Reading 38

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TRANSMISSION LINES

A transmission line connects between a transmitter and an antenna and its purpose is to deliver all the signal power to the antenna. A perfect transmission line does not radiate any energy and does not have any losses.

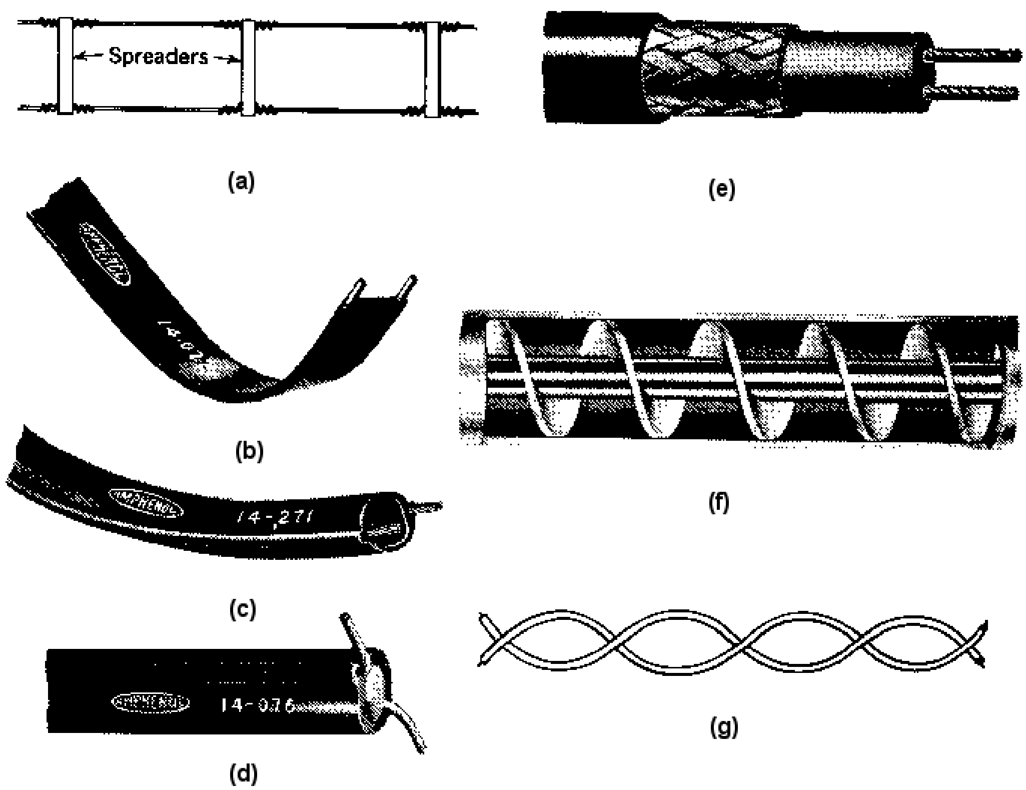


Figure 1

Figure 1 transmission line examples:

(a) Parallel line - open wire - air dielectric.
(b) Parallel line - solid dielectric - typically 300 Ohms.
(c)(d) Parallel line - solid dielectric – round.
(e) Parallel line - solid dielectric - with shield.
(f) Coaxial line - spiral polythene dielectric (low loss) - typically 50 Ohms.
(g) Parallel line - typical plastic dielectric - twisted pair - telephone line - typically 600 Ohms.

note: Speaker cable and some recent telephone lines have a Z_o of around 100 Ohms

WHAT IS MEANT BY "CHARACTERISTIC IMPEDANCE" OF A TRANSMISSION LINE?

When an electromagnetic wave travels through free space, the current and voltage distribution of the wave settles into a particular ratio. For free space, the current and voltage distribution of an electromagnetic wave settles into the ratio E/I equal to 120Π or 377 Ω. So we say the characteristic impedance (Z_o) of free space is 377 Ω.

Similarly, when a wave travels along an antenna or in a transmission line of infinite length, the current and voltage distribution of the wave will settle to a particular ratio of E/I and this is called the characteristic impedance (Z_o) of that line. Now the reason why I said a line of infinite length is to eliminate what is connected to the end of the line, that is, the load. We will come back to this later and connect a load.

So for a particular transmission line of infinite length (and no losses by the way), we could transmit a wave into it and literally measure the voltage across the line at any point, and the current through the line at that point, and the ratio of E/I would give us the characteristic impedance of the line in ohms.

WHAT IS A TRANSMITTER'S LOAD?

When you connect an antenna directly to a transmitter, the load for the transmitter is the antenna. When we use a transmission line to connect a transmitter to an antenna located elsewhere, the load for the transmitter is no longer the antenna. It is the transmission lines input impedance which, under most circumstances, will be the same as the characteristic impedance (Z_o).

We have discussed before the importance of matching a source (transmitter) impedance to a load (transmission line) impedance. Do you recall when we did the exercise on connecting different resistors to a 6 volt lantern battery? Only when the resistance connected to the lantern battery was equal to the internal resistance of the battery did we get maximum power dissipated in the load resistor. Likewise for maximum power to be transferred from the transmitter to the transmission line, the output impedance of the transmitter must match the input impedance of the transmission line. Keep in mind again that although we are talking about transmitters, the same applies to the reception of radio waves.

WHEN IS A 50 OHM TRANSMISSION LINE ACTUALLY 50 OHM?

At first this may seem like a very silly question. After all, if you purchase 50Ω transmission line you expect it to act like 50Ω line. Unfortunately, whether a 50Ω transmission line behaves like 50Ω transmission line depends on how we use it. Just because it has 50Ω written on its side is no guarantee that it will behave as 50Ω. That's up to us to ensure! A transmission line will only exhibit its characteristic impedance when it is terminated in its characteristic impedance. A 50Ω cable is 50Ω when it is connected to a load consisting of 50Ω of pure resistance. If a transmission line is terminated in a load not equal to its characteristic impedance, then the impedance on that line will vary from one point to the next along its length due to the presence of reflected waves.

FACTORS THAT DETERMINE CHARACTERISTIC IMPEDANCE

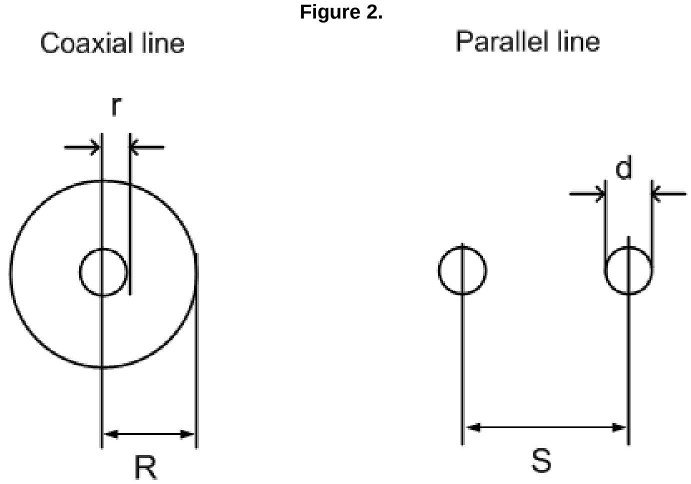
The characteristic impedance of any transmission line is a function of the size and spacing of the conductors and the type of insulating material (dielectric) between them (refer to figure 2).

