Antennas and Wave Propagation

G. S. N. Raju

ALWAYS LEARNING

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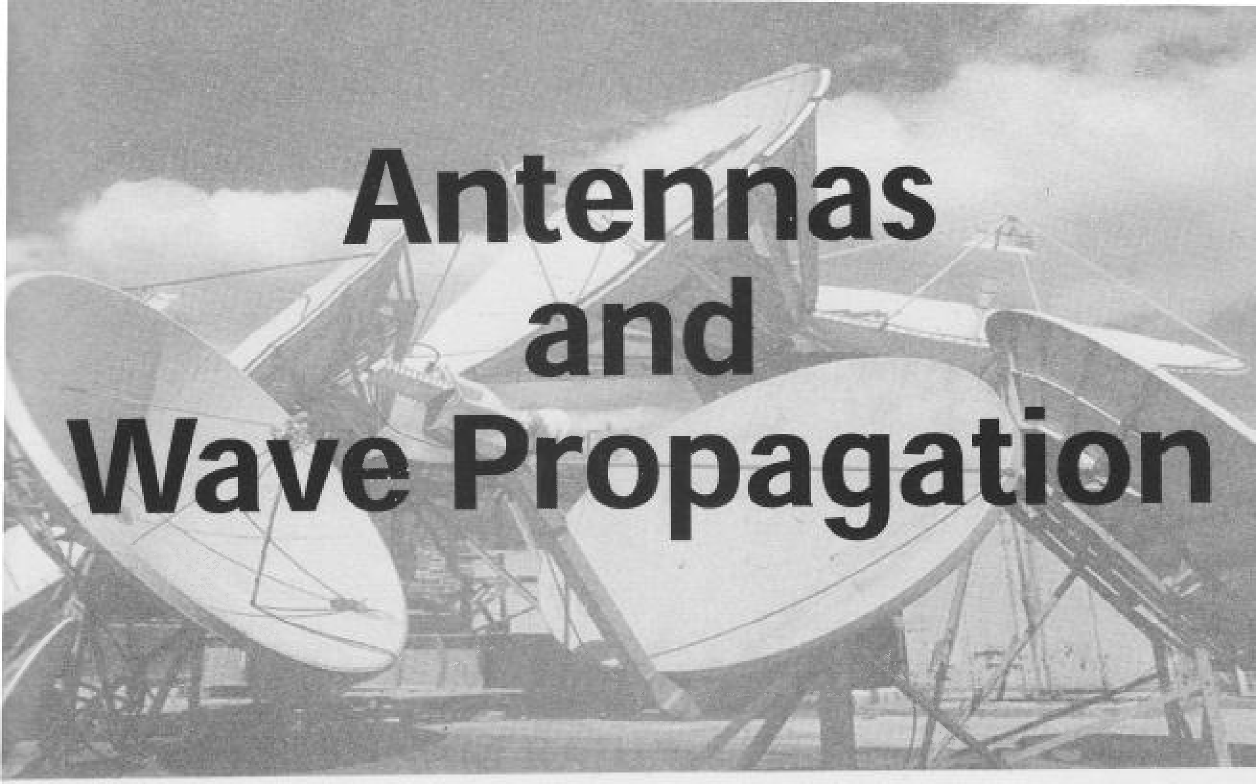

Antennas and Wave Propagation

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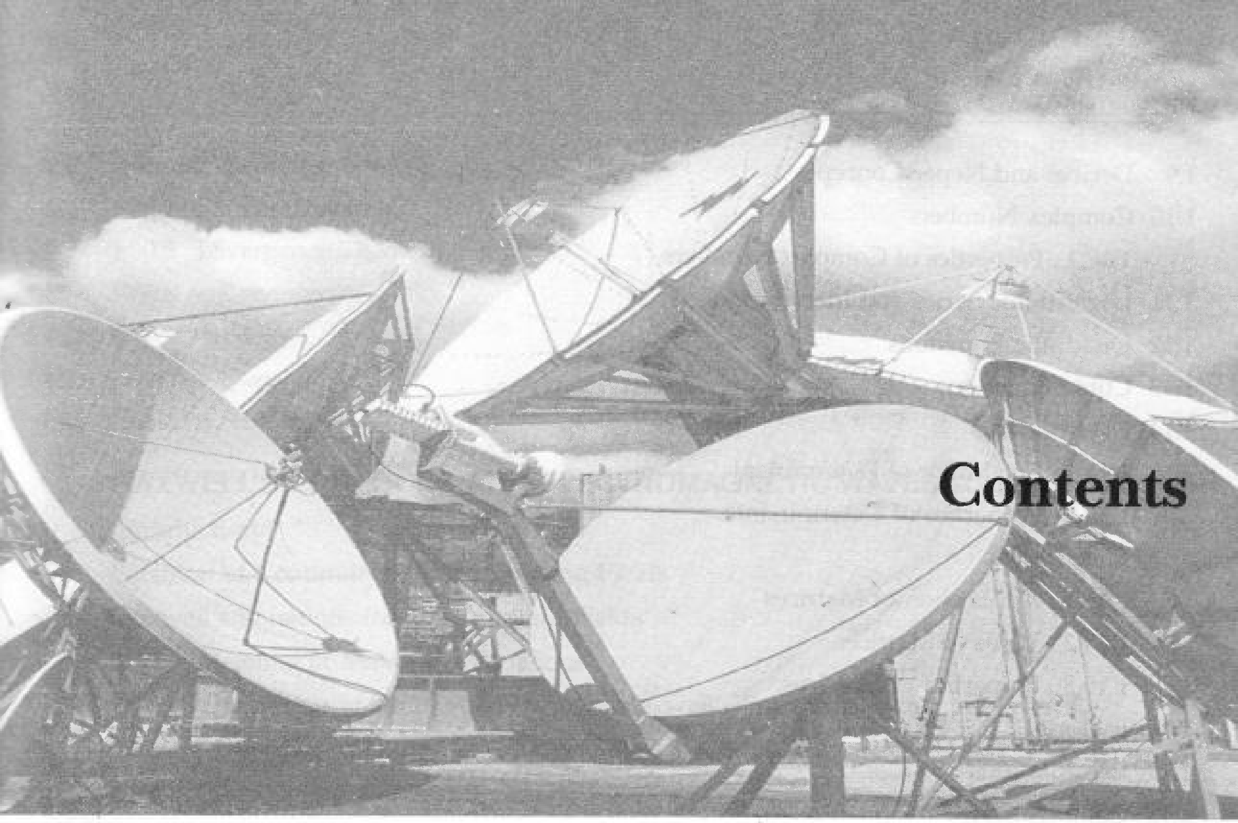
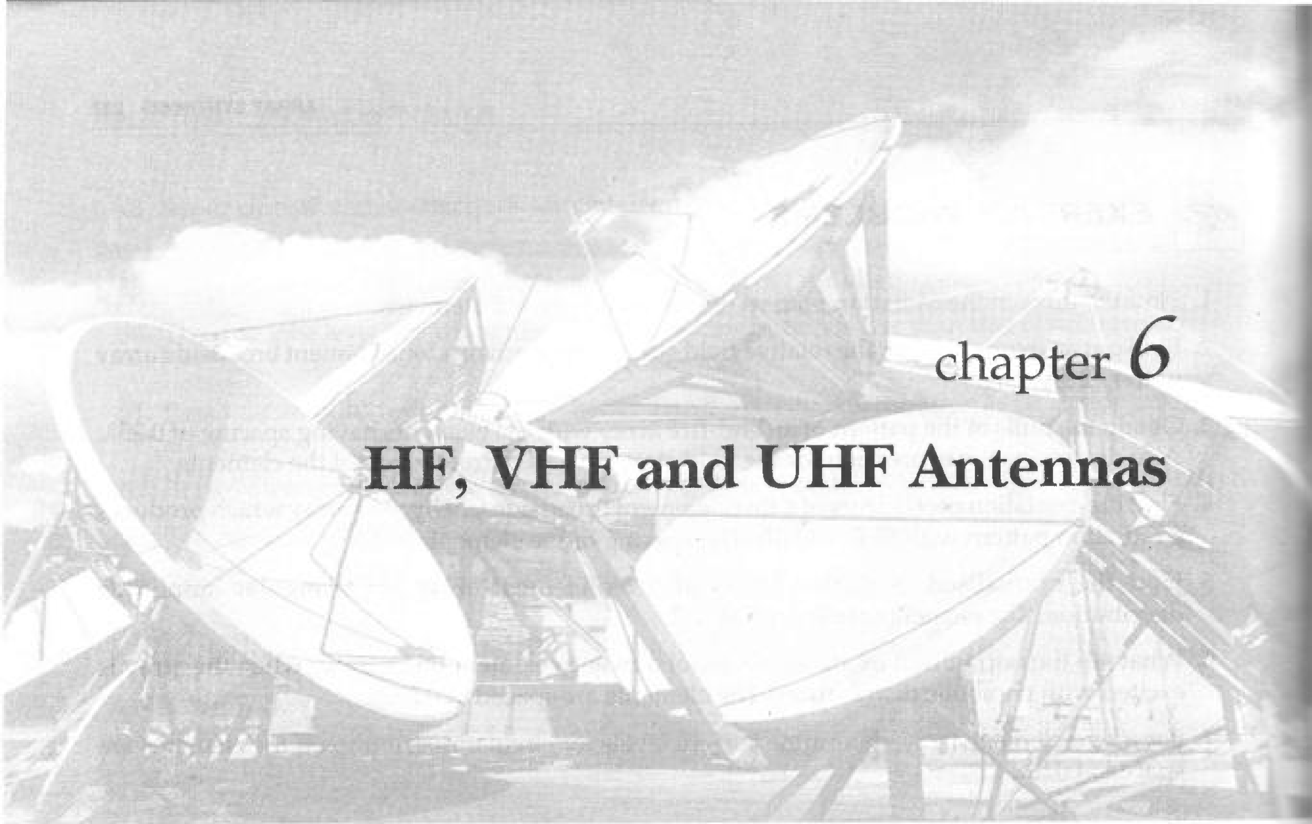


Contents

chapter 6

HF, VHF and UHF Antennas



"The size of antennas is small at high frequencies and it is large at low frequencies."

CHAPTER OBJECTIVES

This chapter discusses

- The design, construction, application and performance parameters of all types of HF, VHF and UHF antennas
- Merits and demerits of antennas
- Objective questions and solved problems useful for class tests, final examinations and also for competitive examinations
- Exercise problems to develop self problem solving skills

6.1 INTRODUCTION

The HF, VHF and UHF spectrum is between 3 MHz and 1 GHz. The range above 1 GHz is usually branded as the Microwave range. The main difference between the lower frequencies and HF, VHF and UHF spectrum is in the operating wavelength. It may be noted that the frequency and the wavelength are inversely proportional to each other. As a result, at low frequency, the wavelength is large and vice-versa. Each application makes use of any one of these ranges of frequency. For instance, a 6-meter amateur band lies in the lower end of the VHF range. It may be noted that the antenna bandwidth is a function of the ratio of its length to diameter. Hence, broadbanding of an antenna in VHF and UHF is easy.

It must be noted that the concept of HF, VHF and UHF antennas has limited validity as, in principle all forms of antennas can be used at all bands. The main limitation lies in the size of the antenna. When the antenna becomes larger, it is difficult to handle and it is also difficult to install.

Large array antennas, even in HF, VHF and UHF ranges, have high "windsail area". These antennas are therefore subjected to a lot of wind force. It is always advisable to install such antennas with a helper and with the help of hosts and other tools.

The impedance matching of VHF and UHF antennas is essential and suitable BALUNS are selected for the purpose.

An antenna is an essential device in all communications and radar systems. It acts as a transducer, impedance-matching device, radiator and receiver of electromagnetic waves. With a well-designed antenna, it is possible to have communication from one point to any other point on the entire globe. With a badly-designed antenna, it is not possible to send signals even beyond the premises of the transmitter.

There are many types of antennas. The choice of antenna depends upon the frequency of operation, polarisation, gain requirements and application.

Antennas are classified into different categories.

First Classification

In this classification, antennas are classified into:

(*a*) Isotropic radiators

(*b*) Directional antennas

(*c*) Omni-directional antennas.

6.2 ISOTROPIC RADIATORS

An **isotropic radiator** is defined as a hypothetical element which radiates equally in all directions.

Examples

1. A point source
2. A star.

It is an ideal antenna but it is not realisable practically. It is useful as a reference antenna for determining directive properties of practical antennas.

If P_i is the input power to a loss-less isotropic radiator, the power density is

$$P_D = \frac{P_i}{4\pi r^2} \text{ W/m}^2 \qquad \text{...(6.1)}$$

Here, r = radius of a sphere

6.3 DIRECTIONAL ANTENNAS

These are the antennas which radiate or receive electromagnetic waves more effectively in some directions than in others.

Examples

1. Dipoles
2. Horns
3. Paraboloids and so on.

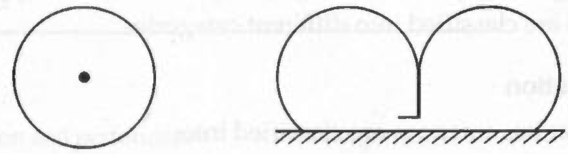
6.4 OMNI-DIRECTIONAL ANTENNA

It is defined as an antenna which has a non-directional pattern in azimuth and has a directional pattern in elevation. An omni-directional pattern is a special type of directional pattern.

Examples

1. A circular loop antenna. Omni-directional refers only to the horizontal plane. In this plane, the pattern is a circle.
2. Vertical Hertz antenna
3. Marconi antenna
4. Quarter-wave monopole

The radiation patterns of uni-directional, omni-directional antennas are shown in Fig. 6.1.



(*a*) Polar plot of omni-directional antenna

(*b*) Pattern of λ/4 vertical antenna

Fig. 6.1 *Polar plots of omni-directional and uni-directional antennas*

Second classification

The antennas are also classified into:

1. Resonant antennas and
2. Non-resonant antennas.

6.5 RESONANT ANTENNAS

The features of these antennas are:

1. The length of a resonant antenna is in exact multiples of $\frac{\lambda}{2}$.

2. These antennas are open at both ends.
3. These are not terminated in any resistance.
4. They are used at a fixed frequency.
5. In these antennas, forward/incident and backward/reflected waves exist.
6. A standing wave exists in these antennas.
7. The radiation patterns of these antennas are multi-directional.
8. The current distribution in resonant antennas is shown in Fig. 6.2.

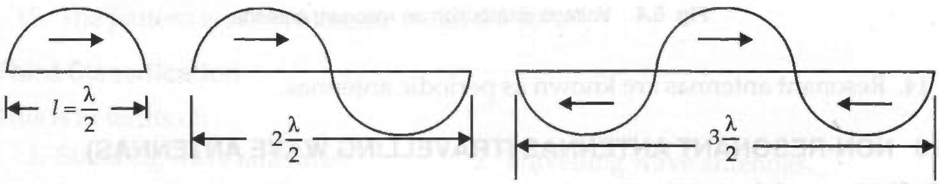


Fig. 6.2 *Current distribution on resonant dipole*

9. Radiation patterns of different resonant dipoles are shown in Fig. 6.3.

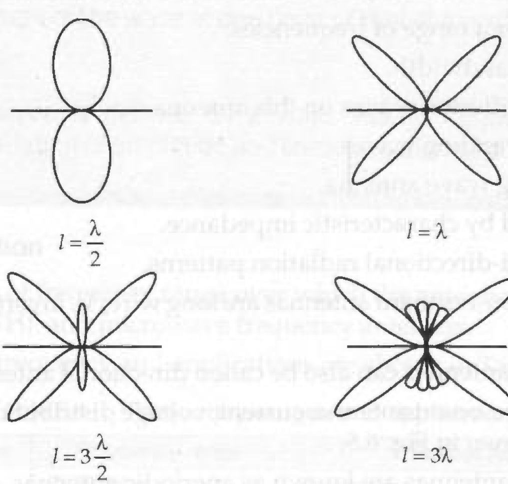


Fig. 6.3 *Radiation patterns of resonant dipoles*

10. The half-wave antenna has distributed inductance and capacitance and it acts like a resonant circuit.
11. The voltage and current on it are not in phase.
12. The voltage distribution on half-wave dipole is shown in Fig. 6.4.
13. The length of a resonant antenna is found from

$$l = \frac{\upsilon_0}{f} \times F$$

Here, F = velocity factor

(The velocity factor of wire compared to air, $F \approx 0.95$)

υ_0 = velocity of propagation.

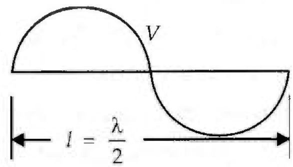


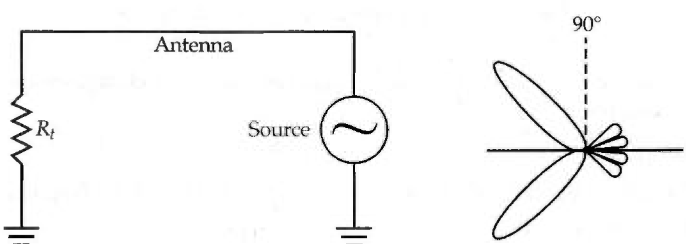
Fig. 6.4 *Voltage distribution on resonant antenna*

14. Resonant antennas are known as periodic antennas.

6.6 NON-RESONANT ANTENNAS (TRAVELLING WAVE ANTENNAS)

The features of these antennas are:

1. The length of a non-resonant antenna is other than in multiples of $\frac{\lambda}{2}$.
2. At one end of the antenna, it is excited and the other end is terminated.
3. It operates over a range of frequencies.
4. It has a wide bandwidth.
5. There are no reflected waves on this antenna.
6. There are no standing waves.
7. It is a travelling wave antenna.
8. It is terminated by characteristic impedance.
9. It produces uni-directional radiation patterns.
10. Examples of non-resonant antennas are long wire, V, inverted V and Rhombic antennas.
11. Non-resonant antennas can also be called directional antennas.
12. A typical non-resonant antenna, current, voltage distribution and its radiation pattern are shown in Fig. 6.5.
13. Non-resonant antennas are known as aperiodic antennas.



(a) Current and voltage distribution on non-resonant antenna **(b) Radiation pattern**

Fig. 6.5 *Non-resonant antenna*

14. The pattern expression of a travelling wave antenna is given by

$$E = \frac{30 I_m \sin\theta}{r(1-\cos\theta)} \{2 - 2\cos[kL(1-\cos\theta)]\}^{1/2} \quad ...(6.2)$$

where I_m = maximum current in the element

r = distance from the source, $k = \frac{2\pi}{\lambda}$

L = length of the element.

15. The pattern is not symmetric about $\theta = 90^\circ$.

Third Classification

This is in terms of:

1. Standing wave antennas.
2. Travelling wave antennas.

It is evident from the previous section that a standing wave antenna is nothing but a resonant antenna. Similarly, travelling wave antenna is nothing but a non-resonant antenna.

> **Standing wave** is defined as a wave in which the ratio of the instantaneous value of any component of the wave at one point of that at any other point does not vary with time.
>
> **Travelling wave** is defined as a wave whose frequency component have exponential variation of amplitude and linear variation of phase with distance.

Fourth Classification

This is on the basis of frequency range over which the antenna can be used. These are LF, HF, VHF, UHF and microwave frequency antennas.

The range of frequency and applications are shown in Table 6.1.

Table 6.1 Frequency ranges and applications

S. No.	Band name	Frequency range	Typical Applications
1.	VLF	(3-30 kHz)	Telegraphy
2.	LF	(30-300 kHz)	Marine and navigational aids
3.	MF	(300 kHz-3 MHz)	AM broadcast, navigation
4.	HF	(3-30 MHz)	Aircraft radio, short wave broadcast
5.	VHF	(30-300 MHz)	FM, television, radar and so on
6.	UHF	(300 MHz-3 GHz)	Radar, television, short distance communication
7.	Microwave	(3-30 GHz)	Radar, satellite communication and so on
8.	EHF	(30-300 GHz)	Experimental purposes

6.7 LF ANTENNAS

These antennas operate at low frequencies (75 – 160 meter band). Examples of these antennas are:

1. Inductance loaded vertical antennas (Fig. 6.6).

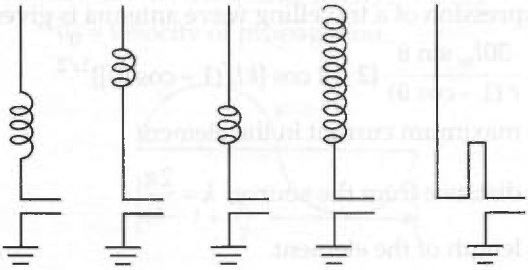


Fig. 6.6 *Inductance loaded vertical antennas*

2. Inductance loaded horizontal dipoles (Fig. 6.7).

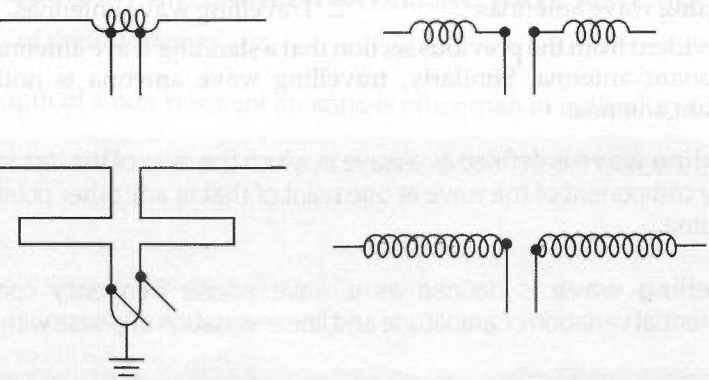
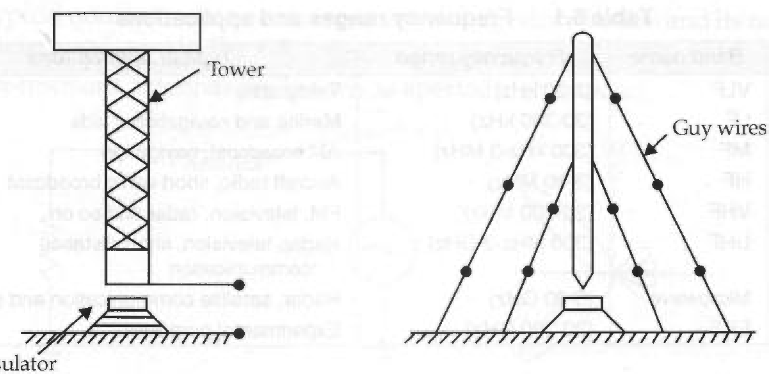


Fig. 6.7 *Inductance loaded horizontal dipoles*

3. Tower antenna (Fig. 6.8).
4. Inverted-*L* antenna. This is shown in Fig. 6.9.



(*a*) Self supporting tower antenna

(*b*) Mast supporting by guy wires

Fig. 6.8 *Tower antennas*

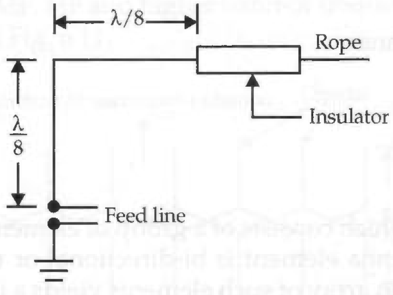


Fig. 6.9 *Inverted-L section quarter-wave antenna*

5. A short vertical monopole with top capacitance. (Fig. 6.10).

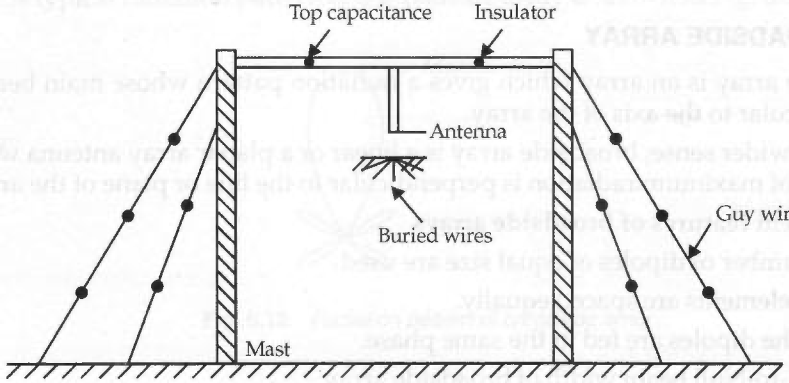


Fig. 6.10 *Monopole*

6.8 ANTENNAS FOR HF, VHF, UHF

In these frequency ranges, the following antennas are used. They are described in detail.

1. Dipole arrays : Broadside and end-fire arrays.
2. Folded dipole.
3. *V* antennas.
4. Inverted *V* antennas.
5. Rhombic antennas.
6. Yagi-Uda antennas.
7. Log-periodic antennas.
8. Loop antennas.
9. Helical antennas.
10. Whip antennas.
11. Ferrite rod antennas.

12. Turnstile antennas.
13. Super turnstile antennas.
14. Discone antennas.
15. Notch antennas.

6.9 DIPOLE ARRAYS

An array antenna is one which consists of a group of elements arranged linearly or in a plane. When an antenna element is bi-directional or multi-directional in its radiation characteristics, an array of such elements yields a uni-directional pattern. An array is said to be linear if the elements are arranged along a straight line with equal spacing. Arrays are divided into:

1. Broadside array
2. End-fire array.

6.10 BROADSIDE ARRAY

Broadside array is an array which gives a radiation pattern whose main beam is perpendicular to the axis of the array.

In a wider sense, broadside array is a linear or a planar array antenna whose direction of maximum radiation is perpendicular to the line or plane of the array.

Salient features of broadside arrays

1. A number of dipoles of equal size are used.
2. The elements are spaced equally.
3. All the dipoles are fed in the same phase.
4. Null-to-Null beam width of broadside array.

   Beam width between first Nulls

   $$= \frac{2\lambda}{Nd} \qquad \text{...(6.3)}$$

   where λ = wavelength
   N = number of elements
   d = spacing between the elements.
5. The length of the broadside array can be 2 to 10λ.
6. Typical spacing between the elements vary from $\frac{\lambda}{2}$ to λ.
7. The number of elements to be used depends on the beam width requirement, cost and space available.
8. A broadside array is often used along with a reflector antenna. The back lobe is now reflected forward and adds to the forward lobe.
9. When a broadside array is used with a reflector, it is possible to improve its gain and directivity and the broadside array becomes uni-directional.
10. This array is often used in overseas broadcast systems.

