

CRYSTAL SETS TO SIDEBAND

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Chapter 12

SIMPLIFIED QRO AMPLIFIER DESIGNS

When I first got back on the air as a retiree, I built a QRP that put out 4 watts on 15 meters. I spent two days answering CQs and calling CQ. Unfortunately no one heard me. I came to the (incorrect) conclusion that QRP is a hobby for guys with expensive, huge beam antennas, not guys with verticals and dipoles. Without that extra 10 dB of gain, I figured my QRP signal must be down in the noise. The other way to get 10 dB of gain is an amplifier. Transmitting more than 5 watts is called *QRO*. In this chapter I shall describe my efforts to build a good linear amplifier. Having QRO power when I need it has made my transmitter a reliable communications system. With 50 or more watts, your contacts won't have to work so hard to hear you and rag-chewing becomes practical.

Now that I'm older and wiser, I realize that low power and simple antennas weren't my biggest problem. In the old days our receivers had passbands several KHz wide and most beginners were stuck with a couple crystals for each band. After we called CQ, we tuned up and down the entire band looking for replies. In contrast, today guys with modern receivers are usually just listening to a few hundred Hz. When I put my 4 watts on 15 meters, I didn't realize that using the upper sideband is the standard convention for 20 meters and higher. On 15 meters the other stations were tuned to the upper sideband while I was often zeroed in on the lower sideband. My old (1967) homebrew receiver was so wideband, it wasn't obvious to me which sideband I was on. When I answered those CQs, I was usually off their frequencies by about 1.4 KHz.

In this chapter I describe three different final amplifier designs that I used successfully on the air. I don't recommend building the first one. I describe it here because it was educational. It was a *tuned class B amplifier*. It worked, I learned from it, and it covers 20 through 10 meters. Unfortunately, it was too hard to tune. Moreover, you would probably have a hard time finding a dual-section, butterfly variable capacitor like the one I used to tune the output to resonance.

The second amplifier is an *untuned class B* design. It works on all bands and is suitable for CW only. Someday when you graduate to single sideband phone you can upgrade this amplifier to the third design, which is an all band *Class AB linear amplifier*. Rather than just read the descriptions of the finished products, you may gain some insights by reading my odyssey of how I worked my way up to a real linear amplifier.

The quest to build a 50 watt amplifier

I began my QRO project by searching my 1998 ARRL handbook for linear amplifier construction projects. I found three examples of linear amplifiers. One of them, "An HF 50 Watt Linear Amplifier," was a complex schematic that covered two pages. The other two examples were buried in diagrams of elaborate transceivers that seemed to be "illustrative" rather

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than something I was encouraged to build. I could almost hear a deep baritone voice saying, “For your own safety, do not build this at home.”

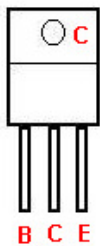
I studied the HF 50 watt linear amplifier project closely. It used a pair of MRF-477 transistors. I looked them up in my RF Parts Company catalog. It said, “call for pricing.” That was ominous. It turned out that a pair of them was \$45. I also worried about all those feedback loops and clamps that protected the transistors from **overdrive**, from **excess SWR**, from **excess collector voltage**, and from **thermal runaway**. In addition, there were at least three kinds of frequency compensation feedback. *In short, the schematic seemed to be telling me that high power RF transistors are extremely fragile.*

The article gave me the impression that, if all those protection circuits didn’t work perfectly the first time I turned it on, my pricey transistors would turn into toast before I could say, “expletive deleted.” I had never built a high power transistorized RF power amplifier before. My only comparable previous projects had been 200 and 300 watt switching power supplies. Until I got those projects working, they had devoured numerous \$20 transistors like popcorn. I was extremely wary of this project.

I retreated to my 1979 handbook and found a more primitive linear transistor amplifier project. This one also had thermal protection, but at least they implied that it didn’t have to work perfectly in concert with a flawlessly adjusted bi-directional power meter. The most reassuring feature was that MRF-454 transistors seemed to be the cheapest power transistors available, about \$13 each. These transistors are big, rugged, and able to dissipate a great deal of heat. Just in case, I bought two extra sets of transistors.

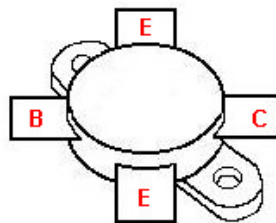
At this point you may be thinking that, even at \$13, those are expensive transistors! Why doesn’t he use a cheaper power transistor that has adequate power and frequency ratings? The answer is that the MRF-454 will produce high power with a 12 volt power supply. Sure, if you’re willing to build a 48 volt, 200 watt DC power supply, you can find dozens of really cheap transistors that will work well.

RF POWER TRANSISTORS



Case T-220

MRF-476, MRF-477,
etc.



Case 211 - 11

MRF-454, MRF-422,
etc.

Notice that there are 2 emitter tabs. The tabs insure low inductance connections to the PC board.

The eyelets must be screwed down to the heat sink.

Basic features of a modern linear amplifier

A typical modern amateur radio linear final amplifier has six basic features:

First, *Two separate power transistors are driven with a center-tapped transformer.* The driver transformer is wired so that it turns on one transistor for half of the sine wave while the other transistor is turned off. During the next half cycle, the first transistor turns off while the second transistor turns on.

Second, *it is a class B design operating in “push pull.”* An advantage of class B is that, when there is no RF on the input, both transistors are nearly completely turned off. This means that they don't get hot and don't waste energy. Even when running with forward bias to make the amplifier linear, very little forward bias is needed and the efficiency approaches 50%. Also, class B tends to cancel out even harmonics.

Third, *the transistors must be cooled with a large heat sink.* Large power transistors are designed to be bolted onto a heat sink. They have metal flanges with mounting holes for this purpose. For a 100 watt amplifier, the heat sink is typically a large, aluminum casting perhaps five or six inches on a side. Heat sinks usually have multiple cooling fins $\frac{3}{4}$ of an inch high.

Fourth, *the output from the two transistors drives a second, center-tapped, untuned high inductance transformer.* Since this output transformer is untuned, it can amplify nearly ANY RF signal over a wide range of frequency. So long as its circuit board is properly designed and the input signal is pure, the output will be a pure sinewave. The tricky part of this design is that, if any noise or “complex waveform” is introduced into the circuit, the amplifier may run away and produce wideband noise - more about this problem later.

