ROYAL SCHOOL OF ARTILLERY

BASIC SCIENCE & TECHNOLOGY SECTION

Waveguides, Lines and Cavities

INTRODUCTION

Electro-Magnetic waves (EM-Waves) at radar frequencies are similar to those used for terrestrial and satellite television signals. These waves, which have frequencies between about 1 GHz and 10 GHz, pass readily through the Earth's atmosphere without significant loss apart from that caused by their spreading out with distance.

Within the confines of the radar equipment, however, it is often necessary to direct these high-frequency signals from one point to another and to prevent their reaching other parts of the equipment. The much lower frequencies that are used in audio circuits and servos, for example, can be carried around using ordinary copper cables with plastic or rubber insulation. Such cables do not function correctly at radar frequencies and it is necessary to use special co-axial cables or waveguides instead.

This handout describes the basic theory of operation of co-axial cables and waveguides when used in radar equipment.

LOSSES IN CABLES

At low frequencies (including dc, which has a frequency of zero) the cables used are familiar to everyone. They are made of copper and insulated with rubber or plastic. The thickness of the copper is determined by the amount of current and the thickness of the insulation by the voltage and the environment in which the cable will be used. Mains cables can be extended without any great difficulty and many kilo-Watts can be sent along a simple cable. At high frequencies, however, things are very different for three main reasons:

- **Radiation Loss**: Any ordinary cable will act as an antenna and broadcast a signal that will allow the energy in the cable to escape and significantly reduce the amount of energy that reaches the other end of the cable. The energy lost might also find its way into other parts of the system and upset their normal operation.
- **Resistive Loss**: At very high frequencies, the electrical resistance (Ohms) increases to many times its value at low frequencies and a significant amount of the energy travelling along the cable is converted into heat. (See the sidebar on page two for more details of this.)
- **Dielectric Loss**: when the insulator (dielectric) between the conductors is not air then the material used will absorb a small amount of power from the alternating electric field. Some materials, such as polythene, have low losses and are commonly used in high-frequency cables.

Of course, the above effects are also happening to the energy of the 50 Hz mains in ordinary cables - but the portion that is wasted at such a low frequency is minute and of no importance. As the frequency is increased then the amount of energy lost increases and this makes ordinary cables quite useless at very high frequencies.

GUIDED WAVES

High-frequency signals cannot be sent along ordinary cable because of the problems described above. Instead, these signals are sent in the form of an EM-Wave that is guided from one place to another by the cable. The energy flows not in the cable's conductors , because the skin effect prevents its penetrating the conductors, but in the space between the conductors. The conductors merely act as guides that direct the energy from one place to another.

You could think of a high-frequency transmission line in a similar way to a railway line - gravity keeps the train on the track and the track guides the train along the desired route. The electro-magnetic fields attach to the conductors and the EM-Wave is guided by them.

PARALLEL-WIRE TRANSMISSION LINE

This consists of two conductors that run side-by-side, like railway lines, kept a set distance apart. The distance has to be much less than the wavelength of the EM energy in free space. When a very high frequency electrical signal is connected across one end of such a line then EM Waves are launched along it - a bit like when you wiggle the end of a rope and 'waves' run along the rope.

The EM Wave follows the conductors of the transmission line because its electric field becomes attached to the surface of the conductor. At the same time, currents flow in the surface of the conductor and these make a magnetic field that encircles each conductor. The pattern of fields is illustrated in Figure One. (The Figure is not to scale, as the distance between the parallel wires must be much less than the wavelength of the wave - the distance between the '+' and '-' points would be much greater than that illustrated.) Features of this field pattern are as follows:

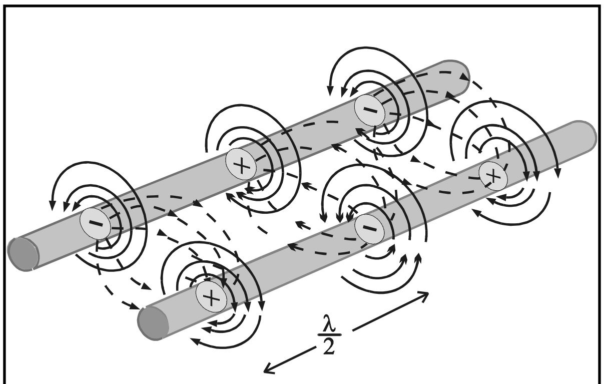


Figure 1: Fields along a Transmission Line

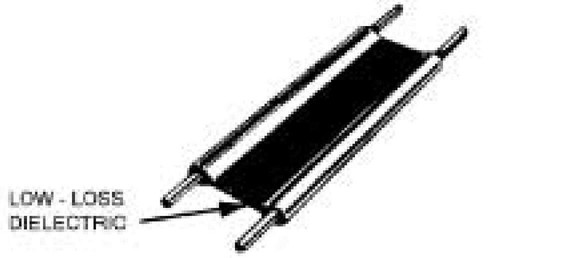


Figure 2: A Practical, Parallel-Pair Transmission Line

- It is a transverse EM-Wave. The electric field lines are at right-angles to the magnetic field lines and they are both at right-angles to the direction of propagation. This guided wave is carrying energy from right to left, as shown.
- The electric field lines all touch the conductor at right-angles. This angle is only 90° for a perfect conductor - in practice, it will be very nearly 90°. This means that the electric field can be very intense without causing large currents to flow in the conductors. Because of the skin effect, currents can only flow along the surface of the conductor - but the electric field (that makes the current flow) is not in that direction. Any current that did flow would take energy from the wave.
- The magnetic field lines run parallel to the conductor and do not intersect (cut) it. One consequence of this is that the changing flux does not induce any significant emf in the conductor - if it did induce an emf then there would be a current flow that would take energy from the wave.

As the wave passes along the transmission line then the pattern shown in Figure One moves along the line at the velocity of light. The presence of the guiding wires does not change the velocity of the EM-Wave. An electron at the surface of the wire would rock back and forth, along the direction of travel of the wave, as the wave passes. It is essential that the surface of the conductors be in good condition since, due to the skin effect, current only ever flows in the outermost surface. Some lines use silver-plated conductors (or other non-corroding metal) to keep the surface in good condition.