11. It is used for LF, MF, HF and higher band of frequencies. A typical broadside array is shown in Fig. 6.11.

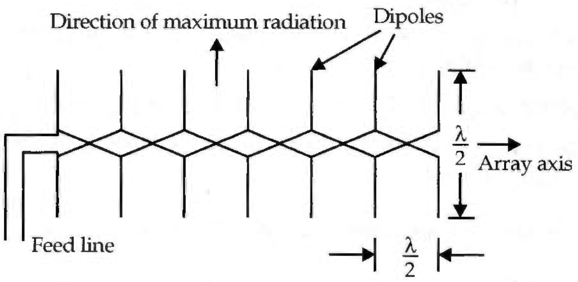


Fig. 6.11 *Broadside array*

12. A typical radiation pattern of a broadside array is shown in Fig. 6.12.

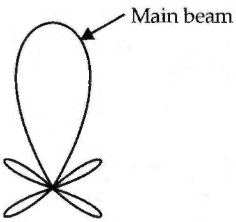


Fig. 6.12 *Radiation pattern of broadside array*

6.11 END-FIRE ARRAY

End-fire array is an array which gives a radiation pattern whose main beam is along the axis of the array.

In a wider sense, end-fire array is a linear or planar antenna whose direction of maximum radiation is along the line or in the plane of the array.

Salient features of end-fire array

1. A number of dipoles or elements of equal size are used.
2. The elements are equally spaced.
3. The elements are fed with different phases.
4. The additional phase for each element is given by

$$\alpha_{N-1} = (N-1)\, kd \cos \phi$$

where $k = \frac{2\pi}{\lambda}$, d = spacing, ϕ is the angle between the line of observation and axis of the array.

5. Null-to-Null to beam width of an end-fire array is

$$\text{B.W.F.N.} = 2\sqrt{\frac{2\lambda}{Nd}} \qquad \text{...(6.4)}$$

6. In this, the pattern is uni-directional.
7. The physical arrangement of the elements in the end-fire array is the same as that of broadside array.
8. The number elements to be used depends on the beam width requirements, cost and space available.
9. These are often used in LF, MF, HF and higher band of frequencies.
10. These arrays are used for point-to-point communications and in overseas broadcasting systems.
11. In this array, the elements are spaced at $\frac{\lambda}{4}$ or $3\frac{\lambda}{4}$.

A typical end-fire structure is shown in Fig. 6.13 and its radiation pattern is shown in Fig. 6.14.

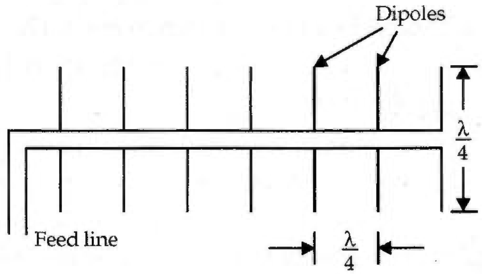


Fig. 6.13 *End-fire array*

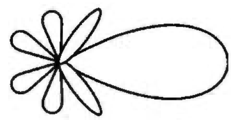


Fig. 6.14 *Radiation pattern*

6.12 FOLDED DIPOLE

It is an antenna composed of two or more parallel and closely spaced dipole antennas connected together at their ends with one of the dipole antennas being centre fed.

The folded dipole antenna is shown in Fig. 6.15.

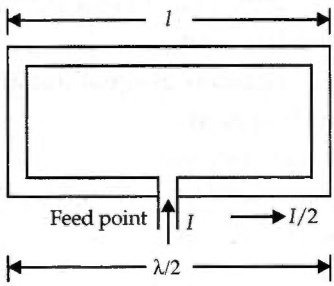


Fig. 6.15 *Folded dipole antenna*

Salient features of folded dipole

1. It is a single antenna, but consists of two elements.
2. The first is fed directly and the second is inductively coupled at the ends.

3. Its radiation pattern is the same as that of a straight dipole.
4. If the current fed is I, then the current in each arm is $\frac{I}{2}$, provided the two arms have the same dimensions. If it is a straight dipole, the total current I flows.
5. When the same power is applied, only half of the current flows in the first arm. Therefore, the input impedance is four times that of the straight dipole. That is,

$$R_r = 4 \times 73 = 292\Omega.$$

6. If the diameters of the two arms of folded dipole are different, impedance transformation of 1.5 to 25 is achievable.
7. The spacing between the arms is very small and is of the order of $\frac{\lambda}{100}$.
8. Folded dipole is used in Yagi-Uda antenna as an active element.
9. It has the advantages of high input impedance, greater band width, ease and low cost of construction with better impedance-matching characteristics.

A typical radiation pattern of a folded dipole is shown in Fig. 6.16.

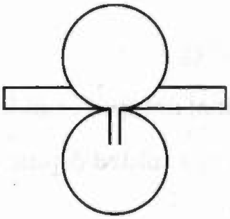


Fig. 6.16 *Radiation pattern of folded dipole*

Impedance of the folded dipole It is given by

$$Z = 292\Omega$$

Proof The equivalent diagram of the folded dipole of Fig. 6.15 is shown in Fig. 6.17.

When a voltage V is applied to the folded dipole, it is divided equally in each arm of the dipole. That is, the voltage in each dipole is $\frac{V}{2}$. Hence, we have

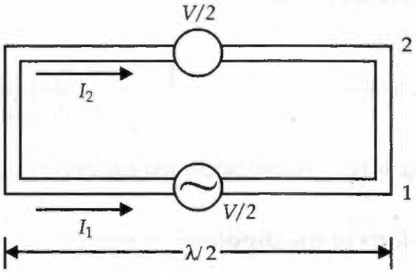


Fig. 6.17 *Equivalent diagram of (λ/2) folded dipole*

$$\frac{V}{2} = I_1 Z_{11} + I_2 Z_{12}$$

Here, I_1 = current in (1) and I_2 is current in (2)

Z_{11} = self impedance of dipole (1)

Z_{12} = mutual impedance between (1) and (2)

For equal dimensions of the dipoles

$$I_1 = I_2 = I$$

So $$\frac{V}{2} = I\,(Z_{11} + Z_{12})$$

As the two dipoles are very close and the spacing is very small,

$$Z_{11} = Z_{12}$$

or $$\frac{V}{2} = I\,(2Z_{11})$$

or $$Z = \frac{V}{I} = 4Z_{11}$$

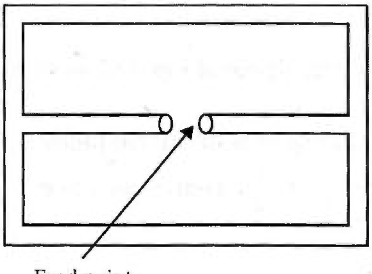
$$= 4 \times 73 = 292\,\Omega$$

$$R_i = Z_r = \text{terminal or input or radiation resistance} = 292\,\Omega$$

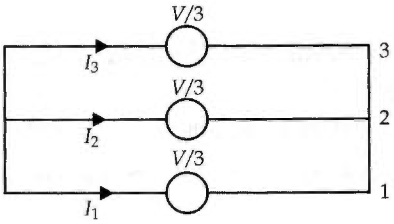
The radiation resistance of a folded dipole with 3 arms It is given by

$$R_r = 657\,\Omega.$$

Proof The three armed folded dipole is shown in Fig. 6.18 (*a*) and its equivalent diagram is shown in Fig. 6.18 (*b*).



(*a*) **Three armed folded dipole**



(*b*) **Equivalent diagram of three armed folded dipole**

Fig. 6.18 *Folded dipole and equivalent diagram*

For equal dimensions of the dipoles,

$$I_1 = I_2 = I_3 = I$$

So $\frac{V}{3} = I\,(3Z_{11})$

or $\frac{V}{I} = 3 \times 3Z_{11} = 9z_{11}$

$= 9 \times 73 = 657\,\Omega$

That is, $Z_i = R_r = 657\,\Omega$

or, in general $R_r = Z_i = K^2 \times 73\,\Omega$

where K = number of arms.

The impedance of the dipole depends on

1. spacing between dipoles and
2. radius of the dipoles.

Case 1 If the radii of the dipoles are r_1 and r_2, then

$$Z_i = 73\left(1 + \frac{r_2}{r_1}\right)^2 \Omega \qquad ...(6.5)$$

Case 2 If the radii of the dipoles are r_1 and r_2 and d is the spacing between the elements, then

$$Z_i = 73\left[1 + \frac{\log \frac{d}{r_1}}{\log \frac{d}{r_2}}\right]^2 \qquad ...(6.6)$$

$$R_r = Z_i = 73 \times b$$

where b = impedance transformation ratio which is given by

$$b = \left[1 + \frac{\log \frac{d}{r_1}}{\log \frac{d}{r_2}}\right]^2 \qquad ...(6.7)$$

In folded dipole, dimension of one element can be changed to obtain desired resistance (Fig. 6.19).

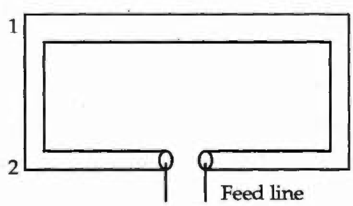


Fig. 6.19 *Folded dipole with different dimensions of arms*

If the diameter of the arm 2 is larger than that of 1, the impedance is reduced. If the diameter of the arm 2 is smaller than that of 1, the impedance is increased.

6.13 *V* ANTENNA

It is an antenna in which the conductors are arranged in *V* shape. It is balanced-fed at the apex and the included angle, length and elevation are chosen to obtain the desired directional properties.

The structure of a *V* antenna is shown in Fig. 6.20.

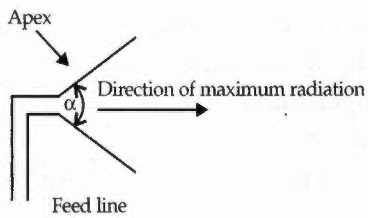


Fig. 6.20 *V antenna*

Salient features of *V*-antenna

1. It consists of two long wire antennas arranged in the form of *V* and it is fed at the apex.
2. The excitation to each wire is out of phase.
3. It offers greater gain and directivity when length of each leg or wire is increased.
4. Its radiation pattern is bi-directional.
5. *V* antennas are of two types: the first one is resonant and the second one is non-resonant.
6. The pattern of resonant *V* antenna is shown in Fig. 6.21.

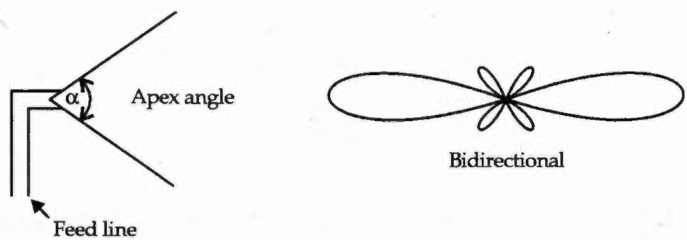
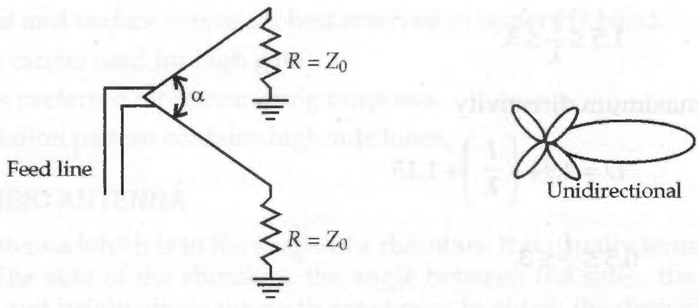


Fig. 6.21 *Radiation pattern of resonant V antenna*

7. The pattern of non-resonant *V* antenna is shown in Fig. 6.22.
8. These antennas are useful in HF band.
9. The main disadvantage is that high side lobes exist.
10. The apex angle ranges between 36° to 72° for *V* antennas of 8λ to 2λ length.



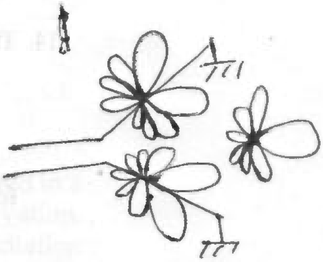


Fig. 6.22 *Non-resonant V antenna with radiation pattern*

11. It is easy to construct and they are cheap.
12. Using *V* antennas, end-fire and broadside antennas can be easily constructed. These are shown in Figs. 6.23 and 6.24 respectively.

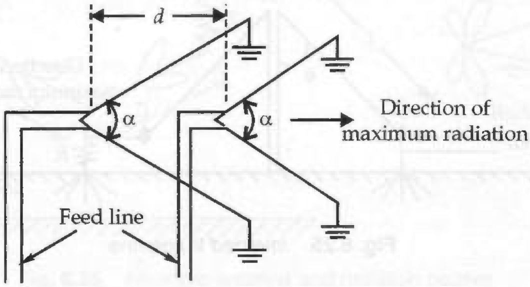


Fig. 6.23 *End-fire array of V antennas*

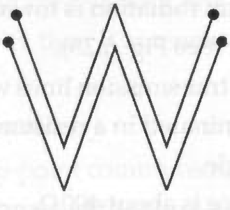


Fig. 6.24 *Broadside array of V antennas*

13. The optimum included angle, α is

$$\alpha = -149.3\left(\frac{l}{\lambda}\right)^3 + 603.4\left(\frac{l}{\lambda}\right)^2 - 809.5\left(\frac{l}{\lambda}\right) + 443.6 \quad \text{...(6.8)}$$

for $\quad 0.5 \le \frac{l}{\lambda} \le 1.5$

and $$\alpha = 13.39\left(\frac{l}{\lambda}\right)^2 - 78.27\left(\frac{l}{\lambda}\right) + 169.77 \quad \text{...(6.9)}$$

for $\quad 1.5 \le \frac{l}{\lambda} \le 3.$

14. The maximum directivity

$$D = 2.94\left(\frac{l}{\lambda}\right) + 1.15 \qquad ...(6.10)$$

for $\quad 0.5 \le \frac{l}{\lambda} \le 3.$

6.14 INVERTED-*V* ANTENNA

It is an antenna in which the conductors are arranged in the shape of an inverted-*V*.

Its typical structure is shown in Fig. 6.25.

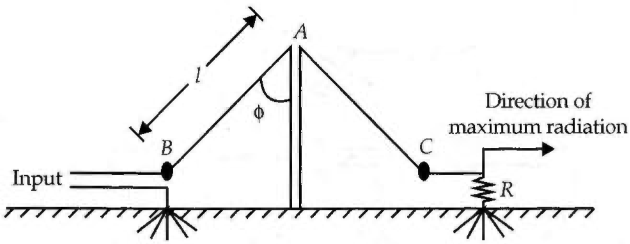


Fig. 6.25 *Inverted V antenna*

Salient features of inverted-*V* antenna

1. It is a travelling antenna.
2. The direction of maximum radiation is towards the terminated end.
3. Input is given at point *B*. (See Fig. 6.25).
4. Feeding is done through transmission lines with respect to radial earth wires.
5. Antenna wire at *C* is terminated in a resistance.
6. The angle ϕ is the tilt angle.
7. The terminating resistance is about 400 Ω.
8. Angle of main lobe corresponds to $\frac{l}{\lambda}$.
9. Gain is a function of angle of tilt, leg lengths and terminating resistance.
10. These antennas are useful in HF band.
11. They have considerable band width.
12. The length of the leg equal to λ is used.
13. The main disadvantage is that it has high side lobes in its radiation pattern.
14. Inverted *V* antenna with its image looks like a rhombus.
15. It is used up to 60 MHz for receiving purposes.

16. Ground and surface waves are best received in upper HF band.
17. Arrays can be used for high gain.
18. It is not preferred for transmitting purposes.
19. Its radiation pattern contains high side lobes.

6.15 RHOMBIC ANTENNA

This is an antenna which is in the shape of a rhombus. It is usually terminated in a resistance. The side of the rhombus, the angle between the sides, the elevation, termination and height above the earth are chosen to obtain the desired radiation characteristics. A typical Rhombic antenna and radiation pattern are shown in Fig. 6.26.

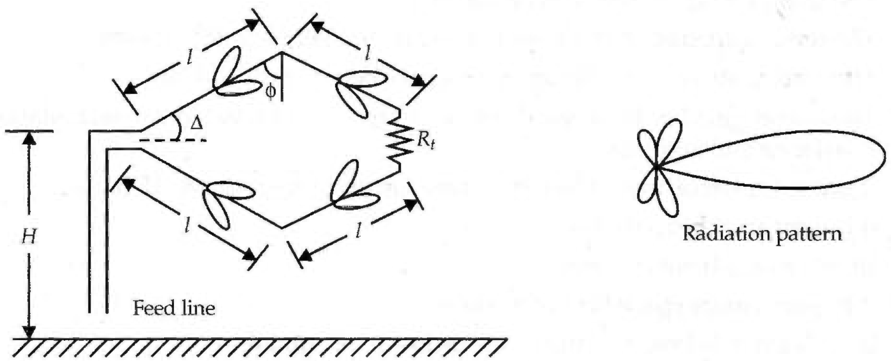


Fig. 6.26 *Rhombic antenna and radiation pattern*

Salient features of Rhombic antenna

1. It is a long wire antenna and consists four non-resonant wires.
2. It provides greater directivity than V antenna.
3. Its band width is high.
4. It is a HF non-resonant antenna.
5. It is very useful for point-to-point communications.
6. It is a travelling wave antenna and there are no reflections.
7. It also finds wide applications where the angle of elevation of the main lobe (measured from the plane of the antenna to the radiation axis) is less than 30°.
8. At elevation angle above 30°, the gain is very low for practical applications.
9. The directivity of each wire is

$$D(\theta) = \frac{60I}{r} \sin\theta \left[\frac{\sin\left[\frac{\pi l}{\lambda}(1-\cos\theta)\right]}{(1-\cos\theta)} \right] \qquad ...(6.11)$$

where I = the magnitude of the current in element

θ = the polar angle

λ = wavelength

l = length of the radiator

r = the distance from the radiator to the elevation point.

The total directivity of the Rhombic antenna is the vector sum of directivity of each wire.

10. The length of equal radiators vary from 2 to 8λ.
11. The tilt angle, ϕ varies between 40° and 75°.
12. ϕ is determined from leg length.
13. The terminating resistance is about $800\,\Omega$.
14. The input impedance of Rhombic antenna lies between 650 to 700Ω.
15. The directivity of Rhombic antenna varies between 20 and 90.
16. The power gain lies between 15 and 60 after taking power loss in terminating resistance into account.
17. It is a very useful antenna for transmission and reception in HF band.
18. It is easy and cheap to erect.
19. Its main disadvantages are:

(i) It requires more space for installation.

(ii) Its efficiency is less, as some power is lost in termination.

20. Its radiation pattern in a vertical plane is shown in Fig. 6.27.

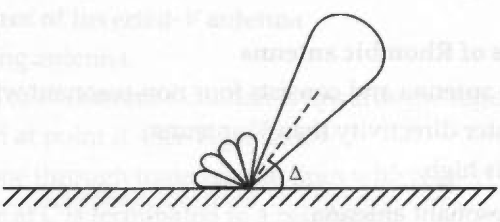


Fig. 6.27 *Radiation pattern of Rhombic antenna in vertical plane*

In the design of Rhombic antennas the maximum point of the main lobe of the radiation pattern is aligned with the desired angle of elevation. The angle of elevation is also called angle of radiation.

The **design parameters** of Rhombic antenna are:

1. Rhombic height, H
2. Angle of elevation, ϕ
3. Wire length, l.

The design equations are

$$H = \frac{\lambda}{4 \sin \Delta} \qquad ...(6.12)$$

Δ = elevation angle

Δ is complement of tilt angle, ϕ

$(\sin\phi = \cos\Delta)$

$$l = \frac{\lambda}{2\cos^2\phi} = \frac{\lambda}{2\sin^2\Delta} \qquad \text{...(6.13)}$$

Alignment design equations.

Tilt angle, $\phi = 90^\circ -$ elevation angle

$$= 90^\circ - \Delta \qquad \text{...(6.14)}$$

Rhombic height,

$$H = \frac{\lambda}{4\sin\Delta} = \frac{\lambda}{4\cos\phi} \qquad \text{...(6.15)}$$

Wire length, $$l = \frac{\lambda}{2\sin^2\Delta} \times K$$

$$= \frac{\lambda}{2\cos^2\phi} \times K \qquad \text{...(6.16)}$$

where $K = 0.74$

The results are given in Table 6.2 for quick reference.

Table 6.2

Frequency, f = 30 MHz, λ = 10 m					
Angle of elevation, Δ	*Tilt angle φ*	*Rhombic height H in λ*	*H in meters*	*Wire length, l in λ*	*Wire length in meters*
10°	80°	1.439	14.39	16.58	165.8
15°	75°	0.966	9.66	7.46	74.6
20°	70°	0.730	7.30	4.27	42.7
25°	65°	0.591	5.91	2.79	27.9
30°	60°	0.500	5.00	2.00	20.0
35°	55°	0.435	4.35	1.52	15.2
40°	50°	0.320	3.90	1.21	12.1

6.16 YAGI-UDA ANTENNA

This antenna was developed by Prof. Yagi and Prof. Uda. It is an array antenna which consists of one active element and a few parasitic elements. The active element consists of a folded dipole whose length is $\lambda/2$. The parasitic elements consist of one reflector and a few directors. The length of the reflector is greater than $\lambda/2$. It is located behind the active element. The length of each director is less than $\lambda/2$ and they are placed in front of the active element. The spacing between each element is not identical and hence it can be considered as a non-linear array. The number of directions in the antenna depends on the gain requirements. The impedance of the active element is resistive. The impedance of the reflector is inductive. The impedances of the directors are capacitive. A typical structure of Yagi-Uda antenna is shown in Fig. 6.28.

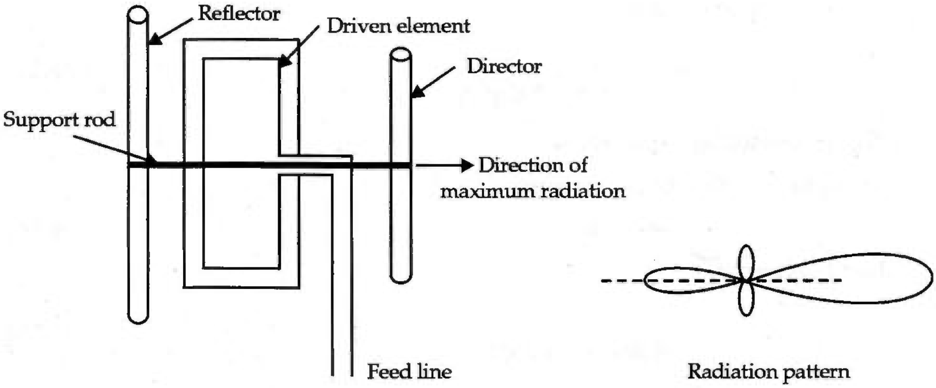


Fig. 6.28 *Yagi-Uda antenna and radiation pattern*

Salient features of Yagi-Uda antenna

1. It consists of a driven element, a reflector and one or more directors.
2. Driven element is usually a folded dipole which is excited. Director is a straight conductor placed in front of the driven element towards transmitter. Reflector is also a straight conductor placed behind the driven element.
3. Directors and reflector are called parasitic elements.
4. The length of the folded dipole is about $\frac{\lambda}{2}$ and it is at resonance. Length of the director is less than $\frac{\lambda}{2}$ and length of the reflector is greater than $\frac{\lambda}{2}$.
5. The optical equivalent of Yagi-Uda antenna is shown in Fig. 6.29.

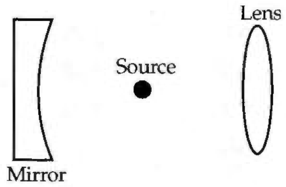


Fig. 6.29 *Optical equivalent of Yagi-Uda antenna*

6. Its radiation pattern is almost uni-directional and gives a gain of about 7 dB.
7. It is used as a transmitting antenna at HF and used for TV reception at VHF.
8. Back lobe can be reduced by bringing the elements closer. This reduces the input impedance of the antenna and hence there will be a mismatch.
9. The effect of parasitic elements depends on their distance and tuning. In other words, the effect depends on the magnitude and phase of the current induced in them.

10. Reflector resonates at a lower frequency and director resonates at a higher frequency compared to that of a driven element.
11. Folded dipole is used to obtain high impedance for proper matching between transmitter and free space.
12. More directors can be used to increase the gain. In this case, directors can be of equal length or decreasing slightly, away from the driven element. But adding too many directors will change the impedance.
13. It is relatively broadband because of the use of folded dipole.
14. Although it is compact, its gain is not high.
15. The purpose of reflector and directors is to increase the gain but they load the driven element.
16. The mutual impedance of the antenna depends on the spacing and the length of the elements.
17. Highest gain is obtained when the reflector is slightly greater than $\frac{\lambda}{2}$ in length and spaced at $\frac{\lambda}{4}$ from the driven element and when the length of the director is about 10% less than $\frac{\lambda}{2}$ with an optimal spacing of about $\frac{\lambda}{3}$.
18. It is possible to produce circular polarisation, when two Yagi-Uda antennas are placed across at right angles on the same boom, when the driven elements are fed in phase quadrature. The driven elements can be fed in phase by displacing one array by $\frac{\lambda}{4}$ along the boom with respect to the other.
19. The directors, whose lengths are shorter than the driven element, are characterised by capacitive reactance at the resonant frequency of the driven element.
20. The current which flows in the directors is the leading current.
21. The reflectors whose lengths are longer than the driven element are characterised by inductive reactance at the resonant frequency of the driven element.
22. Yagi-Uda antenna has exceptional sensitivity.
23. It has a good front-to-back ratio.
24. Its band width is limited.

