CRYSTAL SETS TO SIDEBAND

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 beam antennas on 50 foot high towers. QRP didn't seem to work for guys with verticals and dipoles close to the ground. 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***. "QRO" is the Morse code way of texting, "You're hard to copy. Please raise your power." 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, hams today use modern receivers and are usually just listening to a few hundred Hz bandwidth. When I put my 4 watts on 15 meters, I didn't realize that using the upper sideband is the standard convention for 30 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 probably off their frequencies by about 1.4 KHz.

In this chapter I present 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 but is suitable only for CW. 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 description of the finished product, you may gain some insights by reading my odyssey of how I worked my way up to a real linear amplifier.

The QRO power supply

If you wish to generate 50 or 100 watts of RF from an amplifier, the amplifier must be fed with 100 to 200 watts of stable DC voltage. I use deep-discharge, golf-cart batteries quite successfully for this purpose. Another source of deep-discharge batteries are the 12 volt marine batteries designed for outboard motorboats. Large lead-acid storage batteries are by the far the easiest solution. Building an adequately regulated and filtered line-powered 200 watt power supply is harder, but is a practical home project. These DC supply solutions are discussed in chapter 8.

The quest to build a 50 watt amplifier

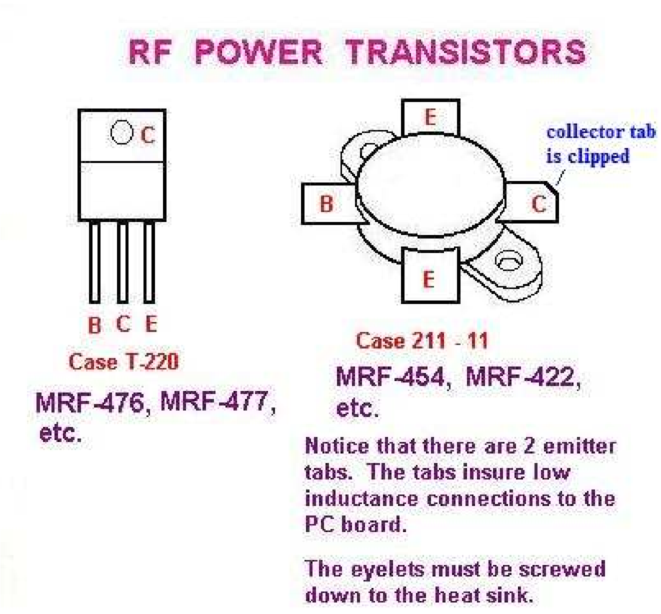
I began my QRO project by searching the 1998 ARRL handbook for linear amplifier construction projects. I found three examples of linear amplifiers. One of them, "An HF 50 Watt Linear Amplifier," was a complex schematic that covered two pages. The other two examples were buried in diagrams of elaborate transceivers that seemed to be "illustrative" rather 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 cost $45. I was also worried about all those feedback loops and clamps that protected the transistors from **overdrive**, **excess SWR**, **excess collector voltage,** and from **thermal runaway**. In addition, there were at least three kinds of frequency compensation feedback circuits. ***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 using 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

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 power transistors are driven separately 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 a metal flange with mounting holes for this purpose. Unlike smaller transistors, the mounting flange is insulated from the transistor drain and no mica insulator is needed. 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 ¾ of an inch high**.**

Fourth, ***the output from the two transistors drives a second, untuned high inductance transformer.*** Since this output transformer is untuned, it can amplify nearly *ANY* RF signal over a wide range of HF frequency. So long as the 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 a "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 level 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 as low as possible.

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

It looked easier in the handbook

When I began my work, I built the linear as close as I could to the drawings in the 1979 handbook, although as usual I had to substitute some parts. After I had carefully tested the forward base bias regulator circuit, I gingerly put 12 volts on the output transistors. Without any RF input drive, the transistors immediately ran away and drew huge currents. Gee, something must be wrong with the bias circuit! I soon discovered that *ANY* forward bias caused the transistors to run away. Obviously, the guy who designed this amplifier used MRF-454s that behaved differently than mine.

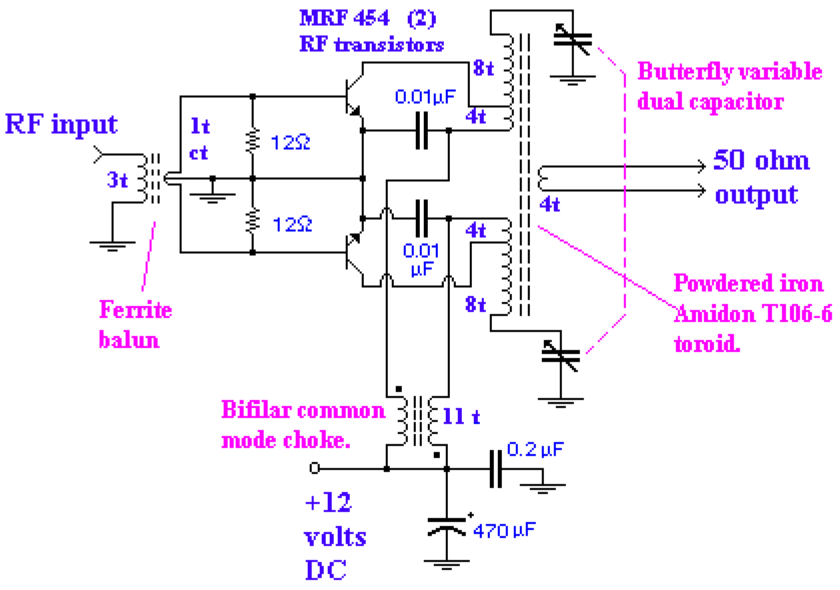
Next I disconnected the bias circuit and powered it up again. In other words, I was hoping it would run as an untuned, push-pull Class B "sort-of-linear" amplifier. This time at least the transistors didn't run away. I put an RF signal on the input and found that the amplifier was operating in what I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

Noise mode

An unfortunate mode of operation for a linear is "HF broadband noise generator." I put in a clean, filtered 5 watt sinewave and I got a blast of wideband noise from the output that made my FM radio roar like a waterfall. Using an oscilloscope, the waveform across the dummy load looked like swirling 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.

