at least a slight improvement over the plastic.

TV cable connectors, the ones that use the cable inner wire as a male connector pin, are electrically superior to phono plugs, but they are dreadfully intermittent. Personally, I’ve found them almost unusable and I wish the TV industry would junk them. There is a TV-compatible first-rate connector called an “F” type that is excellent, but pricey. In general, proper RF connectors like BNC, SMA, or TMA cost \$2 - \$6 each. Some of them are hard to assemble and your receiver could easily contain \$300 worth of “proper” connectors. Also, most of these connectors are too long to fit gracefully in a small receiver. Right-angle phono plugs are quite short and quite cheap. Hurrah for phono-plugs!

Use plastic knobs

One odd little problem I encountered was that touching the metal control knobs or the front panel sometimes causes scratchy noise in the headphones when I listened on the higher bands. Yes, the metal panel was grounded and the chassis was wired to the station ground. The station ground is a heavy 12-gauge wire that grounds all the various metal boxes to a copper water pipe next to the station. I don't really have an explanation for the noises, but I switched from metal to plastic knobs and the annoying scratchy noises greatly improved. That was a shame - the metal knobs looked much more sophisticated.



Bottom view of the receiver

Band switching and power supplies

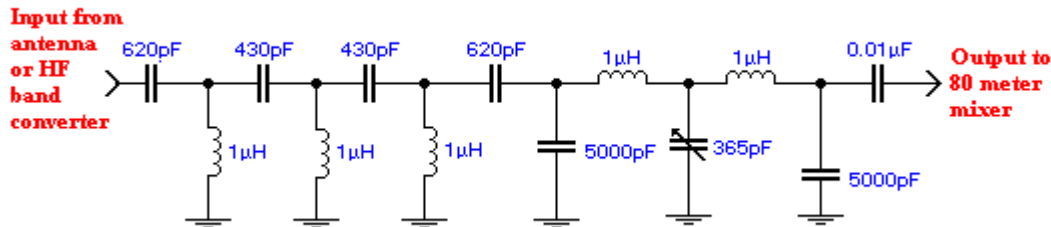
The precision power supply for the VFO is at the top right. The low drop-out regulated supply for the rest of the receiver is at the bottom right. These are the same circuits used earlier with the transmitter VFO and QRP transmitter modules. The band-switch is the multi-wafer ceramic switch on the left. The black wires on the left are skinny coax that interconnect the inputs and outputs of the converters for every ham band except 80 meters. It is desirable to cover the bottom with a metal plate to help keep stray signals out of the power leads.

80 Meter input preselector

The “front end” of the 80 meter receiver is a mixer. No RF pre-amplifier is needed on 80 meters because, if the receiver works well, then the atmospheric noise coming in from the antenna will be louder than the receiver internal noise. In this situation an RF amplifier won't help. However, the mixer does need a sharp bandpass “preselector” filter to keep out the low frequency AM radio and limit the input signals to 3.5 to 4.0 MHz. It's especially important to filter out AM broadcast stations. These stations put big voltages on the antenna and tend to overwhelm the mixer unless they are well attenuated. The high pass AM broadcast filter module described in Chapter 7 for the direct coupled receiver can be used and works well.

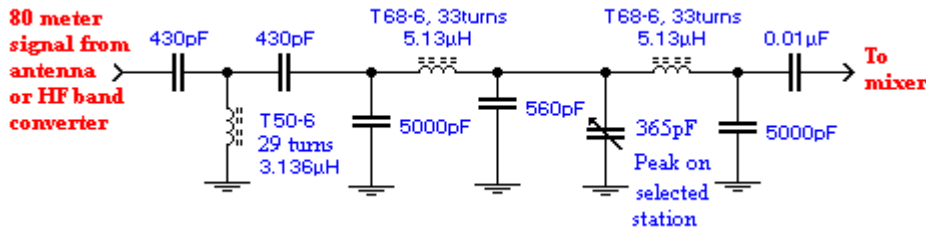
The mixer subtracts the VFO frequency, (5.0 to 5.5 MHz) from the IF frequency, (9 MHz), to tune 80 meters, (3.5 to 4.0 MHz). The two inputs to the mixer are the VFO signal and

the antenna signal. When I first examined the 1986 ARRL design, I was disappointed to see that the pre-selector had a primitive variable capacitor that the operator was supposed to tune for maximum gain for a particular part of the band. After all, the bandpass filters for the other HF bands were fixed and not accessible from the front panel. I attempted to build my own fixed bandpass filter, but my filters had too much attenuation (poor sensitivity) and sometimes let in AM broadcast stations. That is, it was like listening to a crystal set.



The recommended 80 Meter preselector filter for the core receiver mixer input.

So I returned to the ARRL design with the 365 pF variable capacitor. It had so much attenuation on 80 meters, I couldn't hear a thing. I ran the ARRL circuit on a Spice program, and, according to Spice, it should have worked well. However, mine didn't. I must have had a bad part somewhere, but I couldn't find the problem. Using trial and error, I removed some parts and ended up with the circuit shown below. My filter works pretty well, although, according to my Spice program, it is not as good as it should be. Sigh ...

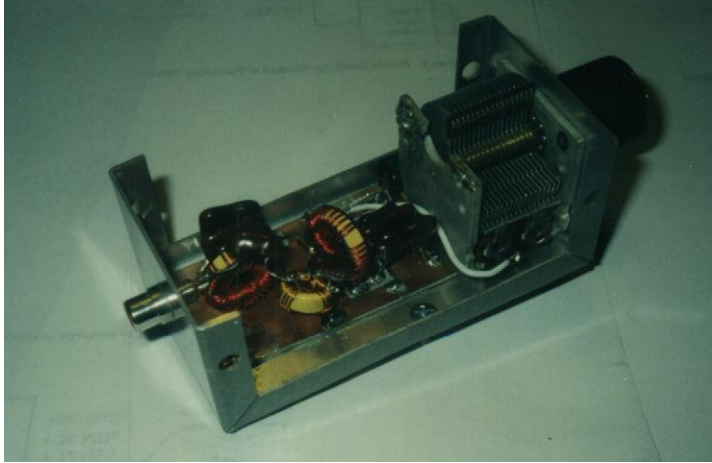


My version of the 80 Meter preselector filter for the mixer input

I mounted the preselector in a shielded box up on the front panel where the peaking capacitor was accessible. Someday, when I figure out how to build a better preselector, I shall replace the whole module.

The 365 pF variable capacitor acts like an attenuator

On the positive side I found that the variable peaking capacitor is quite useful as an attenuator for receiving strong single sideband signals. In other words, strong SSB phone signals are often much more intelligible when the preselector is mistuned and signal strength is decreased. If I didn't have this capacitor as a variable sensitivity control, I would have to build an attenuator.



The preselector is built in a little box up front behind the front panel.

The variable frequency oscillator (VFO)

The receiver VFO is the same design as the 5 MHz transmitter VFO discussed in chapter 10. The big tuning knob controls the VFO. Actually, in superheterodynes the VFO is usually called a *local oscillator* or *LO*. The range and stability of the VFO determine what VFO and IF frequencies are practical. Like a transmitter VFO, a receiver VFO should be stable to less than 5 Hz/ minute drift, although less than 20 Hz will probably be OK.

Unfortunately, if the VFO frequency is too low, it probably won't span enough Hz to cover the bands you're interested in. Notice that 10 meters is so huge, 1.7 MHz wide, that you will have to cover it with multiple converters. So far, my receiver just tunes the first 500 KHz of 10 meters, which includes all the CW activity. I guess I'll worry about the rest when I get on 10 meter SSB. And that will probably happen when the sunspots return. The VFO frequency and its harmonics should avoid the ham bands as much as possible. Frequencies with round numbers are best because they make calibration easy. Put all these factors together and you'll find your choices are fairly limited.

In fact, once you've built separate transmitters and receivers and used them on the air, the disadvantage of having to tune two VFOs makes it obvious why most modern rigs are transceivers. When planning a homebrew receiver and transmitter, you might consider using a common VFO module. A common VFO would be a great help on the air. But, if you use just one VFO, you will have to master the 500 to 800 Hz send/ receive frequency-offset problem. Also, an isolation amplifier is needed to keep the cable connecting one to the other from loading down the receiver VFO. And finally, when used on the upper bands, each crystal oscillator in the converter and each transmitter PMO must be on the corresponding frequencies in order for the receiver to listen on exactly the same frequency used by the transmitter. In other words the converter oscillators need to be shared too. All this represents huge amounts of work. It makes the most sense to build a transceiver from the beginning, starting with a gigantic mainframe cabinet.

How much VFO signal do you need?

As explained in chapter 10, the stability of a VFO is partly dependent on generating the minimum heat possible inside the VFO box. Therefore, unlike me, you should decide out how

much VFO signal voltage you will need before you build the VFO. The required VFO voltage is the level needed to drive your mixer. MOSFET and JFET mixers only need 1 or 2 volts peak, so if you're going to use one of these, there is no good reason to generate 5 volts, then throw away most of it in a potentiometer at the input to the 80 meter mixer. Instead of running the VFO on 12 volts or 5 volts, you can reduce the supply voltage externally to 3 volts or whatever minimum voltage you actually need. Remember that low voltage means low heat which means low drift.



A varactor tuned 5 MHz VFO. Tuning is accomplished with the big round potentiometer.

Mixer magic

The purpose of a mixer is to translate the frequency of an incoming radio signal to a constant intermediate frequency (IF) that can be amplified and filtered more easily. Mixers combine a local oscillator sinewave with the incoming radio signal to make a composite signal. The new signal contains the original frequencies, plus the new sum and difference frequencies. Mixers intended for moving a VFO up to a high band were described in chapter 11. Mixers for that purpose can be quite crude and will work well. Unfortunately, receiver mixers are much more difficult because the incoming signal can be so tiny.

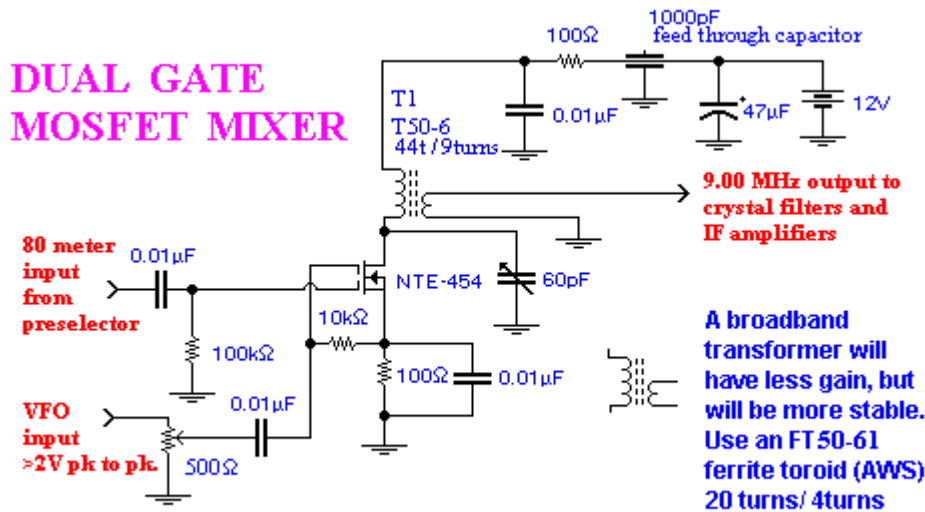
One way to look at mixers is that a big local oscillator sinewave keys the incoming RF signal totally on and off, much like a sequence of fast Morse code dots. The lesson is that the local oscillator (the VFO tuning knob) must be a big signal while the RF input signals may be arbitrarily small.

The ARRL Handbook presents several different mixer designs made with discrete diodes, inductors, and transistors. However, in most ARRL receiver designs since the 1980s, including the W7ZOI/K5IRK receiver, the mixer is an integrated circuit or little canned assembly labeled "mixer." I guess everyone else was having mixer trouble too, so they resorted to integrated circuits. Two years ago there was a receiver project in QST that used an IC that contained both the mixer and the VFO. I'll bet these marvels work fine, but the contents of these ICs are a mystery. Use one if you want.

Mixers will give you lots of static... and squeals, howls, and squawks

So far I've built five different mixer designs from discrete parts. First I built a classic balanced mixer with ferrite cores and a hot carrier diode ring. When I turned it on, I heard loud,

roaring static in the headphones. “Oh goodie!” I thought, “Listen to all that atmospheric static! It must be working!” I soon figured out that the static was coming from the mixer and the IF amplifiers and had nothing to do with the outside world. I had just learned a basic truth about mixers: Mixers aren’t just prone to generate “a little background noise.” They often produce gigantic Niagara Falls noise that obscures everything coming in the antenna. However, once I had proper mixer input levels and resonant circuits tuned up as best I could, the noise disappeared and I began to hear stations. Unfortunately, as I tuned across the band, there were loud whistles like marker beacons every few KHz. In between the whistles, I could sometimes barely hear strong stations.



A practical mixer

My favorite mixer is shown above. Most of the others suffered from noise and “birdies” and had poor sensitivity as well. Unlike diode mixers, the operation of the MOSFET mixer is obvious. It is essentially an ordinary tuned transistor RF amplifier. The radio signals come in on one control gate. This modulates the large current passing from drain to source of the transistor. The small voltage on the control gate controls the large drain current thereby amplifying the original signal. A second input gate amplifies the local oscillator signal. This means that 2 volts of VFO signal is plenty. The local oscillator signal is so strong it turns the drain to source current totally on and off, “chopping” the input RF signal into tiny segments. The big output current from the transistor becomes an amplified “mixture” of the two input signals.

I originally used a tuned version of this mixer in which the transformer primary was tuned with a capacitor to resonate at 9 MHz as shown above. That works OK, but is rather tweaky and subject to noise and birdies. I now prefer an untuned version (also shown above) which has slightly less gain, but isn’t so easily misaligned. Instead of the powdered iron core and 60 pF trimmer, I used a CWS (Amidon) FT50-61 ferrite core with 20 turns primary and 4 turns secondary.

Because of the high gain of the MOSFET, the VFO sinewave signal can be low amplitude, typically 2 volts peak, and still fully chop the radio signals on and off. In contrast, a diode ring mixer needs a big local oscillator signal, 12 or more volts peak, to chop the signal.

Other transistor mixer designs use junction FETs or bipolar transistors. These designs use the emitter resistor as the VFO input port. The emitter or source has no gain, so these designs also need big local oscillator signals.

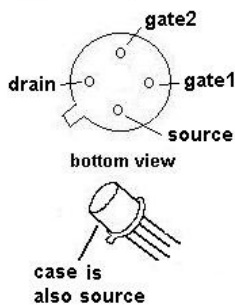
A small local oscillator signal is especially helpful for building the converter or converters you will need for each of the other nine HF bands. Each of these converters must work through its own mixer. If the dual gate mixer were not used in the converters as well, each of the eight local oscillators you will build would need separate amplifiers to get the local oscillator signal up to 12 volts peak. I used a common, broadband pre-amplifier for the crystal oscillator inputs to a common untuned mixer. That is, the mixer has a ferrite, broadband transformer as described above.

All dual gate MOSFETs are not equal

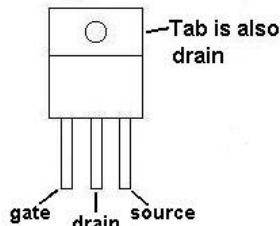
Alas, a dual gate MOSFET mixer isn't a guaranteed success either. When I first built a MOSFET mixer, I couldn't buy any of the transistors recommended in the handbook. I first tried a generic part, the NTE221 transistor. This produced the usual oscillations and insensitivity. I was getting discouraged, but I tried the similar NTE454 and *IT WORKED!* The only obvious difference in the specifications was that the gate shut-off voltage was smaller. In other words, the NTE454 was more sensitive. Since then, I've discovered the NTE222 seems to work as well as the NTE454. The NTE455 seems too sensitive. In my circuit it produced whistles, birdies, and noise. On the other hand, the NTE455 worked great as a product detector (Chapter 7).

MOSFET TRANSISTOR CASES

DUAL GATE MOSFET
TO -72 CASE
e.g., NTE454, NTE 221, etc.



MOSFET POWER SWITCH
TO -220 CASE
e.g., IRF9140, SMP20P10,
MTH25P05, etc.



I first tried to use two dual-gate MOSFETs in a "semi-balanced" configuration. The handbook said this is superior to the simple mixer shown above. Balanced designs are supposed to help cancel images, by that I mean, birdies. My semi-balanced mixer produced the usual oscillations, but at least the noise and sensitivity were adequate and I began to hear weak 80 meter stations with my receiver.

Reading up on mixers, I learned that mixers are only happy when they receive the exact input levels. That's why I put a pot on my VFO drive to inject the optimum level. As I turn up the VFO drive to the mixer the output signal strength rises abruptly then levels off. Higher levels of VFO contribute only slightly more gain, but much more noise. I adjust the VFO input to where the gain first begins to level off. (Note: My VFOs are designed to work into a 500 ohm load, hence the 500 ohm pot.)

The sensitivity of mixers to ideal levels explains why most modern transceivers have input attenuators so that they can be adjusted to tolerate strong signals. I got a QSL card from a guy who wrote, "Sorry about the 529 signal report. After we signed off, I discovered I had the attenuator on." As mentioned earlier, the 80 meter preselector filter may be deliberately mistuned so that it acts as an attenuator to limit signal strength.

Note: Reception on 80 meters and 160 meters is best with a tuned transmatch

By accident I discovered that reception on the two lowest HF bands is much better when the receiver is sharing the antenna with the transmitter and the antenna is tuned with the "T" antenna coupler described in chapter 9. In my neighborhood at least, the signals from the local AM radio stations are so high that they tend to overwhelm the 80 meter mixer. This results in a lack of audible signals on 80 and 160. I didn't realize I had a problem because I wasn't hearing the AM stations in the headphones. However, when I tuned up the transmatch, suddenly numerous ham signals appeared. The obvious conclusion is that my receiver preselector filter is not selective enough. Even my old Collins receiver is greatly improved by a tuned antenna coupler.

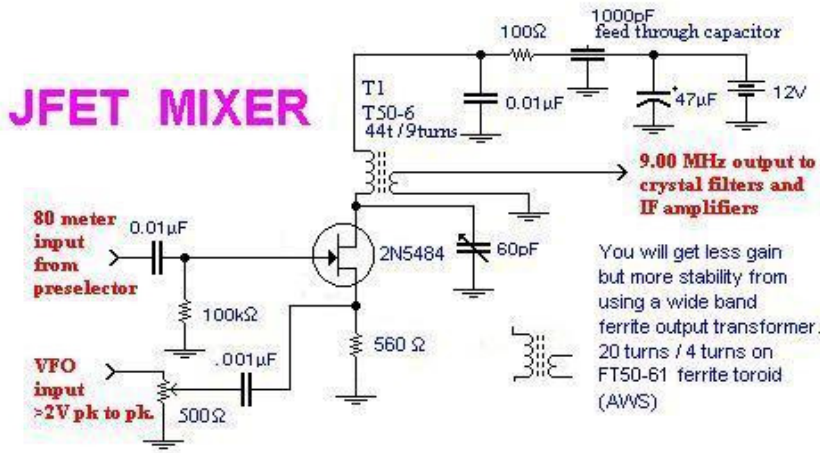
In chapter 7 I described a high pass filter for the direct conversion receiver to attenuate the AM broadcast signals. I have found that this little filter also improves the 80 meter receiver board performance. Because I had built it in a little module with phono plug connectors, I could simply plug it in without building anything new or without altering the rest of the receiver.

A JFET mixer

Since this book was first written, dual gate MOSFETs have become increasingly expensive and hard to find. One part you might try is the RCA 40673 available from Mouser for \$7. I haven't tried them, but my friend Jayram, VU2JN in India, has used them in receiver mixers with great success. Dual gate mixers are his favorite design too.

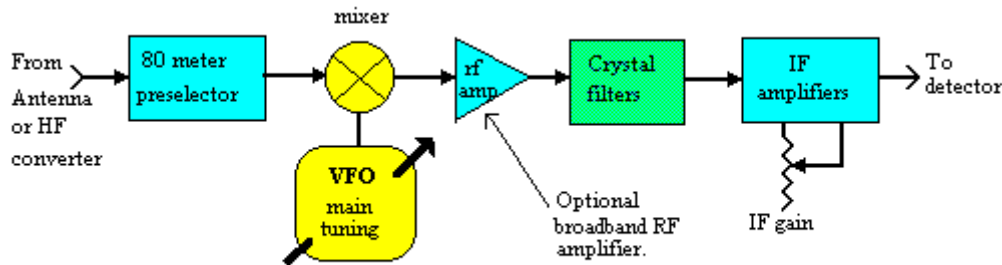
In the event that you need a substitute design, here is a JFET circuit that works but in my opinion, isn't as sensitive. It is practically the same circuit, but instead of introducing the local oscillator signal into a separate gate, it is introduced across the source resistor. Surprisingly the optimum local oscillator signal input level for this circuit is only about 1 volt peak-to-peak. For this reason the signal is first passed through a 500 ohm pot. I would have expected that, for a circuit like this, the optimum peak voltage would have approached the supply voltage so that the transistor would be entirely turned on and off. I guess the answer is that this is a *depletion type* MOSFET that is already half turned off with no bias. Consequently, it doesn't take as much drive to turn it either full on or full off. I also attempted to use the dual parallel JFET PMO mixer design described in chapter 11, but it worked poorly in my receiver.

There is another dual JFET mixer circuit that puts the two transistors in series. In this way, the two voltage signals both have gain and are stacked on top of each other, so their output voltages add. In contrast, the parallel JFET version produces signals that tend to cancel each other. I tried this variation and it seemed no better than the single JFET version above. In other words, it was insensitive. It looks as though it would produce more signal strength and I always wonder if I have missed something. Perhaps with more R&D it can be improved.



Crystal filters and BFOs

Crystal IF filters give you the selectivity you will need for working CW. They eliminate interference from nearby stations and also eliminate a great deal of the atmospheric noise. The output from the superhetrodyne mixer is a weak, broadband, IF frequency signal that needs amplification and filtering before it is ready to be detected. The bandpass filtering is usually done right after the mixer.



Location of crystal filters in a superhetrodyne

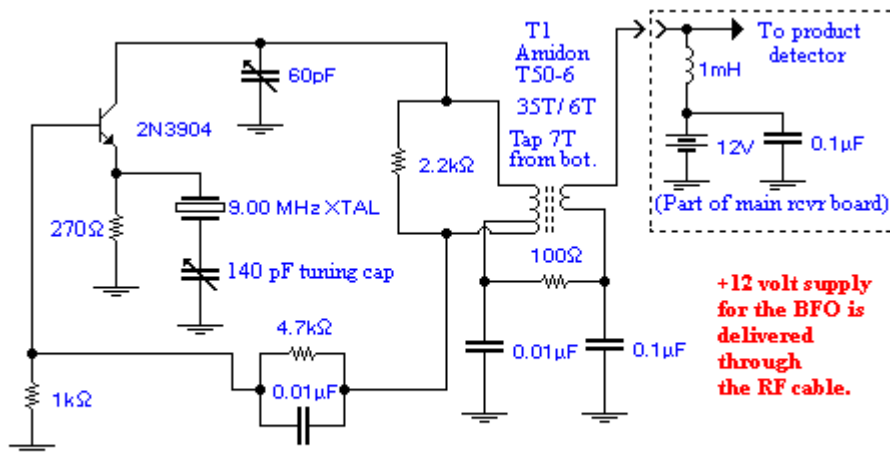
The filter could be a "mechanical filter" if you are using a low frequency IF like 455 KHz. But if your IF is 9.0 MHz like mine, then you'll need one or more crystal filters. Before I describe building crystal filters, I'll discuss the Beat Frequency Oscillator (BFO). You will probably need the BFO as a tool to select the crystals for your filters.

The Beat Frequency Oscillator (BFO)

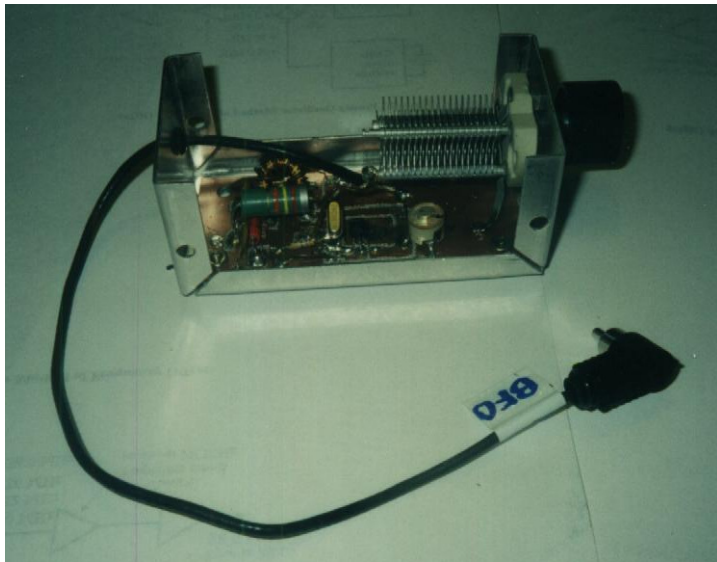
A beat frequency oscillator is an RF oscillator that operates on the intermediate frequency of a superhetrodyne. The BFO mixes with the IF signal to make CW and single sideband transmissions audible and/ or understandable. Without the BFO CW signals would be inaudible or just thumping noises at best. Single sideband phone would be unintelligible "Donald Duck" sounds. In single sideband the transmitter filters out the basic carrier frequency leaving just one of the modulation sidebands. The BFO serves to restore the carrier sinewave, in effect returning the sideband signal to its original amplitude modulation.

During detection, the audio signal passed on to the loudspeaker is the difference between

the IF frequency and the BFO frequency. For example, when listening to CW signals, the IF frequency might be 9.000,000 MHz. The BFO frequency might be 9.000,700 MHz. What you would hear in your headphones is a musical tone of the difference frequency, 700 Hz. If that pitch sounds unpleasant to you, adjust the BFO frequency to say 9.000,500 MHz to produce a musical tone of 500 Hz. For the musical tone to stay constant, the BFO oscillator must be quite stable. Therefore, we use a crystal oscillator and pull the frequency up or down using a variable capacitor, just like we did in the crystal controlled QRP in chapter 6.



The Beat Frequency Oscillator



The Beat Frequency Oscillator (BFO) module

you wish to use this oscillator for matching 9 MHz crystals for filters, I suggest you install the BFO crystal in a small IC or transistor socket.

The BFO frequency tuning range should extend above and below the bandpass of your crystal filters. *When the BFO frequency is below the center of the filter bandpass, you are listening to the upper sideband. When the BFO is tuned above the filter bandpass, you're hearing the lower sideband.* Adjusted for the upper sideband, tuning down the CW band will

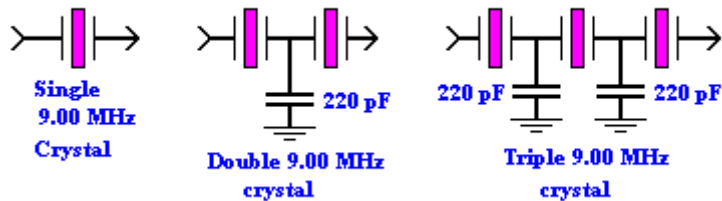
This BFO is taken directly from the W7ZOI and K5IRK receiver in the 1986 ARRL Handbook. Its unusual feature is that its DC power supply rides on the same line as the RF output. This makes it easy to install the BFO in a little metal box up on the front panel remote from the main receiver board. A variable capacitor on the front panel "pulls" the BFO crystal frequency above and below the nominal frequency. The BFO, together with the crystal filter, allow you select upper or lower sidebands. The BFO is connected to the main board with a length of thin coax jumper cable. If

cause the whistle pitch of a signal to start high, drop down to a low pitch, and then disappear. Adjusted for the lower sideband, tuning down the band will cause the pitch to start low then climb up high and disappear. When the BFO is tuned to the center of the filter bandpass, the tone will start at a medium pitch, drop to a low pitch, briefly become inaudible, then climb back up to medium pitch and disappear.

When tuned to sideband phone signals, the signal is harder to make understandable if you select the wrong sideband. Consequently, it will be important to calibrate the BFO tuning knob so that you will know when you are listening to upper or lower sideband.

Ladder filters

Building crystal filters was easy, once I figured out how. Most commercial transceivers use modular crystal filters that have specific bandwidths and are sealed in little cans, something like an integrated circuit. I made my filters from discrete crystals.



One, two, and three crystal “ladder filters”

A ladder filter is just two or more crystals in series with capacitors bypassed to ground at the nodes. The bandpass width is inversely proportional to the number of crystals and the capacitance to ground. *In general, the lower the capacitance on the nodes, the wider the bandwidth.* Large capacitors, like 50 ohms reactance, will give narrow bandwidths and higher attenuation. Long “ladders” of course produce even narrower bandwidths and more attenuation. If all the crystals are all identical, then the “skirt attenuation” on either side of the peak passband becomes steeper and steeper as more crystals are added.

Crystal filters with two or three crystals are selective enough for “CW after dinner.” By that I mean you can work the busy CW bands early in the evening with adequate signal separation. A single crystal filter made from just one 9 MHz crystal is good for single sideband phone (SSB). With three or four crystals the bandwidth becomes so narrow that SSB is totally unintelligible. With strong CW signals and lots of QRM, triple or quadruple crystal ladders are extremely useful. If you tune down to the bottom of 20 meters in the evening, you’ll usually hear a cacophony of CW stations all trying to work the same 5 or 6 DX stations in exotic countries. With only one crystal switched in, you’ll hear practically everyone at once. Switch in two and three crystals and suddenly, you’re not only listening to one clear station, but most of the background noise has gone too.

How many crystals can you use in a ladder?

One limit on how many crystals you can use in series depends on the precision with which you match the crystals. I didn’t match my first set of filters and they produced more attenuation than filtering. I then proceeded to waste time getting more gain out of my IF amplifier. Then, after I achieved the gain, the selectivity wasn’t much better than single crystals.

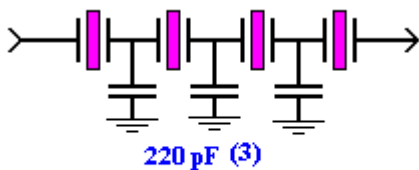
Finally, I tested my crystals one by one by putting them in the BFO and measuring the frequency with a frequency counter.

I didn't expect that the frequency filtering characteristics would be exactly the same frequency as when the crystal is used in an oscillator. However, I figured I could at least select sets of crystals that were similar. When I ran them in the oscillator, I was shocked to discover that the crystals were as much as 2.5 KHz different! No wonder it worked so poorly. I had put 9.001 MHz crystals in series with 9.003 MHz crystals. I had built a "crystal barrier," rather than a crystal filter.

Luckily I had bought twenty 9.000 MHz microprocessor crystals. That sounds extravagant, but they're under \$1 each at Digi-Key or Mouser. Because I had a wide selection of 9.000 MHz crystals, I was able to match up two crystals that were within a few Hz of each other. And I was also able to match up a group of 3 crystals that were within 50 Hz. This time when I put matched crystals in my ladders, the improvement was dramatic. When I switched from a single crystal to a double crystal, the signal strength barely dropped. With three crystals, the signal strength just dropped slightly more.

In theory, you can make perfectly matched crystals by placing tiny trimmer capacitors in parallel (or series) with each crystal. Then you would trim the crystal and capacitor assemblies in the oscillator one at a time so that each crystal/capacitor assembly oscillates on precisely the same frequency. I've only tried this once, but it worked poorly and I went back to the simpler design.

Another limit on the number of crystals in a filter is the shielding and RF isolation between the mixer and the IF amplifier. If the shielding is poor your IF amplifier will "hear" the signal from the mixer without the signals ever passing through the crystal filters. In my receiver, 5- or 6-crystal ladders aren't worth building.



Four matched 9.000 MHz crystals

Switch in your filters with a rotary switch

I first built my filters as "plug-ins," but I soon discovered it was too hard to change them in the middle of a QSO. Eventually I wired them to a rotary switch in a shielded box. As I became more experienced with using the filters, I began to use the triple filter more and more. Finally I built a quadruple filter and now I use it routinely. I find it works well with the S meter (strength meter) as a way to tune my transmitter to zero beat with another ham's signal. I just sweep my transmitter VFO across the band until the S meter jumps up to maximum. This occurs when the VFO frequency converted into the IF matches the frequency of the four matched crystals. The offset of the BFO and the tone of the Morse code signal take care of themselves. That is, if the fellow is on the upper sideband, then the S meter only responds to my VFO when I am on the same BFO offset that he is using. This happens because only one sideband is audible

at a time with 3- or 4-crystal ladder filters. By the way, one of my 20 crystals behaved erratically. While I watched, the frequency wandered about +/- 200 Hz. Consequently, I didn't use it.

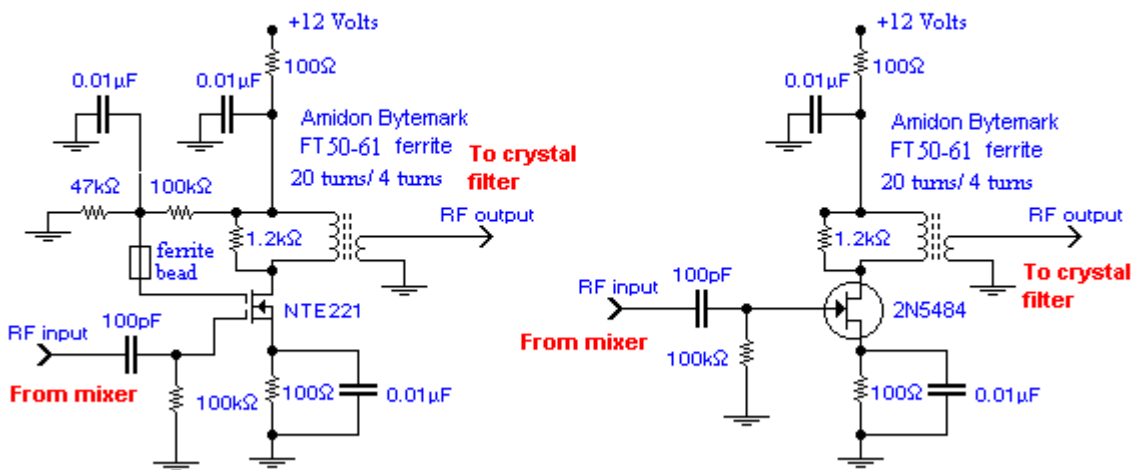
Series and parallel cut "XTALS"

There are two kinds of simple crystals, series and parallel cut. As I understand it, the difference is the oscillator circuit for which they are designed to be used. For example, a series-type crystal is intended to be used in series with a specific capacitance in an oscillator. When this exact capacitance is used, it will oscillate at the rated frequency, for example, 9.000 MHz. In contrast, if you use a parallel cut crystal in the same circuit, it might oscillate at 9.004 MHz. You may use either kind of crystal, but your filter frequency may not be exactly 9.000 MHz.

All 9.000 MHz crystals aren't equal

In my experience larger crystals, size HC-49 or bigger, work well. The tiny surface mount or half-size HC-49 crystals need more signal strength from the mixer output to push the signals through the filter. The broadband "optional" amplifier shown below will give you extra gain if you need it. It's the same design that will be used later as a RF amplifier for the higher HF bands. If you are short of MOSFETs, a JFET alternate circuit is also shown below.

RF Amplifiers, MOSFET and JFET versions



Broadband RF amplifiers Place one between the RF mixer and the crystal filter.

I also observed a difference between different brands of crystals. My crystals from the ICM company were extremely similar to each other. For ladder filters, this would be the brand to buy. My crystals from the ECS company had much wider frequency variation from one crystal to the next. This isn't helpful for building ladder filters, but if you need crystals that are slightly different from each other to build wider pass-band filters, or perhaps SSB oscillators that must operate 2.5 KHz above and below the nominal frequency, then buy the ECS crystals. I found them both useful.

By trial and error I found that the untuned impedance step-down transformer shown in

above pre-amp circuit performs better than leaving the transformer out and simply using an inductor on the drain then coupling to the crystals with a capacitor. In other words, this implies that the crystals with their bypass capacitors look like roughly 50 ohms, but must be matched to the high impedance output of the MOSFET transistor. There's a design in my ARRL handbook that uses impedance step-up transformers to match the filter. I find it hard to believe that design is optimum unless the crystals they used behave differently than mine.

The second input gate in the above dual gate amplifier is used to set the DC bias and make the amplifier class A. A voltage divider delivers about 4 volts DC to the gate. The *ferrite bead* is a tiny inductor (RF choke) that helps insure that the MOSFET doesn't oscillate. The ferrite bead is literally a 1/8 inch cylinder with a tiny hole through the center. For example, you could use a CWS type (Amidon) FB43-101 bead. The type isn't critical. I used several different kinds of beads and have had no trouble with oscillation. If it does oscillate, remove the 0.01 μF bypass cap from the 100 ohm source resistor. The resulting negative feedback should kill the oscillation at the expense of a small amount of gain.

The IF amplifier

The IF amplifier is another tricky part of a superhetrodyne. It's a high-Q (sharply resonant) amplifier that must handle signals with a range of 100 dB or more without oscillation or noise. This is a huge dynamic range. The gain on the IF amplifier stages should be adjustable using an IF gain control. Too much gain and you will have noise and squeals. Too little gain and you can't hear weak DX stations.

Moreover, if you used miniature half-size HC-49 crystals to build your bandpass filters, you will need even more gain to stuff signals through the significant attenuation of the filters. In the last section I described a simple RF amplifier that can be placed between the mixer and crystal filter to overcome this difficulty.

Oscillations in an IF amplifier come in several flavors. As you tune the LC circuit of an IF amplifier stage you will hear squeals, harsh roaring, silent dead spots, and gentle static. The setting that brings in the loudest signals is surprisingly noise free. The first time I turned on my receiver, I quickly learned that *most of the receiver noise is coming from the mixer and IF amplifiers*, not from the outside world. The noise comes from a maladjusted mixer or too much IF amplifier gain.

Although I was able to tune up my 80 meter receiver using a signal generator, real 80 meter ham signals worked the best for me. There's no point in simulations when you have the real thing. A problem with tuning up the IF on 80 meters is that 80 may be dead during the day. During the summer, 80 may not be so hot in the evening either. As a result, you might consider building a converter for 20 or 40 meters early in the project. For most of the 11 year sunspot cycle these bands usually have signals anytime, day or night, all year long. Since your 80 meter receiver may not yet be working, you can adjust your converter by feeding the output into a commercial receiver tuned to 80 meters. Then, after you have the converter working, you'll be confident that there are lots of real signals for your 80 meter receiver to hear.