Design Parameters The design parameters of six-element Yagi-Uda antenna which gives a directivity of about 12 dB_i at the centre of a band width of 10 percent of half-power are given by:

The length of driven active element,

$$L_a = 0.46\lambda \qquad ...(6.17)$$

The length of reflector,

$$L_r = 0.475\lambda \qquad ...(6.18)$$

The length of director,

$$L_{d1} = 0.44\lambda \qquad ..(6.19)$$

$$L_{d2} = 0.44\lambda \qquad ...(6.20)$$

$$L_{d3} = 0.43\lambda \qquad ...(6.21)$$

$$L_{d4} = 0.40\lambda \qquad ...(6.22)$$

Spacing between reflector and driven element,

$$S_L = 0.25\lambda \qquad ...(6.23)$$

Spacing between director and driving element

= spacing between directors

$$S_d = 0.31\lambda \qquad ...(6.24)$$

Diameters of the elements,

$$d = 0.01\lambda \qquad ...(6.25)$$

The length of Yagi array

$$= 1.5\lambda$$

The design equations of a typical Yagi-Uda antenna are:

1. Length of driven element or active element,

$$L_a = \frac{478}{f_{\text{MHz}}} \text{ feet} \qquad ...(6.26)$$

2. Length of reflector,

$$L_r = \frac{492}{f_{\text{MHz}}} \text{ feet} \qquad ...(6.27)$$

3. Length of director,

$$L_d = \frac{461.5}{f_{\text{MHz}}} \text{ feet} \qquad ...(6.28)$$

4. Element spacing,

$$S = \frac{142}{f_{\text{MHz}}} \text{ feet} \qquad ...(6.29)$$

6.17 LOG-PERIODIC ANTENNA

A typical structure of log-periodic antenna is shown in Fig. 6.30.

It is an array antenna which has structural geometry such that its impedance is periodic with the logarithm of the frequency.

It is a non-linear array in which the spacing of the elements as well as their dimensions are unequal. However, excitation is uniform. It is basically called a frequency-independent antenna. It can be used to receive a good number of TV channels without any deterioration of the received field strength.

Salient features

1. It is a frequency-independent antenna.
2. The input impedance variation of the antenna with the log of frequency is periodic and hence the name. This is shown in Fig. 6.31.

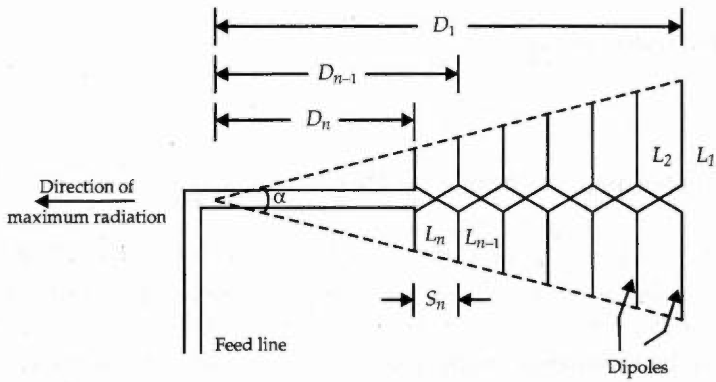


Fig. 6.30 *Log-periodic antenna or array*

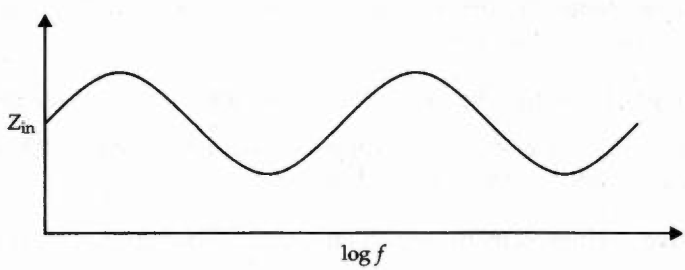


Fig. 6.31 *Impedance characteristics of log-periodic antenna*

3. It is an array of non-identical dipoles which are all excited equally.
4. It is a non-uniform array where the spacing between the elements is unequal.
5. Its impedance, directional patterns and directivity are constant with frequency.
6. The gain of a well-designed antenna lies between 7.5 and 12 dB_i.
7. It is a broad band antenna.
8. It has uni-directional characteristics.
9. There are a variety of log-periodic structures and all of them are not frequency-independent.
10. They are used in VHF and UHF bands.
11. They are used for TV reception and can receive a number of channels.
12. The planar trapezoidal and wire trapezoidal tooth log-periodic antennas can be used.
13. It is more efficient than Rhombic antenna.

Design Equations The design equations are:

Refer another PDF

Scale factor, $$\tau = \frac{D_n}{D_{n-1}} = \frac{L_n}{L_{n-1}}, \quad n = 1, 2, 3 \qquad \text{...(6.30)}$$

$$\text{Spacing factor, } \sigma = \frac{S_n}{2L_n} = \frac{S_n}{S_{n-1}} \qquad \text{...(6.31)}$$

$$S_n = D_{n-1} - D_n$$

where α = wedge angle or included angle $= 2\tan^{-1}\left(\frac{1-\tau}{4\sigma}\right)$.

Isbel curves give the value of τ and σ for a specified gain of the antenna.

The scale factor, τ lies between 0 and 1 for a given wedge angle, α. If α is large, τ is small. The performance in terms of gain is improved if τ is small and α is large.

The analysis of log-periodic array is described in terms of three regions.

1. **Capacitive** In this region, the elements are shorter than $\frac{\lambda}{2}$ and they are capacitive. Hence the current leads the applied voltage by 90°. These elements produce small backward radiation.

2. **Resistive** Here the dipoles are of $\frac{\lambda}{2}$ length and they are resistive. The currents are large and they are in phase with the voltage. These elements produce considerable forward radiation.

3. **Inductive** Here elements are of length $> \frac{\lambda}{2}$. The currents lag the voltage by 90°. The element reflects the incident wave in the backward direction.

The active region band width is given by

$$B_a = 1.1 + 7.7\,(1-\tau)^2 \cot(\alpha/2)$$

When the designed band width is assumed to be greater than the desired band width, it is given by

Designed bandwidth,

$$B_d = BB_a = B\left[1.1 + 7.7\,(1-\tau)^2 \cot\frac{\alpha}{2}\right] \qquad \text{...(6.32)}$$

Here, B = desired bandwidth

Total length of the array is

$$L = \frac{\lambda_{max}}{4}\left(1 - \frac{1}{B_d}\right)\cot\frac{\alpha}{2} \qquad \text{...(6.33)}$$

$$\text{Here, } \lambda_{max} = 2l_{max} = \frac{v_0}{f_{min}} \qquad \text{...(6.34)}$$

The number of elements in the array is

$$N = 1 + \frac{\ln(B_d)}{\ln(1/\tau)} \qquad \text{...(6.35)}$$

The average characteristic impedance, $(z_0)_{av}$ is

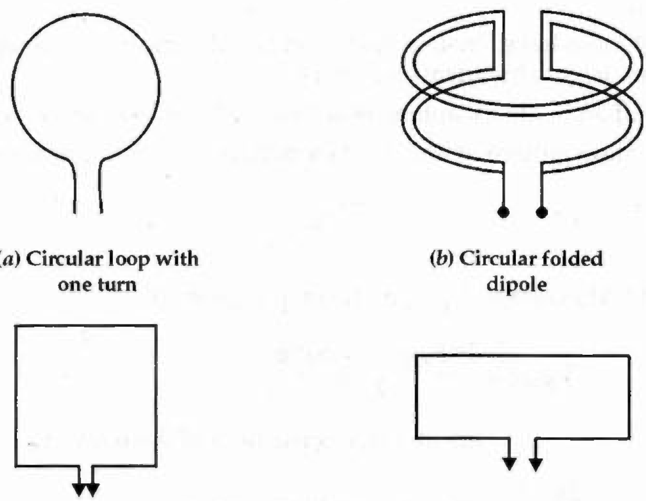
$$(z_0)_{av} = 120 \left[ln \left(\frac{L_n}{d_n} - 2.25 \right) \right]$$

where $\quad d_n$ = diameter of the n^{th} dipole.

6.18 LOOP ANTENNA

It is an antenna which is in the form of a loop.

An antenna which consists of one or more turns of wire forming a DC short circuit is called a loop antenna. The loop antenna can be of circular, square or rectangular shape. Typical loop antennas are shown in Fig. 6.32.



(*a*) Circular loop with one turn

(*b*) Circular folded dipole

(*c*) Square loop

(*d*) Rectangular loop

Fig. 6.32 *Loop antennas*

Small vertical loops are used for finding the direction. The loop is oriented until a null or zero field is obtained. This gives the direction of the received signal.

Loop antennas have advantage over the other antennas in direction-finding as they are small in size. These are more suitable for mobile communication applications.

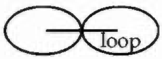
The polarisation of the loop antenna is the same as that of a short dipole.

Horizontal loop antenna produces horizontal polarisation and vertical loop produces vertical polarisation.

Salient features of loop antenna

1. Small loops, whose circumferences are less than 0.1λ at the highest frequencies, are suitable for receiving signals upto about 30 MHz.
2. The loop antennas are characterised by a null along the axis of the loop.

3. Directional characteristics of loop antennas are improved by shielding them electrostatically.
4. A vertical loop antenna is popular and it receives bi-directional signals.
5. A vertical loop antenna, if shielded, receives uni-directional signals.
6. It has excellent directivity.
7. Vertical loop antennas are very useful for direction-finding applications.
8. These are suitable for LF, MF, HF, VHF and UHF ranges.
9. The radiation pattern is in the shape of a doublet.
10. The directional patterns of loop antennas are independent of the exact shape of the loop.
11. In direction-finding applications, a small vertical loop is rotated about the vertical axis. The plane of the loop is perpendicular to the direction of radiation.
12. Loop antennas have ferrite cores to increase the effective diameter of the loop. These are used as broadcast receivers.
13. Cloverleaf and Adcock antennas are examples of loop antennas.
14. The radiation pattern of a vertical loop antenna in horizontal plane is



15. Induced RMS voltage, V_{RMS} in the loop is given by

$$V_{RMS} = \frac{2\pi E_{RMS} AN \cos\phi}{\lambda} \quad ...(6.36)$$

Here, E_m = maximum electric field of the wave, V/m

$\frac{2\pi AN}{\lambda}$ = effective height of the loop

λ = wavelength, m

A = area of the loop, m^2

N = number of turns

ϕ = angle between plane of the loop and direction of incident wave.

16. The radiation efficiency of a small loop antenna is poor.
17. The dimensions of the antenna should be of the order of λ for using as transmitters.
18. The field expressions of small loop antennas are:

$$E_\phi = \frac{120\pi^2 IA \sin\theta}{r\lambda^2}, \text{ V/m} \quad ...(6.37)$$

$$H_\theta = \frac{\pi I \sin\theta A}{r\lambda^2}, \text{ V/m} \quad ...(6.38)$$

Here, I = retarded current

$$= I_0 e^{j\omega(t-r/v_0)} \quad \text{...(6.39)}$$

19. The radiation resistance of small loop antenna

$$R_r \approx 31{,}171 \left(\frac{NA}{\lambda^2}\right)^2 \Omega \quad \text{...(6.40)}$$

Here N = number of turns
A = area of the loop
λ = wavelength.

20. Radiation resistance of a loop antenna is

$$R_r = 3{,}720 \frac{a}{\lambda}, \ \Omega$$

where a = radius of the loop.

21. The radiated power of loop antenna is

$$P_T = 10K^4 A^2 I_m^2, \text{ watts.}$$

22. For small loop $\left(\dfrac{2\pi a}{\lambda} < \dfrac{1}{3}\right)$

The directivity, $D = \dfrac{3}{2} = 1.5$

For large loop, $C = 2\pi a \geq 5\lambda$

$$D = 4.25 \left(\frac{a}{\lambda}\right)$$

23. The maximum effective aperture for small loop antenna is

$$A_{em} = \frac{3\lambda^2}{8\pi}.$$

24. The maximum effective aperture is given by

$$A_{em} = 0.341 \lambda a \text{ m}^2$$

25. Loop antennas are used extensively in radio receivers, aircraft receivers, for direction-finding and also in UHF transmitters.
26. If the current in the loop is uniform and the loop circumference is small compared to the operating wave length, its radiation pattern is almost like that of a magnetic dipole.

6.18.1 Radiation Resistance, R_r of Loop Antenna

Consider a circular loop antenna of Fig. 6.33.

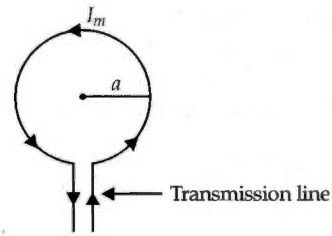


Fig. 6.33 *Loop antenna with feed line*

By definition, radiation resistance is

$$R_r \equiv \frac{\text{radiated power}}{I_{\text{RMS}}^2}$$

$$= \frac{2 \times \text{total radiated power}}{I_m^2} = \frac{2P_T}{I_m^2} \qquad \text{...(6.41)}$$

where $\qquad I_m$ = maximum current in the antenna.

Total radiated power,

$$P_T = \iint_S (P_r)_{av}\, ds \qquad \text{...(6.42)}$$

Here, $\qquad (P_r)_{av}$ = average radiated power density, watts/m^2

$$= \frac{1}{2} H^2 \eta_0 \qquad \text{...(6.43)}$$

where $\qquad H = |\mathbf{H}|,\ \eta_0$ = intrinsic impedance of free space.

For a loop antenna in y-z plane with its centre at the origin, the radiation fields consist of E_ϕ and H_θ components. H_θ is given by

$$H_\theta = \frac{kaI_m}{2r} J_1 (ka \sin \theta) \qquad \text{...(6.44)}$$

where $\qquad J_1 (ka \sin \theta)$ = Bessel function of the first kind

$$\approx \frac{ka \sin \theta}{2} \text{ for small loops} \qquad \text{...(6.45)}$$

$$H_\theta = k \times \frac{aI_m}{2r} \times \frac{ka \sin \theta}{2}$$

$$= \frac{k^2 a^2 I_m \sin \theta}{4r} \qquad \text{...(6.46)}$$

$$(P_r)_{av} = \frac{1}{2} H^2 \eta_0$$

$$= \frac{1}{2} \frac{\eta_0 k^4 a^4 I_m^2 \sin^2\theta}{16r^2}$$

$$= \frac{120\pi \times k^4 a^4 I_m^2 \sin^2\theta}{32r^2}$$

$$= \frac{15\pi}{4} \frac{k^4 a^4 I_m^2 \sin^2\theta}{r^2} \quad \text{...(6.47)}$$

$$P_T = \iint (P_r)_{av}\, ds$$

$$= \int_0^{2\pi}\int_0^{\pi} \frac{15\pi}{4} \frac{k^4 a^4 I_m^2 \sin^2\theta}{r^2} r^2 \sin\theta\, d\theta\, d\phi$$

$$= \int_0^{\pi} \frac{15\pi^2}{2} k^4 a^4 I_m^2 \sin^3\theta\, d\theta$$

$$= 10\pi^2 k^4 a^4 I_m^2 \quad \text{...(6.48)}$$

But the area of the loop is given by

$$A = \pi a^2 \quad \text{...(6.49)}$$

So $$P_T = 10k^4 A^2 I_m^2 \quad \text{...(6.50)}$$

From Equations (6.41) and (6.50), we have

$$R_r = \frac{2P_T}{I_m^2}$$

$$= \frac{2}{I_m^2} 10k^4 A^2 I_m^2 \quad \text{...(6.51)}$$

But $$k = \frac{2\pi}{\lambda}$$

So $$R_r = 31{,}171 \left(\frac{A}{\lambda^2}\right)^2, \Omega \quad \text{...(6.52)}$$

If there are N number of turns in the loop antenna,

$$R_r = 31{,}171 \left(\frac{NA}{\lambda^2}\right)^2, \Omega \quad \text{...(6.53)}$$

As the circumference of the loop is $2\pi a$,

$$R_r \approx 197 \left(\frac{C}{\lambda}\right)^4 \quad \text{...(6.54)}$$

or
$$R_r \approx 3{,}720\left(\frac{a}{\lambda}\right) \quad ...(6.55)$$

The **directivity** for small loop antenna ($C < 0.33\lambda$)
$$D = 3/2 \quad ...(6.56)$$
and for large loop ($C > 5\lambda$)
$$D = 4.25\left(\frac{a}{\lambda}\right) \quad ...(6.57)$$

The **maximum effective aperture** is given by
$$A_{em} = 0.341\lambda a,\ \mathrm{m}^2 \quad ...(6.58)$$

The **maximum effective aperture** for small loop antennas,
$$A_{em} = \frac{3\lambda^2}{8\pi}$$

For a **square loop of side** a, the **radiation resistance** is given by
$$R_r = 31{,}171\left(\frac{a}{\lambda}\right)^4,\ \Omega. \quad ...(6.59)$$

6.19 HELICAL ANTENNA

It is an antenna which is in the shape of a helix.

Its polarisation and radiation properties depend on the diameter, pitch, number of turns, wavelength, excitation and spacing between the helical loops.

A typical structure of helical antenna is shown in Fig. 6.34.

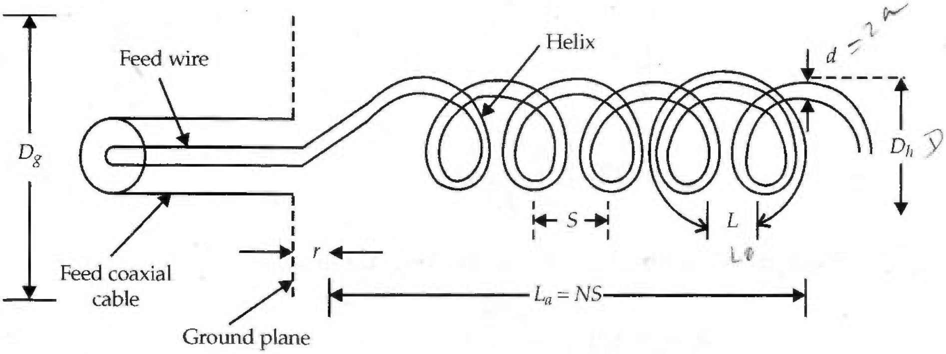


Fig. 6.34 *Helical antenna*

Helical antenna consists of helical loops made of a thick conductor which have the appearance of a screw thread. It is associated with a ground plane made of the conductor. The ground plane is often made of screen or sheet or of radial and concentric conductors. This antenna is fed by a coaxial cable. This can be operated in normal and axial modes. The common antenna parameters are:

C = circumference of helix

α = pitch angle

S = loop separation

L_a = axial length = NR

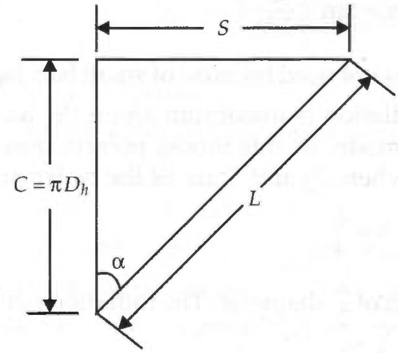


Fig. 6.35 *Pitch angle*

N = number of turns

L = length of one turn

r = distance between ground plane and helix proper

d = diameter of helix conductor

The inter relations between the parameters are

$$L = \sqrt{S^2 + C^2}, \qquad \text{...(6.60)}$$

$$\alpha = \tan^{-1}\left(\frac{S}{\pi D_h}\right) \qquad \text{...(6.61)}$$

In **normal mode**, the radiation is maximum in the broadside direction. This can be called broadside mode. This mode happens if NL << λ, that is, the dimensions of the helix are small. In this, beam width is small and efficiency is low. These two parameters can be increased if the helix is large.

Axial ratio for elliptical polarisation is given by

$$\text{Axial ratio, AR} = \frac{2S\lambda}{\pi^2 D_h^2} \qquad \text{...(6.62)}$$

If $AR = 0$, elliptical polarisation becomes linear horizontal polarisation.

If $AR = \infty$, elliptical polarisation becomes vertical linear polarisation.

If $AR = 1$, elliptical polarisation becomes circular polarisation.

Hence, for circular polarisation,

$$AR = 1$$

$$2S\lambda = \pi^2 D_h^2$$

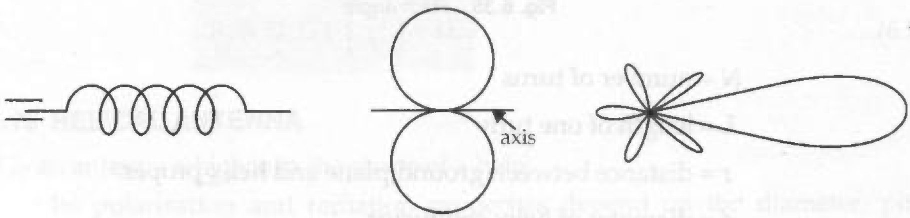
or
$$S = \frac{\pi^2 D_h^2}{2\lambda} = \frac{C^2}{2\lambda} \quad ...(6.63)$$

and
$$\alpha = \tan^{-1}\frac{C}{2\lambda} \quad ...(6.64)$$

The normal mode is not used because of small bandwidth and low efficiency.

In **axial mode**, radiation is maximum along the axis of the helix. It can be considered as end-fire mode. In this mode, polarisation is almost circular. This mode can be obtained when D_h and S are of the order of λ. Circular polarisation occurs when $\frac{C}{\lambda} = 1$ and $S = \frac{\lambda}{4}$.

The ground plane is of $\frac{\lambda}{2}$ diameter. The radiation patterns in normal and axial modes are shown in Fig. 6.36.



(a) **Helical antenna** *(b)* **Normal mode** *(c)* **Axial mode**

Fig. 6.36 *Radiation patterns in both modes*

In axial mode, the terminal impedance of helix is about 100 to 200 Ω.

The empirical expressions for parameters of helical antenna are:

$$Z_i = \text{input impedance} \approx 140\,\frac{C}{\lambda} \quad ...(6.65)$$

$$\text{HPBW} = \text{half-power beam width} = \frac{52\lambda^{3/2}}{C\sqrt{L_a}} \quad ...(6.66)$$

$$\text{BWFN} = \text{Null-to-Null beam width} \approx \frac{115\lambda^{3/2}}{C\sqrt{L_a}} \quad ...(6.67)$$

$$D = \text{directivity} = 15N\,\frac{C^2 S}{\lambda^3} \quad ...(6.68)$$

$$\text{The axial ratio AR} = \frac{2N+1}{N} \quad ...(6.69)$$

The normalised far-field,

$$E = \sin\left(\frac{\pi}{2N}\right)\cos\theta\,\frac{\sin\left(\frac{N}{2}\psi\right)}{\sin\left(\frac{\psi}{2}\right)} \qquad \text{...(6.70)}$$

Here
$$\psi = 2\pi\left[\frac{S}{\lambda}(1-\cos\theta)+\frac{1}{2N}\right] \qquad \text{...(6.71)}$$

Salient features of helical antenna

1. Helical antenna is a simple antenna for circular polarisation.
2. It is used in VHF and UHF bands.
3. It is most popularly used in axial mode.
4. In normal mode, beam width and efficiency are small.
5. It is a wide band antenna in axial mode.
6. It is used for extra-terrestrial communications, satellites and space probe communications, radio astronomy and so on.
7. It is not preferred in normal mode.
8. If axial ratio, AR = 0, linear horizontal polarisation results.
9. If AR = ∞, linear vertical polarisation results.
10. If AR = 1, circular polarisation results.
11. It is simple in construction and has high directivity.

Design equations The design equations of helical antenna in axial mode are:

$$d = 0.02\lambda$$
$$r = 0.12\lambda$$
$$D_h = 0.32\lambda$$
$$D_g \geq 0.8\lambda$$
$$S = 0.22\lambda$$
$$C = \pi D_h = 1.005\lambda$$
$$\alpha = \tan^{-1}\left(\frac{S}{C}\right)$$
$$R = 140\,\frac{C}{\lambda}\,\Omega = \text{terminal resistance}$$

AR = axial ratio for maximum directivity of the circular polarisation

$$= (2N+1)/N.$$

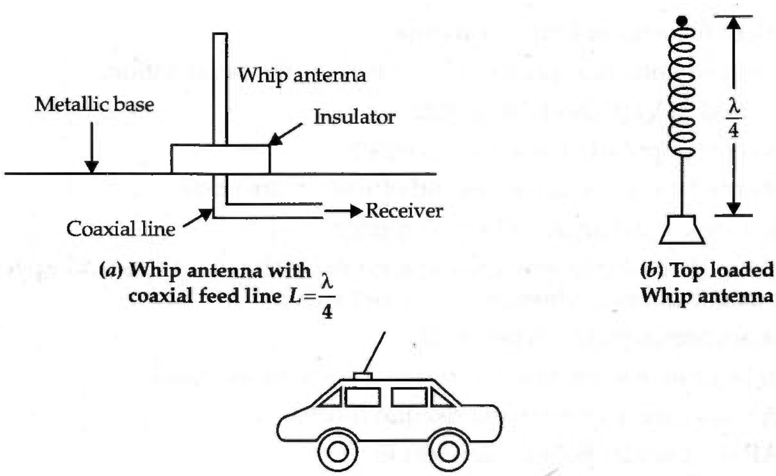
Applications of helical antenna

1. It is used to transmit and receive VHF waves for ionospheric propagation.

2. It is used for the following communications:
(*a*) Satellite, space communications.
(*b*) Space telemetry at HF and VHF bands
(*c*) Radio astronomy.

6.20 WHIP ANTENNA

It is a short vertical monopole used for mobile communication purposes. A few typical whip antenna structures are shown in Fig. 6.37.



(*a*) Whip antenna with coaxial feed line $L = \frac{\lambda}{4}$

(*b*) Top loaded Whip antenna

(*c*) Whip antenna on car top

Fig. 6.37 *Whip antennas*

Salient features of whip antenna

1. It gives a gain of three with respect to isotropic radiator in a direction perpendicular to its axis.
2. Its length can be reduced by loading.
3. It can be used in HF and VHF bands.
4. It is used mostly for mobile communications.
5. A continuously wound step tapered helical conductor with a uniform current distribution gives a 50Ω match at its resonant frequency. Its standard length is 4 feet for most of the applications.

6.21 FERRITE ROD ANTENNA

It is an antenna which consists of a ferrite rod on which a coil with a number of turns are wound. A typical structure is shown in Fig. 6.38.

This is commonly used in all transistorised radio receivers. It has a ferrite rod with one or more coils. A typical structure of ferrite rod antenna is shown in Fig. 6.38.

