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Chapter 6A

BUILDING A HOMEBREW QRP

Crystal controlled, CW transmitters delivering about 5 watts

Among the guys I work, QRPs seem to be the most common homebrew project, second only to building antennas. This Chapter describes a versatile 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 sensitive, selective, all-band ham receiver is complicated to build and most guys don't have the time to do it. (See Chapters 13A & 13B.) On the other hand, Chapter 7A describes building a simple, 5-transistor 40 meter receiver. I have used it with the QRP described 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.

This chapter introduces the many construction methods and tricks you will need to build a QRP from scratch. As a result, it was useful to divide it into two parts. The second half of Chapter 6 concentrates on troubleshooting and some extra features you might want in order to use it successfully on the air.

A 40 meter QRP module



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This QRP transmitter is designed exclusively for 40 meters, (7.000 to 7.300 MHz.) With different coils and crystals, it could also be used on other bands. 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.

The transmitting frequency of the QRP module is controlled by a custom ground 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, building a Variable Frequency Oscillator (VFO) that can cover the entire band is difficult. 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 expensive 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, power supply, pilot lights, an antenna relay and other niceties. My whole transmitter assembly is shown below.



Transmitter mainframe

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 square 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 *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. This was OK because tubes run on hundreds of volts and tiny currents. In contrast, transistors generate high power with low voltage and big currents. The Radio Frequency (RF) voltage loss along a long, skinny wire is proportional to the current. A long wire has significant inductance when it carries large RF currents. Wire does *not* need to be wound into coils to have inductance. In order to work, the inductance of the wiring must be as low as possible. If we build RF amplifiers using transistors *we have to build them on printed circuit boards*, otherwise our transmitter simply won't work.

Let me illustrate: Once I connected an output lead from a 21 MHz (15 meter ham band) transistor power amplifier to the base of the next transistor amplifier stage with a bare wire 4 inches long. If this had been a vacuum tube circuit, this wire connection would have worked fine. But with high current transistors, the wire acted like an RF choke. In other words, the wire blocked current flow as if it were an inductor. Sliding an oscilloscope probe along the bare 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, materials and techniques

I usually use double-sided printed circuit (PC) board material such as Radio Shack part # 276-1499A. This board has layers of thin, one ounce copper bonded to both sides of a 1/16th inch fiberglass sheet. I recently accidentally ordered some 1/32th inch, half ounce copper PC board material. Boy! Was that easy to work with! The trade off is that it has less mechanical strength and bends easily.

I only solder components onto the surface of one side. Using two-sided circuit boards,

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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. Another advantage of double sided boards is that they may be soldered together to make shielded enclosures. You can carve (or etch) a circuit into one side of the board while the other side serves as the uninterrupted metal wall of a shielded box.

NOTE: Single-sided boards work better for the highest HF bands, but you lose the ability to make feed-through holes to the grounded outer layer. Also, you can't solder the boards into shielded boxes. If the bottom layer is intact and grounded, double-sided boards have too much capacitance to ground. In my experience, they won't work at all on 6 and 2 meters.

The first challenge is to cut the somewhat fragile circuit board material into straight, undamaged rectangles with square corners. First I mark where I wish to make my cuts using a fine-pointed felt tip pen. I use a carpenter's T-square to ensure straight lines and right angles. To prevent the PC board from being dented or crushed, I place it between two blocks of wood. I mount the assembly in a large vise on my workbench and make the cut with an ordinary hacksaw. Hacksaws come in different lengths and longer is better to handle large boards. Chipping and peeling the copper layers can be prevented by holding the saw blade at a low angle with respect to the PC board. I pull up a chair in front of the vise, and seated with the board at eye level, I hold the saw almost vertical. Another advantage of the shallow angle is that the blade rides in the cut for several inches and maintains a straight line. This crude method makes it possible to cut a board a foot or more in width, even though the hacksaw frame is only three inches deep.

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 <u>distributed</u> inductance that rings with the <u>distributed</u> capacitance between the center wire and the outside insulation. The energy losses that do occur are only the heating losses in the insulation and the simple resistance losses that occur 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. In theory, a trace can act like coax cable and transmit RF currents with almost no losses. I'm not convinced this is practical with ordinary fiberglass boards at HF frequencies. I have observed that, when RF currents are large, wide traces have far less loss.

UHF and microwave (GigiHertz) printed circuit boards often have traces deliberately designed to act like transmission lines for a particular frequency. The precise, optimum dimensions for these "microstrip" traces are calculated using special software. Moreover, they use circuit boards made out of exotic, expensive, low-loss plastics. Fortunately, high frequency (HF) circuit boards like ours don't have to be designed with so much care.

The highest quality HF circuit boards are two-sided boards with plated through holes. In other words, circuits are etched on each side and interconnected with metal-lined holes. The large components that we homebuilders prefer are designed to be "thru-hole." That means that the wire

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leads poke through the board and engage circuitry on both sides. Commercial 2-sided boards are electroplated to deposit metal on both surfaces of the boards as well as the walls of the tiny holes. Two sided boards allow optimal, compact circuitry and are nearly always used in quality electronic products. There are tiny rivets available that can be used to make conductive holes in non-plated-through boards, but I've never used them. Considering the dozens of holes needed in a complex board, that is probably too much trouble.

Today's commercial boards have grown in complexity to 6 or even 12 or more layers. These boards allow separate outside circuit shielding layers for the ground and power supply. Sensitive circuitry can be enclosed in layers in between the ground and supply sheets to shield it from the outside world. Also, a single modern chip often has a hundred or more tiny connections. A two layer board can't connect to all that complexity and multi-layer boards are essential. Commercial boards are finished with an insulating solder mask that prevents solder from bridging between traces and they are usually printed with labels for each part. Fortunately we homebuilders don't need all that sophistication.

Etched circuit boards

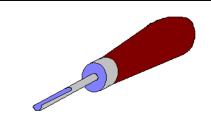
There are at least four ways to make homebrew RF boards. None of them approach the quality of multi-layer modern boards, but we do our best. Originally I tried etching "real" printed circuit boards with ferric-chloride solution. The solution dissolves the unwanted copper and leaves the traces. It's slow, 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 from the year 1960, but without the plated-through holes. Unfortunately, when you copy a circuit board 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 successful homebuilding is building AND TESTING one small circuit at a time*.

Gouged PC boards

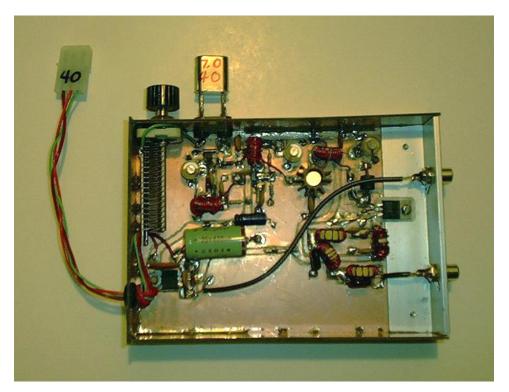
My favorite method for making RF boards is carving them into a bare, two-sided PC board with a small wood-carving "gouge." The gouge is a chisel with a cupped end, about 0.5 to 3 mm across. I have several, but my favorite is about 1.5 mm across. I got it from the Traditional Woodworker Co., (www.traditionalwoodworker.com)



Two small wood-carving gouges



Notice the cupped end of the wood-carving gouge



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.

Guide the gouge along the board at a high angle, nearly 90°, and twist your wrist back and forth. This motion causes the gouge to carve out a straight narrow trench through the copper. Hint: Keep your elbow as high as possible, nearly vertical, and the gouge won't skate across the surface, damage the board and poke into your hand. I've done that several times. Two "trenches" isolate a strip of copper that serves as a wire or "trace." Often I just isolate little islands of copper onto which I solder short component leads. I usually solder components to the surface rather than drilling mounting holes for each lead.