If the distributed inductance and capacitance per unit length of a line is known, then the characteristic impedance can be found from:

$$Zo = \sqrt{\frac{L}{C}}$$

For distributed inductance and capacitance per unit length you can actually measure, or look up from cable data, what the L and C of a cable is for say a one metre length. Using this L and C you can calculate the Z_o.

Figure 2.



$$Z_o = \frac{138}{\sqrt{\varepsilon}} Log_{10} \frac{R}{r} \; Ohms \qquad Z_o = \frac{276}{\sqrt{\varepsilon}} Log_{10} \frac{2S}{d} \; Ohms$$

Z_o = characteristic impedance
R = inside radius of the coaxial outer conductor
r = radius of the coaxial inner conductor
S = spacing centre to centre of the parallel line
d = diameter of the conductor used for parallel line
e = relative permittivity (air=1)

Source: Radio Engineering Handbook – Newnes – Winder & Carr

RANGES OF Zo

In the design of transmission lines there are certain constraints which restrict the range of practical impedances that can be achieved. For two wire parallel lines the Z_o is usually restricted to a range of 100 to 600 ohms, while for coaxial lines the practical range of characteristic impedance is typically 30 to 100 ohms.

Interestingly, though I don't have the space to fully explain why, it is no accident that in radiocommunications a Z_o of 50 ohms is most common for transmission. However, for receive-only systems 75 ohm cable is the most common. The reason? It can be proven that 50 ohms is the best compromise between power handling ability and losses, whereas 75 ohm cable is optimised for having low losses with no regard to the power handling ability.

BALANCED AND UNBALANCED LINE

On a balanced line, such as a parallel wire line, the impedance between each leg of the line above the earth is the same. This line is said to be "balanced". On the other hand, a coaxial line has a larger outer concentric conductor with a smaller diameter solid conductor through the centre. Because of this construction, it is impossible for each leg of the line to have the same impedance above earth. A coaxial line is said to be "unbalanced".

If you find this concept hard to understand, imagine placing an ohmmeter between each side of a parallel line and ground (as in dirt, earth). You will measure a very high resistance (impedance) in the megohm range. However you will measure the same value between each leg and ground. This line is balanced. This is why we have twisted pair cable, and why 300 ohm ribbon is often twisted - in order to maintain the balance. A coaxial line on the other hand has its centre conductor at megohms above ground while the sheath (outer conductor) is at ground - definitely an unbalanced line.

A two wire parallel line such as 300 ohm TV ribbon will “behave” as balanced line only if it is installed correctly. In a TV installation, this line must be held away from metal structures such as the antenna mast, by using stand-offs. If this were not done, the metal structure would unbalance the line and alter the characteristic impedance. A correctly installed 300 ohm TV feeder is twisted at least once every 150 mm. The purpose of this is ensure that each side of the line is "influenced" to the same degree by nearby objects such as metal storm water down pipes. Attaching 300 ohm ribbon to a wall using thumb tacks driven into the centre of the dielectric is absolutely out for the same reasons (don't laugh, I have seen it done often). The latter practice is commonly found in domestic TV installations and frequently leads to poor reception and interference. Balanced line is difficult to install in order to maintain the balance between each leg. Having said that, parallel balanced lines have much lower losses than coaxial lines.

WHY BE CONCERNED?

If a balanced line is installed correctly, then induced currents from your amateur transmissions will flow in opposite directions on each leg of the TV line and be equal in amplitude, thus completely cancelling out and greatly reducing the possibility of interference (for the same reason, a parallel line does not radiate when used on a transmitter). If however the line is unbalanced, it will function more like a long wire antenna and funnel your amateur signal into the TV set, greatly increasing the chances of interference.

A coaxial line is unbalanced by virtue of its non-symmetrical construction. At the transmitter it is usual practice to connect the outer conductor to ground. The cable can be run anyway you like, and can even be buried in the ground (preferably in conduit). The induced voltages in the shield are conducted to earth and do not affect the shielded inner-conductor circuit.

VELOCITY OF PROPAGATION

The velocity of propagation is the speed with which an electromagnetic wave travels through a transmission line. The velocity of propagation within a line depends on the construction of the line. In particular, the dielectric used can significantly alter the velocity of propagation. Manufacturers of transmission line describe the velocity of propagation by stating the velocity relative to the velocity of light (or any other electromagnetic wave) in free space, commonly referred to as the velocity factor. The velocity factor can range from 0.56 to 0.95 depending on the type of cable. A line with a velocity factor of 0.66 means that the wave can travel along this line at 66% of light velocity (light velocity = 300,000 km per second).

Some typical velocity factors are:

1. Parallel line, air dielectric, 0.95 - 0.975
2. Parallel line, plastic dielectric, 0.80 - 0.95
3. Coaxial, air dielectric, 0.85
4. Coaxial line, polythene dielectric, 0.66

Higher quality coaxial cable (unbalanced line) has very good shielding and more air as the dielectric. However care must be taken with bending or the cable will be crushed or linked.

Figure 3.

The most important ones to remember for everyday use (and for the exam) are 0.66 for coax and 0.80 for 300 ohm parallel line. If you use something else look up the velocity of propagation on the manufacturers data sheet.

There is an interesting approximation for determining the velocity factor of coaxial lines. The reciprocal of the square root of the dielectric constant (permittivity) is a close approximation to the velocity factor. $\frac{1}{\sqrt{\varepsilon}}$ Polythene has a dielectric constant of 2.3. So a coaxial line with a polythene dielectric has a velocity factor of: $\frac{1}{\sqrt{2.3}}$ = 0.659 or <u>0.66</u> rounded.

A LINE TERMINATED IN ITS Zo

An electromagnetic wave is travelling down a transmission line but has not yet reached the load. Remember, a wave travels at a finite velocity, a fraction of the speed of light. As it travels its current and voltage distribution, or ratio E/I, will be equal to the Z_o of the line. The wave has not reached the load – it is on its way down the line. The current and voltage of the wave must obey Ohm’s law. When the wave reaches the load, which is equal in impedance to the Z_o, it will be totally dissipated in the load or radiated if the load is an antenna. Such a line is called a flat line as it has no standing waves.

REFLECTED WAVES

An electromagnetic wave upon reaching a mismatched termination, must conform to Ohm's law. You need to imagine a wave travelling in a transmission line of infinite length. The voltage and current ratio (E/I) of the wave will be that of the characteristic impedance. Now let's do away with the infinite line and place a load at the end of the line. The wave has not reached the end of the line yet, so its E/I distribution is still representing the characteristic impedance (Z_o). If the load is not equal to the Z_o, the wave upon reaching the load must go through a current and voltage redistribution so that E/I now represents the load impedance. To do this, the wave goes through a sudden redistribution of the energies contained in its magnetic and electric fields, so that the current and voltage across the load represents the load impedance.

In going through a redistribution of current and voltage, an induced current and voltage wave is created (Faraday's law of induction), and this new wave opposes the wave that created it (Lenz's law). The induced wave will now begin to propagate through the line back towards the generator or transmitter. This is called a reflected wave. How much of the incident wave is reflected and how much is dissipated (or radiated) in the load is determined by the amount of mismatch between Z_o and the load impedance (Z_L).

Again - a wave, before reaching the termination (load), has no knowledge of the termination conditions. The wave's current and voltage distribution will be representative of the characteristic impedance of the line. As close as one micron (a millionth of a metre) away from a load, the wave is still unaware of the conditions at the load. Suddenly, upon reaching the load, an instantaneous change in impedance occurs. The voltage and current must now redistribute themselves to conform with the Ohm's law value established by the load. This rapid redistribution causes an induced reflected wave which travels back down the line from the load.

