Valves Revisited

by

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(Low Resolution Sample)

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Contents

Evolution of the Valve

T HE VALVE WAS BORN out of an ordinary lamp. In fact, for a while, a valve was called "lamp" or "bulb". Sir John Ambrose Fleming (1849 - 1945) found that lamps (which at the time had a carbon filament) deposited a dark layer on the inside of the bulb. He wanted to find out how and why. He inserted a metallic electrode inside the bulb. What he found was that electrons could be captured by the new electrode if it was connected to a positive voltage in relation to the filament. He found a current flow through the lamp. One of Fleming's valves is shown in **Fig 1**.

The filament was given the name 'cathode' and the new electrode 'anode'. These are names that have survived even until today. The diode was used already before Fleming's patent as a detector of radio waves in experiments carried out in Fleming's lab.

Valves can be directly or indirectly heated or of the cold cathode type, depending on how/if they are heated. In a directly heated valve, the filament doubles as the cathode (like in Fleming's lamp and in more recent battery powered valves). The filament is coated with an agent that easily emits electrons when heated. The drawback is that directly heated valves must be powered by a DC source to avoid hum entering the signal path. So, the indirectly heated valve was developed, where the cathode is a cylinder that surrounds the filament which heats it. The principle reduces filament hum considerably. These days most valves are indirectly heated.

The American Lee de Forest (1873 - 1961) added in 1906 yet another electrode to Fleming's valve - a grid shaped structure, which he placed between the anode and the cathode. This became what now is known as a triode. De Forest called it the 'audion'. It was patented in 1907. A gadget was born which could rectify, amplify and oscillate.
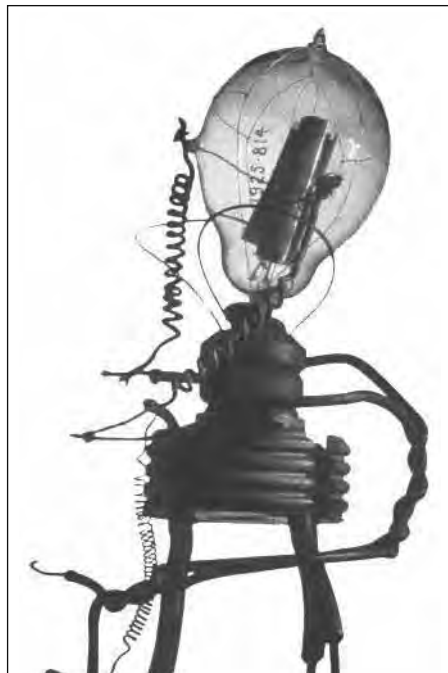
Fig 1: One of Fleming's valves

Fig 2: Restored 1941 Canadian General Electric KL-500 4-band radio *[source: Wikipedia]*

Radio Receivers

All valves were directly heated in the very beginning. The shortcomings of the triode (see below) caused the receivers of those days to be insensitive and their selectivity was bad. Various tricks were invented to overcome those shortcomings and to make radio receivers more efficient. Positive feedback was implemented to increase selectivity and sensitivity. However, a stage with positive feedback increases the noise level. Positive feedback (reaction) played an extremely important role in radio reception in the 1920s and early 1930s. It was the only way in which a receiver could be built with sufficient selectivity and sensitivity. All domestic radios in those days were fitted with some sort of reaction. The degree of reaction could be set with a control on the front panel. In advanced radios, more than one stage had a reaction control. In addition, the tuned circuits, often more than one, had to be tuned to the frequency of interest. Then there were volume controls, band switches, and what have you. Several aerial (antenna) inputs allowed you to choose the best one for reception. The set needed to be properly grounded too. Listening to the radio in those days was a task for the technically-minded.

Receivers designed during the 'golden age' of valve technology, the 1960s, use completely different techniques.

The so called reflex coupling was invented to save the number of (then expensive) valves in a receiver. The principle is that one valve could be used for both RF and AF amplification, so, after detection, AF was channelled back to the beginning of the chain of valves and then separated at the end. However, making the receiver stable could be a problem, because of residual RF.

One or more tuned circuits were added to improve selectivity. This meant in the early days of radio that the front panel could contain a host of controls and

the receiver therefore became more difficult to operate. Most of the controls had to do with the tuning of the receiver. Few, if any, ganged variable capacitors were available, so each filter had to be provided with a separate control.

Another control worth mentioning was the volume control. It was a rheostat - a wire wound potentiometer for high currents - which was connected into the heater chain so that the heater current could be controlled, and thence the temperature of the cathode, the cathode emission, and therefore the volume. These days this method of volume control is not recommended since modern valves are designed to work within a fairly narrow band of heater voltages and temperatures and may be damaged if made to work outside their working range.

In the beginning, all receivers were battery powered, and in most cases an accumulator provided the filament current. This meant that the receiver was big and heavy. The loudspeaker was frequently a separate unit, and sometimes there was also sometimes a frame aerial incorporated into the box.

A receiver from the 1920s was, however, a beautiful creation - a black or wood coloured box. The front panel had big knobs, graded 1 - 100. Sometimes the valves were mounted on the panel too, so you could see them glow. There was also frequently a lid or a 'service door' to allow for servicing. Some radios were built such that the chassis could slide in and out of the box.

Valves for battery power are directly heated. They start immediately to function, just like the transistor radio. 45V or 90V anode battery was standard, but other anode voltages were also common. As a matter of fact, a car radio was made where the valves were powered with 12V anode voltage. In some cases, bias voltages were taken from taps in the array of battery cells that constituted the high voltage source.

It is not surprising to learn that people build valve-based electronics. It is more surprising to learn that people are actually making home-made functioning valves even today.

Valve Evolution

The invention of the thermionic valve is ascribed to Fleming. However, Thomas Alva Edison (1847 - 1931) was the real inventor. Other scientists, too, studied the phenomenon of electron emission in a vacuum, such as Eugen Goldstein, Nikola Tesla and Johann Wilhelm Hittorf. Edison couldn't find any applications for the valve, so he didn't bother to patent it. Fleming invented the Kenotron diode in 1904. The actual design of the original valve is better shown in **Fig 3** which comes from Fleming's patent application.

The valve has since then been developed and refined, and development is still going on.