A strategy for making boards

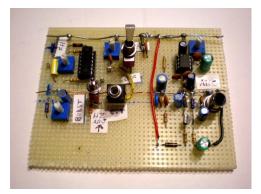
I start a board by figuring out the outer dimensions of the board. I often don't know how big it needs to be, so I just start at one corner of a blank board and work outward, one circuit stage at time. I usually leave a 3/8 inch margin so that, after it is working, I can solder on walls to make a box, if necessary. Before I carve the traces and pads, I place the parts on the board and make sure they fit. I sketch the traces and pads with pencil onto the board. The sketches of pads are usually moved and changed two or three times before I commit to carving the traces. After the trace has been cut, it's easy to erase the pencil marks.

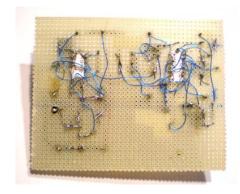
As your boards become more complex, it is easy to isolate areas of ground accidentally so that they no longer connect with the rest of your ground plane. Suddenly the new addition to the circuit doesn't work and you have no clue why. If the connection to the grounded area becomes lengthy or absent, just bore a tiny hole through the board and solder a bare wire through to the unbroken other side of the two-sided board. The inductance and resistance from one edge of an

uninterrupted square of circuit board to the opposite edge are both essentially zero. This technique is especially important with high power transmitters that have big ground currents. In my QRP boards designed for 20 meters or above I usually have several shunts to the unbroken side. This insures that all "grounds" truly are the same and there are no voltage differences between different ground points.

PC boards for integrated circuits

A wood-carving gouge works fine for RF circuits made from discrete transistors, but is more difficult for integrated circuits. For through-hole ICs I usually use 0.1 inch center punch-boards which are designed for wire-wrap circuit connections. They consist of a bare fiberglass sheet with tiny holes drilled in a 0.1 inch grid. Actual "wire wrapping" involves using special IC sockets with long pins. Thin Kynar insulated wires are wrapped onto the pins with a special tool. This produces messy-looking, complicated boards which work fine for low frequencies. Wire-wrap has the advantages that no soldering is needed and they are easily re-wired.





Another way to use punch boards or "perf boards" is to wire and solder the pins and components using the thin wrap wire. The underside wiring is confusing, but it's easier to stay organized if you label and write the IC pin numbers on the underside of the IC sockets. The above circuit is an audio amplifier and tone generator for a VHF 2 meter transmitter (Chapter 16B).

Rather than solder the IC onto the board directly, I use IC sockets whenever possible. If an IC should fail, or if you suspect it failed, you can easily plug in another one as a test. If you remove a soldered-in IC, the chip or copper board traces will almost always be damaged by removing it.

With steady hands and good planning, it *is* possible to carve out pads on tenth-inch centers for larger, old-style integrated circuits using a 1 mm wide wood gouge. I usually mount the IC sockets surface-mount-style by bending the pins of the IC socket outward and soldering them to the pads I have carved on the board. Examples of this technique are in the receiver VFO and power supply shown in Chapters 10 and 13.

Little commercial IC adapter boards

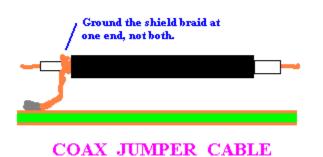
Surface mount components are tiny. The biggest surface mount integrated circuits have pins 0.05 inches apart along the edges of the chips. More modern chips have even smaller dimensions. One method of working with surface mount integrated circuits is to etch (or buy) tiny boards for mounting each type of IC. That is, we make separate little boards for 8, 14 or 16

pin ICs - whatever we need. These little boards have big pads connecting each tiny pin so that we can solder jumpers from the little adapter board down to our relatively crude handmade board. Many modern surface mount ICs simply have contact points instead of projecting pins. Most of these chips are much too small to connect jumper wires over to homemade boards. Chapter 17C has an article about the effort required to connect the contact points of a relatively simple, tiny surface mount chip.

Coax jumpers

If you need to, it is still possible to run long wires that carry RF from point to point. But instead of wire, you must use shielded coax. Sometimes I need to "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 we 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 instance, in the QRP board above, my DC (Morse code) keying signal is transported across the board with a length of thin 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 above. An ordinary wire probably would have worked OK, but I was being cautious.



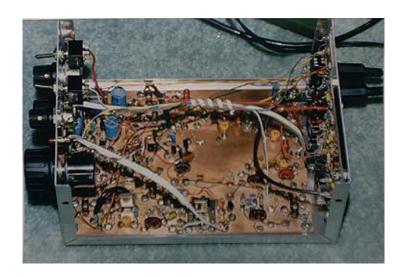
Ground the coaxial shield at just one end. The most common error when using coax jumpers on a board is to ground both ends of the shield. This introduces a "current loop" that can act something like a turn of a winding on a transformer. This current loop may pick up stray currents and the coax might do more harm than good.

In contrast, if you have no reason to worry about the line acting like a receiving antenna, and you just need to supply a DC power supply line from one location of the board to another, then simply solder a wire jumper from that point to wherever you need the power. Another trick is to cut a long, thin strip of PC board which can stand on edge across the larger board. The low inductance strip can carry high currents and provide an accessible ground.

Disk and Super-glue boards

Probably the most popular homebrew RF PC construction method is the "disk and superglue" method. Sometimes this is called "Manhattan style." Small disks or strips are punched or cut out of PC board material. The disks and strips are glued onto the PC board using cyanoacrylate "super-glue" 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 current levels, the more important this advantage becomes. A gouged or etched board can achieve this by soldering feed through wires to the intact, grounded, other side of a 2-sided board.

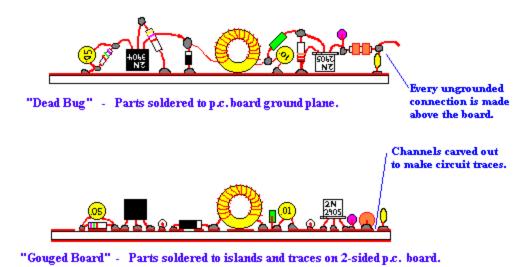


Mike Fitzgibbon, NØMF, built the homebrew QRP transceiver shown on the left using the super-glue technique. I met Mike on the air while he was using this transceiver. The transceiver puts out about a watt and uses a super-regenerative receiver. We easily communicated across 1,400 miles so apparently 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 on the higher HF bands.



"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. I once 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 *the same recycled 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 transmitted RF current. Small squares of circuit board connect the relay terminals to the coax connectors terminals. These squares have essentially zero inductance.

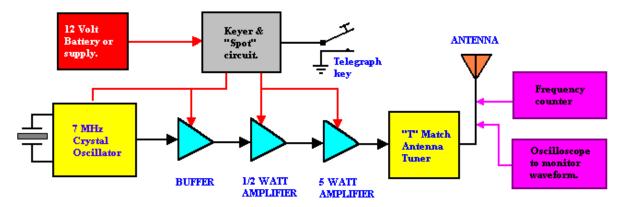
Boxes made out of PC boards

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, two-sided, 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.

A shielded box like the QRP on the first page of this chapter has 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 and is illustrated in Chapters 13 and 15.

The complete crystal controlled QRP transmitter

The block diagram below shows all the 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 a lot of circuit blocks. Two of the modules on the right, the

oscilloscope and frequency counter, are the test instruments I use to be sure I am operating in the correct band. These are tools you will eventually want if you proceed very far into this hobby. If you plan to operate your QRP in the wilderness, obviously these test instruments are impractical. Chapter 9 describes an antenna tuner and simple tuning procedure that will allow you to operate legally with good accuracy. The power supply that I prefer is a simple car battery or preferably 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 is nearly dead. You can also build a power supply that plugs into the wall or buy a supply. Power supplies are discussed in Chapter 8.

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 large lead-acid battery. The oscillator, buffer and amplifiers will be discussed next. The keyer circuit is discussed in Chapter 6B. 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 will probably be damaged. Suitable antennas are discussed in Chapter 5B. Accessories like the telegraph key, a transmit/receive antenna relay and antenna tuners are discussed in Chapter 9.

