Brass Tacks

An in-depth look at a radio-related topic

How vacuum tubes work

You might find the topic of vacuum tubes a little antiquated, if not irrelevant, to most ham radio discussions we have today, and understandably so. Tubes have, for the most part, been made obsolete by smaller, less expensive, cooler, more efficient, and more reliable components in today's electronic equipment. Yet, due to curiosity, nostalgia, or the sheer desire to understand the original or older technology, more and more hams are still asking about it.

They've played a vital role in amateur radio history, after all. Furthermore, the fact that a few questions regarding vacuum tubes remain in the Amateur Extra exam pool only adds to the mystery. So, for those who really want to know, I've decided to try and help you understand the technology behind how these components work. But I caution you: this material can get a little deep and dry, so I'll try and make it as engaging as I could. And to make it a tiny bit interesting, I've decided to take a slightly historical approach, rather than a purely technical one, to explain some of the secrets behind these little, glowing bottles.

A bit of history

In 1880 Thomas Edison arguably discovered that a voltage placed across two pieces of metal, one much hotter than the other, will cause charged particles (later called *electrons*) to jump from the hotter metal to the cooler metal if the cooler metal has a positive voltage compared with that of the hotter metal, placed across them. He thought this was a pretty neat experiment, yet saw no real practical benefit from it, but patented his findings anyway, as was his way with just about every one of his experimental conclusions. Edison soon discovered that the hot metals oxidized at the temperatures that successfully "boiled off" the electrons this way, and so had to maintain the environment in a glass-sealed vacuum.

In 1904 English physicist and experimenter John Ambrose Fleming demonstrated that the *Edison Effect*, as it was later called, could be used to convert AC to DC, since it allowed current flow in one direction. And by convention (no thanks to Benjamin Franklin), that direction is opposite the flow of electrons. Then, following another convention established by Michael Faraday a few years previous, Fleming called the conductor that emits the electrons the *cathode* (meaning *the way downward*), and the other the *anode* (*opposite the way downward*.) And because the whole device presents two electrodes, he named it a *diode*.

The diode was revolutionary, because resorting to mechanical or other unreliable means of converting AC to DC was no longer necessary. Nor was it required to employ huge batteries to provide the needed DC current.

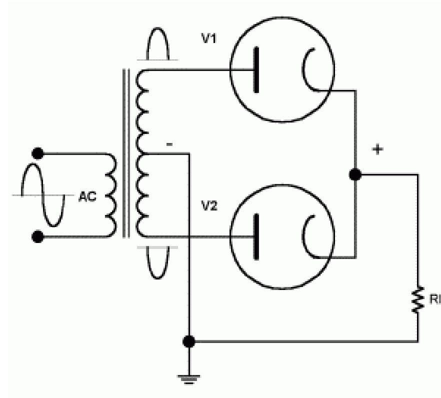
Rectification

If you examine the schematic diagram on the next page, you can see how two diode tubes can be used to convert AC to DC, using a transformer with a center tap. Remembering that current can only flow inside the tube from the anode to the cathode (because current flow is opposite electron flow), each time the AC current from the transformer runs positive, it flows through the top tube, but not the bottom one. Then, when the AC current becomes negative, it flows

Brass Tacks

continued

through the bottom tube, but not the top. The resulting current will therefore only be positive, and we call this *rectification*, meaning to *correct* or *make positive*. The output voltage is then smoothed out by *filtering*, to make it almost truly DC. This very configuration was used in numerous power supplies for decades, as the primary method of obtaining DC power from an AC source.



Full-wave diode rectifier

Early problems

One problem encountered with earlier tubes is that they required 250 to 400 volts across the anode and cathode to even start the electron migration, and make the tube function. Furthermore, to provide an even more efficient electron source, the heated filament, acting as the cathode, was coiled into a helix to present more surface area, which required increased power to heat it to the necessary high temperature. So, tubes generated quite a lot of heat, requiring good ventilation.

And because of the elevated filament temperature, even a little Oxygen or Nitrogen inside the presumed vacuum can shorten tube life dramatically. As a result, tube manufacturers installed *getters*, pasted deposits (the characteristic shiny metallic blotch seen inside the tops of the glass) or metal halos of reactive material that absorb air molecules when heated. You can sometimes tell a broken tube by the getter having turned a powdery white.

Amplification

In 1906 American inventor Lee de Forest experimented with modifying the flow of electrons flying from the cathode to the anode, which caused the anode voltage to vary accordingly. To confirm this effect, he introduced a third electrode to the diode tube, attached to an internal grid of wires placed between the cathode and anode. He then observed that the voltage at the anode changed proportionally with the changes he introduced at this third electrode. And because the anode voltage was large compared with the small voltage on this control grid, the output at the anode was simply a larger voltage version of the grid voltage, regardless what waveform he presented at the grid, and the electronic tube *amplifier* was born.

This new device, called a *triode*, helped propel the electronic industry into a new age of radio and audio engineering. Within just a few years, the vacuum tube triode could be found nearly everywhere there was an electronics need. But soon it was discovered that the amplification came at a price, in the form of an unmistakable hum in the amplified audio.

It turned out that the AC frequency powering the filament acting as the cathode, was transferred through the filament to the output. So, a modification allowed indirect heating of the cathode by isolating the filament circuit from the cathode, which in turn required more energy and more time for the tube to warm up, but de-coupled the AC hum from the audio signal.