Despite popular belief, the valve is still alive and kicking, even though it has gone through some major changes. Today it is perhaps most often used in audio amplifiers in expensive and exclusive equipment (according to some people, semiconductors have no right to exist in audio amplifiers - not even in the power supply). This is true for RF valves too. A valve amplifier gives its owner high status, and, in certain circles, a valve amplifier is the only possible option.
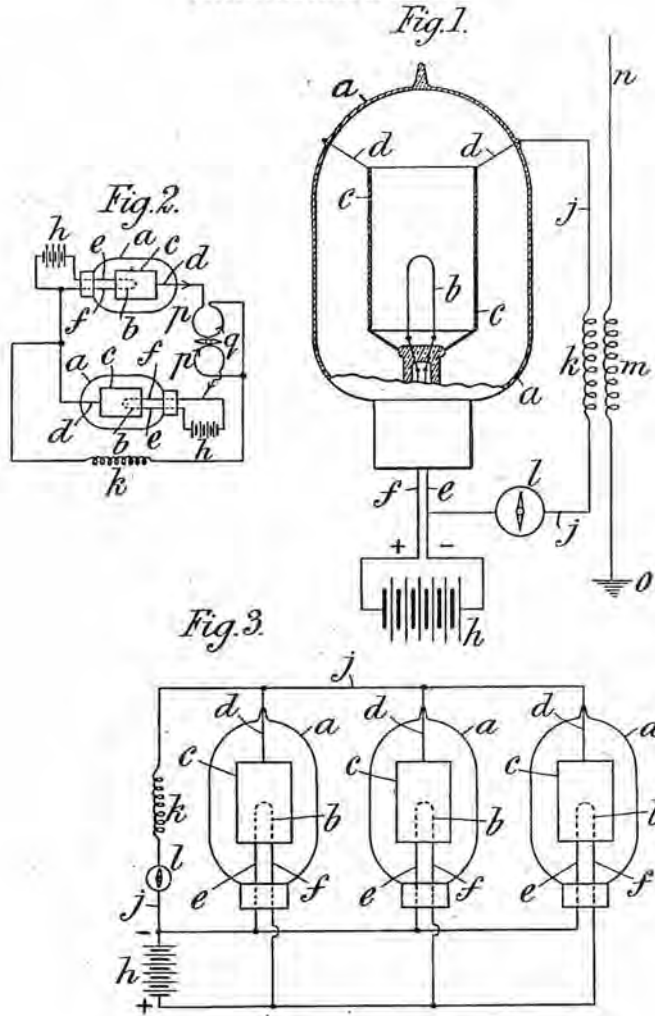
However, many people are also interested in valves for radio reception and measurement instruments, and this is mainly what this book is all about.

Fig 3: Extract from Fleming's patent application
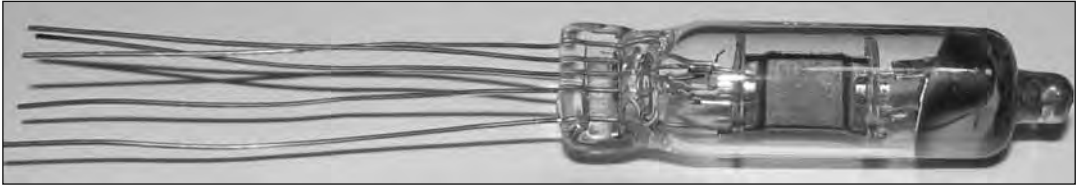
Miniaturising

Already in the 1940s, the valve designers began to feel the need to make smaller valves. They designed miniature and sub-miniature valves. One of the battery powered sub-miniature triodes that were made is the DC70, and a variety of pentodes were also made. Additionally, power pentodes were made that could be used as power amplifiers in transmitters, in receivers and in hearing aids. Their small size made it possible to reduce the inner capacitances of the valve, thereby increasing their usefulness in RF applications. Low anode voltages could be used. They made excellent service in hearing aids and this is perhaps the best known application, even though commercial radio receivers were built using sub-miniature valves (see **Fig 4**). The valve is pen shaped, about 4cm long and 10mm in diameter. They are soldered in place, and the leads are 4cm long.

Yet another miniature valve was launched in 1959: the nuvistor. This is an even smaller creation, with a metal body on top of a ceramic base, as opposed to the glass bottle that housed sub-miniature valves. They were more difficult to manufacture (they were built by robots in vacuum) but are capable of even better performance than the sub-miniature valve. Even lower anode voltage and internal capacitances make them an excellent choice for wideband amplifiers and were included into Tektronix oscilloscopes. They were manufactured as triodes and tetrodes.

A nuvistor is also tube shaped and measures about 2cm by 1cm diameter. They are mounted in special holders as shown in **Fig 5**. The valve itself is shown in **Fig 6**.

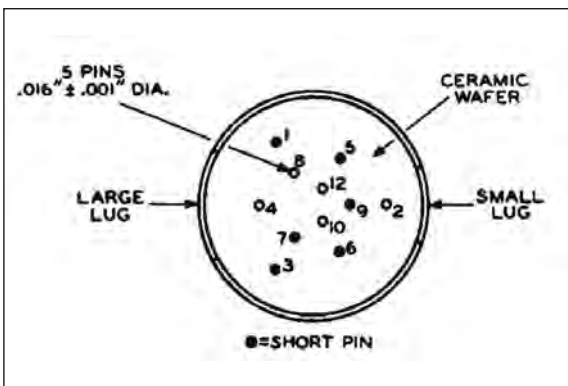Both nuvistors, nuvistor holders and sub-miniature valves can still be purchased at a decent price.

Fig 5: The 6CW4 socket

Fig 6: Nuvistor 6CW4

Fig 7: An acorn valve shown alongside a transistor [source: Wikipedia]
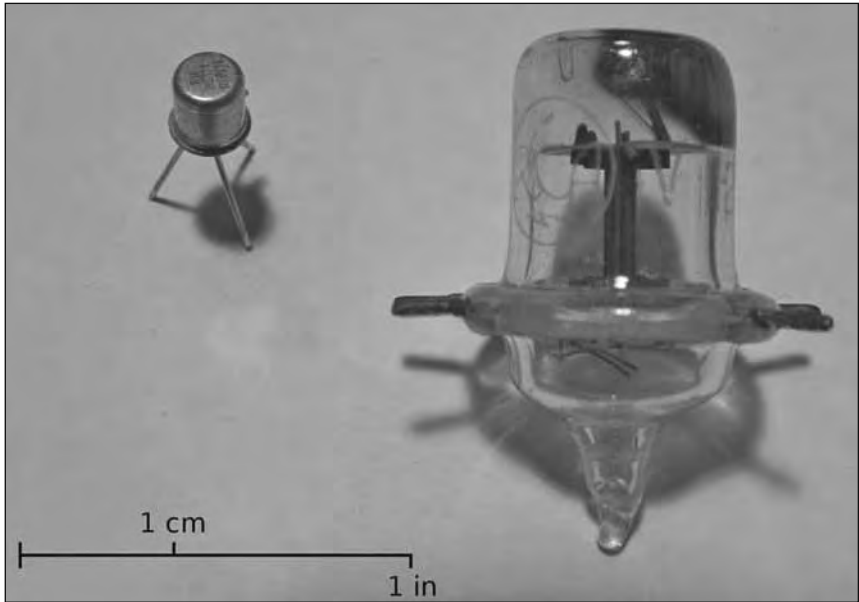

Fig 8: A Nixie valve

The need for higher frequencies and better performance necessitated development of valves with a somewhat different set of connections. **Fig 7** shows an acorn valve. Note that the electrodes are pulled out the side of the valve for lower inter-electrode capacitances.