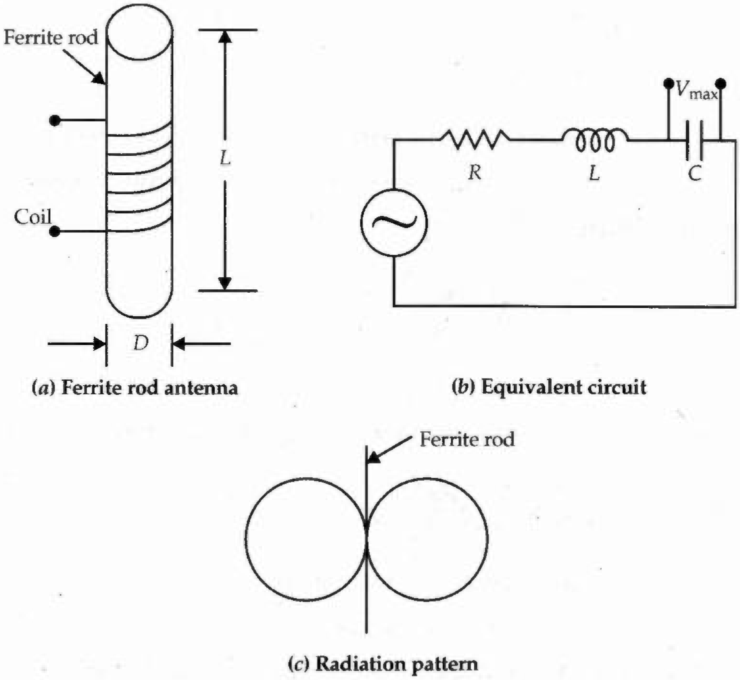


Fig. 6.38 *Ferrite rod antenna with equivalent circuit and radiation pattern*

In the Fig. 6.38,

D = diameter of the ferrite rod

L = length of the rod

The induced voltage is given by

$$V = \frac{2\pi}{\lambda} ESNK\mu_r, \text{ volt} \qquad \text{...(6.72)}$$

where E = electric field present at antenna, V/m

μ_r = permeability of the rod

K = modifying factor which takes care of coil length

= 1 for short coils

= 0.7 for coils of full length of rod

S = cross-sectional area of the rod

N = number of turns in the coil.

Effective length of the antenna is defined as

$$l_{\text{eff}} = \frac{V}{E} = \frac{2\pi}{\lambda} SK\mu_r, \text{ m} \qquad \text{...(6.73)}$$

The relation between radiation resistance of the ferrite coil and that of air core coil is

$$\frac{R_f}{R_r} = \left(\frac{\mu_e}{\mu_o}\right)^2 \qquad \text{...(6.74)}$$

where R_f = radiation resistance of ferrite coil antenna

R_r = radiation resistance of air core coil antenna

If there are N turns, R_f is given by

$$R_f = 2\lambda^2 \left(\frac{C}{\lambda}\right)^4 \left(\frac{\mu_e}{\mu_o}\right)^2 N^2,\ \Omega \qquad \text{...(6.76)}$$

where C = circumference of ferrite loop = πD

μ_e = effective permeability of ferrite rod

That is,

$$\mu_e = \frac{\mu_a}{1 + D_f(\mu_a - 1)} \qquad \text{...(6.76)}$$

μ_a = actual permeability of ferrite

D_f = demagnetisation factor

The magnetisation factor depends on length-to-diameter ratio.

Salient features of ferrite rod antenna:

1. It is used in all radio receivers.
2. It is compact.
3. Its quality factor, Q is very high. It exhibits high selectivity and more induced voltage.

6.22 TURNSTILE ANTENNA

It is an antenna composed of two dipole antennas perpendicular to each other. They intersect at their mid-points. The currents on the two dipoles are equal and in phase quadrature.

Salient features of turnstile antenna:

1. Turnstile antenna consists of two half-wave dipoles which are perpendicular to each other. The dipoles are excited with a phase difference of 90° (phase quadrature) with equal currents.
2. A typical antenna is shown in Fig. (6.39).
3. The excitation is provided by different non-resonant lines of unequal length.
4. It produces almost an omni-directional pattern.
5. The electric field of turnstile antenna is given by

$$E(\theta) = \frac{\cos\left(\frac{\pi}{2}\sin\theta\right)}{\cos\theta}\sin\omega t + \frac{\cos\left(\frac{\lambda}{2}\cos\theta\right)}{\sin\theta}\cos\omega t \qquad \text{...(6.77)}$$

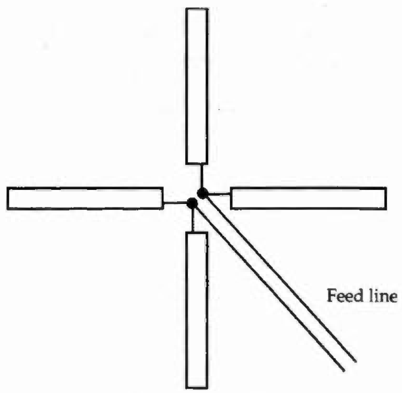


Fig. 6.39 *Turnstile antenna*

6. Directivity is improved by the array of turnstile antennas.
7. This antenna is best suited to match 70Ω dual co-axial line.
8. This is often used for T.V. and FM broadcasting in VHF and UHF bands.
9. This produces horizontal polarisation.
10. The polarisation is disturbed due to loss of power. However, the purity of polarisation is improved by super-turnstile antennas.
11. The super-turnstile antenna can be made of four flat sheets.
12. It is possible to obtain voltage standing wave ratio (VSWR) of about 1.1 over 30% bandwidth.
13. It is used as a mast mounted television transmitting antenna for frequencies about 50 MHz.
14. Bandwidth is improved by an array of super-turnstile antennas with a spacing of λ between the elements.
15. Array of super-turnstile antennas produces more horizontal gain.

6.23 DISCONE ANTENNA

It is an antenna which consists of a disc and a cone. The disc is fixed at the centre conductor of coaxial feed line so that it is perpendicular to its axis. The apex of the cone is connected to the outer shield of the coaxial line. Its variation of impedance and radiation characteristics as a function of frequency is much less when compared with those of a dipole of constant length.

Salient features of discone antenna

1. A disc and a cone together form a discone.
2. It is a ground plane antenna and is evolved from the vertical dipole.
3. It has a radiation pattern similar to that of vertical dipole.
4. A typical discone antenna is shown in Fig. 6.40. It is fed by a coaxial cable.
5. The cone semi-angle is about 30°, disc diameter is about three-fourth of the diameter of the base of the cone.

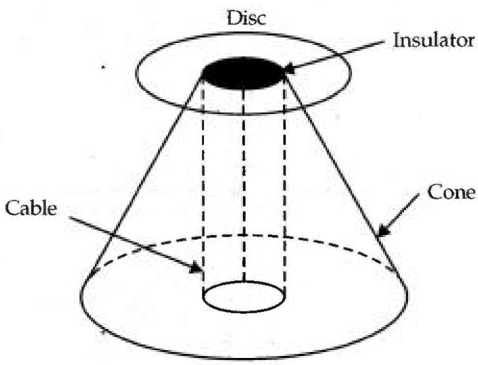


Fig. 6.40 *Discone antenna*

6. It acts as if the disc is a reflector.
7. It is a broad-band antenna.
8. It is simple and easy to fabricate.
9. Voltage standing wave ratio and gain are low.
10. It is basically omni-directional antenna.
11. It can be used at VHF and UHF bands.
12. It is often used in airport communication systems.
13. It is an ideal antenna for mobile communication base stations.
14. It is compact, rugged and economical.
15. Its gain in the horizontal plane is comparable to that of a dipole antenna.
16. Its overall performance as a function of frequency is similar to a high pass filter.
17. It is inefficient below cut-off and voltage standing wave ratio becomes high.
18. The slant height of the cone is about $\lambda/4$ at cut-off.

6.24 NOTCH ANTENNA

It is an antenna which consists of a notch in a metallic sheet.

Salient features of Notch antenna

1. It consists of a notch cut in the edge of a metallic surface.
2. It is an open ended slot antenna (Fig. 6.41).
3. It is a broad-band antenna.

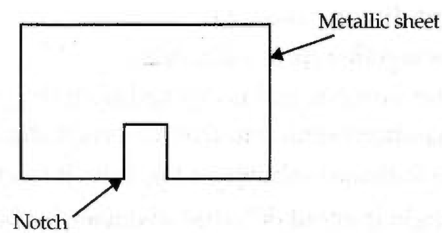


Fig. 6.41 *Notch antenna*

4. A typical radiation pattern of notch antenna is shown in Fig. 6.42.

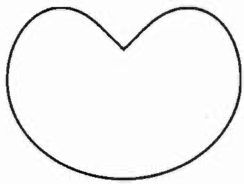


Fig. 6.42 *Radiation pattern of notch antenna*

5. Notch antennas can be easily made on the body of an aircraft.
6. The notches are filled with dielectric materials to avoid aerodynamic drag.

POINTS TO REMEMBER

1. Isotropic radiator is a hypothetical element which radiates in all directions equally.
2. An omni-directional antenna is an antenna, which has non-directional pattern in azimuth and directional pattern in elevation.
3. An example of omni-directional antenna is dipole.
4. Resonant antennas produce standing waves.
5. Non-resonant antennas produce travelling waves.
6. The size of the antenna at low frequencies is very large.
7. Antenna impedance is increased by folding a dipole.
8. The radiation resistance of folded dipole is 292Ω.
9. The radiation resistance of a folded dipole is $73K^2$, K being number of arms.
10. Yagi-Uda antenna is popularly used for TV reception.
11. Yagi-Uda antenna is a narrow-band antenna.
12. Log-periodic antenna is a frequency independent antenna.
13. Log-periodic antenna is a wide-band antenna.
14. Rhombic antenna is a travelling wave antenna.
15. Rhombic antenna is a wide-band antenna.
16. Loop antenna is used in mobile communications.
17. Radiation resistance of loop antenna is $R_r = 31{,}171 \left(\dfrac{\text{NA}}{\lambda^2}\right)^2$.
18. Helical antenna is used to produce circularly polarised waves.
19. Ferrite rod antenna is used in all transistorised radio receivers.

20. Turnstile antenna is used for T.V., FM broadcasting purposes.

21. Discone antenna is a broad-band antenna.

22. Notch antenna is used in aircrafts.

SOLVED PROBLEMS

Problem 6.1 Design a Rhombic antenna to operate at a frequency of 30 MHz with the angle of elevation, $\Delta = 30^\circ$ with respect to the ground.

Solution $$H = \frac{\lambda}{4 \sin \Delta} = \frac{\lambda}{4 \sin 30} = \frac{\lambda}{2}$$

At $f = 30$ MHz,

$$\lambda = \frac{v_0}{f} = \frac{3 \times 10^8}{30 \times 10^6} = 10 \text{ m}$$

Height of Rhombic,

$$H = 10 \times 1/2 = 5 \text{ m}$$

Tilt angle, $\phi = 90 - \Delta = 60^\circ$

Length of each wire, l is

$$l = \frac{\lambda}{2 \cos^2 \phi} = \frac{\lambda}{2 \sin^2 \Delta} = 20 \text{ m}$$

So, The design parameters are $\phi = 60^\circ$, $H = 5$ m, $l = 20$ m.

Problem 6.2 Design a Rhombic antenna to operate at 20 MHz when the angle of elevation, $\Delta = 10^\circ$.

Solution Tilt angle, $\phi = 90 - \Delta = 90 - 10 = 80^\circ$

Rhombic height, $$H = \frac{\lambda}{4 \sin \Delta}$$

$$= \frac{\lambda}{0.6945}$$

or $$H = 1.439\lambda$$

At $$f = 20 \text{ MHz}$$

$$\lambda = \frac{3 \times 10^8}{20 \times 10^6} = 15 \text{ m}$$

$$H = 21.585 \text{ m}$$

$$l = \frac{\lambda}{2 \sin^2 10}$$

$$l = 16.58\lambda$$

or $$l = 248.725 \text{ m.}$$

Problem 6.3 Obtain design data of a Rhombic antenna to operate at 30 MHz if the angle of elevation is 10°, 15°, 20°, 25°, 30°, 35°, 40°.

Solution (*a*) Angle of elevation, $\Delta = 10^\circ$

Tilt angle, $\phi = 90^\circ - \Delta = 90^\circ - 10^\circ$

$$\phi = 80^\circ$$

$$f = 30 \text{ MHz}$$

$$\lambda = \frac{v_0}{f} = \frac{3 \times 10^8}{30 \times 10^6} = 10 \text{ m}$$

Rhombic height, $H = \dfrac{\lambda}{4 \sin \Delta} = \dfrac{\lambda}{4 \sin 10^\circ}$

$$H = 1.439\lambda$$

or $$H = 14.396 \text{ m}$$

Wire length, $l = \dfrac{\lambda}{2 \sin^2 \Delta}$

$$l = 16.58\lambda$$

or $$l = 165.8 \text{ m}$$

$\therefore$ $$\phi = 80^\circ,\ H = 14.396 \text{ m},\ l = 165.8 \text{ m}$$

(*b*) Angle of elevation, $\Delta = 15^\circ$

$$\phi = 90^\circ - 15^\circ = 75^\circ$$

Rhombic height, $H = \dfrac{\lambda}{4 \sin \Delta} = 0.966\lambda$

$$H = 0.966\lambda$$

or $$H = 9.66 \text{ m}$$

Wire length, $l = \dfrac{\lambda}{2 \sin^2 \Delta}$

or $$l = 7.46\lambda$$

$$l = 74.6 \text{ m}$$

$$\phi = 75^\circ,\ H = 9.66 \text{ m},\ l = 74.6 \text{ m}$$

(*c*) Angle of elevation $\Delta = 20^\circ$

Tilt angle, $\phi = 90 - 20 = 70^\circ$

Rhombic height, $H = \dfrac{\lambda}{4 \sin \Delta}$

or $H = 0.73\lambda$

$H = 7.3$ m

Wire length, $l = \dfrac{\lambda}{2 \sin^2 \Delta}$

or $l = 4.27\lambda$

$l = 42.7$ m

$\phi = 70^{\circ}$, $H = 7.3$ m, $l = 42.7$ m

(*d*) Angle of elevation, $\Delta = 25^{\circ}$

Tilt angle, $\phi = 90^{\circ} - 25^{\circ}$

$= 65^{\circ}$

Rhombic height, $H = \dfrac{\lambda}{4 \sin \Delta}$

or $H = 0.591\lambda$

$H = 5.91$ m

Wire length, $l = \dfrac{\lambda}{2 \sin^2 \Delta}$

or $l = 2.79\lambda$

$l = 27.9$ m

$\phi = 65^{\circ}$, $H = 5.91$ m, $l = 27.9$ m

(*e*) Angle of elevation, $\Delta = 30^{\circ}$

Tilt angle, $\phi = 90^{\circ} - 30^{\circ}$

$= 60^{\circ}$

Rhombic height, $H = \dfrac{\lambda}{4 \sin \Delta}$

$H = 0.5\lambda$

$H = 5$ m

Wire length, $l = \dfrac{\lambda}{2 \sin^2 \Delta}$

$= 2\lambda$

$$l = 2 \times 10 = 20 \text{ m.}$$

$$\phi = 60^\circ,\ H = 5 \text{ m},\ l = 20 \text{ m}$$

(*f*) Angle of elevation, $\Delta = 35^\circ$

Tilt angle, $\phi = 90^\circ - 35^\circ = 55^\circ$

Rhombic height, $H = \dfrac{\lambda}{4 \sin \Delta}$

or $H = 0.435\lambda$

$H = 4.35$ m

Wire length, $l = \dfrac{\lambda}{2 \sin^2 \Delta}$

$= 1.52\lambda$

or $l = 15.2$ m

$$\phi = 55^\circ,\ H = 4.35 \text{ m},\ l = 15.2 \text{ m}$$

(*g*) Angle of elevation, $\Delta = 40^\circ$

Tilt angle, $\phi = 90^\circ - 40^\circ = 50^\circ$

Rhombic height, $H = \dfrac{\lambda}{4 \sin \Delta}$

or $H = 0.39\lambda$

$H = 3.9$ m

Wire length, $l = \dfrac{\lambda}{2 \sin^2 \Delta}$

or $l = 1.21\lambda$

$l = 12.1$ m

$$\phi = 50^\circ,\ H = 3.9 \text{ m},\ l = 12.1 \text{ m.}$$

Problem 6.4 Obtain alignment design parameters of Rhombic antenna to operate at 30 MHz when the required elevation angle is 30°.

Solution $f = 30$ MHz

$$\lambda = \frac{3 \times 10^8}{30 \times 10^6} = 10 \text{ m}$$

Elevation angle, $\Delta = 30^\circ$

Tilt angle, $\phi = 90^\circ - \Delta = 90^\circ - 30^\circ$

$$= 60^\circ$$

$$\phi = 60^\circ$$

Rhombic height, $H = \dfrac{\lambda}{4 \sin \Delta} = 5 \text{ m}$

Wire length, $l = \dfrac{\lambda}{2 \sin^2 \Delta} \times k$

$$= \frac{\lambda}{2 \sin^2 30^\circ} \times 0.74$$

$$= 1.48\lambda = 14.8 \text{ m}$$

$$\phi = 60^\circ, \; H = 5 \text{ m}, \; l = 14.8 \text{ m}.$$

Problem 6.5 Obtain alignment design parameter of Rhombic antenna to operate at 20 MHz if the elevation angle is 20°.

Solution Frequency, $f = 20$ MHz

$$\lambda = \frac{3 \times 10^8}{20 \times 10^6} = 15 \text{ m}$$

Elevation angle, $\Delta = 20^\circ$

Tilt angle, $\phi = 90^\circ - 20^\circ = 70^\circ$

$$K = 0.74$$

Rhombic height, $H = \dfrac{\lambda}{4 \sin \Delta} = 10.96 \text{ m}$

Wire length, $l = \dfrac{\lambda}{2 \sin^2 \Delta} \times K$

$$l = 47.44 \text{ m}$$

$$\phi = 70^\circ, \; H = 10.96 \text{ m}, \; l = 47.44 \text{ m}.$$

Problem 6.6 Design a three element Yagi-Uda antenna to operate at a frequency of 172 MHz.

Solution Frequency, $f = 172$ MHz

$$\lambda = \frac{3 \times 10^8}{172 \times 10^6} = \frac{300}{172} = 1.744 \text{ m}$$

The length of driven element,

$$L_a = \frac{478}{f_{\text{MHz}}} = \frac{478}{172} = 2.78 \text{ feet}$$

Length of reflector, $L_r = \dfrac{492}{172} = 2.86 \text{ feet}$

Length of director,

$$L_d = \frac{461.5}{172} = 2.683 \text{ feet}$$

Element spacing,

$$S = \frac{142}{172} = 0.825 \text{ feet}$$

$$L_a = 2.78',\ L_r = 2.86',\ L_d = 2.683',\ S = 0.825'.$$

Problem 6.7 Design Yagi-Uda antenna of six elements to provide a gain of 12 dB_i if the operating frequency is 200 MHz.

Solution Required gain = 12 dB_i

Frequency, $f = 200$ MHz

$$\lambda = 1.5 \text{ m}$$

$$L_a = 0.416\lambda = 0.69 \text{ m}$$

$$L_r = 0.475\lambda = 0.7125 \text{ m}$$

$$Ld_1 = 0.44\lambda = 0.66 \text{ m}$$

$$Ld_2 = 0.44\lambda = 0.66 \text{ m}$$

$$Ld_3 = 0.43\lambda = 0.645 \text{ m}$$

$$Ld_4 = 0.40\lambda = 0.60 \text{ m}$$

$$S_L = 0.25\lambda = 0.375 \text{ m}$$

$$S_d = 0.31\lambda = 0.465 \text{ m}$$

Diameter of elements,

$$d = 0.01\lambda = 0.015 \text{ m}$$

The length of array $= 1.5\lambda = 2.25$ m.

Problem 6.8 Design a log-periodic antenna to obtain a gain of 9 dB and to operate over a frequency range of 125 MHz-500 MHz.

Solution Gain required = 9 dB

Lowest frequency, $f = 125$ MHz

Highest frequency, $f = 500$ MHz

Longest wavelength corresponds to shortest frequency and shortest wavelength corresponds to longest frequency.

$$\lambda_{long} = \frac{3 \times 10^8}{125 \times 10^6} = 2.4 \text{ m}$$

$$\lambda_{short} = \frac{3 \times 10^8}{500 \times 10^6} = 0.6 \text{ m}$$

To obtain a gain of 9 dB, the values of scale and spacing factors are taken from Isbel's curves. They are,

$$\tau = 0.861$$

$$\sigma = 0.162$$

Now the wedge angle is,

$$\alpha = 2\tan^{-1}\left(\frac{1-\tau}{4\sigma}\right) = 24.2^{\circ}$$

We have $$\tau = \frac{D_n}{D_{n-1}} = \frac{L_n}{L_{n-1}}$$

or $$L_2 = \tau L_1, \quad L_3 = \tau L_2, \ldots$$

$$L_1 = \frac{\lambda_{long}}{2} = \frac{2.4}{2} = 1.2 \text{ m}$$

$$L_2 = \tau L_1 = 1.0332 \text{ m}$$

$$L_3 = \tau L_2 = 0.8895 \text{ m}$$

$$L_4 = \tau L_3 = 0.7659 \text{ m}$$

$$L_5 = \tau L_4 = 0.6594 \text{ m}$$

$$L_6 = \tau L_5 = 0.5678 \text{ m}$$

$$L_7 = \tau L_6 = 0.4888 \text{ m}$$

$$L_8 = \tau L_7 = 0.4210 \text{ m}$$

$$L_9 = \tau L_8 = 0.3624 \text{ m}$$

$$L_{10} = \tau L_9 = 0.3120 \text{ m}$$

$$L_{11} = \tau L_{10} = 0.2686 \text{ m}$$

And the element spacing relation is,

$$\sigma = \frac{S_n}{2L_n}$$

or $$S_n = 2\sigma L_n = (D_n - D_{n-1})$$

$$S_1 = 2\sigma L_1 = 0.3888 \text{ m}$$

$$S_2 = 2\sigma L_2 = 0.3347 \text{ m}$$

$$S_3 = 2\sigma L_3 = 0.2881 \text{ m}$$

$$S_4 = 2\sigma L_4 = 0.2481 \text{ m}$$

$$S_5 = 2\sigma L_5 = 0.2136 \text{ m}$$

$$S_6 = 2\sigma L_6 = 0.1839 \text{ m}$$

$$S_7 = 2\sigma L_7 = 0.1583 \text{ m}$$

$$S_8 = 2\sigma L_8 = 0.1364 \text{ m}$$

$$S_9 = 2\sigma\, L_9 = 0.1174 \text{ m}$$
$$S_{10} = 2\sigma\, L_{10} = 0.1010 \text{ m}$$
$$S_{11} = 2\sigma\, L_{11} = 0.0870 \text{ m.}$$

Problem 6.9 Find the induced voltage in a vertical 10 turn loop antenna due to a field strength of 10 mV/m and frequency 2 MHz. The area of the loop antenna is 1.4 m^2.

Solution Electric field strength,

$$E_{RMS} = 10 \text{ mV/m}$$
$$f = 2 \text{ MHz}$$
$$N = 10 \text{ turns}$$

$\phi = 0^\circ$ when the plane of the loop is in the plane of propagation of electromagnetic wave

$$S = 1.4 \text{ m}^2$$

$$V_{RMS} = \frac{2\pi\, E_{max}\, SN}{\lambda} \cos\phi \text{ volts}$$

$$= \frac{2\pi\sqrt{2}E_{RMS}\, SN}{\lambda} \cos\phi$$

$$= \frac{2\pi\sqrt{2} \times 10 \times 1.4 \times 10 \times 1}{150}$$

$$\boxed{V_{RMS} = 8.29 \text{ mV.}}$$

Problem 6.10 Find the radiation resistance of a loop antenna of diameter 0.5 m operating at 1 MHz.

Solution Diameter of the loop antenna

$$= 0.5 \text{ m}$$

Its radius $= 0.25$ m

$$f = 1 \text{ MHz}$$
$$\lambda = 300 \text{ m}$$
$$R_r = 3720 \left(\frac{a}{\lambda}\right)$$
$$= 3{,}720 \times \frac{0.25}{300} = 3.1\Omega.$$

Problem 6.11 Determine the directivity of a loop antenna whose radius is 0.5 m when it is operated at 0.9 MHz.

Solution Radius of loop antenna

$$a = 0.5 \text{ m}$$
$$f = 0.9 \text{ MHz}$$

$$\lambda = 333.33 \text{ m}$$

$$\frac{2\pi a}{\lambda} = 9.42 \times 10^{-3}$$

As $\frac{2\pi a}{\lambda} < \frac{1}{3}$, $\therefore$ $D = 1.5.$

Problem 6.12 If the radius of a small loop is 0.035λ, find its physical area and maximum effective aperture.

Solution Radius of the loop antenna

$$a = 0.035\lambda$$

Physical area $= \pi a^2$

$$= \pi \times (0.035\lambda)^2$$

$$A = 3.848 \times 10^{-3}\, \lambda^2$$

Maximum effective aperture,

$$A_{em} = \frac{3\lambda^2}{8\pi}$$

$$A_{em} = 0.119\lambda^2.$$

Problem 6.13 A circular loop antenna has a diameter of 1.5λ. Find its directivity and radiation resistance.

Solution Radius of the loop antenna,

$$a = \frac{1.5\lambda}{2} = 0.75\lambda$$

$$\frac{C}{\lambda} = \frac{2\pi a}{\lambda} = \frac{2\pi}{\lambda} \cdot 0.75\lambda$$

$$= 1.5\pi$$

The expression for radiation resistance,

$$R_r = 3720 \left(\frac{a}{\lambda}\right)$$

$$= 3720 \times 0.75$$

$$R_r = 2790\Omega$$

The directivity of the loop antenna is

$$D = 4.25 \left(\frac{a}{\lambda}\right)$$

$$= 4.25 \times 0.75$$

$$D = 3.1875.$$

Problem 6.14 An array of dipoles of $\frac{\lambda}{2}$ length in end-fire mode is to produce a power gain of 28. Find the array length, number of elements when spaced at $\frac{\lambda}{2}$ and Null-to-Null beam width.