A line ***not*** terminated in its Z_o will have an incident or forward wave and a reflected wave travelling in the opposite directions.

STANDING WAVE

Standing waves are produced when reflected waves travel from the load back towards the transmitter and interact with the incident (forward moving) waves from the transmitter. The result of this interaction is called a standing wave.

Standing waves are actually an interference pattern caused by the interaction of incident and reflected waves. At certain points along the line, incident and reflected waves will be additive; at other points they will be subtractive.

When incident and reflected waves interact and form a standing wave, the impedance of the line is no longer its Z_o. The impedance at any point along the line is equal to the resultant and measurable E/I at that point.

Imagine placing a voltmeter at some fixed point on a transmission line which has reflected and incident waves present. At the point of attachment, the voltmeter will measure the resultant standing wave voltage. Moving the voltmeter along the line will reveal that the interference pattern exhibits a periodic pattern of maxima and minima. Common terminology refers to the resultant voltage minima as nodes and to the maxima as anti-nodes. Nodes are produced on a line where the incident and reflected waves are equal in amplitude and 180 degrees out of phase. Anti-nodes occur when both waves are equal in phase and therefore additive.

The term 'standing wave' comes from the fact that the position of the nodes and anti-nodes do not move - they are stationary. The distance between adjacent nodes or anti-nodes is a half wavelength.

The effect of standing waves is most dramatic when the line is terminated in an open or a short circuit. In such cases, all of the power arriving at the termination is reflected.

STANDING WAVE PATTERN ON A SHORT CIRCUITED LINE

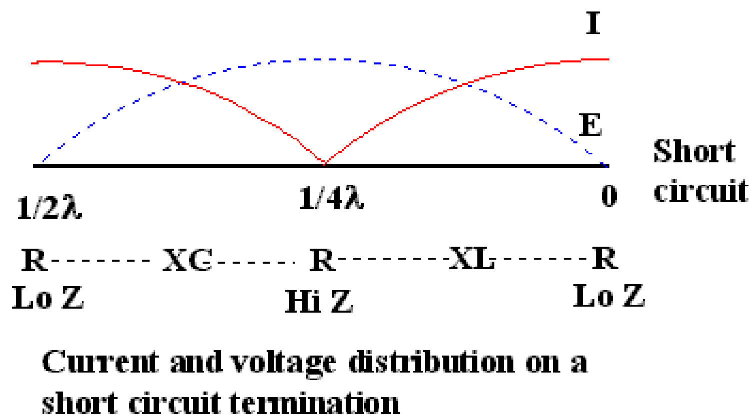


Figure 4.

Figure 4 shows the actual resultant standing wave of current and voltage on a short circuited line. If you have trouble working this pattern out for yourself just remember this: the voltage current ratio E/I must represent the impedance at that point on the line. Now there is one place where you definitely know the impedance, the load. This line is short circuited, so the load impedance is close to zero. Can you see that at the load (the right hand side) the current is high and the voltage is low. Low voltage causing a high current is representative of a low impedance. If the impedance of the load was zero (short circuit) then the impedance 1/4λ back from the load will be infinite. Half a wavelength away from the load the impedance will be equal to the load impedance. I have only drawn a half wavelength of line as this pattern just keeps repeating.

STANDING WAVE PATTERN ON AN OPEN CIRCUIT LINE

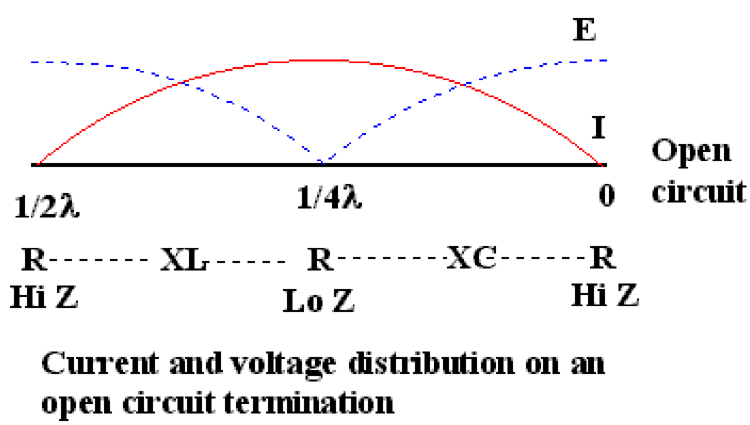


Figure 5.

Figure 5 shows the standing waves of current and voltage on an open circuit line. If the pattern looks familiar to you it should, as this is exactly what happens on a dipole antenna. Again, please note how the E/I ratio represents the impedance at that point. The load is open circuit (infinite impedance). At the load the diagram shows a very high voltage with little or no current. Is not high voltage and low current the same as a high impedance? It is.

VOLTAGE STANDING WAVE RATIO (VSWR)

The ratio of the voltage maximum (anti-node) to the voltage minimum (node) is called the VSWR. The VSWR is an indication of the degree of match or mismatch between the line's Z_o and the load impedance. VSWR means the SWR is just obtained by voltage measurement. You could in fact determine the VSWR by current measurement – this is called ISWR – all three are the same thing.

VSWR (OR SWR) FROM FORWARD AND REFLECTED POWER

Many watt (power) meters allow the measurement of the forward and reflected power on a transmission line. The equation shown in figure 6 can be used to convert these measurements into VSWR.

$$SWR = \frac{\sqrt{FWD\ PWR} + \sqrt{REF\ PWR}}{\sqrt{FWD\ PWR} - \sqrt{REF\ PWR}}$$

Figure 6.

Example: Forward power = 100 Watts

$$SWR = \frac{\sqrt{100} + \sqrt{10}}{\sqrt{100} - \sqrt{10}} \qquad SWR = \frac{13.16}{6.84} \qquad SWR = 1.9:1$$

Reflected power = 10 Watts

VSWR METER

Amateur stations usually have an instrument which measures the amount of reflected voltage relative to the amount of forward voltage on a transmission line. Such a device is called a VSWR meter. The forward voltage is first 'SET' to full scale and then a reading of the reflected voltage is taken. The scale on the metre is calibrated to read VSWR directly. This type of VSWR meter is in fact measuring the coefficient of reflection, which is just the ratio of the forward and reflected voltage. Mid-scale on these type of VSWR meters corresponds to a coefficient of reflection of 0.5 (VSWR=3) and full scale is 1.0 (VSWR = infinite). There is a simple mathematical relationship between VSWR and the coefficient of reflection (ρ - Rho) so the manufacturer is able to calibrate the scale in terms of VSWR:

$$VSWR = \frac{1+\rho}{1-\rho}$$

If you want to calibrate your VSWR meter in terms of coefficient of reflection then just put a linear scale on the meter face from 0 to 1. Quarter scale would be $\rho = 0.25$, third scale $\rho = 0.33$, half scale $\rho = 0.5$ etc.

IMPEDANCE MATCHING

For the transmitter to develop its full power and also to obtain maximum possible power transfer to the load, all components in the transmission system must be matched.