Impedance matching the crystal filter to the IF amplifier

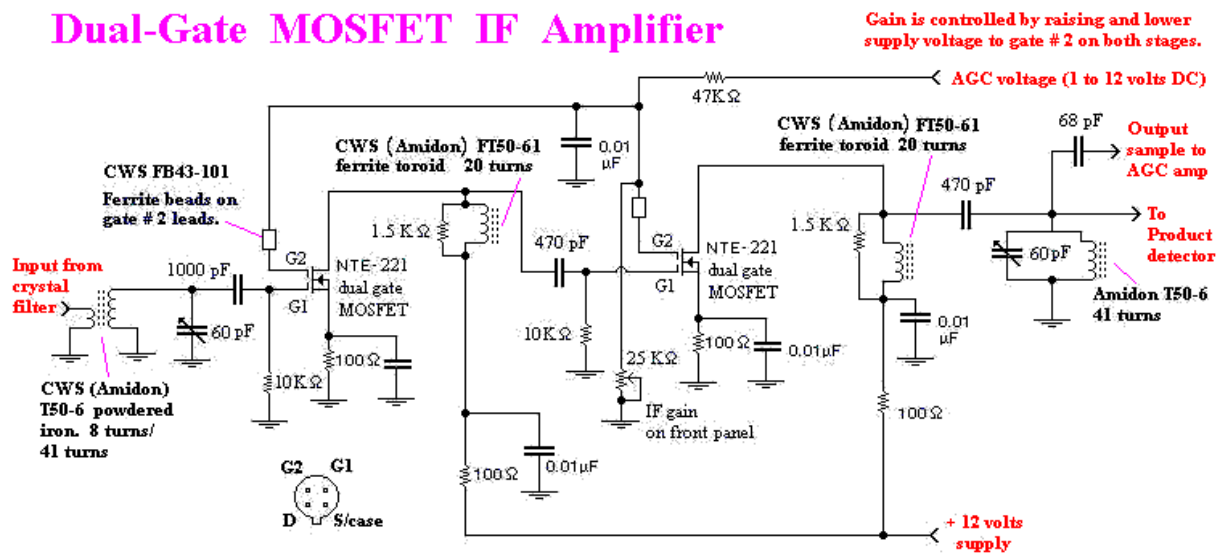
Looking at examples on crystal filter circuits in handbooks from various years, I found circuits that seem to assume the filters are low, medium, or even high impedance. In most of my

attempts, I seemed to get the best gain when my filters were assumed to be relatively low impedance, say 50 to 100 ohms. That's why the optional amplifier described above used a step down transformer output. I tried step-up, step-down and no transformer to feed the signal into the IF amplifier shown directly below. Step up worked best on the two versions as shown below.

A dual-gate MOSFET IF amplifier

My first versions of the IF amplifier used dual gate MOSFET amplifiers, similar to the crystal filter preamplifier described earlier. Just what you need - another circuit made from 7 dollar transistors! The gain of each MOSFET transistor can be controlled by varying the DC bias on one of the two control gates. This control voltage can be generated by either the IF gain knob or by the automatic gain control circuit. In short, the dual gate MOSFET looks ideal for IF stages. Unfortunately, I had lots of trouble with squeals and noise.

With struggle, I eventually managed to get the dual-gate version working. Originally it consisted of two dual-gate tuned amplifiers in series. Each amp was similar to the dual gate amplifier on the previous page. Instead of the fixed 4 volt bias on the second gate, those gates were biased with the variable IF gain/AGC voltage. When I started, I used tuned LC circuits as the impedances between the + supply and the two MOSFET drains. This approach was quite unstable and prone to oscillations. I decreased the instability but retained enough of its sensitivity by replacing the tuned drain LC circuits with ferrite cores - that is, RF chokes. I moved both tuned LC circuits to the input and output respectively. These LCs must be tuned carefully for the maximum signal strength without squeals. The circuit below is the result.



The main lesson I learned from this circuit was that high gain amplifiers shouldn't be tuned unless the input signal is continuous. Whenever there is little or no signal to amplify, a high gain tuned amplifier will amplify any noise that may be present and may begin to oscillate at the tuned frequency. To prevent this, you are better off designing your tuning function to be separate from the amplification. Notice the tuned circuits at the input and output of the IF strip as a whole. The two amplifiers above are wideband but relatively low gain.

I suspect that a similar circuit would work OK with ordinary bipolar transistors, but I haven't tried it. The IF gain would control the forward bias level of the two transistors, that is, the bias that makes them class A. A gain/ bias system like this is used in the cascode amplifier shown below.

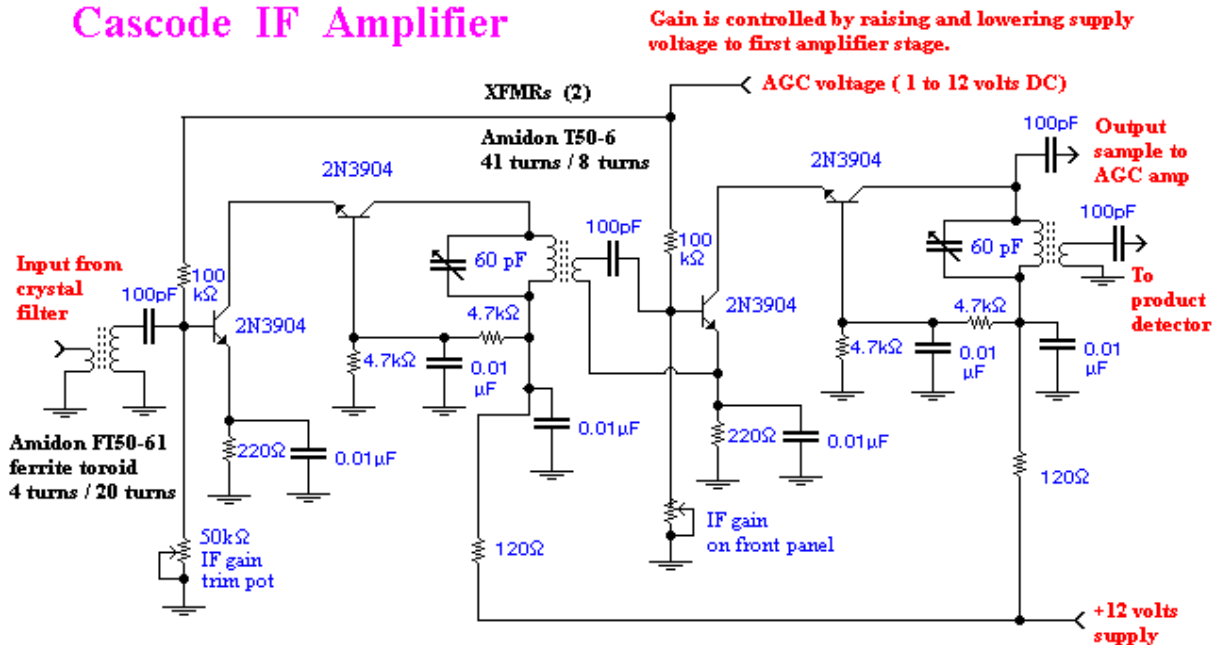
In the circuit above, the input LC attempts to limit input noise to just 9 MHz noise. Similarly, the output noise is similarly clipped with the second LC. Chapter 15 discusses PMOs for single sideband generation, which have a similar problem. Every time there is a pause in the speech being transmitted, a tuned amplifier will usually oscillate. Consequently, all the frequency filtering is done in separate passive filter blocks, rather than being incorporated into the amplifiers.

In summary, the above amplifier stages are broadband and use ferrite transformers that pass on any radio frequency signal to the output with little or no filtering effect. On the other hand, ferrite transformers have lots of internal inductance and capacitance. They will resonate at lower frequencies, perhaps even audio frequencies. Therefore 1.5K Ω resistors were placed across the transformer primaries to lower the Q still more. If you are still plagued with squeals and motorboating oscillation, you might try removing the 0.01 μ F emitter resistor bypass capacitors.

Cascode amplifiers - variable gain with constant Q

I had heard of *cascode amplifiers* but didn't have a clue why they were wonderful. I had already built two other IF strips before I settled on the circuit shown above. Reading in an old handbook, I spotted the IF amplifier shown below. The handbook said that simple transistor amplifiers were poor for IF amplifiers because, when you try to change the gain of a single transistor, the Q of the output tank circuit changes and you get squeals and noise. "Yes!! Yes!!" I cheered. "That's my problem!" The next circuit uses two (cheap) bipolar transistors in each stage in a "cascode" configuration that (hopefully) cures this difficulty.

Cascode IF Amplifier



The input transistor is wired as an ordinary grounded emitter amplifier with its high input impedance. The clever part is that the second transistor is wired to the first in a grounded base configuration. This gives the amplifier a super-high output impedance which supposedly makes it immune to changing the DC bias on the first stage. Besides, the phrase “cascode amplifiers” sounded cool and I wanted to use some. This cascode amplifier has worked well for me.

It’s interesting to see what happens when one tunes up an IF amplifier with a scope probe on the IF amplifier output. As expected, the audio signals ride on the IF frequency signal, just like amplitude modulation should. When the amplifier is tuned for optimum signal reception, the scope shows that the amplifier is producing the most modulation on the IF signal. But when the output is tuned slightly differently to produce the largest 9 MHz signal, the reception is OK, but not the best. I had not realized that these two attributes aren’t the same thing.

How to tune an IF amplifier

When you first turn on your 80 meter receiver module, there will be several modules with variable capacitors and pots that all need to be adjusted. Let’s assume that you have checked out the VFO and it is providing enough voltage sinewave to drive your particular mixer. You should also have a look at the waveform of your BFO after it has arrived at the receiver module. It should be a smooth, clean sinewave. A clean sinewave is more important than high amplitude. You may want to readjust the trimmer capacitor on the BFO oscillator for the best waveform.

To align the IF you could just twiddle pots and trimmers and hope you hit a favorable combination of settings. I’ve tried that - it doesn’t work very well. First, clip an oscilloscope probe onto the output capacitor going from the IF amplifier to the product detector. At this point your BFO comes to your rescue. Clip a test lead onto the connector where the BFO plugs into the 80 meter receiver board. This signal line also has 12 volts riding on it, so connect the other end of the test lead to a small capacitor, say 20 pF. This will filter out the DC. Use the other end

of the capacitor as a signal probe to inject a 9 MHz test signal into your IF amplifiers. Since the oscilloscope probe is at the output of the IF, start by aligning the trimmer and input pot of the last amplifier.

Next move the BFO test signal down to the input of the first amplifier and adjust the trimmer capacitor and input trim pot. Peak the 9 MHz signal at the output as before. Now remove the BFO signal test probe but leave the oscilloscope probe in place.

At this point, if there are strong 80 meter signals at the input to the mixer, you should begin to be able to hear them. Now tune each stage carefully for maximum sound level. Notice that maximum sound level is not the same setting as maximum 9 MHz carrier in the output.

Automatic Gain Control (AGC) is not a luxury

The automatic gain control is a receiver feature that holds the signal level relatively constant while tuning in signals of varying strength. Before I built one, I thought an AGC was in the same category with digital readouts and beautiful cabinets. Why do I need one? Am I too lazy to turn the IF gain up and down? It turns out that an AGC has many advantages. The main one is that it helps you achieve the gigantic signal strength dynamic range (100 decibels) that you need in a practical ham receiver. After I built an AGC, I realized it was it also greatly improved my problems with noise and oscillations.

Although I had been happy with the performance of my IF without an AGC, I could never get rid of the “noise zone” in my IF gain control. That is, I had to keep the IF gain below a certain level or it would produce a roar of receiver-generated static. Apparently, IF amplifier stages are only happy when they are processing signals of a limited range of amplitude. Noise and oscillations happen when the signals in the final IF amplifier are too large. With an automatic gain control, it was easier to tune the IF so that the IF gain control acts like a “volume control” without a noise zone. I have to admit that each of my crystal filter ladders behaves differently and I still have noise when I turn the IF gain too high. I usually just leave the IF gain set very low and let the AGC do the adjusting.

The S meter and other uses for the AGC

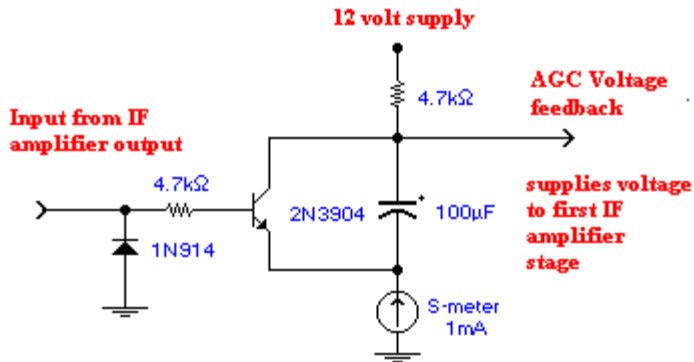
Another benefit of an AGC is that, when I switch in higher selectivity crystal filters, the AGC compensates for the filter attenuation to a large degree. Also, when you put a meter on the AGC signal level, you have made an *S meter* - in other words, a “strength meter.” The S meter taught me that what you hear in the headphones doesn’t always correlate with the signal strength in the IF strip. In other words, the S meter is reacting to big IF frequency signals, not the level of modulation on those carrier signals.

The best use for an S meter is to tune the transmitter VFO to match the receiver. In other words, if you are answering a CQ, you can tune your transmitter right in on top of the fellow you want to call. First, you need to switch in a 3- or 4-crystal filter. Then, as you slew your transmitter VFO across the frequency, the S meter will soar when you are lined up right on top of him. Without using this technique, “zero beating” the VFO is time consuming. Modern transceivers don’t have this synchronization problem because the receiver and transmitter are using the same VFO.

I originally used a digital bargraph S meter that looks very racey. Unfortunately, like

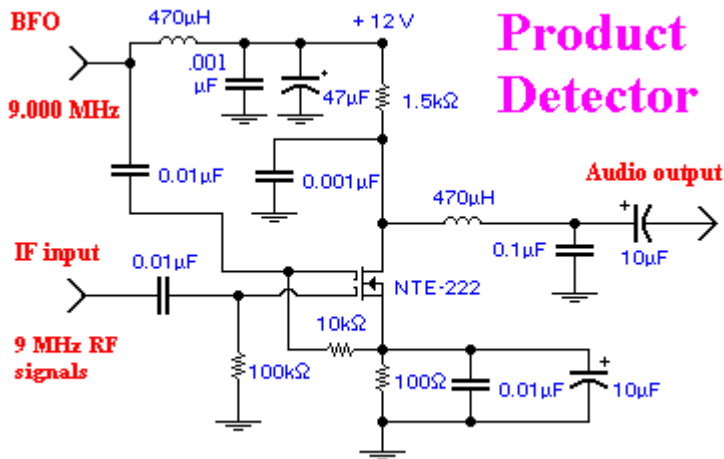
virtually everything digital, it makes a hissing radio noise when it changes level and I don't need that. I tried hard to filter the bargraph circuit, but as usual, I couldn't get rid of the hiss. I finally replaced it with an old-fashioned analog meter and the noise vanished.

Automatic Gain Control (AGC)



An AGC works by sampling the output level of the last IF amplifier stage. Signals are detected like a crystal set using a diode and averaged with a capacitor to produce a DC level proportional to the IF signal strength. This DC level is then amplified and used to bias the IF amplifiers. For example, the above circuit can deliver the positive voltage bias on IF amplifier stages made from dual gate MOSFETs. Or if the IF amplifiers are made from bipolar transistors, the same circuit can put Class A bias current into the bases of the transistors. For big signals, the AGC automatically turns off the bias and runs the transistors “Class C.” When signals become weak, the bases are biased “ON” so that the signals don't have to exceed the 0.6 volt input barrier.

The product detector

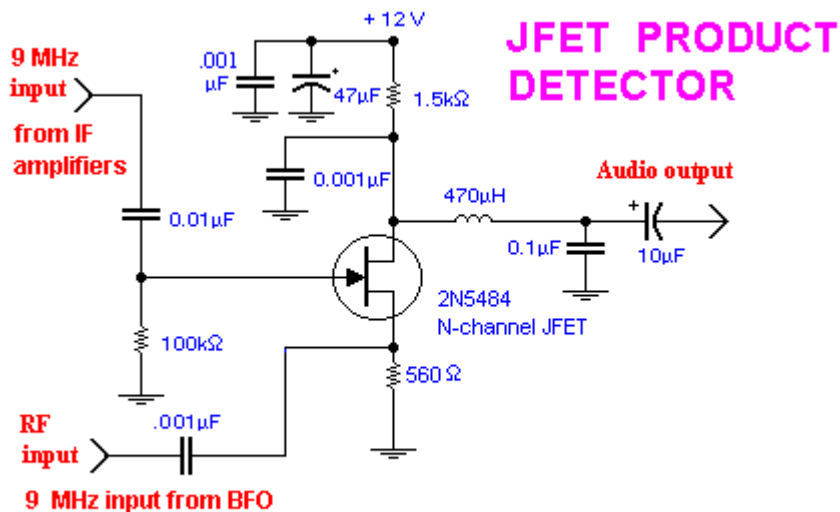


My product detector is basically the same circuit I used as my mixer. Product detectors are “direct conversion mixers” that mix an RF “beat frequency” (BFO) signal with the IF frequency to produce a difference frequency which is the audio signal. This is the same detector

type used in the simple receiver in chapter 7. A 470 microhenry RF choke keeps the RF out of the audio output. To say it another way, the choke keeps the .1 μF cap from shorting out the RF while letting audio frequencies pass on to the AF amplifier.

Notice that the 12 volt DC power supply for the BFO oscillator passes through another choke and goes out to the BFO oscillator box on the front panel. That is, the DC power input for the BFO and 9 MHz RF output from the BFO share the same wire. The 470 microhenry choke prevents the 9 MHz signal from shorting to the power supply line.

Product detectors are exactly what're needed for CW or SSB. However, when you tune in an AM broadcast station, it will have a whistling overtone on it until you tweak the BFO perfectly to get rid of the whistle. If you plan to listen routinely to short wave AM broadcast stations, you'll probably want to replace the IF crystal filter with a short circuit. I have a setting on my crystal filter rotary switch that is a simple short. Otherwise, the 3 KHz width of a single crystal will be too narrow and the sound will be "low-fidelity." Another change you might consider is to put in a switch to bypass the product detector and use an ordinary diode detector for AM signals. In other words, detect it like the crystal set in chapter 4. Any of the four dual gate MOSFET transistor types mentioned earlier will work well for a product detector. Here is a JFET version that also works OK.



With product detectors, anything works at least a little

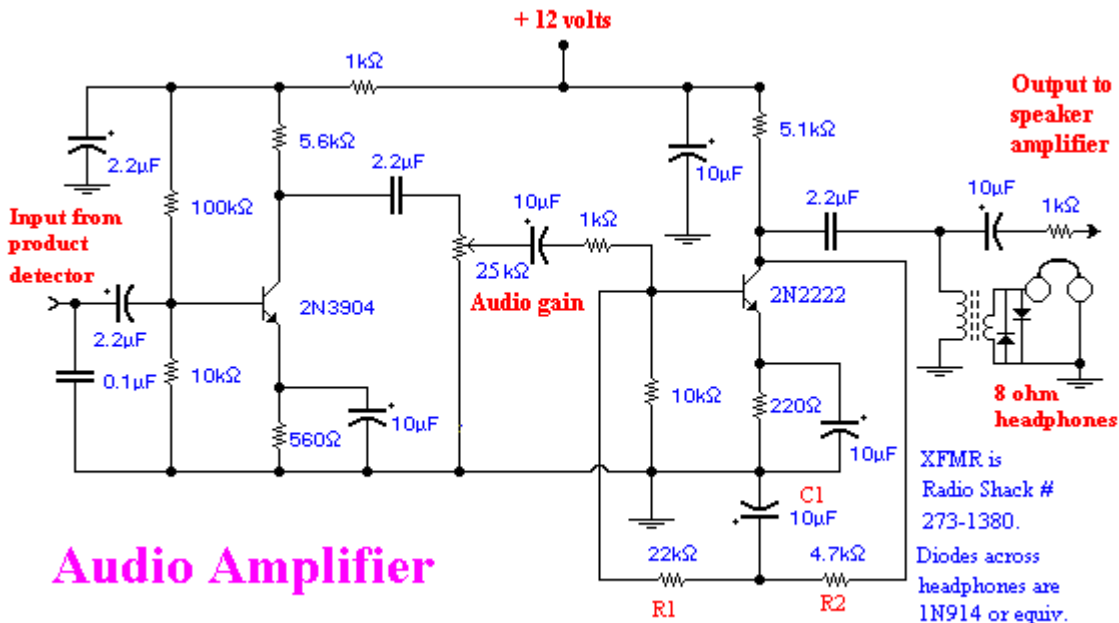
In my experience, receiver RF mixers that produce a quality IF output are extremely finicky and are often plagued with low sensitivity and oscillations up and down the band. In contrast, a product detector is amazingly uncritical. I haven't tried to make one out of wood shavings or pebbles from the street, but I wouldn't be surprised if I could still hear signals.

For example, I built a new IF strip and product detector in hopes of improving the noise problem. It worked, but I was slightly disappointed with the sensitivity. I was inspecting my dual gate MOSFET product detector when I realized that I had soldered the MOSFET in 90° out of alignment. In other words, the drain was connected to the RF input gate, the source was connected to the drain circuit, and the BFO input was connected to the source. Delighted that I

had discovered my problem, I correctly soldered in a new transistor. When built properly, it worked better - but not dramatically better.

In another experiment I disconnected the RF input so that the input to the product detector was just stray coupling from the IF strip. Signals were weak, but it still worked amazingly well! Finally, I disconnected the BFO input. I was relieved to confirm that it no longer tuned and received ham-band signals. Instead it worked like a crystal set and received the loudest signals on or near the ham band input. For example, on 17 meters, it brought in the Deutsche Welle (Radio Germany) loud and clear.

The AF amplifier



The output from the product detector is an audio signal that needs to be amplified before it goes to the earphones or speaker. Most ARRL designs use integrated circuits marked “audio amplifier.” The LM386 is a typical one-chip audio amplifier. I’ve used these and they usually work great. But of course I didn’t learn anything from the experience. So this time I built my audio amplifier out of discrete parts from an example in my 1986 handbook. It looked like two straight-forward “R-C coupled amplifiers” in series. But the design had extra filter components I didn’t understand. Every part that I didn’t understand, I left out. That was my education. The audio amplifier was dead as a doornail when I first turned it on.

An audio Automatic Gain Control (AGC)

I was particularly puzzled by the low frequency feedback link, R1, R2, and C1. I couldn’t understand what sort of “low frequency filtering” the designer was trying to accomplish. But, when the amplifier seemed completely dead, I put these mysterious components back in the circuit. Voila! The earphones came to life. It turns out that this loop biases the amplifier “on” for weak signals and biases it “off” for loud signals. It’s a sort of audio AGC circuit.

Remember that for a bipolar transistor to turn on, the input signal must be greater than 0.6

volts or no current will flow into the base. In a “Class A” amplifier a DC signal is added to the base. This increases the base voltage above 0.6 volts so that it’s always turned on. In this way a class A amplifier can amplify signals much smaller than 0.6 volts. The low frequency feedback adjusts the bias for weak and strong signals. When the signals are weak, the second transistor is turned off, so it’s collector voltage is high and unchanging. This big collector voltage is leaked into C1 to provide a forward bias for its own base, biasing it on and raising the sensitivity. Conversely, when the signals are strong, the collector has a big current flowing but a low average DC voltage from the collector to ground. This lower voltage biases the transistor more “off.”

Protecting your ears from strong signals

The audio amplifier is able to blow your ears off when you encounter a strong signal. Therefore it’s essential to add a clamp circuit to limit the voltage to the headphones to less than about a volt. I first did this with back-to-back 5 volt Zener diodes across the headphone jack. In practice, with sensitive modern 8 ohm headphones, I found that less than one volt peak is plenty of volume for me. Eventually I put in two ordinary silicon 1N914 diodes “shorted” in opposite directions across the headphones. This limits the positive and negative sound peaks to just +/- 0.6 volts and my ears haven’t been blasted since.

How Hi-Fi should it be?

The original circuit was also sprinkled with 0.1 microfarad bypass capacitors as if the designer were trying to kill all higher frequency sounds and shunt most of the audio to ground. Since I was trying to get more gain wherever I could, I left out the bypasses. The amplifier worked well without them, but the sound of the static had an obnoxious, piercing high pitch that irritated my ears. I put the bypasses in and, as I expected, the audio sounded more “bass” and became somewhat weaker. However, getting rid of that piercing, hissing static was well worth the loss of gain. Experiment!

The original design also had no emitter bypass capacitor, the 10 microfarad capacitor across the 220 ohm resistor. Not having this bypass capacitor reduces the gain because some of the audio voltage signal is wasted across the 220 ohm emitter resistor. Since I needed gain, I put in the capacitor and my gain jumped up noticeably. This bypass has no disadvantage that I could detect.

Sharp audio filters

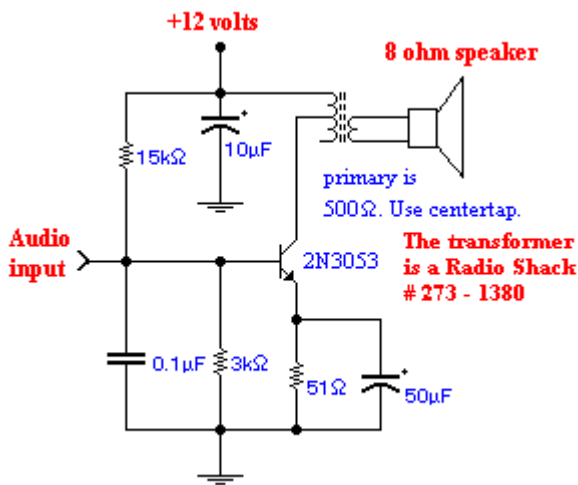
Many receivers have audio filters that limit the audio frequency of signals passed onto the headphones. This can be useful for separating CW signals that are nearly on the same frequency. If I didn’t have my multiple crystal filter selections, I would definitely want audio filters. But in practice, when QRM (interference) happens to me, the guy that is interfering usually has the same audio tone pitch as the fellow I’m trying to listen to. Obviously in this case an audio filter would not help. But if you want to add one later, it is never too late. Unlike IF crystal filters, audio filters can be added external to the receiver. There is an example of a 700 Hz audio filter in chapter 7.

Driving a speaker

If you don’t need a speaker, you don’t need a third amplifier stage. By the same token, an 8 ohm speaker plugged into the 8 ohm headphone output is much too faint. Also, 0.6 volts peak

is not nearly enough to drive a loudspeaker.

In the original handbook W7ZOI/ K5IRK AF amplifier design, the third stage was an emitter-follower for driving either a speaker or low impedance headphones. The advantage of this design was that the emitter-follower drove the speaker directly and there was no need for a high-to-low impedance transformer. The speaker was located between the emitter and ground while the collector was connected to the positive supply. It looked straightforward to me, so I tried it. Unfortunately the emitter-follower distorted the sound and “motorboated” on strong signals. That is, the sound ran in “putt-putt” bursts. I tried several modifications to solve these problems but was never able to fix it. I gave up on the emitter-follower and used another impedance step-down audio transformer to drive the low impedance speaker. I happened to have a handful of tiny speaker transformers in my transformer junk box, so for me this was an easy solution.

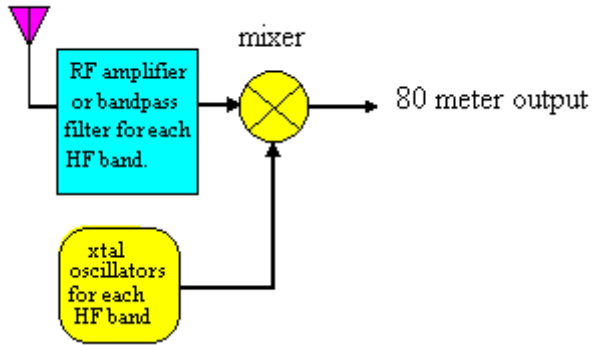


An optional extra amplifier for driving an external speaker

You’ll find that a big speaker sounds much better than a little one. A speaker small enough to fit in the receiver itself will sound “tinny.” I eventually wired my speaker output to a remote, 12 inch wide speaker. This little amplifier doesn’t really provide enough drive for such a large speaker, but it is OK.

**

Converters for the other HF bands



Block diagram of a converter for an HF ham band

I used the RF amplifiers and crystal oscillators out of the W7ZOI / K5IRK receiver. I built these modules close to what was described in the handbook and they worked right away. For my mixer module I used the same dual gate MOSFET circuit I developed for the 80 meter receiver. I had some difficulty with the low frequency preselector filters, so I used other designs as will be described.

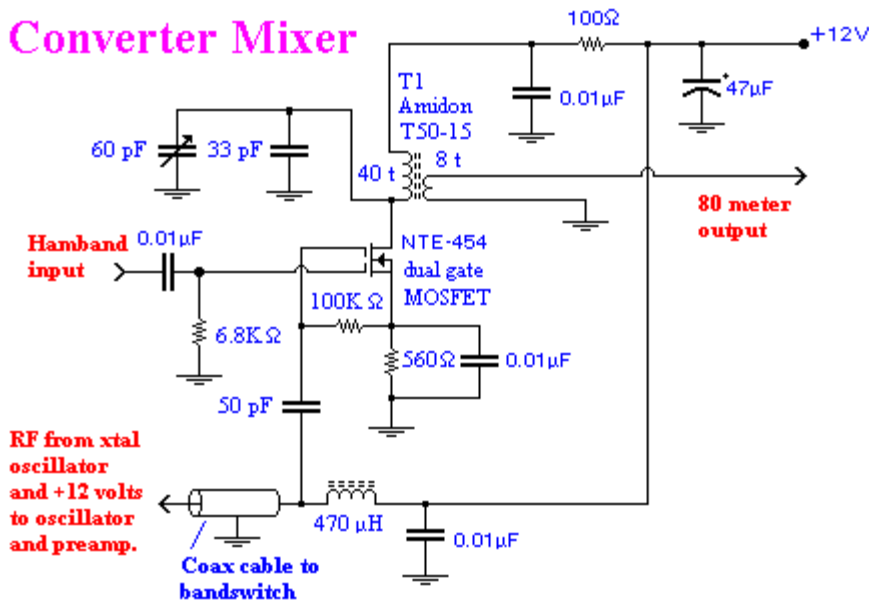
In my receiver all converters for bands other than 80 meters share the same dual gate MOSFET mixer. Band switching would be easier if each converter had its own mixer. On the other hand, those dual-gate MOSFETs are pricey transistors, so do what you like. Each band needs its own crystal-controlled oscillator and a pre-tuned bandpass filter or “preselector” to limit the input to the desired band. Bands above 30 or 40 meters need an RF amplifier. Below 20 or 30 meters, the signals and noise are stronger and an RF amplifier on the antenna input shouldn't be needed. I have had some trouble with weak signals on 30 meters, so I now regret that I didn't add an RF amplifier on 30 meters as well. On the other hand, maybe the signals are just plain weak.

Each ham band needs its own HF converter

In the old vacuum tube days, tubes were physically large and it would have been extravagant for a homebuilder to use a separate converter for each band. My old homebrew vacuum tube receiver had a single multi-band converter that had to be tuned manually for each upper band.

Transistors and powdered iron cores are tiny, so today we can easily house a complete HF converter into a few cubic inches. Moreover, each converter runs on just one low DC voltage. This simplicity means that the power can be routed to the converter using the same coaxial line that receives the output from the converter. Since each converter is optimized for just one band, it can be tuned up once and forgotten.

Converter Mixer



All my converters share the same converter mixer shown above. A rotary bandswitch brings in the filtered and amplified hamband RF signal on the upper input. The lower input takes in the RF from the local crystal oscillator for each band. In addition, the lower “input” is also an output that delivers 12 volt power to the oscillator and the preamplifier for that band.

Hamband Converter Preamplifier

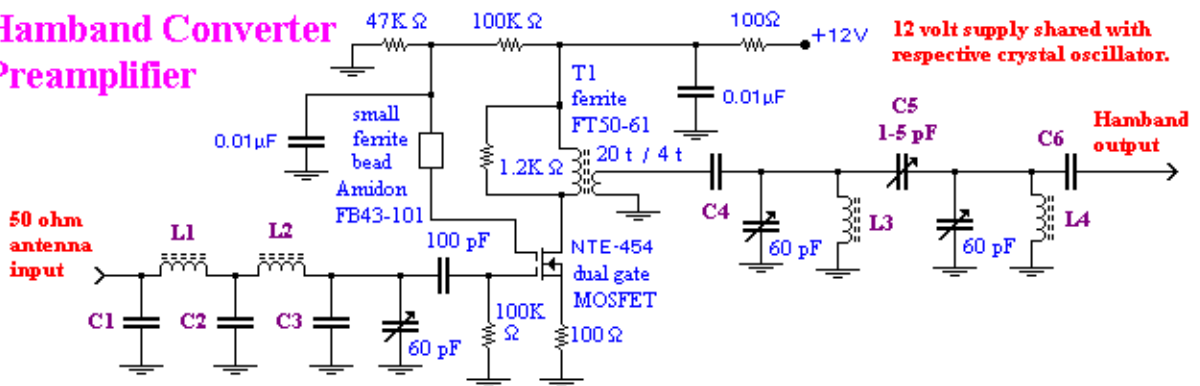


Table of values for converter preamplifier and filters

Hamband	C1	C2	C3	C4	C5	L1	L2	L3	L4	
	(pF)	(pF)	(pF)	(pF)	(pF)	(μH)	(μH)	(μH)	(μH)	
30 meters	300	680	33	33	4.1	0.68	3.36	1.16		
	T50-6 CWS (Amidon) toroids							(13t)	(29t)	(17t)
20 meters	220	500	22	27	4	0.58	2.50	1.16		
	T50-6							(12t)	(25t)	(17t)

17 meters	180	390	none	22	3.9	0.40	1.94	1.44
		T50-6				(10t)	(22t)	(19t)
15 meters	150	330	none	20	3	0.40	1.60	1.44
		T50-6				(10t)	(20t)	(19t)
12 meters	120	200	none	12	2.1	0.26	1.44	0.58
		T50-6				(8t)	(19t)	(12t)
10 meters	110	250	none	12	1.6	0.26	1.16	0.40
		T50-6				(8t)	(17t)	(10t)

Preselectors for the lower hambands

As explained earlier, hambands lower than about 30 meters shouldn't require an RF preamplifier. The only purpose of the preselector is to limit the input signals to the particular hamband. This design shown below is the one recommended by W7ZOI and K5IRK .

Hamband Preselector Filter

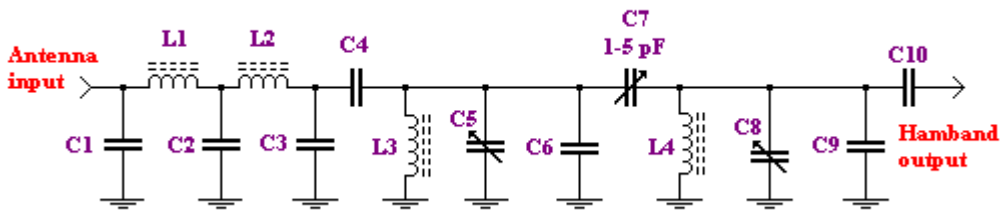
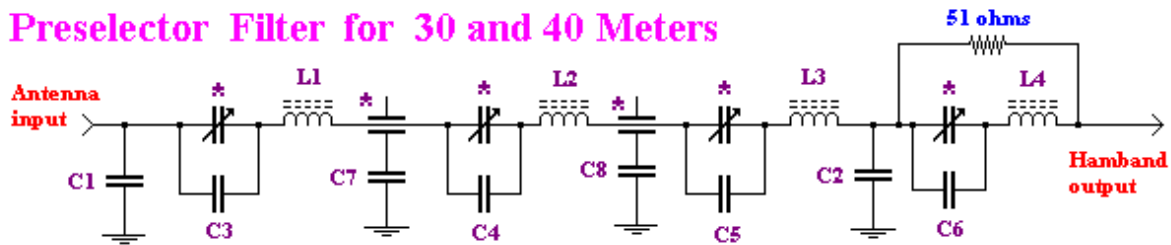


Table of values for preselector filter (without amplifier)

Hamband	C1 C3 (pF)	C2 (pF)	C4 C10 (pF)	C5 C8 (pF)	C6 C9 (pF)	C7 (pF)	L1 L2 (μH)	L3 L4 (μH)
30 meters	300	600	32	180	50	4.1	0.68 (13 turns)	1.16 (17 turns)
			CWS (Amidon)					
40 meters	430	860	42	180	50	4.6	1.16 (17 turns)	2.50 (25 turns)
			CWS (Amidon)					
160 meters	1720	3440	none	250	120	20	4.64 (29 turns)	30 (79 turns)
			CWS (Amidon)					

My 160 meter filter is similar to the original handbook design and was extrapolated from their 40 meter values. For 30 and 40 meters I used the following filter design that I adapted from an article in QEX:

Preselector Filter for 30 and 40 Meters



* All variable caps are 60 pF trimmers

* C7 and C8 are .001 μ F (1000pF) feedthrough caps augmented with 0.001 μ F disk ceramic caps.

Table of component values for alternate preselector filter

Hamband	C1, C2 (pF)	C3, C4, C5, & C6 (pF)	C7, C8 (pF)	L1, 2, 3 (μ H)	L4 (μ H)
30 meters	710	33	2000	3.5	4.6
				CWS (Amidon) T50-6 (30 turns)	(34 turns)
40 meters	1000	47	3000	5.0	6.6
				CWS (Amidon) T50-6 (35 turns)	(41 turns)

The above design is a series of 4 series LC circuits, each in its own egg carton compartment soldered onto the PC board. The signals are fed from one little chamber to the next using .001 μ F feed-through capacitors. Extra capacitors were soldered on to bring the values up to the values listed above. These filters tuned up well and I have no complaints about the receiver performance on 40 meters and above. 80 and 160 meters are more difficult, as discussed earlier and below.

160 meters is hard

160 meters presents two problems. First, standard broadcast signals are huge and just below 1.800 MHz. If you don't attenuate the broadcast band signals, you may be plagued with the loudest local AM stations appearing in your IF. You may find the AM broadcast filter described in chapter 7 useful. It worked best when placed in between the 160 meter preselector and the input to the 80 meter receiver board. It was not so helpful in series with the antenna jack outside the receiver. My 160 meter preselector was primarily a high pass filter.

The second problem with 160 meters is its proximity to 80 meters. When I first got my 160 meter converter working, I immediately heard hams and thought I was successful. It was several evenings before I discovered that some of those hams were actually on 80 meters. Whoops! When I tuned in a ham, I then switched to 80 meters to see if he was still there. If he disappeared, then I knew he was on 160 meters. Not really up to snuff. Since my core receiver is designed for 80 meters, the bandpass filtering on the 160 meter converter must be quite selective to keep out both the broadcast signals and the 80 meter signals. I'm still not satisfied with my present filter. As discussed elsewhere, 80 and 160 meters work much better when you listen to

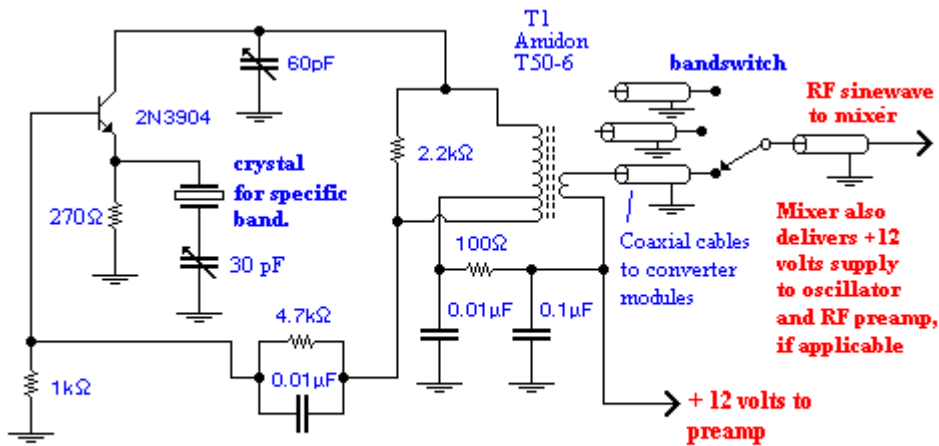
them using your transmitter "T-match" antenna tuner.