Solution For end-fire array, the power gain is given by

$$g_p = 4\left(\frac{L}{\lambda}\right), \quad L = \text{array length}$$

That is,

$$28 = 4\left(\frac{L}{\lambda}\right)$$

or

$$L = 7.0\lambda$$

Number of elements in the array when spaced at $\frac{\lambda}{2}$

$$= 7.0 \times 2 = 14$$

Null-to-Null beam width

$$= 2\sqrt{\frac{2\lambda}{Nd}}$$

$$= 2\sqrt{\frac{2\lambda}{14 \times \frac{\lambda}{2}}}$$

$$= \frac{4}{\sqrt{14}} = \frac{4}{3.7416}$$

$$= 1.07 \text{ rad}$$

$$\text{B.W.} = 61.30°$$

Problem 6.15 If a helical antenna has a spacing between turns 0.05 m, diameter 0.1 m, number of turns equal to 20 and operates at 1,000 MHz, find the Null-to-Null beam width of the main beam and also half-power beam width and directivity.

Solution $S = 0.05$ m

$D_h = 0.10$ m

$N = 20$

$f = 1{,}000$ MHz

$\lambda = 0.3$ m

BWFN, $$\phi_0 = \frac{115\lambda^{3/2}}{C\sqrt{L_a}}$$

where $C = \pi D_h$

$L_a = NS$

$$\phi_0 = \frac{115\,(0.3)^{3/2}}{\pi \times (0.1)\sqrt{20 \times 0.05}} = 60.14^\circ$$

HPBW, $$\phi = \frac{52\lambda^{3/2}}{C\sqrt{L_a}} = 27.20^\circ$$

Directivity, $$D = \frac{15NC^2S}{\lambda^3} = 54.84$$

BWFN = 60.2°, HPBW = 27.2°, D = 54.84.

OBJECTIVE QUESTIONS

1. Isotropic radiator radiates equally in all directions. (Yes/No)
2. Isotropic radiator and omni-directional radiator are one and the same. (Yes/No)
3. If P_i is the input to isotropic radiator, power density is ______________.
4. Marconi antenna is nothing but ______________.
5. Standing waves are produced in non-resonant antennas. (Yes/No)
6. Travelling waves are produced in resonant antennas. (Yes/No)
7. Rhombic antenna is ______________
   (a) travelling wave antenna (b) standing wave antenna
   (c) narrow-band antenna (d) used in LF bands
8. Resonant antenna has a length in multiples of $\frac{\lambda}{2}$. (Yes/No)
9. When the length of the antenna is λ, the polarity of the current in one-half of the antenna is opposite to that on the other half. (Yes/No)
10. The radiation at right angles from λ antenna is zero because ______________.
11. Antennas transmit efficiently when the length is ______________.
12. The voltage distribution on half-wave dipole is ______________.
13. Resonant antenna is
    (a) Aperiodic (b) Periodic
    (c) Travelling wave (d) Rhombic
14. If the length of wire antenna is more, beam width is small. (Yes/No)
15. HF band is ______________.
16. UHF band is ______________.
17. Tower antenna is ______________.

18. A typical inductance loaded LF antenna is ______________.
19. One application of VLF is ______________.
20. Null-to-Null beam width of end-fire array is ______________.
21. Null-to-Null beam width of broadside array is ______________.
22. Radiation beam in broadside array is along the axis of the array. (Yes/No)
23. If the number of elements is more in an array, beam width is small. (Yes/No)
24. *V* antennas are ______________.
25. The excitation to each wire of *V* antenna is ______________.
26. The radiation pattern of resonant *V* antenna is ______________.
27. The radiation pattern of non-resonant *V* antenna is ______________.
28. Arrays of *V* antennas are not possible. (Yes/No)
29. Inverted *V* antenna is a travelling wave antenna. (Yes/No)
30. The directivity of Rhombic antenna is greater than that of *V* antenna. (Yes/No)
31. Rhombic antenna is an HF antenna. (Yes/No)
32. The efficiency of Rhombic antenna is very high. (Yes/No)
33. Rhombic antenna is used for transmission purpose only. (Yes/No)
34. The radiation of Rhombic antenna is ______________.
35. The design parameters of Rhombic antenna are ______________.
36. Radiation resistance of $\frac{\lambda}{2}$ folded dipole is ______________.
37. Radiation resistance of three folded $\frac{\lambda}{2}$ dipole is ______________.
38. Radiation pattern of folded dipole is the same as that of straight dipole. (Yes/No)
39. The voltage and current in resonant antennas are ______________.
40. The length of non-resonant antenna is in multiples of $\frac{\lambda}{2}$. (Yes/No)
41. In end-fire array, all the elements are fed with no additional phase. (Yes/No)
42. The impedance of folded dipole is a function of dipole radius. (Yes/No)
43. The disadvantage of non-resonant *V* antenna is ______________.
44. Isotropic antenna is used as ______________.
45. The director's reactance in Yagi-Uda antenna is ______________.
46. The reflector's reactance in Yagi-Uda antenna is ______________.
47. The sensitivity of Yagi-Uda is very high. (Yes/No)

48. The band width of Yagi-Uda antenna is limited. (Yes/No)

49. The band width of straight dipole is ______________.

50. In end-fire two-element array, the elements are fed with a phase difference of 180°. (Yes/No)

51. In broadside array, the elements are in phase. (Yes/No)

52. The impedance and directivity changes with frequency in log- periodic array. (Yes/No)

53. Log-periodic antenna is frequency independent. (Yes/No)

54. Log-periodic antenna is a wide-band antenna. (Yes/No)

55. Rhombic antenna is more efficient than log-periodic antenna. (Yes/No)

56. Log-periodic array is a uniform linear array. (Yes/No)

57. The gain of log-periodic antenna is more when τ is small and α is large. (Yes/No)

58. Log-periodic antenna becomes compact when scale factor is small and wedge angle α is large. (Yes/No)

59. The designed band width is greater than the desired band width in log-periodic antenna. (Yes/No)

60. The number of dipoles in log-periodic antenna is a function of
    (*a*) desired gain only
    (*b*) desired band width only
    (*c*) wedge angle only
    (*d*) designed band width and scale factor

61. Length of the log-periodic array is a function of ______________.

62. The length of the antenna at an operating frequency of 0.5 GHz is
    (*a*) 570 m
    (*b*) 5.70 m
    (*c*) 57.0 m
    (*d*) 600 m

63. The equivalent of a small loop antenna is ______________.

64. The Marconi antenna is used in ______________.

65. The loop antennas are used for ______________.

66. Loop antennas may have several turns. (Yes/No)

67. Loop antennas may have ferrite cores. (Yes/No)

68. Ferrite cores in loop antennas increase the diameter of the loop. (Yes/No)

69. Loop antennas with ferrite cores are as ______________.

70. The loop antenna is always circular in shape. (Yes/No)

71. The directional properties of loop antennas at medium frequencies are different from those at microwave frequencies. (Yes/No)

72. The direction of the given radiation in loop antenna is indicated by maximum signal. (Yes/No)

73. The direction of given radiation is indicated by null. (Yes/No)

74. The directional loop antenna is independent of the shape of the loop. (Yes/No)

75. The radiation pattern of loop antenna is the same as that of a half-wave dipole. (Yes/No)

76. Helical antenna is used in ______________.

77. Helical antenna produces circular polarisation. (Yes/No)

78. Helical antenna has wide band width. (Yes/No)

79. Helical antenna is mostly used in normal mode. (Yes/No)

80. Helical antenna is used in axial mode. (Yes/No)

81. Helical antenna can be used in HF, VHF bands. (Yes/No)

82. Helical antenna is only for receiving purposes. (Yes/No)

83. Helical antenna is used for transmission and receiving purposes. (Yes/No)

84. Whip antennas are used in ______________.

85. Whip antennas are used at HF and VHF bands. (Yes/No)

86. Whip antenna is a quarter-wave Marconi antenna. (Yes/No)

87. At 30 MHz, whip antenna has a length of

(*a*) 2.5 m (*b*) 25 m

(*c*) 250 m (*d*) 10 m

88. Effective height of quarter-wave grounded vertical wire is ______________.

89. An example of Marconi antenna is ______________.

90. Ferrite rod antennas are used in ______________.

91. The selectivity of ferrite rods is very high. (Yes/No)

92. Radiation resistance of ferrite rod depends on ______________.

93. Antenna efficiency is ______________.

94. The approximate practical $\frac{\lambda}{2}$ dipole length after taking end effects into account is ______________.

95. If the length of antenna is more, its directivity is high. (Yes/No)

96. The disadvantage of Rhombic antenna is ______________.

97. Loop antennas are used in ______________.

98. Loop antenna can be of any shape including triangular loop for direction-finding. (Yes/No)

99. For direction-finding loop antenna is rotated. (Yes/No)

100. The purpose of Adcock antenna is ______________.

101. In general, loop antennas are satisfactory for frequencies between 2 and 30 MHz due to polarisation error. (Yes/No)

102. Discone antenna is a broad-band antenna compared to dipole. (Yes/No)

103. Notch antenna is used ____________.

104. Inverted *V* antenna is balanced fed. (Yes/No)

105. For small square and circular loop antennas, the field patterns are identical. (Yes/No)

106. The radiation patterns depend only on the area and the shape of the small loop has no effect. (Yes/No)

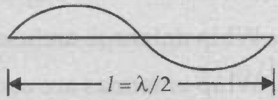
ANSWERS

1. Yes **2.** No **3.** $P_i/4\pi r^2$ watts/m^2 **4.** A quarter-wave monopole

5. No **6.** No **7.** (*a*) **8.** Yes **9.** Yes

10. The currents are out of phase **11.** $\lambda/2$, $\lambda/4$

12.

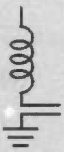


13. (*b*) **14.** Yes

15. 3 – 30 MHz

16. 300 MHz – 3 GHz **17.** LF antenna

18.



19. Telegraphy **20.** $2\sqrt{\dfrac{2\lambda}{Nd}}$ **21.** $\dfrac{2\lambda}{Nd}$ **22.** No

23. Yes **24.** Resonant as well as non-resonant

25. Out of phase **26.** Bi-directional

27. Uni-directional **28.** No **29.** Yes **30.** Yes

31. Yes **32.** No **33.** No **34.** Uni-directional

35. Elevation angle, Rhombic height, wire length **36.** 292Ω **37.** 657Ω

38. Yes **39.** Are not in phase **40.** No **41.** No **42.** Yes

43. There exists high side lobes **44.** Reference antenna

45. Capacitive **46.** Inductive **47.** Yes **48.** Yes **49.** Narrow **50.** Yes

51. Yes **52.** No **53.** Yes **54.** Yes **55.** No **56.** No

57. No **58.** Yes **59.** Yes **60.** (*d*)

61. Frequency, designed band width and wedge angle **62.** (*a*)

63. Magnetic dipole **64.** Commercial radio stations **65.** Direction finding

66. Yes **67.** Yes **68.** Yes **69.** Portable broadcast receivers

70. No **71.** No **72.** No **73.** Yes **74.** Yes **75.** Yes

76. Telemetry, satellite, and probe communications **77.** Yes **78.** Yes

79. No **80.** Yes **81.** Yes **82.** No **83.** Yes

84. Mobile communications **85.** Yes **86.** Yes **87.** (*a*)

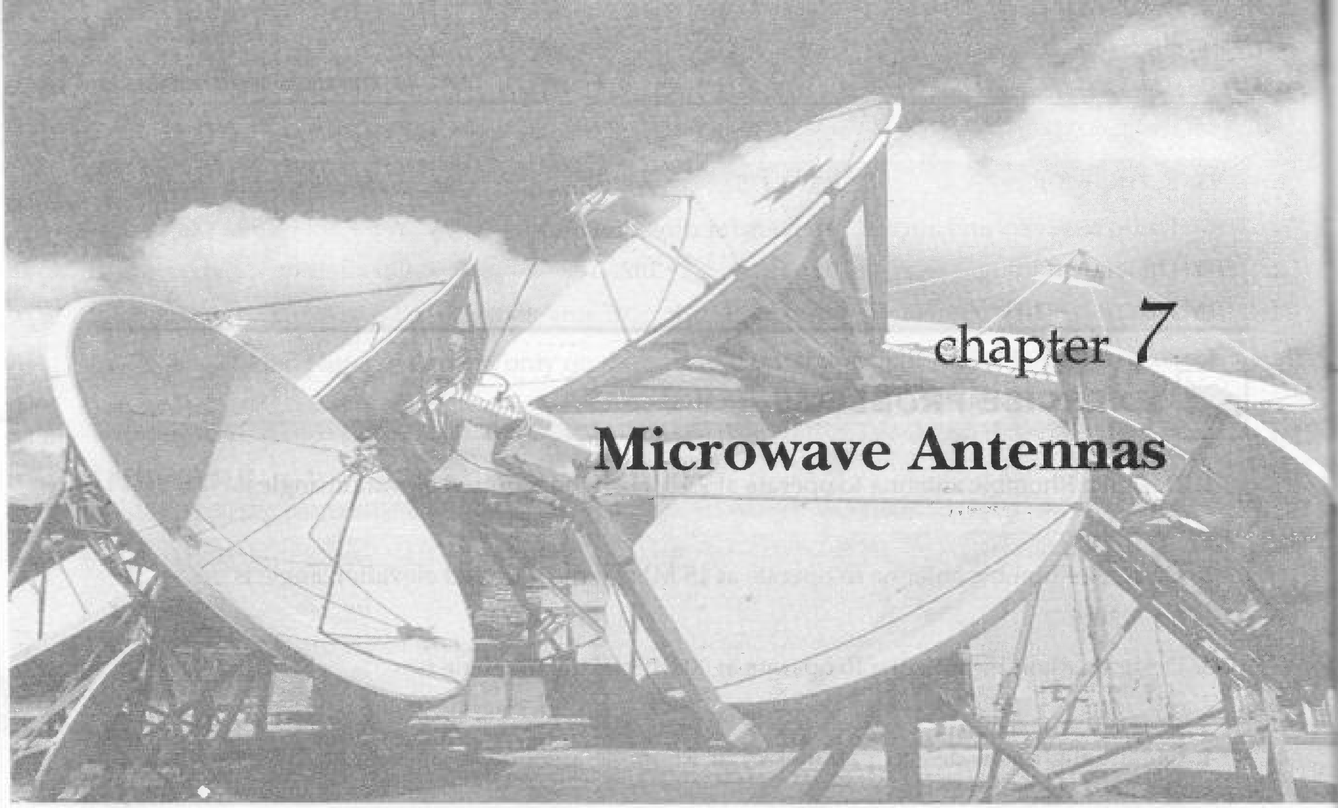
88. $\dfrac{2}{\pi}\times$ actual height **89.** Quarter-wave antenna **90.** Radio receivers

91. Yes **92.** Diameter of ferrite rod, its effective permeability and frequency of operation

93. $R_r/(R_r + R_l)$ **94.** 0.475λ **95.** Yes **96.** It requires more space
97. Radio receivers and aircraft receivers for direction finding **98.** Yes **99.** Yes
100. Direction finding **101.** Yes **102.** Yes **103.** On aircrafts
104. No **105.** Yes **106.** Yes.

EXERCISE PROBLEMS

1. Design a Rhombic antenna to operate at 25 MHz if the required elevation angle is
   (*a*) 20° (*b*) 25°.
2. Design a Rhombic antenna to operate at 15 MHz if the required elevation angle is
   (*a*) 30° (*b*) 35°.
3. Design a Rhombic antenna to operate at 20 MHz if the tilt angle is
   (*a*) 60° (*b*) 65°.
4. Obtain alignment design parameters of Rhombic antenna to operate at 25 MHz when the required elevation angle is
   (*a*) 25° (*b*) 30°.
5. A multiple circular loop of radius 1.0 cm operates at 100 MHz. If its radiation resistance is $10.0\,\Omega$, find the number of turns.



chapter 7

Microwave Antennas

"Microwaves are nothing but Electromagnetic waves with wavelengths at micro level and microwave antennas are small in size."

CHAPTER OBJECTIVES

This chapter discusses

- The design, construction, applications and analysis of all types of microwave antennas including microstrip antennas
- Objective questions and solved problems useful for class tests, final examinations and also for competitive examinations
- Exercise problems to develop self problem solving skills

7.1 INTRODUCTION

The size of the antenna depends mainly on the frequency of operation. If the frequency is low, size of the antenna is large and vice-versa.

Microwave antennas are popular for their small size and better radiation characteristics. In the present day miniaturised world, the smaller the antennas in communication, the more is the attraction.

Different important and popular microwave antennas and their characteristics are presented in this chapter.

It is difficult to classify antennas based on frequency. Most of the antennas are used in overlapping frequency bands. However, in the present chapter, the following antennas are considered to be microwave antennas and they are described in detail.

Microwave antennas:

- Reflector antennas
- Horn antennas
- Dielectric and metal lens antennas
- Slot antennas
- Micro-strip antennas

The microwave region extends from 1 GHz to 100 GHz. The transmitting and receiving antennas in microwave frequencies are directive with high gain and narrow beam width in both vertical and horizontal planes.

Types of reflectors:

1. Rod reflector
2. Plane reflector
3. Corner reflector
4. Cylindrical reflector
5. Horn reflector
6. Spherical reflector
7. Parabolic reflector.

7.2 ROD REFLECTOR

It is mainly used in Yagi-Uda antenna. It is placed behind the driven element. Its length is slightly longer than that of the driven element. That is, it is greater than $\frac{\lambda}{2}$. It offers inductive reactance and contributes in increasing the gain. Here rod reflector is not the main antenna but is only a parasitic element. The main disadvantage of the rod element is that it alters the impedance of the driven element.

7.3 PLANE REFLECTOR

It is the simplest reflector to direct electromagnetic energy in a desired direction. But it is difficult to collimate the energy in the forward direction. In fact, polarisation of the primary antenna and its position with respect to the reflecting surface is used to control the pattern characteristics, impedance, power gain and directivity of the complete system. Infinitely large reflector is ideal. It is difficult to collimate the energy by a plane reflector.

A typical plane reflector is shown in Fig. 7.1.

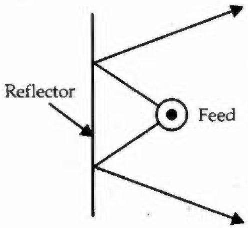


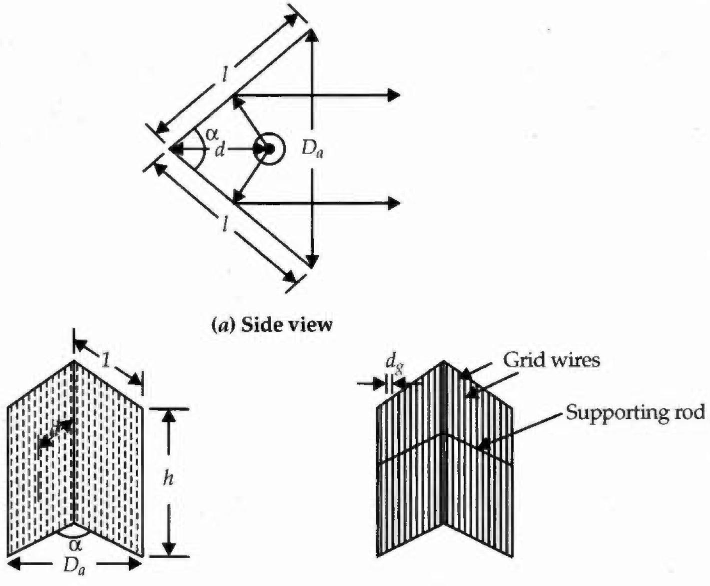
Fig. 7.1 *Plane reflector*

7.4 CORNER REFLECTOR

A corner reflector is a reflecting object which consists of two or three mutually intersecting, conducting flat surfaces.

Dihedral forms of corner reflectors are frequently used in antennas. However, trihedral forms with mutually perpendicular surfaces are used as radar targets.

A typical corner reflector is shown in Fig. 7.2.



(*a*) **Side view**

(*b*) **Perspective view**

(*c*) **Wire-grid corner reflector**

Fig. 7.2 *Corner reflector*

A corner reflector is designed to improve the collimation of electromagnetic energy in the forward direction and to eliminate radiation in the back and side directions.

For the corner reflector shown in Fig. 7.2

$$D_a = \text{aperture size}$$

$$l = \text{length}$$

$$h = \text{height}$$

d = spacing between the vertex and feed point location

d_g = spacing between grid wires

α = included angle

The ranges of the above parameters for a good corner reflector are:

1. $\lambda < D_a < 2\lambda$
2. $l \approx 2d$
3. $\frac{\lambda}{3} < d < \frac{2\lambda}{3}$ ...(7.1)
4. h is 1.2 to 1.5 times greater than the total length of feed element
5. $d_g \leq \frac{\lambda}{10}$.

Salient features of corner reflector

1. It is simple to construct.
2. It is used as a passive target for radar and communication applications to return the signal exactly in the same direction by choosing $\alpha = 90^\circ$. Due to this unique feature, most of the defence ships and vehicles are designed with minimum sharp corners to reduce the chances of their detection by enemy radars.
3. It is also used in home television antennas.
4. The most preferred value of α is 90°.
5. The spacing between the vertex and feed element position is increased if α is decreased and vice-versa, in order to improve efficiency.
6. When α is small, gain is increased by increasing the length of the sides of the reflector.
7. The feed element can be a dipole or an array of collinear dipoles.
8. When the feed elements are cylindrical or biconical dipoles instead of thin wires, band width and radiation resistance are high.
9. When the reflector is large with high λ, the surfaces of corner reflectors are made of grid wires to reduce aerodynamic drag due to wind speeds and overall system weight.
10. If the spacing, d is small, radiation resistance becomes small and hence efficiency is reduced.
11. If the spacing is very large, the system produces undesirable multiple lobes and it loses its directional characteristics.
12. The main lobe is broad for reflectors with finite sides compared to those of infinite dimensions.
13. The array factor of corner reflector antenna is

$$E = 2\,[\cos(Kd\sin\theta\,\cos\phi) - \cos(Kd\sin\theta\,\sin\phi)] \quad ...(7.2)$$

Here, $K = \frac{2\pi}{\lambda}$.

14. For small included angle, the side lengths should be longer.

Cylindrical reflector It is a reflector which is part of a cylinder. The cylinder is usually parabolic in shape. However, cylinders of other shapes also can be used.

Horn reflector It is a reflector antenna which consists of a section of a paraboloidal reflector fed with an offset horn which intersects the reflector surface. Horn antenna is a radiating element which is in the shape of a horn. The horn reflector antenna is either pyramidal or conical.

Spherical reflector It is a reflector which is part of a spherical surface.

7.5 PARABOLIC REFLECTOR

It is a reflector antenna which has the shape of paraboloid and employs the properties of parabola.

It can also be defined as a reflector which is part of a paraboloid of revolution.

The parabola, it is a plane curve obtained by the locus of a point which moves so that its distance from another point, called the focus, plus its distance from a straight line, called directrix, is constant.

A paraboloid is a three dimensional surface obtained by revolving the parabola about its axis. The paraboloid is called the parabolic reflector or dish antenna.

The geometry of a parabolic reflector in transmitting mode is shown in Fig. 7.3.

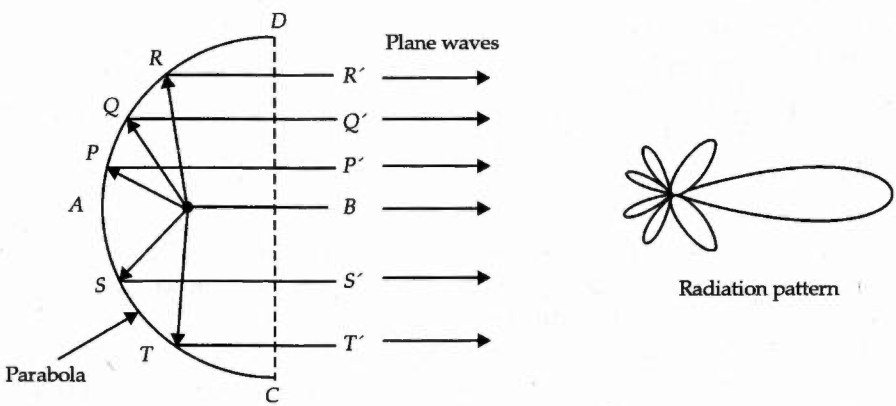


Fig. 7.3 *Geometry of parabolic reflector in transmitting mode and its radiation pattern*

Here AB = axis of the parabola

CD = mouth diameter, D_a

AF = focal length = l_f

A = vertex

F = focus

CAD = parabola

The line CD = directrix

AF/CD = aperture of the parabola

From the definition of a parabola we have,

$$FP + PP^1 = FQ + QQ^1 = FS + SS^1 = \text{constant } (K)$$

K varies with shape.

The equation of the parabola is

$$y^2 = 4l_f\, x \qquad \text{...(7.3)}$$

and the equation of the paraboloid is

$$y^2 + z^2 = 4l_f\, x \qquad \text{...(7.4)}$$

A parabolic reflector in receiving mode is shown in Fig. 7.4.

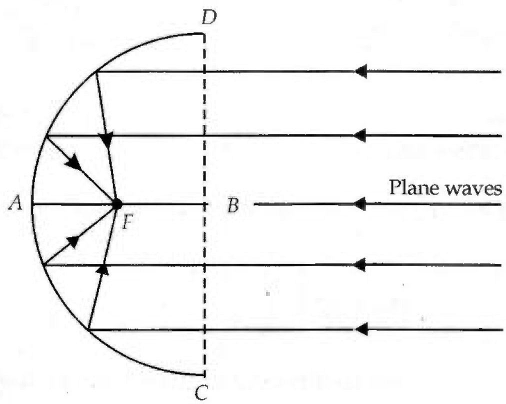


Fig. 7.4 *Geometry of parabolic reflector in receiving mode*

Operation of parabolic reflector If a feed antenna is placed at the focus, all the waves are incident on the reflector and they are reflected back, forming a plane wave front. By the time the reflected waves reach the directrix, all of them will be in phase, irrespective of the point on the parabola from which they are reflected. Hence the radiation is very high and is concentrated along the axis of the parabola. At the same time, waves will be cancelled in other directions as a result of path and phase differences.

The main purpose of the parabolic reflector is to convert a spherical wave into a plane wave.