Tuned amplifiers are easier

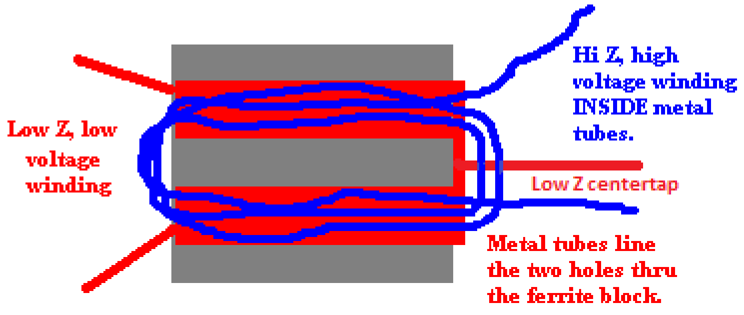
I concluded that my linear had at least two fundamental problems. I had already encountered "noise mode" while I was building my first 15 meter QRP. At that time I hadn't found many cures for that disease, even at the milliwatt level. So I wasn't optimistic about fixing it at the 50 watt level. I was 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 tuned amplifier**

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 through the holes through both cylinders, the ferrite produces a large inductance with very few turns.

Sometimes the two beads are cast as a single block of ferrite with two round 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 <u>through</u> 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 side 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 power transistor inputs.

For the input balun transformer, I made my "U" out of tubular copper wire mesh from the outer conductor of a length of RG-174 coax. I forced holes in the sides of the 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 several 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 DC 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 long enough leads on one coil so that you can 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 tuned 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. Apparently those exotic feedback safety circuits aren't always needed.

The disadvantages of my tuned class B were that it was a bit critical to tune 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. In retrospect, I now realize that a simpler un-tapped transformer coil would be easer to tune and not so sensitive to power supply variation. The tapped transformer I used is a hi-Q design that is good for filtering, but a sharp filter is not really needed for this application. You would still need a double-gang variable capacitor to tune both L-C circuit halves simultaneously.

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. 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 heating or 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 then 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, if you are not 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 Bytemark T106-6 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. 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. The T106 core specifications must have changed over the years.

I started over and redesigned my plug-in filters using the Chebyshev design tables from the 1998 ARRL handbook. I used the same 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 larger powdered iron cores. Instead of T50-6, I used T106-6. For 40 meters and below you might want to use T106-2 cores.

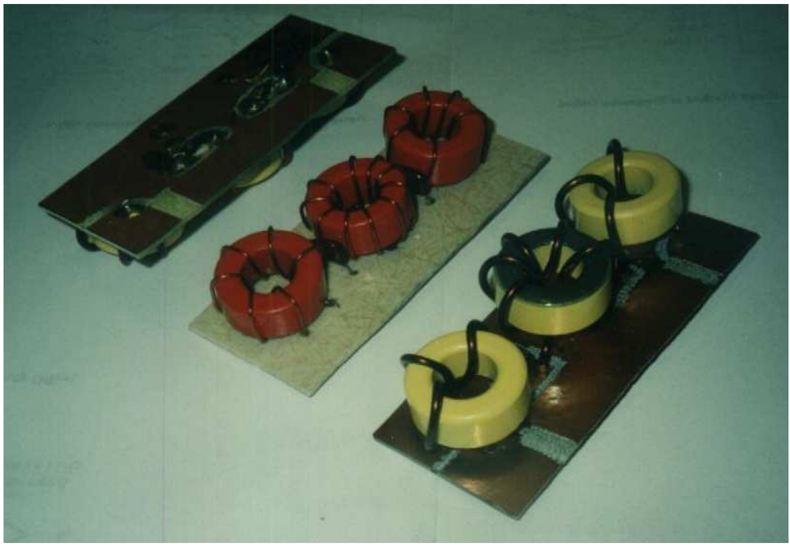
I checked out the redesigned 15 meter filter on my old tuned amplifier and … it worked perfectly! Progress! Next I put the new filter on my new linear amplifier and held my breath. Behold ... it was still operating in noise mode. Now I was mad. I got out my wood-carving gouge and cut the PC board traces 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.

If you construct the filters the way I did, mounting them on a piece of PC board that plugs into a card edge connector, be sure to use double-sided PC board. Connect the two sides of the board together with feedthrough wires. Two sided connections will make the contacts more reliable. After a few years, the contacts on my single-sided filter boards became somewhat unreliable. Sometimes I changed filters when I was switching bands and suddenly had no output. I found I could fix them by cleaning the board contact areas and re-inserting the filter boards for a better connection.

Beware of intermittent connections

One disconcerting phenomenon with "high power" amplifiers like these is that, if you have an open connection anywhere between the final output transformer and the antenna, you might still see a few watts of power appearing at the connection to the outside antenna or the dummy load. The bad connection might be in the antenna relay, the low pass filter or the antenna tuner. A second clue to an open circuit is that the output stage will draw big amperes - 25 amps or more - while it is delivering these 3 or 4 watts to the antenna. Don't spend time trying to retune the antenna. That's probably not the problem. The high current alone is more than enough evidence to begin the search for an intermittent connection.