The acorn valve was developed during the mid 1930s as an answer to the need for higher frequencies. They could handle frequencies up to 400MHz. It doesn't sound much today, but in those days, the number was mind-boggling.

They were made as triodes and pentodes, and there is actually nothing particular about the way they were used, except for the high frequency capability and the requirements that followed.

The list of special valves could be made a lot longer. Higher power handling capabilities was also included in the wish list. Air and water cooled transmitter valves were developed, valves that could display digits ('Nixie valves', **Fig 8**) for instruments such as frequency counters etc, tuning indicators, television screens, and a wide range of other valves came on the market.

So, How Does a Valve Work?

L ET US BEGIN BY LOOKING at a directly heated diode, which is the simplest valve. At the centre of a thermionic diode is a filament which is heated when a voltage is applied to it. Surrounding the filament is a cylinder. When the filament is heated, it begins to emit electrons which gather as a cloud around the filament. They have nowhere to go, though. As you know, equal charges repel each other and different charges attract each other. Without anode voltage, though, there is no charge to attract the electrons, as shown in **Fig 9**. This cloud is called 'space charge'. **Fig 10** shows what happens when a voltage is connected between anode and filament/cathode.

Indirectly heated valves still require heat, so at the centre of those we will still find a filament. Around the filament, however, but inside the anode, there is another cylinder. This is the cathode. The surface of the cathode has a thin layer of material that easily emits electrons when heated. In an indirectly heated valve, the filament is usually powered by AC. If you connect an AC voltage to
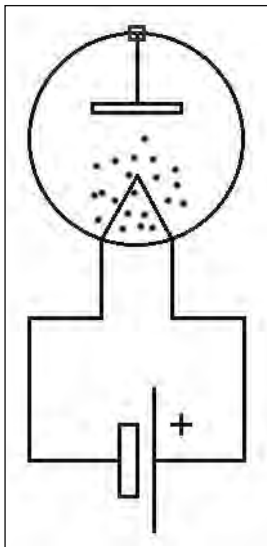
Fig 9: Directly heated diode
**Fig 10: The anode is connected and a current flows.**
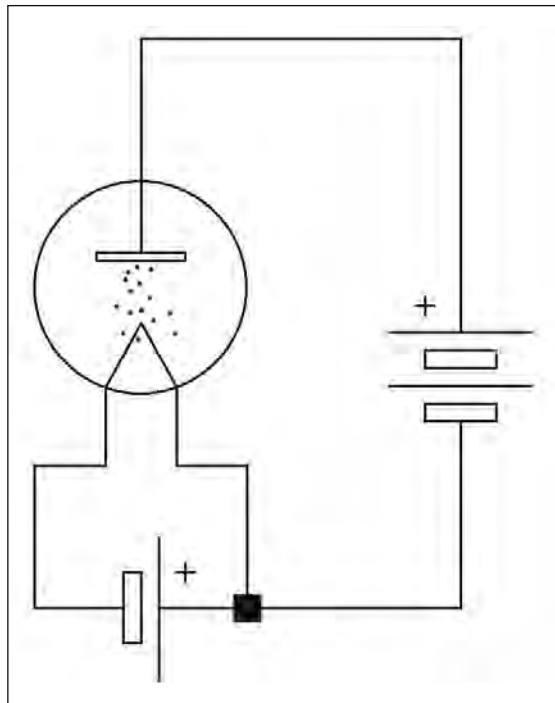
the filament of a directly heated valve, hum from the filament is added to the current through the valve. The advantage of an indirectly heated valve is that it reduces the hum from the filament to a minimum.

Then we connect a positive voltage to the anode and the negative side to the filament. The electrons then begin to move. They feel the positive field from the anode and move towards it. We get a current through the diode. According to conventions, the current flows from the anode to the cathode. This is because of a misunderstanding during the childhood of electronics which has remained until today. In reality, the electrons move from the filament (or cathode) to the anode.

The actual voltage at the anode doesn't matter - there is still a current flowing. However, the polarity does matter. If you connect the positive pole of the battery to the filament and the negative pole to the anode, the current flow stops. So, we have a rectifier.

The Diode

Fig 11 shows the symbolic representation of a semiconductor diode (Note that 'di' = two), and an actual component is illustrated in **Fig 12**.
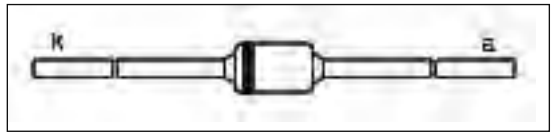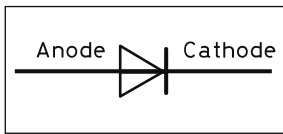
Fig 11: Symbol for a semiconductor diode

Fig 12: Actual implementation of a semiconductor diode

The valve symbol is shown in **Fig 13**, and looks like that shown in **Fig 14** in real life. The valve diode is bigger and has more connection pins. That makes it more awkward to connect. The EAA91 has two independent diodes in the same glass envelope and a seven-pin base.

The screen between the halves, and the fact that they have separate cathodes, enables the diodes to be used in quite different places in a radio without affecting each other's performance. See **Table 1** for a summary.
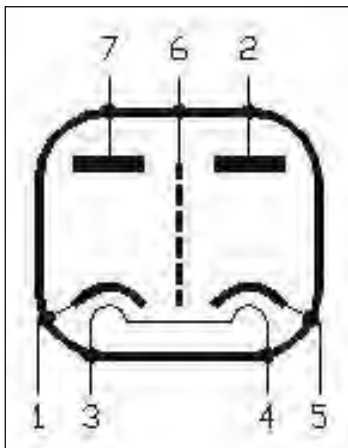
(left) Fig 13: Symbol for two diodes within the same valve (EB91)

(right) Fig 14: The EAA91, a practical implementation of a dual diode. The fingers holding the valve illustrate its size

> ### *Fact Sheet - Diode*
> **Applications:** Detection, rectification
> **Internal capacitances:** Varies

Table 1: Diode fact sheet

If we begin by looking at the valve symbol (most people these days probably recognise the semiconductor symbol), we find that the anodes are drawn at the top (pins 2 and 7). Pin 6 is connected to the screen between the two diodes to reduce the influence between them as much as possible. Pins 1 and 5 are the cathodes, and 3 and 4 are connected to each end of the filament.

The semiconductor diode is undoubtedly the most common diode these days. However, let us take a closer look at the differences between the semiconductor diode and the valve diode. I will use the 1N4148 and EAA91 for comparison, since both are small signal diodes and are frequently used as signal detectors.