The difference between the plane wave and spherical wave are shown in Fig. 7.5.

If the primary or feed antenna is non-directional or isotropic, the beam width of the radiation pattern of the paraboloid is given by:

HPBW, $\quad = \phi = \dfrac{70\lambda}{D_a}$

BWFN, $\quad \phi_0 = 2\phi = \dfrac{140\lambda}{D_a}$ ...(7.5)

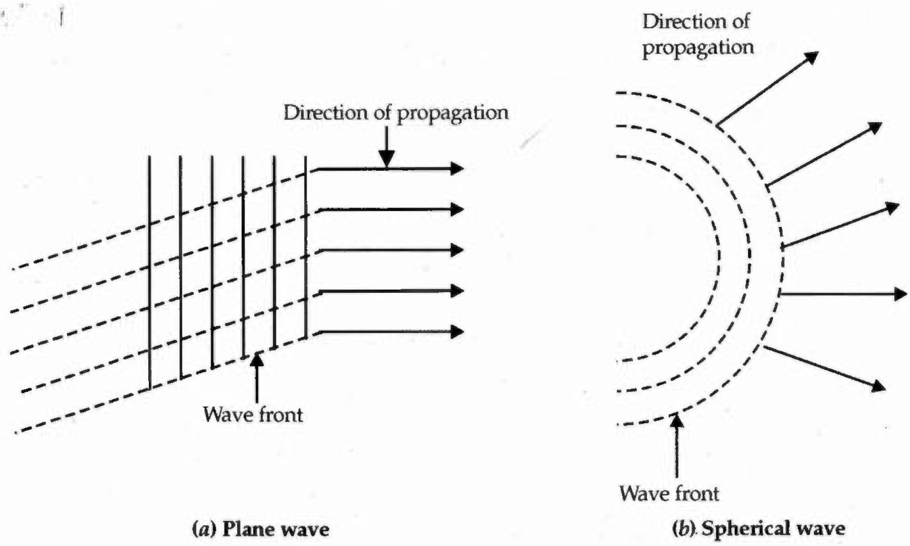


Fig. 7.5 *Direction of propagation of plane and spherical waves*

Directivity, $D = 9.87 \left(\frac{D_a}{\lambda} \right)^2$

Here, ϕ = half-power beam width, in degrees

ϕ_0 = beam width between first nulls, in degrees

λ = wavelength, m

D_a = mouth diameter, m.

For a large, uniformly illuminated rectangular aperture,

HPBW $= \phi = \frac{57.5\lambda}{L}$ (degrees)

BWFN $= \phi_0 = \frac{115\lambda}{L}$ (degrees) ...(7.6)

Directivity, $D = \frac{4\pi A}{\lambda^2}$

Here, L = length of the aperture, in λ

A = aperture area, m^2.

The above equations are for ideal illuminations. No primary feed antenna is truly isotropic. Moreover, the illumination in a paraboloid decreases towards the edges and hence it is not illuminated uniformly. This results in the capture area being always smaller than the actual area. That is,

The capture area,

$$A_c = bA \quad ...(7.7)$$

Here, A = actual area

b = constant depending on the type of primary antenna

≈ 0.65 for dipole antenna

For a loss-less antenna and tapered illumination,

$$\text{Power gain,} \quad g_p = \frac{4\pi}{\lambda^2} A_c \qquad \text{...(7.8)}$$

$$= \frac{4\pi}{\lambda^2} bA$$

For circular apertured paraboloid,

$$A = \frac{\pi D_a^2}{4} \qquad \text{...(7.9)}$$

$$\text{So,} \quad g_p = \frac{4\pi K}{\lambda^2} \frac{\pi D_a^2}{4}$$

$$= \frac{\pi^2 K D_a^2}{\lambda^2}$$

$$= 0.65\pi^2 \left(\frac{D_a}{\lambda}\right)^2 \qquad [K \approx 0.65 \text{ for dipole feed}]$$

$$= 6.41 \left(\frac{D_a}{\lambda}\right)^2$$

$$\text{So,} \quad g_p = 6.4 \left(\frac{D_a}{\lambda}\right)^2 \qquad \text{...(7.10)}$$

Salient features of paraboloid reflectors

1. The directional beam has a sharp main lobe surrounded by several side lobes.
2. The three dimensional shape of the main lobe resembles a fat cigar in the direction of the axis of the paraboloid.
3. If the primary antenna is non-directional,

$$\text{BWFN} = 140 \left(\frac{\lambda}{D_a}\right)$$

and $$\text{HPBW} = 70 \left(\frac{\lambda}{D_a}\right).$$

4. The gain of the antenna with parabolic reflector is influenced by aperture ratio $\left(\frac{D_a}{\lambda}\right)$ and type of illumination.

5. For tapered illumination, the power gain, $g_p = 6.4\left(\frac{D_a}{\lambda}\right)^2$.
6. Directivity with respect to isotropic antenna is $D = 6.4\left(\frac{D_a}{\lambda}\right)^2$.
7. Effective Radiated Power (ERP) = product of input power to the antenna and power gain. It is very high even for small input power.
8. Very large gains and narrow beam width are obtainable with paraboloid reflectors.
9. Paraboloids are not used at low frequencies because of large size.
10. In order to be fully effective and useful, its mouth diameter must be at least 10λ.
11. At the lower end of the television band, say at 63 MHz, the required mouth diameter is 48 m.
12. Performance of paraboloid reflectors depends on the radiation characteristics of primary antenna and its size.
13. Parabolic reflectors have several applications in communications and radars.
14. The reflector is called the **secondary antenna** and feed antenna is called the primary antenna.
15. The radiation pattern of primary antenna placed at the locus of the parabolic reflector is called the **primary pattern**. The radiation pattern of the entire system consisting of primary and secondary antenna is called the **antenna pattern**.
16. A mesh surface is often used to minimise wind effect on the antenna and extra strain on the supports. This also reduces distortion caused by uneven wind force distribution over the surface.

Disadvantages of paraboloid reflectors

1. The radiation beam is a pencil beam and it is surrounded by side lobes. These side lobes create electromagnetic induction and the effect of electromagnetic interference is more prominent in low noise receivers due to the imperfections in the reflector.
2. Deviations from the true shape of a paraboloid should not exceed one sixteenth of λ. Such tolerances may be difficult to achieve in large dishes whose surface is a network of wires instead of a smooth continuous skin.
3. Diffraction is another cause of side lobes and will occur around the edges of the paraboloid. This produces electromagnetic induction.
4. The finite size of the primary antenna also influences the band width.
5. As the feed antenna is not a true point source, it cannot be located exactly at the focus.
6. Defects like aberrations cause the main lobe to be broadened and the side lobes to be reinforced.
7. The primary antenna does not radiate evenly at the reflector and hence distortion is introduced. If a dipole feed is used, the radiation in one plane is different from that in the other and the beam from the reflector becomes broad.

8. Flattened beams are avoided by using horn feed. Here also, paraboloid is not illuminated uniformly and it will taper at the edges. This leads to a small capture area.

7.6 TYPES OF PARABOLIC REFLECTORS

Apart from full paraboloid reflectors, there are other types of reflectors:

1. Cut or truncated paraboloid.
2. Parabolic cylinder.
3. Pill box and cheese antenna
4. Offset paraboloid reflector.
5. Torus antenna.

The advantages of these are low cost and small size. The main disadvantage is that the beam is not directional in both azimuth and elevation.

7.6.1 Cut or Truncated Paraboloid

This is shown in Fig. 7.6. It is not circular in appearance when viewed from a point on the parabolic axis.

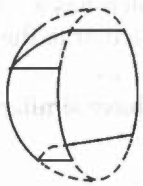


Fig. 7.6 *Cut paraboloid*

7.6.2 Parabolic Cylinder

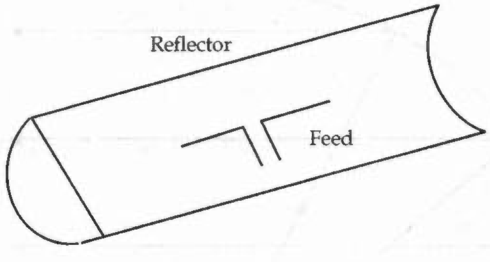


Fig. 7.7 *Parabolic cylinder*

This is formed by moving the parabola sideways. A plane sheet is curved in one dimension to obtain a parabolic cylinder. It is characterised by a focal line instead of a focal point and a vertex line instead of a vertex. When a radiating line source is on the focal line, the parabolic cylinder is illuminated uniformly. This results in a beam in the vertical plane. Its beam width is slightly less than that of a full paraboloid. It gives rise to a wide beam in E-plane and narrow beam in H-plane.

7.6.3 Pillbox Antenna

This is a reflector antenna which has a cylindrical reflector enclosed by two parallel conducting plates perpendicular to the cylinder, spaced less than one wavelength apart. A typical pillbox structure is shown in Fig. 7.8. It looks like a pillbox and

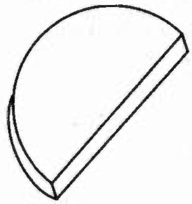


Fig. 7.8 *Pillbox antenna*

hence the name. It is excited by a probe through a coaxial line. It produces a wide beam in *E*-plane and narrow beam in *H*-plane. That is, these reflectors produce shaped beams-wide beam in one plane and narrow in the other. This is used in ship-to-ship radars.

Cheese antenna

This is also a reflector antenna which has a cylindrical reflector enclosed by two parallel conducting plates perpendicular to the cylinder but spaced more than one wavelength apart.

Pillbox and Cheese antennas have similar applications.

7.6.4 Offset Paraboloid

This is one form of cut-paraboloid in cross-section. In this, the focus is located outside the aperture (Fig. 7.9). If the feed antenna is kept at the focus, the reflected

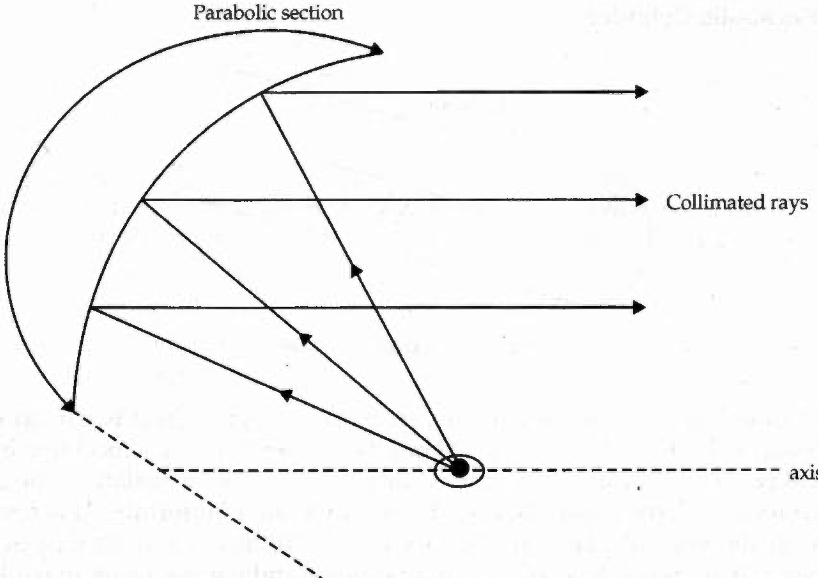


Fig. 7.9 *Offset parabolic reflector*

and collimated rays will be produced without any interference. This reflector is very useful when the size of the feed antenna is comparable with the reflector. In this case feed antenna will not block the reflected rays.

7.6.5 Torus Antenna

It is a better version of an offset reflector. It is similar to cut paraboloid. It is parabolic along one axis and circular along the other. This antenna is useful to transmit or receive a number of beams simultaneously to or from a geostationary satellite orbit. This is possible by placing several feeds at the focus.

7.7 FEED SYSTEMS FOR PARABOLIC REFLECTORS

It is possible to feed the reflector in several ways. Some of them are:

1. Half-wave dipole
2. An array of collinear dipoles
3. Yagi-Uda antenna
4. Centre-fed with spherical reflector
5. Horn
6. Cassegrain feed.

7.7.1 Half-Wave Dipole Feed

This has bi-directional radiation characteristics. Ideally, uni-directional antenna is required as feed antenna. In this case the reflected rays will interfere with the backward radiated rays and disturb the plane wave–front because of phase difference.

7.7.2 Yagi-Uda Antenna Feed

Although this produces a uni-directional pattern, the size of the antenna is a common problem. It blocks the reflected rays.

7.7.3 Array of Collinear Dipoles Feed

This is another possible primary feed antenna. But feeding with a dipole array involves changing from unbalanced system to a balanced system.

7.7.4 Centre-fed with Spherical Reflector

This is shown in Fig. 7.10.

Salient features of centre-fed with spherical reflector

1. The primary antenna is kept at the focus of the paraboloid for better reception or transmission.
2. Direct radiation from the feed spoils the directivity. To prevent direct radiation, a small spherical reflector is used which redirects the direct radiations back to the paraboloid.
3. The spherical shell obstructs the reflected rays. But this is not high. If a spherical shell of diameter 2 cm is placed at the focus of 2 m paraboloid, the obstruction is only one percent.

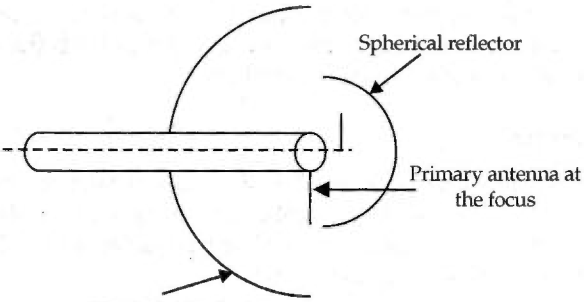


Fig. 7.10 *Centre-fed with spherical reflector*

7.7.5 Horn Feed

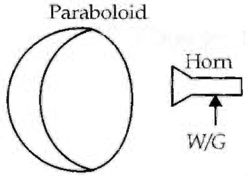


Fig. 7.11 *Horn feed*

Salient features of horn feed

1. Horn has moderate directional characteristics towards the reflector.
2. There is no direct radiation.
3. Horn obstructs the reflected rays when it is placed at the focus. But obstruction is not high. It may be one or two percent of the total reflected energy.

7.7.6 Cassegrain Feed

It is named after the early eighteenth century astronomer. The feed mechanism is shown in Fig. 7.12. It uses:

- a parabolic reflector,
- a hyperbolic reflector and
- a feed antenna, horn with waveguide.

One of the foci of the hyperbolic reflector coincides with the focus of the paraboloid. When electromagnetic rays from a horn antenna are incident on the hyperboloid reflector, they are reflected back and are then incident on the paraboloid. These incident rays are reflected and propagate as a plane wave front.

Hyperbola is a curve traced by a point which moves so that its ratio of the distance from a fixed point, the focus to its distance from a fixed straight line, the directrix is a constant and is greater than unity. The hyperboloid is a three dimensional surface obtained by revolving the hyperbola about its axis. The size of

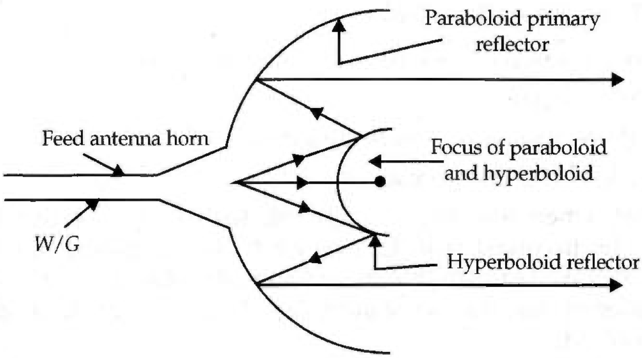


Fig. 7.12 *Cassegrain mechanism in transmission mode*

the hyperboloid depends on its distance from the primary feed antenna, mouth diameter of horn and the frequency of operation.

Applications of Cassegrain feed

1. It is used when it is required to keep the primary antenna in a convenient position.
2. It is used when it is desired to use a short transmission line or waveguide for connecting the receiver or transmitter to the primary antenna.
3. It is used for low-noise receiver applications.

If the active part of the transmitter or receiver is kept at the focus, it is possible to reduce power loss. But the size of the transmitter or receiver prohibits such a placing. This is the reason why Cassegrain feed is best suited for low-noise applications.

Advantages of Cassegrain feed

1. Spill over and minor lobe radiation is less.
2. It is possible to scan the beam or to broaden the beam by moving of the reflecting surfaces.
3. Feed antenna can be kept at a convenient location.

Disadvantages

1. Some of the electromagnetie energy is obstructed by the secondary hyperboloid reflector. This is tolerable when the size of paraboloid is large compared to hyperboloid. The obstruction is reduced by using large paraboloid reflectors and keeping the distance between the horn feed and hyperboloid reflector small. This technique reduces the diameter of the hyperboloid reflector.
2. Large paraboloid is expensive.
3. When vertically polarised waves are radiated by the feed antenna, they are reflected back to the main reflector by the hyperboloid.
4. Polarisation of the waves is twisted by 90° when they are reflected by the paraboloid. That is, the reflected waves are horizontally polarised and they propagate through the vertical bars of the hyperboloid.

7.8 SHAPED BEAM ANTENNAS

High directive radiation beams (pencil beams) are useful:

- to obtain large gain
- to obtain precision direction finding and
- for high resolution of targets.

However, when scanning is required, such high directive beams are not preferred as the involved scan time is more. Broad beams are useful in such applications. It is well known that by reducing the dimension of the aperture, the beam is broadened. But this is not sufficient. In several applications well-shaped beams are required.

Antennas that produce shaped beams are called **shaped beam antennas.**

Some of the popular shaped beams are:

1. Fanned beams
2. Sector beams
3. Cosecant beams.

7.8.1 Fanned Beams

The fan beam is a radiation pattern which exhibits broad beam characteristics in one of the principal planes. Such beams are generated from ship antennas. These are used to compensate roll and pitch of the ships.

Fanned beam antennas are of the following forms:

1. An array antenna with optimally designed amplitude and phase distributions.
2. A section of parabolic reflector with the point source at its focus.
3. A parabolic cylinder with a line source producing a rectangular aperture.
4. A parallel plate antenna which consists of a parabolic cylindrical reflector illuminated by a simple feed at the focus and located between the parallel plates which are perpendicular to the generator of the cylinder. This produces a rectangular aperture.

Applications of fanned beams

1. Air search from ground-based or ship-borne antennas.
2. Surface search from air-borne antennas.

Typical fanned antenna beams are shown in Figs. 7.13 and 7.14.

In Fig. 7.13, the beam is from a ground-based antenna for air search. The beam in elevation provides coverage on aircraft. Azimuth coverage is obtained with scanning. The beam shown in Fig. 7.14 is from air-borne antenna for surface search.

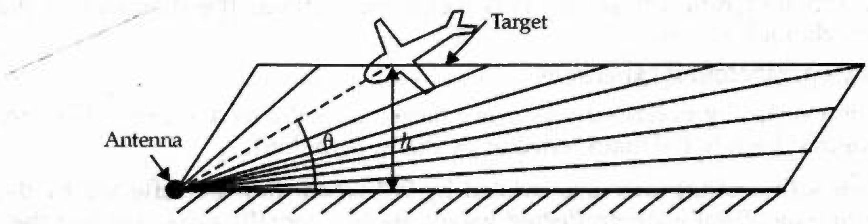


Fig. 7.13 *Fanned beam from ground-based antenna for air search*

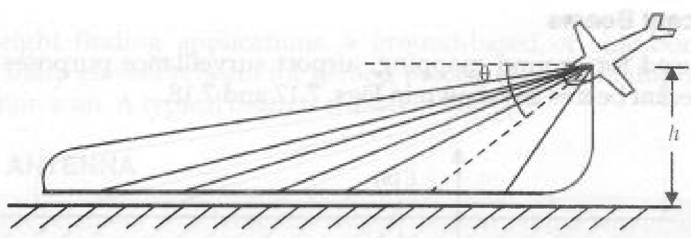


Fig. 7.14 *Fanned beam from air-borne antenna for surface search*

7.8.2 Sector Beam

This beam is basically broad over a desired angular region as shown in Fig. 7.15. This beam is again sharp in azimuth and is broad in elevation to accommodate roll and pitch. This type of beam provides a more constant illumination of the target and is also more conservative.

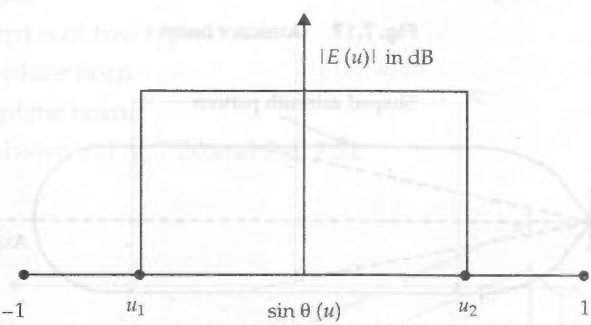


Fig. 7.15 *Sector beam*

Typical sector beams are shown in Figs. 7.15 and 7.16.

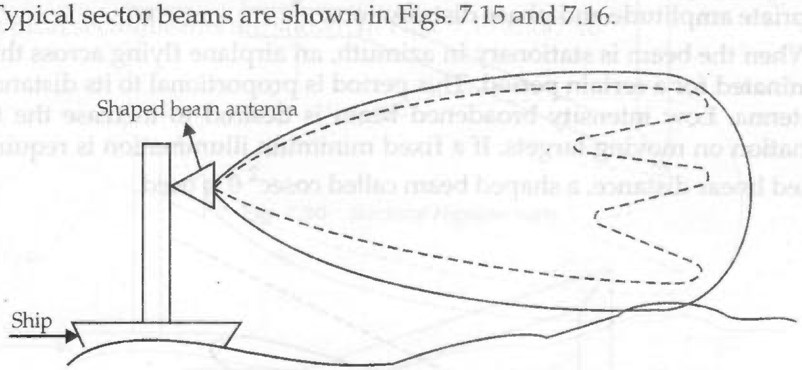


Fig. 7.16 *Sector beam for surface search from ship-borne antenna*

These sector beams are also used for surface search from ship-borne antennas and air search from ground-based antennas.

7.8.3 Cosecant Beams

These are used for ground mapping, airport surveillance purposes and so on. Typical cosecant beams are shown in Figs. 7.17 and 7.18.

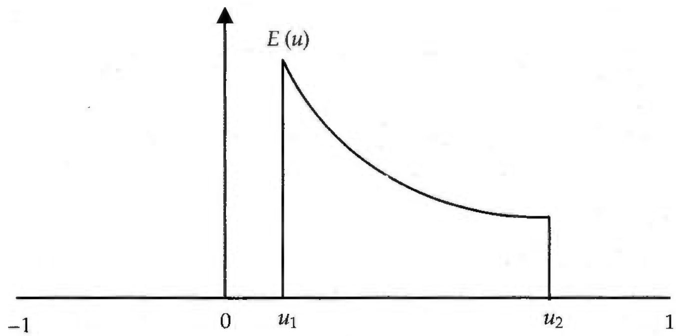


Fig. 7.17 *Cosecant beam*

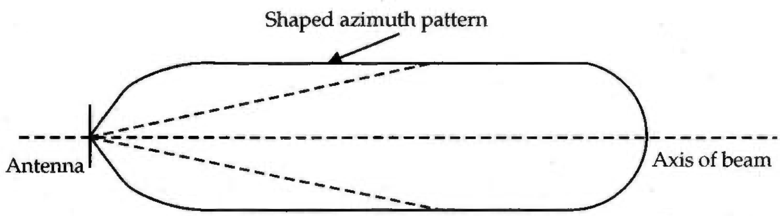


Fig. 7.18 *Double CSC beam*

These shaped beams can be precisely produced from array antennas with appropriate amplitude and phase distributions.

When the beam is stationary in azimuth, an airplane flying across the beam is illuminated for a certain period. This period is proportional to its distance from the antenna. Low intensity broadened beam is desired to increase the time of illumination on moving targets. If a fixed minimum illumination is required at a specified linear distance, a shaped beam called cosec^2 θ is used.

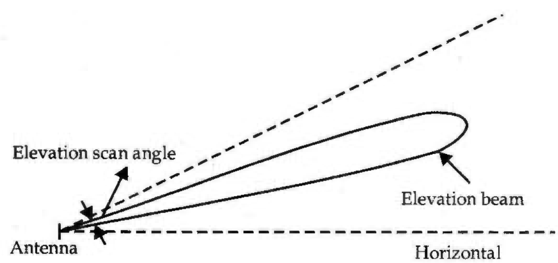


Fig. 7.19 *Elevation sharp beam*

For height finding applications, a ground-based or ship-borne antenna produces a sharp elevation beam for getting precise elevation information and a rapid elevation scan. A typical beam is shown in Fig. 7.19.

7.9 HORN ANTENNA

It is a radiating element which has the shape of a horn. It is a waveguide one end of which is flared out.

A waveguide, when excited at one end and open at the second end, radiates. However, radiation is poor and non-directive pattern results because of the mismatch between the waveguide and free space. The mouth of the waveguide is flared out to improve the radiation efficiency, directive pattern and directivity.

Types of horns:

- Sectoral horn
- Pyramidal horn
- Conical horn.

Sectoral horn is of two types:

(*a*) Sectoral *H*-plane horn

(*b*) Sectoral *E*-plane horn.

These are shown in Fig. 7.20 and Fig. 7.21.

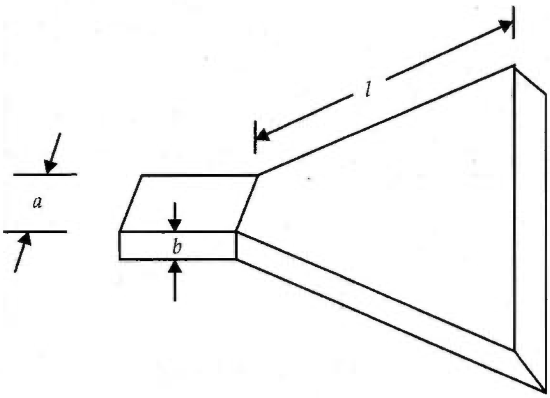


Fig. 7.20 *Sectoral H-plane horn*

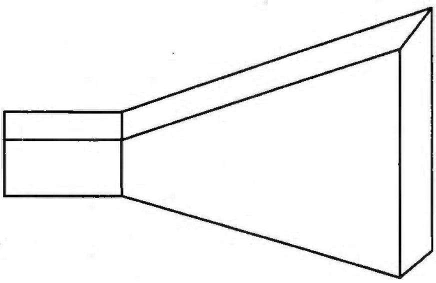


Fig. 7.21 *Sectoral E-plane horn*

A typical pyramidal horn is shown in Fig. 7.22.