It can be hard to find an appropriate, cheap crystal for 160 meters. 5.5 MHz is available as a standard frequency and looked ideal. Unfortunately, this produces a large whistling artifact on 2.00 MHz. 5.6 MHz worked OK because the artifact is now on 2.1 MHz, completely out of the 1.8 to 2.0 MHz ham band.

Still another difficulty with 160 meters is that, if you build a multistage filter like those shown for 40 and 30 meters, the variable capacitors will be physically quite large. I didn't have room for such a large preselector, but if you started out with a big enough chassis that shouldn't be a problem. To scale the 40 meter filter to 160 meters, multiply the value of each capacitor and inductor times four. Good luck!

Crystal oscillators for the converters

These oscillators are nearly identical to the BFO oscillator described earlier. The 12 volt power for each oscillator is delivered via the cable from the bandswitch.



Converter Crystal Oscillator(s)

Data table for crystal oscillators

Hamband	Crystal freq. (MHz)	T1 primary total turns	Primary tap turns	Secondary turns
160 meters	5.600	39	8	7
40 meters	11.000	30	7	6
30 meters	13.800	26	6	5
20 meters	18.000	28	5	4
17 meters	21.900	20	4	4
15 meters	25.000	20	4	4
12 meters	28.200	17	4	4
10 meters	32.000	14	3	3

All toroids are CWS (Amidon) T50-6 powdered iron

Since I am converting to 80 meters, my receiver uses the same local oscillator frequencies I used in my CW transmitter, which has an 80 meter VFO. For most bands I use microprocessor crystals cut for frequencies 4.0 MHz above the bottom of the desired ham band. For example, I used 11 MHz for 40 meters, 18 MHz for 20 meters, 25 MHz for 15 meters, and 32 MHz for 10 meters. The WARC bands are only 100 KHz wide. This allows you to use crystals that are any convenient frequency covered by the 3.5 to 4.0 MHz frequency range of the core receiver. To make your choice, you might consider what other interesting bands are close by. For example, if your 30 meter choice allows you to hear 10.00 MHz, you can check your UTC clock setting from WWV. Ham communications are recorded in logbooks using UTC time so that everyone in the world is on the same time standard. For wide bands like 15 meters and especially 10 meters, you have less choice about crystal frequencies to use.

You could also use local oscillator frequencies below the desired band. For example, to cover 15 meters, you might use a 17.5 MHz crystal oscillator. This will convert the 15 meter band to range from 3.5 MHz to 3.95 MHz. Notice that the *direction* of VFO tuning is reversed from using local oscillator frequencies above the desired band. Whatever you do, it's good to be consistent so that direction of tuning and the calibration can be consistent. Also, if the local oscillator frequencies are round numbers, like 11.0, 18.0, 25.0, and 32.0 MHz, then decimal calibrations on the VFO will be identical. Unfortunately, to get quality crystals for the WARC bands that didn't drift, I eventually had to have custom crystals ground for me. Maybe cheap isn't so important after all.

Mechanical construction of converters

I built my converters on two-sided PC board material. Strips of PC board were soldered onto the main board to provide the walls and partitions in the egg carton construction. A folded aluminum, press-on cover keeps out most stray RF. The assembly shown below contains four converters for 20, 40, 30, and 12 meters. It looks daunting, but I built them one band at a time over several months. I only built another converter when I was ready to listen to a new band.

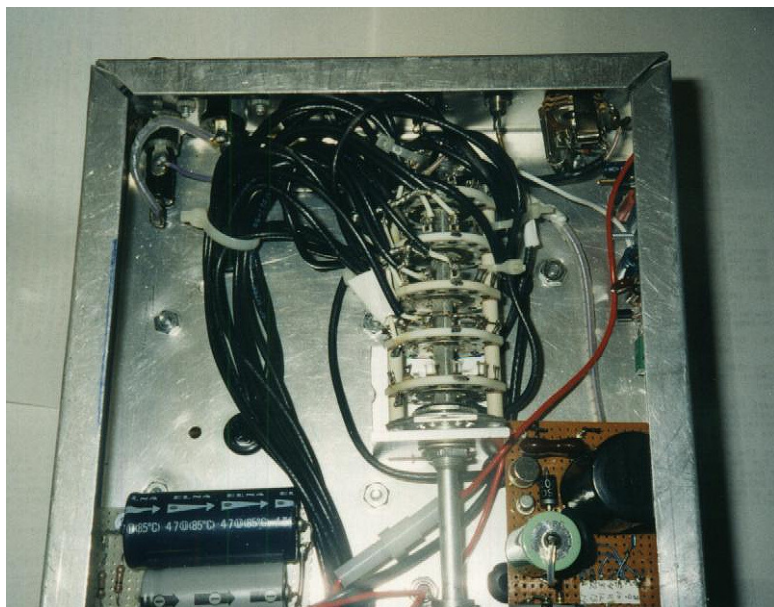


Converter modules for 20 meters, 30 meters, 40 meters, and 12 meters



This module contains converters for 160 meters and 17 meters.

Band switching



The very first module in my receiver that worked properly was the converter for 15 meters. I checked it out by using it with my old receiver tuned to 80 meters. I immediately noticed that it worked better than the old receiver tuned to 15 meters. Later, when the new 80-meter receiver began to work, I was able to listen to 15 meters by plugging the 80 meter receiver to the 15 meter converter directly with phono plug cables. Next I built converters for 10 meters and 40 meters. Whenever I switched bands, I moved my cables around like plugs on an old-fashioned telephone switchboard.

Eventually, as I built more and more converters, this process became increasingly cumbersome. Finally I gritted my teeth and spent a Saturday afternoon wiring up the bandswitch shown above. To switch from one band to another, a rotary switch selects the desired input filter/RF amplifier and local oscillator for each band. Like the BFO design described earlier, the 12-volt power for each local oscillator and RF preamplifier arrives riding on the local oscillator RF signal to the mixer. In other words, a single switching circuit carries both the local oscillator signal and the 12 volt power. Even with this reduction in complexity, the 9 band rotary switch becomes a confusing pile of RG-174 coax spaghetti. Be sure to label each plug and socket. I used a fold of white plastic tape on each cable and labeled it with a fine-point permanent marker pen.

I've had trouble buying quality RG-174. One 100 foot roll I bought was mechanically and electrically just fine. Unfortunately, the insulation had a chemical stench that was quite obnoxious and, for all I know, carcinogenic besides. The smell did not dissipate with age. I even tried hanging it on a fence post in the backyard and letting the sun and rain work on it for a few months. It still stank, so I threw it out. Another roll of RG-174 had no smell, but the inner multi-strand conductor was so fragile, that the slightest bending on a solder joint breaks the wire. To use it, I had to strain relief each connection with a drop of epoxy. In summary, if possible, sniff your coax and look at it closely before buying it.

Receiver muting

While transmitting it is extremely distracting to hear your own signal blasting your ears in

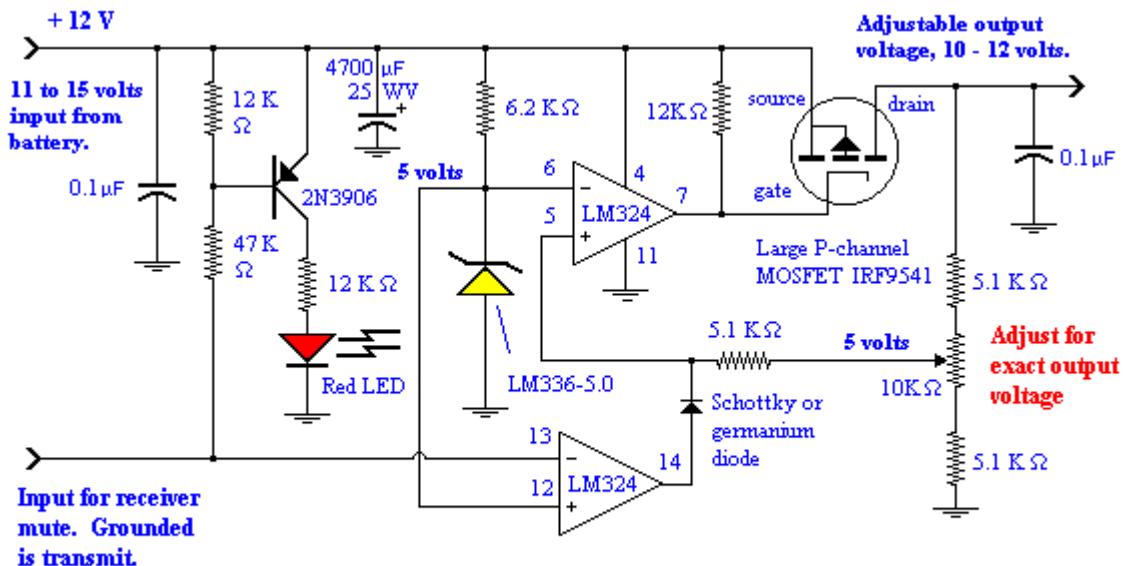
the receiver. Even with the antenna switched over to the transmitter, the receiver will still be overwhelmed by your own loud signal. A CW signal will usually sound distorted and will interfere with your sending. I have found it best to turn the receiver off altogether while transmitting. That is why I built a Morse code sounder into my electronic bug so I would have a clear tone to listen to while I am sending.

Turning the receiver off by hand is too slow, so you will need to build a muting circuit. I trigger mine with the same transmit/ receive signal line used to turn on the transmitter. I have found that the simplest solution is turning off some or all of the power supply lines. I first tried just turning down the audio and IF gain pots by pulling the pot wipers down to ground using the collectors of transistors. This was inadequate, so I have since gone to keying the receiver power supply on and off, just as I did in the transmitter. I leave the receiver VFO supply on constantly to prevent any drifting due to having the VFO circuitry cool off and warm up repeatedly.

Receiver power supplies

The VFO power supply used in the receiver is the same one described in chapter 10. You could also use the line powered regulated supply described in chapter 8. I run my station on a 12 volt battery, so I just needed the low drop-out regulator shown below. The power supply requirements for the receiver are similar to the low power stages of the transmitter. I used the same supply that I developed for use with my QRP modules in chapter 8. This supply is over-designed for a receiver and can supply at least a few amperes.

The mute capability was implemented using an unused op-amp as a comparator. The mute input lead comes from the transmitter. Or in my case, it comes from the transmit/ receive switch on my homebuilt bug. During transmit the mute line is pulled low to ground. During receive, the 12 K and 47 K resistors pull the mute line up to 12 volts.



Low Dropout 12 Volt Power Supply with Mute Capability

Referring to the lower op-amp, when the positive input wired to the 5 volt reference is

higher than the mute line, the op-amp output, pin 14, rises up to 12 volts. This causes current to flow down through the diode to the positive input of the upper op-amp, pin 5. When the positive input (pin 5) is higher than the 5 volt reference on pin 6, the upper op-amp output (pin 7) rises to 12 volts, thereby turning the power MOSFET off and shutting off the current supply to the receiver.

Red mute indicator light

While the receiver is being muted, the base of the 2N3906 transistor is pulled down thereby turning on the transistor and lighting the red LED. My LED was an extra bright type that only needed 1 milliampere to be adequately visible. You may need a resistor smaller than 12 K for good brightness.

Use linear regulators, not switching regulators

I tried to use switching supplies for this receiver, but reception was always impaired by switching supply noise. Switchers cause buzzing and hissing on every ham band. RF filtering was a great improvement, but it was never good enough. Building a low-noise receiver is hard enough without fighting a built-in noise generator. For me, one of the great mysteries of modern receivers is how they incorporate all those digital displays and processors without producing a hash of noise that would make the receivers insensitive to weak signals on the upper bands. I can even hear my Hewlett Packard digital counter, which is located 2 feet from the receiver and operates on a different power source.

Tuning signals with your new receiver

I found that it was easy to tune in CW stations. First, you should have calibrate your beat frequency oscillator so that you can select 500 to 700 Hz above and below the 9.000 MHz IF. For 40 meters and below, set the BFO to 700 Hz *above* 9.000 MHz. For 30 meters and above set the BFO for 700 Hz *below* 9.000 MHz. This will insure that you are listening using the lower and upper sidebands, respectively. If you have built a multi-stage crystal filter, this function will be obvious as you tune up and down the band. With just one crystal filter or no filter you will find you can adjust the IF gain as high as you like. But as more crystals are switched in, the automatic gain control will raise the gain automatically to compensate for the attenuation of the crystals. The S-meter reading will be meaningful with only one or zero crystals in line. If you try to obtain more gain by increasing the IF gain pot setting, the IF strip may oscillate. So for multiple crystals, just turn the IF gain way down.

Tuning in single sideband is also easy, but only if you know the tricks. When tuning in any sideband signal, set your BFO to 9.000 MHz. Think of it as replacing the carrier that was removed from the original amplitude modulated signal. For upper sideband modulation, the modulation will enter your IF in the range of 9.000 to about 9.003 MHz. By beating with your BFO signal, the difference will generate the original audio signal, roughly 200 Hz to 3 KHz.

The main trick to easy SSB tuning is to use the absolute minimum RF and IF gain that will allow you to hear the voice. To make the voice loud enough, you will probably have to crank up the AF gain quite high to compensate. Since my receiver doesn't have an external RF gain, I use the 80 meter preselector capacitor as an attenuator to reduce the RF input signal to a minimum. A single crystal filter helps minimize noise and interference from other stations. Using two or more crystals will chop off the upper audio frequencies and make the voice

unintelligible. If you set up the receiver as just described, it will be easy to make the voices intelligible as you tune up the band. However, to make the tuning perfect so that the voice is undistorted and sounds like your friend's normal voice, you will have to tune precisely. You may find it helpful to tune the last few Hz using the BFO control knob rather than the local oscillator tuning knob.

In summary,

If you've already built homebrew transmitters, you'll find that building a receiver is easier than building your multiband, VFO-controlled CW transmitter. The hardest parts are the 80-meter pre-selector, the 80 meter mixer, and the IF amplifier. After that, it's pretty straightforward. Receivers don't need RF power gain stages, so the currents are low and the circuit board layout is forgiving.

In closing, remember that when you build a transmitter, you will hear no end of complaints about your signal until you get *ALL* the bugs out of it. But when you're on the air with your homebrew receiver, your contacts will never complain about your receiver. Or at least you will never hear them complain.

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, REV 12

Chapter 14

VACUUM TUBE RECEIVERS AND TRANSMITTERS



My old-tech QRP project began the day I acquired an ancient type 216A vacuum tube. It's a wondrous Jules Verne-looking device with a round glass ball mounted on an elaborate nickel-plated brass base. It's the simplest three-element "triode" with all its guts in plain view. It has the filament in the center with a wire "grid" and a plate on each side of the filament. The base is imprinted with several patent numbers dating from 1907 to 1918. I decided I would use it to build a one-tube, crystal-controlled transmitter, just like the old days. As you'll see, there were problems with this dream.

The transmitter described in this chapter uses the most ancient vacuum tube technology I could, while still sounding pretty good on the air. Some of the parts I used were rare and unobtainable as new parts. However, if you can't find similar components at local swapfests, you can always buy them on-line. It's also possible to substitute more modern vacuum tubes that are still commercially available.

How old can you go?

I got a huge kick out of building the spark gap transmitter and crystal set receiver. My only regret was that I couldn't use them on the air. I wondered how old fashioned a rig can still be used today. About 1920 hams began to replace their spark gap transmitters with single tube LC tuned oscillators. In principle, these VFOs weren't that different than the VFOs described in chapter 10. Unfortunately the old VFOs were crude and drifted several kilohertz per minute. Obviously one of those state-of-the-art 1925 transmitters was not going to be acceptable today.

Spark gap transmitters were totally banned in 1927 because they splattered all over the band and wasted spectrum. After the international reorganization of the ham bands in 1929, the hams were confined to what were then considered "narrow" portions of the spectrum. Crystal control for hams was first introduced in QST magazine in 1927. The May 2001 QST had an article on ham transmitters used in the 1920s. The article warned that these early machines

2. Chapter 14, Harris

shouldn't be used on the air. That's no fun! In my local ham newsletter Yardley Beers, WØJF, described a transmitter he built in 1930 that sounded promising. It was a 10-watt, one tube oscillator with a type 210 triode. I figured that a triode oscillator with crystal control would be about as old-tech as I can go.

Why bother with tubes?

A homebuilder who has never built with vacuum tubes has missed an adventure. I told my electrical engineer nephew that I was building a vacuum tube transmitter. There was silence on the phone. "Why?!" he finally blurted. I was startled. To us geezers, "why" is obvious.

Let's use trains as an analogy: I once had the privilege of riding on the French TGV (Le Tran Gran Vitesse) that translates to something like, "The Really Fast Train." At 240 kilometers per hour the TGV is indeed speedy. When it passes another train on the adjacent track, the whooshing roar lasts less than two seconds. When TGV crosses a trestle, the ground drops away under you so quickly you feel as though you were taking off in a rocket. Modern ham equipment is like the TGV. Its attractions are sophistication and high performance.

Every summer narrow gauge steam trains puff and chug up and down Colorado canyons. These old-time anachronisms are packed with tourists. Steam trains aren't popular for their performance, but rather for their sound and appearance. Vacuum tube transmitters, especially ones from the 1930s or 40s, don't have impressive performance, but their visuals are great! Transmitters back then had great big coils, "bread slicer" variable capacitors, and wondrous glowing vacuum tubes. Their plate current and grid drive meters look as though they belong in a power plant.

Vacuum tubes have the same function as transistors. They are constructed like filament light bulbs. Inside an evacuated chamber, usually glass, they have incandescent orange filaments and intricate metal screens and plates. The lightbulb-like filament is heated to incandescence to drive electrons off its surface. The metal mesh, called the control grid, regulates the relatively large current passing through the vacuum between the filament (the cathode) and the metal plate. The grid is analogous to the base of a bipolar transistor or the gate of a field effect transistor.

Vacuum tubes were the first practical small-signal amplifying device. They dominated electronics for over 50 years. Most sophisticated analog circuits and even computer circuits were first implemented with tubes. When transistors became available, it was relatively easy for vacuum tube engineers to redesign the old circuits using transistors.



If tubes are so easy, why did my first two transmitters fail?

I've always been curious why my first two home-built transmitters did not succeed 53 years ago. My first transmitter was a 7 watt 80 & 40 meter rig built with plans in the 1957 ARRL handbook. It worked well around town, but hardly anyone heard me outside of town. Now that I've built modern QRPs and receivers, I realize that the average ham receiver back then was so poor that hardly anyone could hear a QRP. My second homebuilt transmitter was supposed to put out 30 watts but never worked properly. I lacked the test equipment and knowledge to find out why. Eventually I bought a commercial transmitter kit, just like the kits all the other novices were using.

In the transmitter described below, the power supply turned out to be my biggest obstacle. I'm convinced that was also my biggest problem back in 1957. Yes, my power supply was able to supply the required power, but now as then, my power supply was too weak or "soft" to supply the needed power without a significant voltage drop. Whenever the transmitter drew current from the supply, the voltage crashed causing the transmitter to run in bursts called "motor-boating." Since I didn't have a high frequency oscilloscope back then, I couldn't see what was happening.

The power supply

Vacuum tubes work by conducting electrons across a vacuum. Personally, I'm amazed that's even possible. But once you get past that, it shouldn't be a surprise that a vacuum tube has a relatively high resistance. So if you want to pass big currents, you need big voltages to push the current across the void.

$$\text{Power} = \text{Voltage} \times \text{Current}$$

To get big power you need either big voltage or big current, or both. The transmitter

4. Chapter 14, Harris

described here needs at least 250 volts to deliver 5 watts output. And because of its low energy conversion inefficiency, plan on supplying 15 watts DC power instead of just 5 watts. For example,

$$15 \text{ watts} = 250 \text{ volts} \times 60 \text{ milliamperes}$$

High voltage power supply safety

The chief disadvantage of high voltage is the danger of burns and shock. Vacuum tubes almost always operate at high voltages, typically over 100 volts. For high power ham amplifiers the plate voltage can be 1000 volts or even 3000 volts DC. The bad news is that this can cause a severe jolt and burn when your finger touches the **DIRECT CURRENT** supply. I watched a friend adjusting the resonant cavity of UHF diathermy machine with 3000 volts DC on the plate. He finished, smiled and looked up at me as if to say, “There! All done!” As he looked up, he stopped paying attention to the high voltage terminal. It blew a centimeter wide crater in his knuckle exposing the tendon. The good news about high voltage DC is that, although it may knock you across the room, badly burn you, and scare the heck out of you, high DC voltage rarely kills anyone. It can kill, but usually doesn’t.

Shock

Technically, the word *shock* means electrocution, so DC voltage usually doesn’t “shock” hams. On the other hand, a 1000 volt DC power supply has 1000 volts of **ALTERNATING CURRENT** on its rectifier. If you get your hands across that, death is quite possible, even likely. Any power supply that plugs into the AC mains will have at least 120 volts AC on it and that’s plenty to kill you. All power supplies are potential killers if you touch high AC voltage. In contrast, when 60 Hz AC voltage is below about 20 volts, it approaches being “safe.” However, if you wet both hands, grip the two leads firmly so that 10 milliamperes of AC current passes through your chest, even 12 volts AC can kill you. In summary, it pays to be extremely cautious with low frequency (50 – 60 Hz) AC voltage. Whenever possible, unplug the power supply before you work on your line powered equipment.

RF burns

Another safety issue is RF burns. High frequency, high voltage, radio frequency AC voltage doesn’t shock you because your nerves and muscles can’t respond fast enough to be polarized by the changing voltage. However, RF voltage can burn large holes in your hand. If you touch the plate circuit of your vacuum tube transmitter, you can expect at least a small hole in your skin. And, the higher the RF voltage you are using, the bigger the hole it will make. In summary, any voltage, AC, DC or RF, higher than roughly 50 volts deserves great respect. Your first lesson on working with vacuum tubes should be *don’t touch anything until the power is turned off*. And, after the power is turned off, *be wary of large capacitors that may be charged to a high DC voltage*.

**

The Vacuum Tube QRP Transmitter

Once I began planning my tube QRP, reality began to sink in.

5. Chapter 14, Harris

* First, I only have one antique 1918 tube. I'd hate to break it.

* Second, this tube has no cathode. It just has a simple filament. This means that the electrons come directly off the filament. A simple tungsten or carbon filament gives off electrons reluctantly, so these early tubes had low operating currents. That meant that my QRP transmitter would be extremely weak, perhaps a few milliwatts. There was a good reason that many hams used spark-gap transmitters until 1927. Power tubes weren't available until the 'twenties. It was hard to generate any significant power output until tubes were developed that could handle hundreds of milliamperes of current, instead of just a few milliamperes. Also, I'll bet power tubes cost a fortune back then.

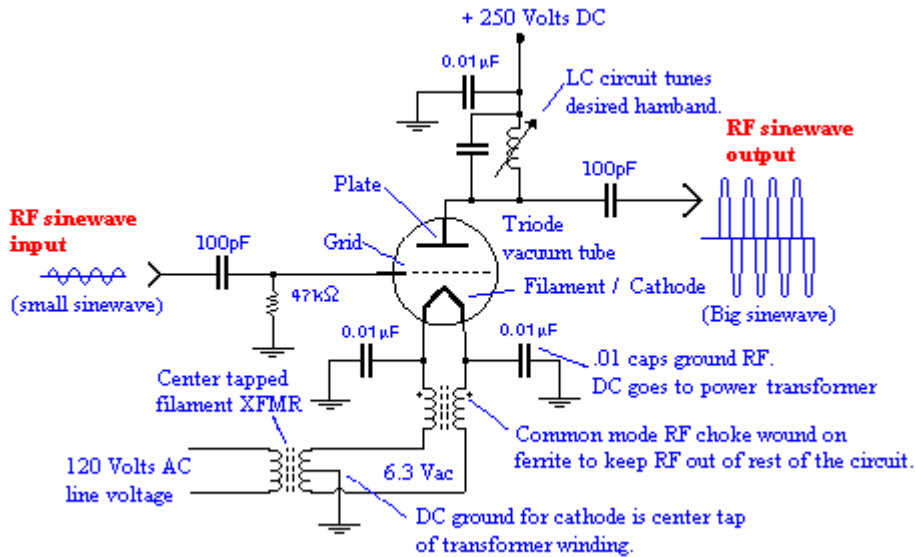
* According to my 1979 ARRL handbook, "It is almost impossible to build a one tube CW transmitter that doesn't chirp to some degree." I guess chirp was normal in the old days. But today your signal will be roundly criticized if you dare to chirp at the modern hams who rule the airwaves. So much for a one-tube transmitter.

* A related problem is that, the better a keyed vacuum tube oscillator sounds, the less output power you will get from it. In other words, a keyed oscillator that sounds good puts out little or no useful RF power. I began to understand that my 100 milliwatt transmitter might easily end up as a 20 milliwatt transmitter.

In my opinion, 1930s technology is about as early as you can go and not embarrass yourself. I eventually built my transmitter using tubes that I had salvaged from old radios built during the 1930s. I like tubes from that era because they are big and spectacular. More modern tubes from the 40s and 50s are only large if they handle high power. Moreover, their glowing filaments are largely hidden by their cathode sleeves. Some of them have metal envelopes and don't glow at all.

In the design described below I used a simple triode as a final amplifier. I believe the filament has been treated with thorium so that it emits electrons readily. Triodes have relatively low gain and were not very linear in their amplification characteristics. The tubes I used were type 68 and type 71. If you can't scrape up some old tubes, the more modern 6L6 is still available commercially. To eliminate the chirp, I used two more tubes to drive the final. So my single tube QRP ended up a 3-tube transmitter. And all I get out of it is 5 watts! The oscillator runs at very low power and can be keyed with little chirp. The oscillator is followed by a "buffer" amplifier, which amplifies the tiny oscillator signal up to the level where it can drive the final. My oscillator and buffer are type 41 tubes, which are small power pentodes. They look ancient, but were made in the 1930s and are equivalent to the more modern 6V6 or 6K6 tubes. The 6V6 and 6K6 were manufactured during the 1940s and 1950s and can still be bought from RF Parts Company and other companies.

Vacuum tube amplifiers



A vacuum tube RF amplifier

The simplest tube is a three-element device. The *control grid* is analogous to the gate or base of a transistor. The *plate* is analogous to the drain or collector and the glowing filament, which acts as the *cathode*, is comparable to the source or emitter. Tubes are principally voltage-controlled devices, although there is a small current that flows into the control grid. The control grid voltage modulates the much larger current that flows from the filament to the plate. So as you would expect, the input signal is placed on the grid and the output signal is the current passing through a load resistor or load inductor, as shown above.

A filament - three circuits in one

Referring to the diagram above, what is all that stuff wired to the filament? This is the kind of complexity that drives beginners in electronics into other lines of work. Actually, once you unravel the parts, it isn't so bad. The difficulty with using an ancient filament tube is that the filament has three jobs to do simultaneously.

Signal cathode function First, the filament serves as a *cathode* to launch our radio frequency current from the chassis ground toward the plate. That is, it serves the same role as an emitter in a bipolar transistor or a source in an FET. RF conducts easily through 0.01 microfarad capacitors, so they conduct RF up from ground into the filament. The common mode RF choke keeps the RF out of the filament transformer. (These chokes were described in chapter 12.)

Heater function Second, the filament must be heated in order to boil the electrons off the filament and into the vacuum. The filament heat function is provided by a 6.3 volt, high current AC signal. So it's necessary to pass a big, low voltage AC current through the filament to warm it up, just like a toaster element. On the other hand, we don't want 60 Hz AC impressed on the signal we are trying to amplify. If we didn't take special steps to prevent it, the guys we are talking to would hear a big 60 Hz hum on our signal.

To keep the AC out of the radio frequency signal, the single loop of filament is powered by AC voltage that is referenced to ground in the center of the filament winding. That is, one

7. Chapter 14, Harris

side of the filament is connected to 3.15 volts AC, while the other half of the filament is connected to 3.15 volts AC with the opposite polarity. In the center of the filament, the voltage gradient passes through zero volts. The 60 Hz AC filament current biases the current flowing across the vacuum. However, because of the grounded tap on the transformer winding, half of the filament is shedding extra electrons, while the other half is shedding fewer electrons. As a result, the 60 Hz signal is cancelled and the RF signal the amplifier produces is not modulated with 60 Hz. Whew!

All this filament complexity is a nuisance, so newer tubes like the 6V6 and 6L6 have a metal tube surrounding the filament that is heated by the filament. When hot, it is the cathode that gives off the electrons. In that way, the heater function is electrically separated from the signals on the cathode.

DC bias function Third, every tube or transistor circuit has an optimum direct current operating point for the kind of amplifier you are trying to build. For example, if you want a high fidelity audio signal amplified with as little distortion as possible, the bias of a tube is turned half way *ON* at rest. That is, in this way it resembles an N-Channel JFET and is biased to operate class A. In class A, as the audio signal goes positive and negative from the resting point, the amplification will be equal for rising and falling voltage levels. If the operating point were wrong, the upper or lower half of the signal might be amplified more than the other, or perhaps cut off altogether. Any distortion would ruin the sound of the music. Unlike bipolar transistors, the tube is already half-turned-on with no forward bias resistor going to the grid from the plate voltage.

In the case of a CW transmitter RF amplifier, the bias for a tube is simple: We just ground the DC on the cathode to provide the correct bias. In the case of a vacuum tube CW transmitter, we use this DC ground connection to turn the amplifier on and off. To send Morse code the telegraph key is used as a switch between ground and the center tap of the filament winding on the transformer.

The RF sinewave oscillator

Modern radio began with the vacuum tube sinewave oscillator. An RF oscillator consists of an RF amplifier that amplifies its own output. That is, a bit of feedback from the output is returned to the input causing the tube to produce a large sinewave output signal. Tube RF oscillators operate on the same principles as the transistor RF oscillators discussed in chapter 6 and chapter 10. If building an adequate transistorized VFO is difficult, you really don't want to use a tube VFO on the air today. I tried it and the criticism wasn't pleasant. Consequently, my old tech QRP uses crystal control.

Quartz crystals

While building my transmitter, I discovered that the old crystals in my junk box no longer oscillated. When new, crystals are so reliable that it never occurred to me that old crystals might not work. My crystals ranged in age from 20 to 50 years and hadn't been used in decades. The ones that still oscillated did so only under extreme stimulation. Fortunately for me, they were large, old-style FT-243 crystal holders that can be unscrewed and disassembled. I took them apart and cleaned the parts with alcohol. Two of them began to oscillate again, but the others remained inert. I suspect the rubber gasket gives off a vapor that condenses on the crystal and literally gums up the vibrations. In summary, if you try to use old crystals and the oscillator

doesn't work, or if it only delivers a tiny signal, you need to clean the crystal or buy a new one.

Triode and pentode oscillators

To be "old-tech," I started with triodes without cathodes. The oldest power tubes I had in that category were the type 68 and 71 tubes. I quickly re-learned that the output signal from a triode varies with the power supply voltage. Those other grids in tetrode and pentode tubes make the amplified signal relatively independent of the power supply voltage. To say it another way, a pentode tube has voltage/current characteristics that resemble NPN or N-channel transistors. This was particularly important for the crystal oscillator. The supply voltage sags slightly when the key is depressed and causes chirp. When using a triode, I could never quite eliminate the chirp, so I ended up using a type 41 pentode. Pentodes work fine.

Circuit "boards"

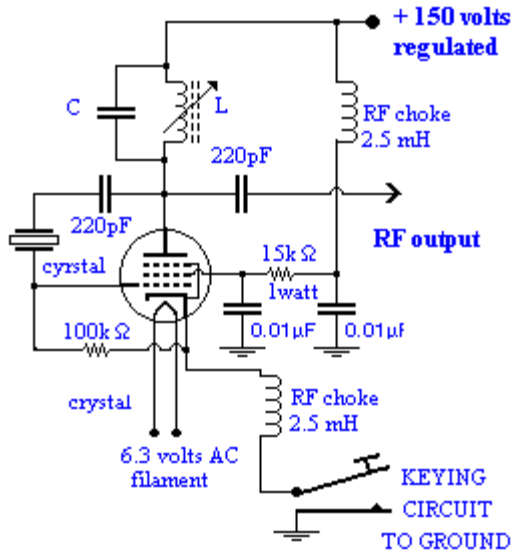
I used a genuine old-tech circuit board made from a pine tree. A wooden board lets me move parts around inside the metal chassis and swap parts with little effort.



Since 6-pin and short 4-pin tube sockets aren't available anymore, I had to make my own tube sockets by drilling holes into a fiberglass perf-board. To grip the tube pins, I wrapped solid copper wire around them. This worked much better than I expected. I can even unplug and replace tubes.

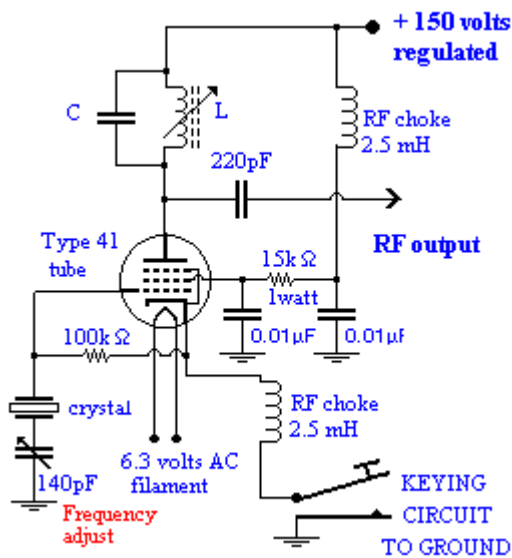
The best oscillator circuit

There are several different vacuum tube oscillator circuits. The one below is the easiest to understand and produces the biggest output signal. The crystal, which is usually wired in series with a capacitor, is connected between the plate (the output) and the grid input. This puts big voltage on the crystal and produces an extremely strong oscillation. I was able to get 10 watts out of this oscillator with a 300 volt supply. That would be wonderful, but this oscillator is difficult to key on and off for Morse code. Mine started up so slowly it was only able to generate dashes. The oscillator simply would not start in time to send "dots." It sounded more like a sick bird than Morse code. Its chirp was beyond "bad."



A powerful but unstable tube oscillator

A better tube oscillator for CW



The circuit on the left is the oscillator used most often in old vacuum tube transmitters. The first question you probably have is, “Where’s the feedback?” There is no visible connection between the input grid and the output plate. However, there is feedback between the cathode and the grid by means of the 100K resistor. There is also feedback by stray (accidental) capacitance between the grid and plate. Remember that a vacuum tube is already turned halfway “on,” even when the grid voltage is zero. If there is any random change in the plate voltage (and/or cathode voltage), a tiny voltage will be coupled to

the grid. When this change in voltage appears across the crystal, the crystal will respond, thereby reinforcing an oscillation at the crystal resonant frequency. The advantage of this oscillator is that it keys well and makes good Morse code. The bad news is that the output signal is small. Mine only put out 6 volt peak sine waves. This compared with 30 volt sinewaves when I used plate-to-grid feedback. As seen in the diagram, I eventually settled on using regulated 150 volts plate voltage.

Notice that there is a 1-watt power rating for the 15K Ω resistor. Because of the high voltages, resistors in tube circuits often dissipate at least ½ watt. Wherever the power rating isn't mentioned, assume it is ½ watt. In modern ham transistor circuits it is rare that a resistor needs

to be more than $\frac{1}{4}$ watt and it's easy to forget that power dissipation is even a consideration.

Old time voltage regulation

My tube oscillator was powered by a simple, line-powered transformer high voltage supply. When the oscillator was in “standby,” the plate voltage on the filter capacitor rose to a level proportional to the height of the power line sinewaves. Then, when I pushed down on the telegraph key, the voltage crashed to a lower steady state. This caused a noticeable “chirp” in the tone.

To fix this I used a 150 volt regulator tube. These tubes are the old-time equivalent of a Zener diode. Regulator tubes are simply glass vials containing low pressure inert gas. They have two electrodes. A central wire “cold cathode” runs down the center and a cylindrical plate collects the electrons from the cathode. When voltage is applied across the two electrodes no conduction occurs until the voltage reaches a threshold voltage where the inert gas ionizes into a glowing plasma. As the current through the gas increases, more and more gas is ionized and the voltage across the tube remains approximately constant. By designing tubes of different dimensions and using different mixtures of gases, the tubes regulate at different voltages. To regulate my oscillator supply I used a 0D3 tube that regulates at 150 volts. This trims the ripple off my supply voltage and greatly improves the sound of the CW. The 0D3 regulator glows with a lovely violet color.

The travails of tubes

After building my own rig, I now suspect that “normal” signal quality was really poor back in the bad old days. Yes, I was able to build a one-tube, crystal-controlled oscillator that keyed well and wouldn't be criticized for key clicks, chirps, drift, sag, or any of the other vacuum tube diseases. Unfortunately, it only put out 300 milliwatts. As the ARRL handbook said, it's almost impossible to build a one-tube transmitter than doesn't chirp. I think they're right. I needed at least a two-stage transmitter.

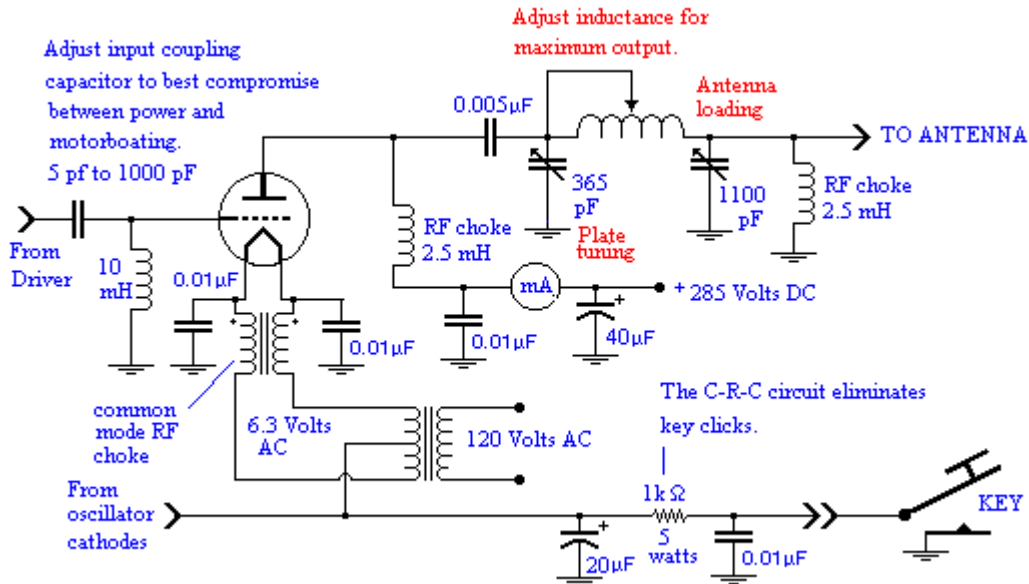
The final amplifier

I still wanted to use the type 68 triode as my final. 68s have a simple round shape like tubes from the 1920s and they have a big, open filament that looks like an orange, glowing, bread toaster element. You can almost imagine dropping little Pop Tarts down in there for breakfast. The type 71 worked as well as a 68, but the glass has the newer, double-curved shape. Unlike more modern tubes, all three elements of these triodes are plainly visible. In order to operate a triode filament as a “cathode,” the filament transformer winding must be insulated from ground and the DC taken off through a centertap. Since both sides of the filament are DC inputs for the cathode function, the cathode choke should be a common mode design.

