

# Designing and Building Transistor Linear Power Amplifiers

## Part 1 — Designing an experimental one transistor amplifier.

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This two part article describes a procedure to design and build a simple transistor linear amplifier. The examples presented in Part 2 are single band HF and VHF amplifiers at the 5 W level — a particularly enjoyable and educational class of amplifiers for the experimenter.

The working amplifier will have the block diagram shown in Figure 1. Here is a step-by-step procedure to do an experimental, measurement-based design:

- Select a device and note its breakdown voltage, maximum current and thermal resistance.
- Turn it on with dc.
- Connect the RF drive and RF load.
- Measure gain, output power and linearity and adjust dc, RF drive and RF load for optimum performance.

After the amplifier is finished, it will need RF and dc switching and an output low-pass filter.

Switching and filtering needs are different for each application. Part 2 will have a few practical examples currently on the air. Note that the step-by-step procedure makes no mention of frequency, efficiency, bandwidth or even the type of device. Each of these will be dealt with in the following sections, but it is useful to remember that the basic procedure is the same whether we are building a 400 W amplifier for 500 kHz or a 100 mW amplifier for 200 GHz.

Most linear amplifier designs are optimized for a particular parameter. It is useful to remember that optimizing for one parameter always involves compromise in others.

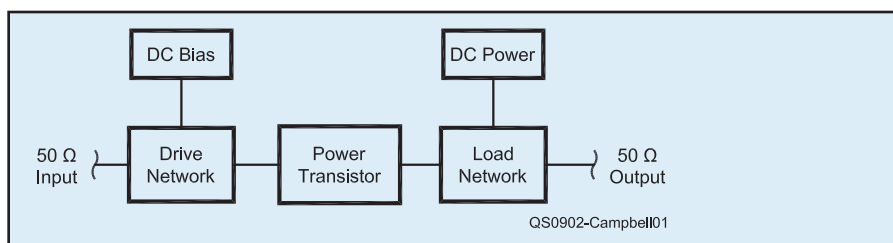


Figure 1 — Block diagram of typical solid state power amplifier.



The design procedure here is optimized to get you on the air with skill, understanding and any available device. The most clever and creative radio designers often have external or self-imposed spending limits on projects — in the absence of fiscal constraints, a person could simply pick an amplifier out of a catalog without learning a thing.

### Select a Device

Let's assume that we are not designing a radio for mass production. As amateurs, scientists and research engineers, we are free to use whatever device is available. The best transistor for our project might be something from the junk box, an experimental device that hasn't yet been released to manufacturing, or something inexpensive from RadioShack or Digi-Key. It is important to have either a data sheet for the transistor, or a small quantity on hand so that you can destroy a few while discovering breakdown voltages and thermal limits.

We are also free to select the operating voltage. The standard voltage for amateur portable equipment is 12 V, and a selection of well-designed, conservative and useful amplifier designs are available as kits and

semi-kits. If you want medium power, a 12 V power supply and wideband operation, that is a good approach. But if you are interested in doing a few experiments and a little design work, the first assumption to throw out is the 12 V supply.

Many inexpensive new devices have been designed for use in switching power supplies, and are not characterized for RF at all. Some of these make excellent linear amplifiers with higher operating voltage. Devices that operate at 60 V are common, and much higher voltage devices are available. RF transistors are now available with a 1000 V breakdown voltage. In a linear amplifier, the output waveform is supposed to be a function of the input waveform, not the supply voltage, as long as the supply voltage is greater than needed. This allows us to use simple unregulated power supplies with a large capacitor on the output instead of more complex regulated supplies.

A simple unregulated power supply is shown in Figure 2. The output voltage may be varied during experiments with a small Variac type variable autotransformer or a

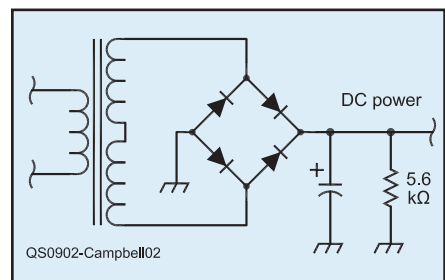
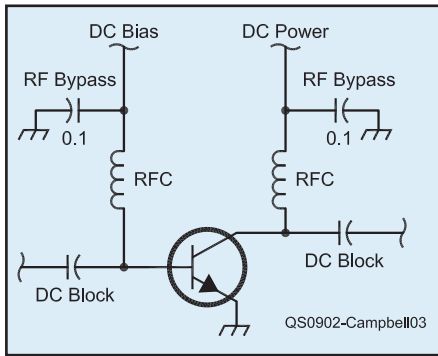


Figure 2 — Collector or drain supply for amplifier experiments.



