ROYAL SCHOOL OF ARTILLERY

BASIC SCIENCE & TECHNOLOGY SECTION
GUNNERY STAFF/CAREER COURSES

WAVEGUIDE

INTRODUCTION

1. The handout on transmission lines discussed the importance of an efficient RF energy transmission system between a transmitter and its aerial, and between aerial and receiver. Above 3GHz coaxial cable becomes inefficient because the skin resistance of the inner conductor results in considerable energy being lost as heat. At the same time losses in the polythene or PTFE dielectric also becomes appreciable.

2. For efficient transmission of EM energy at centimetric wavelengths the main type of transmission line used is a hollow metal tube or **WAVEGUIDE**. The EM wave is propagated inside the waveguide and very little wasted radiation can occur. The large surface area of the waveguide walls also results in low resistance losses and, as the energy is propagated through air inside the waveguide, the dielectric losses are low.

3. For these reasons waveguide is the most efficient form of transmission at any frequency but as will be seen later, the cross-sectional dimensions of the waveguide are related to the wavelength of the energy being propagated, and at low frequencies these dimensions are usually too large for practical use.

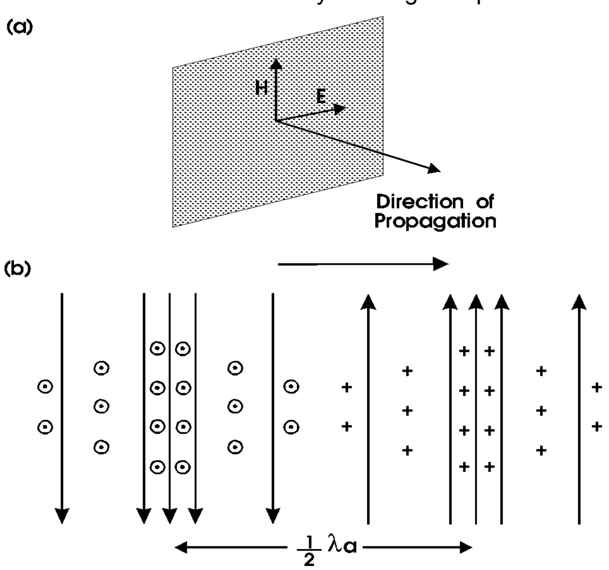


Fig.1. Transverse Electro-Magnetic plane wave

E & H FIELDS

4. In considering the transmission of EM energy along open wire and coaxial feeders the subject was dealt with in terms of voltage between the conductors and current flowing within them. However, it is also true that where there is a voltage difference between two points there must also be an electric (E) field between those points. Similarly, a current flowing in a conductor has a magnetic (H) field around the conductor associated with it. Thus it is just as possible to consider the energy being propagated in terms of E and H fields, and this is the method used in waveguides. A static E-field can exist by itself, as can a static H-field, but if an E-field is **changing** it always sets up an H-field and vice versa.

5. In dealing with radiation from an aerial, the EM energy was considered to be in the form of E and H fields. It is known that in free space a plane wave consists of alternating E and H fields at right angles to each other and transverse (at right angles) to the direction of propagation, as shown by Fig.1. The wave is called a **transverse electromagnetic** (TEM) wave and it moves through space at the velocity of light, c, with frequency, f, and free space wavelength, λa.

GUIDED WAVES

6. In order to think in terms of E and H fields and to see how RF energy may be guided, consider the two metal strips illustrated at Fig.2, in which an alternating current flows. If the two strips are perfect conductors, i.e. they have no resistance, the E and H fields must obey the following rules:-

> **a**. The E lines **always** terminate at 90º to the surface.
> **b**. The H lines **always** lie parallel to the surface of the conductor.

7. These rules are known as **boundary conditions**. No matter what form the fields take at a distance from the conducting surface, they must satisfy the boundary conditions **at the surface**. By applying these rules, a picture of the field pattern inside any shaped waveguide can be built up. The walls of the waveguide are not perfect conductors, i.e. they have some resistance, but this affects the field patterns only slightly.

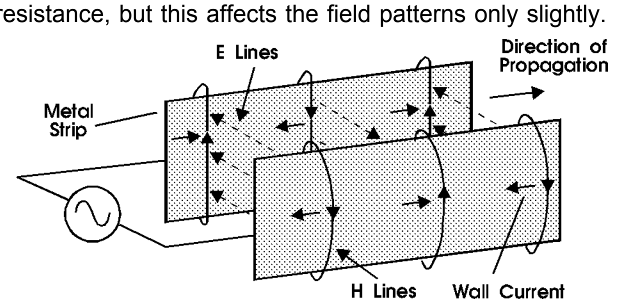


Fig.2. Boundary conditions

8. Associated with an alternating H field at a conducting surface is a current flowing on the surface. Its direction obeys the laws previously outlined during DC theory and is at right angles to the field. The strength of the H field depends upon the magnitude of the current and vice versa for induction.