I made the common mode choke from an FT50-61 modern ferrite toroid core. Oh, well, close enough. They had pretty good powdered iron cores back then. I wound two 12 turn windings around the core as if I were making a bifilar transformer as described in chapter 6. Instead of connecting the windings together as described earlier, this time I kept them electrically separate and wired them as shown below. The windings at one end of the pair were wired to the filament, the windings at the other end were connected to the filament transformer as shown below. The dots on the transformer mean that if positive voltage appears at the end of the winding with a dot, then positive polarity will appear on other winding at the location of the

second dot.

This is the reverse of the way the common mode was wired in chapter 12. I just looked at my linear amplifier and compared the choke wiring with the choke winding in the tube final. The dot marks below are correct as drawn, or at least, both of these units work well when built that way. Feel free to reverse the windings and see what happens!



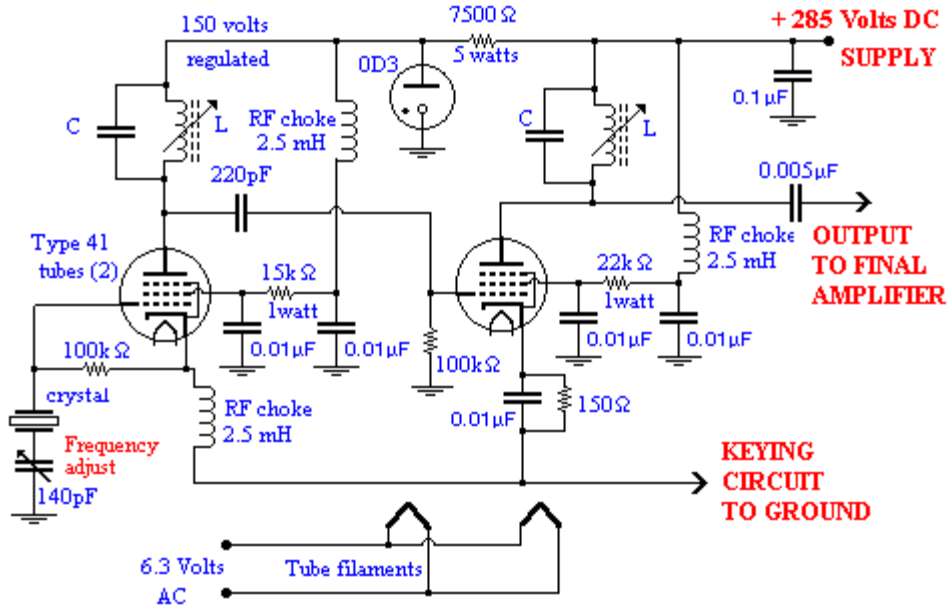
My triode final is shown above. Rather than amplify the input signal, the triode preferred to oscillate all by itself. When the final wasn't self-oscillating, the drive from my puny driver oscillator was insufficient to produce any useful power. I wondered how typical novice transmitter kits 40 years ago managed with only two tubes. I concluded, "It must be those high gain pentode finals!" I threw together a 6L6 final and tried it out. No change. The 6L6 had the same gain as my ancient triodes. If this was going to work, I needed more grid drive. I finally concluded that those old Heathkits, Knight kits, and Viking Adventurers were just darn well engineered. They achieved terrific performance with few parts.

Key clicks

Notice the C-R-C filter in the keying circuit. That's what I had to add to get rid of the key clicks. Key clicks are sharp, unpleasant clicking sounds on the Morse code caused by the dots and dashes turning on and off too rapidly. Although my transistorized CW transmitters seem to have rise and fall times just as abrupt, my transistorized rigs have had practically no problem with clicks. I don't understand this, but the C-R-C filter in front of the key causes the tubes to key on and off gently and the tube transmitter no longer clicks.

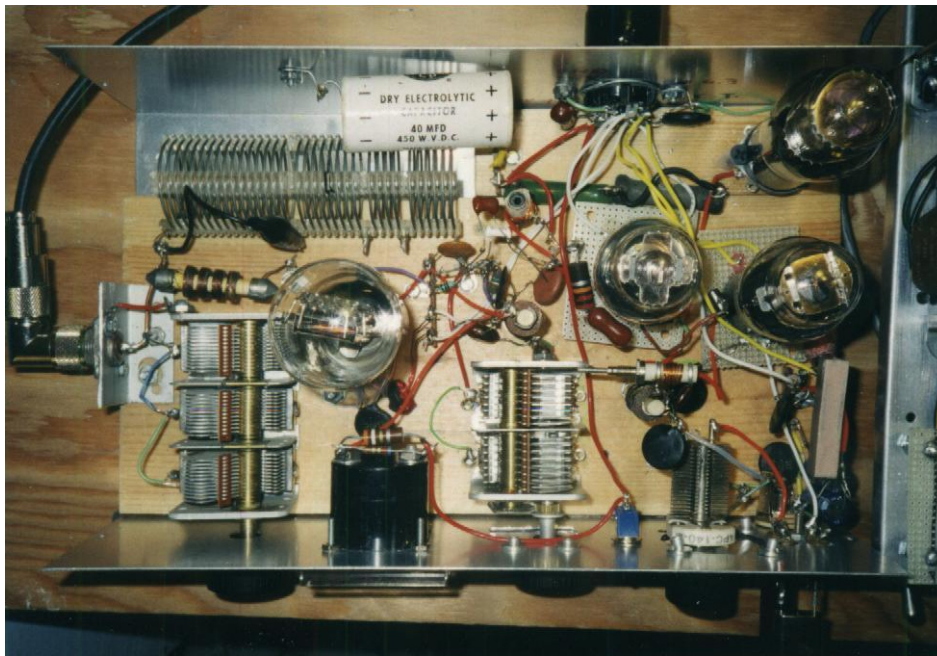
Buffer amplifiers

After struggling for a few hours, I eventually added a "buffer amplifier" made from another type 41 pentode between the oscillator and the final. Now I had enough drive for the triode final.



Oscillator and buffer stages

The oscillator tube drives a buffer amplifier to increase the drive to the final. Notice the OD3 regulator tube for the oscillator plate supply. A 7.5K ohm resistor drops the 285 volt supply down to 150 volts while the regulator tube holds it at that level.



The completed 40 meter transmitter

The final amplifier is on the left. The oscillator, buffer, and regulator tube are at the right rear. The plate coil is the long, tapped coil at the rear. In theory it was supposed to work on several bands, which is why the coil has the multiple sections. However, so far I have only gotten it to work on 40 meters. The plate coils for the oscillator and buffer were wound on slug-

tuned coils, which were the popular way to do it back in the vacuum tube days.

Triodes chirp

While up to my ears in vacuum tubes, it dawned on me that those homebrew “kilowatt linear amplifiers” in the old ARRL handbooks made from triodes can not really be linear. The output voltage of a triode varies with the supply voltage, not just the grid voltage. Well, they could be linear, but the operating range along the load line would have to be really narrow and the supply would have to be perfectly regulated. I doubt those designs meet either of those criteria.

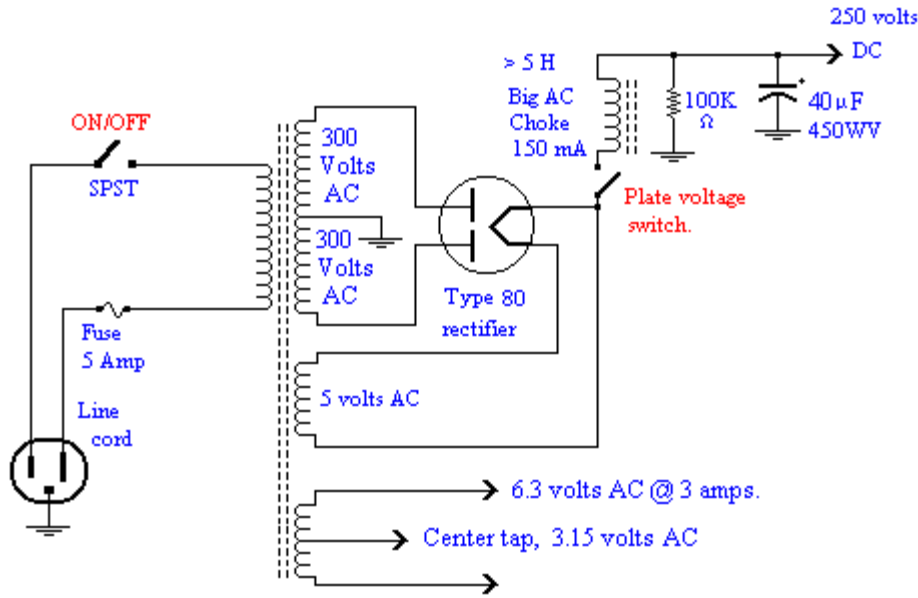
THE POWER SUPPLY

An inadequate power supply made from old-fashioned parts

Before I could try out my QRP transmitter, I needed a power supply. I first tried to use a power supply salvaged from a junked 1935 radio. Unfortunately this power supply didn't deliver enough power for a QRP transmitter but, as always, it was educational.



A power supply made from parts salvaged from an ancient radio.



Schematic of the 1935 power supply

The AC power from the wall comes into the supply and first encounters a 5 ampere fuse. In case the supply is shorted, the fuse can blow and prevent further damage. Five amperes is a larger fuse than needed, but it's within electrical standards for small appliances. A switch connects the power transformer primary winding with the AC line.

The transformer is equipped with three secondary windings. A high voltage winding puts out about 300 volts at 30 milliamperes. Actually, it has two 300 volt windings that allow us to achieve full wave rectification with just two diodes. The type 80 tube contains two anodes that share a common cathode/filament. A filament winding delivers 5 volts at about 2 amperes. This winding is used exclusively to heat the rectifier filament. The winding also has the 300 volts DC on it, so it must remain separate from other circuits. An independent filament winding delivers 6.3 volts at about 3 amperes.

The 6.3 volt winding is center-tapped. In other words, it is a 3.15 volt winding in series with a second 3.15 volt winding. The center tap is essential if you wish to use an ancient tube that has no separate cathode and must use the filament as a cathode. The center tap offers balanced access to the filament circuit to complete the main circuit between the plate and filament. Without a centertap, 60 Hertz power line noise will be impressed on the current and will appear in the transmitted signal.

Tube rectifiers

Before the high voltage can be used, it must be rectified and converted to DC. Vacuum tube rectifiers are a kind of diode and only conduct electricity in one direction. Specifically, they conduct electrons from the filament (or heated cathode) to the plate. The round circle symbol with the single filament and two plates is a dual, "full wave" rectifier. It converts both halves of the AC signal into a single DC signal in which both rectified halves of the sinewave have positive polarity. Both sides of the high voltage winding are connected to the two plates so that, at any moment, one side is always conducting while the other is not. The two positive voltages

are added together at the common filament for a single, continuous, positive output.

Ripple filtering

In order for Morse code to sound clear and pure, the voltage driving the transmitter must have no ripple left over from the sinewave. This is done with an “L” filter. An inductor and a capacitor make the two arms of the “L.” The choke, being a large 5 Henry inductor, doesn’t allow the current flowing through it to change rapidly. This prolongs the charging period of the capacitor and helps smooth out the ripple. Many designs add a second big filter capacitor on the input side of the choke. This practice causes big surge currents to flow into the first capacitor and may saturate the transformer. The saturation in turn causes the transformer to heat and probably isn’t as effective as putting both capacitors on the downstream side of the choke.

So much for theory. In practice, a receiver needs far less DC current than even a small transmitter. One difficulty was that the old-fashioned type 80 tube rectifier cost me 50 volts drop all by itself. Another problem was that the L and C filter were insufficient to prevent the ripple from making the Morse code sound rough and harsh.

But worst of all, the transmitter drew so much current that the voltage dropped precipitously and it often transmitted in “bursts” called *motorboating*. One cure is to use the smallest input coupling capacitance to the grid of the final amplifier. With luck, this can stop the motorboating and still give good output. With a soft (sagging) power supply the coupling cap may need to be as low as 5 pF on 40 meters.

I also tried to use an ancient type 83 mercury vapor rectifier tube. This is a vacuum tube rectifier that contains a touch of mercury vapor gas inside. This lowers the resistance of the tube and raises the current capacity of the power supply. The type 83 was a big improvement, but still not adequate for on-the-air use. I’ve had quite enough bad signal reports, thank you.

Checking out an old transformer

Big power transformers have always been costly. That’s why my 1957 novice transmitter power supply was so wimpy - I thought I couldn’t afford a bigger one. The old ham radio handbooks suggested using power transformers from vacuum tube TV sets. However, junk vacuum tube TVs are rare today. If you have such an old TV, remove the transformer from the chassis carefully being sure to label which pair of wires (usually black) go to the AC line.

Suppose some friend from your ham club gives you a power transformer and assures you it is “perfect” for building a transmitter. He hands you a 5 pound lump of iron with a nest of unmarked black wires protruding from the bottom of the transformer. You think to yourself, “Now what?”

The first step in checking out an old transformer is to strip the ends of the wires so you can measure the resistance of each winding. If you’re lucky, you will find that, once you clean off the dirt and tar, the wires are color-coded. The most common color codes are as follows:

two black wires - the 120 volt primary winding.

two red wires - the high voltage secondary for the plate supply, typically 1000 volts centertap for a 50 watt transmitter.

one yellow and red stripped wire - the center tap of the high voltage winding. This wire will

be grounded in a full-wave rectifier circuit.

two yellow wires - a 5 volt filament winding is usually good for 1 or 2 amperes. This is used exclusively for the rectifier filament.

two green wires - a 6.3 volts filament winding. This supplies the filament current for the transmitter tubes.

one yellow and green stripped wire - This is the center tap for the 6.3 volt winding. You'll need this if you use an old-time triode vacuum tube final amplifier. If you use a more modern tube with a separate cathode, then just tape off the end of the centertap wire and fold it up neatly. Don't cut it off. Someday you may want it.

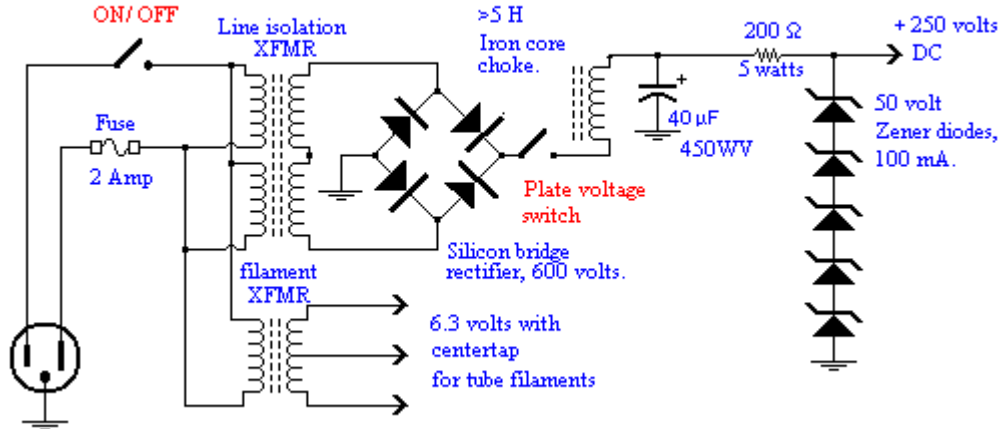
Often there are no visual clues telling you which winding is which. Or sometimes the windings are just solder eyelets mounted on Bakelite strip at the edge of the transformer. Using your ohm-meter, measure the resistances of the windings picking them out one by one. Label them with tape and write down the resistances. The highest resistance winding will be the high voltage winding. For example, it might read, say 40 ohms. The high voltage center tap will have half as much resistance as the whole winding measured end to end. The 120 volt primary winding will have the next highest resistance. The lowest resistance windings will be the two filament windings. These will have an ohm or two at most.

Once you think you have the windings figured out, you need to test them before bolting and soldering the transformer into your transmitter. If this isn't going to work, you want to know as soon as possible. Now that you are considering plugging it in, you have a great opportunity to electrocute yourself, trip circuit breakers, and start fires. But if you're careful and proceed thoughtfully, testing a transformer can be done safely. The idea is to limit the current that flows into the transformer. That way nothing terrible will happen even if you screw up or if the transformer is internally shorted.

Testing a power transformer

First you must expose each of the many windings and keep them un-shorted. You will need to measure the open circuit AC voltage of every lead pair. It would be best to set up your voltmeter with test clips so that you don't need to touch them with bare fingers. Another way is to tape the wires to a board so they hold still. To start you must connect the winding you believe to be the primary to a source of 60 Hz voltage. How safe you want to be is your decision. But AT VERY LEAST don't plug the test transformer into the power mains without soldering a 10K ohm resistor in series with the primary winding. That way, even if the primary is a dead short, little current will flow and nothing bad will happen. Go through the windings one by one and you should be able to confirm the guesses you made earlier from the resistance measurements. Whatever you do, don't just connect it to a line cord and plug it into the wall.

An adequate tube QRP power supply made from modern parts



When my first supply worked poorly, I built another made from modern transformers and semiconductors. This supply was adequate to run the vacuum tube transmitter. Ideally it produces 250 volts at 200 milliamperes. This time there was no significant voltage drop across the modern bridge rectifier and the modern Zener diode string clipped off the ripple and gave me a pure CW tone. That was easy.

I couldn't find an adequate, triple-winding transformer, but there are alternatives. Magnetek makes an isolation transformer that can isolate an appliance from ground for shock protection. (Magnetek / Triad part # VPS230-350 sells for about \$30.). It has four 120 volt windings. Each winding is rated at 350 milliamperes - plenty "stiff." That is, this supply behaves like a good voltage source over a wide range of current. These two pairs of windings may be connected in series or parallel. For this application you could put two windings in parallel for a 120 volt primary. The secondary windings can then be connected in series to give you a 240 volt secondary rated at 350 milliamperes. Notice the dot markings on the windings. These tell you the phase direction of the sinewave voltage. On the primary side, you must connect the leads so that the dots should be connected together. That way, the two windings will work together.

On the secondary side, the dotted end of one winding goes to the un-dotted end of the other winding. Notice that if you connect the secondary windings so that the two dotted ends or the two non-dotted ends are tied together, the voltages will cancel each other instead of add. Instead of 240 volts you would get zero volts.

The other power requirement for vacuum tubes is a 6.3 volt supply to light the filaments. Each tube filament needs about 0.5 to 1.2 amperes of current. Notice that roughly 5 watts is expended just to heat up each tube! Tube transmitters are inherently inefficient.

I used four modern silicon rectifier diodes that were rated for 600 volts peak inverse voltage and I wired them to make a bridge rectifier. Since you aren't using a tube rectifier, you won't need a 5 volt filament winding like the one shown earlier in the 1935 power supply. However, you will need a separate 6.3 volt filament transformer for your transmitter tube filaments. To regulate the output voltage I used five 50 volt Zener diodes in series.

My supply made from modern parts can put out 42 watts and that's sufficiently "stiff" to deliver my measly 10 watts without sag. Using the modern silicon rectifiers I got 4 watts RF out of my transmitter.

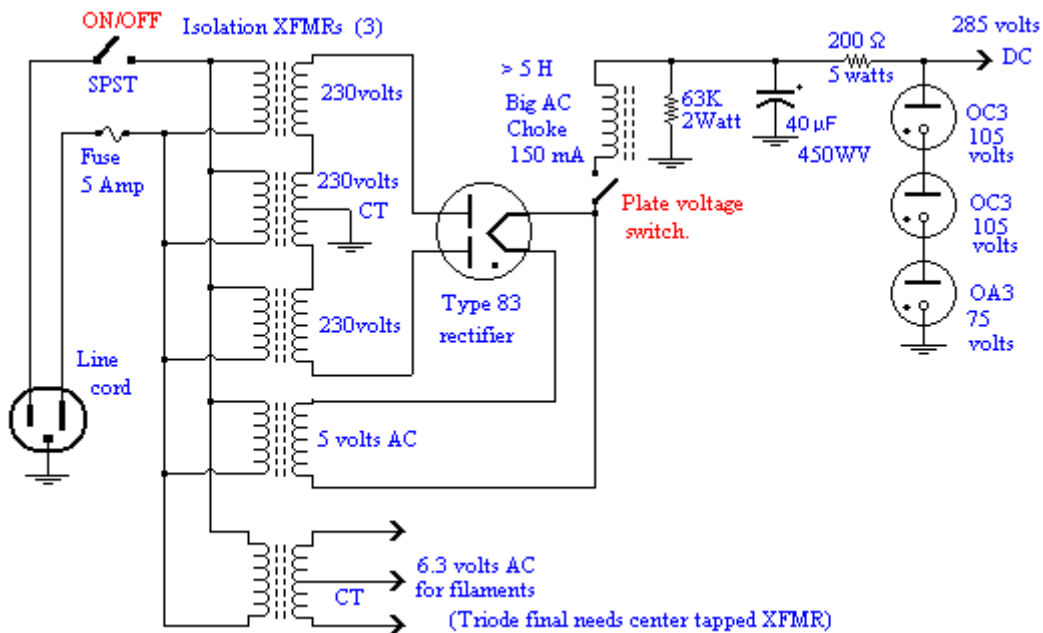
A power supply for the tube transmitter constructed from old style parts

Although I now had the rig working, I still wanted to use my old time parts exclusively. Unfortunately, to use an old tube rectifier with full-wave rectification, I needed 480 volts centertap. So I added a second transformer. This worked, but the extra voltage drop across the type 83 tube rectifier cost me half my 4 watts! Finally I added yet another transformer and got the average, well-regulated DC voltage up to about 285 volts.

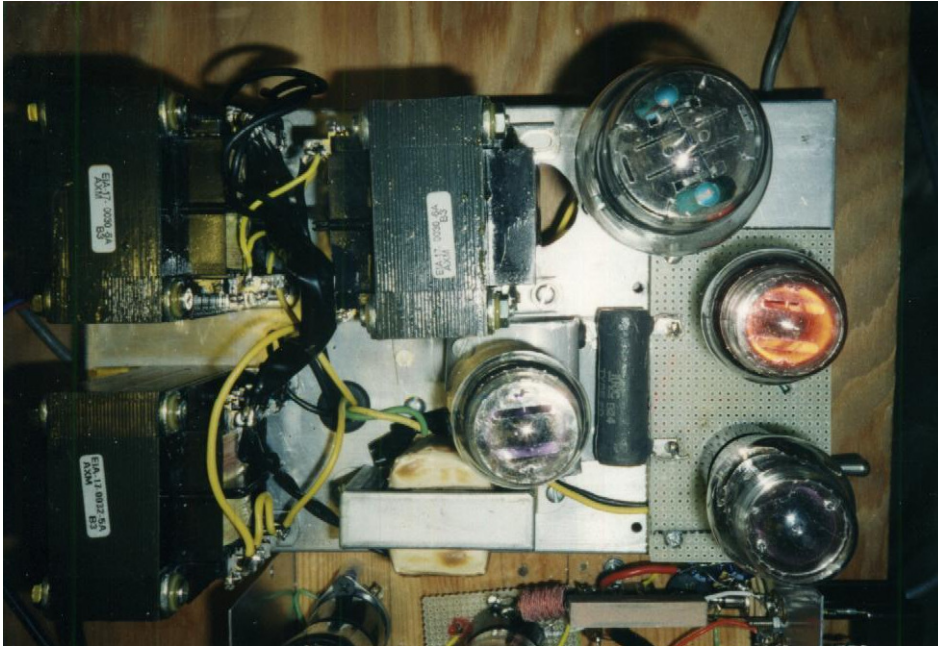
I tried using gigantic filter capacitors, but they weren't available in 1935 and they caused long-term sag. I was surprised to discover that a total of two 40 microfarad caps were plenty when used with voltage regulators. To regulate my 285 volts DC I used one 0A3 (75 volts) and two 0C3 (105 volts) gas tube voltage regulators in series.

In order to regulate while the transmitter is keyed, the voltage regulator tubes should be at least slightly glowing at all times. For best regulation, you may have to reduce the 200 ohm current limiting resistor to 150, 100, or even zero ohms. You will probably find that the regulators only stay lit while the key is down when the transmitter is perfectly tuned to the antenna. When it is out of tune, the transmitter draws too much current and the regulator tubes will be extinguished and essentially take themselves out of the circuit.

I have seen these old gas regulator tubes offered for sale at as much as \$30 each! Hopefully you can find some at a swap fest. Notice that six teeny 100 mA 50 volt Zeners cost less than \$2 each. Anyway, when all was said and done I had 5 watts of pretty good sounding CW. Behold! I have created the world's most inefficient transmitter!



Schematic of the regulated QRP supply made with old-style parts



It isn't that you can't build modern high tech stuff with 1935 parts, it's just that the assembly becomes huge and expensive. Meeting modern specs with old parts reminds me of a scene in the movie Back to the Future III. In this time travel movie Doc Brown replaced a burned up integrated circuit from the future with a tube circuit the size of a laundry basket. It must have been a low scale integration chip!



Old-tech QRP

A happy ending

In conclusion, old parts aren't efficient in any way. On the other hand, you get to use a whole lot of them to accomplish very little and they look terrific. The voltage regulators glow orange and violet, but when you key the transmitter the glow flashes on and off inversely with the CW. When I first turn the mercury vapor rectifier on, mercury condenses on the glass in a silver-

white fog. Then as it heats, the mercury evaporates and the tube runs with a glorious blue glow with bright orange filaments. Great show biz! Oh, yeah. I forgot to mention the “mercury vapor rectifier hash” that you get to listen to on receive. Oh, and another thing - don’t place your transmitter supply transformers close to your receiver. The receiver may pick up a 60 Hz hum. You’ll probably have to turn off the transmitter high voltage supply during receive. There are lots of reasons these old parts are extinct.

Every year my local ham club has a "homebrew night." Hams who have built something during the previous year bring in their devices and give a brief show and tell. Over the years I have showed off most of the projects described in this book. They include all the most difficult projects, the SSB transmitter, the dual conversion receiver, etc. It's fascinating to me that the project my fellow hams remember best is the vacuum tube QRP. I demonstrated it with a Christmas tree light bulb for a dummy load and they all oohed and aaahed over the pretty glowing regulator tubes and lights. In the years since, they always act disappointed that I haven't brought in another vacuum tube light show. Food for thought!

So anyway, I can successfully work people with my old-tech QRP. QRP is quite popular. I call CQ, mention “/QRP” and I get lots of responses from other fanatics. Who else would answer an American “Ø area” RST 449 CQ? Usually we can barely hear each other, but we’re having fun. However, you never know! I got a 599 from Albuquerque. Maybe he was just kidding. Anyway, how old-tech can YOU go?

OLD-TECH SUPER-REGEN

How old fashioned a receiver can you use on the air today?

Once I had my old-tech, 1935-era CW transmitter working, I thought it would be fun to complete my ancient rig with an old-tech receiver. To be successful on the CW bands, I figured I needed a superhetrodyne with a crystal filter. In 1967 I built a pretty good vacuum tube CW receiver so I had little interest in doing the same project again. (There is a photo of this receiver in chapter 13.) The 1930 tubes would be much larger than 1960 tubes, but otherwise it would be the same project.

Yardley Beers, WØJF, told me about the regenerative receiver he built in 1930. I doubted it would work well enough for today’s bands because I had a previous experience with regenerative receivers. So Yardley didn’t inspire me to build another one. Then a few months later I worked Mike, NØMF, who lives about 1,000 miles from me. He was using a homebrew super-regenerative receiver made from modern FETs as described in QEX magazine. Obviously it was sensitive and selective enough to hear my QRP on 40 meters. Maybe a super-regenerative receiver wasn’t so silly.

Ancient tubes

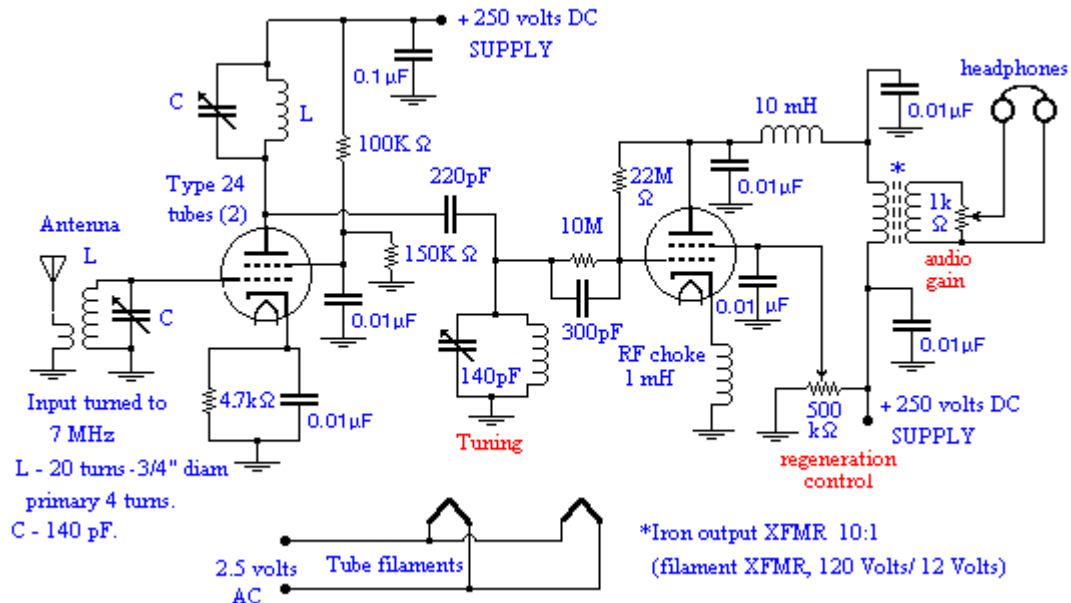
I have never been able to bring myself to throw out vacuum tubes. I have boxes of them in my attic. I’ve always been especially fascinated by the earliest tubes. They have lightbulb-like glass envelopes, bayonet sockets and numbers like 201, 216, 224, 227, and 301A. This was my chance to build a really old-tech receiver.

I started by building an RF amplifier out of a type 201 tube. I had no specs for a 201, but I gently increased the filament voltage until I got a nice warm, orange glow out of the filament. That occurred at 2.5 volts and 0.3 milliamperes. Unfortunately, it didn't amplify the RF noise from the antenna at all. The signal on the plate was smaller than the input on the grid. I tried reversing the grid and plate wires ... no luck. No matter how I biased the grid, the tube didn't turn on. I increased the filament current to produce a yellow glow and promptly burned out the filament. Whoops! Starting over, I tried to build a regenerative oscillator, but it refused to oscillate or amplify. I suspect that these tubes from the 1920s are extremely high impedance.

Old-tech receiver

Since my oldest tubes seemed inert, I gave up on the triodes before I ruined more of them. From there I retreated to a high-tech type 224. This tube is a tetrode. It has two grids and even has a cathode. Pretty modern, huh? 224s are the early version of the types 24 and 24A tubes which were commonly used in the 1930s. The 224s worked immediately in the same circuits I had tried before and soon my super-regen was picking up 40 meter hams and 31 meter commercial broadcasts. The 31 meter stations are mostly religious sermons, but the sound quality was pretty good. One of my 224 tubes has a test label on it from the Marshing Radio and Electric Company at 246 Main in Longmont, Colorado dated December 19, 1932. The note on the label written in pencil says, "doubtful." Shows what they knew!

Like the older tubes, the type 224 and 24 tubes have low voltage (2.5 volt) filaments. A major difference is that the filaments run at much higher power levels to heat the heck out of the cathode so it will shed electrons readily. The high temperature gives the tube much lower internal resistance. The brawny filaments resemble toaster elements and are hard to burn out. The bad news is that each tube consumes 4.4 watts just to run the filament.



Circuit diagram of the old-tech super-regenerative receiver

Motorboating can be a good thing

Super-regenerative means that the amplifier is deliberately designed to “motorboat.” That is, the power supply is deliberately given a high source impedance with a series inductance (10 mH). This causes the tube to oscillate in short bursts. Normally, when RF circuits motorboat it’s a darn nuisance and tough to get rid of. It’s ironic that motorboating was my big problem with the transmitter and here it is vital to achieve the receiver sensitivity. The 10 mH choke can be seen in series with the plate of the tube on the right. The motorboating typically occurs at a rate of 1 KHz.

In a super-regen motorboating does three useful jobs: Maximum sensitivity and selectivity are obtained during the feedback near the peak of each burst. The sidetone caused by this oscillation makes an audio squeal that serves as a BFO. If you are listening to AM modulation, the regeneration control can be turned down until just below the point where the squeal begins.

Super-regeneration re-broadcasts what you’re hearing

Unfortunately, if you wish to use a super-regenerative receiver today, it must be a two stage device. An RF amplifier (or other device) must isolate the oscillator from the antenna. Otherwise, you’ll be rebroadcasting everything you’re listening to on your receiving frequency. Even with an RF isolation amplifier, you’ll be radiating a few milliwatts of RF signal. To demonstrate this, disconnect the antenna from your modern communications receiver so there are no signals audible on the band. Now tune the modern receiver to the same frequency as your super-regenerative receiver. Suddenly, coming out of the modern loudspeaker you’ll hear exactly what you’re hearing in the headphones of your super-regen. The super-regen really does rebroadcast the signals it picks up!

Super-regenerative design

When you think about it, a one-tube super-regenerative receiver is actually quite amazing. One tube is providing RF amplification, detection, audio amplification, and a BFO all in one tube. 80 years ago this economic efficiency made it possible for hams to afford to build receivers at a time when a single tube was a major investment.

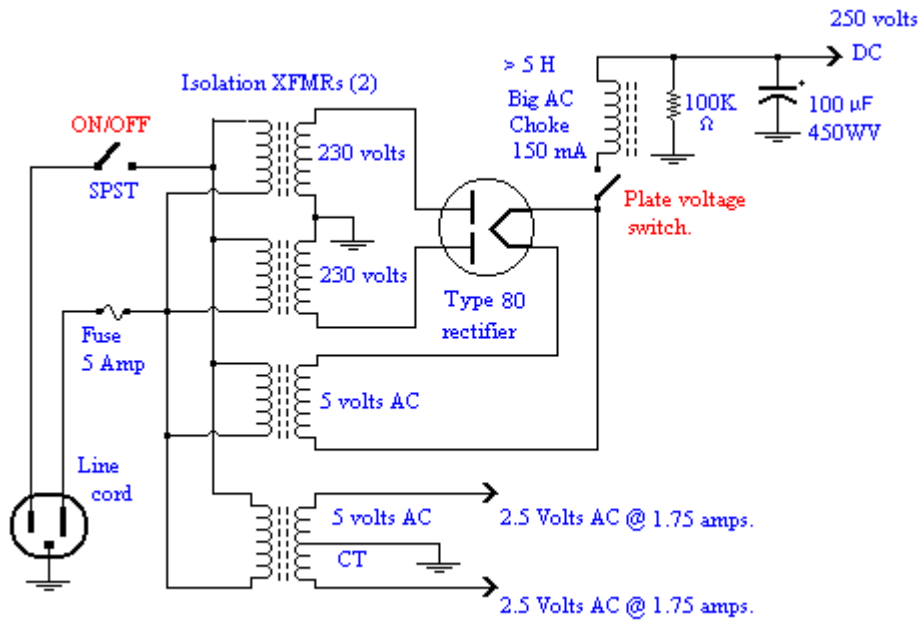
Regeneration is accomplished by feeding back the output from the plate to the grid. In my circuit this is done with the 22 megohm resistor from plate to grid. The gain of the tube is adjusted by the pot that controls the voltage on the second grid. The second grid is called the *screen grid*. The oscillation provides far more gain than a simple RF amplifier can achieve. It takes good sensitivity to hear hams on the HF bands. Moreover, the self-amplification greatly increases the circuit Q, making the amplifier much more selective than it would otherwise be.

For an audio output transformer I used an iron 12 volt filament transformer, i.e., 120 VAC to 12.6 VAC. It works fine and was easier than trying to find a real old time audio transformer. The secondary side goes to the low impedance headphones. The 120 volt primary side goes to the tube plate circuit.

The power supply

Bob, K6VGA, told me about the homebrew super-regen receiver he built back in 1935. He said its worst fault was AC hum. It was so bad, he replaced the AC power supply with

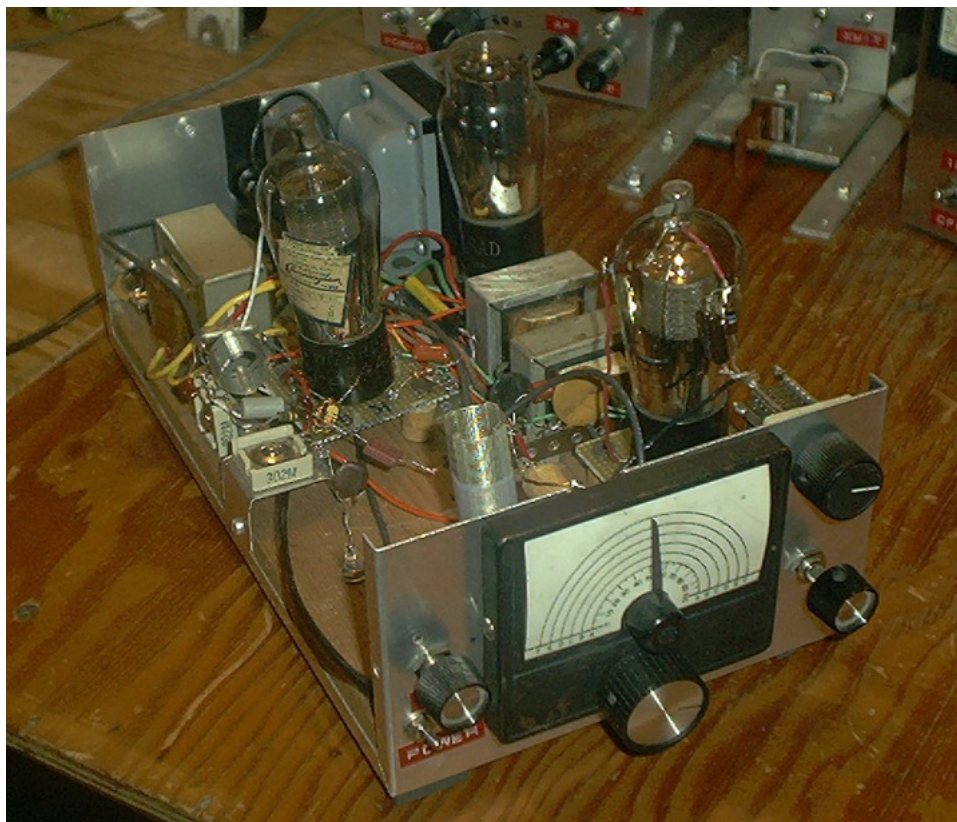
batteries. After that story I figured I would have to filter the heck out of the power supply with a big choke, big capacitors, and a voltage regulator from the 1940 era. However, a voltage regulator turned out to be overkill. Unlike my old-tech QRP transmitter, the power supply for the super-regen turned out to be remarkably easy. In other words, simple power supplies like the ones I tried to use for my transmitter worked fine for the receiver. Yes, the receiver hums slightly, but too little to bother me.