When you use the low-pass filter design procedure described in chapter 6, pick a frequency well above the band you wish to use. For example, a filter for 40 meters can be designed for 8 or 9 MHz. The most likely harmonic will appear on 20 meters, 14 MHz. It isn't necessary to design for 7.35 MHz, just above the band. The higher the frequency you design for, the fewer difficulties you will have loading your antenna. But the lower the cut-off, the more high frequencies will be suppressed. Without a spectrum analyzer, it is hard for us amateurs to judge exactly how much suppression is needed. Just look for a symmetrical, uniform sinewave on the oscilloscope.



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Chebyshev output low pass filters for an untuned class B. They plug into a card edge connector. As explained above, single-sided PC board material is not as reliable as two-sided board with connecting shorts between the two sides.

Years later I built some high-pass filters for 10 and 15 meters using the smaller T68-6 cores. (High pass filters are sometimes needed for SSB operation. See chapter 15.) By then I had figured out how to get 50 watts output on 10 meters and the smaller cores did not overheat. The manufacturer says that overheating will occur long before these cores saturate. Therefore, if the filter is working properly and the core is no more than slightly warm, you don't need the larger T106 cores. On the other hand, "warm" equals inefficiency. Is the power loss significant? I have no data to offer.

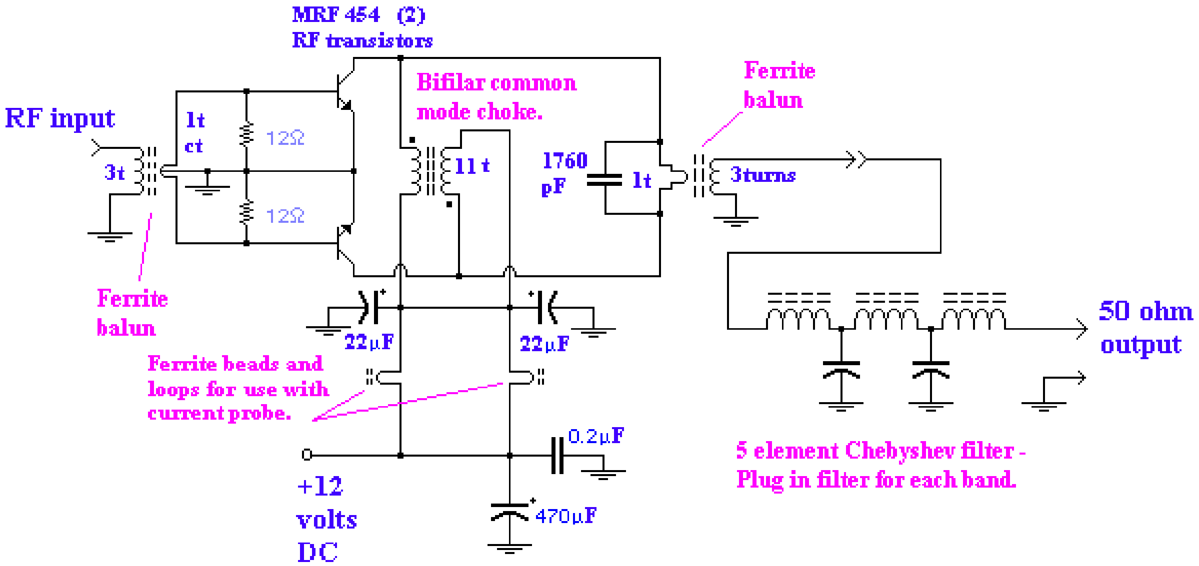
Designing hi-power Chebyshev filters

This is probably obvious, but the high power filters are designed just like the design of the small ones in chapter 6. The input and output impedances are 50 ohms and the inductance and capacitance values for your desired cutoff frequency are the same. The only change is the A_L value and number of turns for the particular large toroid powdered iron cores you are going to use. It is also a good idea to use higher voltage mica capacitors for the filters. I have been getting away with 500 working volts but 1000 WV or more are advisable. Unfortunately, 1KV mica capacitors are hard to find in modern catalogs. When the antenna is mistuned with a high power amplifier, quite high voltages can result.

Band	Core	L1	C1	L2	C2	L3
160M	T106-**2**	11T	1440pF	19T	1440pF	11T
80M	T106-**2**	10T	820pF	17T	820pF	10T
40M	T106-6	7T	500pF	11T	500pF	7T
30M	T106-6	6T	290pF	9T	290pF	6T

20M	T106-6	5T	220pF	7T	220pF	5T
15M/17M	T106-6	4T	120pF	6T	120pF	4T
10M/12M	T106-6	2T	100pF	4T	100pF	2T

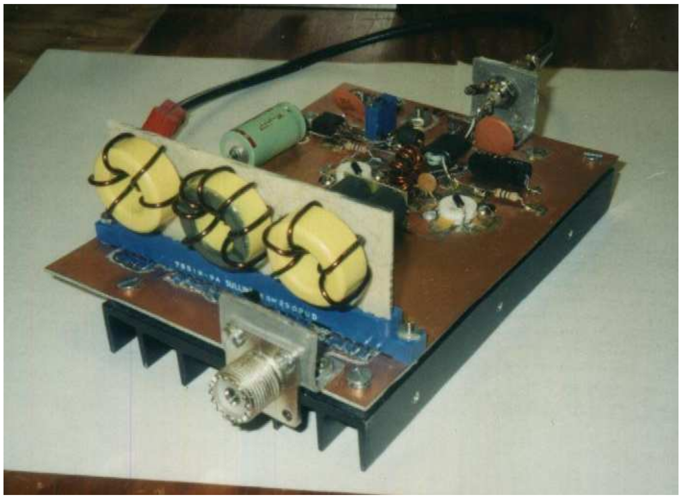
These values are not set in concrete. If you have trouble loading an antenna, lowering the capacitance of C1 and C2 will nearly always make it easier to tune. Naturally, the trade off is less protection against unwanted harmonics.