To keep the wave attached to the line then the spacing of the two conductors must be much less than a wavelength. This is only practicable at frequencies up to a few hundred of Mega-Hertz or so. Above those frequencies, the required spacing between the wires becomes too small for practical use. This type of line must also be kept away from other conductors, otherwise some of the fields will connect to the adjacent conductor and energy will be diverted away. The parallel-pair transmission line is fairly common in the USA, where it is used to connect FM radios and televisions to their antennae. A variation of this line, called 'micro-strip' is easy to construct on a printed circuit board and is common in radio and radar systems. (See Figure)

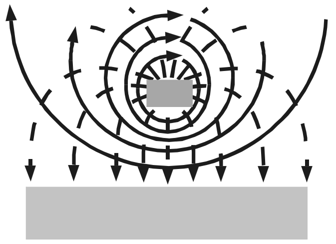


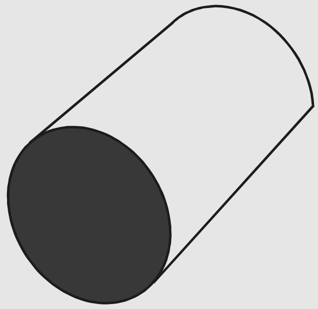
Figure 2: Micro-Strip Line

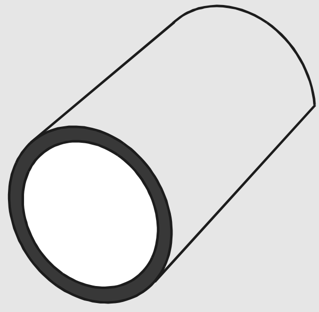
THE SKIN EFFECT

Whenever the magnetic field changes near a conductor then an EMF is induced in that conductor. This effect is used to generate electricity by rotating powerful magnets surrounded by large coils of wire. The amount of EMF depends on the number of turns of wire in the coil and on the rate of change of the magnetic field - for the domestic supply the coils might have many hundreds of turns and the field changes fifty times each second, as the magnet rotates.

At radar frequencies, the magnetic field changes thousands of millions of times each second and this is capable of producing significant EMF in a straight piece of wire - a coil is not necessary. The EMF is induced in the same wire that is carrying the high-frequency current (self-inductance) and its effect is to force the current to move away from the centre of the wire and to flow in a thin layer at the surface of the conductor (the 'skin' of the conductor). As less copper is available to carry the current then this is equivalent to an increase of resistance. As the frequency increases then the skin depth decreases so that, for example, at 10 GHz the current only flows in the outer 0.7 µm of a Copper wire (this is about one-hundredth of the diameter of a human hair).

Of course this effect also occurs at mains frequencies (50 Hz) but the skin depth at that frequency is approximately one centi-metre, so the effect is not significant since few cables approach that size. For a copper cable of diameter 1 mm, its resistance at 10 GHz will be about five million times greater than its resistance at 50 Hz. Consequently, any attempt to send a signal of 10 GHz along an ordinary cable will be very inefficient as this resistance will convert practically all the electrical energy into heat and the signal will fade away as it passes along the wire. If the wire were very short then it might be practicable to use it at 10 GHz, but it would still act as an antenna and radiate a significant amount of energy. The skin-effect is illustrated, below.





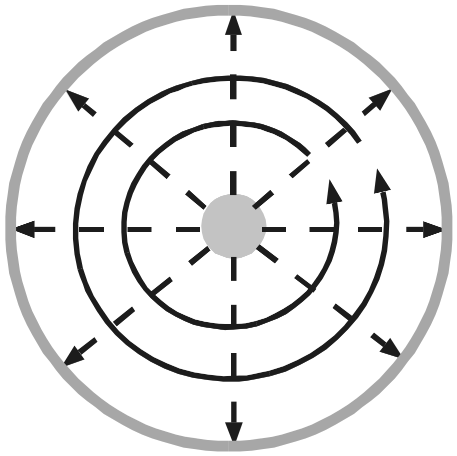


Figure 3: Electric (dotted lines) and Magnetic (solid lines) Fields in a Coaxial Cable

COAXIAL CABLE

This cable is the familiar television aerial cable used in UK homes. It consists of a central conductor that is completely surrounded by a second conductor. It is like a transmission line where one conductor has been extended to surround the other. Some insulation (dielectric) is necessary to maintain a uniform separation of the inner and outer conductors.

There are electric and magnetic fields inside the cable and they have the same features as those for transmission lines. The pattern is shown in Figure Three. One half-wavelength further along the cable - the field directions will both reverse (as with any wave).

One difference between the coaxial cable and the transmission line is that the fields are contained entirely within the coaxial cable whereas the open line has fields that extend a significant distance away from the line. This means that the coaxial cable does not radiate any energy and no energy can get into the cable. This means that these cables can safely be run next to other conductors without interference.

The electric field runs radially, at right-angles to both central and outer conductors whilst the magnetic field circles the inner conductor - cutting neither. The dimensions of the cable are primarily determined by the required impedance. Coaxial cable is limited to powers of a few kW.

Practical cables are often constructed with a braided outer conductor and stranded inner conductor, to give the cable flexibility. This means that the inner conductor does not have a smooth surface and that the outer conductor is not continuous - this type of cable is a compromise between ease of installation and performance. This type of cable is illustrated in Figure Four.

Where there is a need for high power and high performance then both conductors must be made from solid Conductor - even though the cable will be very stiff and difficult to install. As with the parallel-pair transmission line, the copper might be electro-plated with silver or cadmium to maintain a good quality surface to keep the losses as low as possible.

As with transmission lines, the losses increase with frequency. At the frequencies used for terrestrial colour television in the UK (600 MHz), the average installation features a loss of signal of about 6 dB from roof-mounted antenna to living room. This means that only 25% of the received power from the aerial actually reaches your television set. A poor joint or constriction of the cable caused by securing it too firmly to the wall might make things even worse.

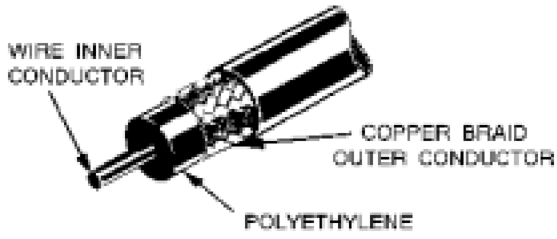


Figure 4: A Flexible, Coaxial Cable

For *short* runs of coaxial cable, the losses are much smaller than that illustrated above, for the television. Much internal cabling in radars is coaxial cable because it is relatively cheap and compact whilst the alternative, waveguide (see later), is expensive and difficult to install as it is usually a large, rigid tube.

Many coaxial cables use a plastic such as polythene to fill the space between the inner and outer conductors and to support the inner conductor. These cables have a velocity of propagation that is about 60% of the speed of light because polythene has different dielectric properties from air. To reduce this effect then the dielectric can be produced in a honeycomb form, with air filling the spaces.

The dimensions of the conductors are chosen to give the correct impedance: this is often 50 Ω or 75 Ω. Throughout the system, the impedances must match because some of the energy in the wave will reflect at a change of impedance and this causes inefficiencies and other problems.

Screened Cable: this resembles coaxial cable and it is used in hi-fi systems to connect audio signals from one place to another (e.g. microphone cable, cable between CD player and amplifier). This cable uses the outer, braided conductor as a screen that blocks extraneous signals (hum and interference) from entering the cable and interfering with the low-power audio signals. The audio signals, frequency around 1 kHz, would have a wavelength of 300 km if they were EM-Waves - since no Hi-Fi system is anywhere near this dimension then the signals do not act as waves in this cable. The outer layer of conductor is primarily a shield, to keep out interference.