Amplifiers and oscillators

In order to generate a radio signal, we first need to make an oscillator. Old-time spark gap transmitters generated radio waves by the electronic equivalent of banging on a bell. On the modern ham bands we need continuous, pure sinewaves. Think of oscillators as the radio equivalent of an electronic organ. You hold down a telegraph 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

Transistor Amplifier 470 µH RF input RF choke 33KΩ sinewave 2N3904 NPN transistor Voltage output 6.2KΩ The voltage on the collector is 120Ω the opposite 0.01 µF polarity of the base voltage.

output. Before we can understand an oscillator, we need to describe 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 the power supply polarity and use a PNP transistor (e.g., a 2N3906). PNP will work just as well. The amplifier on the left 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 a *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, milliamperes 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 type N collector to the type N emitter (top to bottom). In the 2N3904 transistor used above, the transistor "gain" causes a big current to flow from collector to emitter that is as much as 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 the minimum of parts would be just the transistor 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 voltage arrives at 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*. Notice that the polarity of the output sinewave *voltage* taken from the collector is the reverse of the input sinewave voltage on the base.

What does the 470 microhenry inductor "choke" do?

The choke produces an RF voltage output on the collector terminal without wasting energy. We could replace the inductor with a resistor, but it would become hot and waste energy. This amplifier is designed to generate a big RF voltage. The output is the voltage that rides on the transistor collector. The inductor has two purposes: First, it separates the constant DC voltage of the 12 volts supply from the average and lower DC voltage on the collector. Second, it allows a large RF voltage to exist on the collector. We use a large inductor relative to ham band frequencies so that the inductor can't charge (increase stored magnetic field energy) between RF sinewave cycles. (Remember that *the current through an inductor cannot change instantly.*) RF cannot pass through the choke, but DC (zero frequency) current can. The inductor is just a coil of low resistance copper wire. Consequently, a big RF voltage appears on the collector and little energy is wasted.

Another way to look at a Radio Frequency Choke (RFC) is that it is like a metal, helical spring that stores current instead mechanical energy. Each sinewave voltage polarity stores or removes energy from the inductor, like compressing or expanding a metal spring. The energy is returned to the circuit when the sinewave voltage polarity reverses and no energy is dissipated in the choke.

Stabilizing the transistor operating point

An RF amplifier like this can be thought of as two circuits at once, a DC circuit and an RF, alternating current circuit. The DC circuit prepares or "biases" the transistor operating point so that the RF sinewaves have room to rise and fall without running into the 12 volt supply

voltage or zero voltage ground. 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.

Hot transistors turn on more fully and become hotter. 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 decreasing the collector to emitter current. So long as this resistor isn't too large, it simply makes the transistor resistant to temperature change. In practice, the emitter resistor causes little or no loss of RF output voltage. 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** from base to ground makes sure that the charge in the base of the transistor always has a way to leave and turn off the transistor promptly. The 6.2K resistor also stabilizes the operating point and insures that the circuit will work every time you build it.

Notice that the 33K and 6.2K DC bias resistors establish a resting state for the transistor. If there is no RF input signal to the base, the base, emitter and collector DC voltages will settle to their resting voltages. In the case of a class A transistor amplifier, this resting state can be dissipating significant power. It's like a parked car with the transmission in neutral and the engine running at half speed ... hard on gas mileage!

Bypass capacitors

So what does the 0.01 microfarad capacitor across the emitter resistor do? This is a *bypass capacitor*. As just explained, an RF amplifier can be thought of as two circuits superimposed on each other. The DC circuit establishes the resting DC voltages and currents. The radio circuit handles the transient RF sinewaves that modulate the average DC voltages and currents. RF current passing through the emitter 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 average 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 bypass capacitor "short circuits" RF currents and eliminates the RF voltage between the emitter and ground.

The result is that the RF voltage between emitter and ground will be zero and no RF output voltage will be lost. In contrast, *the voltage across an inductor can change instantly*, *so all the RF output voltage appears on the collector*. Another way to look at bypass capacitors is that they "shunt" RF to ground, but do not affect the DC voltage.

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.

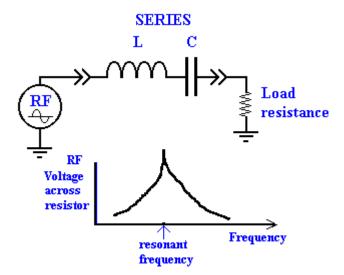
Notice that a one-stage transistor amplifier inverts the polarity of the input waveform. Rising voltage on the base causes the voltage on the collector to fall. In theory at least, if you were to feed the output of this amplifier back to the base circuit, the opposite polarity of the output could cancel out any signal that begins to form on the input. For this reason, if you wish to make an oscillator, ideally the waveform needs to be turned up side down or *phase inverted* before the feedback is introduced to the transistor base.

Transistor oscillator

Positive feedback 180 degree phase shift network Transistor amplifier inverts and amplifies the sinewave. Output

Series LC resonant circuit

In Chapter 4 you were introduced to the parallel resonant LC circuit. The <u>series</u> resonant LC circuit also resonates at a specific frequency and can be used in much the same way. The <u>parallel</u> 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 <u>series</u> resonant circuit looks like *zero resistance* at the resonate frequency. As shown below, 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.

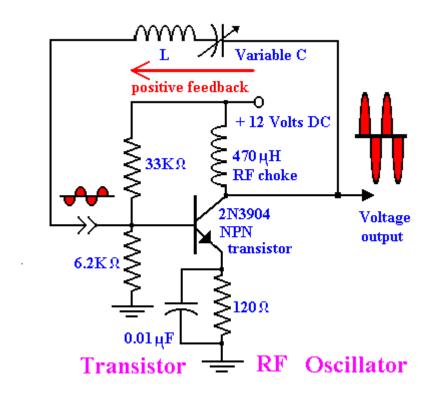


The need for a phase inverter circuit gives us the opportunity to use this inverter circuit as

a filter that also restricts the oscillation to just one frequency. A series LC circuit will attenuate every frequency except its resonant frequency. A series LC circuit located between the collector and base of a transistor amplifier will oscillate on a specific frequency determined by the series inductance and capacitance.

A working transistor oscillator

The circuit below 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 an extremely 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 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 well below the 0.6 volt Restore the threshold. 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 0.6 volt 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 class A amplifiers. 65% versus 30% is typical.

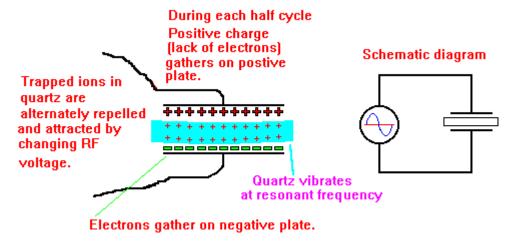
Quartz crystal oscillators - the key to modern frequency stability

Electronic wrist watches today use quartz crystals as the frequency standard that gives

cheap everyday watches accuracy that rivals the old time mechanical chronometers that were once vital for navigation. I wear a crystal controlled Casio watch that I bought on sale for \$7 at Radio Shack. By dumb luck, my particular crystal happened to be exactly on the desired frequency. The watch loses one second in 5 months! Eat your heart out, Rolex! When I realized what an amazing watch it was, I rushed out and bought another watch. Sadly, its error was 18 seconds/month. The first watch accuracy was random good fortune. Even cheap crystals can be extremely stable in a low voltage oscillator. However, getting them precisely ground is a different challenge. Analog color TVs used crystals as a time standard so that the color separation circuit could accurately display red, blue and green. Computers use crystals as clock standards so that receiving modems will run accurately and remain in step with the sending station.

Quartz is a crystalline form of silicon dioxide glass. It is an extremely good electrical 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 has been manufactured artificially in ovens.