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 watching 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 20 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. This is primarily because I don't have a special antenna for each of the ten HF bands. Consequently I'm often trying to stuff RF into non-resonant antennas. 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.

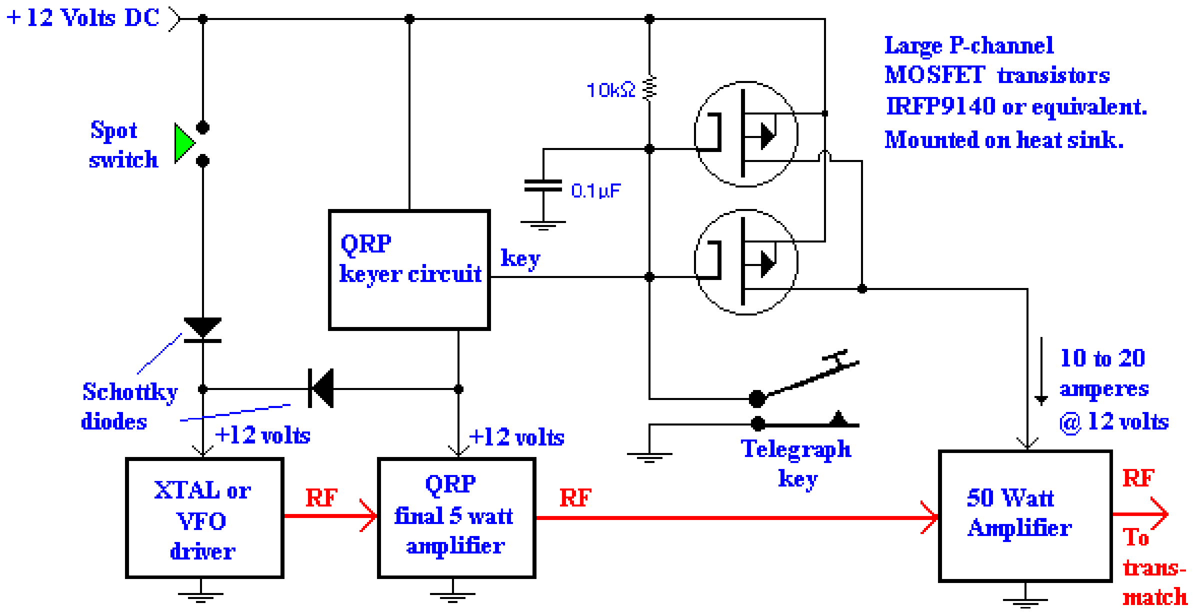
Eventually it occurred to me that I was already using the multistage 30 MHz cut-off low-pass TVI filter described in chapter 9. Therefore, for those high bands my 10 meter output filter on the final was redundant. I built a “blank” filter that was just a piece of RG-58 coax that shunts from one end to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

Another trick to achieve a cleaner sinewave from your QRO amplifier is to add a small capacitor in series with output of the 5 watt **driver**. In effect, the capacitor is on the input of the QRO amplifier and serves as a simple high pass filter to attenuate low frequency noise. In other words, if defects in the sinewave repeat after several cycles, that's low frequency noise. For example, I rebuilt my 20 meter QRP driver, supposedly "improving" it. The output from the rebuilt driver into a 50 ohm load was quite clean. But mysteriously it caused low frequency contamination on the output of the high power amplifier and the frequency counter would not lock. A 220 PF capacitor in series with the output of the 5 watt driver corrected the problem. Correction for a higher band such as 15 meters requires a proportionately smaller capacitor.

Keying the 50 watt linear amplifier

When I first began using my finals, I kept 12 volts DC on them continuously. 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 more with this simple approach. However, if you don't like your results, you can always fall back to my keyer circuit shown below.