Fifth, *a push-pull linear amplifier is not really running “Class B” but rather it runs “Class AB.”* This means that a small amount of forward DC bias is injected into the bases of both transistors to turn them slightly on at all times. By having the transistors already turned on, they respond instantly when a tiny input signal appears on the bases. Without the bias, an input signal would have to exceed some threshold limit before the transistors could turn on. The advantage of matched pairs of transistors is that the forward DC bias for each transistor can be equal and low.

Sixth, *a low pass output filter limits the frequency components in the output waveform.* In other words, the filter suppresses harmonics so that, if you're transmitting on 40 meters, nobody will be able to hear you on 20, 15, or 10 meters. Each band you operate on needs a separate filter that clips off harmonics that would radiate at higher frequencies. You can get by with using the same filters for 12 and 10 meters and for 15 and 17 meters. I built my filters on little circuit boards that I plug into a card edge connector on the main board. I use several connector pins in parallel to keep the inductance of the connection as low as possible.

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It looked easier in the handbook

When I began my work, I built the linear as close as I could to the drawings in the 1979 handbook, although as usual I had to substitute some parts. After I had carefully tested the forward base bias regulator circuit, I gingerly put 12 volts on the output transistors. Without any

RF input drive, the transistors immediately ran away and drew huge currents. Gee, something must be wrong with the bias circuit! I soon discovered that *ANY* forward bias caused the transistors to run away. Obviously, the guy who designed this amplifier used MRF-454s that behaved differently than mine.

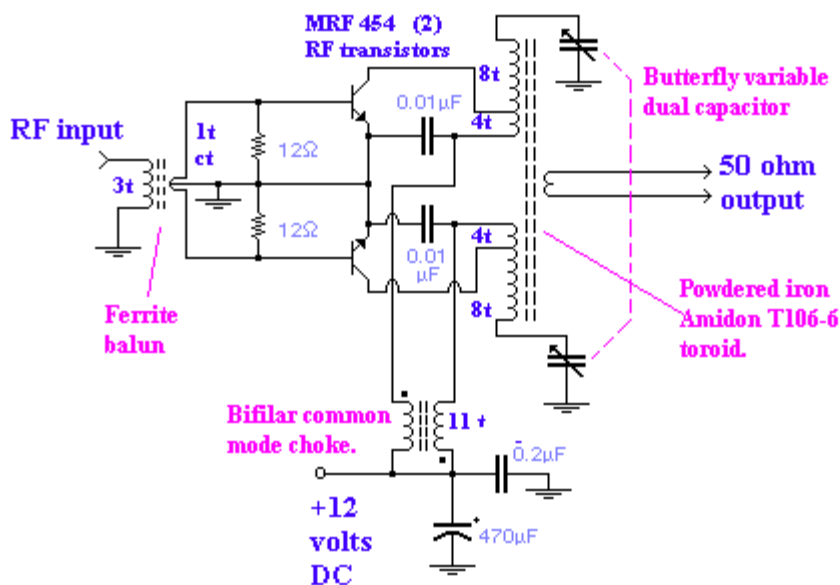
Next I disconnected the bias circuit and powered it up again. In other words, I was hoping it would run as an untuned, push-pull Class B “sort-of-linear” amplifier. This time at least the transistors didn’t run away. I put an RF signal on the input and found that the amplifier was operating in what I call “noise mode.” As you know, linears are supposed to act like hi-fi amplifiers. They uncritically amplify whatever frequency signals you put in. If you put 80 meters or 10 meters in, you are supposed to get amplified 80 meters or 10 meters out.

Noise mode

An unfortunate mode of operation for a linear is “HF broadband noise generator.” I put in a clean, filtered 5 watt sinewave and I got a blast of wideband noise from the output that made my FM radio roar like a waterfall. Using an oscilloscope, the waveform across the dummy load looked like dancing grass in a tornado. My new amplifier had terrific power output into a dummy load. Unfortunately, little if any power was at the desired frequency.

Class Bs are easier

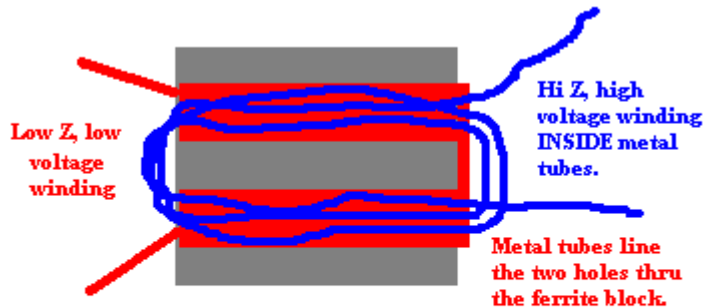
I concluded that my linear had at least two fundamental problems. I had already encountered “noise mode” while I was building my first 15 meter QRP. At that time I hadn’t found many cures for that disease, even at the milliwatt level. So I wasn’t optimistic about fixing it at the 50 watt level. I was tired of not having a working transmitter, so I decided to start over and build a simple class B *TUNED* amplifier. I was almost certain I could get that to work. Of course a tuned class B would only work on two or three bands without changing the output transformer and tuning capacitor. However, that was better than being off the air, possibly for months.



Amplifier # 1. **A simple class B tuned amplifier.** This works, but I don't recommend it.

The tuned class B worked well. The only trouble I encountered was getting the input transformer to match properly and deliver the required big drive currents. After two unsuccessful attempts at winding powdered iron toroid input transformers, I tried the ferrite balun transformer from the linear amplifier. Success! Ferrite balun transformers really are different from powdered iron toroids. They match those low impedance power transistors when nothing else will. At least *SOMETHING* from the linear design worked.

Ferrite balun transformers



BALUN TRANSFORMER

(Cut-away to show construction)

Think of the ferrite balun transformer as two large ferrite beads placed side by side. The beads are simply hollow cylinders made from high A_L ferrite. When a coil is wound around them, the ferrite produces a large inductance with very few turns. Sometimes the two beads are cast as a single block of ferrite with two cylindrical holes side by side through the block. In principle, the transformer is just like the transformers you have met before. That is, it consists of two coils wound on the same iron core. The high impedance, higher voltage winding has the most turns and is just 3 or 4 turns of wire wound through the hollow centers of both beads. So far, this is pretty ordinary.