RECTANGULAR WAVEGUIDE

9. In order to form a rectangular waveguide and so enclose the E and H fields of the plane wave shown at Fig.1, it is necessary to add two further conducting strips AB and CD as shown at Fig.3a. In trying to draw the E and H fields as before, it can be seen that the boundary rules are not obeyed. The E lines terminate at 90º on conductors AC and BD but are parallel to conductors AB and CD. Also the H lines, whilst being parallel to AC and BD, are at right angles to AB and CD.

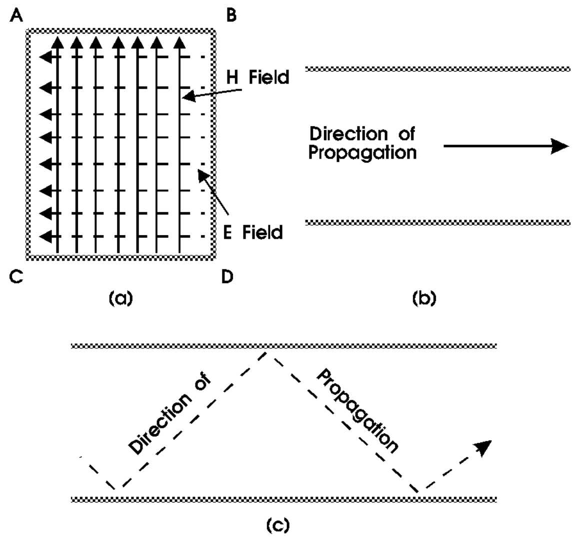


Fig.3. Propagation in a waveguide

10. Thus it is not possible for a plane wave to travel directly along the axis of a waveguide as required by Fig.3b. However, if the wavefront moves at an **angle** to the top and bottom walls of the waveguide as shown at Fig.3c, a field pattern which does obey the boundary rules is produced and energy may be propagated down the waveguide as illustrated by Fig.4. It is now necessary to consider how this field pattern is formed.

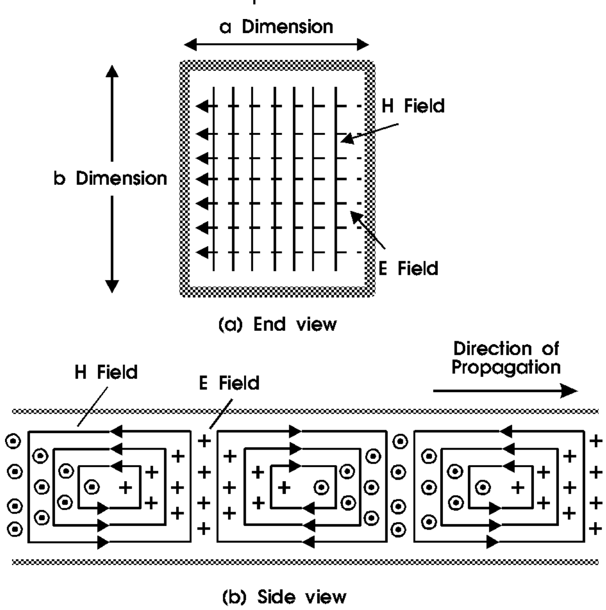


Fig.4. Field pattern in a rectangular waveguide

RECTANGULAR GUIDE FIELD PATTERN

11. Fig.5a shows an EM wave striking a horizontal conducting surface at an angle θ. The E field is parallel to the conducting surface and therefore the E field maximum is shown going into and out of the paper with phase reversals every half wavelength ($\lambda a/2$). Where λa is the free space wavelength. The H field maximum is represented by full lines at right angles to the direction of propagation, the arrows also showing reversal of phase every half wavelength. For clarity, only the maximum E and H fields are shown although, of course, the fields will vary sinusoidally. The direction of propagation is shown by the dotted line.

12. When the wavefront strikes the conducting surface it is reflected, as shown by Fig.5b, the new direction of propagation making the same angle θ with the reflecting surface as did the incident wave. The boundary condition is that at the surface the E field cannot exist parallel to the surface - it must be perpendicular or not exist at all. Therefore, since there is no perpendicular component, the E field must be zero at the surface. To satisfy this requirement an E field of equal amplitude but opposite phase to the incident E field is reflected from the surface. The sum of the two is then zero.