Looking at the curves for the two, **Fig 15** in the valve case and **Fig 16** for semiconductor diodes, we find a number of significant differences:

1. The EAA91 curve passes through zero. This means that when the forward voltage across the diode is zero, the current is zero. This is not the case of the semiconductor diode, where the current remains zero until the voltage across the diode is about 0.6V. This means in turn that the semiconductor diode is not very well suited for small signals, which is the case with the valve diode.
2. The semiconductor diode is strongly temperature dependent, as opposed to the valve diode.
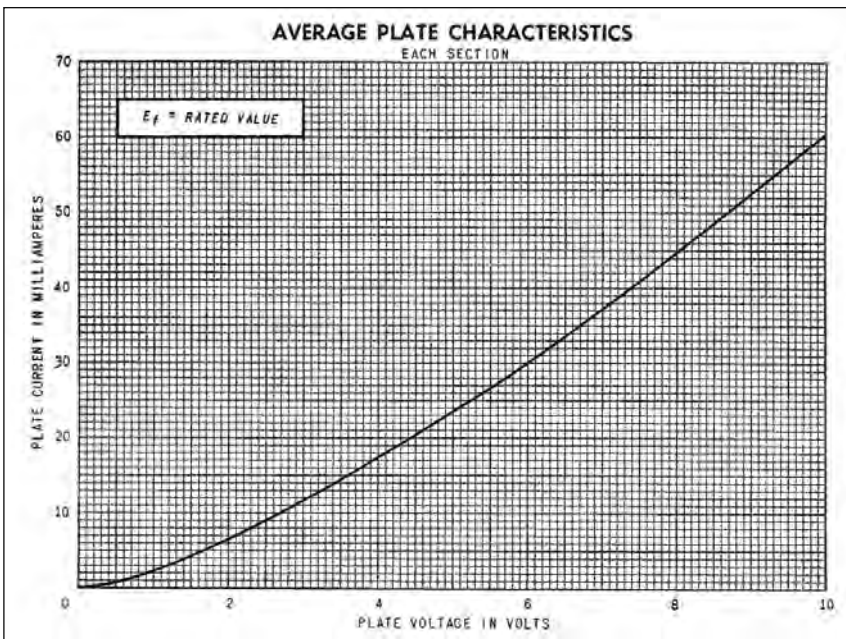
Fig 15: Transfer function for the EAA91 valve

3. The lower part of the semiconductor curve has a bend, which causes distortion. Even though the valve diode has a bend too, it is not as prominent as that of the semiconductor.
4. The semiconductor can handle higher current.
5. The valve diode can handle higher voltages.

Fig 16: Transfer function of the 1N4148 semiconductor
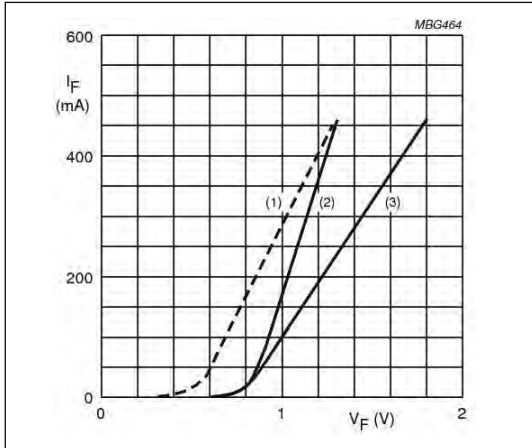
The anode voltage (Va) is shown along the X-axis, and the anode current along the Y-axis. To determine the anode current for a specific anode voltage, first find the anode voltage along the X-axis.

Then follow the grid lines upwards until you meet the curve. A horizontal line to the left from that point gives you the anode current.

The Triode

The triode (tri = three) was invented by the American Lee de Forest (1873-1961), who called it the 'audion'. It is shown in **Fig 17**. A modification of the audion became what we now know as the triode.

What happened when another electrode was placed inside the valve between the cathode and the anode? Well, it turned out that varying the voltage (in relation to the cathode) of the third electrode made it capable of varying the current through the valve, as long as the third electrode was negative in relation to the
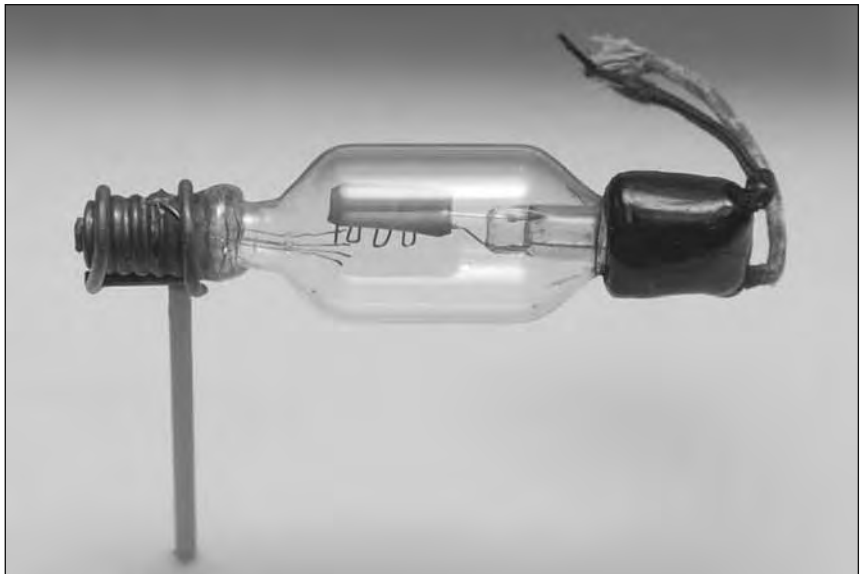
Fig 17: de Forest's audion, 1903

cathode (or filament). The third electrode didn't draw any current. It turned out that the most efficient shape for the electrode was a grid. so it was named the 'grid'. Since this electrode controls the current through the valve, it was called the 'control grid' (or G1). A symbolic representation of a dual triode is shown in **Fig 18**.

Fig 18: Symbol and connections for a dual triode (ECC82)

Eventually, more and more grids were added, for different reasons. We shall take a look at most of them later.
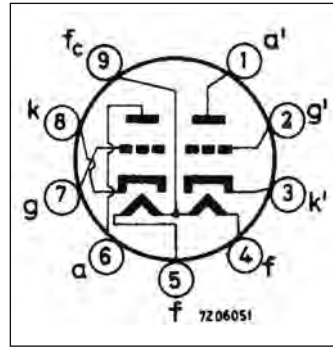
A triode has the following qualities:

- Low internally generated noise.
- Relatively low amplification. The amplification factor depends on the anode voltage.
- Relatively low anode impedance.
- Relatively high capacitances between its electrodes. UHF amplifiers often need to be neutralised.