An old-tech power supply for the super-regen.

As explained earlier, you can't buy a new, old-time tube transformer with both high voltage and rectifier filament windings anymore. Brent, KDØGLS, pointed out to me that tube transformers are still manufactured by Hammond Mfg. for tube hi-fi amplifiers. Some modern hi-fi addicts say tube amplifiers sound better, so there is still a demand for them. Perhaps one of these transformers would work. In any case, 5 volt filament transformers are still available as separate units. A center-tapped 5 volt, 2 ampere transformer is needed to provide the 2.5 volt filament voltage for the type 24 tubes. You could also use a 5 volt winding and wire the two tube filaments in series - that is what I did. The tube filament transformer must be separate from the transformer winding used for the rectifier. Otherwise all the filaments would have +250 volts DC on them.

In my receiver I used an old plate transformer I happened to have. However, you may use two of the same transformers I used for my old-tech QRP transmitter. For a choke I used the primary of yet another filament transformer. Because the current drain is so low, a voltage regulator tube isn't needed.



Super-regen on the modern hambands

In summary my super-regen worked quite well for listening to shortwave broadcast stations on the 31 meter band, around 10 MHz. These are extremely powerful stations like Die Deutsche Welle (Radio Germany) and various religious stations. To hear AM stations, the regenerative control is turned down just below where it begins to squeal.

To hear CW stations, the regeneration is turned up just above the squeal. The squeal modulates the Morse code and makes it audible. Unfortunately, as I feared, my super-regen isn't sensitive and selective enough to be used on the air today. Yes, I heard lots of ham CW stations on 40 meters, including guys I had worked before. The stability seemed OK once a signal was tuned in. But that's because I was hearing at least 20 KHz bandwidth at once. In other words, I was hearing half of the CW stations on 40 meters simultaneously. The worst problem is that the reception is "flaky." If I just touch a control, the pitch of the CW signal jumps to inaudible. Or it leaps from a nice tone to a harsh, static-like sound. When I try to tune it in better, the signal is likely to vanish altogether. Yes, I can work guys with this receiver, but it would be a stunt, rather than practical. How does it compare with the little direct conversion receiver described in chapter 7? There's no comparison. The transistorized direct conversion receiver is far better in every way.

In conclusion, the modern FET super-regenerative designs apparently achieve much higher Q and stability than I got using gigantic old-time parts with their stray capacitance and leakage inductance. But the project was fun and I learned a great deal. On the other hand, there's no reason I couldn't build a 1930 superhetrodyne using 6 or 7 ancient tubes and 1927 crystals. That would fill a huge chassis and require loads of work. Until I can muster the

25. Chapter 14, Harris

enthusiasm, I guess a practical old-tech receiver will remain one of those unfinished projects in my attic. But wait! I just got a QSL from Biz, WDØHCO. He claims that when he worked me he was using a super-regen made from two type-30 tubes. He found the design in a 1932 ARRL handbook. Hmm... Maybe I'm being too hasty.

CRYSTAL SETS TO SIDEBAND

© Frank W. Harris 2010, REV 12

Chapter 15

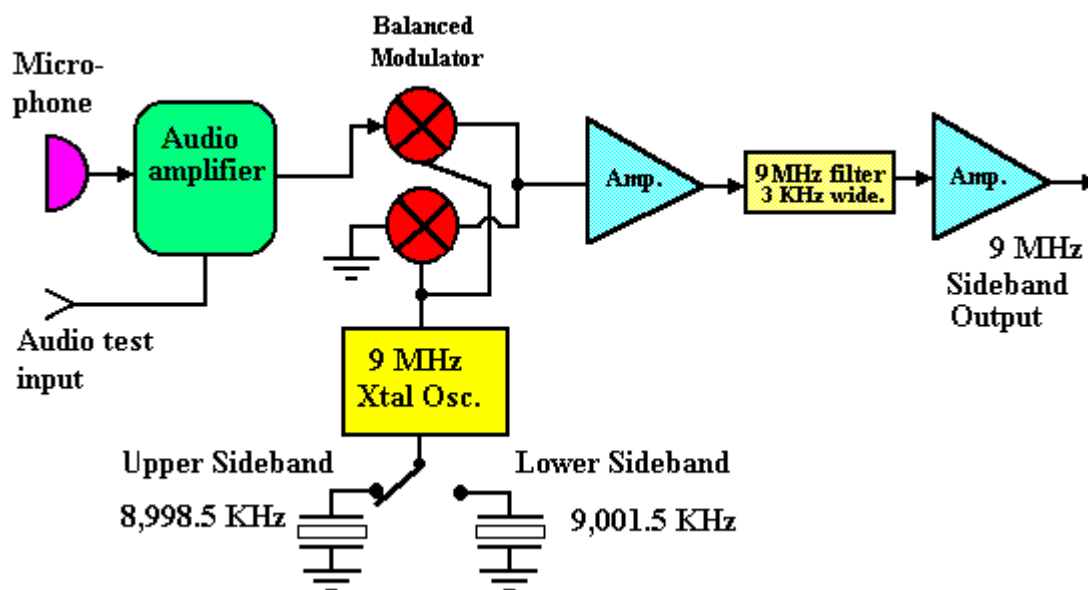
THE NOBEL PRIZE FOR SIDEBAND

How sideband works

In the beginning of the book I mentioned that Glenn Johnson, WØFQK, was an elementary school principal who made a project out of recruiting kids into ham radio. We were in the 8th grade walking down the street minding our own business when Glenn ran out of his house and grabbed us. “Come on in boys and I’ll show you how sideband works!” Glenn’s wife served milk and cookies while Glenn worked bunches of guys on 20 meter sideband phone. I sat quietly and watched while Glenn effortlessly operated massive equipment that cost enough to buy a car. I was fascinated by ham radio, but I didn’t learn much about how sideband worked. I had the impression that sideband was *MODULATION FOR MILLIONAIRES* and too complicated to homebrew. The 1957 ARRL handbook’s opaque descriptions of “phase shifters” and “balanced modulators” only confirmed my opinion.

Today SSB is affordable, but the technology is still exotic to the average ham. I overheard a conversation at my local ham club meeting that went something like this: “I once knew a guy who built his own sideband rig.” “*REALLY!* That’s amazing. Are you sure it wasn’t a kit?” The implication was that homebrewing sideband was about the same level as a Nobel Prize in physics. So, is anyone interested in the Nobel Prize for Sideband? If you’ve already built homebrew QRP’s, VFO’s, and a receiver, then sideband is the next logical project. SSB uses all the same basic circuits. Besides, you won’t really understand sideband until you’ve built one.

You begin with the sideband generator



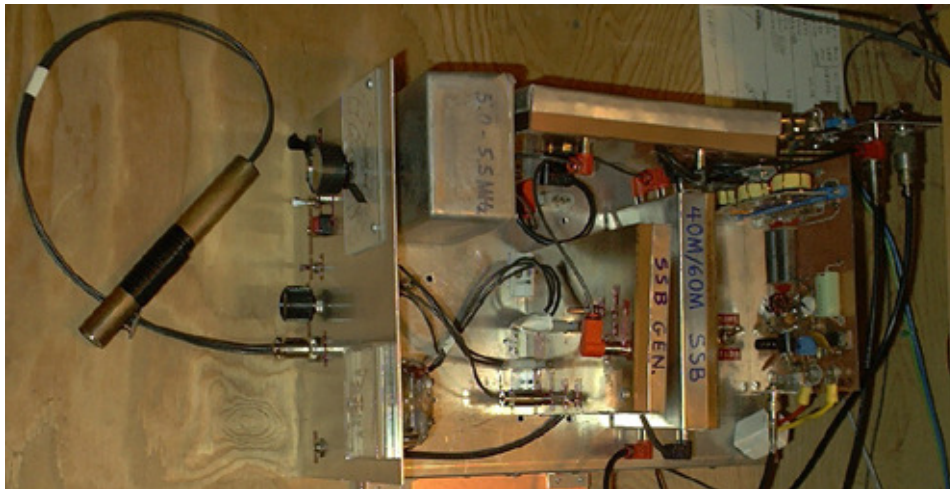
2. Chapter 15, Harris

There are different ways of generating an RF sideband phone signal, but the most straight-forward one I've seen is outlined above. The block diagram shows the five circuit blocks needed to generate a sideband signal on 9.000 MHz. This generator is similar to one found in the 1986 ARRL handbook. After the 9 MHz SSB signal has been generated, it must be moved to the desired ham band using a mixer and a high frequency VFO of the correct frequency range.

The circuits you've used in previous chapters are the audio amplifier, the crystal filter, the RF oscillator/ amplifier, and the conversion modules to move the VFO signal to ham bands. The audio amplifier design is similar to the one in the homebrew receiver in chapter 13. The 9 MHz RF oscillator/ amplifier uses the same technology used in the QRP described in chapter 6. In theory, the VFO could be the VFO signal from your receiver. When I started this project, I figured if the sideband generator didn't work, I would at least have a CW signal that was slaved to my receiver so that it would be easier to zero-beat my signal with the guy I was trying to talk to. Unfortunately, that goal turned out to be harder than it looked.

Don't burn your bridges

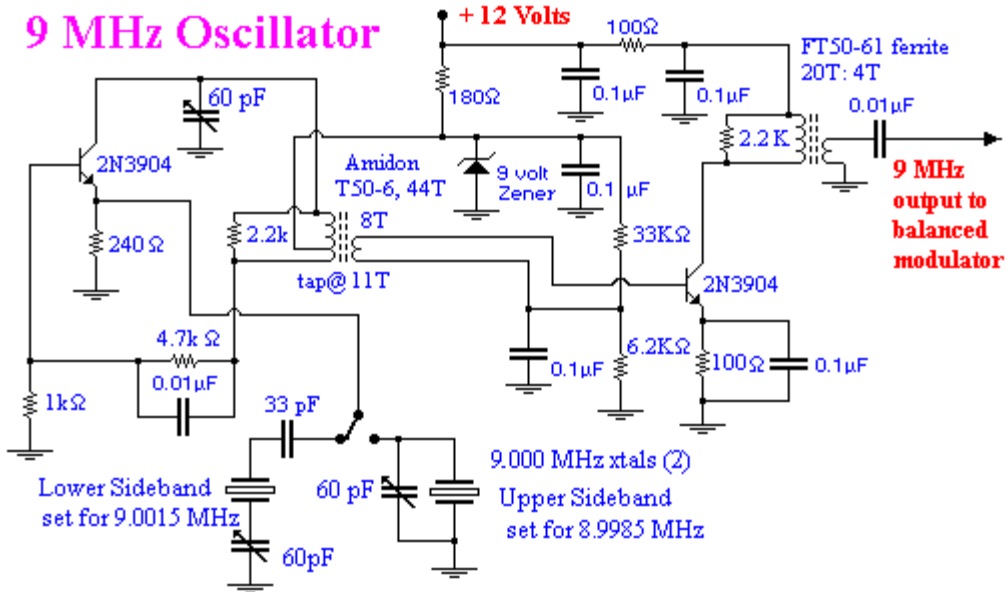
If you're thinking about modifying a working CW transmitter to sideband, I don't recommend it. If you already have a working QRP driver based on chapters 6 or 11 from this book, those designs are full of tuned amplifiers and mixers. Tuned amplifiers tend to self-oscillate when used for sideband. To have a good chance of working, every gain stage should be converted to broadband. If you convert your old transmitter, you are likely to have months of struggle in which you aren't on the air at all. Start from scratch! Don't ruin a rig that works!



Homebuilt SSB transmitter

How sideband really works

Ordinary broadcast band AM modulation transmits three separate signals. These are the carrier signal and two sidebands of speech modulation. Single sideband begins with AM, but a cancellation process removes the carrier leaving a double sideband signal (DSB). Next one of the two sidebands is filtered out with a crystal filter. Let's begin with the crystal oscillator:



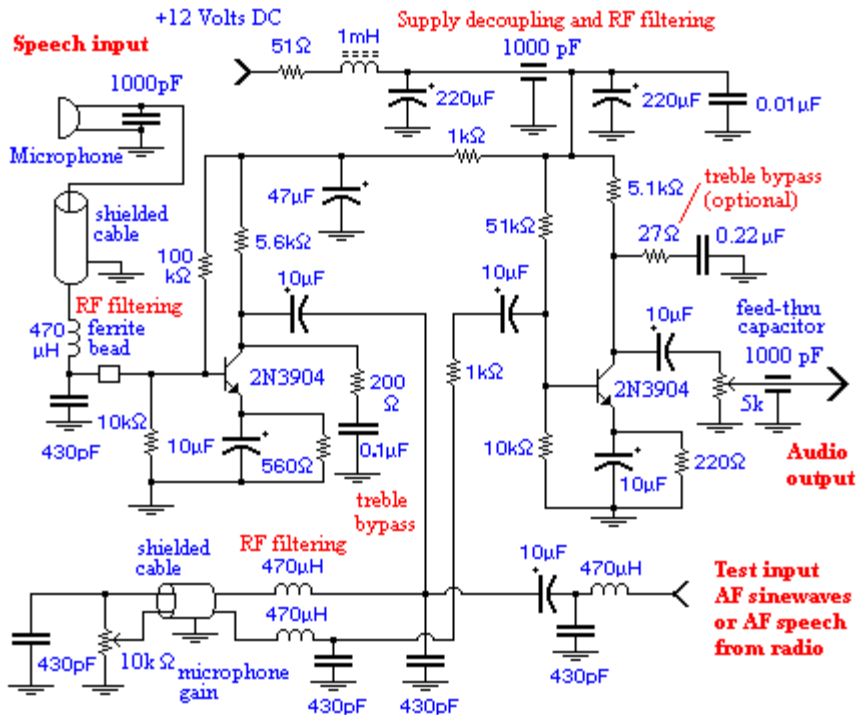
9 MHz sinewave oscillator / amplifier

A stable, fixed frequency RF sinewave signal is generated by a crystal-controlled 9 MHz oscillator and amplifier that resemble the 7 MHz QRP transmitter described in chapter 6. The crystal oscillator has two crystals. Each crystal has tuning capacitors so that the frequency can be pulled about 1.5 KHz up and down. This allows the two AM sidebands to be lined up properly with the ladder-style crystal sideband filter that follows the balanced modulator. The filter shears off the unwanted upper or lower sideband.

A switch enables the oscillator to select two crystal/ capacitor pairs so that the operator can switch between upper and lower sideband. The crystal filter that removes the unwanted sideband is at 9.000 MHz, almost exactly. Notice that the upper sideband is generated by a sinewave 1.5 KHz below 9.000 MHz. The lower sideband is generated by a sinewave 1.5 KHz above 9.000 MHz. To pull the crystal above 9 MHz, the tuning capacitor is in series with the crystal. To push the crystal below 9 MHz, the tuning capacitor is in parallel with the crystal.

Just like the receiver project in chapter 13, you will need a bunch of inexpensive 9 MHz microprocessor crystals. How much capacitance is needed in parallel or series with a crystal depends on the individual crystal. The low side oscillator is the difficult one. Start by selecting the lowest natural oscillation frequency among your collection of crystals. For some crystals 8.9985 MHz might be reached with the capacitor in series with the crystal. For other crystals the parallel capacitance method is necessary and you may even have to pad the trimmer with an additional fixed capacitor. You may find that none of your crystals will go that low without becoming unstable and losing control of the frequency. You might even need to buy a custom crystal. As always, the oscillator collector circuit LC must be tuned to the region where the frequency "locks in" to the crystal.

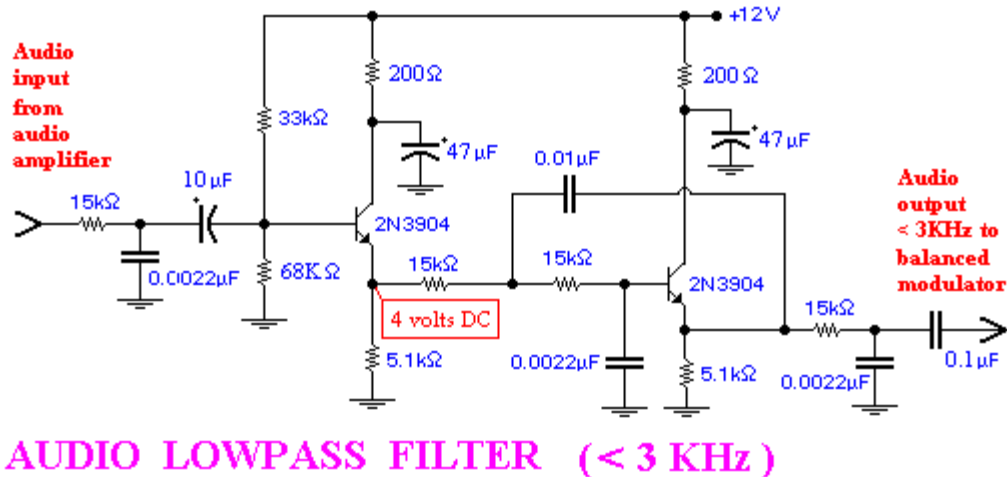
The audio amplifier



An audio amplifier with test input

The microphone needs a high gain audio frequency (AF) amplifier before it can drive the balanced modulator. The audio amplifier is pretty routine except that heroic effort is needed to shield it from RF. Notice the RF chokes and bypass capacitors on the two audio inputs, the audio gain pot and the 12 volt power input. Because crystal mikes have a puny output, it took me two stages to get the signal up to roughly 5 volts peak. My crystal microphone exaggerated the high frequencies, so I attenuated the high frequencies with series RC *treble filters* on the collectors of both amplifier stages. You may be tempted to add another stage of audio gain. Don't! It's much better to run the audio gain wide open than to have extra gain and keep the gain turned low. Surplus gain just invites noise and sensitivity to RF feedback. If you like, you can replace most of this circuit with an IC, but as always, building your own amplifier with discrete parts will be more educational.

After you get the amplifier working, look at the audio waveform critically. You may find that the negative and positive voice peaks are not symmetrical. If this is the case, you may have too much or too little forward bias on the second stage. That is, you may want to increase or decrease the resistance of the 51 K ohm resistor biasing the second 2N3904. Ideally, the amplifier should be able to deliver a 10 volt peak-to-peak symmetrical signal.



I added the *Butterworth* filter shown above to be sure the bandwidth of my final signal would be less than 3 KHz. Like the treble filters discussed earlier, your generator may not need this. The Butterworth sharply cuts off practically all audio signals higher than 3 KHz. In contrast, the treble filters will just emphasize the lower frequencies. The filter uses two transistor amplifiers wired in the *emitter follower* configuration. Notice that the load resistor (5.1K Ω) for each transistor is wired between the emitter and ground, rather than between the collector and the positive supply.

This audio filter is probably unnecessary because the crystal filter trims the bandwidth down to 3 KHz anyway. So, you might try the SSB generator first without the filter, then add it later if necessary.

The advantages of emitter followers

Emitter followers have the advantages that the input impedance is extremely high and the output impedance is very low. High input impedance means they will not load down or affect the input signal strength. Low output impedance means they deliver big currents into low resistance loads. Another feature of the emitter follower is that *the voltage gain is less than unity*. That is, they don't amplify voltage. This is an advantage here because it insures that the amplifier will not oscillate. Butterworth filters are usually implemented with operational amplifiers. Until this filter, I had never built a Butterworth with transistors. Yes, simple transistors work too.

No matter what audio amplifier circuit you use, it will be sensitive to RF interference from any strong RF signal in your radio shack. For example, if you are using a simple antenna coupler with no shielding like mine, those RF signals will tend to feedback into your microphone cable. To prevent this I added RF chokes, bypass capacitors, and a ferrite bead in series with the microphone input. Since my microphone gain pot is remote from the audio module, the shielded wires to the pot are also filtered with RF chokes and bypass capacitors. Even the output from the amplifier passes through a capacitive feed-through (bypass) capacitor on its way to the balanced modulator.

The 0.1 μ F audio output capacitor

Notice that the output from the filter circuit is not the usual big 10 μ F capacitor but is

only a 0.1 μF cap. This cap goes to the audio input of the balanced modulator. If you use a larger capacitor here, the capacitor will take time to charge when the transmitter is first keyed and power is applied to the audio amplifier. A big cap would take two seconds or so to charge and would cause the balanced modulator to turn on causing a brief, shrieking whistle to go out over the air. The input resistance to the balanced modulator is very high, about 100,000 ohms. Therefore, the time constant of 100K ohms times 0.1 μF is about 0.01 second. This allows for 100 Hz audio and is plenty Hi-Fi for SSB ham work.

Decoupling for the power supply lead

The 12 volt power supply lead for the audio amplifier also has a large RF choke (one millihenry) in series with the lead and passes through another feed-through capacitor bypass. In addition, the power supply lead is isolated or *decoupled* by means of the 51 ohm resistor and the large 220 microfarad bypass capacitors. The purpose of these capacitors is to insure that the voltage supplied to the amplifier cannot change as fast as the audio signals. All of the modules in an SSB transmitter, except the final amplifier, need to be decoupled from changes in the 12 volt supply level. Otherwise, as you talk into the microphone, the current drawn by the high power final varies rapidly and the voltage delivered to each module will rise and fall in time with the speech. Because the voltage is rising and falling, the RF output from each module will rise and fall too. This feedback produces surges in the radio signal that sound like noise superimposed on the speech. In fact, it makes nearly the same buzzing roar as RF interference.

The final amplifier draws too much current for it to be practical to decouple the 50 watt linear amplifier supply lead. In fact, it is the big 10-ampere surges of current drawn by the final that cause the noise in the rest of the transmitter. In general, the less current drawn by a circuit block, the more extreme the decoupling must be. For example, the audio amplifier has a series 51 ohm resistor and 440 microfarads bypass. In contrast the 5 watt RF driver stage has only a one ohm resistor and a 0.1 microfarad capacitor.

Microphones are important

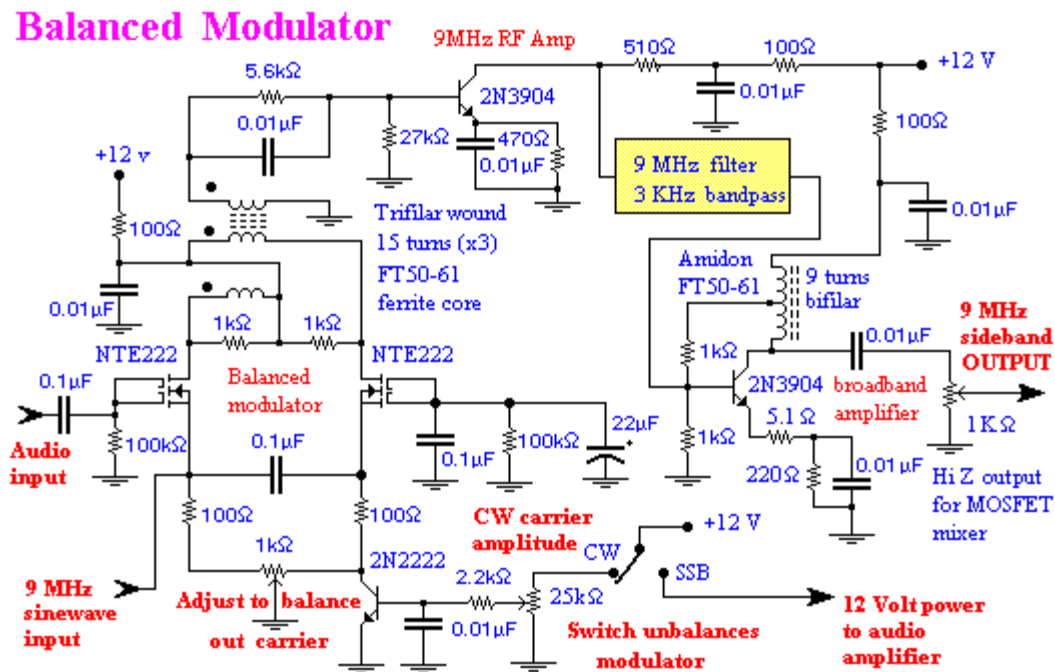
Not all microphones are equal. I tried three different crystal microphones. Two small Radio Shack microphone cartridges gave a “tinny” sound. I was able to compensate with RC bypass networks on the collectors of all three transistors to limit the high frequency components (treble) of the speech. For example, notice the 200 ohm resistor and 0.1 μF capacitor combinations going to ground from the first two transistor collectors. I also tried a 40 year old Hallicrafters crystal microphone designed for mobile radio. It worked fine without the RC bypasses. Next I tried two tiny condenser-type electret microphones. One was too “bassy” and made a low frequency hum. The other, a Radio Shack PN # 270-092A, worked perfectly. To bias the electret with about 4 volts, I used a 3.9K resistor in series with a 7.5K resistor to step down the 12 volt supply.

When I finally had a working SSB generator, I was able to use either my ancient Hallicrafters mike or a homebrew mike built around the Radio Shack electret. To shield the electret I mounted it in a length of 3/4 inch copper pipe. I soldered copper disks (PC board) to the top and bottom of the pipe section so that the microphone would be well shielded. The electret is force-fit into a snug hole at the top of the pipe. I put a 1000 pF capacitor across the microphone to further reduce RF interference. The electret is connected to the transmitter by two short pieces of RG-174 coax: one for the audio signal and the other coax for the 4 volt DC supply

line for the electret. Keep the microphone cord(s) as short as practical. A long cord invites RF interference.

The microphone case/ copper pipe also contains a push-to-talk SPST button switch. This switch turns on the transmitter just like the switch mounted on my electronic bug. The switch lead-in has its own separate piece of RG-174 coax. So as you can see, my microphone cord is actually three parallel RG-174 coax cables. Obviously my mike cord should be a single, shielded three-conductor cable. But since I didn't have such a thing, I used the three separate single-conductor shielded coax cables. To connect the mike to the transmitter, I used a (fairly) standard microphone connector that has 4 inner conductors plus the outer shield ring. I found this connector pair at Radio Shack and by some miracle it was the same connector used on my old Hallicrafters crystal mike.

The balanced modulator



The balanced modulator is the “carrier cancellation circuit.” It is a kind of dual mixer in which an audio signal is mixed with the 9 MHz sinewave to produce an AM modulated RF signal, exactly like AM radio. An AM signal has a carrier signal just like the CW input plus the two RF sidebands caused by the audio modulation. What’s different about a balanced modulator is that it consists of two mixers in parallel. The second mixer has no audio input so its output is simply another CW signal, just like its RF input. The two mixers share a common output transformer that has three windings - two primaries and one output winding. There is a primary for each mixer.

The clever part happens when the primaries generate magnetic signals in the transformer iron. The windings are oriented so that the two primaries work against each other. The CW signals in both windings are “balanced” with an adjustment pot so that they exactly cancel. This means that the only signals that appear in the secondary winding are the two sideband signals. *In*

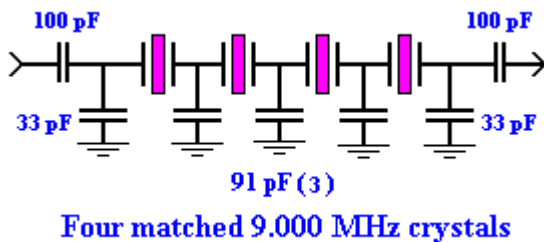
summary, a balanced modulator produces a double sideband signal with no carrier.

The transistors are dual-gate MOSFETs with the gates shorted together. The idea is to use transistors without any P-N diode junctions. According to the handbook, P-N junctions act like varactors and distort the speech slightly. I used dual gate MOSFETs simply because they were the only small RF MOSFET available. Single gate small RF MOSFETs are fine, but you may not be able to find any. I haven't tried JFETs, but they might work too. The above circuit was adapted from the 1986 Handbook.

To use this modulator for CW, there is a CW/SSB switch that unbalances the modulator and allows some carrier to pass through to the filter. Notice that when the switch is in the SSB position 12 volt power is fed to the microphone audio amplifier, thereby turning it on. When the switch is in the CW mode, pure CW carrier is sent to the filter. Unfortunately, this CW signal will be hard to use for actual CW contacts because the crystal filter will tend to remove most of the carrier again. However, this small 9 MHz sinewave is useful for tuning an antenna with a "test signal" or for "spotting" the VFO on top of the station you wish to call. For real CW operation, you could bypass the SSB filter with another switch or you could build a separate 9 MHz oscillator.

This sideband generator can also be modified to generate amplitude modulation. This is discussed in chapter 16. You can also go on the air with double sideband, DSB. Many homebrew sideband builders take this shortcut. It will sound like sideband, but the signal will be twice as wide as single sideband.

The sideband filter



You can buy sideband filters that select a 3 KHz passband, typically 9,000 KHz to 9,003 KHz. Sometimes matched oscillator crystals are also available that will position the RF signal optimally to line up with a particular filter.

In chapter 13 we made a 4-crystal CW receiver crystal ladder filter that was quite similar. The difference is the sizes of the accompanying shunt capacitors. In the receiver the shunt capacitors were 220 pF. However, ***The smaller the shunt capacitors, the wider the pass band of the filter.*** The 91 pF capacitor value in the above filter was scaled from a sideband filter used in a sideband transmitter designed around an 8.000 MHz SSB generator that used 100 pF caps. This filter seems to work, so I haven't had to experiment.

The homebrew way to build the filter is to buy a bunch of 9.000 MHz microprocessor crystals from Mouser or Digi-Key for less than a dollar each. Using the RF oscillator shown earlier and a frequency counter, measure the frequencies of each of your crystals. When used as filters, their natural frequencies may not be the same as in your oscillator, but their *RELATIVE*

frequencies will be comparable. Pick four crystals that are as closely matched as you can. Matching within 100 Hz should be adequate. I tried tuning each crystal to the same frequency using trimmer capacitors in parallel with the crystals. This proved to be unnecessary and I later removed the trimmers. This application is not nearly as critical as crystal filters for receiving CW in a receiver.

Using a signal generator as a test signal, these filters seem to peak very close to their nominal frequencies. For example, a crystal might oscillate at 9.0015 MHz in your test oscillator, but the filter will peak quite close to 9.000 MHz. So far I have built three of these filters and each one worked well and was centered more or less on 9.000 MHz.

The crystal oscillators are misaligned for CW

The crystal filter is set up to cut off either the upper or lower sideband. When you unbalance the balanced modulator to produce a CW signal, you will indeed get a small sinewave signal through the filter that may be strong enough to tune the antenna coupler or adjust the transmitter. However, because the center of the SSB crystal filter (9.0000 MHz) is lined up 1.5 KHz away from both crystal oscillators (8.9985 MHz and 9.0015 MHz), this CW signal will be far weaker than the maximum power you would get on voice peaks in SSB.

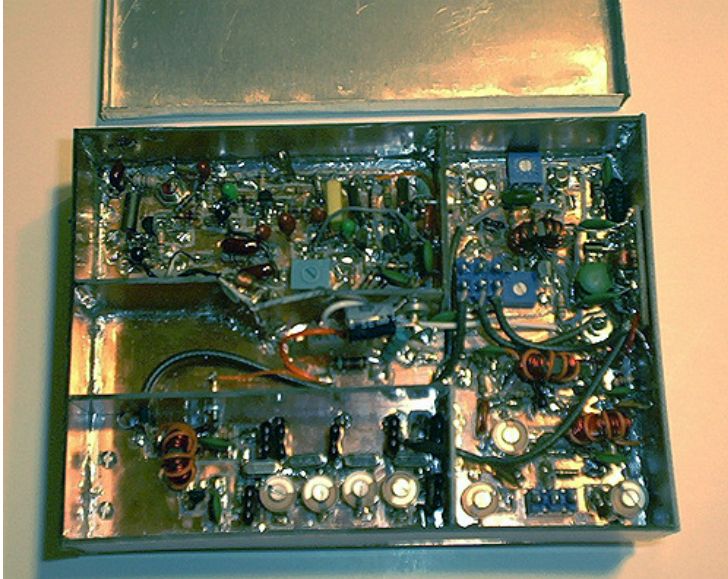
When I built a comparable filter for 8.000 MHz, the filter was centered on 7.995 MHz, 5 KHz low. I don't understand why this filter was different, because on an oscillator, the crystal frequencies were all well above 8.000 MHz. Because the filter frequency was so low, the upper sideband 8 MHz oscillator had to run on 7.9935 MHz. To drive the oscillator that low, I had to put a huge 150 pF cap across the 8.000 MHz crystal. I was amazed that the frequency locked in. Better engineering practice would dictate a custom crystal. A cheaper solution would be to start off with a different collection of cheap microprocessor crystals that center properly on 8.000 MHz.

MECHANICAL CONSTRUCTION

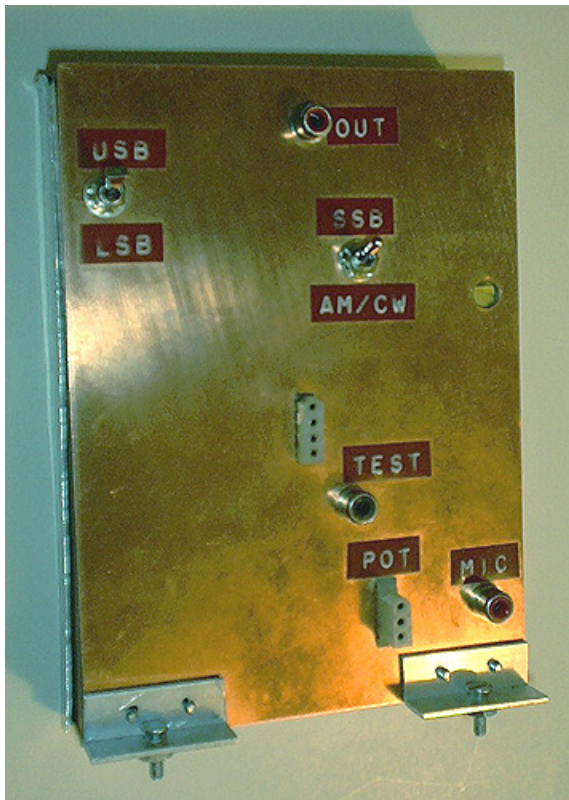
Sorry! You must shield sideband.

When building CW transmitters some of us think it's cool to have the pretty little parts out in the open where we can admire them. Unfortunately a huge problem with SSB is RF feedback. To help prevent that, you must enclose all the modules of your SSB transmitter in metal. All the connections between modules should also be shielded cables. I started out using shielded power cables to my RF modules, but eventually I worked out a way to mount the Molex connectors directly to the shielded boxes. In this way I could plug the module onto the chassis with no long exposed wires.

Actually, I still leave the linear amplifier out in the breeze, but all the low power modules and the power supplies are well shielded. If I were building a new linear, I would design in a shield from the start. All my modules consist of a two-sided PC board with walls of PC board soldered onto the edges to make a box. Then I fold an aluminum cover over the top to provide the lid.



The completed 9MHz SSB generator. An aluminum lid fits over the top of the box.



The 9 MHz SSB generator as seen from the control side



A dual frequency 9 MHz and 8 MHz SSB generator module is shown above

After learning that 9 MHz was impractical on 17 meters, I built a new SSB dual frequency generator. The 8 MHz crystals are in a row at the top left. The 9 MHz crystals are in a row just beneath them. The two frequency oscillators are at the bottom left. The balanced modulator is at the lower right. Notice that many of the components are mounted on inch high PC board strips and soldered in vertically. This allowed me to cram in about 50 percent more components than would otherwise be possible.

A major advantage of this technique is that circuits that don't work well can easily be removed and replaced. The loose little board on the right is a low pass filter that I took out when it appeared to be unnecessary. I removed it with little or no damage to the module. As you can see, some components, especially those directly wired to controls and connectors, are mounted on the "floor" of the box. If you wish to replace the circuitry on the "floor," you can unsolder all the old components and start over with a new board that makes a "patch" over the old circuit board laying out all the circuitry on the floor of the module box in the usual way.

Tuning and testing the sideband generator

The essential tools for tuning up your generator are *a frequency counter, an oscilloscope, and a good ham receiver*. Ideally, you need one of those same modern receivers that will be listening to your signal. The SSB generator above can generate a sideband signal on 9 MHz. Keep in mind that when you listen to the 9 MHz signal on your ham receiver, unless your generator is well shielded, you'll still hear the carrier signal and the suppressed sideband leaking from your 9 MHz oscillator. That's because those signal components are present on your circuit board and your receiver will have little difficulty in hearing them.

To check out the generator introduce audio from a Walkman radio into the test input allowing you to align the generator. Tune the Walkman to a talk radio station and inject the audio into the test input. Speech should not only be understandable in your ham receiver, the fidelity should be good enough that you can easily recognize the person's voice. When you turn off the BFO and set up the receiver for AM modulation, speech should become unintelligible. Music should always sound awful. If music sounds pleasant, your bandwidth is too high.



The 9 MHz SSB voice signal seen on an oscilloscope.

An SSB voice RF signal should appear on your scope as shown above. The audio modulation is symmetrical about the zero axis. In between syllables or words, the signal strength drops to near zero. The edges of the sinewave bursts should be reasonably sharp, meaning that the frequency should remain pure with varying levels of speech. When there is no audio input, there should be essentially no RF output.

Checking out the microphone and microphone pre-amplifier can be complicated. It's hard to listen to your own voice critically. Also, the audio from the ham receiver loudspeaker will feedback into your microphone. My solution was to put the microphone up against a high fidelity Walkman headset. Then I wrapped the headset in cloth to muffle the sound. To hear how it sounded on the air, I listened to the sideband generator signal in the ham receiver using headphones. Unfortunately, when used with the 50 watt amplifier, the RF from the dummy load and transmatch interfered with the Walkman so this technique only worked well for 5 watts. I was able to partly test the 50 watt linear by listening to my own voice while wearing headphones with no receiver antenna plugged in. I could at least confirm that there was no RF feedback.

Audio signal generator testing

It is instructive to feed an audio tone from an audio oscillator into the audio input test jack. This input is shown on the audio amplifier diagram. As you sweep the audio spectrum from 20 Hz to 3 KHz, watch the sideband generator RF output on the oscilloscope. Unlike AM modulation, there should be no audio frequency modulation visible on the radio signal. That is, for each audio sinewave frequency you should see a pure, CW-like signal. Another way to think about single sideband is that it is a kind of extremely narrow-band frequency modulation. As the audio frequency changes, the signal frequency shifts up and down in direct proportion. Unlike AM modulation, the amplitude of the transmitted signal shouldn't change when you introduce a constant amplitude audio frequency. That is, with SSB, you shouldn't see sinewaves impressed on the signal amplitude proportional to the frequency. The amplitude should only change with speech amplitude, not with speech frequency. In contrast, pure FM modulation does not change its amplitude with speech amplitude or with audio frequency.

Suppressing power supply RF feedback and low frequency coupling

My first sideband contact said, “Sorry, old man! I hear some hissing noises, but I can’t understand a word you’re saying.” It turned out that the power supply leads in the generator and other modules in the transmitter needed low frequency decoupling. In the sideband generator this consisted of the 51 ohm resistor and the two 220 microfarad caps on the 12 volt line. Without decoupling, the audio turns into noise as the generator competes with the final amplifier(s) for operating voltage. That is, the 12 volt supply voltage surges up and down with the speech and the amplifiers exaggerate this.