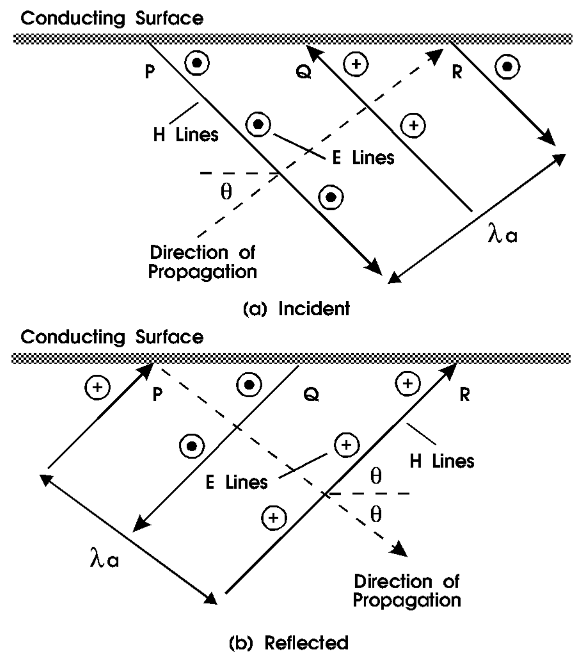


Fig.5. Incident and reflected waves

13. The boundary condition for the H field is that at the surface it must lie parallel to the surface, with no perpendicular component. Hence, on reflection the H field suffers a 2θº change in direction and its phase reverses. The vector sum of the incident and reflected H fields now lies parallel to the conducting surface at the surface. In this way boundary conditions for the combined incident and reflected waves are satisfied for both E and H fields. Adding vectorially the fields at all of the points, illustrated by Fig.6, gives H field loops and a diamond pattern of E fields as shown in more detail at Fig.7.

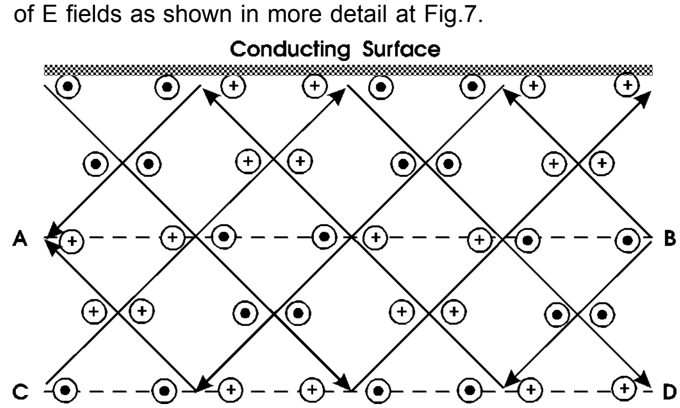


Fig.6. Incident and reflected wavefronts together

14. In addition to satisfying boundary conditions at the conducting surface, the rules are also satisfied at planes AB and CD. Therefore, a second conducting surface may be inserted at one of these planes, for example at plane AB. This gives rise to further reflections and the incident wave would then be propagated by "**bouncing**" between the two surfaces. The field pattern will be that shown in the upper portion of Fig.7. The *resultant* direction of propagation is parallel to the reflecting walls.

15. Had the lower reflecting surface been placed at plane CD

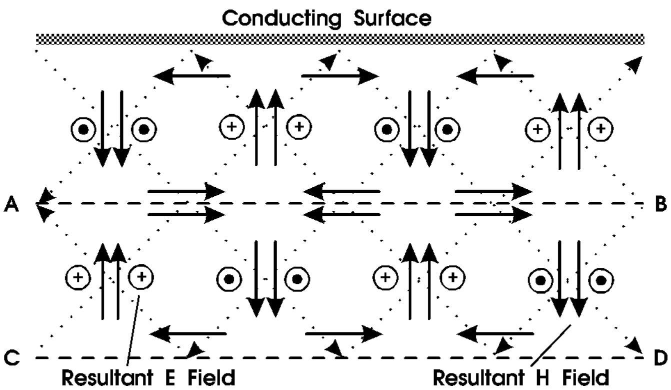


Fig.7. Incident & reflected waves combined

instead of at AB the pattern would contain *two* H loops, one above the other and energy is said to be propagated in a higher *mode*. Both possibilities are shown at Fig.8.