**Figure 3 — Arrangement to turn on the transistor for static measurements.**

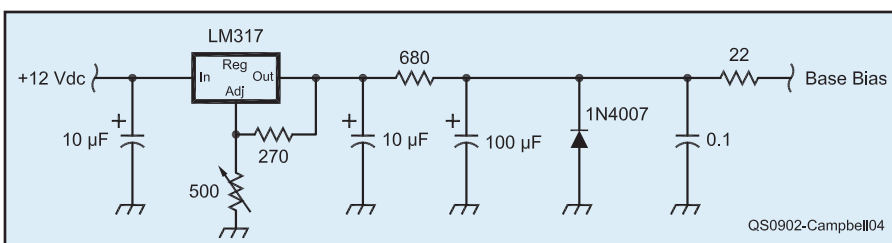
junk box transformer with the windings all connected in series to serve as a tapped auto-transformer.

After looking at breakdown voltages and pondering power supplies, we need to look at how much current the device can handle. A transistor rated at 1 A and 120 V could control 120 W — if it could dissipate the heat. Thermal conductivity is the last parameter we need, and a quick look at the dissipation in watts will tell us whether the device is suitable for our power level.

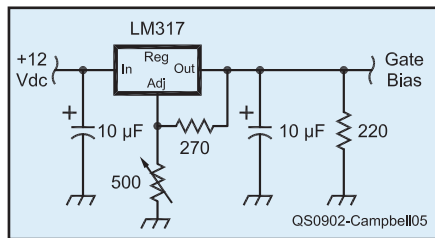
The power dissipation is determined by the device package and how it is connected to the heat sink. One other criterion for an experimental linear PA device is that it be cheap! When I design and build an experimental amplifier, I expect to burn out a few transistors in the process. As the old blues song goes: *A man should never gamble more than he can stand to lose.*

## Turn It On with DC

A linear amplifier transistor needs a collector (drain, if an FET) power supply and a base (gate) bias supply. The basic circuit is shown in Figure 3. If the transistor dc is fed through an RF choke or RF transformer winding, then the no-signal resting voltage on the collector (drain) equals the dc supply voltage. Assuming a symmetrical output waveform, the collector voltage can drop down to near 0 V on the negative peaks, and up to near twice the dc supply voltage on positive peaks. That means we should pick a dc power supply voltage comfortably less than half the rated breakdown voltage of the transistor.



**Figure 4 — Simple base bias supply for bipolar power amplifier development.**



**Figure 5 — Simple gate bias supply for FET power amplifiers.**

How do we define *comfortably less*? That all depends on how expensive the device is, and how annoying it is to replace! I believe it is both necessary and desirable to burn out a few transistors while experimenting with a new design. Maybe that's why I quit rock climbing and started windsurfing — the splash is the best part! It is also part of the reason why it is more fun to experiment at the 5 W level than at 1500 W.

Once the collector supply is connected, turn the device on with a little base current (or gate voltage for an FET). The current mirror in Figure 3 is a generic circuit I use for base bias, and Figure 4 is what I use for gate voltage if the amplifier device is an enhancement mode FET. These are variable supplies that have a knob to adjust bias while you are watching the collector (drain) current on a meter. Note that the bias supplies in Figures 4 and 5 have very low impedance — they can supply considerable current.

I usually design my base supplies to supply about the same current as the collector. That is called a *stiff* bias supply, and it needs to be stiff at audio frequencies, so that the dc bias doesn't change with variations in the driving waveform. That statement raises the question of the operating class of the amplifier. I prefer to run my amplifiers with enough resting current to operate in pure class A during the pauses and subtle nuances of speech, and then carefully adjust them on the bench for an acceptable level of distortion on the voice peaks.