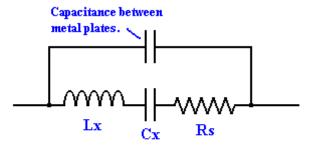
When voltage is applied across the quartz, the charged metal ions contaminating the quartz are physically attracted to the charged plates as shown below. The thin quartz sheet literally bends back and forth as the voltage changes polarity. If the voltage is an RF voltage, the polarity changes back and 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, large, wide, thick crystals vibrate at low frequencies. Tiny, thin 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, which are 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.

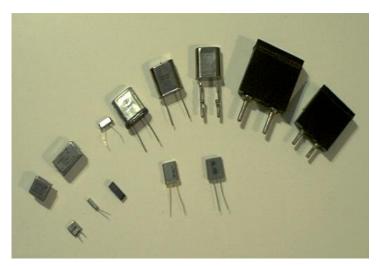
Although the oscillation is mechanical, it also acts as though it were oscillating electrically. Quartz crystals act like a series LC circuit. They are equivalent to the LC components we used to tune the crude oscillator above. The equivalent circuit is shown below. Rs is a resistance that represents the energy lost due to mechanical heating caused by bending the crystal repetitively.



Series "equivalent" components are determined by the mechanical properties of the crystal.

Equivalent circuit of a crystal.

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 extremely fragile. On the other hand, if the crystal was already inert, breaking it isn't a loss.

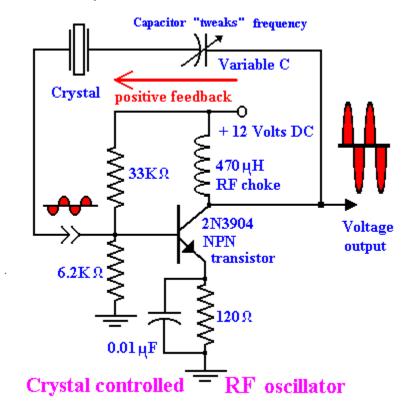


The three big silver-colored crystals in center rear are size HC-33 and are modern-manufactured, first-rate parts. The two medium size HC-49 crystals in the front center are mass produced microprocessor crystals. These are

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 Bomar Crystals for about \$65 each - not cheap. The little bitty crystals at the lower left should be used with caution. If the voltage across them is too high, little crystals warm up quickly 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 below 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.



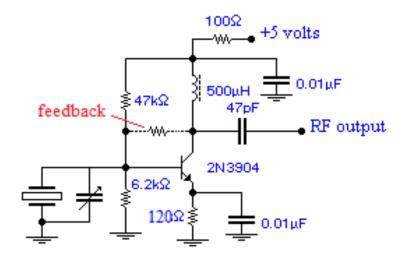
The circuit above is useful and you will occasionally see it used in homebuilding projects. It has the advantage of producing a large output voltage.

Yes, if you like, you can leave out the variable capacitor. However, it is not a good idea to put big sinewave voltages directly across 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 the quartz wafer and ruin it. For these reasons, although this circuit is easy to explain, I don't 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 below 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.



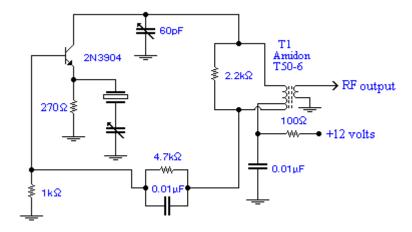
An alert reader, Don Singer, pointed out to me that the above oscillator as drawn in a previous revision of the book had no feedback. Yes, I also thought this was mysterious when I first encountered this circuit. When I looked up crystal oscillators in the ARRL Handbook, I discovered that all of their illustrations had some sort of feedback from collector to base or from the emitter over to the crystal. Consequently, for the above schematic I added a feedback resistor with the dotted lines from collector to base.

If you build this, I believe you'll find that the resistor or other feedback isn't really necessary. So long as the amplifier is class A, there will always be a little random noise on the base that the transistor will amplify. The crystal will reinforce the noise that happens to be at the crystal frequency and soon the oscillation will be self-sustaining. For example, when an audio public address system feeds back, it makes a single frequency scream. This tells us that the amplifier has preferred frequencies that it settles on. It doesn't vary the oscillation in accordance with the speaker's last word.

Butler is better - No warm-up drift

One day I checked out every oscillator in my home-built receiver and transmitter. I discovered that some of them didn't have the warm-up drift when turned on. The stable ones were Butler oscillators as shown below. Notice that *the crystal and its capacitor are in parallel*

with the emitter resistor. This circuit has little voltage across the crystal and heats it minimally. The frequency is stable the moment it is turned on.



A Butler crystal oscillator

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 when 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 decreasing the 270 ohm resistor to 150 ohms. This will turn the transistor more "on" and, surprisingly, the voltage across the 150 ohm resistor will be larger. If it is still too weak, increase the 1K base to ground resistor to 2K. Also, big crystals tend to put out much larger signals than small ones.

Another way to make a reluctant oscillator work is to increase the value of the 2.2K ohm resistor across the inductor. Unfortunately, the higher the resistance, the more the drain LC circuit dominates the frequency instead of the crystal. This makes the oscillator unstable with changing temperature and voltage. If the resistor is left out, the LC circuit will completely determine the frequency and the crystal becomes irrelevant. As you watch an oscilloscope trace, adjust the 60 pF trimmer capacitor across the inductor. The sinewave amplitude should rise or fall, but the spacing between the sinewave cycles should be constant. Also, raise and lower the supply voltage while monitoring the output with a scope, frequency counter or both. With crystal control, the frequency will not vary with voltage change.

The series capacitor in the Butler oscillator 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 mysterious Integrated Circuit (IC) oscillators, like "NE602." Among other circuit blocks, these ICs contain oscillators. To wire it, the crystal is simply

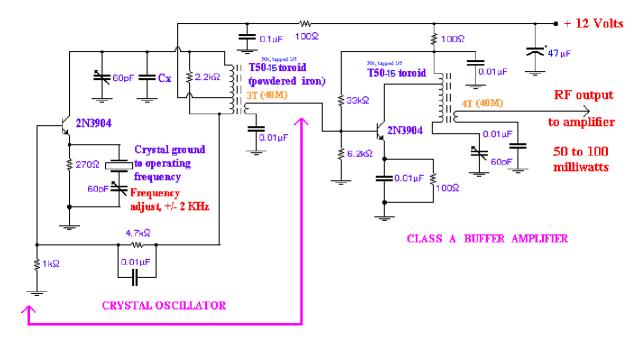
connected to pins on the little square package. Heaven only knows what's in there! Apparently we homebrewers are the only people who care.

Power supply bypass capacitors

Notice that most transistor circuits have a $0.01~\mu F$ capacitor to ground on the supply side of the collector or drain LC circuit. There is a $100~\Omega$ resistor separating the supply voltage and this $0.01~\mu F$ capacitor. This RC circuit isolates and stabilizes the supply voltage right at the transistor so that the power supply voltage regulator or changing load current will not "talk" to the oscillator and interfere with the oscillation. In the case of the Butler circuit above, sometimes it will not even begin to oscillate if you leave out this capacitor and its isolation resistor!

The 40 meter QRP circuit

The circuit shown below is the core of my QRP transmitters. 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 LC circuit for a specific band, 40 meters in this case. Also, its output is a transformer winding that "matches" the high impedance output (roughly 600 ohms) to the next stage of amplification.



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, when used with the final amplifiers that will be described below, my QRP put out 15 watts with a 12 volt power supply instead of the 5 watts

I was expecting. Oops! When I ran it on 6 fresh D-size flashlight batteries (9 volts) it put out 7 watts.

Old crystals often have low output

After this project I put the crystal controlled QRP aside and moved on to the VFO controlled QRPs described in Chapter 11. In 2015 I dusted off the crystal-controlled QRP and combined it with the direct coupled receiver from Chapter 7A and an antenna tuner to make a stand-alone 40 meter transceiver. (See Chapter 9 for the antenna tuner.) When I tested it, I was startled to discover that the output power had dropped to only 2 watts! To shorten a long story, my ten year old HC-33 crystals no longer generated big RF output voltages. One of them wouldn't even oscillate in the Butler circuit. The working HC-33s behaved the same as a 5 year old, much smaller, 40 meter HC-49 crystal.