After these improvements my next contact could understand me, but he said my voice was “raspy with popping sounds.” I didn’t have laryngitis, so I asked Jack Quinn, KØHEH, about the criticism. He instantly diagnosed the problem: “That’s RF feedback. Improve the shielding of your microphone and audio amplifier.” I placed the 1000 pF capacitor directly across the microphone, the 430 pF bypass capacitors and the 470 microhenry inductors in series with the inputs and power line. Also, the power and audio output pass through feedthrough capacitors to further attenuate the RF. When RF feedback is really bad, the signal turns into a roar of noise that can sound similar to low frequency power supply decoupling problems.

**

The Hard Part --- Moving the SSB signal to a hamband

Is 9 MHz a hamband?

To get on the air you need to amplify the 9 MHz sideband signal up to 50 or more watts. Unfortunately, the last I heard, 9 MHz isn’t a hamband. Unfortunately, the hardest part of this project turns out to be moving the 9 MHz signal to the band(s) of your choice. Alternatively, we could all write to the WARC to ask them to establish a little 3 KHz hamband centered on 9.000 MHz. Maybe not.

Although moving the SSB to a hamband is the most difficult part of sideband, maybe it won’t be so bad if you don’t make the mistakes I did. Six principles I learned the hard way were:

*** *Move your sideband signal only once.*** Double conversion might appear convenient, but it’s extremely hard to do without distortion. In other words, don’t do the hardest task twice.

*** *In the conversion between 9 MHz and your HF band, make sure that the mixer input frequencies are far away from the final frequency.*** For example, to get on 20 meters, it is practical to add a 5 MHz VFO to 9 MHz to get 14 MHz. On the other hand I found that it was impractical to move a 4 MHz sideband signal to 21 MHz using a 25 MHz crystal oscillator. Every time I stopped talking, a significant 25 MHz signal went right out through the transmitter output filters.

*** *Plan your VFO and sideband frequencies so they do not divide evenly into the desired ham band frequency.*** For example, 2 times 9 MHz is 18 MHz. This fact makes using a 9 MHz SSB generator and/or a 9 MHz VFO to generate 17 meters extremely difficult. Notice that 6 MHz is also difficult because 3 times 6 MHz = 18 MHz.

****Don’t use tuned amplifiers and mixers.*** When you stop talking, tuned amplifiers tend to

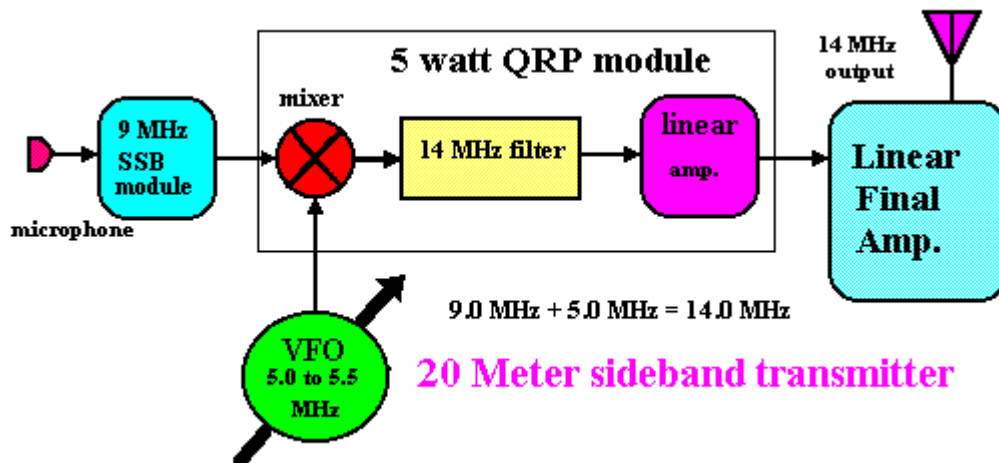
oscillate by themselves at the frequencies to which they were tuned. Actually, getting rid of the noise and oscillations when you're *NOT* talking is harder than making the speech intelligible. Unlike CW, it is best to use broadband mixers and amplifiers and to put all your ham band filtering into two passive filter networks. Sideband is different from CW!

* *Beware of having too much gain in your SSB generator and frequency converter.* I originally had unnecessary broadband amplifiers in the generator output and also right after the converter mixer. These extra amplifiers amplified noise. Every time I wasn't talking, they often began to self-oscillate.

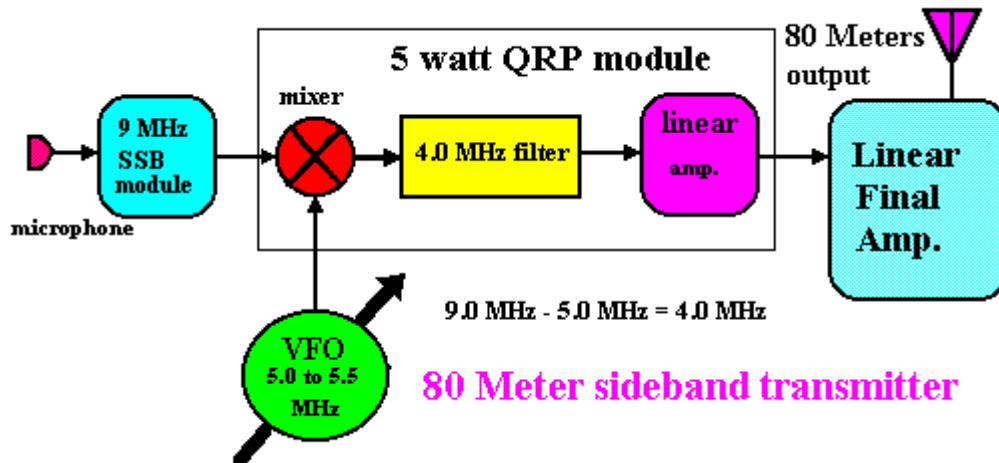
* *It sometimes helps to connect all ground connections to the outside layer of your two-sided PC board.* The ground connections for all high current RF stages must be extremely low inductance. Otherwise, if your board layout isn't well designed, RF voltages on all the ground traces inside the PC board box will "bounce up and down" with the currents in the power amplifier stages. This feedback introduces noise into the mixer stage and makes the QRP module difficult or impossible to adjust. If you are using 2-sided PC boards, solid grounds can be added by drilling the PC board at each ground connection and soldering wire shunts through the board to the unbroken sheet of grounded copper outside the PC board.

Getting on 20 and 80 meters

Hetrodyne converter for the SSB generator



When starting with a 9 MHz sideband signal, 20 meters is the easiest hamband to reach. For 20 meters, a 5.00 to 5.35 MHz VFO signal is mixed with 9 MHz to give 14.0 to 14.35 MHz. 9 MHz is 36% different from 14 MHz. Consequently, building a filter to extract the 20 meter component and suppress the 9 MHz signal is relatively easy.

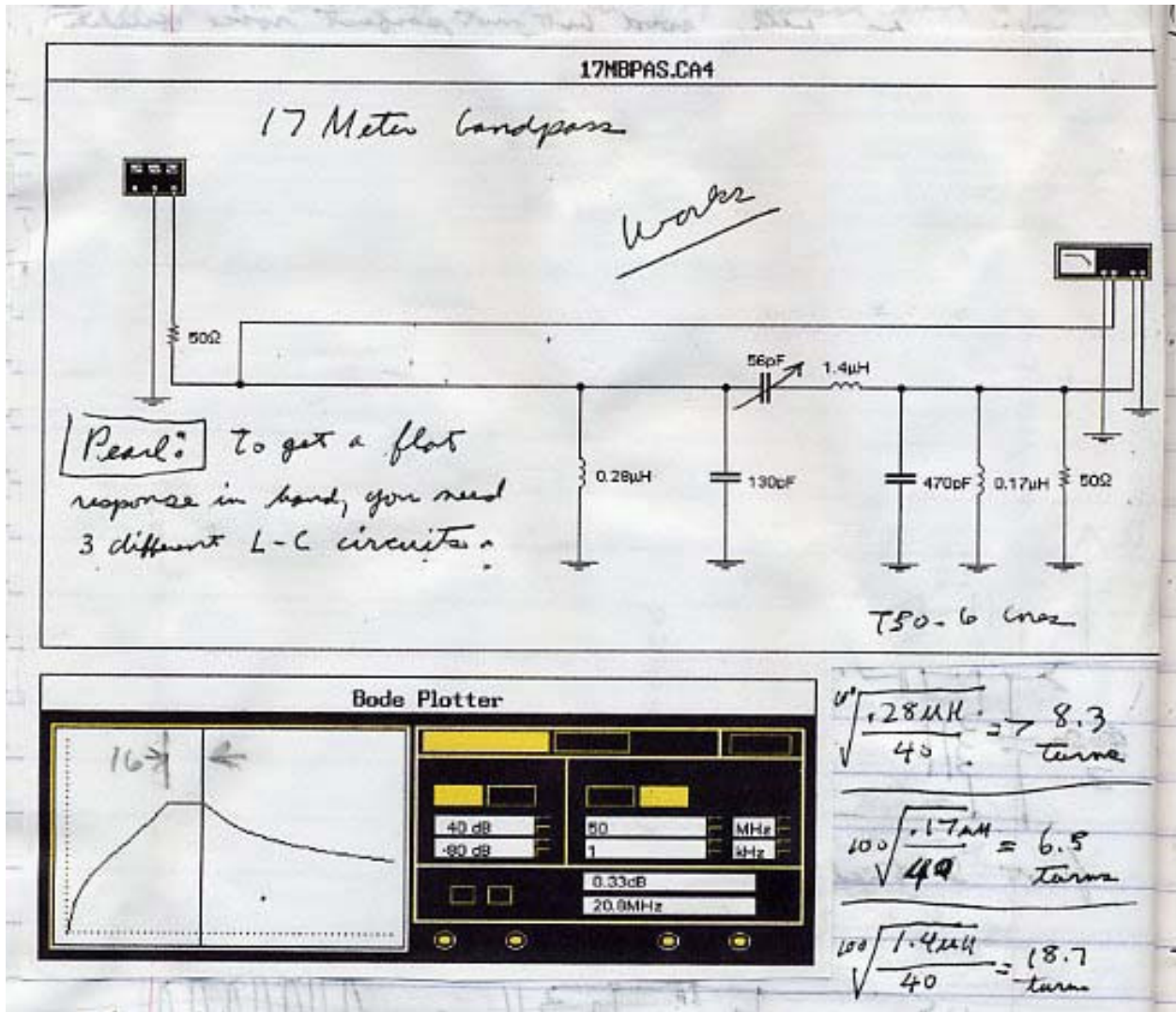


Now suppose that you wish to move the 9 MHz sideband signal down to 80 meters. 9 MHz minus 5 MHz is 4.0 MHz. The phone band extends right up to 4.0 MHz. So the 80 meter (75-meter) output signal can be as little as 20% different from the VFO signal. Filtering the 80-meter signal is almost twice as hard as 20 meters. What happens if your filtering is inadequate? Every time you stop talking, your linear final amplifier will be transmitting a sinewave carrier on your VFO frequency, 5 MHz. As we'll see, when you start with a 9 MHz sideband signal, all the other HF bands are harder than 20 meters.

Spice will make filter design bearable

I found my Spice program essential for simulating filters before I built them. I use a rather elderly program called Electronics Workbench, version 4. If I had had to calculate the component values or build all the filters by trial and error using real components, this project would have completely stalled. Using the program I could enter a possible filter design with trial values. When I ran the simulation, it plotted the frequency response instantly. It would inevitably be way off from what I had intended. But then I could quickly plug in dozens of values until I got the response I wanted. I get discouraged just thinking about building and testing those filters the old way and plotting the results at each frequency with real components.

Below is a copy of a page from my notebook showing one of the most difficult filters I built. It was a low impedance band pass for 17 meters. After it looked right on the computer, I built a real one and it tuned up immediately using the variable cap in the center. The simulations are amazingly trustworthy. I found that when the simulation predicted small capacitor values, it was wise to use a variable capacitor in that location. If the capacitance or inductance came out extremely small, for example, a few picofarads or hundredths of a microhenry, I changed the design until all the components had significant values. Once I had a design on paper, I built the real filter and tested it using a frequency generator and scope to confirm that it really behaved as simulated.



Self-oscillation

When you build a high-Q amplifier-filter stage, it tends to oscillate on its own whenever there is no signal coming into the input. This means that, in between words, your QRP module may be oscillating on some random frequency on or near the ham band you are using. Sometimes this oscillation can be suppressed by placing a 50 or 100 ohm resistor across the input of the offending stage. Another method is to place a 1K to 2K resistor across the RF transformer primary on the collector or you may add a small resistance (such as 10 or 20 ohms) of un-bypassed resistor in series with the emitter of the transistor. Unfortunately, these tricks are usually not enough. **The best solution is to use untuned broadband amplifiers!** Even with broadband amplifiers, you will still have to use some or most of these tricks to keep them from oscillating.

No wonder most rigs are transceivers

There is a great deal of similarity between a sideband receiver and a sideband transmitter. Once you've built a receiver, it dawns on you that the transmitter has most of the same modules and that you are building the same circuits twice. On the other hand, using the same circuit

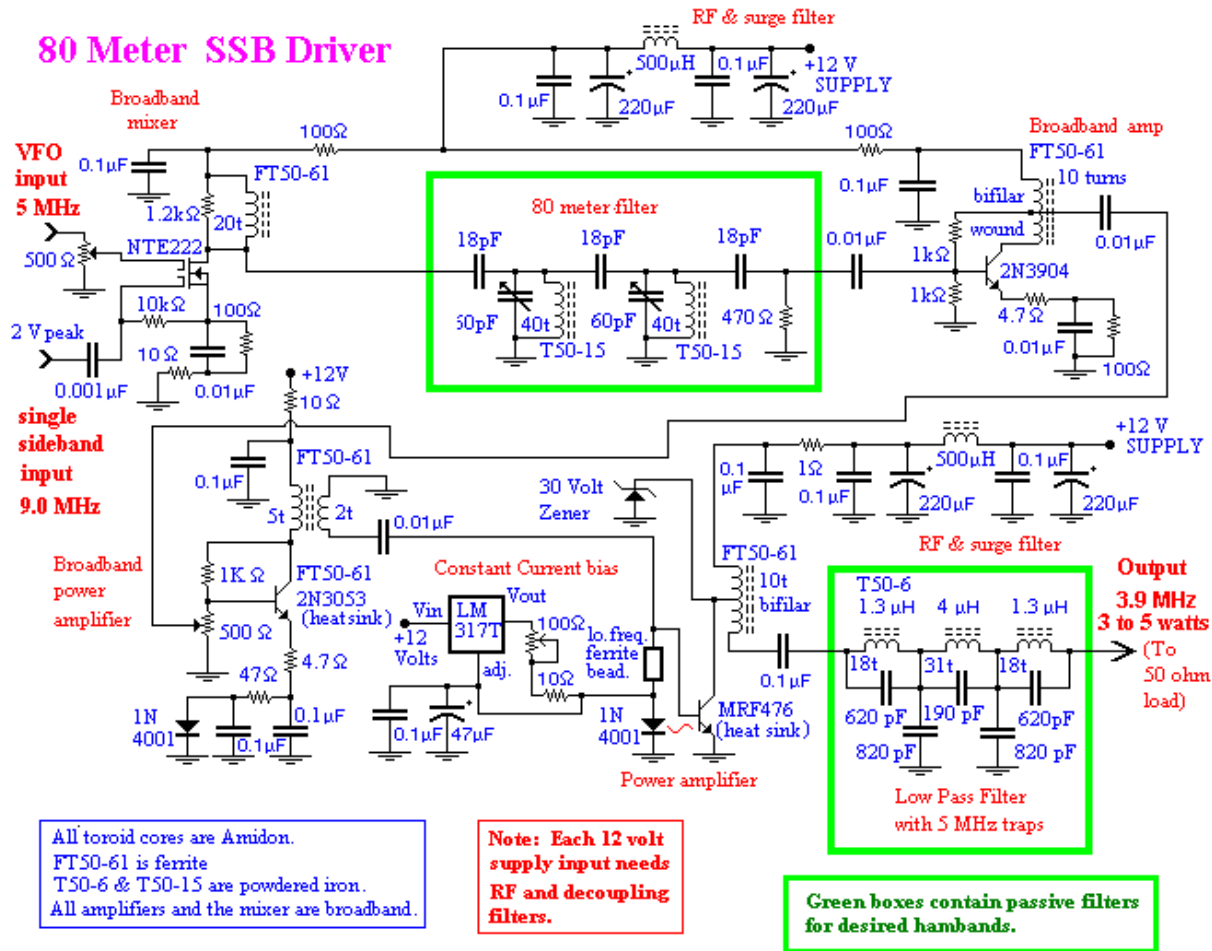
modules for both tasks takes finesse. Unfortunately we homebrewers have enough problems without that extra complexity.

Ideally, it would be best to use the 5.0 MHz VFO from your receiver. That way the transmitter frequency and receiver frequency can zero beat exactly. When you answer a CQ, you don't want to take the time to tune the transmitter VFO. When I got on the air with my separate 5 MHz VFO, I found that, by the time I had it precisely zero beat with the guy calling CQ, he was often already talking to somebody else.

Unfortunately, using the receiver VFO isn't simple. If you simply connect it to the transmitter by a long cable, the receiver will suddenly acquire intermodulation, noise, and whistles. To get past this, the VFO signal must be isolated from the receiver by an isolation amplifier. Also, the 9.000 MHz BFO and the sideband generator oscillator must be on the exact same frequencies. It really should be the same 9 MHz oscillator. Furthermore, the VFO band conversion oscillators in the receiver and transmitter must be aligned to within a Hz or two. Hmmm ... this isn't so easy after all. The transceivers solve the problem by using the same oscillators for all those tasks so alignment isn't a problem. I believe a homebrewer can enjoy all the convenience of a transceiver, but only if we design it as a transceiver from scratch. It seems to be impractical to merge an SSB transmitter with an existing receiver.

An 80 meter sideband QRP driver

As explained above, an untuned mixer should be followed by a *totally passive filter*. That is, the filter should be just a network of LC circuits. It should have no transistors. Instead, the gain is provided by two or *three untuned stages in series*. Three high-gain broadband amplifiers in series can work without oscillating, provided that their input has very little noise. The basic design shown below has the advantage that, it can be used on any HF band. To change bands, you plug in different filter sections shown in the green boxes below.



All transistor stages are broadband, including the mixer. Note the 1.2K resistor across the primary of the mixer ferrite core transformer. Without this or other feedback device, the broadband amplifiers tend to generate an uncontrolled signal whenever the SSB input drops to zero between spoken words. The un-bypassed 4.7 and 10 ohm emitter resistors in three of the amplifiers also help prevent oscillations. To reduce surging and RF feedback to the driver module I filtered my 12 volt input leads with RF chokes, big capacitors, and small ceramic capacitors.

Unlike the CW QRP modules, the SSB module output stage needs forward bias to operate in linear mode. The LM317 circuit current source supplies the needed current. This temperature compensated circuit was used in the 50 watt linear in chapter 12 and is overkill for this 5 watt final, but what the heck! With experimentation I found that just 20 milliamperes of forward bias is plenty to operate linear and give good speech quality. In theory, a 560 ohm, one watt resistor can provide this bias much more cheaply. However, I haven't tried this.

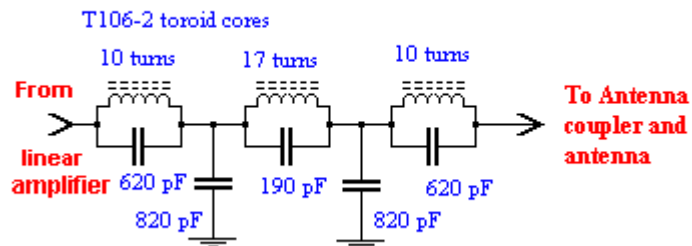
A passive high impedance (500 ohm) 80 meter filter is placed between the mixer and the first broadband amplifier. The output stage filter is the usual 50 ohm Chebyshev low pass except that capacitors have been placed in parallel with the inductors. These make the inductors resonate at 5 MHz and provide extra attenuation to get rid of the 5 MHz VFO signal. Notice that

the equivalent of five parallel and series LC circuits were used to clean up the 80 meter signal. In contrast, as you'll see on the next page, a 20 meter QRP (5 MHz + 9 MHz) can be done with just two LC circuits and an output high pass filter.

Beware of residual VFO signal

Once I had the 80 meter driver (shown above) working well, I fed it into my linear amplifier described in Chapter 12. With the amplifier it produced 60 to 100 watts on voice peaks. However, whenever I stopped talking, the frequency counter probe on my antenna shifted to the 5 MHz VFO frequency, even though the amplitude of the signal on the scope screen looked negligible. When I turned up the scope amplitude, sure enough, there was a 5 volts peak sinewave on the output. That represented about 0.25 watts of 5 MHz sinewave. To get rid of it, I rebuilt the final (high power) amplifier 80 meter low pass output filter using another "elliptical" filter design. Once again each inductor has a parallel capacitance that resonates at 5 MHz and keeps the 5 MHz out of the antenna. I used the values shown below. After that change the residual, no-speech signal was only 1 volt peak and the counter measured it as the correct output frequency, 3.9 MHz.

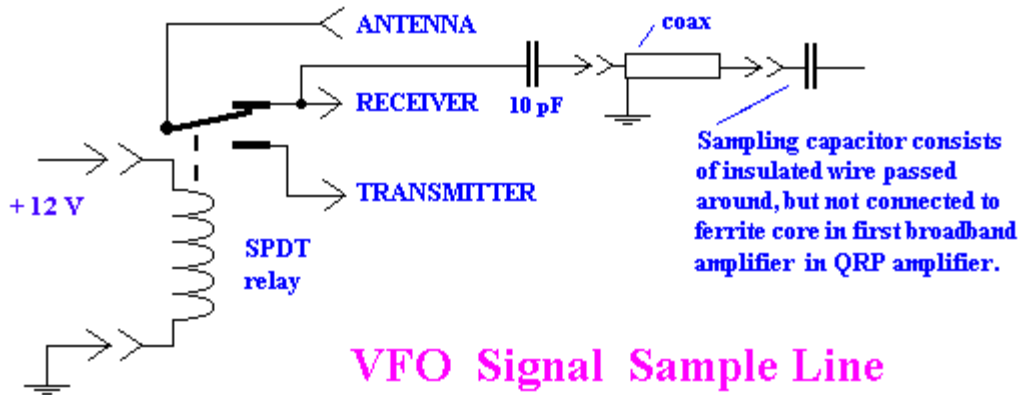
80 Meter lowpass Elliptical Filter for Linear



If you are like me, you will have a devil of a time getting your SSB drivers to produce intelligible speech without hissing and noise problems. All I can tell you is to keep your brain mulling over your difficulties. Shield and filter your prototype until the darn thing works. Keep careful notes so you don't make the same mistakes twice. Persistence will win in the end.

Hearing the transmitter VFO in your receiver

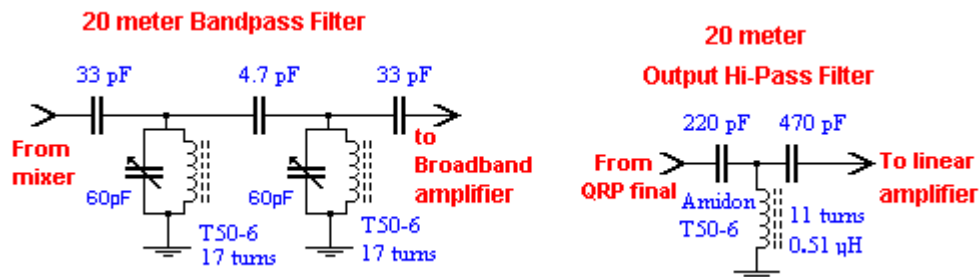
One consequence of shielding and filtering every low power module of my SSB transmitter was that I could not hear my own VFO signal. This made it impossible to tune the VFO to a station I might wish to talk to. Eventually I solved the problem by connecting a tiny capacitor, 10 pF, to the receiver antenna terminal on the antenna relay. This capacitor is connected to a shielded cable that runs over to my QRP module and plugs into a shielded phono connector on the side. Inside the QRP module an open-ended wire runs over to the first of the three broadband amplifiers (not the mixer) and passes one turn through the ferrite toroid core. This sampler wire is not a complete winding turn. It is *NOT* connected to ground or anywhere else. The wire just serves as a tiny capacitor or antenna to sample a bit of VFO signal for the receiver. During transmit the antenna relay disconnects the sampler wire from the transmitter to prevent it from causing feedback from the antenna into the transmitter.



When I push the "Spot" button on my transmitter, 12 volts power is connected to all the low power modules of the transmitter. During "Spot" mode, the 12 volt power is *NOT* connected to the last two power amplifier stages of the QRP. The 12 volts goes to the 5 MHz VFO, the SSB generator, the VFO frequency converter (if one is used on that particular band), the mixer, and first broadband amplifier of the SSB QRP module. The first amplifier is the first place in the transmitter where the actual broadcast frequency is present for sampling. Because the final frequency depends on the 9 MHz signal from the SSB generator, there will be no signal from the SSB generator unless you are actually talking or the generator is set to "CW." In summary, to hear the VFO without transmitting, the SSB generator must be set to "CW," the "Spot" button must be pushed, and the receiver antenna needs a tiny capacitive coupling to the first broadband amplifier. In SSB, even simple things are complicated. See the fun most hams are missing?

Adding 20 meter capability to the 80 meter QRP module

In the 80 meter module above there are two filter networks. You can put this same QRP module on 20 meters by switching in a 14 MHz filter after the mixer and by replacing the low pass on the output with a high pass filter. On 80 meters the 9 MHz and 5 MHz unwanted signals are above 4 MHz. Therefore, the 80 meter QRP module has a low pass filter. In contrast, on 20 meters the unwanted frequency components are below 14 MHz. Therefore, a high pass is desirable for 14 MHz. The filters to put the module on 20 meters are shown below. My module uses two DPDT switches to switch back and forth between the 80- and 20 meter bands.



Feedback and distortion – don't overdrive!

A frequent problem I ran into was using too much drive on a stage. For example, I built my prototype for 20 and 80 meters. And after many changes and fussing I got it to work. Then I

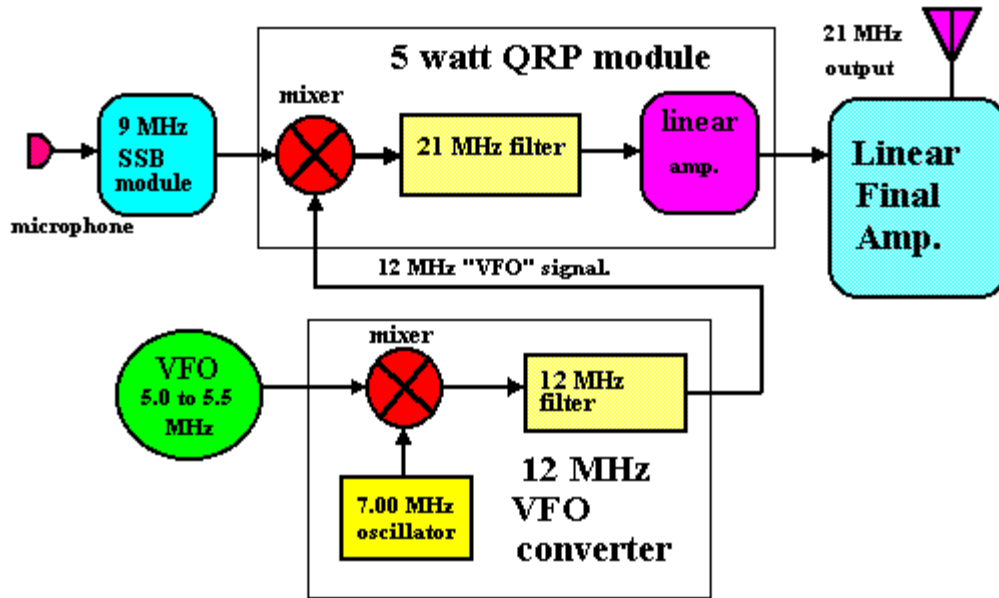
reproduced the circuit for use on 17 and 12 meters. However, the second time I knew what I was doing and the new circuit was much “cleaner.” The result of my compact, pretty wiring was higher efficiency and more power out of each amplifier stage. Instead of 3 watts output, now I had 6 or 8 watts or more and I was overdriving the linear final. Excess drive gave my signal a rough, rasping sound and made the speech hard to understand. To fix this, I had to go back and decrease the output by various methods. I decreased transformer turns driving bases, used more negative feedback (emitter resistance), etc. Finally I put the 500 ohm pot in front of the 2nd broadband amplifier. This enabled me to deliver just what I needed and no more. Now the voice quality was acceptable. The pot worked so well, I went back and installed one in my 80/ 20 meter driver module.

Moving an SSB signal to the “difficult” hambands

As explained above, the easiest hambands to reach with your SSB generator are 80 and 20 meters. Unfortunately, on weekends 20 meters is the most crowded ham band. It's full of guys running 1,500 watts peak into Yagi beam antennas 50+ feet in the air. If that weren't bad enough, their sideband transmitters are exquisitely designed to get the most modulation out of every watt. If you do get on 20 meters with your little homebuilt, it will probably average 20 to 40 watts on voice peaks. Combine that with your dipole antenna and it's going to be hard for those big guys to hear you. On the other hand, a band like 15 meters (or possibly 17 meters) is less crowded and you are more likely to make solid, enjoyable contacts there.

Getting on 15 meters

How do we move the 9 MHz to 21 MHz with a 5 MHz VFO? My solution was to move the 5 MHz VFO to 12 MHz. Then I added my 12 MHz VFO to 9 MHz to get 21 MHz. ($12 \text{ MHz} + 9 \text{ MHz} = 21 \text{ MHz}$) After mixing, the 21 MHz signal was 43% different from the nearest frequency component and filtering was relatively easy. Unfortunately, moving the VFO to 12 MHz is quite cumbersome. However, it uses technology you have already mastered. So, in the long run, I believe moving the VFO is the easiest way to go.



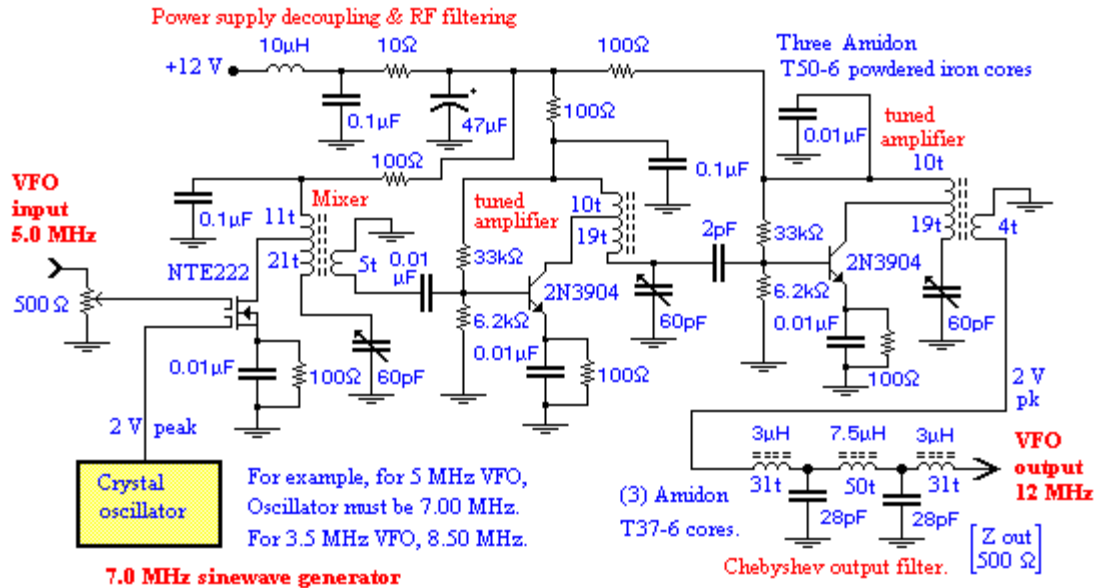
Generating a 12 MHz VFO signal

The VFO signal is just a sinewave. Therefore, compared to moving sideband, moving a sinewave to 12 MHz is relatively easy. There are no frequency or amplitude modulation components present, so the 12 MHz signal is easily filtered and purified. To move the 5 MHz VFO to 12 MHz, mix it with a 7.00 MHz signal from a crystal oscillator. Think of the VFO mover as a primitive frequency synthesizer.

A 5 MHz to 12 MHz VFO converter

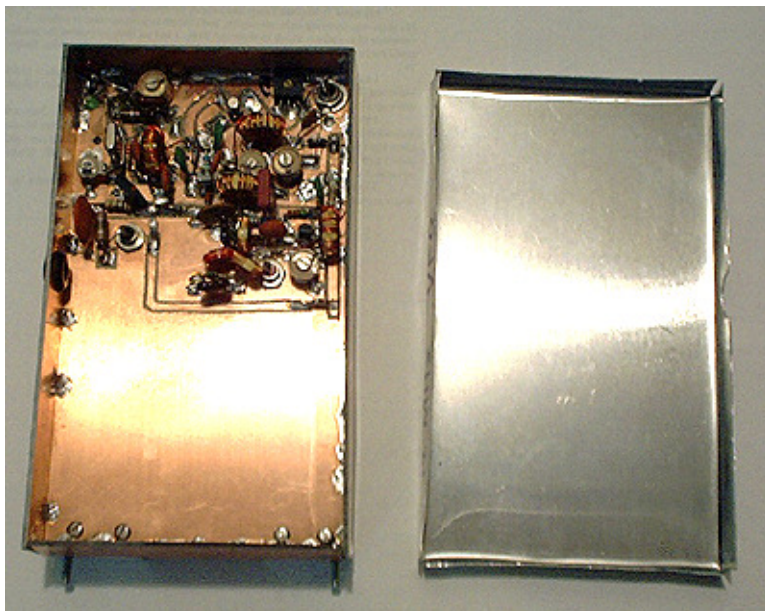
The frequency converter contains the same circuits I used in my CW QRP boards in which I used an 80 meter VFO to drive a CW signal on each HF band. I used the dual gate mixer because it was simpler than the bipolar transistor mixers I used in my first QRP boards. If you start with an 80 meter VFO, it can be combined with a 8.5 MHz sinewave to give 12 MHz. You get the idea.

12 MHz VFO Converter for 15 Meters



The VFO converter moves the 5 MHz VFO up to 12 MHz

Before you build this, I suggest you look at the VFO movers for 17 meters and 10 meters shown later. I believe these newer VFO converter designs are more stable, more versatile, and easier to adjust.

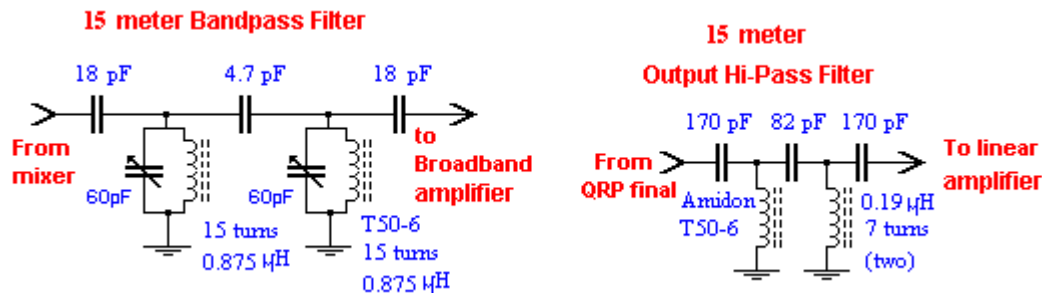


The 12 MHz VFO converter. I left room for a second VFO converter for some other band.

A linear sideband QRP module for 15 meters

Once you have generated a stable 12 MHz VFO, it needs to be mixed with the 9 MHz

sideband signal to get on 21 MHz. Using the same design as the 80 meter QRP shown earlier, now all you need are the two passive filters to go into the QRP module. The bandpass filter is the same design as before, but I used a 5-element high pass filter on the output to get rid of the signals below 15 meters that tend to appear when I'm not talking. The two filters are shown below.



Notice that the output of the QRP driver described above has a *HIGH PASS* filter designed for 50 ohms that works best for driving a final amplifier. If you wish to run the driver “barefoot” and go on the air with just 5 watts peak, you’ll also need a low pass filter, just like the ones you built for the CW QRP drivers. The most troublesome unwanted frequencies are the second harmonic of the 12 MHz VFO (24 MHz) and the second harmonic of the SSB generator, 18 MHz.



A 21 MHz Driver module. The box lid is shown above the board.

Notice the “pigtail” power supply cable in the above driver. This was an invitation to RF interference. This cable acts like an antenna. I later modified the Molex connector so that it is imbedded in the bottom wall of the module. Now the module is plugged directly into the metal transmitter chassis with no exposed cable. RF feedback has not been a problem.

17 meters can be really tough

My first problem with 17 meters was that the sweep oscillator in my oscilloscope makes an 18 MHz signal that my receiver picks up right in the middle of the 17 meter band. Another odd problem with 17 meters was that it interferes with my cordless phone and my stereo. The other bands don't cause this interference so it's a mystery to me. More importantly, I'm nervous about what might be happening over at the neighbors.

Anyway, even without those troubles, 17 meters is particularly difficult when starting with a 9 MHz SSB generator. 18 MHz is the second harmonic of the 9 MHz SSB signal. Therefore the 17 meter frequency converter will also amplify the second harmonic of the sideband signal. This means that, although there may be a good signal on 17 meters where it is supposed to be, (for example, 18.130 MHz), there will also be a small sideband-like signal on 18.000 MHz. Of course the frequency deviation of the unwanted signal will have twice the audio frequency modulation. In the old days it was routine to move low frequency VFOs to high frequencies using frequency multiplier amplifiers. It is difficult to avoid building a multiplier/amplifier here and it will be hard to get rid of unwanted 18 MHz signals with simple filters.

In addition, if you generate a 9.130 MHz VFO signal to add to the 9.000 MHz SSB to get 18.130 MHz, you will also be transmitting the second harmonic of the 9 MHz VFO sinewave signal. That is, if the desired frequency is 18.130, there will also be another small second harmonic sinewave transmitted on 18.260.

Practical approaches to getting on 17 meters

In spite of these harmonic troubles I first pressed on with 9 MHz. To avoid the 2nd harmonic of a 9 MHz VFO, I added my 5 MHz VFO to a 22 MHz oscillator producing a 27 MHz VFO signal. Then I subtracted the 9 MHz from 27 MHz to get 18 MHz. *Notice that when you subtract an SSB signal from a higher frequency, the upper sideband becomes the lower sideband and vice versa.* The VFO worked fine, but occasionally I discovered that I was loading up on 18.000 MHz, the second harmonic of the SSB generator signal, not the correct frequency component. In short, the behavior with a 9 MHz SSB generator was too flaky to trust.