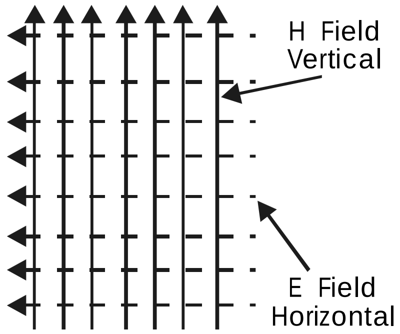


Figure 5: A Plane Wave in Free Space

WAVEGUIDES

The skin effect drives high frequency currents towards the surface of a conductor. In a coaxial cable, the inner conductor has a relatively small surface area and, at frequencies above a few GHz, its resistance becomes too large for efficient use, except over very short distances. A waveguide is a development of a coaxial cable in which there is no central conductor - the waveguide is just a hollow tube. Currents flow only at the inside surface of the waveguide and, as this surface is relatively large, very smooth and made from a good conductor, its resistance remains sufficiently low to allow high efficiency at frequencies of tens of GHz.

You have already seen how the electric and magnetic fields of the EM-Wave can be fitted into a parallel-pair line and a coaxial cable. The ‘golden rule’ was that the electric field must be at right-angles to a conductor and that the magnetic field must not intersect a conductor. If these conditions are not met then the conductor gains (heat) energy from the wave and the wave is absorbed - not very much use for a device that is supposed to guide the wave from one place to another!

Figure Five shows a plane, EM-Wave (its form in free space), with fields at right-angles to each other and also at right-angles to the direction of propagation. This is called a ‘transverse’ EM-Wave because the fields lie at 90° (transverse to) the direction of propagation of the wave. This arrangement cannot be fitted into a waveguide without violating the golden rule. However, there are several ways (called ‘modes’) that these fields can be re-arranged to fit into a waveguide and still obey the rule. Most waveguides operate using the simplest way that the fields will fit into the guide.

The correct mode of operation is important when you consider how energy gets into and of of the guide. To launch a wave into the guide then the electric and magnetic fields must be converted from the transverse mode of free space or coaxial cable into the correct mode for the waveguide. Similarly, to extract energy from the guide and into, say, a coaxial cable, then the same conversion must be done in reverse. Waveguides may be rectangular or circular.

RECTANGULAR WAVEGUIDES

The waveguide is constructed using a good conductor (e.g. Copper) and it is the inside surface that must be the good conductor. Consequently, some waveguides are electro-plated with a corrosion-resistant coat-

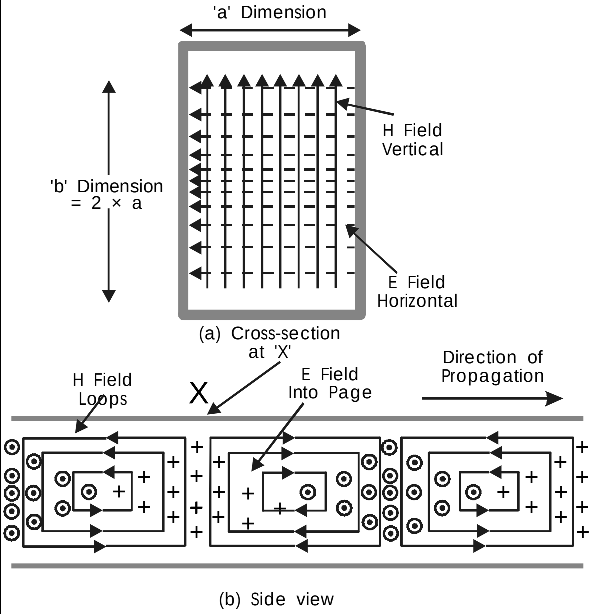


Figure 6: Electric and Magnetic Fields in a Rectangular Waveguide

ing on the inside. The height of the waveguide (usually referred to as its ‘b’ dimension) is, generally, twice its width (usually referred to as its ‘a’ dimension).

Figure Six shows an EM-Wave enclosed by a rectangular waveguide - within the waveguide, the electric and magnetic fields are different from what they would be when in free space. As a transverse EM wave passes from free space into a waveguide then it changes into a slightly-different form. This new form of an EM wave, with the fields slightly re-arranged, can travel tens of metres along a suitable waveguide, with little loss. The same change, in reverse, occurs when a wave reaches the end of a waveguide and emerges into free-space. One function of the ‘horn’ at the end of a waveguide is to provide a gradual transition from one environment to the other.

The Electric Field: the electric field is strongest across the centre of the guide, across the short dimension (a), from face to face. The lines of electric field lie across (at 90° to) the direction of propagation, just as they would do for a wave in free-space. Near the corners, the electric field is zero, otherwise it would be parallel to one surface or the other. As with any wave, the directions of the fields reverse every half-wavelength.

The Magnetic Field: the magnetic field lines form loops within the guide, avoiding the conducting surfaces. This feature distinguishes the EM Wave within the waveguide from an EM Wave in free-space: the lines of magnetic field lie along the direction of propagation in the waveguide whereas they lie across it in free-space.

The changes that occur to the fields cause changes to the properties of the EM Wave in the waveguide. Some waveguide devices rely on these changed properties for their operation (see later).

Properties of an EM wave in a guide: The EM wave in the guide is different from the EM wave in free space in the following ways:

- The wavelength in the guide is longer - typically by a factor √2, but this depends on the frequency of the

wave. The longer wavelength is called the ‘guide wavelength’ and is given the symbol λ_g.
- The phase of the wave is advanced as it travels along the guide.
- The impedance of the guide (typically 530 Ω) is greater than that of free space (377 Ω).

Minimum waveguide height: the pattern of fields in the waveguide can only exist if there is sufficient space available - the waveguide must be tall enough to admit half a wavelength. The height (‘b’) of the waveguide must be greater than half the normal wavelength of the EM Wave in free-space. For example, a wave of 3 GHz, wavelength 10 cm, cannot enter or pass along a waveguide that is 5 cm high. The wavelength that equals 2 × b is called the ‘cut-off’ wave length and represents the longest wavelength that can be used with a particular waveguide. However, the efficiency of the waveguide falls near the cut-off wavelength so, in practice, one would not try to operate the waveguide near to cut-off.

Maximum waveguide height: The basic field pattern also has a maximum height - If the height (‘b’) of the waveguide is bigger than one wavelength then the field pattern doubles and a mirror-image forms in the height of the waveguide. This changes the mode of operation of the waveguide and is usually avoided in practice by using a waveguide whose height is less than one wavelength.

Practical waveguide height: since the height of a waveguide must be both greater than half a wavelength and less than a whole wavelength then all waveguides operate around the middle of this range. Typically, the wavelength used will be chosen so that $\lambda = b \times \sqrt{2}$. Alternatively, for a given wavelength, the height of the guide (‘b’) should be chosen so that $b = \lambda \div \sqrt{2}$.

Once the height (’b’) of the waveguide has been chosen then the width (‘a’) is chosen so that a = b / 2. The guide is deliberately made rectangular and its width (‘a’) is always less than the cut-off wavelength so that the field pattern can only fit into the guide along its height. This ensures that the field pattern can never rotate by 90° to orient with the ‘a’ dimension. This is necessary because any connections to the waveguide must be made in line with the fields within the waveguide - this will only work when the alignment of the fields is predictable.

The pattern of electric and magnetic fields is not static because they form an EM Wave that is travelling along the waveguide. In the time taken for one half-cycle of the wave, for example at 3 GHz it is one-sixth of a nano-second, the pattern moves along by one half-wavelength. The pattern currently shown would appear similar but the directions of the fields would have reversed.