16. To confine the wave pattern in the horizontal plane a pair

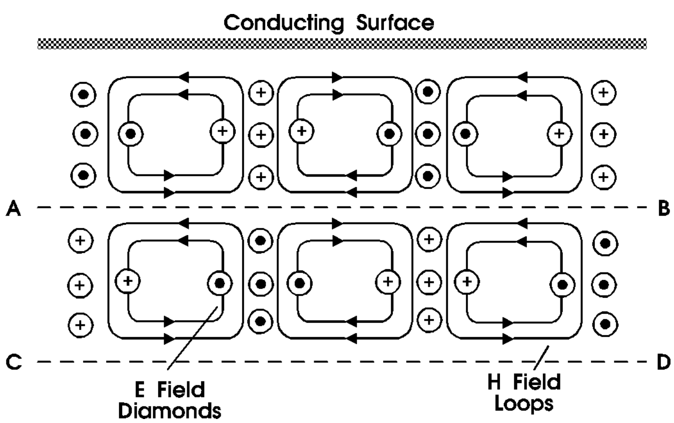


Fig.8. The resultant field pattern

of plates is placed as "***sides***" at right angles to the reflecting surface, forming a rectangular waveguide as shown at Fig.9. These plates satisfy boundary conditions, their minimum distance apart depends upon the power to be propagated, since if they are too close the resultant concentrated E field may arc between the plates. The narrow dimension between the side walls of the waveguide is usually called the ***a*** dimension and the broader side the ***b*** dimension.

So far it has been seen that:-

a. A plane wave cannot go directly down a waveguide since it does not satisfy boundary conditions.

b. A wave that "bounces" can move down a waveguide because the overlapping field patterns of the incident and reflected waves combine to produce a pattern that *does* obey boundary conditions.

c. This new pattern is not a TEM wave.

17. The field pattern formed inside the waveguide is shown in Fig.9 and, since there is a component of the H field in the direction of propagation, it is called an ***H mode***. This is sometimes called a ***transverse electric*** (TE) mode because the E field is transverse to the direction of propagation. To distinguish this mode from other H modes it is known as an H_{01} mode. The subscript 0 indicates that there is no change in field strength across the narrow side of the guide and the subscript 1 indicates that the field goes through one maximum value in traversing across the broad side of the guide.

GUIDE DIMENSIONS AND WAVELENGTH

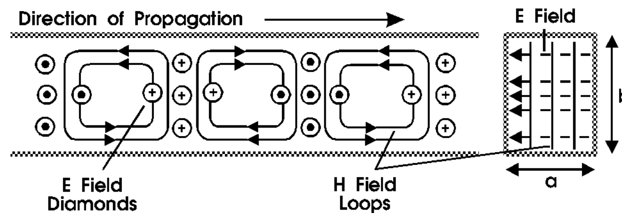


Fig.9. The H_{01} mode in a rectangular waveguide

19. Fig.10a represents a section of the field pattern of Fig.9. For clarity only the incident and reflected H field maxima are shown also the E field and resultant H loops are not indicated. The length of one complete field pattern is λg, a **guide wavelenth**. In Fig.10b the broad, ***b***, dimension has been reduced and λa remains unchanged. In order that boundary conditions are satisfied the angle θ increases, the diamond-shaped H lines become "squashed out" and $\lambda g/2$ *increases*.