While the above statement is true, it often leads to the false conclusion that reflected power is lost. Reflected power is **not** lost since it will be re-reflected at the transmitter. Reflected power does *not* go back into the transmitter and burn out the finals! The power amplifier may be damaged if the VSWR is high, however this is due to the power amplifier itself creating high voltages across its components due to impedance mismatch. Reflected waves actually travel back and forth from the transmitter to the antenna – each time they arrive at the antenna a little more power is radiated. They bounce back and forth, if you like, until most power is eventually radiated along with some power dissipated in the transmission line due to the multiple reflections. Generally speaking, a matched system is better because:

1. If VSWR is low, then line losses are low.
2. The transmitter will develop its full output power.
3. A flat line can carry more power than one with a standing wave present.

The above is particularly true of coaxial lines. Parallel open wire lines have virtually no losses even with very high VSWR.

Standing waves place the transmission line under unnecessary electric stress. Anti-nodes (maxima) of voltage can break down the dielectric while the anti-nodes (maxima) of current cause increased copper losses (heat loss).

The impedance of a transmission line varies along its length if it has standing waves. Look at how the impedance varies along the length of a transmission line which is terminated in a short circuit or an open circuit. By a line terminated in a short circuit, we mean there is no antenna or other load, the two sides of the transmission line are just connected together. By a line terminated in an open circuit, we mean a transmitter connected to take transmission line that goes nowhere and is just left unconnected.

The line terminated in a short circuit will be inductive for the first quarter wave, then capacitive for the next quarter wave, then inductive again, and so on. Whether the line is inductive or capacitive depends on the phase of the current and voltage at that point. On short circuited lines less than 1/4 λ the current is increasing towards maximum at the short circuit, and the voltage has already been at maximum and is decreasing. The current is lagging the voltage, hence the impedance is inductive.

Let's get this clear even though you may not be asked about the input impedance of a transmission line which is short or open circuited. The principles are the same for antennas.

Let's make the statement again:

A line terminated in a short or open circuit will have an input impedance which is either inductive or capacitive – your job is to work out what the input impedance type is, that is, inductive or capacitive. Don't memorise it, but work it out by looking at the current and voltage on the line.

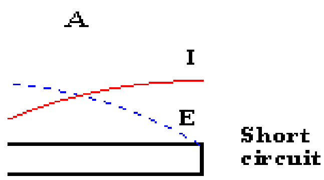
Before we start, recall this:

Current LAGS voltage in an inductive circuit (think of L for inductance and L for Lag).

Current LEADS voltage in a capacitive circuit.

Figure 7 show a transmission line terminated in a short circuit. The short circuit is the load, and the line is less than ¼ wavelength.

Figure 7.



First look at the load – always look at the load first – and work out what the voltage and current would be at the load. The load is a short circuit. A short circuit means HIGH current and LOW voltage. That's what a short is. As we move back from the load, from right to left, the current must begin to fall since it is maximum at the load. Voltage is minimum at the load and as we move back from the load, from right to left, the voltage must rise. This is the voltage and current distribution on a short circuit line less than ¼ wavelength long.

Now the important bit. Looking into the transmission line from the left hand side – is it inductive or capacitive? Looking into the line from the left hand side we see current increasing and voltage decreasing. Current is on the increase and is lagging. Hence the input impedance of this transmission line is inductive.

A length of transmission line terminated in a short circuit and less than ¼ wavelength is inductive. In fact, by changing the length you can obtain any value of inductance you like. So if you need to add inductance to something (perhaps an antenna) you could use a shorted length of transmission line and adjust its length until you got the correct inductance.

Just for interest sake, I have calculated what the inductance would be for a shorted length of transmission line at various wavelengths. These calculations are for 50 ohm coaxial cable. Remember, this is the inductance you would get looking into the end opposite to the short circuit:

0.1λ = 36.327 Ω (inductive reactance)
0.125λ = 50 Ω (notice anything?)
0.2λ = 153.884 Ω
0.22λ = 262.109 Ω
0.24λ = 794.727 Ω
0.245λ = 1591 Ω
0.248λ = 3978 Ω
0.25λ = $2.50197630472884 \times 10^{15}$ Ω (infinite impedance – open circuit)

To experiment with these calculations yourself download the suite of programs in "RadioBox" on the Radio & Electronics School web site.

As you can see from the values above, if the length of a shorted transmission line (less than ¼ wave) is varied, its input impedance is inductance and varies. At 0.125 wavelengths the inductance will always be equal to the characteristic impedance of the line (50 ohms in our example).

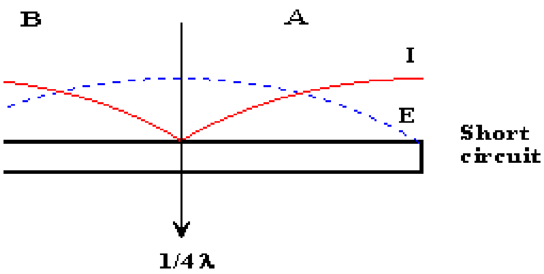


Figure 8.

What happens at ¼ wavelength? Well that number is huge and it was the best my calculator could do to define an open circuit. A ¼ wavelength of line terminated in a short circuit (zero impedance) will have an open circuit (infinite impedance) at its input.

Let's increase the length of the line beyond ¼ λ but less than ½ λ (refer to figure 8).

Looking into the line now the current is high and falling and the voltage is rising. Current is ahead of the voltage, that is, current is leading. The input impedance is capacitive.

Let's increase the length of the line now to exactly one ½ λ (refer to figure 9).

Can you see that the current and voltage at the input (the left hand side) is now exactly the same as it is at the load? One ½ λ back from a short circuited transmission line we again have a short circuit, or if you prefer, zero impedance.

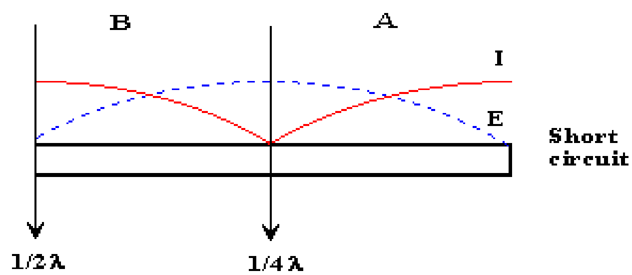


Figure 9.

This pattern continues for any length of short circuit transmission line.

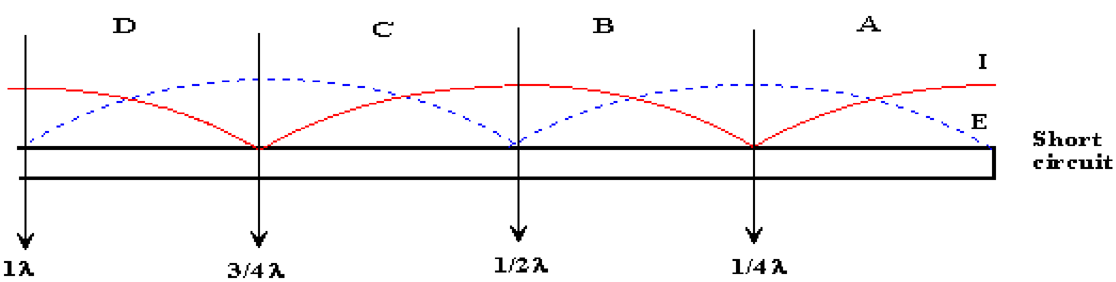


Figure 10.