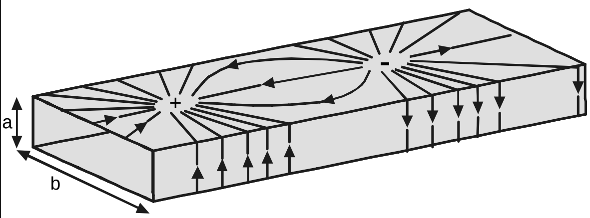


Figure 7: Pattern of Wall Currents in a Waveguide

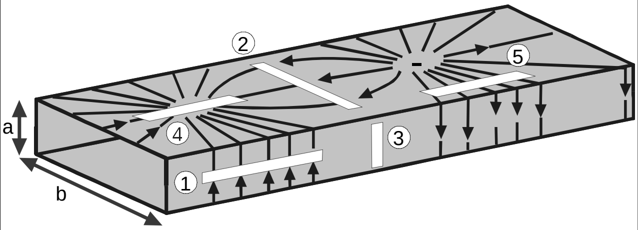


Figure 8: Slots of Differing Orientation in a Waveguide

WALL CURRENTS IN A WAVEGUIDE

As the wave travels along the guide, its fields cause currents to flow on the inside surface of the guide. These currents flow between points of maximum electric field (the currents are alternating - at each half-cycle of the wave). Figure Seven shows the pattern of wall currents at one instant - the whole pattern moves rapidly along the guide. Note that these currents flow only on the inside surface of the waveguide.

It is often necessary to insert probes into a waveguide, for example to check that a radar transmitter is operating at the correct power. If a small slot is cut into the waveguide so that it runs parallel to the wall currents then that slot will have little effect on them. The currents just part, slightly, to pass the slot. A probe can then be inserted without affecting the propagation in the guide. (See Slots Three and Four in Figure Eight.)

When some energy is to be extracted from a guide then a slot can be cut across the wall currents. This impedes their flow and produces an electric field across the slot. The slot acts as an antenna and energy is radiated outwards. (See Slots One, Two and Five in Figure Eight.) Note that the slot is equally effective as a receiving antenna because the incoming EM wave causes currents to flow on the outside surface of the waveguide. The slot interrupts these currents and an electric field is produced across it. This field transfers energy into the guide.

WAVEGUIDE JOINTS

Figure Seven shows the pattern of wall currents in a waveguide. These currents must also flow across any joint between two waveguides and any misalignment or gap at the joint could act like Slot Two of Figure Eight. This would cause energy to escape and, at high powers, could even cause sparking across the gap. Any ordinary joint between two waveguides would never achieve the required contact over the entire joint. To overcome this problem, special types of joins have to be made in waveguides and one common type of waveguide joint is the ‘choke-flange joint’, shown in Figure Nine.

These joints do not attempt to make a perfect physical connection between two waveguides - instead, the joints use the properties of waves. Whenever a wave meets a discontinuity then the wave is reflected. This means that any part of the wave that passes into the choke joint can be made to reflect back out again.

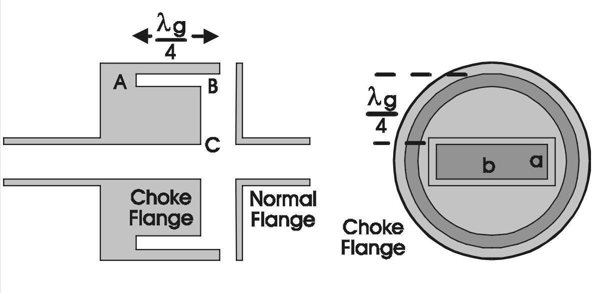


Figure 9: A Choke-Flange Joint

The distance between Point ‘C’ and Point ‘B’ is chosen to be equal to one-quarter of the wavelength of the EM Wave in the guide. As the energy flows along the guide then some will leak into the joint - but it will be reflected from Point ‘B’ and arrive back at Point ‘C’ in anti-phase. This will cause cancellation and, effectively, no energy will leak from ‘C’ to ‘B’.

The depth of the groove on the choke-flange, distance C - A on the Figure, is exactly half a wavelength of the EM energy in the guide. If any energy leaks from Point ‘C’ to Point ‘A’.then it will be reflected by the solid, metal end of the groove. A wave that is reflected by solid metal is reflected with a change of phase of 180°. The reflection then returns to Point ‘C - having travelled a distance of one whole wavelength and been inverted by the reflection - this again, causes cancellation of the energy.

Thus, the choke joint provides a perfect connection, regardless of any poor contact at the joint. The choke joint can also be used most effectively in rotating joints where it is not practicable to try to maintain a perfect electrical contact, due to the movement of the joint.

A long string of choke-flanges can be used to make a flexible waveguide, as shown in Figure Ten.

CONNECTING COAXIAL CABLE TO A GUIDE

The energy in a coaxial cable can be coupled to the electric field of a waveguide using the arrangement shown in Figure Eleven. The central conductor of the cable protrudes through a slot into the waveguide - and it is arranged across the short (‘a’) dimension. When EM energy comes down the cable then the ‘probe’ acts as an antenna and radiates into the guide. The probe may be moved in and out to adjust the amount of energy transferred. (Slot Four in Figure Eight would be a suitable slot for such a probe.)

Probe coupling: The end wall is one-quarter of a wavelength from the probe. (This is one-quarter of the

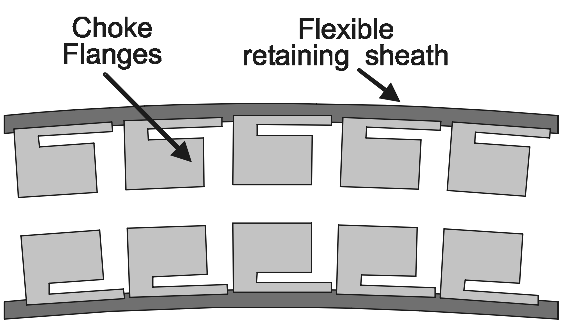


Figure 10: A Flexible Waveguide

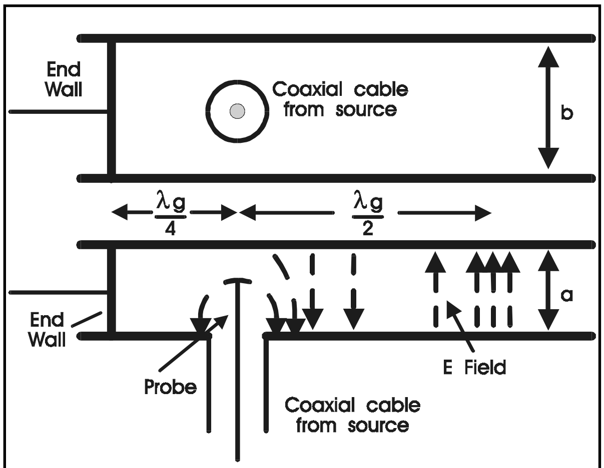


Figure 11: Probe Coupling, between Coaxial Cable and Waveguide

wavelength in the guide - which is about √2 greater than the free-space value.) The energy that goes left, towards the end wall is reflected back and arrives in-phase to re-inforce the energy from the probe. (It is in-phase because the distance travelled is 2 × λ/4 plus another 180° caused by the reflection - this amounts to one wavelength or 360°.) The end wall can be made from a moveable piston (as shown in the Figure) that can be adjusted for optimum performance during manufacture and then locked into position for normal use.