The tricky, unobvious part is the low voltage, low impedance winding. What I haven't mentioned yet is that the hollow centers of the two beads are lined with non-ferrous metal tubes. The high impedance, high voltage winding is passed through these tubes. At one end of the assembly, the two tubes are connected together electrically so that they form a "U" passing through both beads. This "U" is the entire low impedance winding. Like any transformer winding, it has two output leads and these are the two legs of the "U." The center tap of the low impedance winding is the connection between the two tubes, on the right in the above drawing. That is, the bottom of the "U" is soldered to the PC board ground. The ungrounded ends of the tubes go to the balanced, low impedance transistor inputs.

For the input balun transformer, I made my "U" out of tubular mesh from the outer conductor of a length of RG-174 coax. I forced holes in the sides of the outer braid mesh to bring the insulated secondary winding wire in and out of the braided tubing. This is tricky to make and you may have to try a couple times. Using thin-walled brass or copper tubing would

be easier and more elegant. I used Teflon insulated multi-strand wire for my secondary windings to be sure there would be no short circuits between primary and secondary. I bought the small input balun ferrites from CWS Bytemark. These small ferrites consist of a single, flat block of ferrite with two parallel holes molded through the longest dimension.

Bifilar wound RF choke

The power to the final is delivered by a small bifilar wound choke. Bifilar wound transformers were discussed in chapter 6. Wind about a dozen turns of a pair of #26 wires onto a small ferrite core. The two wires are wound on the core simultaneously as if they were one wire. An FT50-61 CWS toroid ferrite core will work well. The exact type of core or number of turns is not critical. Just be sure that the RF that appears from one winding will generate an opposite voltage in the other winding. If you don't, the two transistor collectors will be effectively shorted together. That's the meaning of the dots next to the coils on the diagram. Yeah, I get as confused as you do about dot marks. Leave the leads on one coil long enough to swap the ends when it doesn't work!

The tuned class B worked, but I don't recommend it

The diagram of the tuned class B was shown earlier. Depending on the range of the ganged, dual tuning capacitor, it can tune between 10 and 20 meters. I got on the air using CW and talked to lots of people with my 50 watt Class B. I was pleased, but whenever I changed frequency more than about 50 KHz, I had to retune the amplifier. Using a scope, my procedure was to tune the amplifier and a "T" type transmatch for maximum amplitude with minimal low frequency artifacts. When tuned, it produced a clean sinewave output and I could see no evidence that the lack of forward bias was distorting the output. Just to be on the safe side, I ran the output through the multistage, TVI low pass filter described in chapter 9. This TVI filter is designed to work with any HF band since it cuts off above 10 meters. The amplifier ran quite cool and I didn't burn up any transistors, even though I had omitted all those exotic feedback safety circuits.

The disadvantages of my tuned class B was that it was a bit tweaky and tended to go out of tune whenever the battery voltage declined. The best reasons for not building one are that the class B untuned amplifier described below works better and doesn't use any hard-to-find parts.

A CLASS B, UNTUNED, SORT-OF-LINEAR AMPLIFIER

Episode two of the power amplifier saga

15 meters was dead in the evenings so I wanted to get on 40 meters. Rather than build a new tuned Class B amplifier just for 40, I went back to work on the linear. First I ordered a data manual for Motorola RF transistors. When I got my manual, I discovered that the MRF-454 was the only transistor in its class that *WASN'T* recommended for linear operation. The manual didn't say why it wasn't, but I thought to myself, "No wonder MRF-454s are so cheap and no wonder they run away with forward bias!" I got out my RF Parts Company catalog and priced all the similar RF transistors that were recommended for linear operation. They were all much more expensive than the MRF-454, but I picked out the cheapest and ordered a matched pair of MRF-422s. The output from the transistors goes to a large balun ferrite transformer. Large balun transformer assemblies are also available from RF Parts Company. I have used the 1 inch and 1.5 inch versions (PN # T1 & T1.5). Both seemed to work fine with no signs of saturation.

When my new transistors arrived, I put them in the linear and ... they ran away, just like the MRF-454s. Each transistor had swamping resistors that connected each base to ground. I lowered the values of these again and again until the transistors stopped running away. Of course by that time I had zero RF output. Apparently forward bias works for everyone else but the laws of physics are different at my house. On the other hand, unless you are planning to go on SSB (voice), you don't really need a linear amplifier. Old fashioned class B or class C amplifiers work fine for CW.

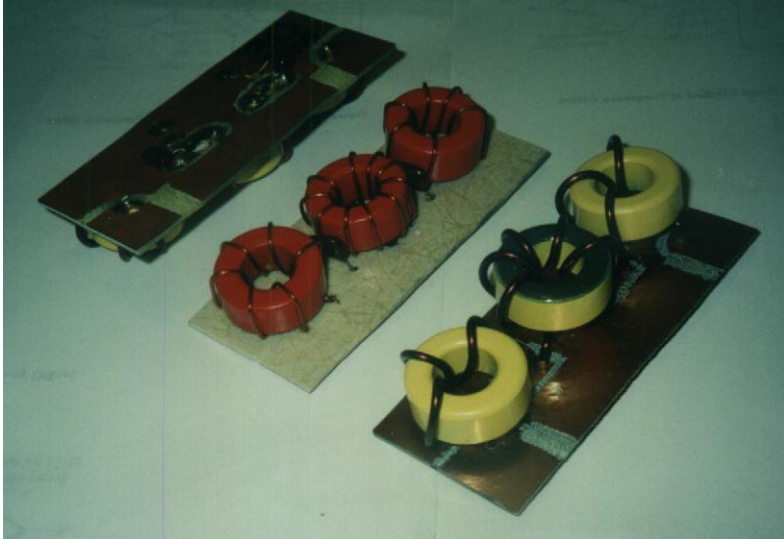
Trouble with Chebyshev output filters

I tried again to run my "linear" amplifier as an untuned class B. As before, it just produced high power noise. I looked more closely at my Chebyshev output filters. Were they defective in some way? I had built them from the 1979 handbook linear amplifier plans. I had followed the winding instructions exactly using identical CWS (Amidon) 106-6 toroid cores. To test the 15 meter Chebyshev filter, I substituted it for the TVI low pass output filter on my working tuned Class B amplifier. It should have worked fine, but instead, the old tuned Class B amplifier went into noise mode, just like the new amplifier. Very little power arrived at the dummy load and the filter cores got quite hot. Something was wrong with the filter.