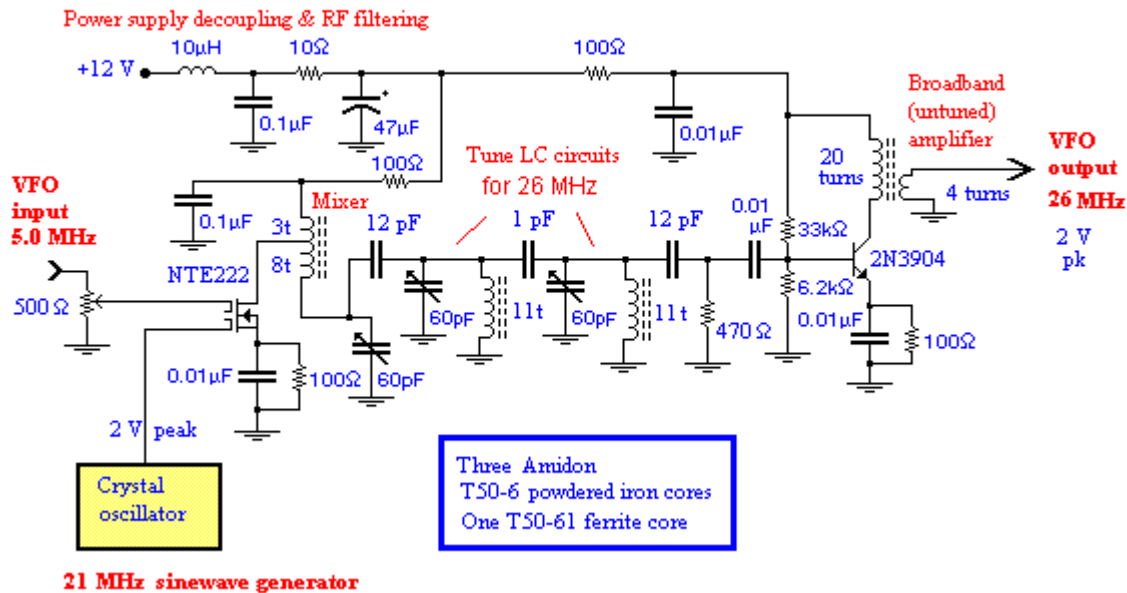
The best way to get on 17 meters is to start over with a different SSB generator frequency, say 8.0 MHz. Then you can combine that with a 26 MHz VFO and it will work OK. In other words, 26.13 MHz - 8 MHz = 18.13 MHz. With this approach you aren't using any 9 MHz frequency components and second-harmonic, out-of-band emissions will be much less likely. I strongly recommend this approach. I really don't think a 9 MHz SSB generator can be reliable on 17 meters without first moving the 9 MHz SSB signal up above 18 MHz. That is, you would have to move the sideband signal twice. My solution was to start over and build a new SSB generator with two filters switch-able between 8 MHz and 9 MHz. My 8 MHz crystal filter was just like the 9 MHz filter, but the 91 pF capacitors were proportionately increased to 100 pF.

There are lots of ways to screw up on 17 meters. For example, *start with a 6 MHz SSB signal and the 3rd harmonic of the signal will be on 18.000 MHz and will be just as bad as 9 MHz.* You can also screw up with 8 MHz. For example, the 8 MHz SSB can be added to a 10.15 MHz VFO to get 18.15 MHz. Unfortunately, the 2nd harmonic of 10.15 MHz is 20.30 MHz. This continuous sinewave is close enough to 18 MHz to go right out over the air whenever you stop talking.

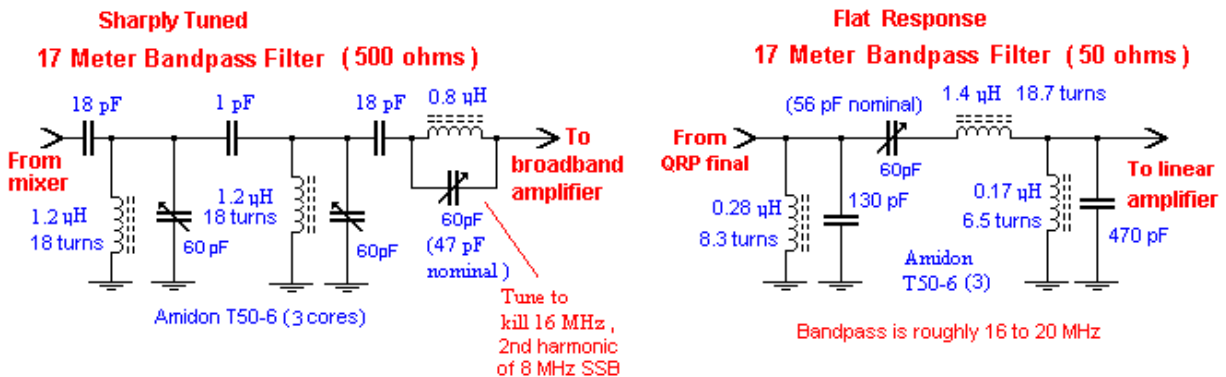
17 Meters with an 8 MHz SSB generator:

As shown below, I eliminated the VFO harmonic problem by generating a 26 MHz VFO. The second harmonic of an 8 MHz SSB generator is 16 MHz. Fortunately it wasn't hard to avoid accidentally tuning it to 16 MHz. Notice again that the SSB is subtracted from a higher frequency so *the SSB generator must be set to the lower sideband to get upper sideband on 17 meters.*

26 MHz VFO converter for 17 meters



The output of the 5 watt driver needs both a low-pass to get rid of the 26 MHz artifact and a high pass filter to avoid the low frequency “bursting” problem. Rather than choosing between high pass or low pass, I used a second 18 MHz bandpass filter that severely attenuates both 8 MHz and 26 MHz. This flat response bandpass filter is designed for 50 ohms. In contrast, the sharply tuned bandpass filter following the mixer is designed for high impedance, 500 ohms input and output. The 500 ohm bandpass filter is easier to design, but it can't handle any power and the impedance is incorrect for the QRP output.

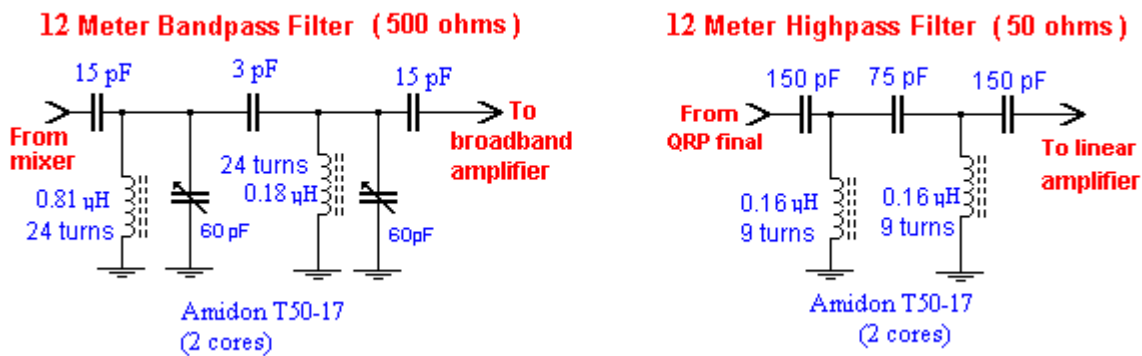


The filter on the right has a flat response from about 16 MHz to 20 MHz. In order to get the flat response, the three LC resonant circuits all have different values. And, of course, the three L-Cs interact, so a simple calculation wouldn't work anyway. I derived this circuit by trial and error using my Spice program. The component values must be rather precise otherwise the response has sharp peaks. Notice the fractional turns on the cores. These should help you be aware that wrapping the wire a tad more or less might make a difference. I found that making the

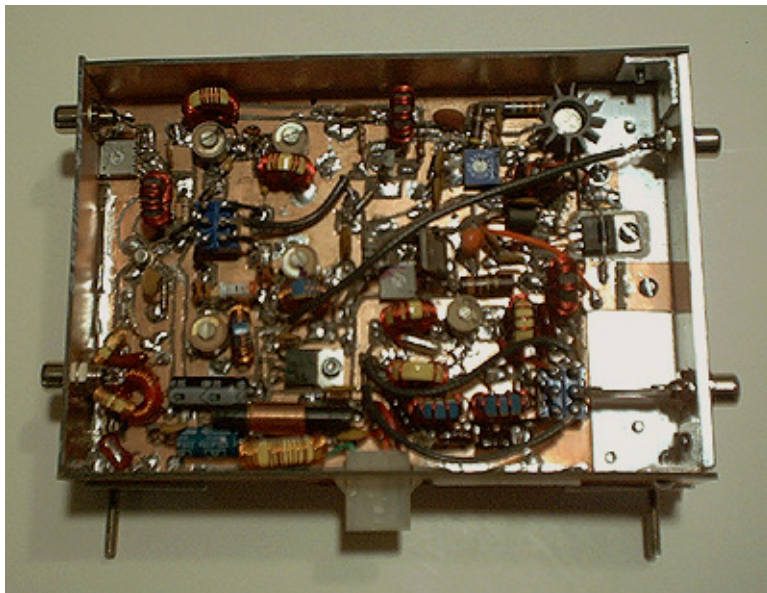
smallest capacitor(s) variable was useful for final tune up. A few picofarads can make a big difference. Anyway, it was a struggle but eventually it worked. Tuning the series variable cap peaks it up nicely on 18 MHz.

Filters for 12 meters

In contrast to 17 meters, 12 meters was much easier. I generated a 15.9 MHz VFO signal by adding my 5 MHz VFO to a 10.700 MHz crystal oscillator. The QRP combines the 9 MHz SSB signal with the 15.9 MHz VFO to produce 24.9 MHz. The high impedance bandpass filter following the mixer is tuned for 24.9 MHz. At the output of the QRP module all the unwanted frequencies are well below 12 meters. Therefore the low impedance output filter is a simple high pass.



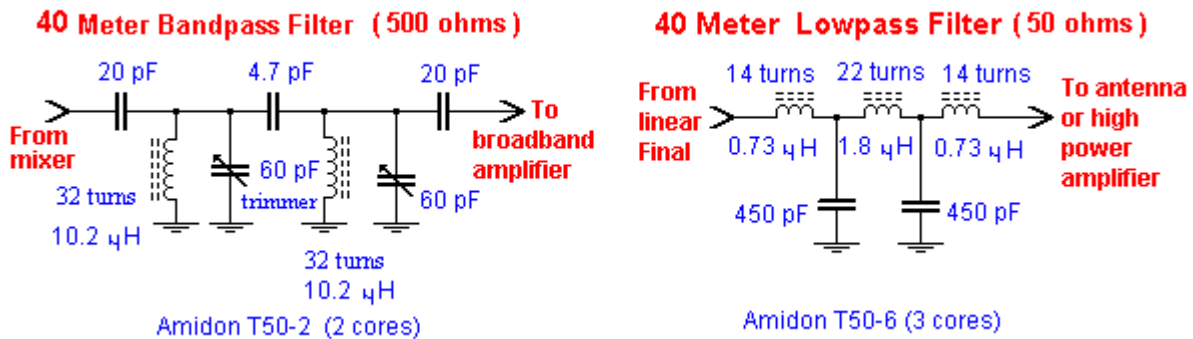
The driver for 12 and 17 meters is shown below. Notice how this module has its Molex power plug mounted on the bottom. It plugs directly into the transmitter chassis and avoids exposed wires. This QRP driver also has an aluminum cover to shield the circuitry from RF.



Getting on 40 meters SSB

Forty meters was also straight-forward. I generated a 16 MHz to 16.5 MHz VFO signal by adding the 5 MHz VFO to an 11.000 MHz crystal oscillator. Then I subtracted the 9 MHz

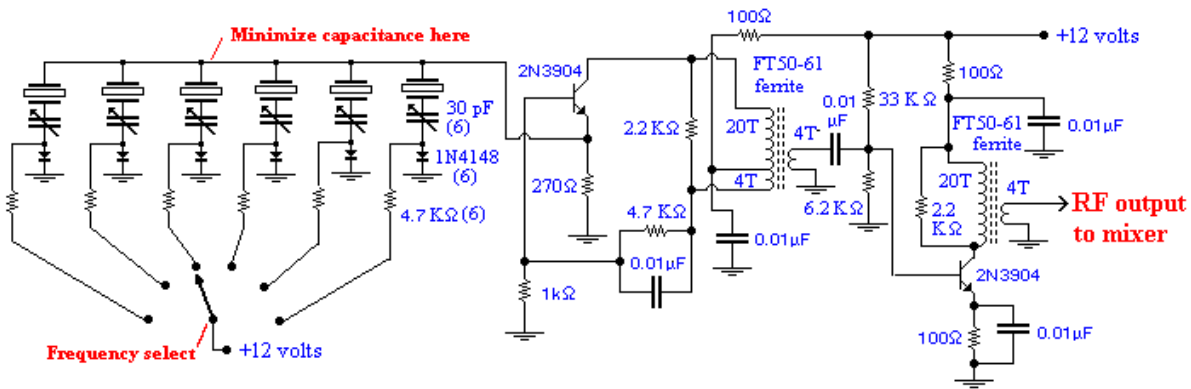
SSB to get 7.00 to 7.50 MHz. Because of the subtraction, the upper sideband 9 MHz SSB signal generated the lower sideband signal on 40 meters. The 40 meter QRP mixer filter uses almost the same tunable bandpass filter used in the DC receiver in chapter 7. Since all the frequency components are well above 7 MHz, a low impedance lowpass filters the output. As usual, 40 meters was kind to me and it worked right away. I was immediately able to check into my local state-wide 40 meter noon net.



SSB on 10 meters

The tricky part about 10 meters is that it's 1.7 MHz wide, 28.0 MHz to 29.7 MHz. My VFO only tunes a range of 0.5 MHz. Therefore it takes 4 crystal PMOs to cover the whole band. I solved the problem with a quadruple frequency crystal oscillator. A 6 position rotary switch switches in the appropriate crystals for 28, 28.5, 29.0, and 29.5 MHz. My oscillator uses the other two switch positions to cover 12 meters and 40 meters. The crystals aren't switched directly, but rather, they are grounded one at a time by means of diodes that are biased *ON* by means of a 12 volt DC signal passed through the 4.7 K resistors. The advantage of this DC switching method is that, if you like, the rotary switch can be far away from the oscillator up on the front panel.

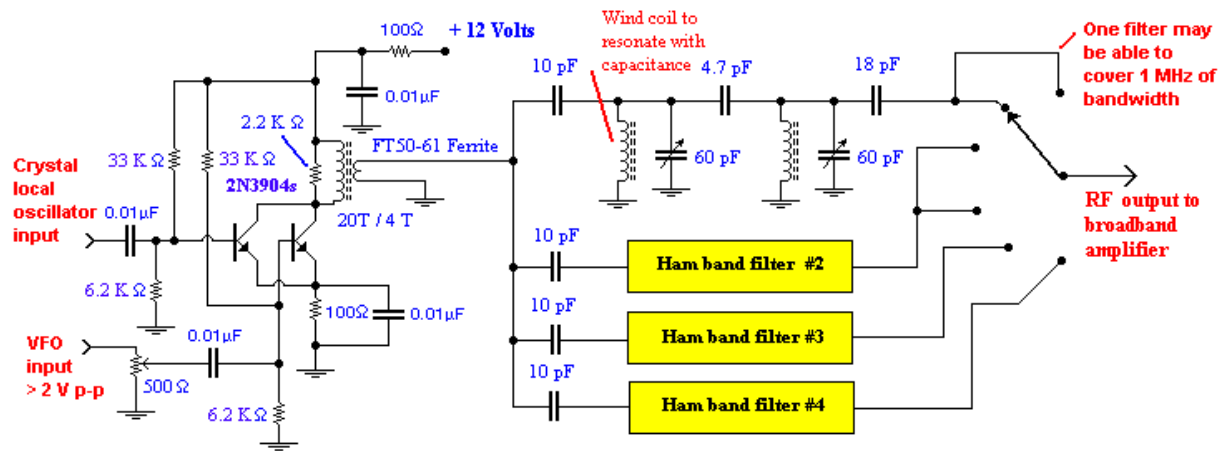
Be sure to minimize the capacitances between the oscillator emitter and ground. All those crystals connected to the emitter will be affected by the extra capacitance. This will tend to pull each crystal frequency away from its nominal value. Too much capacitance and it may not oscillate at all.



MULTI - CRYSTAL OSCILLATOR

The multi-crystal oscillator covers a wide range so the oscillator could not be tuned and had to be broadband. Therefore the oscillator frequency is entirely controlled by the crystal frequency. Obviously the particular crystal must spontaneously oscillate on that overtone frequency and not a lower, primary frequency. And, because the oscillator stage isn't resonant, its signal output is tiny, tenths of a volt. Consequently, I had to pass the oscillator signal through a broadband amplifier to make it large enough, about 2 volts p-p, to be sent to the mixer to be mixed with the 5 MHz VFO.

After the mixer each VFO signal must be filtered to select the desired frequency component. My 6 position rotary switch has a second section that allowed me to switch in a filter for each frequency. I found that just two tuned filters could cover the whole 10 meter band. I didn't need 4 separate filters after all.



MULTIPLE FREQUENCY MIXER

The tuned filters are high impedance and connected to the mixer with 10 pF capacitors. Because all the filters are connected to a low impedance transformer winding, the mixer can drive all of them at once. As shown the total load is only 40 pF. The rotary switch on the right then picks out the desired filter output. Another broadband amplifier amplifies the filter output before it goes to the SSB QRP driver where it is combined with the 9 MHz SSB signal. By the

way, I tried to use the switching-by-grounded-diode trick to switch filters but that idea worked poorly. For 10 meters this VFO converter generates VFO signals from 19 to 21 MHz.

Frankly, my 10 meter QRP only seems to work well up to 29 MHz. It doesn't work properly above that frequency because my QRP mixer filter isn't broadband enough. I guess I need two high impedance tuned filters. Also, since 10 meters has been dead for several years now, I have yet to make a 10 meter SSB contact. Needless to say, my 10 meter SSB is still a work in progress.

Getting on 60 meters SSB - don't bother!

Before the 60 meter (5 MHz) SSB frequency became available to American hams on July 4th 2003, I thought it would be fun to get on the air before commercial gear became available for this new frontier. I naively thought that homebrewers would own the band for at least a little while. My sad story about my attempt to be a pioneer on 60 meters is told in Chapter 16.

Checking out the QRP module

You will have to experiment with how to listen to your sideband signal at a signal level that simulates what it would sound like if you were receiving it off the air. I run my QRP into a 50 ohm dummy load. Then I disconnect my receiver from the antenna and leave the antenna coax from the receiver lying on the bench a few feet from the sideband generator. If that's not strong enough, I clip a test lead to the transmitter ground, then clip the other end to the center conductor of the receiver antenna coax connector.

I start by feeding a 9 MHz sinewave (CW) signal into my QRP board and then tune the filters to produce the largest, stable sinewave output into the dummy load. I monitor the frequency with a counter to be sure the VFO is controlling the frequency properly over the entire ham band. I adjust the VFO input level to produce the maximum output signal. However I just use the minimum 5 MHz VFO level that achieves this. When you are *NOT* talking, excess VFO will tend to induce signals on unwanted frequencies. I increase the DC bias to the output transistor until that transistor draws about 20 milliamperes DC more than it does with the bias set to minimum.

After the CW mode is working properly, I switch to SSB and use an audio signal injected into the "test input" of the SSB generator. I use speech from a talk radio station as supplied by a little Walkman radio. If you're lucky, the speech should sound pretty good in your ham receiver. If it doesn't, decrease the drive to the last two stages of the QRP using the 500 ohm pot. You may also need to reduce the number of secondary turns on the transformer feeding the output transistor. For example, instead of 3 turns, 2 turns or even one turn may be optimum for your particular QRP board. I found that overdriving stages was a common cause of poor audio.

Driving a QRO linear amplifier

A QRP sideband transmitter is just fine for communication around town. One or two watts are plenty for talking a few miles. But unless you have a great antenna and good conditions, you won't talk to many stations with just a few watts. For distant stations a linear amplifier will be a big improvement. Building a 50 watt linear is explained in chapter 12. If you are going to have trouble with RF feedback and insufficient power supply decoupling, a big linear amplifier will bring out these troubles. RF from my antenna coupler feeds back to my

Walkman radio and (usually) makes that speech source impractical for testing. I usually listen to the receiver with headphones with the receiver volume turned way, way down. Don't deafen yourself! When you speak into the microphone, your voice should sound clear, as though you were talking on a public address system. It should not sound rough and gravelly.

Watch the output waveform across the dummy load with your scope. The waveform should look just like it did coming out of the 9 MHz generator. You will probably find that speech sounds terrible before you have everything adjusted. It may just be bursting, sputtering sounds.

Adjusting DC bias to the final

You'll have to adjust the DC bias to the final (50 watt) amplifier for optimum speech quality. As you increase the bias current, watch the DC current drawn by the entire transmitter. It should not be more than about 2 amperes when you are not talking. As you talk, the current should jump up to 6 to 12 amperes, depending on the drive levels, the band you're on, etc. As always, the higher the frequency, the more difficult it will be to obtain clear speech. ***DC bias for the high power amplifier that is adequate for one band, may not be enough for another.*** This little pearl of wisdom cost me days of frustration.

If the speech still sounds bad, RF chokes and RC decoupling filters for power leads to each module can help the problem. Also, filter the DC power line entering the transmitter chassis and the remote "mute" line going to the receiver. If troubles persist, filter all the wires entering your transmitter. Sometimes a clamp-on ferrite filter block around power leads or cables can be helpful.

Finally, SSB works best with a good antenna

A high gain, beam antenna is highly desirable. As you listen to the other SSB stations, you'll find that most strong signals come from a beam antenna. Directional antennas improve the signal by focusing most of the RF energy toward the guy you are talking to. Think of beam antennas as being comparable to the mirror reflector in a flashlight. The mirror concentrates the energy in one direction only.

In conclusion

My first real sideband contact was with W9WFE, a fellow about a thousand miles away. When I explained to him that my rig was homebrew, he said, "Well, it certainly sounds like sideband to me. It seems to work!" Sweet success.

My sideband transmitters are still in the experimental category. You will find that it takes a great deal of tweaking and fussing to get SSB tuned so it sounds good and doesn't radiate on unplanned frequencies. You won't believe how many diseases your SSB transmitter will create for you to conquer! Sideband is not a project for impatient people.

Shortly after I got my sideband working, I tried to arrange a schedule with Doug, KD6DCO, in California. We failed to make contact. In that weak moment I thought I should stop messing with homemade junk and buy a modern transmitter. No, wait. If I want to communicate with Doug, all I have to do is write him an e-mail or call him on the phone. I'm already on-line and long distance calls are cheap. If I wanted to use radio, I could even talk with him by cellphone. No, it was back to the drawing board for me.

32. Chapter 15, Harris

And after some major redesign, my next schedule with Doug was successful, but my signal was pretty weak out in California. That's OK. I have to keep reminding myself that, so long as my station falls short of what is technically possible, my hobby continues. Woe to me if I ever finish. Long live homebrew!!



CRYSTAL SETS TO SIDEBAND
© Frank W. Harris 2010, REV 12

Chapter 16

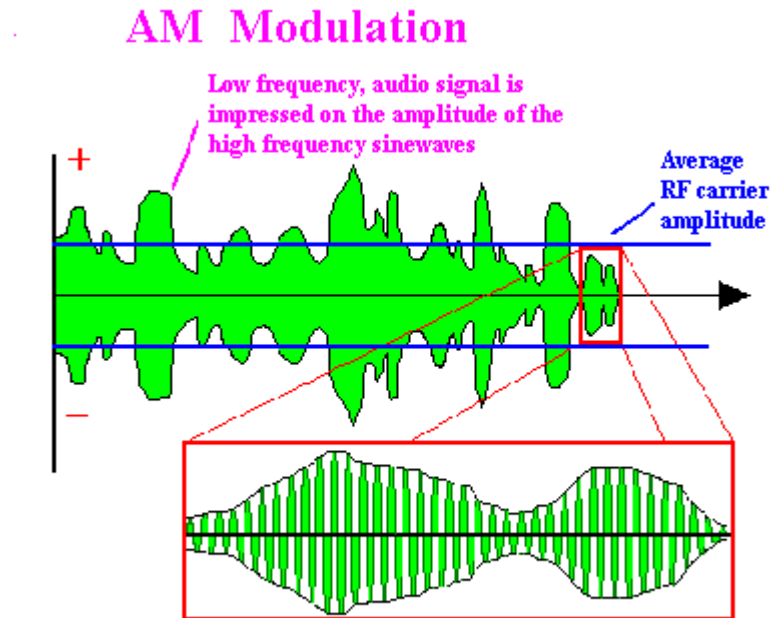
ANCIENT MODULATION

And other topics

When I got back into ham radio 11 years ago, my ham friends told me that amplitude modulation (AM) was extinct. I was under the impression that SSB was the only mode of HF phone permitted. Later I learned that AM isn't actually illegal and there are a few diehards using AM on the 75 and 10 meter phone bands. I've also heard AM stations on 15 and 160 meters. In short, you might find a use for it. Besides, it's an interesting challenge to AM-modulate a transistorized transmitter.

Homebuilt AM

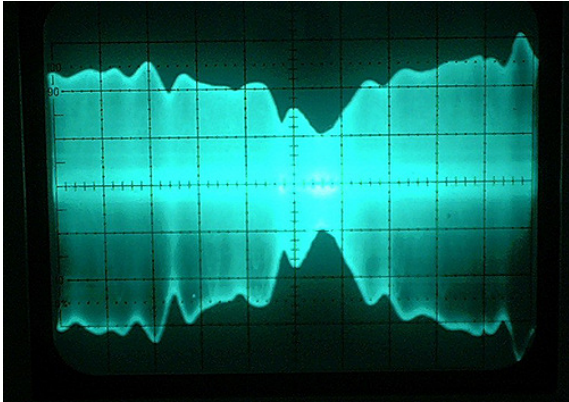
Back in the vacuum tube days many of us built our own transmitters and AM modulators. My first AM transmitter was a Heathkit DX-20. That was a 50 watt, CW-only, kit-built, vacuum tube transmitter to which I added a homebuilt AM modulator. Unlike SSB, AM could be added onto an existing CW transmitter. Rather than generate a low power AM signal and then amplify it with a linear amplifier, in the old days the usual method was to AM-modulate the final amplifier of the CW transmitter.



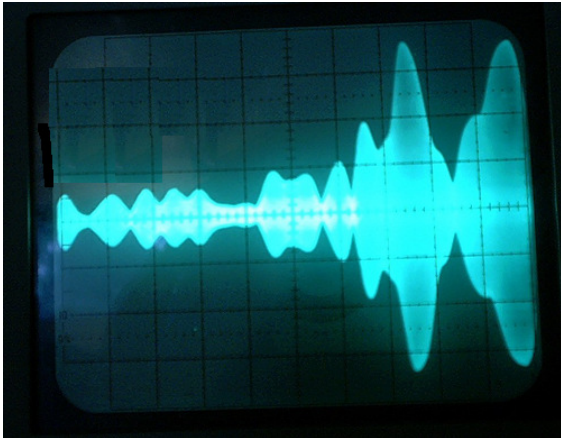
On an oscilloscope, the hallmark of AM is that, when you are **not** speaking, the RF carrier wave runs continuously at an average power. That is, in AM the highest peak power and zero power only occur at the very highest voice peaks. Although I could see these transient peaks

2. Chapter 16, Harris

on the scope, when I tried to catch one with a storage scope, they are statistically rare and I couldn't catch a zero power level. The waveform below was typical of what I saw.



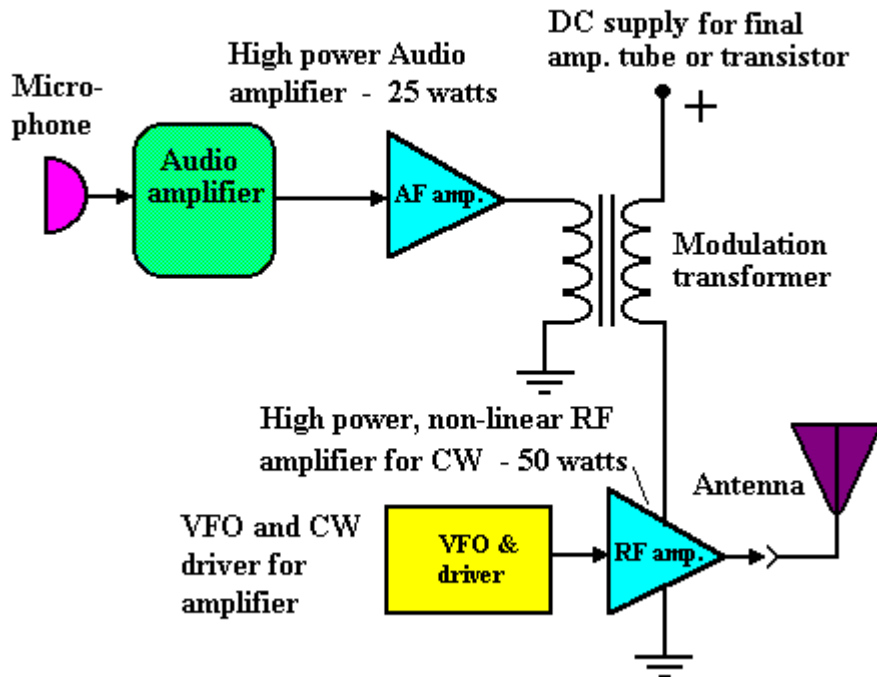
In contrast to AM, the RF output amplitude in SSB is always **zero** whenever you aren't talking. Notice in the SSB oscilloscope picture below that each RF blip representing the audio starts from zero. It doesn't start from a halfway, continuous carrier level.



Plate, screen, and cathode modulators

Formerly, there were three common methods of AM modulation. The "Mercedes" method was to use a *plate modulator transformer*. These large iron transformers impressed the audio signal onto the DC supply current. That is, as you talked, the DC input current rose and fell above and below the level of what it would be for a CW sinewave. For a 100 watt transmitter, this transformer was about the size of a softball, weighed a ton, and cost like crazy. The transformer was driven with a big audio amplifier that put out at least 50% of the CW carrier power. In other words, the plate modulator circuitry was nearly as large and expensive as the rest of the transmitter.

"PLATE" OR "COLLECTOR" MODULATOR



The "Toyota" and "Bicycle" approaches to AM modulation were to modulate the gain of the final amplifier tube by impressing the audio on the screen or cathode, respectively. Screen modulators usually sounded pretty good. Cathode modulation, sometimes called Heizing modulation, tended to produce "down modulation" which meant that power decreased whenever you talked. It sounded just fine, but was inefficient use of RF power output. These methods required less audio power than plate modulation and were easy for a high school kid like me to afford and build.

Modern AM construction

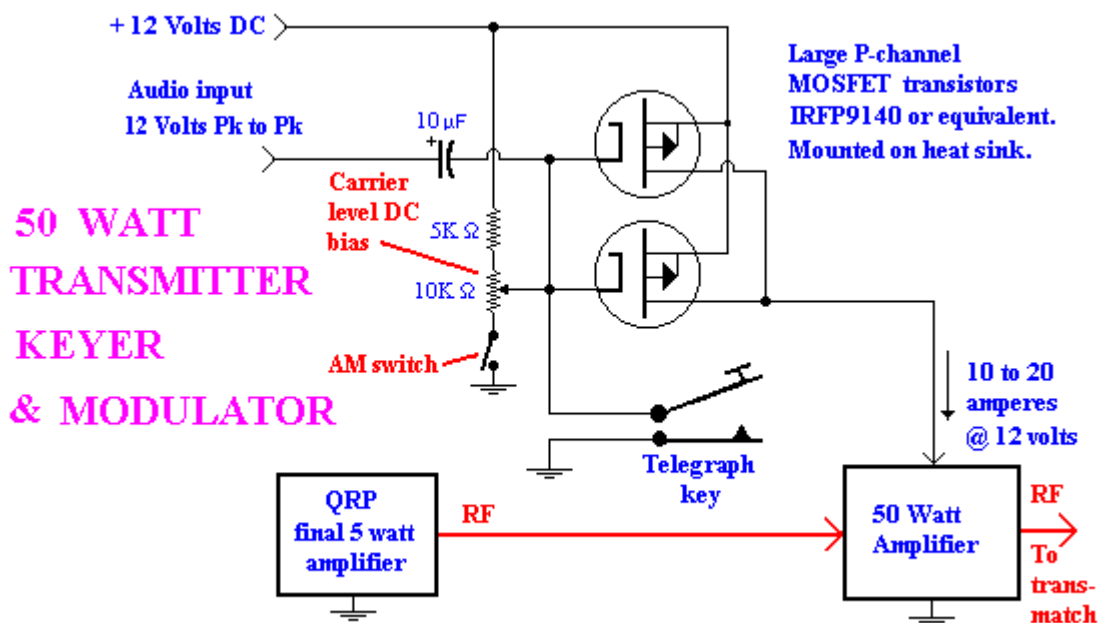
Now forward to 2003. Most modern SSB transceivers have the capability to generate AM modulation. To get into this mode, you read your manual for 20 minutes, bring up menu #26, push button numbers 14, 7, and 12 and you're done. That wasn't hard, I guess. But did you learn anything?

Let's suppose that you're a homebrew fanatic and wish to scratchbuild your own AM rig using transistors. Is that hard? Hmmm. Well, for one thing, transistors don't have cathodes and screen grids. Emitters are analogous to cathodes but, as explained above, cathode modulation wasn't all that great. Another difference between tubes and transistors is that, for the same power levels, *the final amplifier transistor has DC currents about 50 times larger*. So for DC supply modulation, you must impress 5 or 10 ampere audio signals onto the 12 volt DC power supply line. The modulation transformer will have to be just as large, but it will need a super low impedance output winding.

Modulating a transistorized 50-watt CW transmitter

I have a 25-watt, plate modulator transformer from the 1960s designed for use with a

transistorized audio amplifier modulating a vacuum tube transmitter. In other words, it was designed to modulate a vacuum tube final amplifier, but the modulator itself was transistorized. In those days high power, high frequency transistors didn't exist, so transmitters were built with tubes, but audio circuits could be built with transistors. Since my transformer had low impedance primary windings, I thought I could "run it backward" and supply enough audio current drive to build an AM "collector modulator." I happen to have an old 10-watt vacuum tube hi-fi amplifier, so I used that to drive the high impedance winding on my modulation transformer. Sure enough, even with music my AM modulation sounded great when I broadcast into a dummy load. However, it only modulated about 30% of the carrier amplitude. That is, I was wasting most of my RF power. I could have built a 25-watt vacuum tube output audio amplifier, but I had a more modern idea. Why not use my MOSFET CW keyer as an audio modulator?



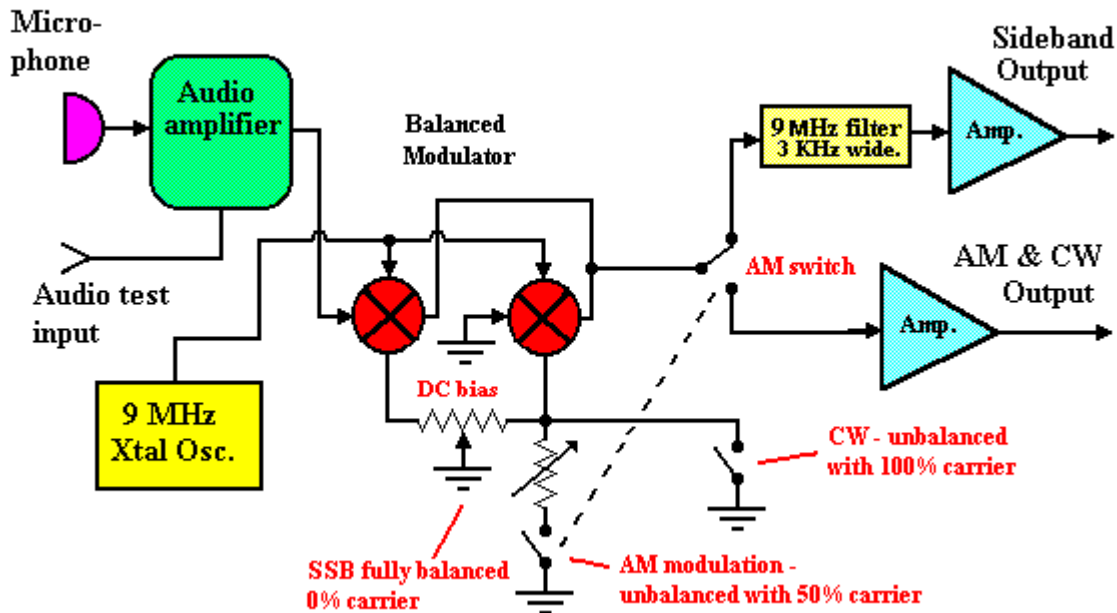
The above keyer was originally designed to turn the DC power to my final on and off with a telegraph key. My AM modulation scheme was to turn the MOSFETs half-on with a simple DC potentiometer, then modulate the gates with a 12 volt P-P audio signal. Because I was driving MOSFETs with a low (audio) frequency signal, hardly any power was needed. This simple scheme worked pretty well, but it was extremely finicky to adjust. It was easy to have too much bias or too little and too much modulation or too little. The difficulty was that the gate voltage versus drain current transfer characteristic is rather non-linear. With feedback and a more sophisticated drive circuit, I believe this method can be made to work well.

The SSB approach to AM

At this point in my R&D, I had not yet succeeded in building a practical SSB transmitter. So rather than invest more time on "obsolete modulation," I went back to work on SSB. I figured that, if I ever got the SSB working, it would be easy to downgrade my SSB generator to AM. This turned out to be true. I tried out several variations. *The method that was simplest and*

worked the best was bypassing the SSB crystal filter with a switch and unbalancing the balanced modulator circuit using a circuit that resembles the CW switch.

BALANCED MODULATOR



AM resembles CW in that a sinewave carrier is generated continuously. However, the same "unbalance" switch used as a SSB/ CW mode switch can't be used for AM. When modulation is applied, the instantaneous power must rise above and below the no-speech carrier level. Ideal AM modulation drives the carrier alternately between zero and 200% of the carrier level. Because there is a limit on the signal amplitude available, *the carrier must be set to 50% of the level used for CW*. This provides a modulation amplitude range of +/- 100%. A separate AM mode, double-pole switch bypasses the SSB filter and unbalances the modulator 50%. The AM switch is in series with an adjustable 5K ohm resistor that unbalances the modulator just enough to produce the 50% carrier.

The audio gain pot and your voice level should be adjusted to produce voice peaks twice the carrier level. Compared to SSB, you'll find that AM modulation is quite HI-FI. While testing the generator and transmitter on an 80 meter dummy load, music retransmitted from a Walkman was quite acceptable. In contrast, when using SSB, speech sounds OK, but music is really terrible. The principle difference is that the sideband filter greatly attenuates frequencies below 300 Hz whereas AM preserves the low frequencies. Speech transmitted on SSB can sound like the person's normal voice, but music on SSB is really bad. It's just as well. The last I heard, ham music is still illegal.