Some systems use a small probe, located off-centre, to extract a small sample of the energy passing along the guide for test purposes or to monitor the performance of the system. In this arrangement, most of the EM Wave misses the probe and just a small sample is taken.

The energy in a coaxial cable can also be coupled to the magnetic field in a waveguide, using the arrangement shown in Figure Twelve. The probe can be rotated to adjust the amount of energy transferred. When the probe lies across the magnetic field then there is maximum coupling. If the probe is rotated until it runs parallel to the field then the amount of coupling reduces to zero.

DIRECTIONAL COUPLING

A directional coupler allows only signals travelling in one direction to cross from one waveguide to another. A simple directional coupling is shown in Figure Eleven.

The device of Figure Eleven requires that the distance between the two coupling slots is one-quarter of the wavelength of the energy in the guide. Energy from

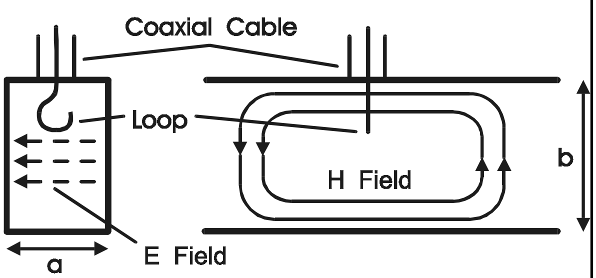


Figure 12: Loop Coupling, between Coaxial Cable and Waveguide

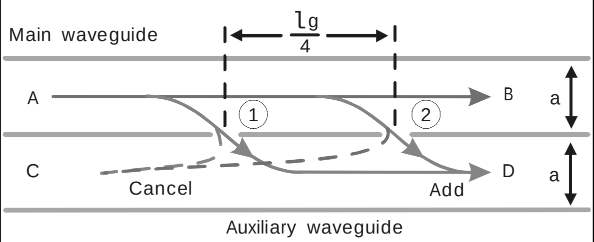


Figure 11: A Directional Coupling

an EM wave passing from left to right can reach Point 'B' and Point 'D' because the energy that passes through Slot '1' has travelled the same distance as the energy from Slot '2.

For energy travelling from Point 'A' towards Point 'C', the path to Point 'C' via Slot '2' is half a wavelength longer than the path via Slot '1'. This means that no energy can pass from Point 'A' to Point 'C'.

Similarly, energy can pass from Point 'B' to Points 'A' and 'C' but not to point 'D'.

WAVEGUIDE ATTENUATORS

One way to reduce the power emerging from a waveguide is to absorb it in an attenuator. This might be an easier option that trying to adjust the device that is generating the energy (e.g. magnetron). One type of waveguide attenuator is a block of resistive material, such as carbon, that is mounted inside the waveguide. As the EM waves pass through the material then it converts their energy into heat - effectively reducing the energy in the wave. Such an attenuator can be used as a 'dummy load' - replacing the antenna during tests so that no energy is actually radiated.

If the resistive material is made in the shape of a vane then it can be inserted through a slot in the waveguide and the depth of insertion can be changed to determine the amount of attenuation. Such a device is used in the Command transmitter of Rapier systems to reduce the transmitted power whilst the missile is close to the launcher. This is necessary to avoid damaging the receiver circuits on the missile, whilst it is a close range. When the missile is at a safe distance then the attenuator is withdrawn and full power is transmitted.

Examples of waveguide attenuators are shown in Figure Twelve. These attenuators get hot in operation and might require cooling if in constant use. The attenuator block, wedge or vane is often tapered so that the EM wave encounters it gradually, as this reduces reflections from the attenuator.

HYBRID RING (RAT-RACE) MIXER

This device is used where microwave signals are combined or 'mixed'. Mono-pulse tracking radars need to combine up to four radar echoes to track a target. This involves adding or subtracting the signals and it is performed using a hybrid ring, illustrated in Figure Thirteen. The operation of this device relies on the differences in lengths between the clockwise and anti-clockwise paths between one Port and another. All the paths differ by either one whole wavelength (constructive interference) or by a half-wavelength (destructive

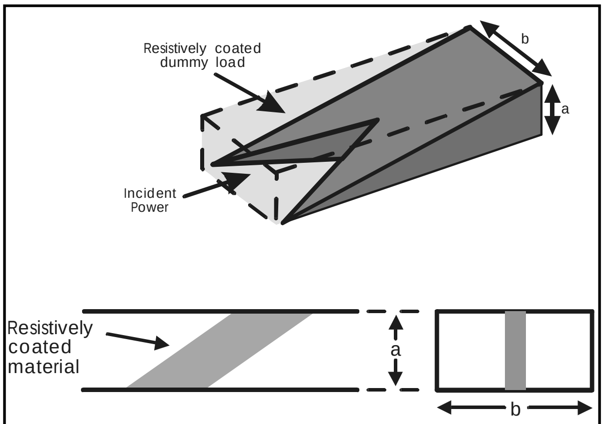


Figure 12: Waveguide Attenuators: Top: Tapered Dummy Load Bottom: Resistive Coated Vane

interference). The operation to add and subtract two signals is as follows:

- **Signal in at Port 'A'**: output at Port 'B' because the clockwise energy travels $1^1/_4\ \lambda$ and it is re-inforced by the anti-clockwise energy that has travelled $^1/_4\ \lambda$. Output at Port 'D' where both routes are $^3/_4\ \lambda$ but this is in anti-phase to that at Port 'B' because it has travelled an extra $^1/_2\ \lambda$. No output from Port 'C' because the two routes differ by $^1/_2\ \lambda$.
- **Signal in at Port 'C'**:output at Port 'B' where the two routes are $^1/_4\ \lambda$ and $1^1/_4\ \lambda$. Output at Port 'D' where the two routes are again $^1/_4\ \lambda$ and $1^1/_4\ \lambda$. Unlike the previous case, these two outputs are in the same phase as each other. No output from Port 'A' because the two routes differ by $^1/_2\ \lambda$.

Thus, if two signals enter the device, one at Port 'A' and the other at Port 'C' then the outputs are:

- **Port 'B'**: the SUM of 'A' and 'C' because each travels the same distance to get to Port 'B'.
- **Port 'D'**: the DIFFERENCE between 'C' and 'A' because the signal from Port 'A' has to travel by an extra $^1/_2\ \lambda$ to reach Port 'D' (compared to the signal from Port 'C') so it is in anti-phase, upside down or negative.