The fact is that a triode works against itself. The anode current increases as the voltage at the grid becomes less negative. This current needs to be converted to a voltage in preparation for the input of the next stage. A common way of doing this is to connect a resistor between the anode and the power supply. The increased current causes the voltage drop across the anode resistor to increase. The voltage drop subtracts from the power supply voltage, causing the anode voltage to decrease. The amplification of the stage decreases as the anode voltage decreases. This effect limits the possible amplification you can get from a triode.

Fig 19: Ia / Vg-curve for a triode (ECC83)

There are methods of getting around the drawbacks (the three last points above), and we will take a closer look at them. It is the first quality - the low noise - that makes triodes so useful in various applications. Noise in various valves is dealt with later.

Under certain circumstances, the inter-electrode capacitances of a triode result in a phase relationship and a coupling between input and output which can cause the stage to oscillate. This can be corrected by neutralisation.

Neutralisation is done by 'compensating away' the internal capacitances with an external capacitor or an inductance. By varying the capacitance or inductance, the phase relationship is also varied so that the stage stops oscillating. This made it a bit more complicated to build stages with single grounded cathode triodes for higher frequencies. Other solutions, as we shall see, addressed the problem in different ways (see the sections about RF and IF amplifiers).

> ### *Fact Sheet - Triode*
>
> **Applications:** Detection, amplification
> **Internal capacitances:** High
> **Amplification factor:** Medium
> **Anode resistance:** Medium
> **Benefits:** Low noise
> **Drawbacks:** Amplification dependent on anode voltage.

Table 2: Triode fact sheet

The dependence between amplification and anode voltage can be seen in the curves of **Fig 19**. Here you can clearly see that the slope of the curve varies with varying anode voltage. The higher the anode voltage, the steeper the slope. In other words, the higher the voltage, the higher the amplification. The same thing is shown in the table of typical values in the data sheet. At 100V anode voltage, the transconductance (amplification factor) is 1.25mA/V, and at 250V it is 1.6mA/V. **Table 2** gives a summary of triodes.
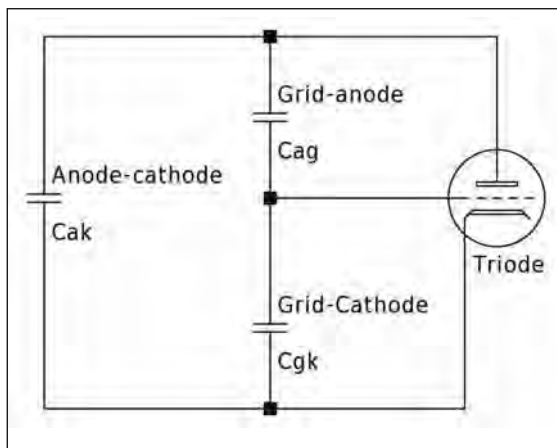
One interesting triode that was designed when car radios became more common is the ECC86. It is specified for anode voltages up to 25V, and is designed to run directly off a car battery, 12V or 6V.

Valve Capacitances

A capacitor consists of two isolated metallic objects, separated by a dielectric. A valve contains metallic objects, the cathode, the grid and the anode. Due to their metallic nature, they form capacitances. In a triode, the most important capacitances are the ones between the anode and the grid, and between grid and cathode. Additionally, there is one between the anode and the cathode. The most important one of these is the grid-anode capacitance. The inter-electrode capacitances in a triode are all in the order of one or two picofarads.

Miller Effect

The Miller Effect (discovered and described by the American John Milton Miller in 1920) causes the input capacitance to increase by the amplification of the stage. The capacitances can reach such magnitudes as to affect the bandwidth of the stage even in AF applications. So, a countermeasure would be to decrease the amplification of the stage. Also the stray capacitances (illustrated in **Fig 20**) of the stage are subject to the Miller effect.

Fig 20: The internal capacitances of a triode

Other countermeasures would be to:

- decrease the output impedance of the previous stage
- connect a couple of triodes in a cascode or cathode coupled configuration

A wider consequence is that valves for RF applications have to be built with smallest possible input capacitances. An RF stage also needs the smallest possible stray capacitances.

The increase in input capacitance is given by:

$C_M = C * (1 - AV)$

where AV is the voltage gain of the amplifier and C is the feedback capacitance.

The Tetrode

In order to reduce the capacitance between the grid and the anode, a fourth electrode was inserted (tetra = four), as shown in **Fig 21**, by Walter Hermann Schottky (1886 - 1976).

This new electrode is another grid, called the 'screen grid'. As we all know, connecting two capacitors in series yields a total capacitance smaller than the smallest one of the two.
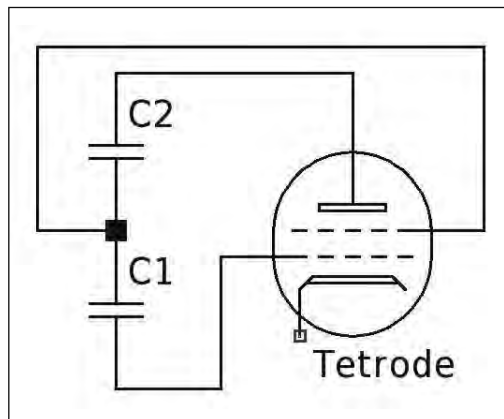
Fig 21: Grid-anode capacitances of a tetrode

In this case, the grid-anode capacitance is made up of the two capacitances C1 and C2.

Secondary Emission

Secondary emission is a phenomenon which occurs when an electron from the cathode strikes the anode. The electrons travel through a valve at high speed, and it is inevitable that each electron hits an atom and knocks one or more electrons from the atom.

Those 'secondary' electrons form a cloud near the anode. In a triode, the secondary emission is not important, because the anode is the electrode with the highest positive voltage, much higher than the cathode and control grid. All secondary electrons are pulled back to the anode.

The situation is different in a valve with a screen grid. Because the voltage of the screen grid is slightly below or equal to that of the anode, not all of the secondary electrons will be pulled back to the anode.

Some of them travel to the screen grid instead. As a result, the screen grid current increases, and the anode current decreases. This will cause distortion of the signal.

A tetrode has a higher output impedance than a triode. Additionally, the tetrode has a higher amplification and the anode current (and thereby the amplification) dependency on the anode voltage is nearly eliminated.