The big drop in power is partly explained by Ohm's law: If the voltage across a load drops to one half, the current also halves and therefore the power drops to one quarter. It you aren't getting 5 watts from my design described here, it may be necessary to add another tuned amplifier between the buffer and the final. If that produces too much power, then reduce the turns of the secondary winding that drives the base of the final amplifier. Build your QRP one stage at a time until it produces the power you need into approximately a 50 ohm load.

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. The important issue is that it works, not beauty or compact size. When building a project, *use parts you can get and circuits you understand*.

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 often only frustrate you. The inductor cores are the only critical part. They should be toroidal in shape (like a donut) and made from **powdered iron**. They should be designed for approximately the right frequency range. Toroid cores from CWS Bytemark, Micrometals, or Fairrite manufacturers are all fine. What's important is that **you need the** A_L **inductance value so that 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		
			for the two stages		
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, tapp	ped 1/3 7 turns & 9 turns		

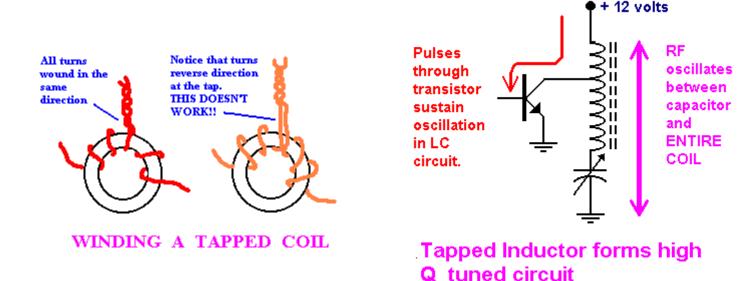
20 Meters	T50- 6	28 turns, tapped 1/3 3 turns & 4 turns
17 Meters	T50- 6	22 turns, tapped 1/3 3 turns & 5 turns
15 Meters	T50- 6	22 turns, tapped 1/3 3 turns & 4 turns
12 Meters	T50- 6	16 turns, tapped 1/3 3 turns & 3 turns
10 Meters	T50- 6	16 turns, tapped 1/3 3 turns & 3 turns

The number of turns is NOT necessarily critical. – if it tunes up well in the center of the variable capacitor range, that's the right number. (The toroids I used are CWS Bytemark, formerly Amidon, cwsbytemark.com)

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. To make a "tap" in the coil, wind the correct number of turns to the first tap. Next scrape the exposed magnet wire coating so it will accept solder. Then, leaving a free loop of scraped wire, continue to wind the rest of the coil.

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 the 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 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 an inductor, it is just a "wire."

Q = equals quality

Inductors and capacitors have a quality factor called "Q." The higher the Q of a tuned circuit, the more precisely it tunes. Crystals are extremely high Q which is why they make excellent frequency standards. Q 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 having 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 oxidation) 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-child-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 turns wound around the primary coil, but *not* connected to ground. Because it is floating, this winding isn't intended as an inductor or secondary winding, it just serves as tiny capacitance, 1 or 2 pF,

between the oscillating LC circuit and the next amplifier stage.

<u>Crystal</u> oscillators are so stable, it's practical to use frequency multipliers for generating signals on the upper ham bands. For example, if you have a 40 meter QRP operating on 7010 KHz, you could multiply its frequency and operate on 14020 KHz, or 21030 KHz. In contrast, if the frequency standard is a low frequency VFO like the ones discussed in Chapter 10, the drift will usually be too great by the time it is multiplied to the higher bands. How to "move" a low frequency VFO up to the higher bands while retaining the low drift is explained in Chapter 11.

If inductive and capacitive resistances are called "reactance," what's impedance?

Impedance is the effective sum or total result of all the reactances and resistances in some portion of 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

Suppose you wish to transfer power from one circuit to another and you don't have a perfect voltage source with zero internal impedance. You can transmit the most power to your load 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 this voltage. This means that very little power can be drawn out of the exhausted battery. As soon as current begins to flow, the voltage at the battery terminals crashes. 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. Play with the arithmetic and see if you agree!

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 is not intuitively obvious, 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 couple 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.

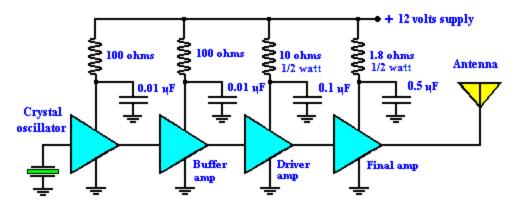
Power supply communication is more difficult. Suppose a powerful sinewave signal is being generated in a final amplifier. As the current rises through the large output transistor, this

big current loads down the power supply voltage and may 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 oscillator 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 the reading will not hold still.

The internal resistance of your batteries determines how much power your transmitter can generate without instability and chirp. For example, using two 125 ampere-hour 6 volt golf cart batteries, I have found that 100 watts RF output is the practical limit for my battery powered station. If I use eight 1.5 volt alkaline D-cells in series to power my QRP, the limit is 5 to 7 watts and only works well for brief transmissions.

Transmitter stability 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 lowers the rate of voltage change to the output stage to make it slower than an RF cycle. That is, $1/0.9~\mu$ sec = 1.1 MHz. For the QRPs described here we are operating on 3.5 MHz or higher, so the voltage on the final stage doesn't vary much with every cycle. *To fully charge a capacitor requires about 5 time constants*.

These RC decouplers prevent the voltage changes from feeding back to earlier stages. The stages that draw the most current need smaller resistance. This keeps the DC voltage loss across the resistors as low as you can tolerate. Also, The more current each stage draws, the more capacitance it needs. The capacitors should be low loss types designed for RF bypass applications such as disk ceramic or mica. If you leave out these R-C circuits, the QRP will still work fine IF you have a stable 12 volt supply. However, if you use a weak supply, such as old flashlight batteries, it will be very difficult to maintain a clean sinewave output.

I have observed that, if I disconnect the supply decoupling capacitor on a Butler crystal

controlled oscillator, the oscillation stops. These are critical components!

LC decouplers

The first transistorized QRP that I built was from a design in the 1979 ARRL handbook. This design used inductors instead of resistors in the decoupler circuits. Since there is no appreciable DC energy loss in an inductor, inductors look like a good idea. Unfortunately my circuit was extremely unstable until I took out the LC decouplers completely. It was later when I ran the QRP on flashlight batteries that I discovered how important RC decouplers were. In contrast, at 145 MHz RC decouplers waste voltage while simple, low inductance LC decouplers work well.

The time constant for inductors is calculated the same way as capacitance:

RL time constant for inductors is resistance times inductance = time constant in seconds

For example, for a 0.5 microhenry inductor and 1.8 ohms, the time constant for current change will be:

1.8 ohms x 0.5×10^{-6} Henries = 0.9 microseconds

To fully charge (i.e., saturate) an inductor with current requires about 5 time constants.

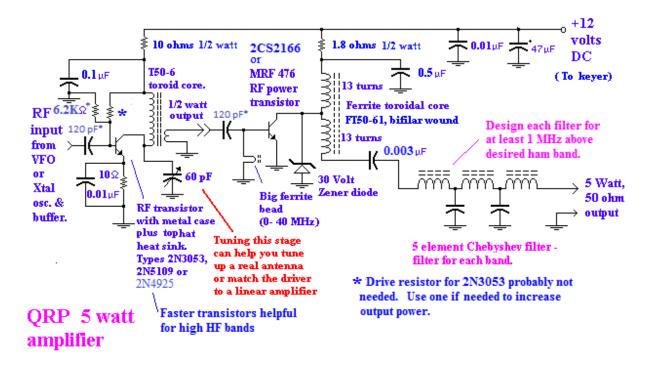
The final amplifier stages for the QRP - Power Amplifiers

Power amplifiers are much harder to build than voltage amplifiers. Power amplifiers running on low voltages mean that big, stable RF currents must be stuffed into the bases or gates of large power transistors. That is the reason low voltage transistor RF transmitters are much harder to build than high voltage tube transmitters at a given power level. One way to decrease the difficulty is to use 100 volt transistors with a high voltage power supply. But even 100 hundred volt transistors will be much harder to design than 500 volt vacuum tubes for the same power gain.