20. Fig.10c shows the ***b*** dimension further reduced until it

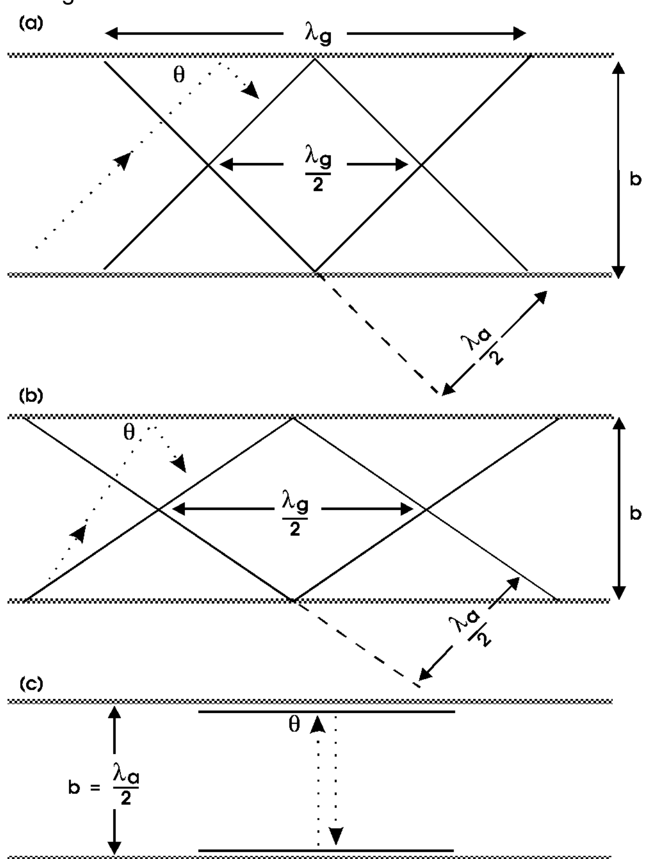


Fig.10. Effect of reducing the broad dimension with λa held constant

equals $\lambda a/2$. The angle θ becomes 90° and the wave front becomes parallel to the top and bottom guide walls. The wavefront bounces between these walls and no propagation along the guide occurs, i.e. **cut-off** has been reached.

21. In Fig.11 the ***b*** dimension is greater than λa. This allows two

H loops to form and the wave is propagated in the higher H_{02} mode. Cut-off wavelength for this mode occurs when λa=b.

22. Thus to propagate energy in the H_{01} mode, called the **dominant mode**, the waveguide must be designed with a ***b*** dimension *between* $\lambda a/2$ and λa. The ***b*** dimension is usually made $0.707\lambda a$, as θ = 45°, and the waveguide losses are lowest. The narrow, ***a***, dimension must be less than $\lambda a/2$ to prevent the field pattern moving through 90° into the other plane, i.e. to prevent the pattern shifting to the other walls so that ***a*** becomes ***b*** and vice versa. However, the ***a*** dimension must not be made too narrow otherwise arcing between the walls may result.

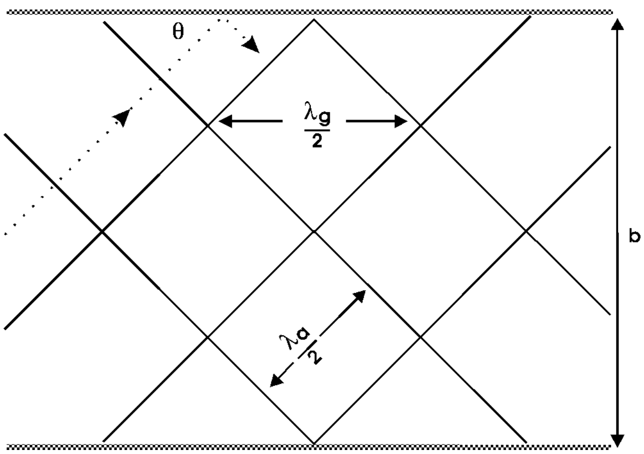


Fig.11. Effect of increasing the broad dimension with λa held constant

23. The normal waveguide is designed to propagate energy of a certain free space wavelength and its dimensions are fixed. However, similar effects to those illustrated by Fig.10 are obtained by variations in λa. Thus, for the fixed ***b*** dimension of Fig.10a, an increase in λa (decrease in frequency) would result in an increased λg as in Fig.10b. If λa is increased until it equals ***2b***, cut-off is reached as in Fig.10c. Similarly, if λa is decreased (frequency increased) such that λa is less than the ***b*** dimension, the H_{02} mode can propagate as in Fig.11. *Small* variations in λa do not affect wave propagation greatly.

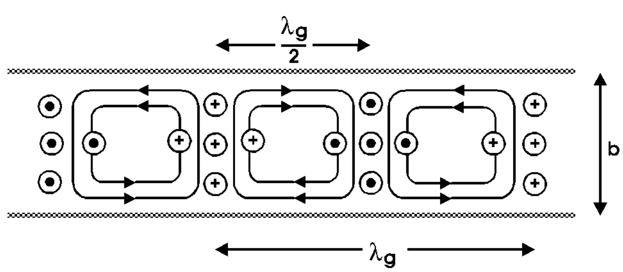


Fig.12. Guide wavelength λg

18. The field pattern illustrated by Fig.9 is that normally used to propagate EM energy down a rectangular waveguide and the following differences between this H_{01} guided wave and free space propagation should be noted:-

a. The length of waveguide occupied by a complete cycle of wave pattern (two H loops) is called a guide wavelength, λg, see Fig.12. This is always greater than a free space wavelength, λa.

b. The relation between λg and λa depends upon the *broad* dimension of the waveguide but is independent of the *narrow* dimension.

c. The free space wavelength must always be less than twice the broad dimension otherwise the wave is not propagated. The ***critical*** or ***cut-off*** wavelength for which λa = 2b is denoted by λc.

d. The velocity with which the ***pattern*** moves down the guide is called the **phase velocity**, vp, and is always greater than the velocity of light, c.

e. The component of the wave velocity along the axis of the guide is the **group velocity**, vg, and is the velocity with which the energy actually travels down the guide. This is always less than the velocity of light.