Figure 10 shows a full wavelength of the same line. At the load the impedance is a short circuit (zero impedance). In section "A" the reactance is Inductive. At exactly ¼ λ the short circuit at the load is converted to an open circuit. In section "B" the reactance is capacitive, and ½ λ from the load we have a short circuit again. In section "C" the line becomes inductive again and in "D" capacitive, and so on.

EXACTLY the reverse happens on a line which is terminated in an open circuit. Try drawing the voltage and current distribution on an open circuit length of transmission line one wavelength long for yourself.

The current and voltage distribution on an open circuit length of transmission line is the same as that which appears on an antenna.

What we have learnt is that standing waves on open and short circuited lengths of transmission line can be used to simulate any value of inductance or capacitance we like – or we can convert a short circuit to an open circuit or vice versa. All of this has many applications - from tuning antennas, impedance matching, and even making filters. Who said standing waves weren't useful?

THE STUB

A stub is a length of open or short circuited transmission line. The input impedance of such a line is reactive, and the amount of reactance and its type (X_L or X_C) can easily be determined by equation or measurement.

Stubs are frequently used to bring an antenna to resonance. If an antenna is not resonant it will be reactive. The reactance of a stub can be used to cancel the unwanted reactance of the antenna, thus bringing it to resonance. Short circuited stubs are favoured for this application, as open circuit stubs tend to radiate somewhat.

Figure 11 shows a vertical antenna which is electrically short and should therefore have inductance added to it in the form of a loading coil. Here the inductance is provided by a short circuited stub. Sometimes the antenna and its stub are made from the one bent piece of aluminium rod.

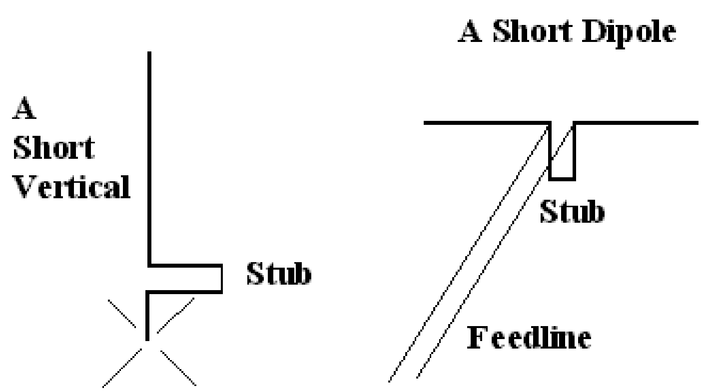


Figure 11.

The second example in figure 11 is a non-resonant dipole. The stub hanging down vertically at the centre of the dipole is just a length of transmission line (does not have to be the same as the feeder). The length of the stub is adjusted to resonate the antenna.

THE QUARTER WAVE TRANSFORMER

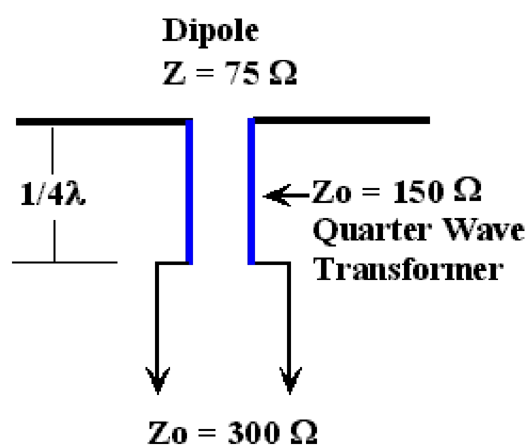
A length of transmission line called a "quarter wave transformer" can be used to match an antenna's feedpoint impedance to that of the transmission line. The characteristic impedance of a quarter wave transformer is given by:

$$Zo\left(\frac{\lambda}{4}\right)=\sqrt{Z1x\ Z2}$$

Where Z_o is the impedance of the transmission line used for the quarter wave transformer. Z1 and Z2 are the two impedances to be matched.

As a practical example, suppose it was necessary to connect 300 ohm transmission line to a dipole antenna which has a feedpoint impedance of 75 ohms (figure 12).

Figure 12.



$$Zo\left(\frac{\lambda}{4}\right)=\sqrt{300\,x\ 75}=150\Omega$$

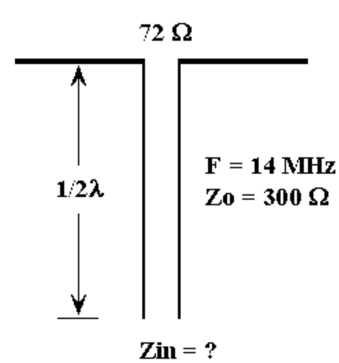
As Figure 12 shows, a quarter wavelength of transmission line which has a characteristic impedance of 150 ohms will match the 75 ohm and dipole impedance to the 300 ohm impedance of the transmission line. Remember that when calculating the length of a quarter wave transformer, the velocity factor (VF) of the transmission line must be taken into account as follows:

$$Length(m)\left(\frac{\lambda}{4}\right)=\frac{300}{f\ (MHz)}\,x\ 0.25\,x\,V_f$$

For examination purposes coaxial cable can be considered to have a velocity factor of 0.66 and parallel transmission line 0.80, unless otherwise told.

A ONE HALF WAVELENGTH 1:1 TRANSFORMER

Figure 13.



In figure 13 we see a dipole antenna that has a feedpoint impedance of 72 ohms. There is exactly one half wavelength of transmission line connected to the antenna.

Something like this has appeared in AOCP(A) exams.

Whatever the impedance of the dipole, it will be reflected to the input of the transmission line. In other words, the input impedance of the transmission line is 72 ohms! There is a lot of irrelevant information on this diagram. A half wavelength of transmission line has the property of reflecting its load impedance to its input. The characteristic impedance of the line makes no difference - whatever the load impedance is, this impedance will be 'reflected' to the input of the line. So a half wavelength of transmission line acts as if it were a 1:1 transformer. Of course the same would apply to one full wavelength of transmission line, or in fact any multiple of half wavelength of transmission line. This can be very useful when making antenna measurements. Suppose you are using a device called an Impedance Bridge to measure the feedpoint impedance of an antenna. Suppose it is not practical to work at the antenna. Provided you use a half wavelength or multiple thereof, of transmission line, the measurement taken at the input of that line will be as if it was taken at the antenna (neglecting the effects of losses).

QUARTER WAVE NOTCH (Bandstop filter)

We have learnt that a half wavelength of transmission line 'reflects' the identical impedance to its input. If you look at the diagrams showing the current and voltage distribution of an open circuit line, you will see that on a line terminated in an open circuit the impedance 1/4λ back will be a short circuit. Remember that the line is only a quarter wavelength for a particular narrow band of frequencies.

AN EXAMPLE OF USING A STUB NOTCH

Suppose a TV viewer was getting overload by a nearby CB radio operator on 27 MHz.

To fix the problem we need to connect a filter on the back of the TV. The purpose of the filter will be to block the 27 MHz and pass all other frequencies - most importantly the VHF/UHF TV band.

A quarter wavelength of transmission line in the middle of the 27 MHz CB band, terminated in an open circuit, will act as a notch filter.