A good linear amplifier will dissipate about half of the dc power as heat. Professional linear amplifier designers devote entire careers to improving from 45% efficiency to 55% efficiency, but we can do more to save the planet by turning off the overhead when

we leave the room — so *about half* is close enough for our estimates. A 10 W linear amplifier needs to be capable of comfortably dissipating 10 W as heat. Turn up the bias until the amplifier is dissipating the desired output power, and watch it for a while.

Keep your hand on the BIAS ADJUST knob. Does the current rise as it warms up? You might cure that by thermally coupling the diode in Figure 3 to the device, and by adding a little emitter resistance. I like emitter resistance, particularly for higher voltage amplifiers. Then turn it up to twice the desired output power and watch its behavior. Turn the bias up and down and watch for any jumps in the collector current — those indicate oscillation. If the device is unstable during the dc operating point tests, add ac loads to the input and output, as shown in Figure 6.

After the actual drive and load networks are designed and connected to the transistor, run all of the dc tests again and look for any signs of instability. A few ohms in series with the base or collector, a 1 Ω emitter resistor, or a UHF suppressor consisting of a few turns of wire around a 22 Ω, ½ W carbon resistor are ancient cures, well-known in the 1960s. A major advantage of higher voltage power supplies is that both the absolute voltage drop and voltage drop relative to total supply voltage across these resistors is much lower for a device running on 48 V and 250 mA than for one running on 12 V and 1 A. For lower voltage devices, a ferrite bead on the base or collector lead right at the device might work. But don't cure oscillations you haven't observed! Some modern devices are wonderfully stable.

Many RF power transistors have built-in emitter or base resistance, and unnecessary resistors and ferrite beads can have unintended consequences. Once the part behaves with dc bias and successfully generates heat, go ahead and find its limits. Turn the collector supply up, turn up the base bias, and burn out the device. Note the smell, and look for signs of thermal stress or a cracked plastic case.

It's a good idea to burn one up with too much voltage, and another one with too much current (heat). If you burn up transistors on the bench, you will have the experience to correctly debug a suspected power transistor failure in the final circuit, and not spend hours extracting a perfectly good transistor from an amplifier that failed because of a disconnected power supply wire.

Note that these simple bias circuits are designed to make it easy to adjust amplifier dc operating conditions at the bench while making linearity and gain measurements. After the amplifier design is complete and satisfactory performance has been verified with measurements, it may be useful (or necessary) to add temperature compensation and other features to the bias circuit — but that is

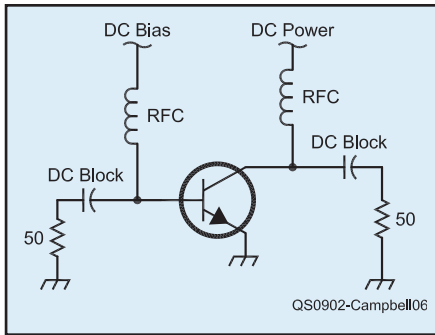


Figure 6 — RF loads during dc tests.

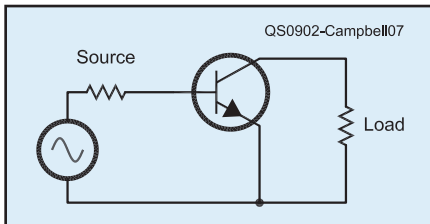


Figure 7 — RF amplifier, small signal equivalent circuit.

a subject for another day.

### Drive and Load the Amplifier

Transistors like to amplify, and at HF they often have considerably more gain than necessary. In that case, there is no need to match the input of an HF linear amplifier device. We want to drive it with a known, well-behaved impedance. Similarly, we don't match the output of a linear power amplifier; we present it with a known, well-behaved load impedance. The terms *drive network* and *load network* are useful to avoid some of the confusion surrounding *impedance matching* of non-linear active devices. At higher frequencies, devices have less gain, and we often adjust the drive and load networks to get more gain per stage. These techniques are illustrated in the