PHASE AND GROUP VELOCITIES

24. In the rectangular waveguide of Fig.13, the H lines move at an angle of incidence, θ, to the guide walls with the velocity of light, c. Thus in the time that point B moves to D, point A moves *along the guide wall* to D. As the distance AD is greater than the distance BD the point A moves along the guide wall at a velocity *greater* than that of light. This is the **phase velocity**, vp, of the wave in the guide. It should be noted that the phase velocity does not represent any physical movement down the guide, but is merely the movement of a point at which a phase change occurs at the guide wall.

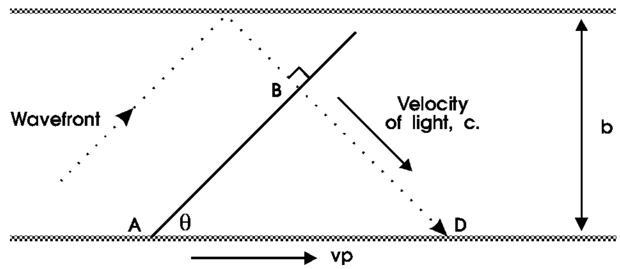


Fig.13. Phase velocity, vp.

25. Since the EM energy is following a zig-zag path down the waveguide with a velocity c, the resultant velocity *along the axis* of the guide must be less than c. This resultant velocity is the **group velocity**, vg, of the wave in the guide and is illustrated at Fig14. For a wave in free space of frequency, f, and wavelength, λa, c = f × λa. The corresponding relationship for a guided wave is vp = f × λg. Since is λg always greater than λa, vp must be greater than c.

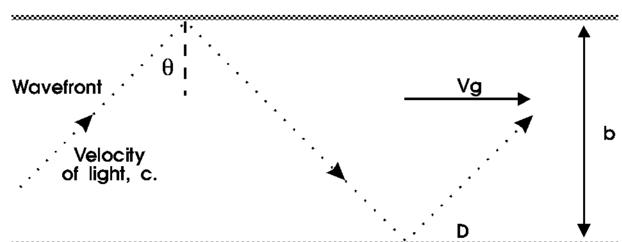


Fig.14. Group velocity, vg.

WAVEGUIDE LOSSES

26. An alternating magnetic field parallel to a conductor induces a current in the conductor. The direction of current flow is at right angles to that of the field causing it, and the amplitude of the current depends upon the intensity of the field. In a waveguide these currents are confined to a very thin skin on the inside surface of the walls.

27. In a rectangular waveguide propagating an H_{01} wave the wall current pattern is as shown at Fig.15. This is an instantaneous picture of the wall currents which are, of course, alternating and change direction every half cycle so they do not build up on the waveguide walls. The whole wall current pattern moves along the guide walls at the phase velocity of the wave.

28. The waveguide walls possess some resistance which means that power is lost as the wave travels down the guide. Attenuation in a rectangular guide depends upon:-

a. Guide dimensions.
b. Resistivity of the walls.
c. Frequency.
d. Mode of propagation.

Since attenuation depends upon surface resistance it is important to avoid corrosion on the inner surfaces. For this reason waveguides are often silver or cadmium-plated on the inside walls or are sealed off at each end by plastic diaphragms.

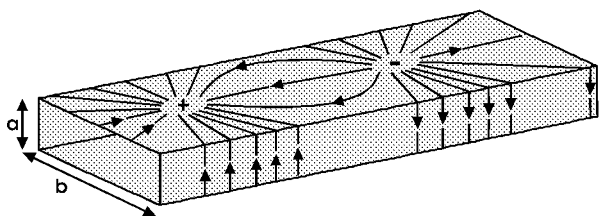


Fig.15. Waveguide wall currents

CIRCULAR WAVEGUIDE

29. Rectangular waveguides propagating the H_{01} mode are used for the main lengths of waveguide runs in most radar systems. However, short lengths of circular waveguide are required in systems which use a rotating aerial.

30. The E and H fields inside a circular guide must also obey boundary rules and if these rules are applied it is possible to build up the field pattern within a circular waveguide.