Say we are using 300 Ω TV cable to make our notch (we could use anything), then the length of the line is:

27.25 MHz is about the centre of the HF CB band and the width of the notch will cover the whole CB band. The actual width will depend on the quality of the cable used but 700kHz – 1.2 MHz is typical for a notch of this type.

$$Zo\left(\frac{\lambda}{4}\right)notch = \frac{300}{27.25}\,x\;\,0.25\,x\;\,0.8 = 2.2metres$$

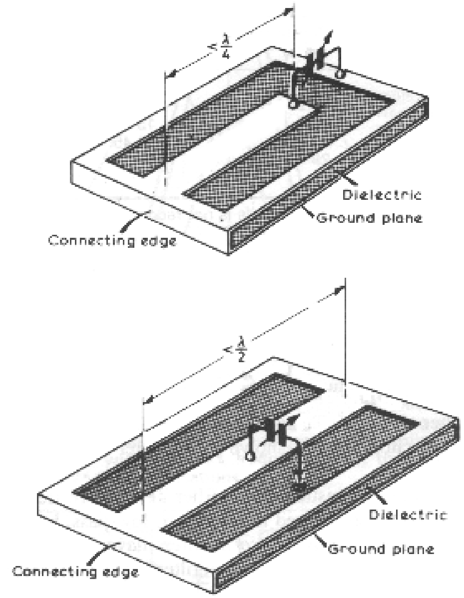
Connect 2.2 metres of open circuit 300 Ω line to the back of the TV set in parallel with the existing feeder which goes to the TV antenna. You will effectively be placing a notch of around 20-25 dB on the 27 MHz band for the cost of 2 metres of ribbon.

SOMETHING TO TRY

If you have a radio receiver on any band, one that you can get to the antenna terminals, tune the receiver to a constant signal and make a notch for that frequency to eliminate or reduce that signal. If you try this, work out the stub length from the above equation and cut it a little long. Connect it to your receiver and then trim 2-3 mm off at a time using pliers. Watch the 'S' meter dip as you cut (tune) the stub.

THE STRIPLINE

Figure 14.



We mentioned earlier in this course that filters for UHF are often too difficult to make from standard capacitors and inductors and, it was mentioned, that filters could be made using transmission line principles. Such a filter is called the stripline. At UHF and higher frequencies transmission lines become so short in terms of wavelength that half and quarter wavelength lines can easily be made of copper printed circuit board track. These printed circuit board transmission line filters are called striplines. They can be used to create an inductive or capacitive reactance, act as resonant tank circuits, or filters.

You can go much further into transmission lines than I have covered in this reading. I actually run an entire course on transmission line theory. I am restricted by fairness to all to limit this reading to what is important for examination and understanding purposes.

When you have passed your exam I would highly recommend you learn more about transmission lines (before antennas). You will find that you can do all sorts of 'magic' things using transmission lines.

TRANSMISSION LINE BALUNS

Important note: *Guanella baluns are a requirement of the AOCP(A) Syllabus. The information in this section on other types of baluns is for information purposes only.*

The most popular type of Balun and the type most often used by Radio Amateurs is the Transmission line type. These are called “Transmission line transformers” (TLT) because the work on transmission line principles hence their inclusion here and not in the reading on “transformers”. Ordinary transformers that have a primary and a secondary are more correctly called “mutually coupled transformers”. This is because they are really two or more inductors magnetically coupled and operate on the principle of Faraday’s Law.

TLT’s are NOT mutually coupled transformers

These Baluns are also widely misunderstood. It does not help when amateur radio literature going back to the 1950’s contains much conflicting information or unsubstantiated claims. Often when fallacies survive for a long time they become entrenched and more or less accepted as fact.

An exhaustive treatment would require a book. We will try to cover the essentials here and perhaps dispel some of the worst fallacies.

I think one of the major misconceptions comes from the fact that a transmission line Balun looks like a transformer. That is, it looks similar to a conventional mutually coupled transformer which also can be used as a Balun. Mutually coupled transformer baluns are not broadband – TLT's baluns are and the preferred choice for Amateur radio use.

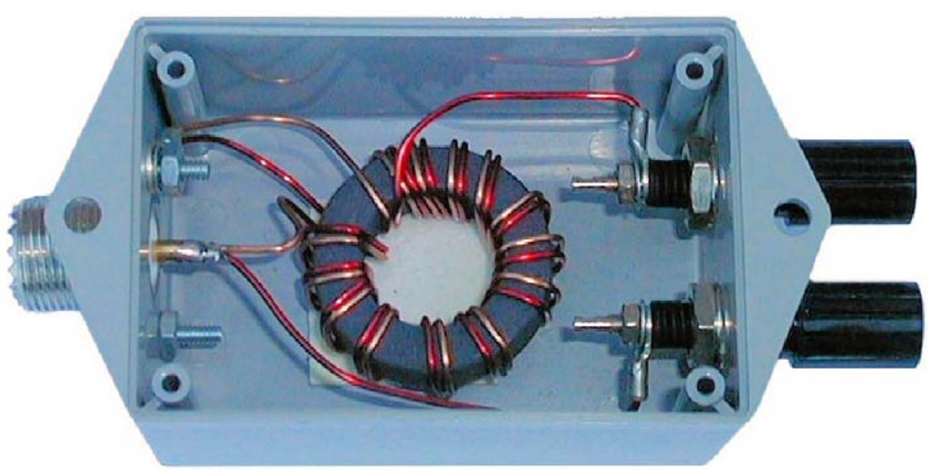
The name is also confusing. A "Transmission line Balun" does ***not*** mean a balun used in a transmission line. Though it is used in a line this is not what the name means. Such a Balun is one that utilise "transmission line principles" principles for its operation.

Parallel wire (or coaxial cable) lines can be wound on to ferrite cores or even air cores to create a 1:1 balun. When a toroid or rod is wound with a parallel wire transmission line it may appear on casual inspection that it is a conventional mutually coupled transformer – it is not – it is actually a 1:1 guanella balun though many just refer to this balun as an RF choke.

The two most common baluns used in amateur radio are the "Ruthroff", often referred to as a "voltage balun" and the "Guanella" often referred to as a "current balun" it is the latter that you need to know a something about for the AOCP(A)

Figure 15 shows a 4:1 transmission line (Ruthroff) 4:1 balun. This is one type of TLT balun. When we look closely at TLT baluns we find some very interesting features. Firstly the magnetic core is nearly passive when it comes to transferring energy between input and output. Ordinary mutually coupled transformers are effected by a degradation in balun action at high frequencies due to the transformer acting more like a capacitor as frequency is increased together with increased core looses. Transmission line baluns on the other hand have an astonishingly wide operating bandwidth. They don't appear to have enough windings on them and it seems hard to believe that such small devices can transfer so much power. The power transfer efficiency of a good TLT balun is in the order or 95-98%

Figure 15.



A 4:1 Ruthroff Balun also called a voltage balun. Wound on a ferrite toroid with a permeability (μ) of about 140.

Note: *having excessive* μ *causes too much choking reactance and high voltages to be produce across a balun.*

The reason for this is that the "windings" of a transmission line balun are not windings at all! What we have wound around the toroid is a very short "transmission line". There is no reliance on inductive (magnetic) effects between what "appears" to be windings. These short transmission lines are less than 1/8th λ. The coiling of the very short line around a toroid has no direct electrical significance for balun action. However if there are leakage currents down one side of the antenna through the balun there will be a choking reactance or RF Choke effect. These leakage currents are often referred to as "common mode currents". Common mode currents would cause the transmission line to radiate and significantly increase the probability of interference.