7 MHz and 50 MHz amplifier examples that are described in detail in Part 2.

### The Load Network

Let's start at the output. We already mentioned that the collector quiescent voltage is  $V_{CC}$ , and that it drops to near zero and up to nearly twice  $V_{CC}$  with a symmetrical output waveform at the peak output power. A sine wave with a peak-to-peak voltage of twice  $V_{CC}$  has a power given by  $V_{CC}^2/2R$ .<sup>1</sup> So once we have set the power supply voltage, the peak output power is determined by the load resistance  $R$ . A particularly convenient choice for  $R$  is  $50 \Omega$ . Then the peak power output is a simple function of the supply voltage: 12 V supply for 1.44 W, 24 V for 5.76 W, 100 V for 100 W and so forth. The 1.5 W CW rig with a 13.8 V supply is a classic [Ugly Weekender, Optimized].<sup>2</sup>

For other values of  $R$ , we use a transformer between  $50 \Omega$  and the collector. Vacuum tube amplifiers use high voltages, so the transformer (often a pi-network) typically steps up from  $50 \Omega$  to a few thousand  $\Omega$ . Transistor amplifiers use lower voltages, so we often step down from  $50 \Omega$  to something much lower. Cell phone power amplifiers with 3.5 V power supplies typically present about  $1 \Omega$  impedance to the PA collector. Transistors inexpensive enough for our experiments are good for 10 or 20 W, with supplies up to 60 V or so, which means that either a direct connection to  $50 \Omega$  or simple 4:1 transformers down to  $12.5 \Omega$  are useful for our experimental amplifiers. Note that the network between the output and the transistor is determined by primarily the desired output power level and the power supply voltage, not the particular type of transistor.

### The Drive Network

Now, what about the input? A very simple view of the transistor is that the base drive needs to supply the collector current divided by beta into a resistance approximately equal

to the emitter resistance multiplied by beta. RF beta is less than dc beta. A good choice for drive impedance is approximately equal to the collector load impedance. So, if the output is directly connected to  $50 \Omega$ , the base can be driven by  $50 \Omega$ , and if the output has a 1:4 transformer to present a  $12.5 \Omega$  load to the collector, the input can be driven by  $12.5 \Omega$  through a 4:1 transformer. Since the base of a transistor is a non-linear semiconductor junction, drive should be well-behaved when connected to an impedance that changes with drive level. This can be achieved by including loss in the drive network.

Because the transistor is fundamentally non-linear, it is important to think about the drive and load impedances at harmonics of the input waveform, and also at all the frequencies generated by intermodulation — for example, the difference frequencies between a two-tone source. The fewer distortion products the amplifier generates, the easier it is to gracefully handle them all, so linear amplifiers are easier to design in this respect than highly efficient amplifiers that use the transistor as a switch. A pure class A amplifier generates little harmonic and intermod energy, so it is common for a linear amplifier to be very clean at low drive level and exhibit unexpected behavior as drive increases.

### Putting it All Together

Figure 7 is the RF equivalent circuit of an ideal amplifier. It has a drive circuit, a load, the active device — and nothing else. If we could build circuits with zero lead lengths, no transmission lines and dc power supplies built into the source and load, our amplifiers might look just like Figure 7. In ancient times, radio designers learned to use transmission lines to present any desired drive and load

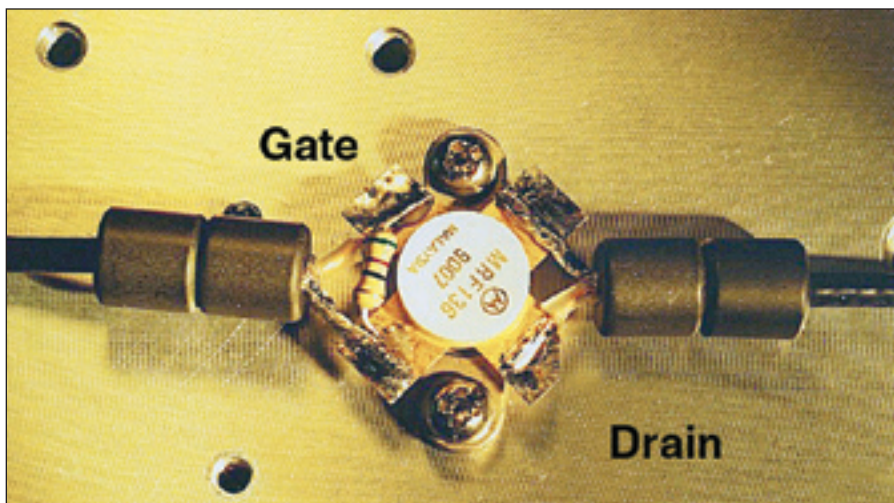


Figure 8 — RF power device with sleeve baluns.