31. Fig.16a shows the field pattern inside a length of coaxial cable. It can be seen that the boundary rules are satisfied for both inner and outer conductors. Fig.16b shows how this pattern alters to obey boundary rules when the centre conductor is removed and a circular waveguide is formed. This field pattern is called the $\mathbf{E_{01}}$ mode, where:-

a. E indicates that a component of the E field is parallel to the direction of propagation.
b. The first subscript, zero, indicates the number of *complete* wavelength changes in the field pattern moving around the *circumference*.
c. The second subscript, one, indicates the number of *half-wavelength* changes moving across the diameter.

32. The E mode is sometimes called a **transverse magnetic** (TM) mode. The E_{01} mode is not the only field pattern which can form in a circular guide but it is the one most suitable for use with a rotating aerial since it has circular symmetry.

33. The H_{11} mode shown in Fig.16c does not have circular symmetry and although this is the dominant mode for circular waveguide, i.e. it has the longest cut-off wavelength, it is not suitable for use with a rotating device. Therefore, steps are usually taken to stop the H_{11} mode forming, and to encourage the formation of the E_{01} mode.

34. The cut-off wavelength for a circular guide is proportional to the diameter of the guide. Guide wavelength, λg, is always greater than free space wavelength, λa, just as in a rectangular guide.

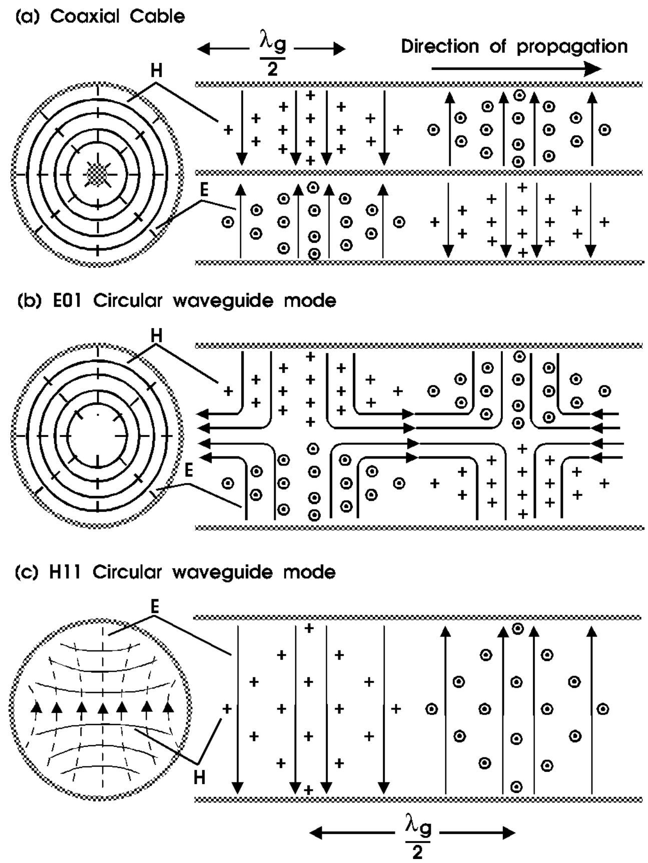


Fig.16. Coaxial cable and circular waveguide field patterns

WAVEGUIDE CHARACTERISTIC IMPEDANCE

35. In transmission line theory the concept of characteristic impedance was considered. For a plane wave in free space, the impedance of the medium through which it is passing is the ratio of E field strength to H field strength at any point, where the E and H fields are at right angles to to each other and transverse to the direction of propagation. This ratio is known as the **characteristic impedance of free space**, $\mathbf{Z_W}$. It has the value 377Ω.

36. The characteristic impedance of a waveguide, $\mathbf{Z_H}$, propagating a wave in the H_{01} mode can be calculated in a similar manner. The relationship is:-

$$\mathbf{Z_H} = 377 \times \frac{\lambda g}{\lambda a}\ \Omega.$$

Since λg is always greater than λa, Z_H is greater than Z_W. If the ***b*** dimension is gradually increased, λg becomes smaller and the guide impedance falls towards that of free space. Hence the horn shaped feed found in most point fed parabolic radar aerials. They cause the waveguide to be matched to the surrounding space.

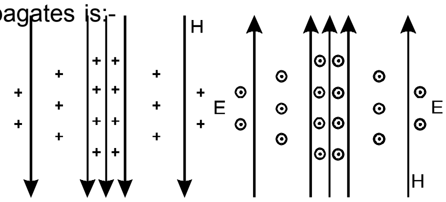
SELF TEST QUESTIONS

Read each question carefully and then select the single answer that you believe to be fully correct.