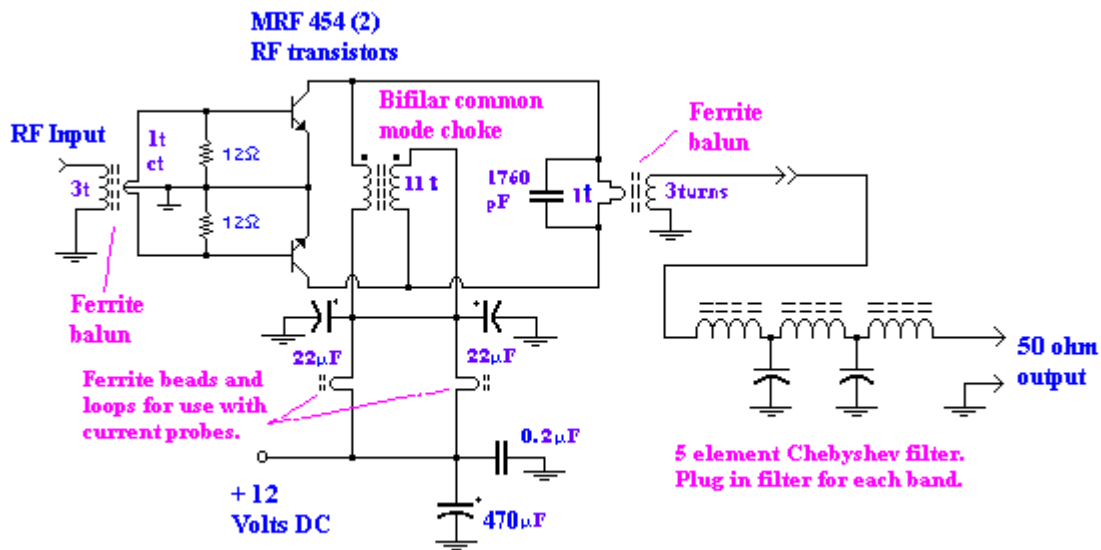
It turned out that the parts list or coil turns listed in the table were just plain wrong. I started over and redesigned my plug-in filters using the Chebyshev design tables from the 1998 ARRL handbook. I used the procedure described for making 5-element low pass Chebyshev filters that I previously explained in chapter 6. The main difference between the QRP filter and the big amplifier filter is that, for 100 watts, you need large powdered iron cores. Instead of T50-6, I used T106-6. For 40 meters and below you might want to use T106-2 cores. T68 cores might be big enough, but I haven't tried them at high power levels.

It turned out that the instructions in the 1979 manual described filters that were more appropriate for several bands below each band listed. For example, the 15 meter filter was designed about right for 160 meters, and so on. The filter for 160 meters would have been correct for low frequency transmissions from submerged nuclear submarines. Something in the T106 core specifications must have changed over the years.

I checked out the redesigned 15 meter filter on my old amplifier and ... it worked perfectly! Progress! Next I put the new filter on my new linear amplifier and held my breath. Behold ... it was still operating in noise mode. Now I was mad. I got out my wood-carving gouge and cut the PC board traces to the transistor bases. Now they were free from all that R-C-L frequency compensation network gobble-de-gook. I wired the bases up just like the tuned Class B linear input above. As far as I can tell, it works perfectly. It puts out 100 watts of lovely sinewave on 40 meters and doesn't blow transistors. I only get 50 watts on 15 meters because my driver isn't as powerful. I soon worked dozens of stations on 15 and 40 and got excellent signal reports.



Chebyshev output low pass filters for an untuned class B. They plug into a card edge connector.

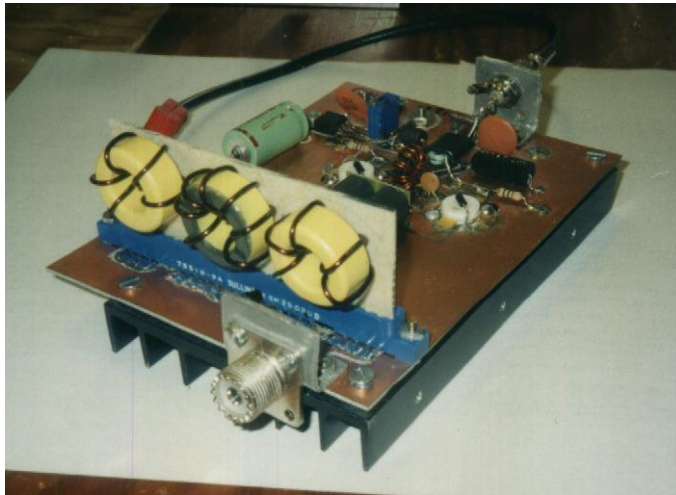


Amplifier # 2. A simplified class B untuned amplifier

Why didn't I need fancy frequency compensation feedback loops? The answer may be that the purpose of the feedback loops was to equalize the outputs on all bands. Also, I am driving the linear with complete QRP transmitter drivers that have their own Chebyshev output filters. In other words, the input signals are quite pure. I have observed that any defect in the input sinewave is faithfully reproduced in the output. Even without forward bias to make it class AB, it is "hi-fi" to a large degree.

After all my worry, I never did ruin any transistors. On one occasion I was testing the linear at 80 watts output. I was happily looking at the scope when I smelled something burning. Oops. I had forgotten to screw the big heat sink back on. I shut off the linear and no harm was

done. RF power transistors aren't so fragile after all.



The completed linear amplifier. A 15 meter low pass filter is plugged into the output.