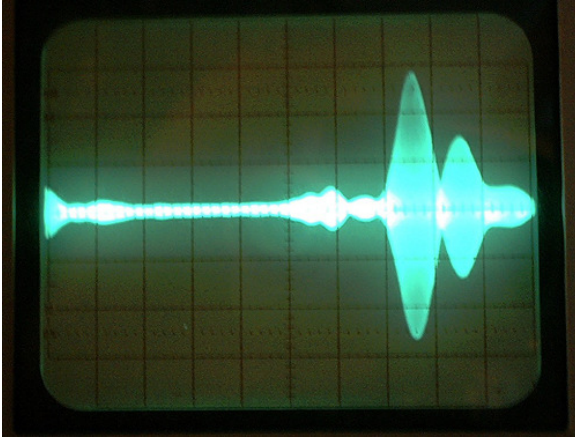
COMPRESSION BY ACCIDENT

Or, sometimes we get lucky

A modern single sideband generator processes the amplified audio from the microphone

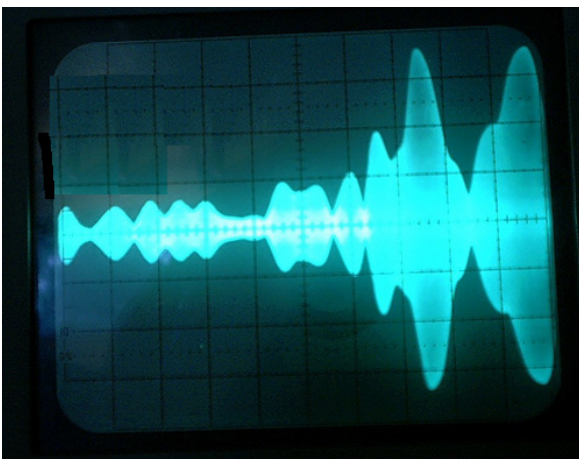
6. Chapter 16, Harris

before the audio is fed into the balanced modulator. This "*compression*" process attempts to equalize the voice peaks so that as many voice elements as possible are transmitted with full Peak-Envelope-Power. Without this process, most of what you have to say will be transmitted with far less than the nominal peak power. When most of your sentences are reduced to QRP muttering, your intelligibility suffers.



In other words, without compression, the single sideband RF envelope of a spoken word is close to zero most of the time. It would look something like the waveform shown above. A compressor circuit attempts to leave the peaks alone while proportionally amplifying the subtle, low voltage waveform wiggles near the horizontal axis. I guess the latest transceivers use digital processing to accomplish this feat. However, 15 years ago a compressor circuit usually performed the following tasks:

1. It amplified the whole audio waveform.
2. It clipped off the highest audio peaks.
3. And finally, it filtered the clipped audio with a 300 Hz to 3KHz bandpass filter.



After compression, the same RF sideband waveform might look something like the above picture. The idea is that all the tiny stuff near zero has been expanded. (These waveforms aren't actual before-and-after pix, but they illustrate the principle.) After transmission some modern

receivers "re-expand" the waveform to try to restore the original waveform. This entire process is called *companding*. However, for me, building a homebrew SSB that worked at all seemed plenty difficult. Consequently I didn't worry about secondary issues like "companding."

A crystal filter does more than clip the unwanted sideband

In the beginning I was afraid my RF signal might be too wide. So, because it was relatively easy, I built a 3 KHz audio low pass filter. It turned out that I didn't need it. Once I had passed the 9.000 MHz RF double sideband signal through the crystal filter to cleave off the unwanted sideband, I found that the filter had also removed virtually everything above 3 KHz anyway. Also, when I adjusted the original sinewave frequency to get rid of every trace of the carrier, I found the filter had also clipped off the lower 300 Hz of the audio. It's remarkable how normal a voice can sound without the lower 300 Hz. Voices are quite lifelike. In any case the crystal filter accomplished the same frequency filtering that the ARRL Handbook specified for the audio compressor. Interesting!

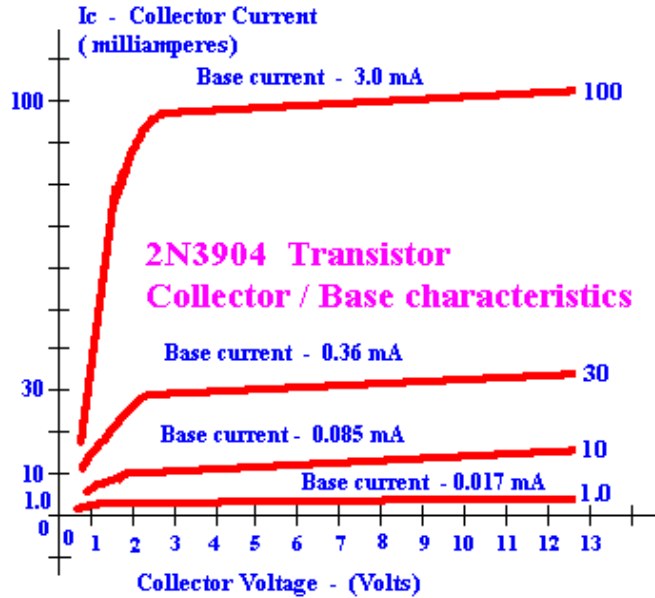
An SSB transmitter has several linear amps in series

After the SSB RF signal has been generated at a milliwatt level, the signal must be amplified and converted to the desired hamband. Including the mixer, this meant that my SSB signal had to pass through 5 stages of amplification to get to 100 watts peak. Each linear stage is forward biased so that even tiny signals will be amplified. Without this bias, all you hear are the voice peaks. In other words, an unbiased amplifier cuts off all the little audio signals a compressor tries to accentuate. I knew that the linearity of all these stages in series couldn't possibly be "perfectly linear." But since voices sounded good, I stopped worrying about linearity.

Where has all the AM modulation gone?

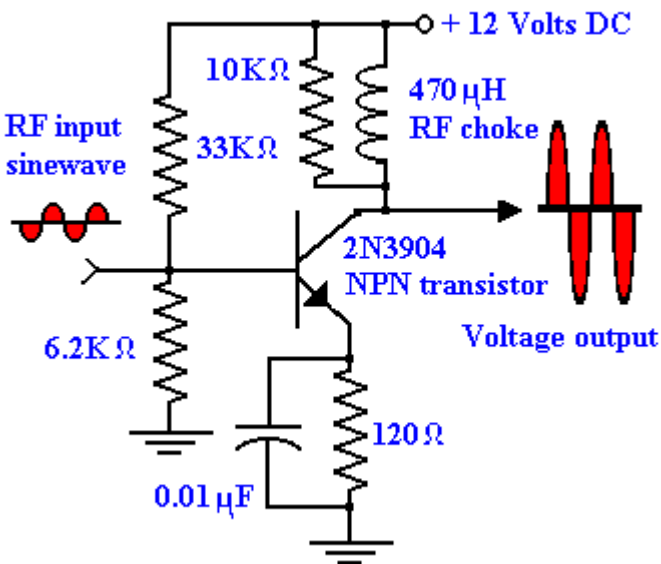
I didn't realize that my RF amplifiers were significantly non-linear until I added an Amplitude Modulator mode to my SSB generator. I listened to my little 9 MHz AM generator in my all band shortwave receiver. It sounded great and looked like 100% modulation on the scope. Next I fed the signal from the 9 MHz AM generator into my 80 meter "linear" QRP module which put out about 3 watts on 80 meters. Yes, it worked, but the signal was nearly all carrier. Instead of 100% modulation, on 80 meters I only had about 5% modulation. Where did that huge carrier signal come from? What happened to my modulation?

Transistors aren't linear



"Linear" implies that big signals will be amplified just as much as the small ones. However, if the raw output of the transistor covers most of the collector operating range, then it happens that small signals are amplified more than big ones. I have two 2N3904 transistors in my chain of amplifiers, so the Base/ Collector current characteristics for this transistor are shown above. Notice that one milliampere of collector current requires 0.017 milliamperes base current. But to get 10 milliamperes of collector current takes 0.085 milliamperes. That's 5 times more base current to get 10 times more collector current. But if you want 100 milliamperes of collector current, you need 3.0 milliamperes of base current. That's an additional 35 times more base current. Sure looks non-linear to me. **BEHOLD, A NON-LINEAR COMPRESSOR!**

Transistor Amplifier



The "linear" amplifier above illustrates an accidental compressor circuit. The 33K resistor biases the transistor ON so that even tiny RF signals will be amplified. (By the way, the 10K resistor across the inductor keeps the amplifier from oscillating when there is no input signal.) The main reason for the 120 ohm resistor is to provide negative DC feedback to make the amplifier thermally stable. Without the emitter resistor, the amplifier works, but the transistor runs extremely hot. The emitter resistor also makes the amplifier more linear than the transistor characteristic would suggest because the feedback restricts the transistor to a narrower range of operation. However, 120 ohms feedback makes it a long way from linear. 470 ohms is much better, but still far from perfect.

Oh, well, why fight it? To fix my AM mode, I reduced the imbalance of the balanced modulator to just a few percent of voice peaks. This gives me roughly 50% carrier by the time it arrives at the final amplifier. And as for the SSB, it already works well. Apparently I had a pretty darn good compression system all along and I didn't even know it. Imagine! A happy accident! They sure don't happen often.

**

HAM TELEVISION - The Old Way



First, a glimpse of modern amateur TV

I was inspired to write this article for my local newsletter by Jim Andrews, WAØNHD. At our August 2003 ham club meeting he gave a wonderful hour-long presentation on modern Amateur TV. He showed us oscilloscope and spectrum analyzer images of audio, RF, and video waveforms and block diagrams of all the required black boxes. At the end of his presentation he included a run-down on the available commercial ham TV equipment. It turns out that you can

put together a first-rate ATV station for under \$1000. Less than that if you already own a suitable camera, antenna, etc. If you plan to support your local emergency service and televise forest fires, floods and riots, then a station like Jim's is what you need. On the other hand, if you just like to play around with circuits like I do, then building something from scratch may be more satisfying.

Homebuilt ham TV

Paradoxically, one of the best attributes of the old days was our relative poverty and the lower level of technology. Many services and gizmos that are routine today existed 50 years ago but were rare or unaffordable. Long distance telephony, walkie-talkies, RTTY (radio teletype), and TV cameras are obvious examples. Ham radio allowed us high school kids to play with these toys decades before they were cheap or even available to ordinary adults. Since our toys were the latest technology, we were extremely excited about them. If you show a TV camera to modern kids, they fall asleep.

Television fascinated me as much as short wave radio. So after I had a working HF station, I wanted to get on TV. In the 1950s, the hard part of ham TV was the camera. The cheapest way to get one was to buy a WWII Navy surplus flying bomb camera. The Navy built radio-controlled flying bombs that could crash into enemy ships, Kamikaze-style. After much searching I was finally able to buy a camera with its huge iconoscope camera tube. Unfortunately, by the late 1950s finding an iconoscope that still worked was difficult and mine didn't. In contrast, TV monitors were easy to get. I toured the TV repair shops and bought old sets for a few dollars that their owners didn't want to pay to have repaired.

A flying spot camera



Since TV camera tubes were out of reach, I resorted to using a TV set as a scanner. Large paper or grease-pencil transparencies were taped to the TV tube. A 914 photo-multiplier tube

was mounted on the tilted aluminum box on the left. The photo tube "looked" at the light from a blank TV picture raster passing behind the slide. The flying spot of light scanned the slide, one line at time. It took five stages of amplification to boost the signal to the required few volts. I usually used the retrace blanking pulses from the TV to make crude synchronization pulses. The pulses were combined with the varying light signal to make a complete TV signal. I wired a polarity switch on my combiner circuit so my slides could be either black on white or vice versa.

The TV signal was relatively high frequency and was easily separated from the constant background lighting signal. Consequently it wasn't necessary to operate in the dark or enclose the scanner in a box. The crude blanking pulse sync worked, but it pulled the image down and to the left. The easy way to get real sync pulses was to receive channel 4 from Denver, 30 miles away, then remove the picture. My light signal was recombined with the channel 4 pulses then sent on to the monitor.

Fun with flying spots

Obviously we couldn't televise forest fires with this scanner, but we played with it in other ways. When you're in high school, silliness can be great fun. Aside from televising test patterns, I liked to do silhouette hand puppets and rude finger gestures. My friends and I used to draw up transparencies of signs like, "Help! I'm trapped in your TV set" or we would draw single frame cartoons and slides showing supposedly humorous TV ads.

Synchronizing the picture to channel 4 had a more nefarious advantage. I could broadcast images and superimpose them on top of real channel 4 broadcasts. For example, I had a tiny cutout of a vulture that I could place on David Brinkley's shoulder during the NBC Huntley-Brinkley evening news. Alternatively, a giant black silhouette of a hand might slide into the picture and tickle him under the chin.

Normally I just broadcast this entertainment around the house. However, the kids across the street were interested so I thought, "It's only a few milliwatts. I'll just broadcast it over there on channel 3, which happened to be vacant in our area. It's 200 feet instead of the legal 50 feet maximum, but beyond that, how far can it go?" My little slide and puppet show for the kids worked great. Nothing more came of "The Frank Show" until several years later when Jim Synder, WØUR, was visiting my shack. I told him about my former flying spot project and he said, "So you were the culprit!" He described how his brother was watching TV in their living room across town from my house, about 5 miles away. Suddenly he began hollering for Jim to come look at the TV. Jim sprinted into the room just in time to see the word "HELP!" written on top of channel 4. A few moments later the mysterious signal disappeared. I dug out my old slides for Jim and he thought he recognized the perpetrator. This was interesting because I never deliberately broadcast on top of channel 4 using an outside antenna. Even in high school, I wasn't that reckless. On that other hand, if my lower sideband was on channel 3, the upper sideband would have been on ... channel 4.

Broadcasting properly on 420 MHz UHF

Unfortunately, being a poorly equipped kid, I was unable to generate and receive a signal on 70 CM over any distance. I scratch-built a little 420 MHz transmitter that appeared to work OK. That is, a 50 ohm ½ watt resistor on the output got hot and all the stages "dipped" when tuned. For all I could tell, it was working. At that time I had never even heard of filtering the

output with a resonant cavity filter to get rid of the lower sideband, so the vestigial sideband issue was blissfully ignored. That is probably why Jim saw it across town. I also built an alleged 420 MHz converter that received my own signal, although I had no real knowledge of what frequency I was actually sending and receiving. Another barrier was that none of my ham friends were interested in putting up UHF antennas, building converters, and all that. They all were too busy with DX, building kilowatt finals, walkie-talkies, RTTY, and so on. We all had different interests and high school was a busy time.

As you can see, my ham TV project wasn't a complete success. It illustrates the difficulties with homebrew VHF and UHF. To be sure you're producing a quality signal on the right frequency, you need expensive UHF test equipment. Moreover, you need a high level of craftsmanship to control the unwanted oscillations. If 10 meters is tricky, imagine getting 0.70 meters to work right! The only advantages are that you can use low QRP power levels and compensate by building small, high gain antennas. Most of the difficulty with the high HF bands happens when you try to generate high powers over one watt. In contrast, with a small rooftop antenna a few milliwatts of VHF or UHF can get you around town.

In the final analysis, my TV project was loads of fun and I learned plenty. When you scratch-build, the rewards are usually quite different from store-bought ham radio and can be quite unexpected. For example, who would have thought QRP television could work so well?

**

GETTING ON SIXTY METERS

A ham band frontier?

Every generation or so, hams have been granted a new ham band. When 30 meters first opened up, Bob Hamilton, NØRN (former KØIYF), was ready with his homebrew CW transmitter. The bad news was that he was practically the only American on the band. The good news was that 30 meters had been open for years in Europe and suddenly *Bob was hot DX*. Everyone was calling him. This delightful situation lasted about a year, but as soon as the commercial equipment covered 30 meters, Bob's private DX band became history. After hearing this story I wanted to try out 60 meters when it opened on July 4, 2003.

What 60 meters is

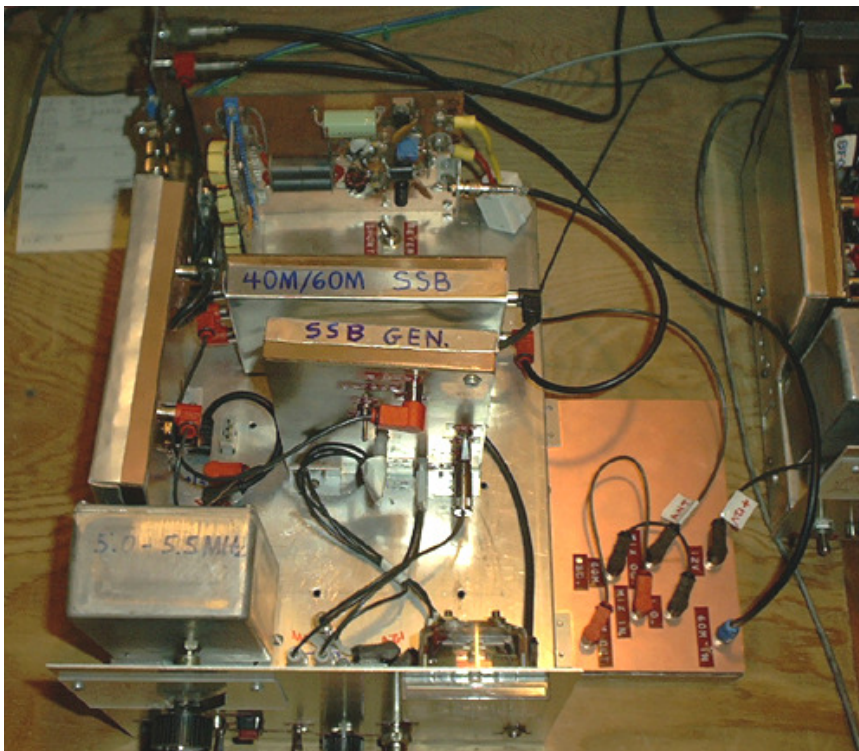
60 Meters consists of five, 2.8 KHz wide channels with center frequencies on 5532, 5348, 5368, 5373 and 5405 KHz. They may be used by General Class and above. The only mode permitted is USB SSB and 50W effective radiated power. ARRL recommends that we set the carrier frequency to 1.5 KHz below the centers of each channel and restrict the audio to between 200 and 2.6 KHz. Unfortunately this band is shared with several other services.

Modifying your present SSB rig

You may already own a 60 meter rig. Bob has a collection of transceivers and set out to put one of them onto 60M. His first try was an old Drake R4 that, with the proper crystal, supposedly "covers everything from 1.8 to 30 MHz." It turned out that the R4 could be used on any HF frequency *except 5.0 to 5.5 MHz*. The IF and VFO are in that range and spurious signals would result. Next he tried a Kenwood TS-180. His particular unit was missing a surface-

mount, broadband filter that needed to have been assembled on a PC board at the factory. It's possible to kludge a filter, but it wouldn't be easy because there is little room for it.

In modern rigs that use VHF IF frequencies, the only barrier preventing transmitting on 5 MHz is the firmware that vetoes illegal frequencies. Bob was able to put his Kenwood TS-50 on 60M by just clipping a diode to reprogram the microprocessor. The miniature Yaesu FT-817 can be modified by tearing the unit apart and soldering and unsoldering some tiny programming jumpers on a board. The Yaesu FT-1000MP was the easiest. He turned off the unit and then turned it back on while holding down two buttons. That brought up a menu that allowed him to select frequency ranges for different regions of the world. At the bottom of the list was "general coverage." This permits operation over the entire spectrum, even on standard broadcast.



A homebrew 60 meter rig

My 60 meter transmitter and receiver converter are shown above. The copper box on the right is the receiver converter. The transmitter consists of 5 main modules: These are a 5 MHz VFO, a frequency converter for the VFO to make a 14 MHz VFO signal, a 9 MHz SSB generator, the mixer/ driver to combine 14MHz with 9 MHz SSB to make 5 MHz SSB and, at the rear, a 50 watt linear amplifier. To get on 60, I added a crystal and 60 meter filters to two of my transmitter modules and I built the receiver converter box. The converter has jumpers all over it because I eventually plan to use it on 6 and 10 meters.

July 4th 2003

I knew 60 meter SSB wouldn't be as much fun as 30 meters, but I naively hoped I might meet some eccentric homebrewers there. As midnight July 3rd approached I tweaked my

homebrew 60 meter rig on a dummy load. I could hear 4 strong RTTY stations between 5.3 and 5.4 MHz that ran continuously. One of them was parked pretty much on top of channel 2. At 11 p.m., just before the band opened, I found faint SSB stations on all five new channels way down in the noise. I couldn't copy any of them, but they were definitely there under the RTTY and static. They may have been those special-licensed experimental hams or perhaps they were the Coast Guard, far, far away. At 10 minutes after midnight, some relatively loud signals appeared on channel 4. One of them was Milo, NL7SA. These Alaskan hams were gushing about being the first to try out the new band. They said they were using Alaskan CB radios, but for me they were only about Q2-S2. For many years there have been 5 MHz SSB CB channels assigned just for Alaska. I had no graceful opportunity to call them and after a few minutes they faded.

The next night I heard two Alaskan fishermen trading shrimp stew recipes. One recipe featured shrimp, chipped beef and cabbage. Yuk! The other guy said he had just motored 35 miles back from his favorite fishing spot. They never gave call signs, so I believe I was hearing an Alaskan 5 MHz SSB CB channel. After a few days, more and more stateside hams appeared during the evening hours. Channels 1 and 5 had the least RTTY interference and were the most popular. Most guys were using FT1000MPs but I also heard a Kenwood TS-930 and an ICOM 746. Each channel turned into an impromptu "net" with the loudest guy serving as net control. For example, on July 10, Bob, K9CGD, in Longmont, Colorado served as moderator on channel 5 for several hours. As for me, apparently my signal was too puny to get more than a "Sorry old man, you're too weak." For one thing, my antenna is probably inadequate. However, my rig has been successful on four other SSB bands, so I'm mystified about what's wrong.

In conclusion,

60 meters is a band inhabited by RTTY, buzzing data signals, crashing static and two or three channels of weak SSB signals. Basically, it's a whole continent of Yaesu owners trying to get their 60 meter WASs (Worked All States) sharing two or three "party line" channels. After just 7 days, some guys were already claiming as many as 28 states.

When you tune in, you will hear the two loudest guys talking about how neat 60 meters is and that they're going to sign off now so others will have a chance. And ten minutes later the same two guys will still be talking about shutting up, but not actually doing it. The other annoying category is the East Coast guys who are apparently talking to England. But of course, we can't hear England from Colorado and yet it seems impolite to interrupt, even though static is all that's on the channel.

So, what did I learn from getting on 60 meters? I learned that I better be prepared to be disappointed when I start a project and that perhaps I should have done more homework about what units might be the first on the air. I was naive to think I might be among the first. Oh, well, the Alaskan gourmet fishermen were interesting. Hmmmm ... I'm going back to 20 and 30 meter CW. As for something to build, modern ATV still looks interesting. I ought to be able to do a better job this time.

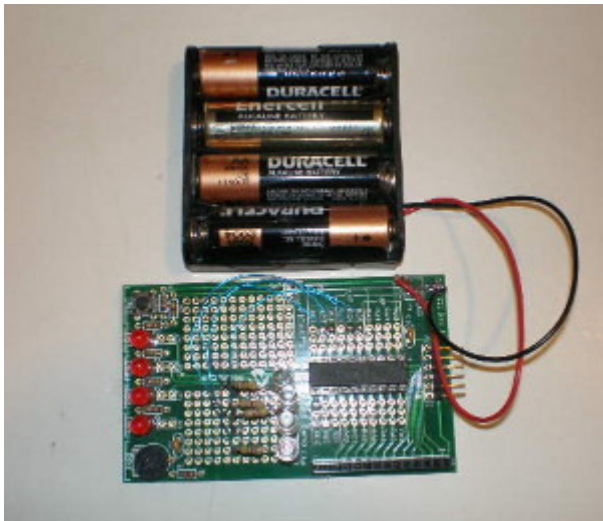
HOMEBREWING WITH PICs

By Frank Harris, KØIYE

Difficult, but still practical

The little ham kits advertised in QST often contain a PIC microcontroller. For example, when a modern ham says he “built a homebrew CW keyer,” what he probably did was buy a kit with a pre-programmed PIC microcomputer and a PC board. There are perhaps 6 or 7 parts that he must solder. Such a kit may produce a great keyer, but it won’t produce much sense of accomplishment. The guy who designed the kit has already enjoyed the homebrew fun, not the guy who buys the kit.

The PIC controllers you find in the kits look simple. They usually have 8, 14 or 20 pins in an old-fashioned DIP package. They look so innocent, how can those little things be hard to program? 20 years ago, microprocessor projects involved building an 8”x 11” PC board full of parts to complete a system. You needed a microprocessor IC, a crystal, EPROM, the RAM, A-to-D converters, D-to-A converters, a modem chip, a timer or two, perhaps some EEPROM and the peripheral interface adapter chips. These ICs were interconnected by busses of 24 different data and address lines. Whew! No wonder microprocessor homebrewing was rare!



PIC16F690 development board.
A 20 pin PIC version.

The good news about PIC micros is that they do ***EVERYTHING internally – no giant PC board is needed.*** Another neat feature is flash programming – 14K or more. That’s a lot of ROM, really! You can build your project with its own 6 pin interface that allows you to download a new program into it in seconds. Supposedly the programming will last for 40 years, but I doubt I’ll be around long enough to find out. As I recall, the old UV-erasable EPROMs were only good for 10 years.

Selecting the desired pin and feature configuration

The bad news about PICs is that programming them has big challenges: The first obstacle is turning off the wondrous capabilities that you DON’T want. This includes programming nearly every pin on the package to be assigned as a comparator input, voltage reference input, LED driver, analog input, etc, etc. Typically each pin has 3 to 5 possible roles it can serve. These capabilities often interfere with each other. If two capabilities are mutually exclusive, obviously it won’t work.

Because of all the capabilities you don't need, each version of the PIC typically has a **300 page set of datasheets**. Also, whatever your application, there's a PIC processor for every imaginable job. There are literally over a hundred PIC chip variations. Each one of those is available in 5 or 6 different physical packages that are mostly tiny kinds of surface mount. A few years ago electronics parts catalogs were the size of magazines. Today catalogs like Mouser and Digi-Key are the size of the L.A. phone book with thousands of fragile pages. That's why most people use the on-line catalogs that have built-in search engines to help you find your needle in the haystack. The on-line catalogs are so huge they make the phonebook size catalogs look like abstracts.

Primitive RISC programming

Another odd problem with the PIC is the "reduced instruction set code" (RISC). RISC is often extolled as good, but I'll be darned if I see why. RISC runs very fast. It allows you to do almost nothing really quickly – up to 20 MHz! It's like programming the 8008 Intel processor from 1970. There's just one accumulator, no index register, no divide command, no multiply and no byte test. There are only two simple conditional branch commands that just skip the next instruction when the carry or zero flag is set. Therefore, every branch needs a "**goto**" following the "**skip if**" command. However, the PIC assembler is quite good. But I'm easy to please. In the bad old days I used to hand-calculate addresses and write out programs in pencil on ruled sheets. Then I Scotch- taped the sheets together to make long scrolls.

In fairness, the PIC professionals use C language programming which bundles huge chunks of RISC programming into clumps usable with a single command. ProBasic for PICs is also popular. Unfortunately, C or Basic programming can't do all the unique stuff that you need for your project. Therefore, you still have to write some of your own subroutines using RISC machine language. It was obvious to me that I had to master RISC anyway, so my first project was done 100% with RISC.

PIC development systems

PIC development systems consist of a little capsule the size of a playing card that plugs into a USB port. The capsule then plugs into the similar sized sample circuit board on which the PIC is mounted. Once you get launched, you can build the flash programming right into your own project board and you may no longer need the sample development board. Of course if you do that, you may lose the ability to step through programs, read internal registers, and so on. I bought two development systems for about \$25 each, one for the PIC16F690 and the other for the more capable PIC16F887.



A PIC16F887 development board wired into a speech chip programmer. The black plastic programmer unit is plugged into the development board.

The little development boards come with a disk containing zillions of data files, help instructions and example programs. It also includes an editor, a debugger, the assembler and the PIC ROM programmer. It does NOT contain a C or Basic compiler. Compilers range from \$150 to \$500 or more, depending on which PIC families they are designed for.

The Debugger Program

In theory, the debugger program combines all your functional programs, such as the editor, assembler and even 3rd party compilers, so that they may be operated together “seamlessly.” If you can make it work on your project, I imagine it would be wonderful. You could step through programs, watch constants change, set breakpoints, read internal registers, etc., etc. Sadly, I could never get mine to work. Fortunately, all the parts like the compiler, editor, programmer and so on, can all be called independently, so I pressed on without the debugger. Basically I use lots of trial and error and intuition.

A talking dynamometer

My only PIC project so far has been a talking rope tension meter, (a.k.a, dynamometer), for the rescue group. My original plan was to use the PIC to run a voice synthesizer chip, something like the old “Speak and Spell” Texas Instruments technology. Ironically, the only programmable speech chip I could buy on the Internet was a PIC micro that had been programmed to be a speech synthesizer. Since PICs include multiple oscillators, a modem, D-to-A converters, etc, I shouldn’t have been surprised to find that my programmable speech synthesizer chip was just a programmed PIC microcontroller. Yes, they really are versatile.

It took me weeks to get the serial interface to work. The instructions didn’t mention that the speech synthesizer needed both receive AND transmit lines. There is apparently a “clear to send” confirmation that had to be sent back that wasn’t mentioned in the data sheets. Anyway, I soon had it working as well as it was going to. Sadly, I was the only one who could understand what it was saying. Not good for rescue situations. “Did it say let go of the rope?” ... AHHHHHHHHhhhhhhhhh ... Splash! Apparently not.



A PIC16F887 breadboard for developing software to drive the speech chip. Note the 6 pin connector on the left used to program the large, 40 pin PIC microcontroller.

My next attempt used an obsolete American speech recording chip that works well, but has a limited audio frequency response (ISD25120, 1.7 KHz). The speech chip can be hard to understand, but by putting it through a severe hi-pass audio filter, I managed to accentuate its high frequencies and compensate pretty well. But when I tried to buy more speech chips, they were extinct. I finally found a newer chip, the ISD17240, that is superior in every way – except for its modern Serial Peripheral Interface (SPI). Programming that sucker is way beyond what mortals can do with just data sheets and trial and error. Not only must I figure out how to get the PIC to send the instructions and receive the responses, the speech chip has its own complementary SPI digital nightmare I have to decipher. No luck so far. Oh, and by the way, the PIC “weak pull-up” feature for digital input lines is so weak, it’s prone to the slightest noise – use pull up resistors!

In summary,

PIC homebrewing is NOT for people with limited patience and time. It turns out that there is a good reason for buying those little pre-programmed PIC kits – you’ll be done in less than 6 months! On the other hand, if you keep the project simple, such as just directly driving LEDs and reading switches, it’s not so bad. But when you have to talk to other PIC processors or peripheral chips, the fun begins. My next project is going to be a CW keyer because it’s basically lights and switches. That’s where I should have started.

*

CLASS D AUDIO AMPLIFIERS

By Frank Harris, KØIYE

Big hi-fi sound, high efficiency, low voltage

Class D amplifiers chop an analog sinewave signal into a pulse-width-modulated stream of rectangular pulses. In other words, the density of high frequency (400 KHz) rectangular pulses varies with time and represents the amplitude of the wavy simple analog signal. When applied to audio amplification, a chopped series of high frequency square pulses can drive a 4 ohm loudspeaker with surprisingly good fidelity. Because the amplifier output only has two states, the highest voltage and zero voltage, there is no time spent half on and half off. Consequently there

is little power dissipated in the chip. A tiny chip can deliver big power, 1 to 3 watts or more. And it does all this with just 5 volts or less.

Why you might want to use one, or not

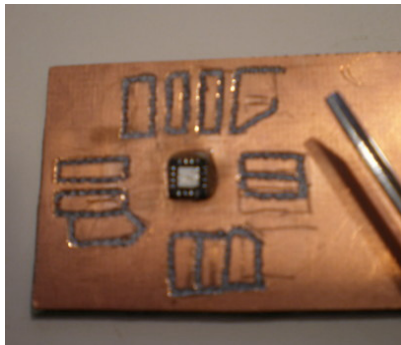
Suppose you are building a small, portable battery-powered receiver to go with your QRP transmitter and want to use 6 or 9 volt batteries. If you look at the data sheets for the good old LM388 or LM386 analog amplifiers, you'll see they are rated to work from 5 to 15 volts. If you are listening with sensitive earphones, a low voltage supply will work fine. On the other hand, if you want audio that's both Hi-Fi and LOUD, then you'll discover you need big voltage to go with your 4 inch or larger speaker. Yes, low voltage can be loud with analog chips using just 5 volts and, but the distortion is intolerable.

It is theoretically possible to use op-amps and comparators to build your own Class D audio amplifier. But when you diagram what has to be done, you quickly discover that you would need a huge array of components, a big circuit board and lots of trial and error. Class D amplifiers are the reason other people's tiny cellphones can be so annoying - they're both loud AND hi-fi and they accomplish this with tiny low voltage batteries.

EMI – digital hash in your receiver

If you've ever home-built a sensitive ham receiver, you probably discovered that a pulse-width-modulated regulated power supply or even a simple digital display, will make noise in your receiver that destroyed much of the sensitivity you worked so hard to achieve. The class D audio chips I used, **Maxim MAX9719** and **MAX9759**, have "spread spectrum" PWM systems to reduce EMI. Moreover, you have your choice of 3 different sample frequencies that supposedly make it less likely that the hash will appear outside your desired ham band. Unfortunately, the wires from this board up to my speaker radiated VHF RF noise like crazy. Since my project needed to work around VHF hand-helds, I was relieved to discover that I could silence the racket by stringing 5 large ferrite beads on the speaker wires. Unfortunately, the noise was still unacceptable for use around my HF receiver. Sure, I could still hear the hams over the hiss, but that's not good enough. Oh, well. At least Class D worked for my immediate application.

And now more bad news



Modern chips are often surface mount and really tiny. Even surface mount with projecting leads are becoming scarce. The tool is the tip of a 1.5 mm wood carving gouge used to cut the pads.

You have probably already noticed that the modern world does not want us to build cool stuff in our basements. The complexity is bad enough. But modern surface mount is providing the coup-de-grace to homebrewers like us. In the old days, chips came in DIP packages with big pins. They have 0.1 inch spacing that we can plug into sockets. Even the early surface mounts weren't impossible to solder. Yes, 0.50" spacing was a little tight, but the leads stuck out from

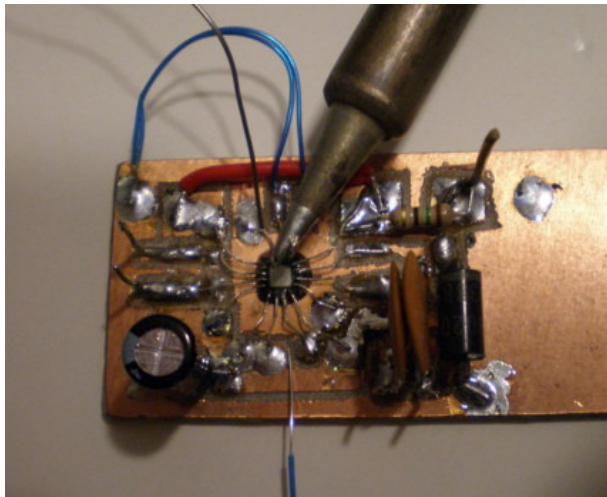
the body of the chip and most of us figured out ways of soldering them. For example, you can buy tiny adapter circuit boards to accept the “SO” surface mount chips. The periphery of the little board has pads big enough to accept reasonable sized wires. I’ve even managed to successfully solder SOs with 0.020” spacing onto the little boards.

Today many of the new chips aren’t available in DIPs or even SOs. When I ordered my Class D amplifiers, I studied the 5 or 6 versions of surface mount and ordered the biggest one. It had no leads that stuck out, but the contacts were at least on the periphery of the tiny squares and I hoped I could solder wires to those.

I was shocked when I opened the package and found tiny square black flakes 4 mm on a side. Using a microscope, I could read the labels on the chips. Yes, those were the “big” versions I had ordered. Sure glad I didn’t get the little ones! The 16 contacts were positioned around the circumference of the chip, but they were just metallic dots. My first reaction was that the project was over. But then I thought: These chips are too cheap to bother sending back. I might as well have a go at it.

How to solder chips you can barely see

First you must give up caffeine and booze. If you have benign familial tremor like some members of my family, I’m sorry, you’re already screwed. I talked about this at the local ham club meeting and I was told that the professional way to solder surface mount is using low temperature solder available in a paste. The paste is applied to the circuit board using a syringe with an extremely fine needle. The chip is then lowered onto its pads and heated with a heat gun. I haven’t tried this, but because of the small size, it isn’t going to be easy, fine gauge needle or not.



Sharpen your soldering tip and set the temperature to 600 degrees. I use 24 gauge solder and stripped wire-wrap wire to make the connections. Bring your iron in radially as shown and solder quickly before you fry the chip.

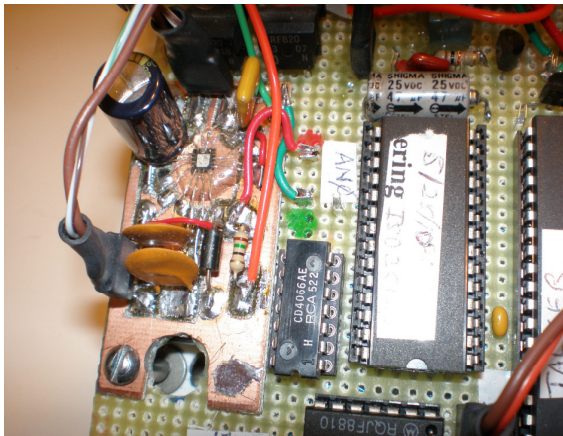
Even if I had the solder paste and needle applicator, I would still need the PC board with the tiny traces and pads. I use two methods of making PC boards. For big DIP chips I use perfboards with pre-drilled holes spaced on 0.1 centers. RF circuits need real printed-style circuit boards to reduce lead inductance. I make crude but effective PC boards using a fine wood gouge to carve off the copper between the traces. I start by gluing the chip down to the PC board with 5 minute epoxy. Tiny hand-held gouges intended for wood carving are hard to find. I bought mine from www.TraditionalWoodworker.com. “Two Cherries” brand, micro-carving tools are the smallest I’ve found. They have cupped ends as small as 1mm. However, a 1/8” (3mm) V-

parting gouge can be made to work.

Next, you'll need a really fine-tipped, temperature controlled soldering iron. I use a Weller model WES51. I filed the tip to make it as sharp as possible. Also, the solder needs to be the thinnest you can find. I use 0.022" (24 gauge) diameter solder. I use stripped wire-wrap wire, about 30 gauge, to contact the chip pads. I solder the easy end of the jumper first onto the big pads and then bend the tiny wire down into position over the tiny dot. You have to solder each contact as swiftly and deftly as possible. You might want to practice before you ruin too many chips. The higher the temperature, the easier it is to make the contact, but the more likely you'll kill the chip – a bit of a dilemma there. 600 degrees seems to be a good compromise.

My class D amplifier board

Here's the final product installed in my talking meter project. One interesting observation is that over half the sound I get out of my box depends on the resonance chamber behind the speaker. That empty space in the speaker cabinet isn't poor planning - it's vital. One of my major challenges in this project was making it loud enough. But the first time it was used on a practice mission, my teammates demanded that I install a volume control. Success!



I like to pot the working chip with a cover of clear epoxy to protect it.

In summary, I was totally amazed that I was able to make this work. Who says we old guys have lost the touch? It rarely hurts to try.