Fig 22: Ia / Va curve for a tetrode (RENS1204)
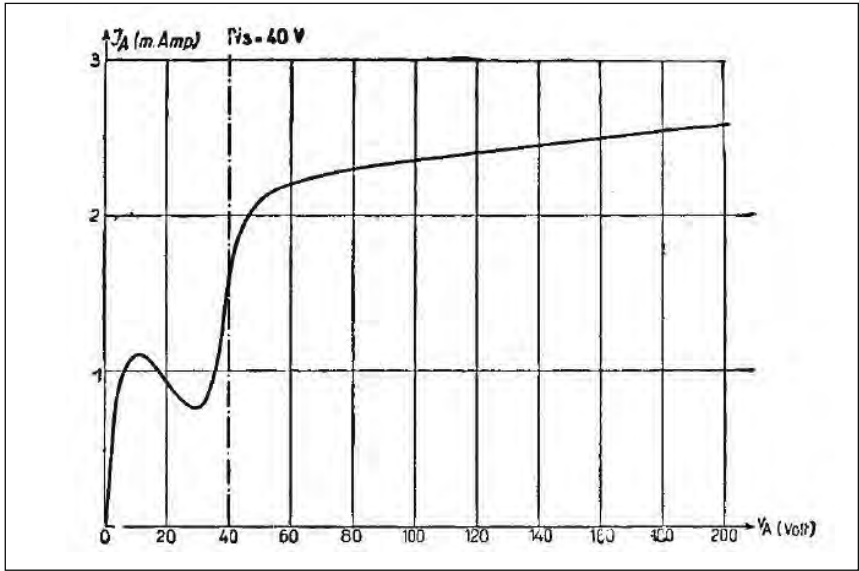
However, a tetrode does have shortcomings. At low anode voltages, the tetrode becomes unstable. This can be deduced from the curve in **Fig 22**.

The curve shows the relation between the anode voltage and anode current at a fixed control grid voltage. Compare this curve to **Fig 23**, the corresponding curves for a triode. The curve is nearly horizontal at anode voltages above about 40V for the tetrode. In other words, the tetrode's anode current is nearly independent on the anode voltage. In the triode, however, the anode current depends heavily on the anode voltage.

Also, some of the electrons from the cathode end up being absorbed by the screen grid, which causes a grid current to flow. The cathode current is consequently equal to the sum of the anode current and the screen grid current.
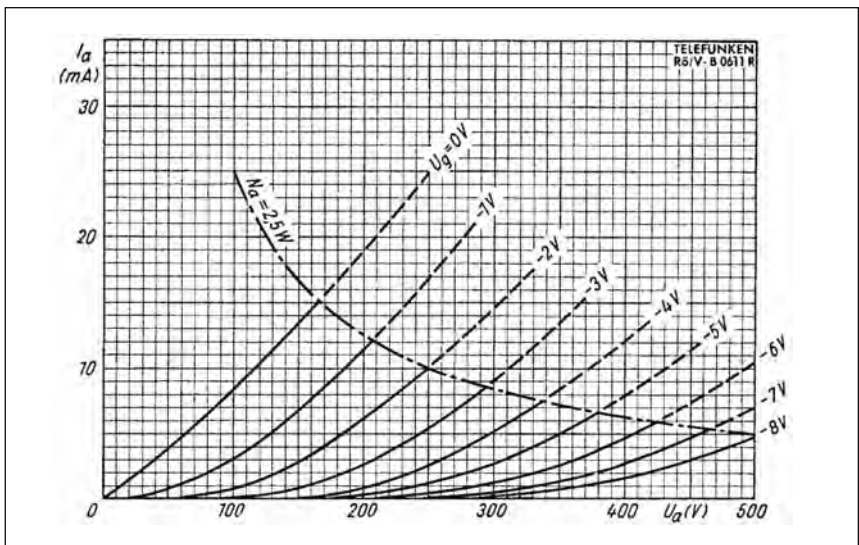

Fig 23: Ia / Va curves for a triode (ECC81)

Another consequence of this is that the internal noise of a tetrode is higher than that of a triode.

Since the stability of a tetrode depends on the stability of the screen grid voltage, the screen grid has to be properly decoupled.

The best known tetrode among radio amateurs would be the legendary 807, shown in **Fig 24**. It was mainly used as the power amplifier in transmitters. These days many people design an 807 into their power amplifiers in audio equipment. Its base connections are shown in **Fig 25**.

As you can see from the tetrode curve, the anode current decreases between 10V and 30V anode voltage. This constitutes a negative resistance which causes instability. Tetrodes other than the one shown in the curve have this area at higher anode voltages, eg between 50V and 150V.

The fact sheet shown in **Table 3** summarises tetrodes.

One method of coping with the problem (without really solving it completely) was to insert a 'box' of metal between the screen grid and the anode.

The box had two slits through which the electrons could pass on to the anode. The box was internally connected to the cathode. However, one of the best solutions turned out to be inserting yet another grid in place of the box. The Pentode was born.
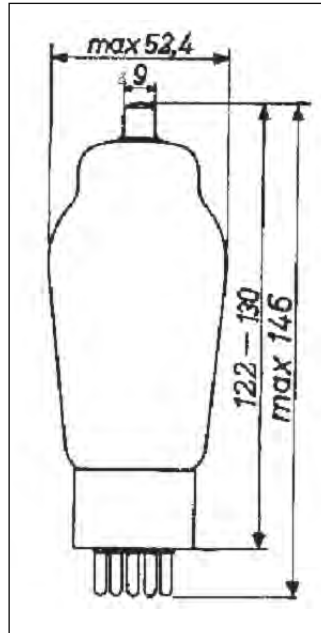
Fig 24: Power tetrode 807
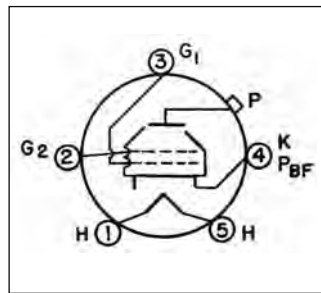
Fig 25: The tetrode symbol and its pin connections

Fact Sheet - Tetrode

Applications: Generally power amplification
Internal capacitances: Medium
Amplification factor: High
Anode resistance: High
Benefits: Amplification independent of anode voltage
Drawbacks: Tendency to instability, 'kink' in curve

Table 3: Tetrode fact sheet

The Pentode

The pentode (penta = five) was invented by the Dutchman Bernard D H Tellegen (1900 - 1990). **Fig 26** show its curves. The pentode has the advantages of the tetrode, but lacks the negative resistance area. Therefore, the pentode is more stable than the tetrode. The inserted grid is called 'suppressor grid'. In some

Tuned Circuits

V IRTUALLY EVERY RECEIVER or transmitter, however simple or complicated, must contain a number of coils. Generally speaking, the more advanced the equipment, the more coils. This is the motivation for mentioning coils and how to make them.

Winding Coils

Winding coils is not very complicated. It requires a bit of calculation before getting started, though. There is an enormous amount of documentation on coils, and those who are into crystal receivers know a lot about coils and how to make them.

The unit Henry is a measure of the inductance of the coil (from the American scientist Joseph Henry, 1797-1878). In radio frequency (RF) applications, the unit is frequently microhenries (µH) for coils, whereas chokes are in the order of millihenries (mH).