You may already be using an adequate low pass filter

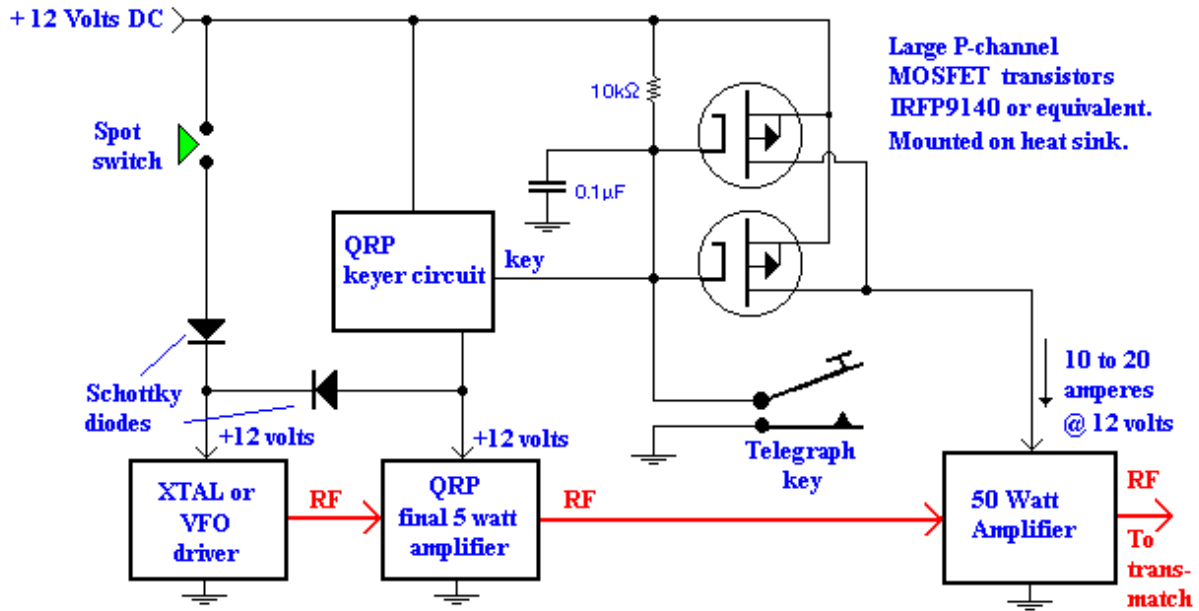
I have occasionally had trouble loading antennas on 17 meters and above. Even with the T-match coupler described in chapter 9, sometimes I couldn't get a good sinewave signal on the antenna lead wire. The waveform was contaminated with low frequency modulation(s) and the frequency counter was usually reading low and wouldn't lock. Sometimes I have been able to correct the problem by using an output filter for the next band higher than the one I was on. For example, if it wouldn't load on the correct 15 meter filter, it would sometimes load well using the 10 meter filter.

Finally it occurred to me that I was already using the multistage 30 MHz cut-off low-pass TVI filter described in chapter 9. Therefore, for those high bands my 10 meter output filter on the final was redundant. I built a "blank" filter that was just a piece of RG-58 coax that shunts from one end to the other of a blank PC board plug. To summarize, using the TVI filter by itself is another alternative for your bag of tricks.

Keying the 50 watt linear amplifier

When I first began using my finals, I kept them turned on all the time. That is, whenever a QRP signal appeared at the input, the final was supposed to amplify it. When there was no input to the amplifier, there should have been no output. This way, I could leave the 12 volt power supply connected all the time. Unfortunately, every so often the final would begin oscillating all by itself at some random frequency outside the ham bands. I often had two or three successful QSOs without trouble. Then suddenly, for no reason that I could determine, the oscillation began.

I have been told that professionals solve this problem by loading down the input of the final amplifier with a resistor, perhaps as low as 100 or even 50 ohms. I haven't experimented much with this approach, but I'm certain that it cuts drive to the final and lowers my output power. If I were you, I'd experiment some more with this cheap approach. However, if you don't like your results, you can always fall back to my keyer circuit shown below.



50 WATT TRANSMITTER KEYER

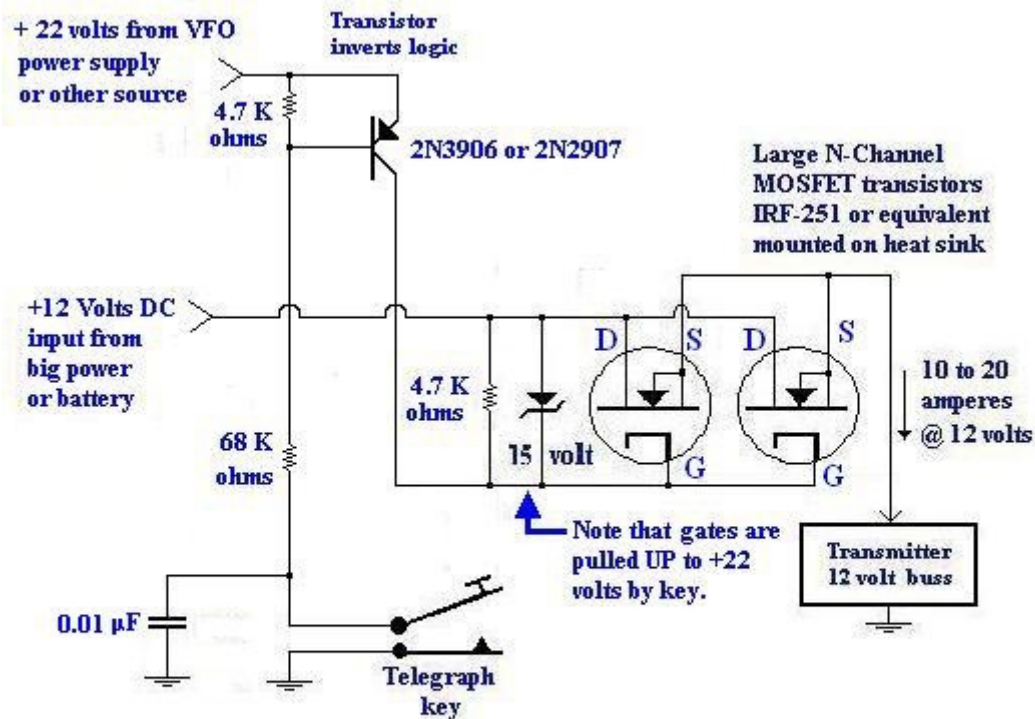
My solution was to build a giant version of the same MOSFET power switch I used to key my QRP modules. Naturally I had to use humongous P-channel MOSFETs with low on-resistance. Referring to the figure above, the telegraph key pulls the MOSFET gates down turning on the MOSFETs and bringing power “down” to the amplifier. The MOSFETs are mounted on a small sheet of 1/8 inch thick aluminum plate which in turn is bolted to the thin aluminum chassis. Even at heavy current loads I haven’t noticed the MOSFET transistors becoming warm to the touch. The cases are the drain connection and must be insulated with mica or equivalent insulators. A light layer of silicon heat sink grease on the mica insulator fills the air gaps and improves heat conduction.