1. When waveguide is used for energy transmission:-

   a. the large guide wall area gives lower resistance losses
   b. all of the energy is constrained to remain within the guide
   c. dielectric losses are low
   d. all of a, b and c above are true

2. The following diagram shows a transverse electromagnetic plane wave during propagation. The direction in which the wave propagates is:-

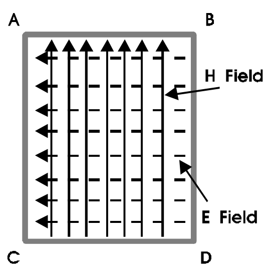


   a. left
   b. right
   c. up
   d. down

3. The boundary conditions associated with E and H fields adjacent to a conducting surface are:-

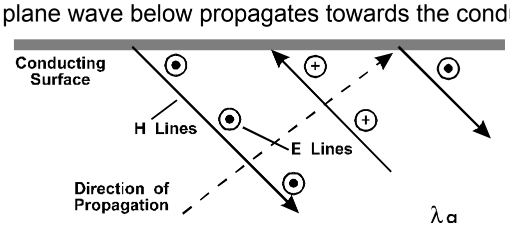
   a. E lines always terminate at 90° to the surface and H lines lie parallel to the surface
   b. H lines always terminate at 90° to the surface and E lines lie parallel to the surface
   c. E lines always terminate at 45° to the surface and H lines lie parallel to the surface
   d. H lines always terminate at 45° to the surface and E lines lie parallel to the surface

4. The rectangular waveguide structure illustrated below contains a plane wave. One of the reasons why the wave will not



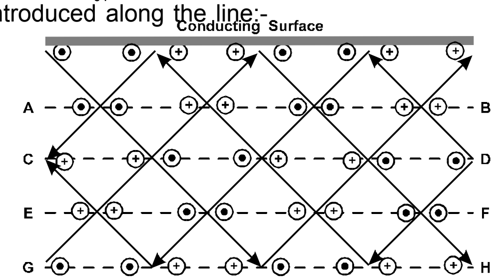
   be able to propagate within the guide is because:-
   a. the H field is parallel to the walls AC and BD
   b. the E field is perpendicular to the walls AC and BD
   c. the H field is not parallel to the walls AB and CD
   d. all of the answers at a, b and c above are true

5. The plane wave below propagates towards the conducting



   surface. In order to be reflected from that surface the:-
   a. direction of propagation must be reversed
   b. the E-field must be maximised at the surface
   c. the H-field must be minimised at the surface
   d. the E-field must be reduced to zero at the surface

6. The following diagram shows the E and H field patterns produced when a plane wave is reflected from the conducting surface within a waveguide. In order for the energy to propagate in the H_{01} mode, a second conducting surface must be introduced along the line:-



   a. AB
   b. CD
   c. EF
   d. GH

7. The difference between a TEM wave and a TE wave is that:-

   a. the TEM wave can be established in waveguide and the TE wave cannot
   b. the TE wave is used mainly for atmospheric propagation and the TEM wave is not
   c. a TE wave is able to propagate in waveguide with the H-field component along the guide. The TEM wave cannot
   d. a TEM wave is able to propagate in waveguide with the H-field component along the guide. The TE wave cannot

8. A rectangular waveguide is used in the dominant 'H' mode and its cut-off frequency is 6GHz. The dimensions of this waveguide are likely to be:-

   a. 1.25cm × 25mm
   b. 125mm × 2.5mm
   c. 2.5mm × 12.5cm
   d. 12.5mm × 50mm

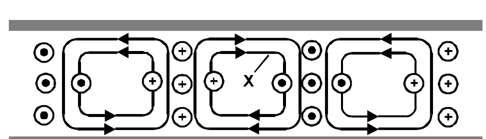
9. A rectangular waveguide used in the dominant 'H' mode measures 8cm × 4cm. The frequency at which this guide is designed to operate is:-

   a. 113.14MHz
   b. 2.65GHz
   c. 3.75GHz
   d. 7.5GHz

10. A rectangular waveguide operating in the dominant mode has a cut-off frequency of 12GHz. Its dimensions are likely to be:-

    a. 1.25cm × 0.625cm
    b. 0.625cm × 0.3125cm
    c. 2.5cm × 1.25cm
    d. 12.5cm × 6.25cm

11. The picture below shows the waveguide pattern for an H_{01}



    mode. The feature marked with an 'X' is:-
    a. an E-field loop
    b. the H-field directed across the narrow section of guide
    c. an H-field loop
    d. the E-field directed across the narrow section of guide