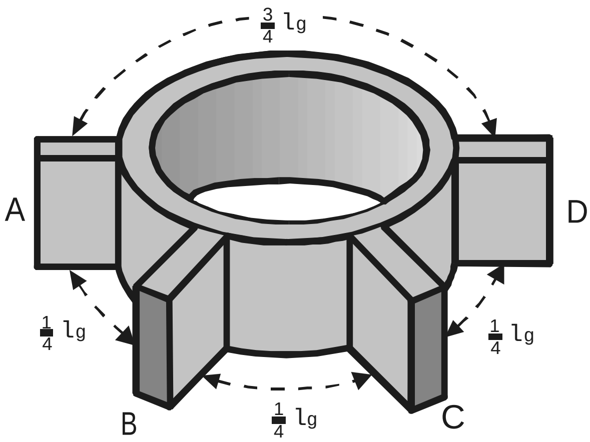


Figure 13: The Hybrid Ring (Rat-Race) Mixer

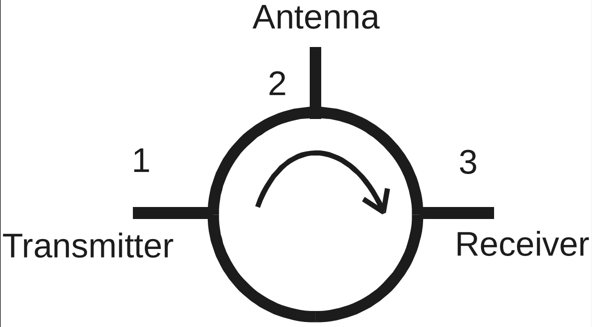


Figure 14: Three-Port Circulator used for T/R Switching in a Radar System

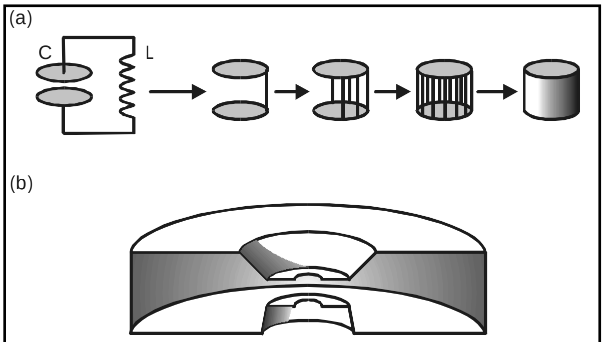


Figure 15:
a. Evolution of LCR Resonant Circuit into a Cavity
b. A Practical Resonant Cavity

THREE-PORT CIRCULATOR

This is a device similar to the hybrid ring, but with three ports. The ports are usually numbered 1, 2 and 3 and the device has the useful property that energy entering one port can only reach the next port around the ring. Thus, energy can pass from Port '1' to Port '2', from Port '2' to Port '3' and from Port '3' to Port '1'. Other combinations are prevented by the geometry of the device.

One use of the three-port circulator is in a pulse radar where the transmitter and receiver both use the same antenna. When the transmitter produces a pulse then the receiver must not be connected to the antenna. The outgoing pulse would destroy the receiver if it could reach it. A few micro-seconds later, the radar echo must be directed from the same antenna into the receiver. A mechanical switch could not be used because it would be much too slow. The three-port circulator can be used as shown in Figure Fourteen, to solve the problem.

The output from the transmitter circulates from Port '1' to Port '2' (the antenna) but cannot reach Port '3' (the receiver). The radar echo returns from the antenna into Port '2' where it circulates to Port '3' (the receiver). This device is called a Transmit/Receive Switch (T/R Switch) when it is used to switch the radar signals in this manner.

These switches are not perfect and some energy inevitably leaks past. Therefore, a practical radar system will have additional devices to reduce further any energy from the outgoing pulse that might find leak into the receiver.

When the radar is powered down, an adjacent friendly radar or an enemy could direct sufficient EM energy into its antenna to damage the receiver's circuits. To reduce the threat from this, a mechanical 'shutter' may be used to close-off the waveguide when the radar is off. When the radar is turned on then an electromagnet (solenoid) automatically pulls open the shutter. When the power is removed then a spring automatically closes the protective shutter.

CAVITY RESONATORS

At radio frequencies, a 'resonant' or 'tuned' circuit can easily be used to set the frequency of operation of a circuit. These resonant circuits contain an inductor (coil of wire) and a capacitor (pair of metal plates); their theory is covered in the Alternating Current handout. Briefly, the resonant circuit gives maximum response over a narrow band of frequencies, centred on its 'resonant' frequency. Frequencies outside that band are rejected.

At radar frequencies, it is not practicable to use ordinary inductors and capacitors to make a resonant circuit. This is because the skin effect would make the resistance of standard tuned circuits too high and their open construction would cause them to act as aerials, giving excessive radiation loss.

To reduce the resistance due to skin effect, a large conducting area is required, and to prevent radiation loss, the tuned circuit must be enclosed in such a way that it cannot radiate EM fields. Both of these provisions are met by the cavity resonator.

The equation for the resonant frequency (f) of a circuit that contains and inductor (L) and a capacitor (C) is given by the equation:

$$f = \frac{1}{2\pi\sqrt{(LC)}}$$

Consequently, as the operating frequency rises then the values of inductance, L, and capacitance, C, in a tuned circuit must be reduced. To make a tuned circuit for microwaves, the number of turns in the coil would be reduced to one, and the capacitance would also be made smaller, by increasing the distance between the metal plates. The final result would be a straight piece of wire providing the inductance, with two small discs mounted at either end to provide the capacitance, as illustrated in the first diagram of the sequence at Figure Fifteen, (a).

To lower the inductance still further, other pieces of wire would be placed in parallel with the first until eventually the parallel wires form a hollow cavity of high surface area with very low surface resistance. This is a resonant cavity, which is the tuned circuit used at microwave frequencies. The cavity resonator shown at Figure Fifteen, (a), is cylindrical, but any hollow metal structure can act as a cavity resonator. The smaller the dimensions of the cavity, the higher the frequency at which it resonates. High-power cavities are difficult to implement at high frequencies because the wavelength is small and, consequently, the cavity must also be small. This makes electrical breakdown (arcing) more likely as the sparks have a shorter distance to jump across the smaller cavity.

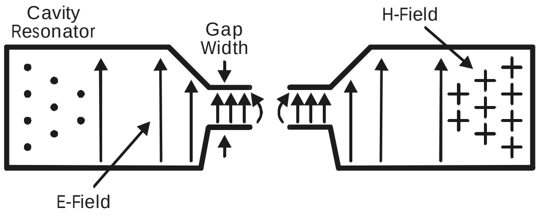


Figure Sixteen: The Electric (vertical) and Magnetic (horizontal) Fields in a Rhumbatron

Figure Fifteen, (b), shows the cross-section of a particular type known as a 'rhumbatron'. In this type of resonator, the centre is pinched so that the electric field is more concentrated there. The signal is connected to the centre part of the rhumbatron. It acts as a parallel combination of inductor and capacitor, forming a resonant circuit.

Bandwidth: cavity resonators have a very narrow range of resonance - much narrower than that of conventional tuned circuits. The tuned circuit used in a radio receiver might have a bandwidth of around 0.5 - 1% of the operating frequency. A resonant cavity could have a bandwidth of around 0.05% of the operating frequency (i.e. around twenty times better).