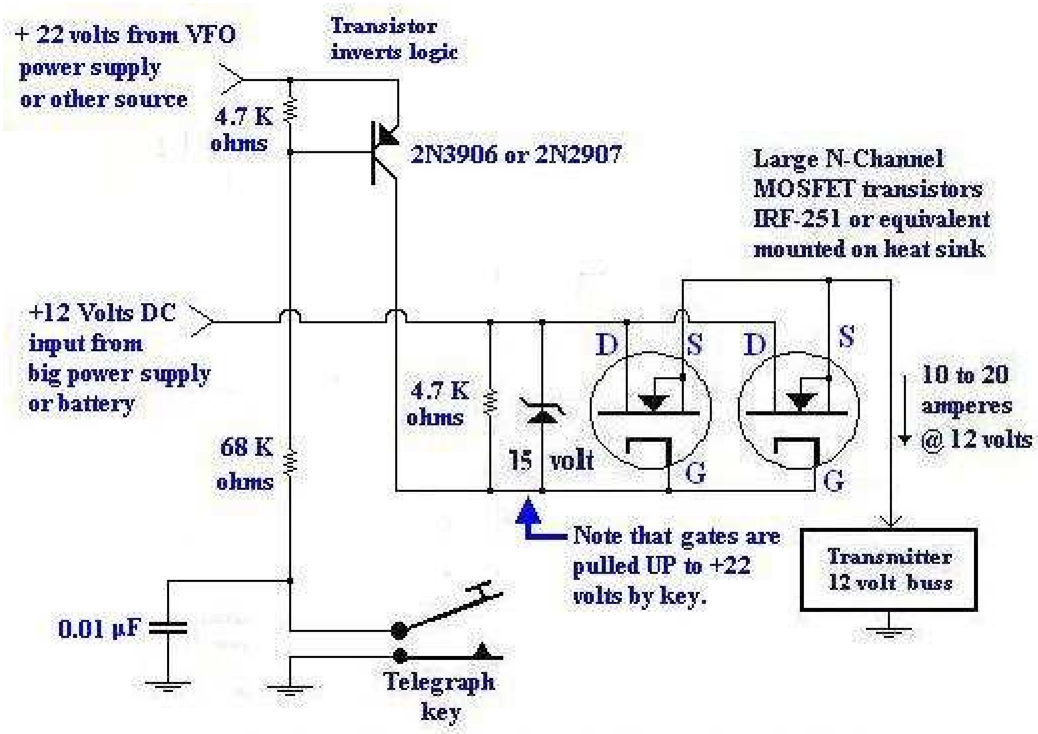
50 WATT TRANSMITTER KEYER

My solution was to build a high power 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 serves as a heat sink. The heat sink 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 that 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 paralleled 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 you may already have a convenient 22 volt DC 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, at this time 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 a defective temperature feedback circuit 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 explanation for this. 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 magazines is great in theory, but sometimes unnecessary in practice. The fellows who wrote those articles are over-educated. Their sophistication often discourages us. Don't let them rain on your parade! Build it simple and work up from there.

A LINEAR AMPLIFIER, THIS TIME FOR SURE

Adding linear bias to the Class B amplifier

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

Sideband needs a linear

Eventually I got bored with HF CW and built an SSB QRP 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 have to retune it every time you QSY (change frequency) 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) or gate(s) of the final amplifier and you get a big, constant output signal with about 10 dB power gain over the input. The big drive signal exceeds the base forward voltage drop of the output transistors by a wide margin. ***During CW operation the amplifier only delivers one amplitude***, so the base voltage threshold problem never arises.

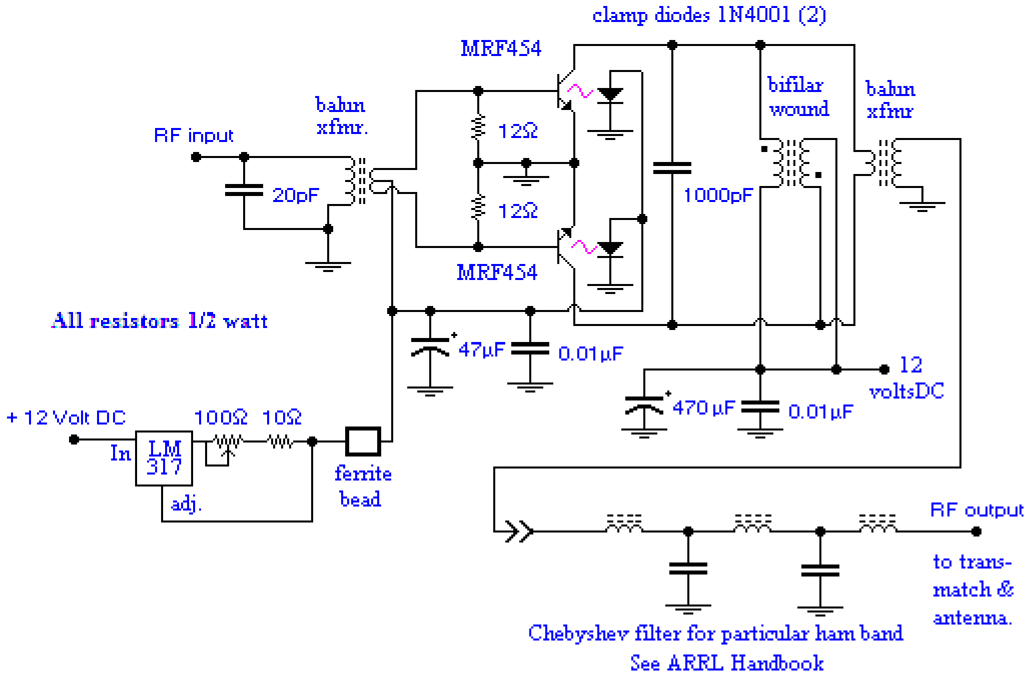
Why does sideband need a linear when AM modulation was so easy?

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.

In the old days 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 (1N4001) 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. Notice that a 47 μF electrolytic capacitor and a disk ceramic 0.01 μF stabilize this DC bias voltage. Ceramic capacitors conduct RF well, whereas electrolytics store large amounts of DC charge. The two kinds are put in parallel to achieve both characteristics. 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.

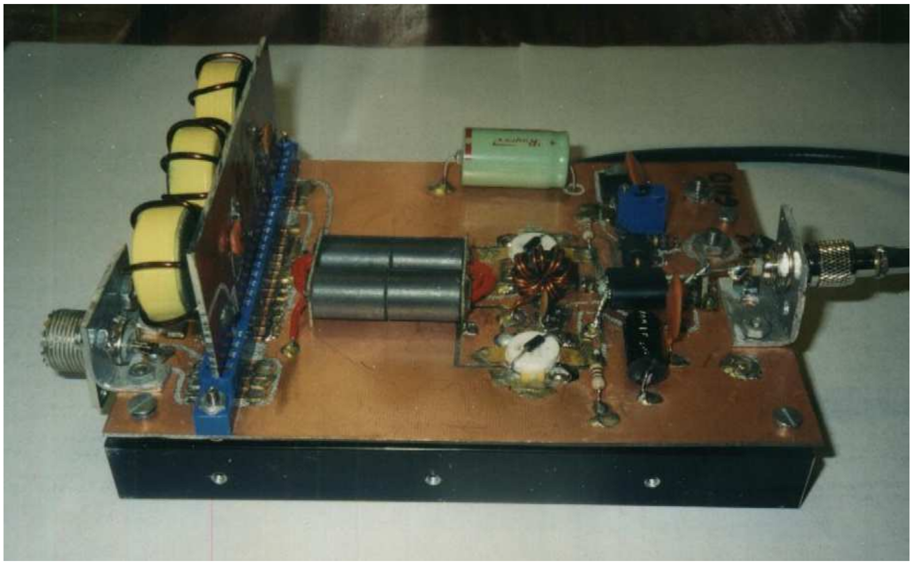
The second function of the diodes is that they also change with temperature and automatically compensate for temperature rise. ***They are strapped across their respective transistors so they are in thermal contact with the transistor cases.*** As the transistors and their piggyback diodes heat up, the 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 before is that this circuit has 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.