Illustrated below are two versions of working QRP output power-gain stages for 40 meters. The first one was built for the crystal controlled QRP. The second version was built much later for use with a VFO driver as described in Chapter 11. The tunable LC driver design is difficult to get working. The asterisks are next to the parts that I had to modify to make it work.

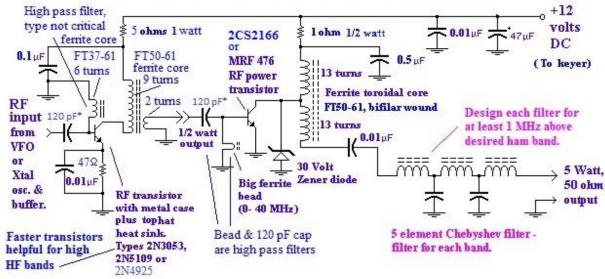
I eventually realized that *TUNING high power*, *low voltage*, *transistor amplifiers is just plain difficult*. The 2N3053 amplifier stage is hard to design so that there is a solid resonance with two distinct resonance points with each 360° rotation of the trimmer capacitor. I notice that modern SSB transmitters always have *broadband* power amplifiers and do the tuning with separate high Q filters.

A QRP Two Stage Power Amplifier - original tuned driver



Below is shown a broadband version of the same amplifier.





This untuned amplifier relies on the preceding tunable, resonant, voltage amplifiers for its frequency purity and control. It solves the resonance problem but *both the tuned and untuned versions have difficulty with low frequency stability*. Both designs tend to "jitter," dance around on our scope displays, rather than hold still with pure RF sinewaves. This instability occurs at frequencies much lower than the desired frequency, so the cures are *high pass filters*. These filters allow the desired frequency to go through the amplifier with no attenuation while

suppressing the low frequencies. The big ferrite bead on the base of the MRF476 and the 120 pF coupling capacitors are examples of high pass filters.

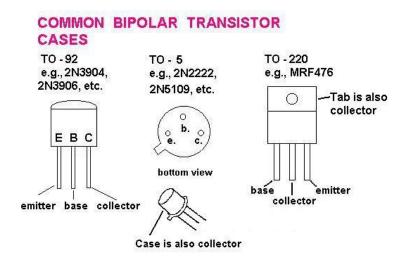
The FT37-61 ferrite core I used to suppress low frequencies on the driver stage is not critical. You may use the same FT50-61 core or a big bead or any other large millihenry choke that works for you. Just be sure the inductance is large enough so that the current through it can not change noticeably during an RF sinewave cycle. The diagram shows the component values of the VFO controlled 40 meter QRP discussed in Chapter 11.

To test this broadband amplifier I measured 4.7 watts into a 51 ohm 1 watt resistor using the resistor temperature rise power measurement described in Chapter 16A. This matched the result I got using the scope to measure and calculate power = $Vrms^2/51$ ohms.

The final amplifier stage

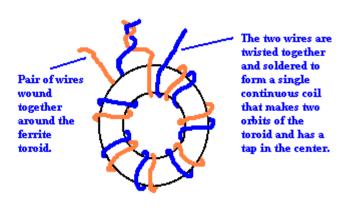
The broadband final amplifier stage works well over the entire HF range, 80 through 10 meters. However, you will need different Chebyshev filters for most bands. It is important to suppress the 2nd and 3rd harmonics of 40 meters so it won't be heard on 20 meters or 15 meters.

A small power transistor, like the 2N3053, has a metal TO-5 case resembling a tiny tin can to help conduct away the heat. A "top hat" heatsink can be clipped onto this transistor to radiate more heat. Look in your catalogs under heatsinks and you should find a large assortment. The newer and **inexpensive** type 2CS2166 transistor has a large TO-220 case and, to my surprise, works well in the driver circuit as a substitute for the 2N3053. The 2CS2166 can share the large aluminum heatsink with the MRF476 and can also substitute for the hard to find MRF476.



Obviously, I don't fully understand the intricacies of tuned power stages. Moreover, as you build versions of this stage for different ham bands, your capacitor choices will probably need to change. For higher bands like 15 to 10 meters, you may need to use more high speed versions of this transistor, like the 2N5109 and 2N4925. Experiment! If you master it, please tell me what I'm missing.

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 CWS T50-61 **ferrite** instead of powdered iron. Ferrite is a more dense, glass-like iron ceramic material. Ferrite provides much higher inductance than you would obtain if the same coil were wound on powdered iron cores, such as the T50-6. A transformer wound on powdered iron typically

has inductances in *micro*henries. Transformers wound on ferrite typically have *milli*henries of inductance - 100 or 1000 times more. In other words 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 no resonance when using this transformer at HF frequencies.

Although the transformer is wound with two parallel wires, the two wires are soldered together to make *one winding that circles the toroid twice*. Bifilar wound transformers are a kind of center-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. This clever winding scheme makes the coupling between the two windings as intimate as possible and minimizes power loss.

Before you wind one of these coils, examine the drawing 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 resistance betweens them. If you find that your "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.

Tuning an amplifier in the QRP can act like an antenna tuner

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 to tuned amplifiers, 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 chaotic 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.

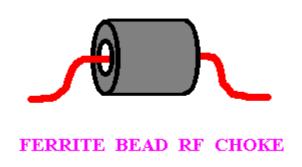
The output stage in the QRP is a broadband amplifier that uses a five-element Chebyshev filter to suppress high frequency harmonics in the output. Chebyshevs are described in detail below. The filter component values can be found in tables and formulas in an ARRL Handbook, e.g., 1986 or later. *The higher the band, the more difficulty you will have reaching 5 watts*.

For example, I rebuilt the 10 meter QRP several times to get up to 4 watts. Chapter 11 covers QRPs driven with a VFO that covers 500 KHz of bandwidth instead of just a few KHz from a crystal. Chapter 11 has several more ideas about how to address low power and noise problems. If you're going to attempt a crystal-controlled QRP higher than about 20 meters, you might first study Chapters 10 and 11.

Expensive RF transistors

The final amplifier uses a Motorola MRF-476 transistor. They are pricey, \$13 or more and you may have trouble finding them today (2015). The newer type 2CS2166 is a direct replacement for the MRF-476 and costs \$1.95. I tried some and they seem to have as much gain, or almost as much gain, as the MRF-476. There must be hundreds of cheap transistors that can put out 5 or 10 watts at HF frequencies. Unfortunately, the other 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. At the time, even \$13 seemed worth the cost.

Ferrite bead RF chokes



Notice the bead RF choke on the MRF-476 base. It's just a short piece of wire through a **big** ferrite iron bead (1/4 inch diam. or more) soldered from the base to ground. Unlike toroids for which we hope to calculate an accurate inductance, beads aren't very critical. The bigger the bead the more inductance they will produce. Which type of ferrite and the size of the bead are not critical. However, a bead that is too small will work well at VHF frequencies, but may

ground or attenuate our desired HF signal.

The beads eliminate low frequencies from the output and turn a "roller coaster," chaotic output waveform into a clean sinewave. This bead serves as high pass filter that allows high frequencies to "pass by" into the transistor base while it shunts low frequencies to ground. It looks as though it would act as a short circuit to ground and that is exactly what it does to low frequency components below the HF ham bands. Even if you run the amplifier on low frequencies 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 on an oscilloscope.

I experimented with different sizes of ferrite bead. When I used one that was smaller than my final choice, it produced a perfect sinewave but cost about a watt of power. As I watched the scope, the power output gradually faded away as the temperature of the bead rose, dissipating the missing watt of power. Ferrite loses its magnetism when it passes its "Curie temperature." As soon as it cooled, the power returned.