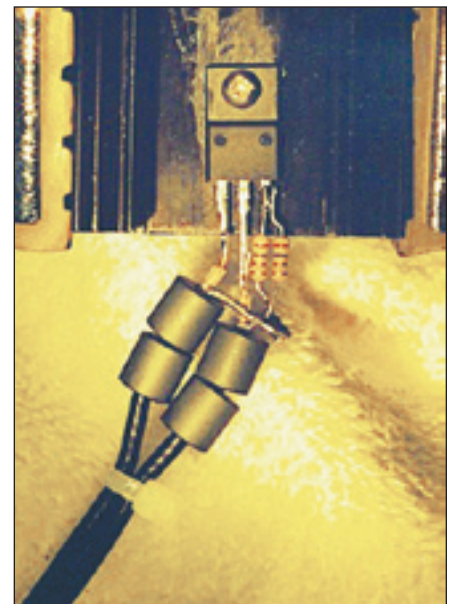


Figure 9 — Bipolar transistor with sleeve baluns.

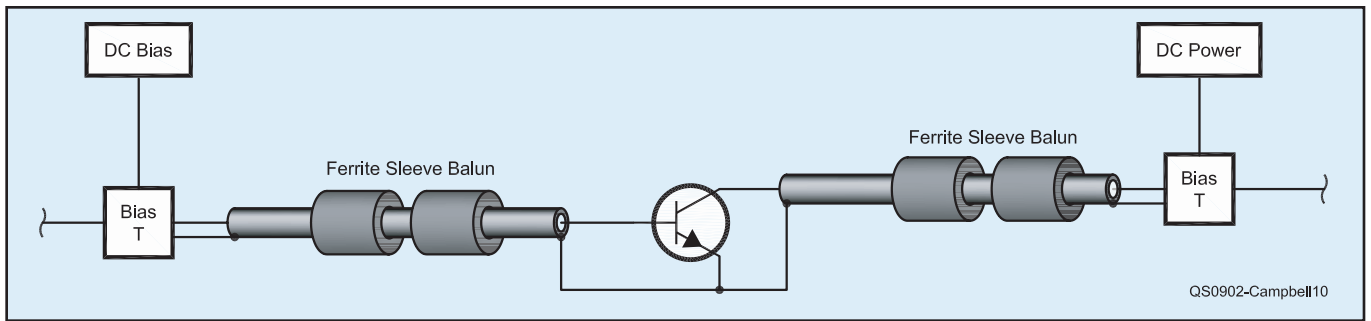


Figure 10 — Experimental amplifier with no ground at device.

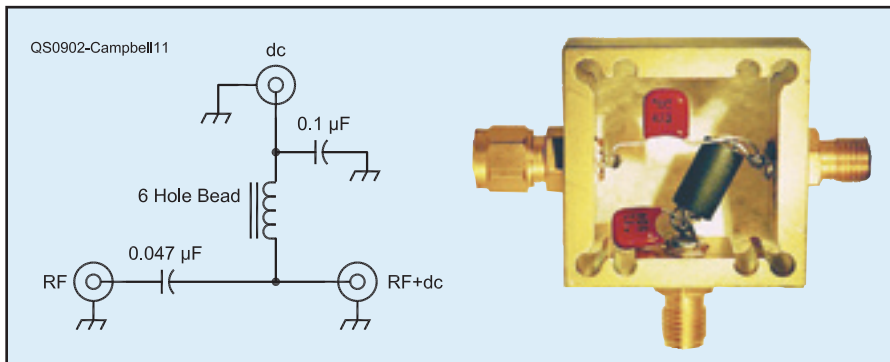


Figure 11 — 1:1 bias T.