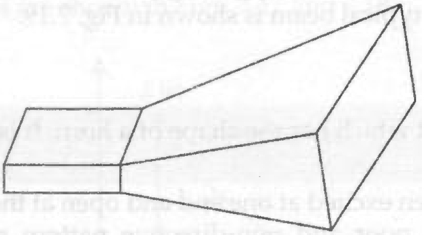


Fig. 7.22 *Pyramidal horn*

The horn parameters are described in Fig. 7.23.

δ = path difference

l = axial length

d = aperture dimension

θ = flare angle

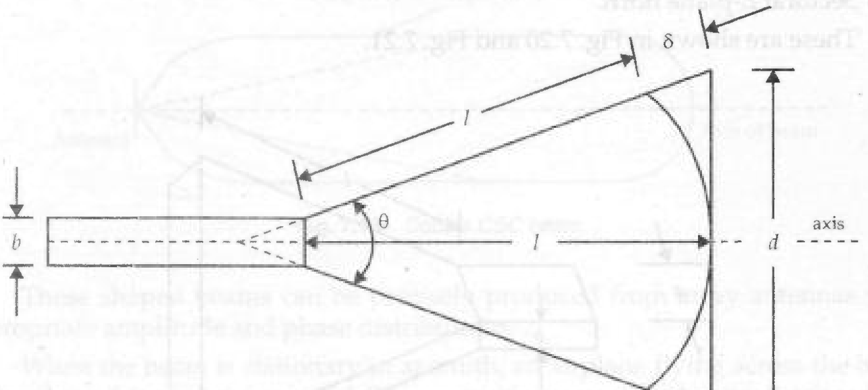


Fig. 7.23 *Horn parameters*

Typical conical horn is shown in Fig. 7.24.

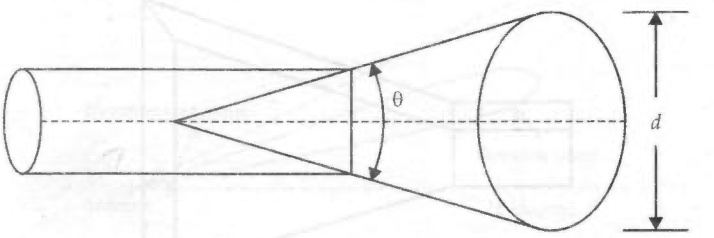


Fig. 7.24 *Conical horn*

Sectoral horn is a horn in which flaring exists only in one direction.

If flaring is along the direction of electric field, it is called **sectoral *E*-plane** horn.

If flaring is along the direction of magnetic field, it is called **sectoral *H*-plane** horn.

If flaring is along *E* and *H*, the horn is called **pyramidal horn**. It has the shape of a truncated pyramid.

If the walls of a circular waveguide are flared out, a **conical horn** is obtained.

Operation The electromagnetic wave propagation in a waveguide is different from that of free space. In waveguide, propagation is restricted by the conducting walls and waves will not spread. After reaching the mouth, waves spread laterally and wave front becomes spherical. At the mouth of the wave-guide, there exists near-field region where the wave front is a complicated one. This is considered to be the transition region where change of propagation from waveguide to free space takes place. As the waveguide impedance and free space impedance do not match, walls of the waveguide are flared out. This flared out structure is called a horn. The flaring provides impedance matching, more directivity and narrow beam width. Horn produces a uniform plane wave front with a larger aperture in comparison to a waveguide. As the aperture is large, directivity is high.

The design equations of horn antenna are:

$$\theta = 2\tan^{-1}\left(\frac{d}{2l}\right) = 2\cos^{-1}\left(\frac{l}{l+\delta}\right) \qquad \text{...(7.11)}$$

and $$l = \frac{d^2}{8\delta}$$

Half-power beam width of optimum flared horns are

$$\phi_E = \frac{56\lambda}{d_E} \text{ degrees}, \qquad \phi_H = \frac{67\lambda}{d_H} \text{ degrees} \qquad \text{...(7.12)}$$

Here, ϕ_E = HPBW in *E*-plane

ϕ_H = HPBW in *H*-plane

d_E = aperture in *E*-plane in free space wavelength

d_H = aperture in *H*-plane in free space wavelength

$$\left.\begin{aligned} &\text{The directivity of horn is } D = \frac{7.5A_a}{\lambda^2} \\ &\text{Power gain, } \quad g_p = \frac{4.5A}{\lambda^2} \end{aligned}\right\} \qquad \text{...(7.13)}$$

Here, $A_a = d_E \, d_H$ = physical area of the aperture.

Applications of horns

1. Horns are used at microwave frequencies where moderate gains are sufficient.
2. They are used as feed elements.
3. They are often used in laboratories for the measurement of different antenna parameters.

Salient features of horns

1. Horn becomes small if the flare angle is small. Its radiation pattern is directive, wave front is spherical, mouth area is small and its directivity is small.
2. Flare angle is related to axial length.
3. If $\theta = 15^\circ$, when $l/\lambda = 50$, the beam width is 23° and directivity is 120.
4. Directivity of pyramidal horn is more as the flare is in more than one direction.
5. Its directivity is not as high as that of paraboloid.
6. It is used as radiator.
7. It is easy to use with the waveguide.
8. It is used as primary antenna for paraboloid.
9. The gain of the conical antenna is optimum for a given slant length of flare, l and

$$d \approx \left(\frac{3}{\lambda}\right)^{1/2} \qquad \text{...(7.14)}$$

Here, d = diameter of the aperture.

10. The directivity of a loss-less horn antenna is its gain and it is given by

$$D = \frac{4\pi A_e}{\lambda^2}$$

$$= \frac{4\pi\eta_a}{\lambda^2} A_a$$

Here, A_e is effective aperture, m^2

A_a is actual area or physical area, m^2

η_a is aperture efficiency $= \dfrac{A_e}{A_a}$

λ is operating wavelength, m.

11. In the case of rectangular horn $A_a = d_E \, d_H$

Here, d_E is aperture size in E-plane

d_H is aperture size in H-plane

The rectangular horn is a pyramidal horn.

12. In the case of conical horn $A_a = \pi d$

    Here, d is aperture diameter.
13. If aperture efficiency is about 0.6,

$$D \approx 7.5\, A_a/\lambda^2.$$

7.10 CORRUGATED HORNS

Corrugation means groove. A typical corrugated horn is shown in Fig. 7.25.

ψ_c = half of the flare angle

t = width of the groove

w = separation between adjacent grooves

b_1 = aperture dimension

d = groove depth.

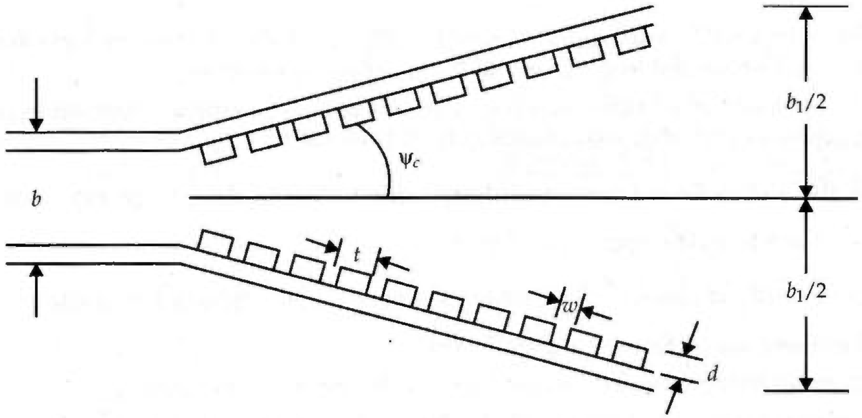


Fig. 7.25 *Corrugated horn*

Salient features of corrugated horn

1. When corrugated horns are used as feed antennas for paraboloids, spill-over efficiency and cross polarisation losses are reduced and aperture efficiency is increased. These systems are used in radio astronomy and satellite communications.

   Spill over is defined as part of the power radiated by a feed which is not intercepted by the secondary radiator.
2. For feed systems using conventional horns, the aperture efficiency is about 50-60%.
3. For feed systems using corrugated horns, the aperture efficiency is 75-80%.
4. The corrugations on the walls of a horn modify the E-field distribution in the E-plane from uniform at the waveguide horn junction to cosine at the aperture.

5. The corrugated surface reactance is given by

$$x = \frac{w}{w+t} \eta_0 \tan(kd) \quad ...(7.15)$$

Here, $\frac{w}{w+t} = 1$, if $t \leq w/10$, $w < \lambda/10$ and $w << d$

$$\eta_0 = 120\pi\Omega$$

$$k = 2\pi/\lambda.$$

7.11 SLOT ANTENNA

It is a radiating element formed by a slot in a metallic surface. An opening cut in a conducting sheet or in one of the walls of the waveguide acts as the antenna. It is excited suitably either by a co-axial cable or through the waveguide.

Salient features of slot antennas

1. A basic slot has a length of $\frac{\lambda}{2}$ and its width is much less than $\frac{\lambda}{2}$.
2. Slots are usually excited by a co-axial cable at a distance of about 0.05λ from one end of the slot to get reasonable impedance properties.
3. A horizontal slot with such an excitation produces vertical polarisation and vice-versa. In fact, the slot radiates from both sides.
4. If the slot is boxed with an internal dimension of $d = \frac{\lambda}{4}$, the radiation is outward from the opening of the box.
5. A slot and a dipole of $\frac{\lambda}{2}$ length have similar gain and radiation characteristics. But there is a difference in polarisation.
6. In order to increase the gain and directivity, array of slots is used.
7. Cylindrical arrays of slots are found to produce omni-directional radiation in the horizontal plane with horizontal polarisation.
8. When a high frequency field exists across a thin slot in a conducting plane, it radiates.
9. A slot excited by a two-wire line is shown in Fig. 7.26. The electric field in the $\frac{\lambda}{2}$ slot is sinusoidal.

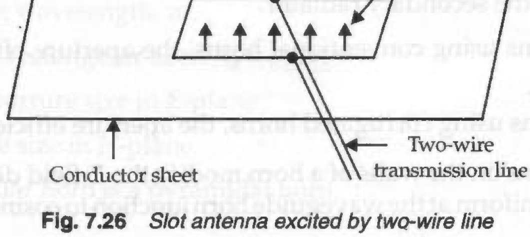


Fig. 7.26 *Slot antenna excited by two-wire line*

10. The impedance of such an excited slot is purely resistive and is 365 ohms.

A complementary dipole antenna made of a conductor is shown in Fig. 7.27.

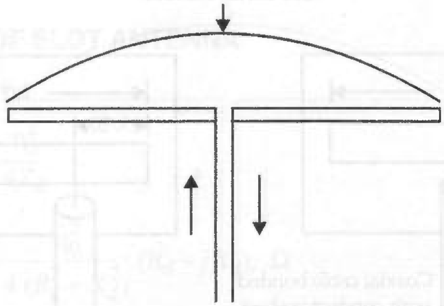


Fig. 7.27 *Dipole antenna*

A dipole and a slot in a conducting sheet have similar shapes except that the metal region and free space are interchanged as shown in Fig. 7.28.

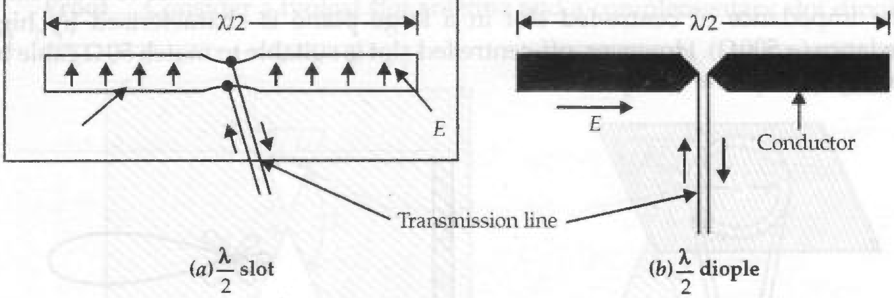


Fig. 7.28 $\frac{\lambda}{2}$ *slot and dipole antenna*

The main difference is that the slot of Fig. 7.28 (*a*) is vertically polarised and dipole of Fig. 7.28 (*b*) is horizontally polarised.

The slot and dipole impedances are related by

$$Z_s\, Z_d = \frac{\eta_0^2}{4}, \quad \eta_0 \text{ is free space} \qquad ...(7.16)$$

Intrinsic impedance $= 377\Omega$

If the width of the dipole is very small, $w << \lambda$.

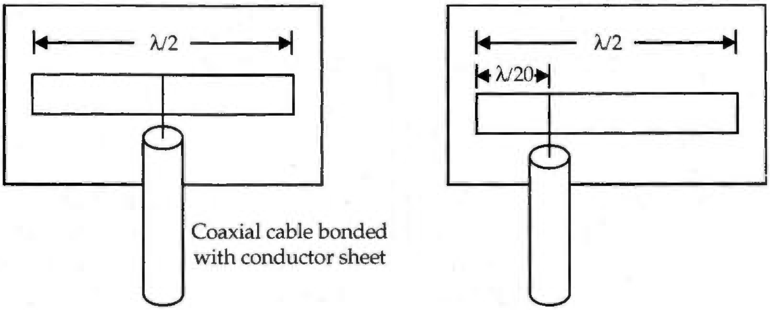
Then $Z_d = 73 + j42.5\Omega$

Slot impedance, Z_s

$$Z_s = \frac{\lambda_0^2}{4Z_d} = \frac{(377)^2}{4\,(73 + j42.5)}$$

$$Z_s = 363 - j211 \text{ ohms}$$

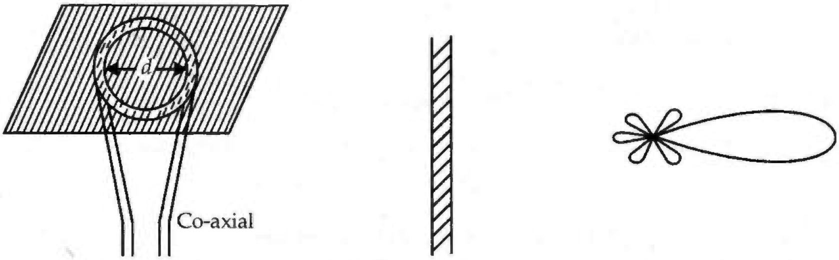
By changing the feed point from one end of the slot, its impedance can be changed. For example, two slots of different feed points are shown in Figs. 7.29 (*a*) and (*b*).



(*a*) **Centre fed slot** (*b*) **Off-centre fed slot**

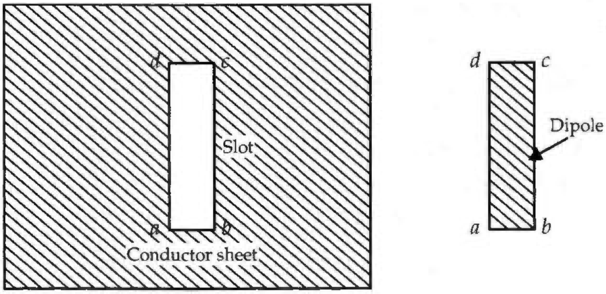
Fig. 7.29 *Feed points*

Centre-fed slot is not suitable for matching with conventional co-axial cable as the impedance of centre-fed slot in a large plane is characterised by high impedance ($\approx 500\,\Omega$). However, off-centre fed slot is suitable to match $50\,\Omega$ cable by choosing appropriate feed point.



(*a*) **Annular slot** (*b*) **Cross-sectional view** (*c*) **Radiation pattern**

Fig. 7.30 *Annular slot*



(*a*) **Slot in a conductor sheet** (*b*) **Complementary dipole**

Fig. 7.31 *Slot and complementary dipole*

In an annular slot, the fields are in the same phase. A typical annular slot is shown in Fig. 7.30. It produces a radiation pattern with narrow beam width.

A rectangular slot in a conducting sheet and its complimentary dipole are shown in Fig. 7.31.

7.12 IMPEDANCE OF SLOT ANTENNA

The slot impedance is

$$Z_s = \frac{\eta_0^2}{4Z_d}$$

$$= \frac{\eta_0^2}{4\,(R_d^2 + X_d^2)}\,(R_d - jX_d),\ \Omega \qquad \text{...(7.17)}$$

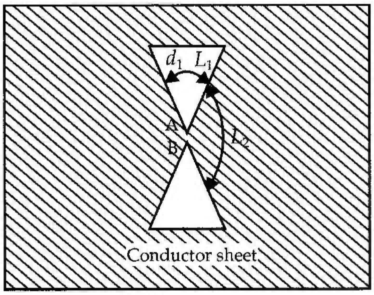
Here, $\eta_0 = 120\pi\Omega$

Z_d = impedance of complementary dipole = $R_d + jX_d,\ \Omega$

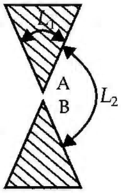
R_d = real part of $Z_d,\ \Omega$

X_d = reactive part of $Z_d,\ \Omega$.

Proof Consider a typical slot antenna and a complementary slot dipole of Fig. 7.32.



(*a*) **Slot antenna**



(*b*) **Complementary slot dipole**

Fig. 7.32 *Slot and slot dipole*

Let the slot and dipole be excited at AB.

Assume Z_s = slot impedance

Z_d = dipole impedance

V_s = slot terminal voltage

V_d = dipole terminal voltage

I_s = slot terminal current

I_d = dipole terminal current

$\mathbf{E}_s$ = electric field in the slot at any point

$\mathbf{H}_s$ = magnetic field in the slot at any point

$\mathbf{dL}$ = differential length along L_1

$2L_2$ = path around a complete circle, V_s at AB is given by

$$V_s = \lim_{L_1 \to 0} \int_{L_1} \mathbf{E}_s \cdot \mathbf{dL} \qquad ...(7.18)$$

and
$$I_s = \oint \mathbf{H}_s \cdot \mathbf{dL} \qquad ...(7.19)$$

$$I_s = 2 \lim_{L_2 \to 0} \oint \mathbf{H}_s \cdot \mathbf{dL} \qquad ...(7.20)$$

The dipole impedance, Z_d is

$$Z_d = \frac{V_d}{I_d} \qquad ...(7.21)$$

Now
$$V_d = \lim_{L_2 \to 0} \int_{L_2} \mathbf{E} \cdot \mathbf{dL} \qquad ...(7.22)$$

$$I_d = \oint \mathbf{H}_d \cdot \mathbf{dL} \qquad ...(7.23)$$

$$= 2 \lim_{L_1 \to 0} \int \mathbf{H}_d \cdot \mathbf{dL}$$

As
$$\lim_{L_2 \to 0} \int_{L_2} \mathbf{E}_d \cdot \mathbf{dL} = \eta_0 \lim_{L_2 \to 0} \int_{L_2} \mathbf{H}_s \cdot \mathbf{dL} \qquad ...(7.24)$$

and
$$\lim_{L_1 \to 0} \int_{L_1} \mathbf{H}_d \cdot \mathbf{dL} = \frac{1}{\eta_0} \lim_{L_1 \to 0} \int_{L_1} \mathbf{E}_s \cdot \mathbf{dL} \qquad ...(7.25)$$

We have
$$V_d = \eta_0 \frac{I_s}{2} \qquad ...(7.26)$$

or
$$\frac{V_d}{I_s} = \frac{\eta_0}{2}$$

Similarly,
$$\frac{V_s}{I_d} = \frac{\eta_0}{2} \qquad ...(7.27)$$

Now we can write

$$\frac{V_d}{I_s} \cdot \frac{V_s}{I_d} = \frac{\eta_0}{2} \times \frac{\eta_0}{2} = \frac{\eta_0^2}{4}$$

That is,
$$Z_s \cdot Z_d = \frac{\eta_0^2}{4}$$

$$Z_s = \frac{\eta_0^2}{4Z_d} \qquad \text{...(7.28)}$$

If $\qquad Z_d = R_d + jX_d$

Z_s becomes

$$Z_s = \frac{\eta_0^2}{4}\left[\frac{1}{R_d + jX_d}\right] \qquad \text{...(7.29)}$$

or

$$Z_s = \frac{\eta_0^2}{4}\left[\frac{R_d - jX_d}{R_d^2 + X_d^2}\right]$$

$$Z_s = \frac{\eta_0^2}{4\,(R_d^2 + X_d^2)}\,[R_d - jX_d]. \qquad \text{...(7.30)}$$

7.13 IMPEDANCE OF A FEW TYPICAL DIPOLES

1. If the length of dipole, $l = \frac{\lambda}{2}$, diameter of dipole, $d = 0$

$$Z_d = 73 + j42.5\,\Omega.$$

2. If $\qquad l \leq \frac{\lambda}{2}, \; \frac{l}{d} = 100$

$$Z_d \approx R_d = 67\,\Omega.$$

3. If $\qquad l \approx \lambda, \; \frac{l}{d} = 28$

$$Z_d = 710\,\Omega.$$

The length, diameter and impedance of a cylindrical dipole are shown in Fig. 7.33.

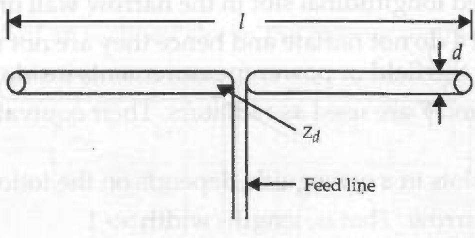


Fig. 7.33 *Cylindrical dipole*

7.14 SLOTS IN THE WALLS OF RECTANGULAR WAVEGUIDE

The slots can be cut in one of the walls of a rectangular waveguide. Different slot configurations are shown in Fig. 7.34.

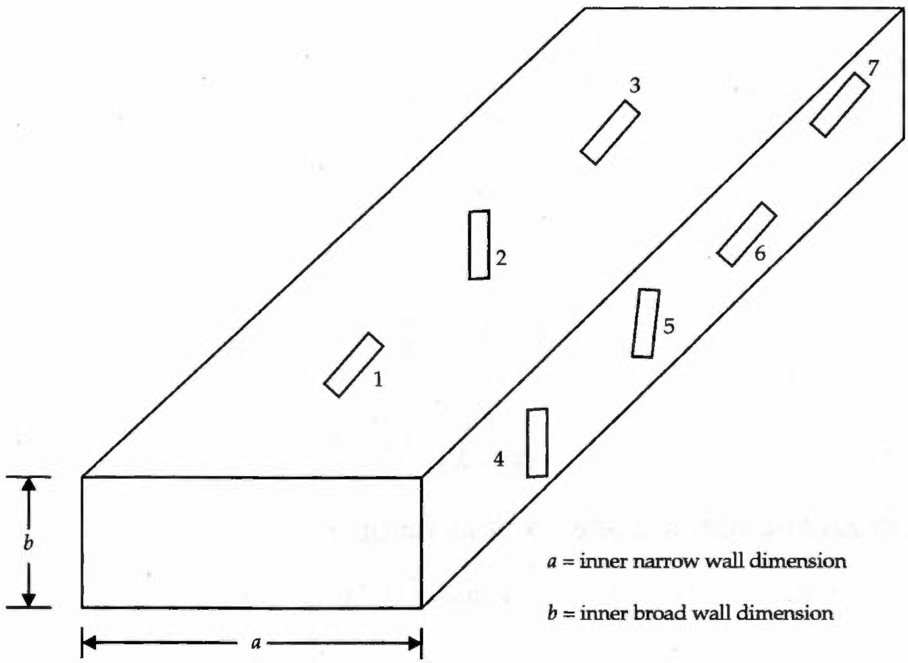


Fig. 7.34 *Slot configurations in a waveguide*

The types of slots are:

Slot 1: Longitudinal slot in the centre of broad wall.

Slot 2: Inclined slot in the broad wall.

Slot 3: Displaced slot in the broad wall.

Slot 4: Vertical slot in the narrow wall of the waveguide.

Slot 5: Inclined slot in the narrow wall of the waveguide.

Slot 6: Longitudinal slot in the centre of the narrow wall of the waveguide.

Slot 7: Displaced longitudinal slot in the narrow wall of the waveguide.

The slots 1 and 4 do not radiate and hence they are not used as radiators. But they can be used for the field or power measurements inside the guide.

Slots 2, 3, 5, 6 and 7 are used as radiators. Their equivalent circuits are given in Fig. 7.35.

The theory of slots in a waveguide depends on the following assumptions:

1. The slots are narrow. That is, length/width >> 1.
2. The slot length ≈ λ/2.
3. The field in the slot is transverse to the long dimension. It varies sinusoidally and is independent of the exciting system.
4. The guide walls are perfectly conducting and infinitely thin.
5. The field in the region behind the face containing the slot is negligible compared to the field outside the guide.