Cavity resonators are used in klystrons and magnetrons (these devices are used to produce high-power signals in radar transmitters) and they form integral parts of the valves, so that no connecting wires between valve and tuned circuit are necessary. The resonant frequency of the cavity determines the frequency of operation of the whole system and many systems have cavities fitted with moveable metal vanes that can be used to vary the size of the cavity and, hence, its operating frequency. Some cavities might have 'tuning screws' that can be screwed into or out of the cavity to adjust its frequency.

The electric and magnetic field distribution within a cavity at one instant is shown at Figure Sixteen. The electric field crosses between top and bottom surfaces, near the centre. The magnetic field is made up of circular lines of force, running horizontally around the ring, towards the outside edge. When resonating, the fields will continually grow to maximum, reduce to zero and then grow to maximum in the opposite directions at the same frequency as the RF oscillations.

Effectively, an EM wave is passing from the centre, radially outwards to the rim and then being reflected back to the centre again. Resonance occurs when there is an external signal at the centre of the cavity whose frequency is the same as the resonant frequency. Energy from each cycle of the signal then arrives synchronised with the stored energy of the EM wave in the cavity. The two add and a larger signal results.

Some devices use several cavities to give a combined effect where the resonance is much more effective (a bit like a four-cylinder engine, compared to a single-cylinder engine). This results in both more power and a narrower bandwidth. The drawback is that all cavities must be adjusted so that each has the same resonant frequency. This requires high accuracy and it can be accomplished using a set of screw adjusters for each cavity that move small pieces of metal into or out of the cavity. Changes of temperature, vibration and the passage of time cause small variations in the settings. Consequently, such a system requires regular re-adjustment.

FORMULAE & TERMS IN THIS HANDOUT

Coaxial Cable:
Typical Impedance 50 - 100 Ohms.
Losses increase significantly above GHz.
Short runs only at GHz frequencies.

Ribbon Cable (Transmission Line):
Typical Impedance 300 Ohms
Balanced line, used in USA for TV and VHF systems,
Radiates more energy at high frequencies

Skin Effect:
Current moves towards surface of a conductor as the frequency increases. At GHz frequencies, the skin depth might be only few microns. Causes an increase in resistance (and power loss) at high frequencies.

Waveguides:
Current flows on inside skin - large surface area gives low resistance. Inside surface must be good conductor and not corroded.
Not easy to bend as they are made from solid copper (or other good conductor) tubes.

The 'a'-dimension is half the 'b'-dimension.
Longest Wavelength: when 'b' = the wavelength.
Shortest Wavelength: when 'b' = half the wavelength
Optimum Wavelength: when 'b' = Wavelength ÷ √2
Typical Guide Impedance 530 Ohms
Low loss: only a few dB per 100 m (on a good day)

Probe Coupling:
Through a slot at the middle of the long ('b'-dimension) side, projecting into the guide across the short ('a') dimension. Couples to electric field.

Loop Coupling:
Through a slot across the short side of a guide, projecting into the guide at the top of the long ('b') dimension. Couples to the magnetic field.

SELF-TEST QUESTIONS

1. When an ordinary mains cable is used to convey energy at GHz frequencies then it is true to say that:

a. no energy is radiated.
b. current flows in the centre of the conductor.
c. the cable has a much higher resistance than normal.
d. the magnetic field passes through the conductors.

2. The ‘Skin Effect’ causes the current through a conductor to:

a. decrease at high frequencies.
b. increase at high frequencies.
c. flow along the centre of the conductor.
d. radiate outwards from the surface of the conductor.

3. When a pair of parallel wires is used to convey EM energy then the:

a. energy travels between the wires in the form of fields.
b. electric field lines encircle the conductors
c. gap between the wires is about one wavelength.
d. energy travels along inside the conductors.

4. The electric field inside a coaxial cable is directed:

a. along the length of the cable.
b. circulating around the central conductor.
c. entirely inside the central conductor.
d. radially, between inner and outer conductors.

5. At a frequency of several GHz, a coaxial cable would be used for:

a. connections over short distances and in confined spaces.
b. long runs, in mostly straight lines.
c. carrying mains power.
d. eliminating the skin effect.

6. One difference between a ribbon cable and a coaxial cable is that the coaxial cable:

a. has a lower impedance.
b. has a higher impedance.
c. radiates more of the energy it is transmitting.
d. is a balanced transmission line.

7. A plane wave cannot propagate along a waveguide because its:

a. electric field would be at right-angles to a conductor.
b. electric field would cut a conductor.
c. magnetic field would cut a conductor.
d. magnetic field would lie parallel to a conductor.

8. For optimum transmission of a 5 GHz signal, the height of the waveguide (‘b’-dimension) should be approximately:

a. 3.0 cm
b. 4.25 cm
c. 6.0 cm
d. 8.5 cm

9. A waveguide of height 1 cm gives optimum transmission when used with a wavelength of approximately:

a. 0.71 cm
b. 1.0 cm
c. 1.4 cm
d. 2.0 cm

10. A waveguide of height (‘b’-dimension) 5 cm could be used for EM waves with wavelengths between the extreme limits of:

a. 5 cm – 10 cm
b. 2.5 cm – 5 cm
c. 5 cm – 50 cm
d. 5 cm – zero cm

11. When a probe is used to couple energy into the electrical field of a rectangular waveguide then the probe is:

a. oriented across the long dimension of the guide.
b. placed right at one end of the guide.
c. oriented across the short dimension of the guide.
d. rotated to adjust the flow of energy

12. A horn is used at the end of a waveguide to:

a. reflect energy back into the guide.
b. form a gradual transition between the guide and free-space.
c. connect to a coaxial cable
d. connect to a ribbon cable.

13. In the diagram of Figure STQ1, energy can be coupled to the magnetic field in the guide by inserting a:

a. loop through Slot ‘3’.
b. probe though Slot ‘1’.
c. probe though Slot ‘5’
d. loop through Slot ‘4’

14. In the diagram of Figure STQ1, the slot that would radiate the least power is:

a. Slot ‘1’
b. Slot ‘2’
c. Slot ‘3’
d. Slot ‘5’

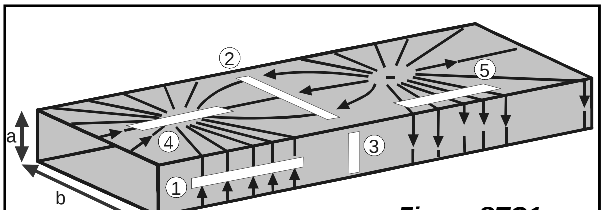


Figure STQ1

15. In the diagram of Figure STQ2, at Point ‘C’ there will be effectively:

 a. no electric field.
 b. no current.
 c. a poor connection between the two guides
 d. an open circuit.

16. In the diagram of Figure STQ2, any electric field that might appear across Gap ‘C’ will be:

 a. re-inforced by its reflection from Point ‘A’
 b. cancelled by its reflection from Point ‘A’
 c. used to stop current flowing from left to right.
 d. used to stop current flowing from right to left.

17. An attenuator in a waveguide is tapered in order to:

 a. reduce reflections.
 b. warm up quickly.
 c. only absorb energy in one direction.
 d. reduce surface area.