Power bipolar and MOSFET transistors and the necessary size TO-204 mounting kit

As with the QRP module, turning on the power abruptly by shorting out the 0.1 microfarad capacitor with the key looks like a recipe for producing key clicks. I haven't had any trouble yet with this, but I wouldn't be shocked if someone received complaints of key clicks. David, VK6KI, suggests turning the keyer on gradually with an op-amp keyer will prevent any abrupt turn-on and turn-off. He also suggests using cheaper bipolar PNP power transistors. Use whatever works for you. It's your homebrew and it's fun to try different ideas.

N-Channel MOSFETS have much lower ON resistance and are harder to damage. They can also be used as keyers and fewer transistors can do the same job. Of course, the problem is that, instead of pulling the gates down to ground as we did above, now the gates have to be pulled UP to 10 or 12 volts above the 12 volt supply. If you have built the VFO described in chapter 10, then already you have a convenient 22 volt source. This is the keyer in my CW transmitter:



HIGH POWER TRANSMITTER KEYER Using N-Channel MOSFET transistors

What had I learned up to this point?

1. The ARRL Handbooks are excellent but occasionally they print errors. Don't believe everything you read in a parts list.
2. I understand the need for class A forward bias. In practice, for CW use it isn't necessary. However, I was still mystified how the experts do it without a runaway. In my experience, the transistors ran away instantly with the first milliamp of forward bias. This happened even when

the transistors were stone cold. It couldn't have anything to do with temperature feedback being defective because there wasn't time for heating to occur. Moreover, runaway wasn't related to the RF drive, because it happened with or without RF input.

3. Ferrite balun transformers are impressive components. They produce tight coupling at really low impedances and they don't need tuning.

4. If your Chebyshev output filter doesn't work the first time, check it out carefully for solder splash shorts on the PC board. If you're sure it should work, but it doesn't, go to the design table in a recent ARRL handbook and redesign the filter yourself starting from scratch. If it still doesn't work, try a different core size.

5. A Chebyshev filter in a QRP driver worked poorly when I designed it with T68-6 cores. But the same filter worked great when I rebuilt it using smaller T50-6 cores. Sorry, but I have no idea why. Sometimes it helps to be open-minded and try things that may seem silly. Persistence is your ultimate weapon!

6. Finally, it seems to me that much of the complexity in designs in QST and QEX is great in theory, but sometimes unnecessary in practice. The guys who wrote those articles are over-educated. Their sophistication often discourages us. Don't let them rain on your parade! Build it simple and work up from there.

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A LINEAR AMPLIFIER, THIS TIME FOR SURE

Adding linear bias to the Class B amplifier

As explained above I was able to run my final amplifier as an untuned Class B, but when I applied DC bias to make it "linear," the amplifier "ran away." That is, it drew huge currents and blew fuses. In the end, I left it as a class B broadband amplifier. Class B amplifies both halves of the driving sinewave, so there's only a small cross-over non-linearity. So who cares if it isn't class AB? At the end of my project I was happily working guys on CW and I always used a lowpass filter to suppress harmonics. So what's the fuss over "linear" amplifiers? *I* certainly didn't need one!

Sideband needs a linear

Eventually I got bored with HF CW and built an SSB exciter. I fed SSB English speech into my class B "nearly-linear." All that came through were the voice peaks. It sounded something like African click language. I couldn't understand the speech, but I finally got the message: ***The key virtue of linears for sideband is that they amplify all AMPLITUDES.*** Yes, linears also amplify all *frequencies* equally. They are a sort of "RF Hi-fi," but the broadband part isn't so important. A sideband amplifier only has to amplify a signal 3 KHz wide. In theory at least, a tuned class A amplifier would work fine on sideband, even if you had to retune it every time you QSY a hundred kilohertz. In practice, a tuned amplifier on sideband would tend to self-oscillate every time you stopped talking.

When class C or class B amplifiers are operated CW, a big drive signal comes in on the base(s) of the final amplifier and you get a big, constant output signal with about 10 dB gain over the input. The big drive signal exceeds the base forward voltage drop of the output transistors by

a wide margin. *When operating CW the amplifier only operates at one amplitude*, so the base voltage threshold problem never arises.

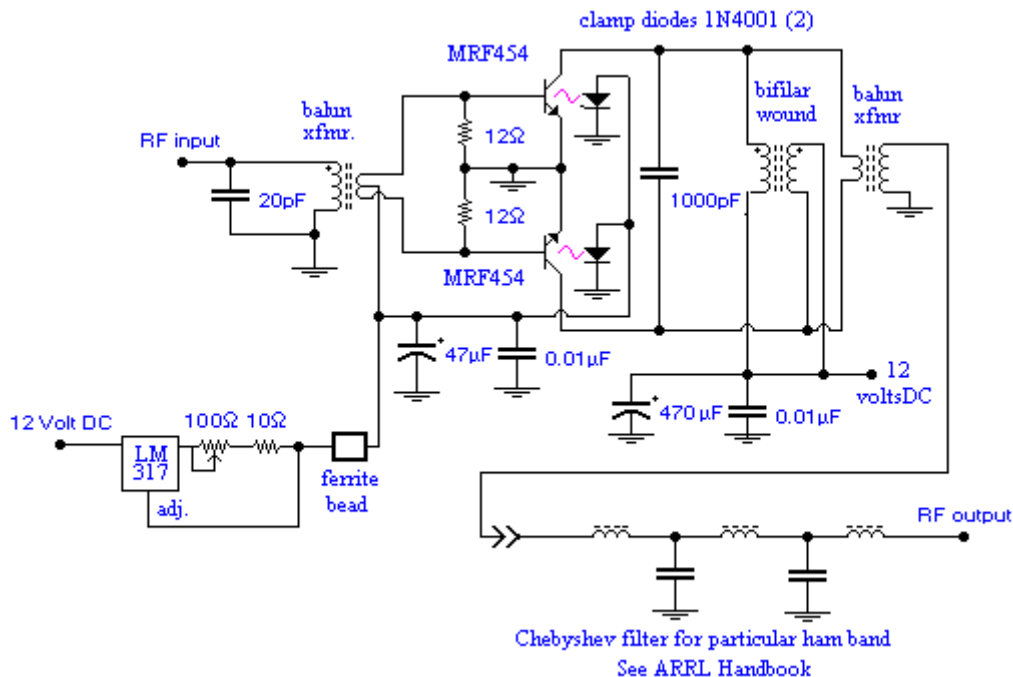
Why does sideband need a linear when AM modulation was so easy?