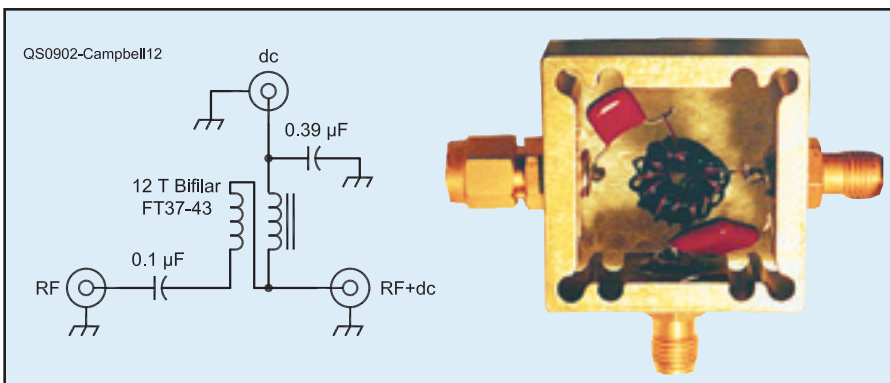


Figure 12 — 4:1 bias T.

impedances right at the active device terminals. One problem is defining where the drive and load impedances are connected.

Is the load connected between the collector and emitter, or between the collector and ground? Is the drive connected between the base and emitter, or between the base and a different ground? Are there multiple connections to ground, creating the possibility of ground loops? For decades the lore for transistor RF power amplifiers has been to use a large ground with all connections as short as possible, and any reactances soldered directly across the transistor leads. This is a very good plan, but it makes it hard to replace the device or experiment with different devices in the same circuit. An alternative approach is eliminate the entire concept of ground from the circuitry around the amplifier device. Figure 7 includes no ground symbol for that reason.

How can we connect to a device without ground? As radio amateurs, we already know how to do this. We connect to loads with no ground all the time — for example, dipole antennas. We can use a feed line with a balun to connect to a resistor dangling in space, an antenna, or the input of an amplifier. The balun ensures that all of the drive energy is connected directly from base to emitter, and that all of the RF energy traveling toward the transistor or reflected from it stays inside the coax, between the outside of the center conductor and the inside of the outer conductor.

Figure 8 is a photograph of an RF power MOSFET with balun connections to the input and output. The resistor soldered directly from the gate to the source is suggested in the Motorola data sheet for the device. The outside of the coax is not part of the circuit, and we can touch it without getting an RF

burn or affecting circuit operation. If we connect the drive using a balun, and the load using a balun, then only drive signals flow in the drive circuit and only load signals flow in the load circuit. There are no shared ground currents, and no ground loops. It may seem counterintuitive, but eliminating a ground connection at the device can actually improve stability. Figure 9 shows an inexpensive power bipolar transistor with sleeve baluns and 0.5 Ω emitter resistance. The ferrite sleeve baluns are simply RG-174 miniature coax slipped through pairs of ferrite beads. The hole in these particular beads is a little too small, so the outer insulation was removed before sliding on the beads.

One significant advantage of driving and loading the amplifier transistor with a pair of baluns is that the need for short leads and matching components right at the transistor is eliminated. This makes it much easier to experiment with different devices. The lengths of coax through the ferrite beads are a component of the drive and load networks, and are easily handled using a Smith Chart.

Figure 10 is a block diagram of a complete experimental amplifier, showing coaxial sleeve baluns for connecting to the power amplifier transistor, a pair of bias Ts for separating the RF and dc signals on the base and collector coax and two power supplies. Figure 11 is a photograph of a simple 1:1 bias T with a six hole ferrite bead, a 0.1 μF dc blocking capacitor, and a 0.1 μF RF bypass capacitor. All three connectors are type SMA, a convenient choice for my test equipment and junk box. Figure 12 shows a bias T with a 4:1 transformer, presenting an impedance of 12.5 Ω to the active device.

### A Proper Amplifier Test Facility

A good experimental amplifier test bench includes two signal generators, a power combiner, a driver amplifier with 50 Ω output, a step attenuator, an assortment of low pass filters, a dummy load and power attenuators, an accurate RF power meter, an oscilloscope and a spectrum analyzer. That may sound like a big investment in test equipment. I have probably invested nearly the price of a new medium-grade transceiver in my RF test bench. My spectrum analyzer is homebrew,



**Figure 13 — 40 meter band low pass filter.**

but all of the other test equipment on my bench was purchased on the surplus market. Any piece of test equipment can be replaced by some clever substitution, but I have always used at least a dummy load and oscilloscope when experimenting with amplifiers.