Zener diode transistor protection

Notice the 30 volt Zener diode on the collector of the output transistor. Any time a switching transistor has an inductive load like a transformer or a relay, when the transistor turns off, the inductor will "try" to maintain the current flow by increasing the voltage. "The current through an inductor can't change instantly." Theoretically, this voltage can go to infinity. It doesn't, of course. But it could easily reach 30 volts, especially if you forget to plug in a load on the output. If the collector voltage were to rise higher than 30 volts, it might punch through the base of the transistor shorting to the emitter and ruin it permanently. Surprisingly, the Zener adds little capacitance to the circuit and doesn't effect operation. By the way, I used 30 volt Zeners because I had a bunch of them. 20 volt Zeners might be a better choice. I have accidentally left out the Zener and didn't kill any \$13 transistors. Be brave if you like!

CAPACITORS

Capacitors are rarely a problem

In contrast to inductors, mica and ceramic capacitors rarely give you trouble. However, sometimes the labels are confusing. If the label on the capacitor says "330 picofards," that's probably what it is. Small mica and ceramic 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 zero number of zeros so it would be labeled "330." That's annoying! On the other hand, on rare occasions, "330" really does mean 330 pF, so it pays to test it. A capacitance meter usually tells you everything you need to know about the unlabeled capacitors in your junk box.

Electroylytic capacitors

Electrolytic capacitors can be a little tricky. Those are the caps with the plus and minus labels on the leads. *You must orient them with the correct polarity*. The positive end must be aligned with the average positive DC voltage in your circuit. For example, if an audio signal is traveling toward the next stage, it is reasonable to assume that the upstream side of the current will be slightly higher average voltage than the destination. If the circuit is all N-channel or NPN transistors, the driving side gets the positive mark. If the circuit is all P-channel or PNP, the driving side would be negative. In a coupling capacitor, the polarity barely matters. In contrast, *power supply capacitors must be installed with the correct polarity* or they will soon fail.

There are a few rules about what kind of capacitor to use in what location. **Aluminum electrolytics have large capacitances** and are often used to stabilize power supplies. They are usually packaged in plastic-coated aluminum cans and have + marked on the positive lead. They do not conduct RF particularly well so it is sometimes advisable to shunt an aluminum electrolytic

capacitor with a small ceramic or mica RF bypass.

If you orient the **positive** end of an electrolytic capacitor toward a circuit node that usually has **negative** DC voltage, the backward voltage will erode the oxide insulation inside the capacitor. Sooner or later this may cause it to fail dramatically. Backward aluminum electrolytics usually die with a "Bang!" and release a cloud of foul smelling chemical steam, often right in your face. The chemistry in the capacitor resembles putting a battery in a charger backwards.

Resurrecting old electronics

If you plug in an old piece of electronics from your attic, the electrolytic capacitors may have been degraded by the years of inactivity. Often, if you abruptly plug them into line voltage, one or more electrolytics in the power supply may die. Ideally we should first plug them into a "variac" variable voltage AC transformer. Over an hour or two, gradually increase the AC voltage up to the normal line voltage. This will allow the oxidized layers in your electrolytic capacitors to reform and the capacitors will be as good as new. Replacing dead electrolytic capacitors is often difficult because finding and buying the right physical sizes and electrical ratings can be hard.

Tantalum electrolytic capacitors

Tantalum electrolytics are physically small but have the largest capacitances relative to their size. They rarely have working voltages greater than 25 volts. Backward tantalum electrolytics don't fail with a jet of steam, they burst into flames! 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 side 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 catch fire.

For example: Before I knew better, I 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. If I had used a 20 volt rated tantalum, it *probably* would have worked OK. I switched to an aluminum electrolytic rated at 16 volts.

CONQUERING INDUCTORS

Inductors are often a challenge

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 or pass the right frequencies and your equipment will work! The ability to wind the right inductance is a vital skill.

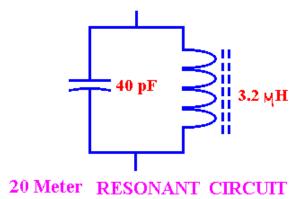
LC circuits. What size inductor do I need?

Radio technology is based on LC circuits. Sure, some circuits use piezo devices like crystals and "SAWs" that only *act* like LC circuits. They are LC circuits none the less. The C part is easy enough. Just pick a capacitor value. If I'm using a variable capacitor trimmer to tune it, I choose the center of the capacitor tuning range. Now, how big does the inductor need to be?

$$\omega^2 = 1/LC$$
 where $\omega = 2\pi f$

f = frequency in Hertz, L = inductance in Henries and C = capacitance in Farads. " π " is the constant 3.1416. This is the same π you used in school to calculate the area and circumference of a circle. Sinewaves are the projection of a point on the edge of a rotating circle, so the math is exactly the same geometry we learned in middle school.

Hopefully you have a "scientific" calculator that will do squares, square root, divide into one (1/x, or "invert") and handle large exponents gracefully. If you *really* remember your high school algebra you could do these calculations using just a pencil, a slide rule or a table of logarithms. My grocery supermarket sells adequate calculators in the school supplies section.



Suppose you're building a transistor amplifier stage that has an LC resonant "tank circuit" between the collector and the DC supply. 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. $(1 \text{ pF} = 1 \text{ x } 10^{-12} \text{ Farads.})$ That way, you can adjust the frequency if necessary.

$$\omega^2 = 1/LC$$
 where $\omega = 2\pi f$ and $f = frequency in Hertz.$

Using the above formula:

$$[2 \times 3.1416 \times 14.1 \times 10^6 \text{ Hz}]^2 = 1/(40 \times 10^{-12} \text{ Farads})(\text{ L})$$

First, reduce the ω^2 to a single number:

$$\omega^2 = 7.85 \times 10^{15}$$

Solving for L,
$$L = 1/C\omega^2 = 1x \cdot 10^{15}$$
) /C (7.85 x 10^{15})

$$L = 1/(40 \text{ pF}) (7.85 \times 10^{15})$$

Now multiply both sides by the capacitance, 40 pF.

$$L = 1/(7.85 \times 10^{15}) \times (40 \times 10^{-12} \text{ Farads}) = 3.18 \times 10^{-6} \text{ Henry or } 3.18 \text{ microhenries}.$$

Now that we know how big the inductor must be, we're ready to wind the appropriate coil on a toroid core.

Using CWS 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.cwsbytemark.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. The cores come with a little sheet with the formula for your calculation.

Ferrite vs. powdered iron

Ferrite cores have high iron content and produce high inductance for a given number of turns. In HF 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. The output transformers of **BROADBAND** linear amplifiers are ferrites. The final amplifier of the QRP circuit above uses a T50-61 ferrite toroid. Ferrites are rarely used for resonant, tuned LC circuits unless the resonant frequency is very low, such as 500 KHz.

In contrast, powdered iron cores contain far less iron and more ceramic. They are used



for *HIGH-Q RESONANT* RF circuits and filters. Notice that the powdered iron cores are color coded for their permeability, i.e., iron content. In contrast, all the ferrites are just plain black or gray, semishiny toroid cores. A small ferrite is shown at the lower left.

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 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 21 MHz and above. Type 26 (yellow-white) cores are most useful for frequencies below 80 meters.

The power level is proportional to the size of the toroid core. If your toroid becomes hot during use, it's too small. When the "Curie" temperature is reached, the inductance will crash. I've had bad luck with little bitty size T-37 cores. They produce low gain in receivers and are hard to wind. Don't use them unless you are pressed for space. On the other hand, type T-50 works fine for very low power receiver circuits up to a few watts in a QRP. In my experience type T-68 stays cool with as much as 50 watts on the high HF bands. Type T106 and T200 handle 200 watts or more and are used for output filters in high power linear amplifiers and antenna tuners.

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, low frequency, high inductance coils usually need 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) $^{1/2}$

(For those of you are rusty on your high school math, a number multiplied to the 1/2 power is the same as saying, "square root of." A wide square root symbol is hard for me to generate in Word.)