Adjusting the bias current

One surprise was that forward bias that was adequate for one band, was not enough for another. If you're troubled by voice distortion on a particular band, it may need a few more milliamperes of bias current. Just tweak your constant current bias trimmer pot to add a few more milliamperes. So long as you don't overheat your final, all bands will work OK at the higher level.

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. Appropriate 4-40 size holes and threads had to be drilled and tapped into 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.

Now that I know more about these amplifiers, I believe T106-6 powdered iron cores are larger than necessary for less than 100 watts. My experimentation suggests that T68-6 cores are adequate and do not overheat. Also, the 1.5 inch long ferrite balun is larger than needed. The smaller balun I used in my other linear, visible in the photo below, seems to stay cool and perform well.

Designing the PC board

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 BNC, 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 QRO power, >5 watts, I suggest avoiding connectors like phono plugs that were not designed for RF power. You can get away with phono plugs on 20 meters and below, but the standing waves make it difficult 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.

A linear amplifier installed in my CW transmitter. The VFO and a 40 meter QRP board can be seen in front of the linear. Directly behind the VFO is the antenna relay. Some of the controls on the front panel are from an early failed attempt to add sideband capability.

Why stop at 100 watts?

I opened up the June 2006 issue of QST 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 saw such a beast at homebrew night at my ham club. It was beautifully crafted by Bill, ABØDH, and was way more complex than the basic output stage. Bill owned a spectrum analyzer and was able to discover all its unwanted (and illegal) harmonics. Consequently he equipped it with harmonic "diplexers" to capture and dissipate the energy of all unwanted emissions. He diagnosed and cured defects I wouldn't even know existed! The amplifier ran too hot, so he cools it with water circulated with a small pump from a 5 gallon can. I felt completely outclassed by Bill Hedrick's amplifier.

I also remember 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 neighbors' poorly designed TVs and stereos. In contrast, his 100 watt transmitter had never bothered them. Bob fought the problem for several months. He even hired a technical firm recommended by the FCC to check out his rig and prove that it was operating legally. Sadly, his neighbors didn't care whether it was operating legally or not and they refused to fix or replace their shoddy electronics. In the end Bob mothballed his kilowatt linear 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. Consequently 300 meters is vastly different from 30 meters distance.

Surprisingly, in the U.S.A. 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 RMS. Similarly, an old "kilowatt" Class B amplifier, the kind you find for sale at hamfests, is 50% efficient and delivers at most 500 watts to the antenna. On the other hand, with AM voice modulation, when the modulation is maximum, "100% modulated," the peak power could rise as high as 1,000 watts momentarily. Today on many bands we are allowed 1,500 watts PEP (Peak Envelope Power) measured at the antenna. That means 50% more power than an old “kilowatt.” When you consider that SSB concentrates all the power into a single sideband, the modern SSB kilowatt can have at least 4 times the effective power as an old AM modulated kilowatt.

Maintenance and antenna tuning

The only maintenance trouble I've had with the amplifier has been the gold-plated fingers on the **card-edge connector**. Spray-on contact cleaner will help clean the gold fingers. You can clean the PC filter board copper contact surfaces with a pencil eraser. More to the point, the Chebyshev output filter cards are much more reliable if you use 2-sided PC board material and take advantage of contact with the contact fingers on both sides of the filter PC board. Drill and solder feedthrough connections so that both sides of the filter board are connected in parallel.

On rare occasions I have had comments about my transmitter having a **slight chirp** at the end of long dashes. For example, after 10 minutes of the usual CW chat, the other fellow might say, "Are you homebrew? There's a tiny chirp that comes and goes." The subtle frequency shift is truly minor and is related to low frequency contamination of the output waveform. This occurs whenever the antenna is difficult to load and the waveform on the scope changes from moment to moment. That is, when I tune it up, I see a perfect sinewave on the scope. But as soon as I start sending, the pure waveform acquires some extra wavy-ness that varies moment to moment. On 20 meters my vertical antenna can produce a clean sinewave at two different combinations of settings of the antenna tuner variable capacitors. One of the settings is stable while the other is likely to shift to the wavy/chirp waveform. When I load my dedicated dipoles designed for specific bands, the waveform is clean and stays that way.

Ammeters in series with the 12 volts supply can cause a significant voltage drop, tenths of a volt. For years I used an ammeter in series with my battery supply to monitor current. This allowed me to indirectly keep track of the total power being drawn from the battery. I was checking out a new 200 watt power supply and noticed that I had a 0.25 volt drop across the ammeter at high levels. This drop will contribute to chirp and make decoupling the 12 volt supply to the amplifier stages in your QRP more difficult. My eventual solution was to remove the ammeter and put it inside my new line-powered power supply. The ammeter is now inside the voltage regulator feedback loop. This way when voltage drop appears across the ammeter, the regulator transistors turn on harder to compensate and the voltage to the transmitter remains rock steady.

Another cause of chirp can be **corrosion of the positive terminals** of my deep-discharge lead-acid batteries. When I notice that my LED pilot light is beginning to flicker significantly while sending CW, I know it's time to clean the terminals. In my experience, above 100 watts it is nearly impossible to send chirp-free CW, no matter how well charged the batteries are or how carefully I clean the battery contacts. The efficiency of a class AB amplifier is about 50 percent. In order to get 120 watts output I need about 20 amperes input from the battery. I heard a fellow on the air with a kilowatt amplifier mounted in his car. He said he solved his battery sag problem by putting gigantic multi-farad capacitors across his battery. Capacitors this huge are indeed available, but they are pricey - hundreds of dollars.