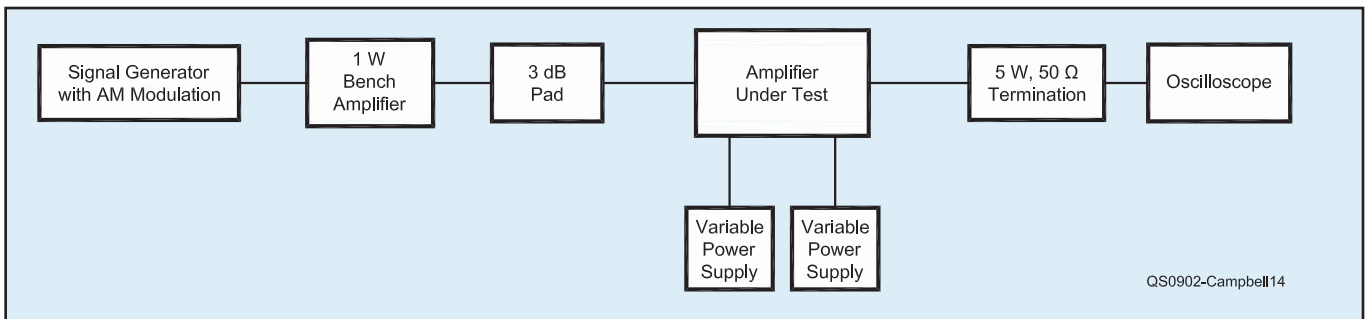
Oscilloscope outputs can be confusing and messy when harmonics are present, so I usually use a low pass filter on the amplifier output. The low pass filter should have connectors, so that it can be removed for examining harmonic waveforms, and particularly at VHF and up it is highly instructive to add

a quarter wavelength of 50  $\Omega$  coax between the output network and low pass filter and observe the effects. Figure 13 is a photograph of the 40 meter low pass filter I use for experimental amplifiers up to several hundred watts' output. Since there is no penalty for having a cleaner output than the FCC requires, all of my bench low pass filters are of seventh order. Suitable designs are tabulated in *The ARRL Handbook*.<sup>3</sup>

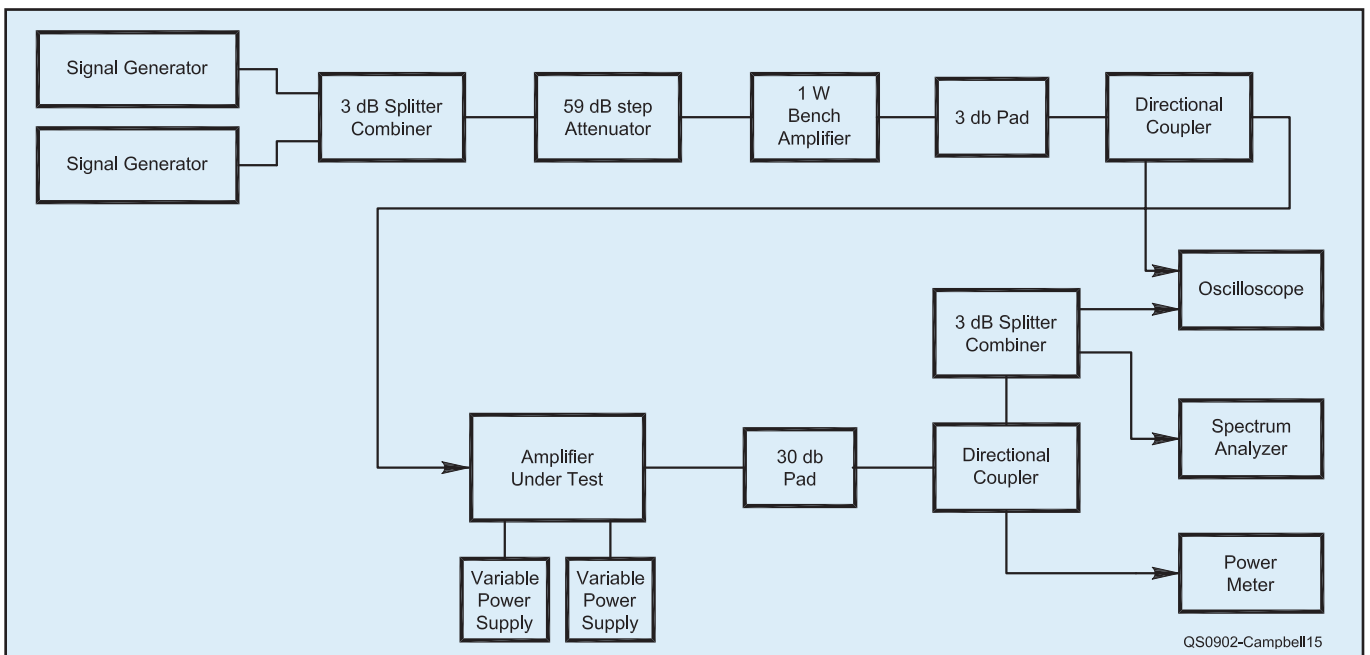
When I want numerical measurements of linear amplifier performance, I use the complete bench shown in Figure 15, but when I