A few general pointers:
- The larger the diameter, the more Henries (although less Q)
- The shorter the coil, the more Henries
- The more turns, the more Henries
- A coil should be at least as long as its diameter.

One formula (Formula 10) for calculating the inductance of a cylindrical single layer coil is:

$$L = \frac{r^2 \times N^2}{(228 \times r + 254 \times l)} \qquad \textit{Formula 10}$$

where:
L is the inductance in µH
l is the length of the winding in mm
r is the radius of the coil in mm
N is the number of turns.

Separating the turns decreases the inductance. Inserting a ferrous core increases the inductance (and the Q). Inserting a brass core decreases the inductance.

There are other formulae for calculating the inductance of other types of coils.

Q of a Coil

Q is a measure of the quality of the coil and is determined by:

- The frequency at which the coil is to be used
- The length of the wire
- The diameter of the wire
- The material of the wire
- The impedances of the circuits connected to the coil

Q has no unit, but it can be calculated. One way is shown in Formula 11:

$$Q = \frac{X_L}{R + r} \qquad \textbf{\textit{Formula 11}}$$

where:
X_L is the reactance of the coil at the given frequency
R is the ohmic resistance of the coil and
r is the equivalent resistance as a consequence of the skin effect (see below).

Another way of calculating Q is given in Formula 12:

$$Q = \frac{f}{BW} \qquad \textbf{\textit{Formula 12}}$$

where:
f is the resonance frequency and
BW is the bandwidth of the filter.

The reactance is given by Formula 13:

$$X_L = 2 \times \pi \times f \times L \qquad \textbf{\textit{Formula 13}}$$

where:
f is the operating frequency
L is the inductance of the coil
π is a constant, 3.141592

Skin Effect

The phenomenon called 'skin effect' is caused by the fact that the RF current through a coil tends to move towards the surface of the wire. Then a resistance occurs which can be represented by a resistor in series with an ideal inductance. It is a pure loss, whose value increases with the frequency. The equivalent resistance can be calculated, but it is rather complicated and involves parameters that are not generally known. Suffice it to mention its existence, because it does have an impact on coils. The depth of the conductive layer is in the order of millionths of a meter, so it is easy to see that the skin effect does have an influence.

The Wire

At low frequencies below a couple of megahertz or so, Litzendraht (which is a German word. usually shortened to Litz) can be used. It is a wire composed of

a great number of very thin wires twinned together. The total surface is thereby increased (or, if you will, the losses are connected in parallel), whereby the skin effect decreases. At higher frequencies the wires act like a number of coils connected in parallel with very hard coupling, and the advantage disappears. Consequently, at higher frequencies, a thicker wire and a bigger coil diameter should be used instead.

In high power transmitters copper tubing was frequently used for winding coils. This is made possible due to the skin effect, which essentially renders the inner core of a coil wire superfluous.

The Q of the coil dominates the Q of a tuned circuit and hence its impedance and bandwidth at resonance. The Q of the coil is easy to measure, since, according to Formula 12 above, if a circuit has a resonant frequency of 5MHz and a bandwidth of 50kHz, then the Q will be:

$$Q = \frac{5000}{50} = 100$$

Increasing the frequency will decrease Q due to the skin effect. Generally speaking, the smaller the coil and bigger the capacitor, the higher the Q. However, there is an optimal point. A coil in the order of 3µH and 330pF gives a good (theoretical) Q at 5MHz.

Q can be measured by first finding the resonant frequency of the circuit, then finding the points at which the voltage across the circuit is 0.707 times the voltage at resonance. Then subtract the lowest frequency of the three from the highest, which gives the bandwidth. Finally, divide the resonant frequency by the bandwidth, and you have the Q. Use instruments with the highest possible impedance and lowest possible capacitance. A good way of removing the influence from the instrument is to connect its probe to another coil which is held at the largest practical distance from the test circuit.

Various Types of Coils and Cores

Pot cores

One way of increasing the Q of a coil is to use a ferrite core, or simply putting the coil inside a ferrite pot. Since ferrite is a material which increases the inductance of a coil, you have to remove a number of turns to maintain the same inductance. This decreases the amount of wire necessary and the skin effect and resistive losses will be reduced. A pot core, as the one in **Fig 69**, is very common these days.

This type of core is sometimes adjustable. One problem could, however, occur. Since the pot is so small, you might find that a thin
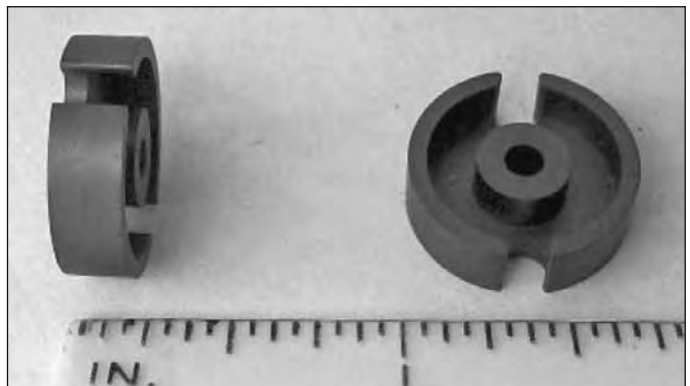

Fig 69: Example of a pot core

Fig 70: Inductor wound on a toroid core   **Fig 71: Plug-in cylindrical coil**

wire is needed, increasing the skin effect again, and you are back to square one. The Q of these pots may be as high as about 600. Note that the ferrite material has to be the correct one for the desired frequency range.

Toroid cores

Toroid cores (shown in **Fig 70)** are a good idea if the correct material is used and you don't need the core to be adjustable. They are a bit tricky to wind, though.

There are formulae to calculate the inductance for a toroid coil, frequently provided by the core manufacturers. Toroids can yield a Q of over 400 for certain materials and frequencies.

Cylindrical cores

Then there is the classical cylindrical coil.

One type such as the one in **Fig 71** can be plugged in. This coil is exchangeable, which was fairly common in the olden days. The principle is, however, not bad, because it rids your receiver from switches that tend to oxidise and cause other mechanical problems.

Modern cylindrical exchangeable coils can be built with a coil former and a male 3-pin or 5-pin DIN connector.

The variometer

Another older coil is the variometer. It consists of two coils, one inside the other, and they were used in TRF (Tuned Radio Frequency) receivers to vary the coupling between two coils. One coil (the large one) was connected to the grid circuit of the detector valve, and the other to the anode circuit. By varying the coupling between the coils by turning the small coil you also varied the

Fig 72: A home-made variometer

positive feedback (the reaction) of the detector, increasing selectivity and sensitivity, but increasing the noise level of the receiver. They were very common in the 1920s and 1930s, before the superheterodyne was in general use.

The variometer shown in **Fig 72** is actually home-made.