Sideband is different. The drive from an SSB exciter has a range of amplitudes and all must be amplified equally. Actually, it's useful to amplify the low amplitude signals *more* than the high amplitude voice peaks. This raises the average power and makes the SSB signal better able to compete with noise and QRM.

At first glance SSB doesn't seem so different from AM. So why was AM phone so easy to build back in the old days? Amplitude modulators usually modulated the final, not the driver. For AM we tuned up the tube final on CW, then *we modulated the power supply, or the screen grid, or the cathode of the final tube amplifier with audio frequency*. The final amplifier acted like a mixer that produced sum and difference frequencies. With no conscious engineering effort we produced two audio frequency sidebands in addition to the original RF carrier. Another advantage of an AM transmitter final is that, whenever there is no speech, it is still generating a carrier, just like CW. Therefore it can't self-oscillate.

Guys who could afford big AM modulation transformers modulated the power supply for the final. We cheapskates modulated the screen grid or cathode of our final amplifier tube. Either way, we were modulating the gain of the final amplifier, not the drive signal. Now that I think about it, I guess I knew that some guys used *LINEAR AMPLIFIERS* to boost the power of their low power AM exciters. The fog clears. Yes, you can broadcast AM with class B or even Class C final amplifiers, but you can't amplify a low level AM or SSB drive signal without a linear.

Biasing a linear amplifier without thermal runaway



Amplifier # 3. A push-pull linear amplifier

The entire linear final is shown above. The bias circuit at the lower left solved my run-away problem and gave me the linear amplification I needed. I found the bias circuit lurking in a big schematic describing a commercial transceiver in the 1998 ARRL handbook. This deceptively simple circuit performs three functions:

- * It provides an adjustable, constant DC bias current into the transistor bases.
- * Diodes (1N4002) shunt the bases to ground, limiting how high the base voltages are allowed to rise.
- * The diodes heat up with the transistors and provide temperature compensation.

An LM317 voltage regulator is used as an adjustable current source to feed roughly 100 milliamperes of DC into the bases of the high power output transistors. The LM317 is a three-terminal, 1.2 volt voltage regulator. The regulator output passes through a variable current set-resistor. The voltage drop across the resistor is monitored by the “adjustment” lead of the regulator so that the voltage across the resistor is held constant at 1.2 volts. The regulator is RF-isolated from the amplifier by a big ferrite bead on a short chunk of wire. The rest of the circuit is almost identical to the final in an SSB transceiver in the ARRL 1986 handbook. The 1000 pF capacitor across the collectors is found in all these push-pull circuits. I took mine off and I got a few percent more gain. I don’t know what it’s supposed to do.

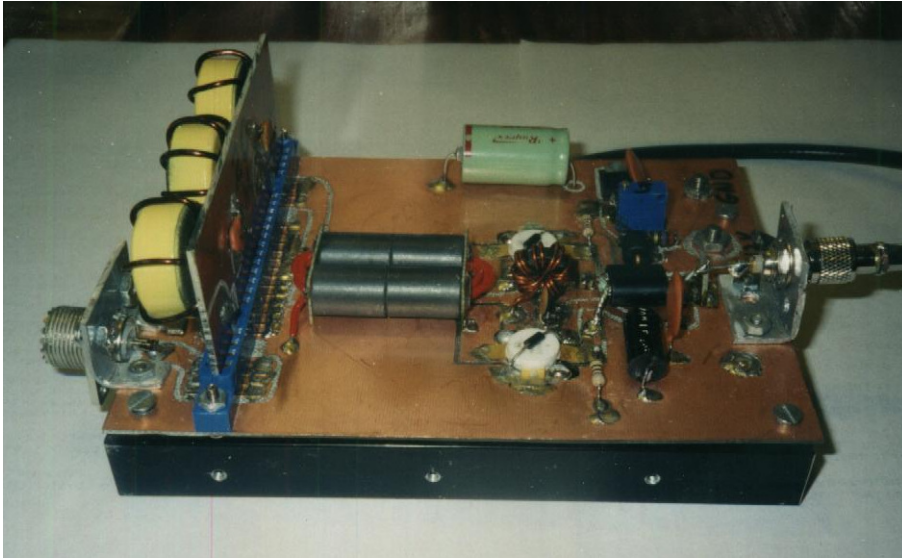
Clamp diodes prevent run-away

The critical parts of the bias circuit are the two rectifier diodes which clamp the base voltage (V_{be}) to ground. Their most important function is that they instantaneously clamp the base voltage to less than roughly 0.8 volts, like a Zener diode. They limit how high the drive voltage to the transistors can rise when the whole assembly gets hot. Hot transistors draw more current, causing more heating. This positive feedback is called thermal runaway. As the input drive to the transistors increases, the DC base-to-emitter voltage of the output transistors rises which causes the collector to draw bigger and bigger currents. For example, while operating sideband, the DC base voltage rises to well over 0.8 volts on voice peaks. If it were allowed to rise to 0.9 or 1.0 volt, runaway might result.