18. In the diagram of Figure STQ3, EM energy from Point ‘A’ is only able to reach:

 a. Point ‘B’
 b. Point ‘C’
 c. Points ‘B’ and ‘C’
 d. Points ‘B’ and ‘D’

19. A signal cannot pass from Port ‘A’ to Port ‘C’ of a hybrid ring (see Figure Thirteen) because:

 a. there is an attenuator in the way.
 b. waves that take different routes around the ring arrive in-phase.
 c. the path difference between the two routes is one wavelength.
 d. waves that take different routes around the ring arrive in anti-phase.

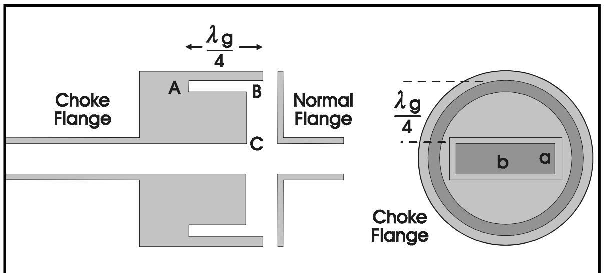


Figure STQ2

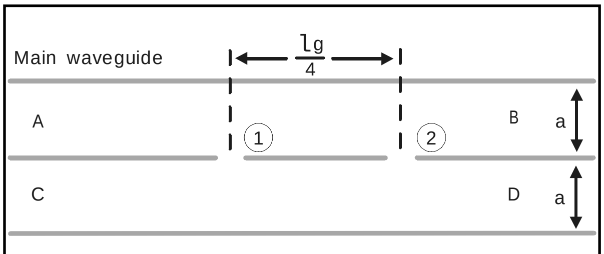


Figure STQ3

20. A three-port circulator allows energy that enters at Port ‘1’ to:

 a. exit from any odd-numbered port.
 b. exit from Ports ‘2’ and ‘3’
 c. exit from Port ‘2’ only
 d. exit from Port ‘3’ only

21. A resonant cavity would be used at microwave frequencies because it features:

 a. wide bandwidth.
 b. narrow bandwidth.
 c. high resistance.
 d. low resistance.

22. A resonant cavity is equivalent to a capacitor and:

 a. a resistor in series.
 b. a resistor in parallel.
 c. an inductor in series.
 d. an inductor in parallel.

23. The electric field of a cavity resonator is concentrated near the:

 a. pinch-point at the centre.
 b. flat metal disks top & bottom.
 c. vertical sides.
 d. large hollow space inside the cavity.

Answers

1. The Skin Effect increases the resistance (c)
2. More resistance = less current (a)
3. Transmission lines carry energy as fields (a)
4. Coaxial cables have a radial electric field (d)
5. Long coax, at GHz frequencies has high loss (a)
6. Coax = 50 - 75 Ohms, Ribbon = 300 Ohms (a)
7. Magnetic field cuts conductor = energy loss (c)
8. Wavelength = 6 cm, ‘b’ = 6 ÷ √2 = 4.25 cm (b)
9. Optimum Wavelength = ‘b’ × √2 = 0.71 cm (a)
10. Extreme range from λ = b to λ = 2b (a)
11. Probe goes in centre, across short dimension (c)
12. Horn used for gradual (smooth) transition (b)
13. Loop goes in slot across short side of guide (a)
14. Slots parallel to current radiate least (c)
15. Any electric field is cancelled by reflection (a)
16. See above (b)
17. Tapered to reduce reflections (a)
18. Reaches B & D. Routes to C differ by $\lambda/2$ (d)
19. Path difference is $\lambda/2$ & the two waves cancel (d)
20 Energy into any port and out of the next one (c)
21. The cavity has a narrow bandwidth (b)
22. Parallel LC Circuit. (d)
23. Electric field concentrates at narrowest point (a)
24. The metal screw adjusts the frequency (c)

Teaching Objectives		Comments
J.01.01 Describe the causes of losses when rf is conducted.		
J.01.01.01	Describe the origin of the skin effect.	
J.01.01.02	State that the skin effect causes increasing resistive losses that are significant as frequency and cable length increase.	Skin depth for Copper at 3 GHz is about 1 micron.
J.01.01.03	Describe how ordinary, open cables can radiate significant rf.	
J.01.01.04	State that radiation is reduced if the conductors are significantly closer than $\lambda/2$.	At 3 GHz, wavelength is 10 cm and conductors too close together.
J.01.02 Describe the basic principles of operation of coaxial and ribbon cable		
J.01.02.01	Describe the pattern of electric and magnetic fields along coaxial and ribbon cables.	Include boundary conditions.
J.01.02.02	State that the energy flows mostly in the fields between the conductors and guided by them.	
J.01.02.03	Compare the parameters of typical coaxial and ribbon cables.	
J.01.03 Describe the basic principles of operation of a waveguide		
J.01.03.01	Describe the reasons why a plane wave cannot pass along a waveguide.	Reason why waveguides need 'special fittings' (e.g. horn) to get the wave in and out.
J.01.03.02	Describe the basic pattern of electric and magnetic fields along a rectangular waveguide.	Determines orientation of attenuators (e.g. command transmitter).
J.01.03.03	Describe the basic pattern of wall currents around the inside of a rectangular waveguide.	Determines orientation of slots for probes, etc. Need to reduce corrosion on inside.
J.01.03.04	Calculate the longest, shortest and optimum wavelengths & frequencies for a rectangular guide.	Determines limits of operating frequencies and powers.
J.01.03.04	State that circular waveguides are used to connect to rotating antennae.	Similar field patterns to those in coaxial cable.
J.01.03.06	State the parameters of typical waveguides.	
J.01.03.07	State that waveguides may be pressurised to reduce or eliminate arcing at high powers and frequencies	E.G. Blindfire tracking radar

Teaching Objectives		Comments
J.01.04 Describe the various ways of coupling energy into and out of a waveguide		
J.01.04.01	Describe the principles of loop and probe coupling.	E.g. between magnetron & guide.
J.01.04.02	Describe the principles of slot coupling.	E.g. command antennae on rapier missile
J.01.04.03	Describe the principles of directional coupling.	E.g. rearward looking antennae on missile
J.01.04.04	Describe the principles of the choke joint.	Used to connect one waveguide to another.
J.01.04.05	Describe the principles of the waveguide horn.	Used for matching.
J.01.04.06	Describe the methods used to attenuate and absorb the energy in a waveguide.	
J.01.05 Describe the operation of the hybrid ring and circulators.		
J.01.05.01	Describe the operation of a hybrid ring as a means of adding and subtracting waves.	E.g. processing signals in tracker radar.
J.01.05.02	Describe the operation of a three-port circulator.	
J.01.05.03	Describe the operation of a T/R switch using a three-port circulator.	
J.01.05.04	Describe the operation of a mechanical shutter to protect a receiver.	
J.01.06 Describe the properties of resonant cavities		
J.01.07.01	Identify a resonant cavity.	
J.01.07.02	Recognise the equivalent LCR circuit of a resonant cavity.	
J.01.07.03	Describe the electric and magnetic fields in a resonant acvity.	