Spider coils

Spider coils, were also used where the coupling factor of two coils needed to be varied. One coil would be fixed and the other could slide to overlap the fixed coil more or less, much like the vanes of a variable capacitor. **Fig 73** shows the components necessary to make a spider coil.

Other arrangements to vary the coupling between the coils is to mount the movable coil onto an axis. Turning the axis allowed the moving coil to approach or distance the fixed coil.

Note that there needs to be an odd number of vanes for the winding to work!
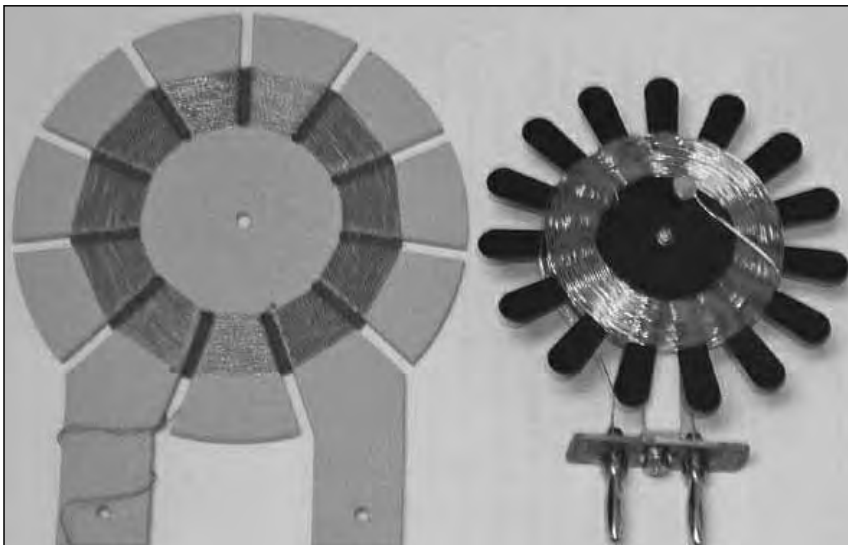
Fig 73: How to make a spider coil

Fig 74: A plug-in honeycomb coil

Honeycomb coils

A honeycomb coil (**Fig 74**) is wound in a zig-zag pattern so that no adjacent turns are parallel to the previous. This way, the capacitance between the turns is low (as opposed to, for instance, cylindrical coils, where all turns are parallel). Low capacitance of a coil means that the tuning range for a given tuning capacitor increases.

They were mounted on holders, one fixed and one movable, as described above.

Oscillator coils

Special rules apply to oscillator coils. They need to be as mechanically stable as they can possibly be made. They should be core adjustable, since it is difficult these days to find trim capacitors. They need to have as high a Q as possible. And, of course, they need to connect to a high impedance environment.

Impedances

Tuned circuits

Tuned circuits are two-pole networks which are often used simultaneously as input and output devices. They are frequency dependent, and can be capacitively reactive or inductively reactive. The impedance varies with the input frequency and appears to their environment to be resistive at resonance.

The impedance is high at resonance for a good tuned parallel circuit, up to 50kΩ or more. Measuring the DC resistance, though, returns a low result. The RF current flowing inside a tuned parallel circuit is very high, much higher than the current that is fed into it.

A variable tuning capacitor is frequently not a very good device. The vanes are often very close together (to increase capacitance and decrease physical size), which makes them sensitive for temperature variations. Additionally, particularly in oscillators, they require a high degree of mechanical stability.

Impedance of a tuned circuit

The properties of a tuned parallel circuit are such that its impedance is high at resonance - then it goes down on both sides of the resonance frequency. This means that a signal that appears at the resonance frequency passes with nearly its full strength, whereas a signal to the side of the resonance frequency is dampened.

The Q (or Quality) factor is an important part of a tuned circuit, whether it is parallel or series. Q should be as high as possible because Q determines the

bandwidth of the tuned circuit. However, a Q that is too high may result in the bandwidth becoming too narrow for the purpose of the circuit. In some applications, such as the IF amplifier of a TV, it is necessary to decrease Q.

Q was discussed in more detail earlier in this chapter.

What determines the Q of a tuned circuit are:
- How the coil is wound (how many turns of wire)
- What wire is used for the coil (wire's specific resistance, influence from skin effect)
- The Q of the capacitor (which mostly can be ignored)
- The impedance of the environment

In order for a tuned circuit to perform well, it needs to sit in an environment with high impedance. This applies to all environments, be it an oscillator or an RF or IF stage. If this impedance is too low, the quality of the tuned circuit will inevitably deteriorate, causing instability in oscillators, and bad selectivity and low amplification in IF and RF stages.

Since a parallel circuit grounded at one end is both input and output at the same time, any inputs and outputs connected to the circuit need to be high impedance. It is a matter of affecting the circuits as little as possible.

Coupled circuits

Literature mentions 'mutual inductance', or the coupling between two tuned circuits. Amongst other things, this is determined by the distance between the coils. If the coupling is too loose, the amplification of the signal will decrease. If it is too tight, a dip in the middle of the resonance curve will appear. There is an optimal point where the coupling gives the best result. This point is called 'critical coupling'. **Fig 75** shows a series of curves for three different couplings. The one with the double peak is said to be 'overcritical'. The others are 'critical' and 'under-critical'.
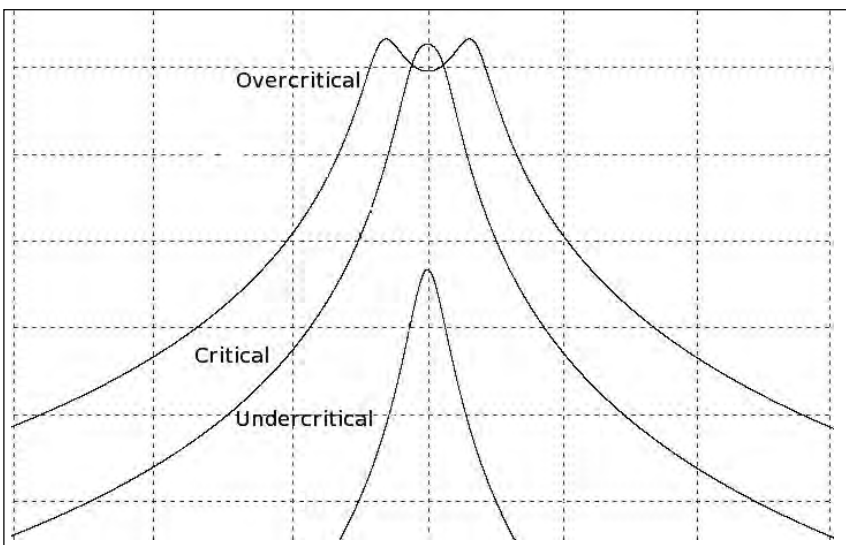
Fig 75: The results of various circuit couplings