The second function of the diodes is that they also change with temperature and automatically compensate for temperature rise. *They are strapped across their respective transistors so they are in thermal contact with the transistor cases.* As the transistors and piggyback diodes heat up, the forward voltage drop of the diodes *decreases* with increasing temperature. When cold, the V_{be} peaks might start at 0.8 volts, but as the transistors heat up, the V_{be} voice peaks will try to rise higher still. So, under the same bias current level, but at a higher temperature, the diode clamp voltage might typically drop from 0.8 to 0.7 volts or even lower. The decreasing voltage drags the base voltages down, preventing runaway. While holding the telegraph key down, I could watch the DC base voltage slowly sink, while the total DC current drawn by the entire amplifier remained constant.

The difference between this bias circuit and the ones I tried earlier is that there were no clamp diodes. Yes, there was a reference diode mounted on the heat sink for temperature compensation, but my output transistors ran away immediately before the temperature had a chance to rise. A current source with just a temperature compensation circuit has no instantaneous clamping function.

Mechanical construction



The linear 50 watt amplifier. Notice the large ferrite balun output transformer in the center of the assembly. The bias circuit is at the right rear. Also notice how the base clamping diodes are strapped across the output transistors so that any transistor heating will immediately be passed on to the diodes. The holes in the PC board adjacent to the white output transistors are where the machine screws bolt the transistor bodies to the heat sink. A thin layer of silicon grease between the transistors and the heat sink is advisable, but mica insulation is not needed. These mounting tabs are not electrically connected to the transistor leads.

The completed amplifier module is made from a two-sided circuit board screwed down into holes tapped in a large, finned heat sink. The major RF traces are wide, about 3/8 inch or more, to keep the inductance down. This is a simple circuit and all the traces were cut into the board with a small wood-carving gouge. **It is vital to arrange the collector and emitter traces so that they are symmetrical and equal in every way to the other transistor.** Otherwise, one transistor will have more trace capacitance and inductance than the other. The input and output transformers are the balun type which were described earlier.

The input comes in through a mini-UHF connector. Mini-UHF connectors are the only affordable, small RF connectors I have found. At \$5 a mated pair they are expensive compared to phono plugs. But if you must pay \$12 a pair for SMA, SMB, or SMC connectors, \$5 looks cheap. The output connector is a big UHF SO-239 that, strangely enough, has always been affordable. For high power, >5 watts, I suggest avoiding connectors like phono plugs which weren't designed for RF power. You can get away with phono plugs on 20 meters and below, but the standing waves make it difficult or impossible to tune the amplifier on 10 meters. Also, if you plan to amplify sideband with this, it's a good idea to build a shield cover to fit over the top of the board. As you can see, I didn't. However, all commercial transmitters have their linears sealed in extremely tight metal enclosures. In my SSB transmitter all the low level modules are sealed individually in separate metal boxes.

I built my Chebyshev low-pass filters for the linear on separate PC boards that plug into the linear board using a card edge connector. To keep the inductance low, I soldered eight

connector pins in parallel at each end of the card connector and the rest of the pins were used for ground. To change bands, I plug in another low-pass filter. If you like, you can use little RF reed relays to switch in different filters. Personally, I like the old-time flavor of plug-in coils. It is probably practical to use smaller ferrite toroids, such as T68-6, but I haven't tried them at this power level.

Why stop at 100 watts?

I opened up an issue of QST (June 2006) and discovered plans for a homebrew 600 watt linear amplifier. It uses two pairs of MRF-150 transistors to reach this level. It is quite similar to my linear in many respects. I was surprised to see that it's practical to get so much power from so few parts.

I was tempted to build one until I remembered Bob Hamilton's experience with his kilowatt amplifier. Bob, NØRN, used to live in the city like I do. He quickly found that his new kilowatt interfered with the neighbor's TVs and stereos. In contrast, his 100 watt transmitter had never bothered them. Bob fought the problem for several months and even had his station checked out by a government accredited expert. It turned out that his station was operating correctly and in accordance with the law. The difficulties were in the sensitivity of the neighbor's appliances. Bob was "legal" but that didn't really change anything. His neighbors were still mad at him and weren't willing to buy new TVs, cordless phones, etc. In the end, Bob mothballed the linear in a closet and went back to 100 watts. Since then Bob has moved out into the country where his nearest neighbor is hundreds of meters away. He resurrected the kilowatt amplifier and has had no complaints from his neighbors. Signal strength falls off with the square of the distance and 300 meters is vastly different from 30 meters distance.

Surprisingly, in the US the maximum power on most HF bands has been increased. Formerly transmitter power was defined as the DC power input to the final stage. For example, in the old days a "50 watt novice transmitter" might have 500 volts DC on the tube plate and draw 100 milliamperes. That is, 500 volts times 0.1 amps = 50 watts. Since the efficiency of a class C amplifier is no greater than 65%, "50 watts" was really only 32.5 watts PEP. Similarly an old "kilowatt" Class B amplifier, the kind you find at hamfests, is 50% efficient and delivers at most 500 watts to the antenna. But now on many bands we are allowed 1,500 watts PEP measured at the antenna. That can be three times as much power as an old "kilowatt." And, when you consider that SSB concentrates all the power into a single sideband, the modern SSB kilowatt has at least 6 times the effective power as an old AM modulated kilowatt.

In conclusion,

In the end I was able to build a linear using the cheap MRF-454 transistors, just like the handbook said - even if their darn bias circuit didn't work. I talk to guys on sideband and they seem to understand what I'm saying. If my final weren't close to linear, they wouldn't have understood a word.

How much power the linear amplifier delivers depends on how much power I put in and what band I'm on. Not all my QRP drivers are equal. On 10 meters I only get 20 watts, while on 40 or 80 meters I get as much as 120 watts. As usual, lower frequencies are easier. The efficiency is about 50 percent. For example, to get 120 watts output I need 18 amperes input from the battery.

17. Chapter 12, Harris

Hmmmm ... Now that it works, I wonder what would happen if I unsoldered the base clamping diodes? It should run away, of course. After all, these are the same individual transistors I used before. It better run away! So I unsoldered the diodes. It didn't run away. The temperature compensation no longer worked, but it didn't run away. I have no idea why it didn't. Sometimes electronics drives you crazy! Persistence is your only weapon against the innate perversity of inanimate objects.