The use of a toroid also enables the transmission line to fit into a convenient small space and brings the "opposite" ends together for easy interconnection. Remember we can coil these transformers from parallel or coaxial line. It makes no difference provided the correct impedance of line (Zo) is used. If we can wind them from coaxial line then it should be obvious that we are not relying on mutual inductance – (the linking of magnetic fields) for the operation of these devices.

The pictorial diagram of the Ruthroff 4:1 balun of figure 15 is shown below in figure 16.

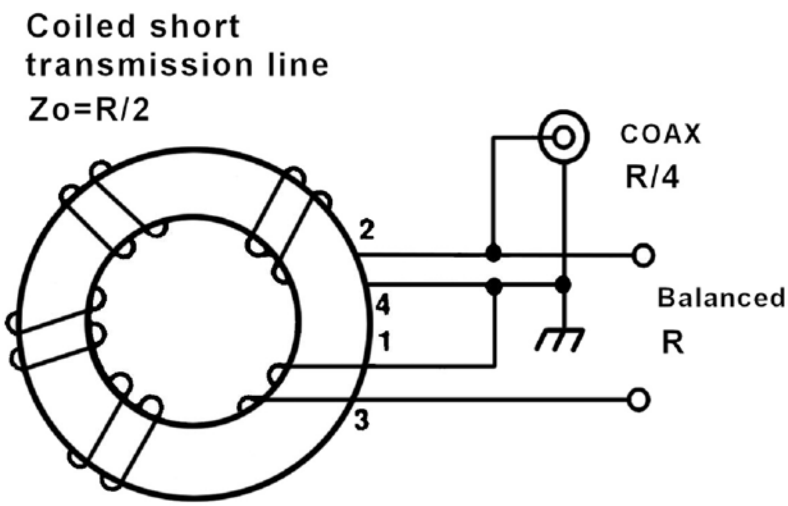


Figure 16.

The characteristic impedance of the coiled transmission line should be the geometric mean of the input and output impedance. This is a 4:1 balun so it could be used to match 200 Ohms (balanced) to 50 Ohms (unbalanced). The characteristic impedance of the short length of transmission line wound around the toroid should be:

$$Z_o = \sqrt{R_{in}\ x\ R_{out}} = \sqrt{200\ x\ 50} = 100\Omega$$

What does 4:1 mean?

Now it is often wrongly thought that a 4:1 Transmission line Balun can be used to match any two impedances with a ratio of 4 to 1. Not so. A 4:1 balun designed to match 200 to

50 Ohms cannot be used to match say 100 to 25 Ohms. The characteristic impedance of the line wound on to the toroid is an intrinsic parameter of the design. The Z_O of the line wound on to the toroid is a determining factor of the input and output impedances to which the balun can be connected.

Hopefully you are beginning to see how different these devices are from conventional transformers – though this critical difference is not always stated in much of the popular literature including some major handbooks.

In practice the three impedances (R_{in}, R_{out} and Z_O of the coiled line) from the equation given above can vary somewhat and the balun will still work. For example the Z_O of the coiled line in the 4:1 balun shown in figure 3 above should be exactly 100 Ohms. If you think about what determines the Zo of a transmission line you should realise <u>you can't just wind a balun with any two wires</u> of any diameter and with just any old insulation as it is the size of the wires and their distance apart and the type of insulation between them that determines the Z_O of the line that they produce.
There are some that go to great lengths to get this just right. In practice you don't have to be too fussy.

If you look at the balun in figure 15 you will notice how the spacing of the line around the toroid varies slightly in a couple of spots. Well this would mean that there is a variation in impedance at those spots. It would be better if the two wires making up the line were bound together every 10-15 mm with a narrow strip of tape 3-4 mm wide. Having said how it should be ideally, small variations in spacing (and consequent aberrations in Z_O) don't seem to matter that much. The SWR of the balun figure 15 when terminated in 200 Ohms should have an SWR of 1.5:1 or better from 2-30 MHz.

I mentioned that the type of transmission line used to make the balun is not important as long as its characteristic impedance is correct. Figure 17 shows the same (as in figure 15) 4:1 Ruthroff Balun made using coaxial cable and coiled around a ferrite rod. Here it is even more obvious that the magnetic core does not influence the transmission line. The core does not participate in the transfer of energy as in a conventional transformer. This is why high power baluns can be such small devices.

Figure 17.

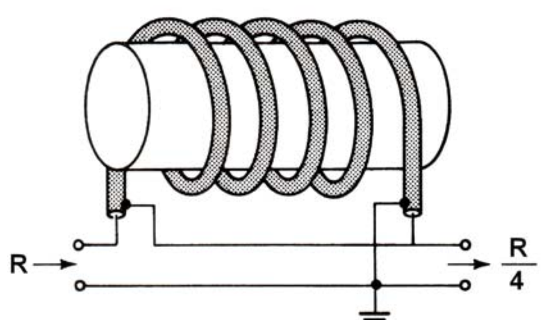
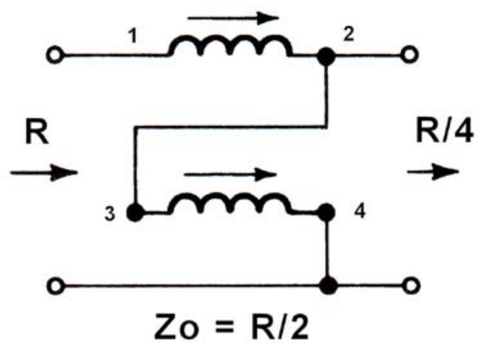


Figure 18 shows the schematic diagram of the Ruthroff balun. The terminals 1 and 3 represent one end of a short parallel or coaxial transmission line. Terminals 2 and 4 the other end. I think it is the common use of this type of schematic which leads to the misconception that this type of balun relies on inductive transformer action. The coil symbols are not meant to imply inductive coupling. However we do have the property of inductance from end to end. Looking at the schematic you can seen that coil (3-4) is in shunt across the output. It appears to be short circuiting the output. There really is no short circuit because the line element (3-4) does present an ordinary reactance in shunt with the output terminals. The important thing to understand is that this shunting reactance comes from the line elements behavior as a single conductor. The shunting reactance has nothing to do with the (3-4) element working in conjunction with the (1-2) element to form a transmission line.

Figure 18.



This undesirable low frequency shunting action of element (3-4) is reduced if the inductance is increased. A higher inductance in element (3-4) means a greater low frequency response from the balun. How can we increase the inductance of element (3-4) without changing the characteristic impedance of the line?. Well we would wind the transmission line into a coil. If this is done on a toroid it also brings the ends close together for easier interconnection. The effect of a ferrite core is to make element (3-4) a more effective RF Choke. So we use a core really just to extend the low frequency response of the balun. As we go up in frequency the length of the coiled transmission line gets longer in wavelengths. As the length of the line approaches 1/8th wavelength the high frequency response rolls off and the balun becomes ineffective.