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. Notice that when calculating with the manufacturer's formula, the "micro" part is left out of the calculation. 3.18 microhenries is just "3.18."

Number of turns =
$$N = 100 (L/A_L)^{1/2} = 100 (3.18/40)^{1/2} = 28 turns$$

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 thicker wire, say # 22.

Magnet wire

RF coils are usually wound with magnet wire. As the name implies, magnet wire was named for the type of enameled wire used to wind electromagnets. It is just copper wire which has a very thin enamel coating, a baked-on paint insulation. The paint insulates it from the adjacent turns in the coil. The voltage difference between the neighboring turns of a coil is usually low, so relatively thin, low voltage insulation will prevent the coil turns from shorting to each other. If you wish to use ordinary plastic insulated wire, that will also work, but the insulation will take up much more room on the coil form and the coupling between turns will not be as efficient.



Magnet wire coating usually has a shiny, brown or coppery color, but some magnet wires are lovely shades of red or green. Before you can solder the ends of the coil to other components, the ends need to be scraped free of the enamel. The enamel coating is quite difficult to get off. I usually press the end of the wire against my work table and use a sharp Swiss Army knife blade to scrape off the coating. Sandpaper can also be used. There are some brands of magnet wire that can be soldered directly, without scraping. However, I have rarely encountered it and I doubt the insulation is as rugged.

Thin wires produce more inductance than fat wires wound on the same core.

As a result, the calculated inductance may be somewhat different than what you expected. In practice, the parallel trimmer capacitor allows you to correct for any variation from your calculated inductance. That's why it's a good idea to calculate using a capacitance value that is the center of the range of your trimmer.

Inductors, Plan B

Some readers of earlier editions of this book were intimidated by my method of winding custom inductors. An approach I have not used in my ham work exploits those gigantic Internet catalogs from companies like Mouser and Digi-Key. With thousands of choices, it's possible to find surface mount components at pretty much whatever inductance, current capability and Q you may need. OK, I suppose tapped transformers may be hard to find, but I have never looked. However, a tapped inductor can be simulated by placing two inductors in series and connecting a lead between the two.

For example: I once redesigned a VHF transmitter for an elk tracking collar. My employer was trying to cut the cost of manually winding 1/4 inch diameter toroids and tuning trimmer capacitors. I bought a selection of surface mount inductors and capacitors and was able to copy the performance of the original design with a fixed network of parts that didn't need adjustment. My boss was happy and the elk didn't care. Some surface mount inductors are physically large enough so that a ham with steady hands and patience should be able to make them work on the HF bands. Just pick inductors with the right inductance, current rating and the highest Q available. If the inductance isn't quite right, your trimmer capacitor can compensate for the difference.

Calibrating the trimmer capacitors

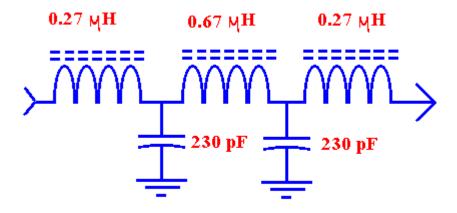
I use small, cylindrical variable "trimmer" capacitors to tune the resonant stages of a QRP module. They are about the size of a pea or a grape and are adjusted with a small screwdriver. A difficulty with these devices is that often you can't tell what capacitance they are set to by just looking at them. Since the adjustment screw goes around and around without stops, it isn't obvious when the capacitors are set to maximum or minimum.

Suppose you tune up an amplifier stage and you find that it produces the maximum signal at one certain setting. If you knew that this set point was the maximum capacitance point, you could guess that you probably 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 discovered that the best performance set point happened to 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. When the variable capacitor is optimum, it should tune to a maximum signal TWICE as you rotate the trimmer screw one 360° revolution. If there is only one optimum setting, the capacitor is either too large or too small.

My solution is to measure the capacitor with a capacitance meter, then mark the minimum and maximum set points. With most of 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.

Chebyshev filters

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 desired transmitting frequency. *The virtue of Chebyshevs is that they handle big currents and work into low impedance loads.* 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 and data sheets 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!" I struggled for enough hours to come up with a compromise set of values:



20 Meter CHEBYSHEV FILTER

"Design Factors"

I used the 1998 Handbook design method, page 16.12. It uses "normalized capacitance" and "normalized inductance" values. These are multiplied by "design factors" to produce the final value. We calculate normalized numbers from the desired cut-off frequency and desired input/output impedance. The "design factors" are a kind of final result quality factor. The tables present choices of design factors. If you are happy with a sloppy filter, then some sets of factors will give you an easy-to-build filter that will tolerate wide variability in components. For example, perhaps you could use 120 pF or 150 pF capacitors and get a usable result. Other sets of design factors might need precise values, like say, 131.7 pF. Precision components will produce a precise cut-off frequency, but they are hard to build because stray capacitance and inductance plus component variability will cause attenuation and poor performance. I picked a compromise between these two extremes and used the set of design factors listed below:

First: What operating impedance do you need? Let's assume $\mathbf{Z} = 50$ ohms. That's the most common transmitter output impedance and antenna impedance.

Second: What frequency is it for? Let's assume we want to attenuate everything above the 20-meter band. That is, 14.35 MHz. (In practice, this is overly precise. 16 MHz or higher will prevent even and odd multiple harmonics, which is the reason for the filter.)

Third: Calculate the "normalized" capacitance for the filter:

$$Cs = 1 / 2 \pi (Z) f$$

where $\pi = pi$, 3.1416 , Z = impedance in ohms and f = frequency

Capacitance, Cs = $1/2\pi$ (50 ohms) (14.35 MHz) = 222 picoFarads (pF)

Fourth: The "normalized" inductance is defined as:

$$Ls = Z/2 \pi f$$

Inductance, Ls = 50 ohms / 2π (14.35 MHz) = 0.55 microHenries (μ H)

Fifth: Multiply the normalized C and L by the **design factors** for each of the five elements. The

design factor values I selected from the 1998 Handbook for the five element low pass are:

$$L1 = 0.4869 \text{ Ls} = (.4869) (0.55 \,\mu\text{H}) = 0.27 \,\mu\text{H}$$

$$C2 = 1.05 Cs = 1.05 (222 pF) = 230 pF$$

L3 = **1.226** Ls = 1.226 (0.55
$$\mu$$
H) = 0.67 μ H

$$C4 = 1.05 Cs = 1.05 (222 pF) = 230 pF$$

$$L5 = 0.4869 Ls = (.4869) (0.55 \mu H) = 0.27 \mu H$$

For the capacitors, 220 pF (a standard value) will work just fine. When in doubt, use a capacitor or inductor *a little smaller* than the calculated value. Larger values will attenuate your desired signal. In practice, I have found that if I'm using antennas that are not specifically designed for a given ham band, designing the low pass for a somewhat higher frequency makes it easier to couple to the antenna. For example, instead of designing the 20 meter filter for just above the band like 14.35 MHz, design it for 16 MHz or even higher. That will make it easier to tune the antenna when trying to run 20 meters into a 17 meter dipole or other mismatch.

Another method for calculating low pass and high pass Chebyshev filters is presented in Chapter 11. You may find it easier than the above equations.

Heat sinks and insulators 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 can be tapped into the aluminum with 4-40 thread so that no nut is needed. The mounting kit includes an insulating plastic collar so that metal (conducting) 4-40 screws can be used. Alternatively the transistor can be screwed onto a tapped heat sink with a 6-32 plastic machine screw and no insulating collar is needed.

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 small, cheap and easier to wire. There seems to be no difference in performance, so long as the power level (proportional to the square of the current) is under roughly 10 watts and frequency is below 30 MHz. Phono plugs have twice as much capacitance (4 pF more) than an equal length of coax. I have gone as high as 147 MHz at 2 watts without obvious loss of power.

Small card edge connectors are another way to snap PC board modules together. For example, in my 50 watt HF amplifier in Chapter 12, I used 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

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The 2nd half of this Chapter, 6B discusses how to troubleshoot your QRP and suggests adding some features that can make it easier to use on the air.