In conclusion,

In the end I was able to build a linear using the cheap MRF-454 transistors, just like the handbook said. 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 to 25 watts, while on 80 meters I get as much as 120 watts. I learned later that my 25 watts on 10 meters could be doubled by using the "Fri-match" antenna tuner described in chapter 9. As usual, lower frequencies are easier.

Hmmmm ... Now that my linear 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.

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A CLASS B AMPLITUDE (AM) COLLECTOR MODULATOR

Or if you prefer, this could be something more useful in the modern world:

A HIGH POWER AUDIO AMPLIFIER

Recently there was one of those weekend QSO "radio sport" contests for vintage rigs using AM modulation. Being a vintage kind of guy, I thought it would be fun to participate. I had developed AM modulation by detuning my SSB transmitter so that it preserved the carrier wave instead of canceling it. This is explained in chapter 17A. I tuned up the SSB transmitter to be sure it still worked and sounded OK in AM mode. When the big day arrived I got on the air ... and all the stations were on SSB doing their usual radio sport and rag-chewing. Eventually I did hear an AM station, but he was too weak to understand his speech. Darn!

Back when I was beginning my serious homebrewing, I attempted to add SSB to my old CW transmitter. Being naive, I did not realize that a transmitter with tuned RF amplifier stages can not run SSB. This is because, when I stopped talking, each tuned stage sometimes began to oscillate all by itself. Apparently SSB needs 100% broadband amplifier stages. Of course by the time I realized this, I had added a low power microphone amplifier and the front panel was equipped with a microphone connector, audio gain control and switches for phone operation. There was a fair amount of empty space on the chassis left over from the SSB generator. Just for fun, I thought it would be an interesting technical challenge to AM modulate this 50 watt CW transmitter.

Collector modulation

Anode modulation, also known as collector/drain modulation for transistors and plate modulation for tubes, is the best AM method because the peak power can be twice as high as the average CW power of a transmitter like mine. So, if a station can hear my CW signal well, they will almost certainly be able to understand the AM modulated signal. To AM modulate a CW transmitter, the DC current supply of the final amplifier stage is passed through a transformer secondary winding. The primary winding is driven by a powerful audio amplifier, generally one half the power of the RF final stage. The secondary winding impresses audio sinewaves onto the DC supply current. These surging currents power the RF output stage with peaks and troughs of RF output proportional to the variations in the audio signal.

AM is an almost useless capability in 2019, but I still thought it would be an interesting challenge. Instead of a low impedance winding modulating DC current, the same winding could be powering a powerful loudspeaker. Because my entire ham station runs on 12 volts DC, I needed a 25 watt audio amplifier that would run on 12 volts. Notice that a 12 volt audio amplifier could be installed in your car to infuriate your neighborhood with 25 watts of booming bass notes which no door or window can keep out.

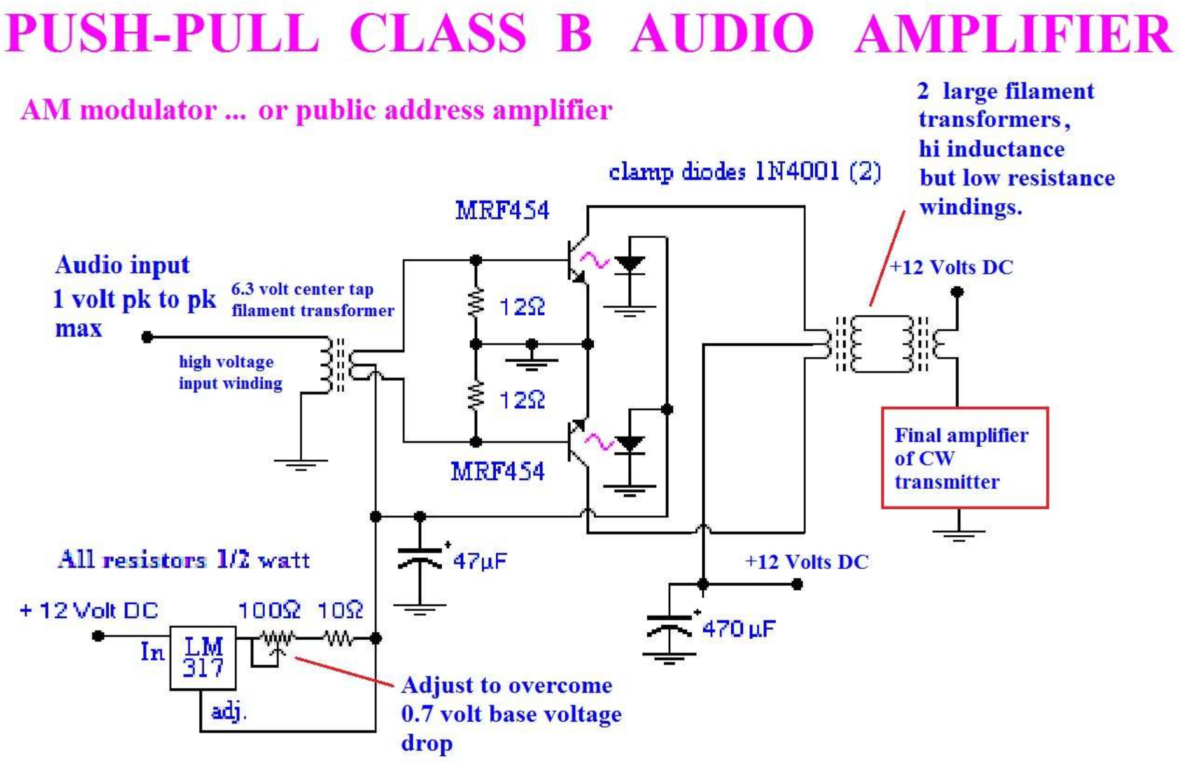
Working on this project brought up **two issues** I had not previously noticed:

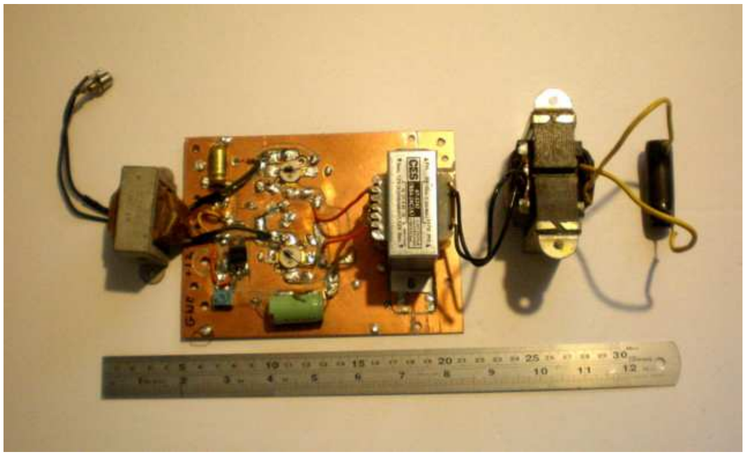
First, building a high power audio amplifier is difficult if the power supply is limited to 12 volts DC. The modern way to build an amplifier with over 10 watts of power is to use a push-pull amplifier consisting of a P-channel transistor and an N-channel transistor stacked vertically. The output to the speaker is delivered by a large capacitor connected between the two transistors, half-way between Vcc and ground. No transformer is needed because positive-going waves turn ON the N-channel or NPN transistor. Negative-going waves turn ON the P-channel or PNP transistor and vice-versa. In chapter 13B there is a small, half-watt audio amplifier that is built this way. Very large modern audio amplifiers have complex transistor circuitry to prevent the output from saturating or distorting. A modern amplifier that delivers 20 or more watts invariably runs on a supply voltage of at least 24 volts DC. Really large kilowatt public address amplifiers often run on 120 volts DC or more.

If you're interested in building a modern, high power audio amplifier, just Google "high power audio amplifier circuits." You will immediately find dozens of similar stacked N-channel and P-channel push-pull amplifiers. The high power transformer-less designs all need intricate, multi-transistor drivers to set up and regulate the waveforms to drive the transistor bases or gates. These designs are much more complicated than my transformer solution, but much cheaper to build and far smaller and lighter.

Second, although a transformer and special low voltage power transistors solve the problem explained above, the output transformer must be huge with high inductance but very low resistance windings. The output transformer is broadband, much like the RF broadband transformers used in chapters 6 and 12. But of course it needs very large inductances, many Henries, to handle audio frequencies without saturating.

High inductance means many turns of wire. Simultaneously, because this is for 20 or 30 watts of power, the resistance of the copper wire must be low. If the output winding has, say 5 ohms of ordinary resistance, not AC resistance, then the DC current passing through the winding will dissipate large amounts of wasted power and produce a large voltage drop across the transformer. For example, 5 ohms resistance with 2 amperes of DC current will drop 10 volts, leaving little voltage to power the RF output stage.





The breadboard prototype shown above accomplished my technical goal. It delivered over 20 watts of audio power to the 3 ohm power resistor on the far right. Unfortunately it's too large to fit in my old transmitter and wasn't practical. I didn't have a single transformer with low impedance for both input and output windings, so I simulated one with two filament transformers back to back. The two transformers are connected with the 120 volt AC windings. If I were to run this amplifier for more than about 20 seconds at a time, I would need a big aluminum heat sink for my transistors, just as I did for the RF amplifier.

The average reader may not be **OLD** enough to be familiar with vacuum tubes. It's possible some of you don't know about "filaments." Every vacuum tube had a metal filament, just like an old time light bulb. Filaments were powered by separate transformer windings that provided 2.5, 5, 6.3 or 12 volts AC at relatively high currents. Today many of these same old filament transformers are still manufactured for use in low voltage transistor power supplies.

The input transformer I used was a 120 volts to 6.3 volts filament transformer with the low voltage center-tapped winding driving the two base inputs. The output transformer is a center-tapped 24 volt winding driven push-pull by the same MRF454 transistors that I used to build the RF output final stage presented in this chapter. Except that it runs at audio frequencies, the design is the same as the RF version using the same transistors. Notice that much of the complexity goes away when RF bypass capacitors, the ferrite bead and common mode, RF canceling transformer aren't needed. In other words, audio is simpler.

As we did with the RF push-pull amplifier, an adjustable current source is used to overcome the 0.7 volt base diode voltage drop and activate the two bases. This adjustment is quite sensitive. I doubt that a fixed resistor would be practical. Also, the audio drive voltage for the amplifier is quite sensitive. Too little audio signal and there is no output. As you increase the audio drive, the output quickly rises from no signal to saturating the audio sinewaves into a train of square waves. There is little "head room" between zero and 12 volts. The modern designs with 24 or 40 volts on the output transistors have a much less critical operating range.

I explained earlier that the RF final amplifier transistors must be mounted on a PC board with wide traces that are laid out as equal and symmetrical as possible. Otherwise, the amplifier will not produce a clean RF waveform because the unmatched sides will have RF reflections that fight with each other. My first PC board above performed poorly at RF frequencies. Fortunately perfection isn't as important at audio frequency, so I was able to rescue this failed board from the scrap heap.