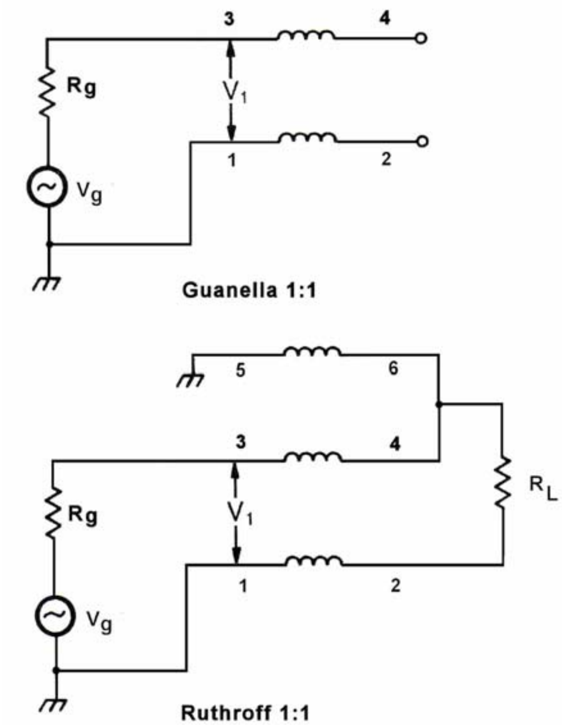
GUANELLA BALUN

This type is commonly referred to as a “current” balun. Whatever can be done with a Guanella can be done with a Ruthroff.

I find the Guanella (current) Baluns easier to construct and a little more tolerant to variations in impedance. <u>The Guanella balun is in the AOCP(A) syllabus</u>.

Guanella and Ruthroff 1:1 Baluns

Figure 19.



We use a 1:1 balun when we don't need an impedance transformation. Figure 19 shows two popular and effective 1:1 transmission line baluns. I prefer the Guanella type for ease of construction. This Balun is just what it looks like. It comprises a transmission line of characteristic impedance equal to the line in which it is to be placed coiled around a ferrite rod or toroid. The coiled transmission line of the Guanella forms a choking reactance for any unwanted common mode currents. The choking reactance isolates the output from input and only flux canceling transmission line currents are able to flow. This is the reason why this type of balun has been in recent years referred to as a "current" or "choke balun".

Making a 1:1 Guanella Balun: *for information only*

The Guanella 1:1 balun is a short length of transmission line, of any type, usually wound on a low permeability (μ 50-250) toroid or rod.

The characteristic impedance of the short line should be equal to the impedance of the system. If you're using the balun in a 50 ohm system, then the line used to wind the balun should be 50 Ohms. The balun should be used in its impedance. It should not be used in a system mismatched by more than 2:1 (VSWR) for best results. As the SWR increases there will be a higher voltage gradient along the length of the coil transmission line resulting in increased dielectric type losses.

Since the line is short it is easy to wind the toroid with parallel line or small physical size coaxial cable.

There are two common methods of winding a Guanella 1:1 Balun. These are both shown in figure 20. I have used coloured wires here for photographic purposes.

Figure 20.

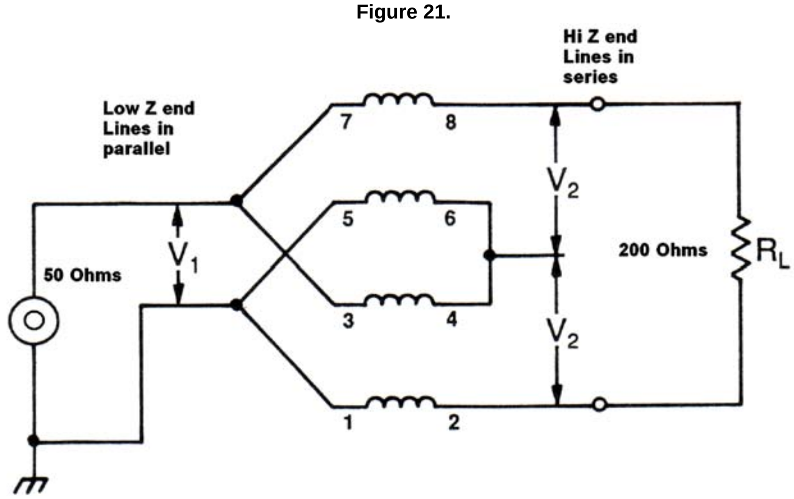
The winding method on the right of the photo is often referred to as a “magic crossover”. It’s proper name is a Reisert’s 1:1 Balun. It really is just a Guanella with a crossover on the toroid. It is not a “magic” anything! Whilst it looks a bit more formidable than the previous photo, electrically these devices will work exactly the same. This method may have an advantage when using coaxial cable and you need to distribute the turns around the toroid to get your 10 turns.

Using Ferrite Rod

Ferrite rod works well but the impedance may vary toward the upper end of HF. It does work and it does work well and its even less expensive. About $3-4 at most popular parts stores and has a permeability of 150. You can wind it with RG58 or similar and have connectors on each end. A popular mounting method is to place the entire assembly into a length of PVC pipe with end caps.

The 1:1 Guanella Balun is a basic building block for a range of baluns. It is easy to use two 1:1 Guanella Baluns to produce a 4:1 (or 1:4) impedance transformation. You can coil two 1:1 baluns on to each side of a toroid. At the low impedance end you connect these two transmission lines in parallel and at the high impedance end (four times higher) the lines are connected in series. This will be obvious if you look at the schematic diagram of the 4:1 Guanella balun in figure 21.

Figure 21.



Note: you *may be asked to identify schematic of a Guanella balun in assessment*

In figure 21 we simply have two short transmission lines. One line is formed by elements 1-2 and 3-4. A second line is formed by elements 5-6 and 7-8. Each of these lines taken in isolation form a 1:1 Guanella balun. On the low impedance side they are connected in parallel and on the high impedance side they are connected in series. The phasing of this connection produces a 4:1 impedance transformation. The two 1:1 baluns can be wound on separate cores for very high power use or for most purposes on each side of a single toroidal core will be fine.

Figure 22 is a pictorial diagram using coloured wire to further illustrate how two 1:1 baluns are configured to produce a 4:1 transformation. The optimum impedance of the line used to wind this balun is as before the geometric mean of the input and output impedances. So if our 4:1 balun is matching 50 to 200 Ohms the line impedance making up the balun should be; $Z_o = \sqrt{(200 \times 50)} = 100$ Ohms.

Figure 22.

We have seen how two simple 1:1 Guanella Baluns parallel connected on one side and series connected on the other side can make a 4:1 impedance ratio. By using more parallel series connections other impedance ratios are possible.

Braid Breaker

Television interference can be caused by the radio amateurs signal being picked up by the outside braid of the TV cable. A simple fix is to add a braid breaker at the back of the TV set. This can be as simple as a one to one balun as described above. The easiest way to do this is with a ferrite rod and simply wind the TV coaxial lead around it and hold it in place with cable ties. This method requires no cutting. I have actually done this many times and watched the interference disappear as I wound more windings on to the ferrite rod.

This will cure a lot of TVI problems and its is so easy to try. I have even wound the TV lead around a screw driver and if this even reduces a little interference then I know doing the same with ferrite rod will do the trick. A braid breaker is nothing more the an RF choke to prevent the braid of the TV cable receiving signals from you and getting into the TV set. Remember the braid breaker (RF choke) must go at the back of the TV set.

One case I had no screw driver or ferrite so I just wrapped the coaxial lead around my finger (the householder, and elderly lady, I was helping must have thought I was crazy) and it worked but I ran out of finger before the interference was eliminated. There was a yard broom nearby so I wrapped the cable around the handle for about 150mm and all the interference went. I then explained to the lady that is she went to somewhere like Jaycar she could buy a ferrite rod and much shorter and smaller and wrap the cable around and hold it in place. “No” she said! I quite happy to have the one metre brush yard broom on top of the TV. She insisted it was fine. I have to wonder what people would have thought when they saw it or did she ever get the ferrite rod ☺.

End of Reading 38
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