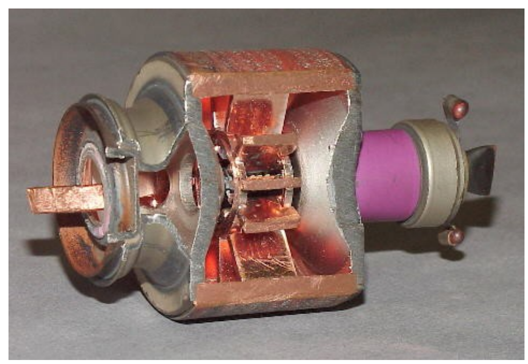
Brass Tacks

continued

As more anomalies with the triode became apparent, a solution by way of another grid was introduced in the *tetrode*, which greatly increased gain and helped screen, or isolate, the input and output signals, and so was named the *screen grid*. But the screen grid added an undesirable effect of its own, and a third grid, the *suppressor grid*, was introduced in the *pentode* to remove the effect. After that, many new tubes were developed, but just about all subsequent vacuum tubes were designed from one of these types, especially the pentode.

Specialized tubes also began to spring up for many applications. One such tube that found its way just about everywhere was the CRT, or *cathode-ray tube*, so-called because inside the tube the cathode emitted an electron "ray" toward the anode, which was a phosphorescent screen. Among many other appliances, CRTs were used in television sets, computer monitors, and oscilloscopes. Another specialized tube still in use today is the X-ray tube. Yet another is the magnetron, used for radar. A similar one is used in today's microwave ovens.

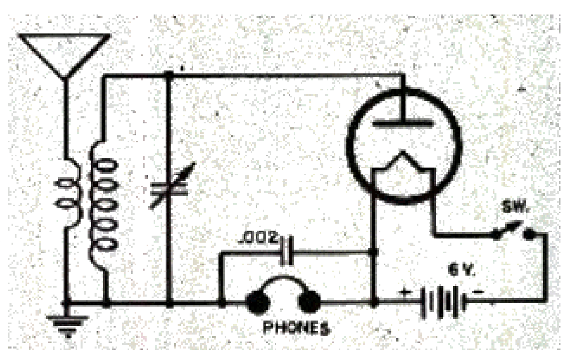
Television cathode-ray tube



Radar magnetron

Detection / demodulation

As mentioned, vacuum tubes became integral to the design of amplifiers in a variety of circuits that needed them. But for amateur radio they were also key components in *oscillators*, *mixers*, and *detectors*. For example, the schematic diagram below shows a rather simplified AM radio signal detector (*demodulator*) made from a single tube diode. The radio signal is introduced to the circuit by a *monopole* antenna (dipole with one pole in the air and the other in the ground), with the two separated by an inductor coil in an air-core transformer. The variable capacitor and inductor *resonate* at a radio frequency (RF) selected by the capacitor, creating a *tuned circuit* at that frequency, meaning all the radio signals except the ones at that frequency will be filtered out.



Simple diode AM detector circuit

Brass Tacks

continued

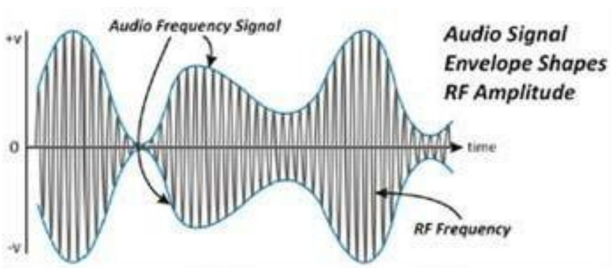


Figure 1— incoming RF (AM) signal

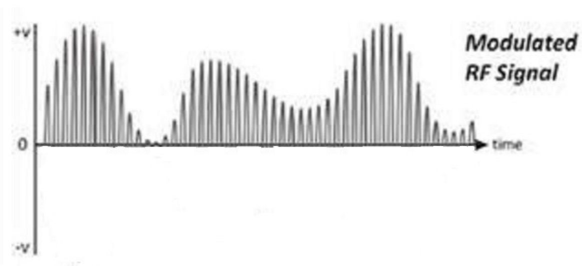


Figure 2 — incoming signal rectified

The resulting signal across the variable capacitor will appear like the AM waveform in Figure 1. Once the switch in the circuit is turned on, the battery will heat the tube filament, which will start sending electrons to the plate. In this diode configuration, only the positive signals of the RF waveform will go through the tube from the plate to the filament, resulting in the rectified waveform in Figure 2, which will appear across the headphones.

The purpose of the fixed capacitor is to filter out the RF portion of the signal, so that every time after the RF signal reaches a peak, instead of falling back to zero, it falls at a rate of RC, which is much slower. By the time this signal has fallen even a tiny amount, the next rise in the RF signal brings it back to the peak again. What you hear in the headphones, then, is close to the envelope of the RF waveform, which is the original unmodulated audio of Figure 3.

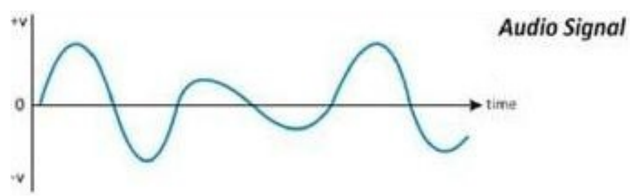


Figure 3— output audio signal

The vacuum tube today

Before you completely scrap the vacuum tube for being obsolete or old-school, you might be surprised to learn that tubes can still be found in many modern audio (think guitar) as well as amateur radio amplifiers. Some specialized devices, like radar, X-ray machines, high-powered broadcast radio transmitters, and microwave ovens, still rely on vacuum tubes to perform their magic.

As transistor and other solid-state amplification solutions improve, the vacuum tube might one day become a thing of the past. Still, tubes tend to be more immune to electrostatic discharge, power surges, and electromagnetic pulse, than solid-state electronics, so their future remains to be seen. But when I see them in action, they still give me a warm glow.

— Noji Ratzlaff, KNØJI (kn0ji@arrl.net)