first turn on an amplifier, adjust the bias, and explore its gain and undistorted power output I often use the much simpler setup in Figure 14. If a linear amplifier can provide undistorted amplification of an AM signal, it will have very low distortion when amplifying SSB. This is very old lore, taken directly from the 1966 *ARRL Handbook*. Both my HP8640 signal generators and my older military surplus URM-25 generators have the option of AM modulating the output, and most modern transceivers will provide an AM output as well. After I have completed the design, I often use a variable source of AM drive and an oscilloscope with 50  $\Omega$  termination for adjustments to a linear amplifier.

A quick look at the test bench reveals some of the appeal of 5 W class amplifiers for experiments. The RF load can be a simple 5 W BNC 50  $\Omega$  termination on the front panel of the oscilloscope, and the driver amplifier on the bench need only put out a watt of undistorted linear output. An FT-817 with a 6 dB pad on the output can drive the amplifier input. A DTMF microphone will generate two tones. The penalty for burning out devices is low at



**Figure 14 — Simple linear amplifier test bench.**



**Figure 15 — More complete linear amplifier test bench.**

the 5 W level. Besides, it has been widely observed that experiments at the low power (QRP) level are simply a lot of fun.

The AM waveform peaks are at 10 V, for a peak output power of 1 W. The carrier level is approximately 250 mW. Efficiency is low, of course, but one advantage of low power transmitters is that the power dissipated as heat in an inefficient transmitter output stage is often much less than the power used in other parts of the station. It is impossible to save 35 W in the output stage of a QRP transmitter that only draws 10 W — but it is very easy to save 35 W by turning off the overhead 75 W light bulb and turning on a 40 W desk lamp!

### Evaluate What You've Got

The last activity is to experiment and think about what you observe. Try every input waveform you can generate, and look at the output waveforms. Perform two-tone tests at different tone separations. Dig up an old *ARRL Handbook* that shows how to obtain AM trapezoid patterns. The goal is to learn

what makes your amplifier work well. How does it respond to high and low level input signals, high and low quiescent bias levels, and different modulation formats? Does the transistor burn out or oscillate if the load is disconnected? A good amplifier design is not based on a particular schematic or parts list — it is an amplifier designed by someone who has observed performance over a wide range of conditions and understands how all of the adjustments, components and circuit blocks interact. When you have completed this step, you don't quite have an amplifier you can use on the air, but you do have an education. Congratulations, you are an amplifier designer!

#### Notes

<sup>1</sup>W. Hayward, W7ZOI, R. Campbell, KK7B, and B. Larkin, W7PUA, *Experimental Methods in RF Design*. Available from your ARRL dealer or the ARRL Bookstore, ARRL order no. 8799. Telephone 860-594-0355, or toll-free in the US 888-277-5289; [www.arrl.org/shop](http://www.arrl.org/shop); [pubsales@arrl.org](mailto:pubsales@arrl.org).

<sup>2</sup>See Note 1, pp 4-27, 4-28

<sup>3</sup>*The ARRL Handbook for Radio Communications*, 2009 Edition. Available from your ARRL dealer or the ARRL Bookstore, ARRL order no. 0261 (Hardcover 0292). Telephone 860-594-0355, or toll-free in the US 888-277-5289; [www.arrl.org/shop](http://www.arrl.org/shop); [pubsales@arrl.org](mailto:pubsales@arrl.org).

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