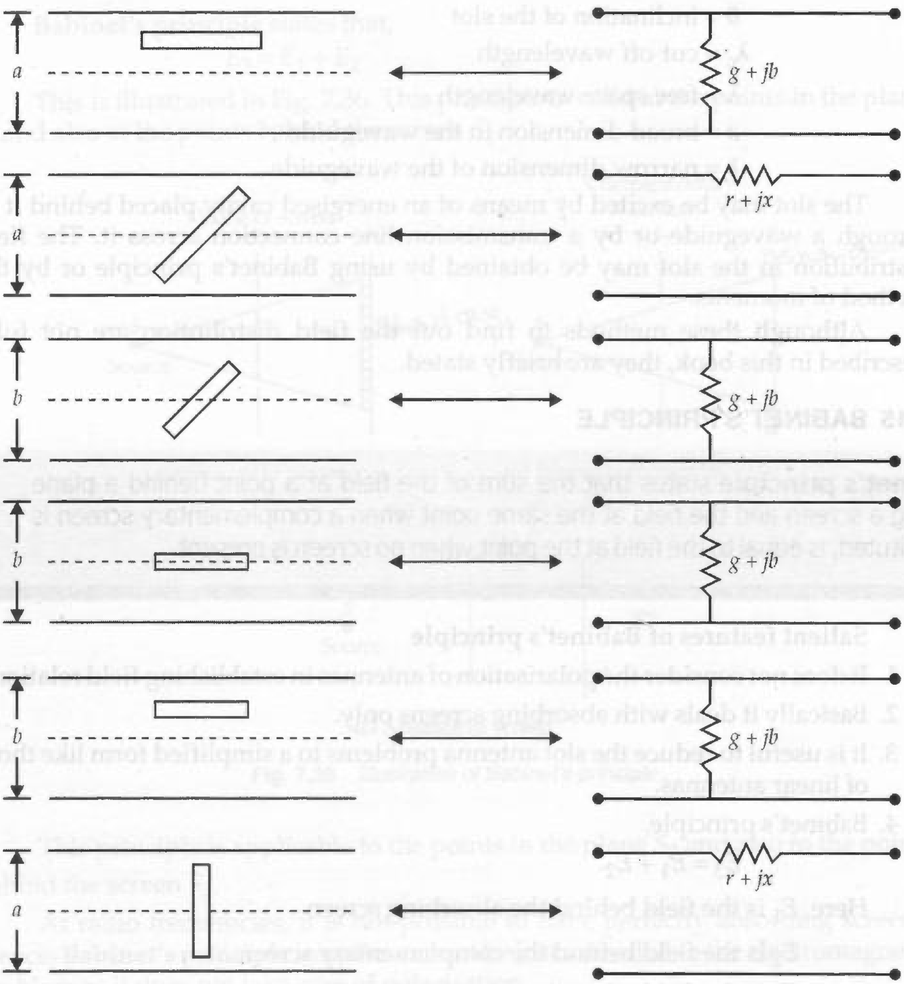


Fig. 7.35 *Slots and their equivalent circuits*

The conductance of an inclined slot in the narrow wall is given by

$$g = \frac{30}{73\pi}\left(\frac{\lambda_g}{\lambda}\right)\frac{\lambda^4}{a^3 b}\left[\frac{\sin\theta\cos\left(\dfrac{\pi\lambda}{2\lambda_g}\sin\theta\right)}{1-\left(\dfrac{\lambda}{\lambda_g}\right)^2\sin^2\theta}\right]^2 \quad ...(7.31)$$

Here, λ_g = guide wavelength

$$= \frac{\lambda}{\sqrt{1-\left(\dfrac{\lambda}{\lambda_c}\right)^2}}$$

θ = inclination of the slot

λ_c = cut-off wavelength

λ = free space wavelength

a = broad dimension in the waveguide

b = narrow dimension of the waveguide

The slot may be excited by means of an energised cavity placed behind it or through a waveguide or by a transmission line connection across it. The field distribution in the slot may be obtained by using Babinet's principle or by the method of moments.

Although these methods to find out the field distribution are not fully described in this book, they are briefly stated.

7.15 BABINET'S PRINCIPLE

Babinet's principle states that the sum of the field at a point behind a plane having a screen and the field at the same point when a complementary screen is substituted, is equal to the field at the point when no screen is present.

Salient features of Babinet's principle

1. It does not consider the polarisation of antennas in establishing field relations.
2. Basically it deals with absorbing screens only.
3. It is useful to reduce the slot antenna problems to a simplified form like those of linear antennas.
4. Babinet's principle,

$$E_3 = E_1 + E_2$$

Here, E_1 is the field behind the absorbing screen

E_2 is the field behind the complementary screen

E_3 is the field when there is no screen.

5. It is not applicable in the presence of the conducting screens.
6. It is valid in optics.
7. It cannot be extended to electromagnetic problems as it is not possible to have absorbing screens at radio frequencies and as polarisation of electromagnetic fields is common.

Meaning of Babinet's principle

If S_1 is a plane of screen,

S_2 is a plane of observation,

S is a point source,

E_1 is the field at a point (x, y, z) behind the screen,

E_2 is the field at (x, y, z) behind the screen when S_1 is replaced by its complementary screen,

E_3 is the field at the same point (x, y, z) when no screen is present.

Babinet's principle states that,

$$E_3 = E_1 + E_2$$

This is illustrated in Fig. 7.36. This principle is valid at the points in the plane S_2 and also at the points behind the screen S_1.

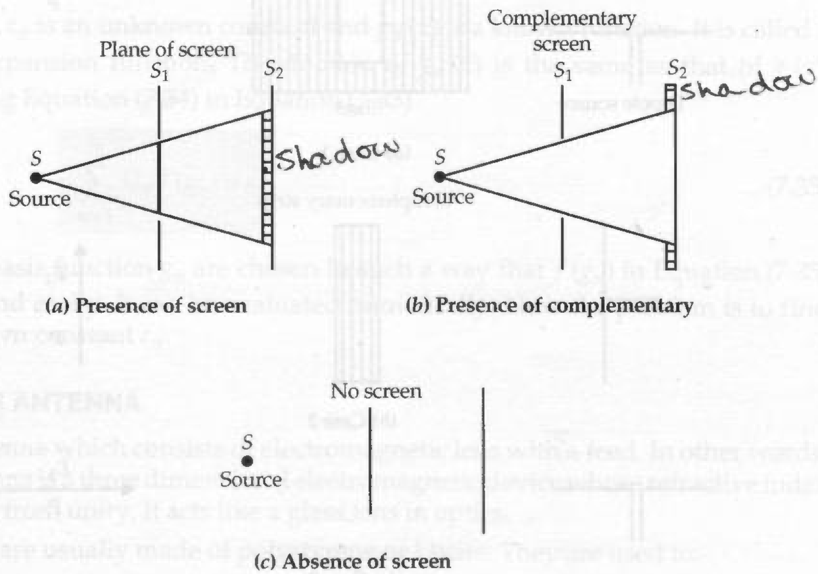


Fig. 7.36 *Illustration of Babinet's principle*

This principle is applicable to the points in the plane S_2 and also to the points behind the screen S_1.

At radio frequencies, it is not possible to have perfectly absorbing screens. Hence, **Babinet's principle** in optics cannot be just extended to the electromagnetic problem as it does not take care of polarisation.

A principle valid for conducting screens and polarised fields is described by **H.G. Booker**.

Illustration of Booker's theory **Booker's extension** of Babinet's principle is illustrated below:

Consider three cases. The source is a short dipole (Fig. 7.37).

If the screen in an infinite conducting thin sheet with a vertical slot is considered, the field behind the screen at a point, P is E_1.

If the slot is replaced by a complimentary dipole (a thin strip of conducting sheet), the field is E_2 at the same point, P behind the screen.

If there is no screen, the field is E_3 at the same point. Then according to Babinet's principle,

$$E_1 + E_2 = E_3$$

The same principle can be applied to points in front of the screens. When transmitted wave is very high through the slot, $E_1 \approx E_3$. Under these conditions, the complementary dipole acts like a reflector and E_2 is small.

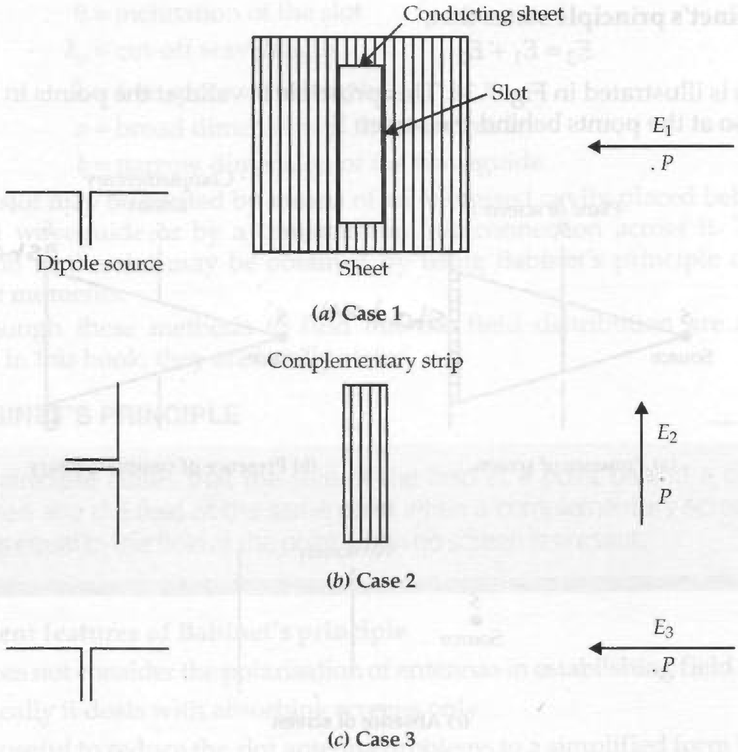


Fig. 7.37 *Illustration of Booker's principle applied to slotted structures*

When the screen and its complement are immersed in a medium whose intrinsic impedance is η, Z_s and Z_c are related by

$$Z_s Z_c = \frac{\eta^2}{4} \qquad \text{...(7.32)}$$

7.16 THE METHOD OF MOMENT (MOM)

This method is used to solve integral equations.

An integral equation is an equation which contains an unknown function under the integral sign. This method is useful for finding field distribution in the slot.

Consider an equation

$$f(g) = a \qquad \text{...(7.33)}$$

Here, f is a known linear integral operator, a is a known excitation function, and g is the response function. The aim is to find g once f and a are specified. The linearity of the operator f makes it possible to have a numerical solution.

The method of moments requires that the unknown response function, g is expanded as a linear combination of N terms and it may be written as

$$g(x) = c_1 g_1(x) + c_2 g_2(x) + \ldots + c_N g_N(x) = \sum_{n=1}^{N} c_n g_n(x) \qquad \ldots(7.34)$$

Here, c_n is an unknown constant and $g_n(x)$ is a known function. It is called a basis or expansion function. The domain of $g_n(x)$ is the same as that of $g(x)$. Substituting Equation (7.34) in Equation (7.33)

we get
$$\sum_{n=1}^{N} C_n f(g_n) = a \qquad \ldots(7.35)$$

The basis function g_n are chosen in such a way that $f(g_n)$ in Equation (7.35) can be found easily. It can be evaluated numerically. Now the problem is to find the unknown constant c_n.

7.17 LENS ANTENNA

It is an antenna which consists of electromagnetic lens with a feed. In other words, a lens antenna is a three dimensional electromagnetic device whose refractive index is different from unity. It acts like a glass lens in optics.

They are usually made of polystyrene or Lucite. They are used to:

1. Control the aperture illumination.
2. Collimate the electromagnetic rays.
3. Produce directional characteristics.
4. Converge the incoming wavefront at its focus.
5. Produce plane wavefront from spherical wavefront.

Principle A lens antenna in association with a primary feed antenna in transmitting mode is shown in Fig. 7.38.

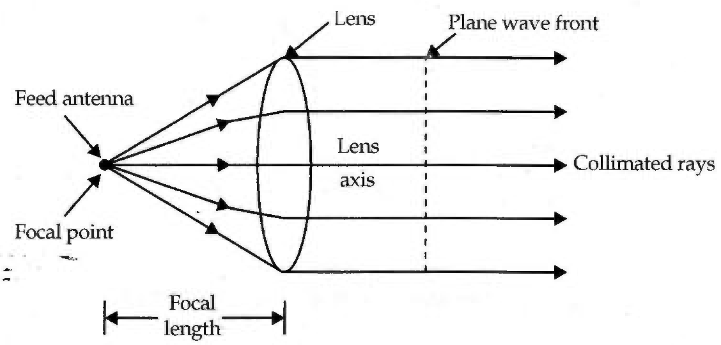


Fig. 7.38 *Lens antenna in transmitting mode*

When the feed antenna is kept at the focal point of the lens antenna, the diverging rays (spherical wave front) are collimated (parallel rays) forming a plane wave front after their incidence on the lens and passing through it. Collimation occurs because of refraction mechanism.

Lens antenna in receiving mode is shown in Fig. 7.39.

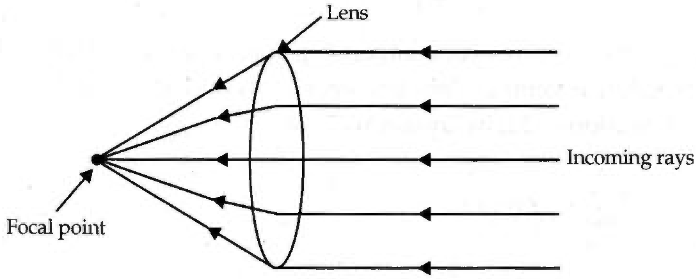


Fig. 7.39 *Lens antenna in receiving mode*

Here again, incoming parallel rays converge at the focal point after passing through the lens due to refraction mechanism. This is an indication of the validity of reciprocity theorem. Collimation is also possible if the lens has refractive index less than unity. Lens antennas are used in association with a point source (ideally). But in practice, it is used with horn-like antennas.

7.17.1 Types of Lens Antennas

These are of two types:

1. Dielectric lens.
2. Metal plate lens.

1. **Dielectric lens** are also known as the **delay lens**. Here, outgoing electromagnetic rays are collimated and are retarded or delayed by the lens material or media. This is illustrated in Fig. 7.40.

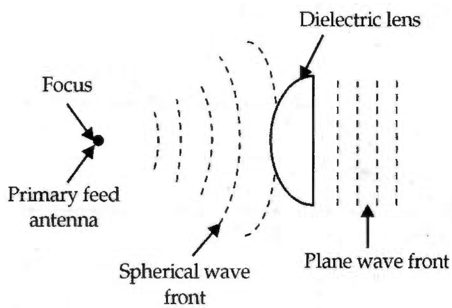


Fig. 7.40 *Mechanism of dielectric lens (delay lens)*

2. ***E*-plane metal plate lens** In this, outgoing wavefront is speeded up by the lens material. This is illustrated in Fig. 7.41.

   Dielectric lens are again of two types:

(*a*) Non-metallic dielectric type.

(*b*) Metallic type.

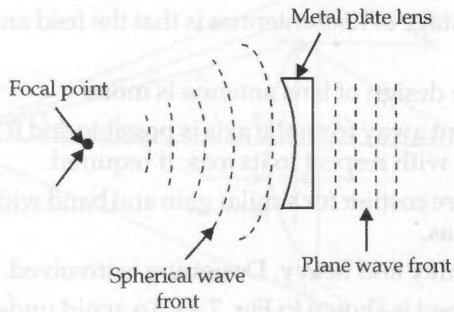


Fig. 7.41 *Mechanism of E-plane metal plate lens*

Salient features of dielectric lens

1. They are usually made of polystyrene or lucite and polyethylene.

   Dielectric constant of polystyrene $\epsilon_r = 2.56$, refractive index, $n = 1.6$

   For polyethylene, $\epsilon_r = 2.25$, $n = 1.5$.
2. They are bulky and heavy for $f < 3$ GHz.
3. Uniform illumination for lens antennas is better if focal length is long.
4. At $f < 10$ GHz the lens become excessively and undesirably thick.
5. This can be avoided by zoned or stepped dielectric lens as in Fig. 7.42.

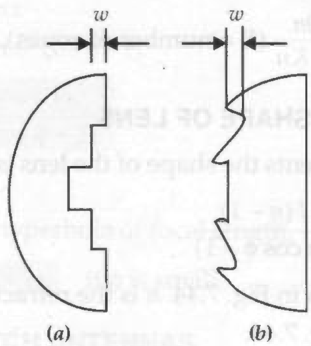


Fig. 7.42 *Zoned or stepped dielectric lens antenna*

6. The width w of a stepped lens is

$$w = \frac{\lambda}{n-1} \qquad ...(7.36)$$

7. The zoned lens of Fig. 7.42 (*b*) is mechanically stable.
8. Weight of stepped lens is less. Power dissipation is also less.
9. The main disadvantage of dielectric lens antenna is its frequency sensitivity.

10. Un-stepped dielectric lens antenna is wide-band and its shape does not depend on wavelength.
11. The main advantage of lens antennas is that the feed antennas do not obstruct the aperture.
12. Tolerance in the design of lens antenna is more.
13. Feeding at a point away from the axis is possible and it is suitable to move the beam angularly with respect to its axis, if required.
14. Lens antennas are costlier for similar gain and band width in comparison with reflector antennas.
15. They are also bulky and heavy. Designing is involved.
16. A typical horn feed is shown in Fig. 7.43. To avoid undesirable radiation from the sides, horn mouth is extended upto the location of the lens.

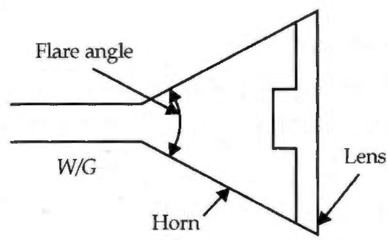


Fig. 7.43 *Horn of lens antenna*

17. The band width of zoned lens is

$$\text{B.W.} = \frac{50n}{1 + Kn} \ (K = \text{number of zones}).$$

7.18 EQUATION OF THE SHAPE OF LENS

The equation which represents the shape of the lens is given by

$$r = \frac{l\,(n-1)}{(n \cos \phi - 1)} \qquad \text{...(7.37)}$$

Here, r, l, ϕ are shown in Fig. 7.44. n is the refractive index of lens.

Proof Consider Fig. 7.44.

The electrical paths of all rays from S to AB are equal so that the field is in phase on the entire plane surface. The outgoing rays from the source will have constant phase across the aperture, d for suitably shaped lens.

If the velocity of electromagnetic wave in air is v_0 and in lens medium if it is v, then due to equality of electrical paths

$$SQ + QQ' = SB + BP' = SB + BP + PP'$$

That is, $$SQ = SB + BP$$

or $$\frac{r}{v_0} = \frac{l}{v_0} + \frac{x}{v}$$

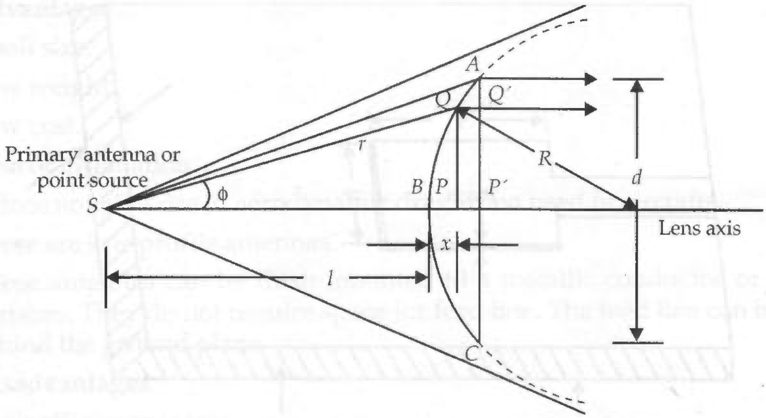


Fig. 7.44 *Ray paths in lens*

or $$r = l + \left(\frac{v_0}{v}\right) x$$

But the refractive index,

$$n = \left(\frac{v_0}{v}\right)$$

and $$x = SP - SB = r\cos\phi - l$$

Hence $$r = l + nx$$

$$= l + n\,(r\cos\phi - l)$$

or $$r = \frac{l\,(n-1)}{(n\cos\phi - 1)} \qquad ...(7.38)$$

Hence proved.

This is the equation of hyperbola of focal length, l and radius of curvature, R

$$R = l\,(n-1) \quad \text{if } \phi \text{ is small} \qquad ...(7.39)$$

7.19 MICROSTRIP OR PATCH ANTENNAS

These are antennas made from patches of conducting material on a dielectric substrate above a ground plane.

Construction It consists of a very thin ($l << \lambda$) metallic strip called a patch placed above a ground plane. The strip and ground plane are separated by a dielectric sheet called substrate as shown in Fig. 7.45. The radiating element and feed lines are usually photoetched on the dielectric substrate. The wide use of printed circuits led to the construction of radiating elements and inter-connecting transmission lines using similar technology.

The side view of a patch antenna is shown in Fig. 7.46.

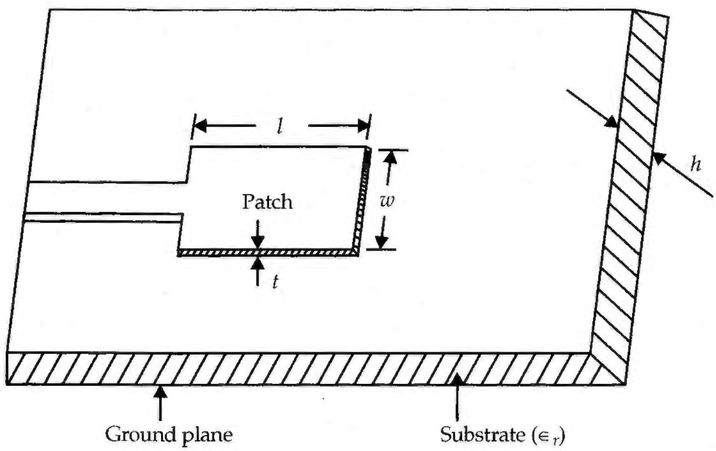
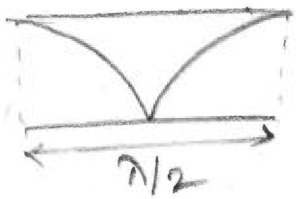


Fig. 7.45 *Microstrip antenna*



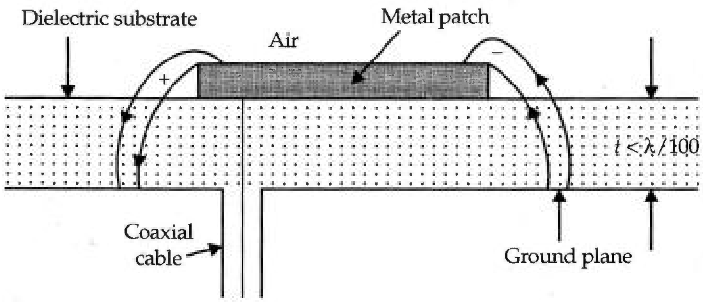


Fig. 7.46 *Side view of a patch antenna*

Typical patch parameters:

1. Dielectric constant of substrate, $\in_r \approx 2$.
2. The thickness of the patch, $t \approx \lambda/100$.
3. The height of the substrate, $h << \lambda$.
4. $\lambda < 3$ m.
5. $f \approx 100$ MHz.
6. $l \leq \lambda/2$.
7. $w < \lambda$.

Applications

1. They are used in spacecrafts and aircrafts.
2. They are used in applications where aerodynamic drag due to antennas should be nil.
3. They are used in telemetry, satellite communications and defence radar systems to operate over a frequency range of 1 to 10 GHz.

Advantages

1. Small size.
2. Low weight.
3. Low cost.
4. Ease of installation.
5. It does not give rise to aerodynamic drag when used in aircrafts.
6. These are low profile antennas.
7. These antennas can be flush mounted to a metallic conductor or to other surfaces. They do not require space for feed line. The feed line can be placed behind the ground plane.

Disadvantages

1. Their efficiency is less.
2. Their band width is small and is typically a few percent.

Shapes of patch antennas

1. Square
2. Circular
3. Elliptical
4. Rectangular
5. Triangular
6. Diamond.

These are shown in Fig. 7.47.

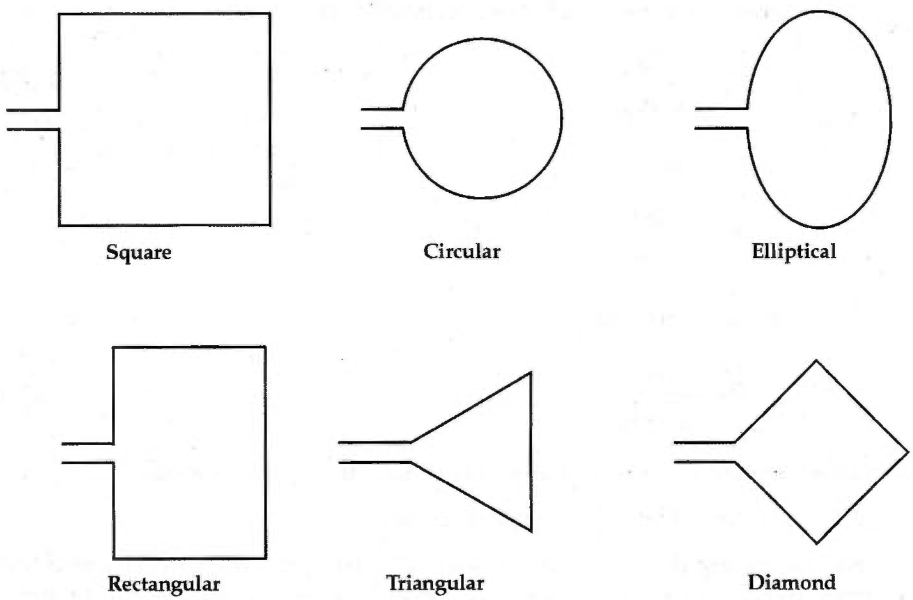


Fig. 7.47 *Different shapes of patch antennas*

The patch antenna acts as a resonant $\lambda/2$ parallel-plate microstrip transmission line. Its characteristic impedance Z_0 is equal to the reciprocal of the number, n of parallel field cell transmission lines.

Each field cell transmission line has a characteristic impedance, Z_i of the medium where

$$Z_i = \sqrt{\frac{\mu}{\epsilon}} = \eta_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \; \Omega \qquad ...(7.40)$$

An end view of the patch antenna from the left side is shown in Fig. 7.48.

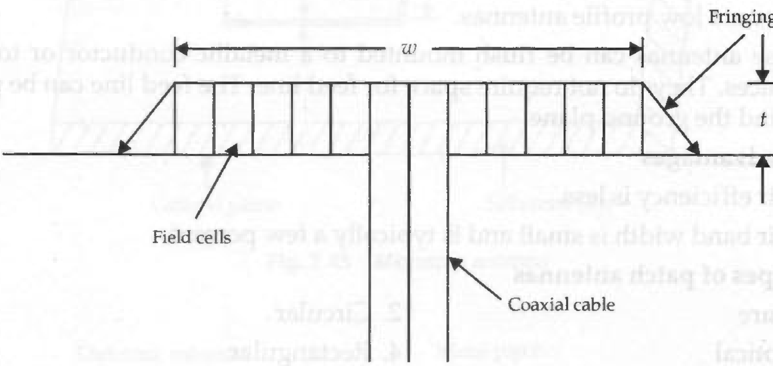


Fig. 7.48 *End view of patch antenna*

The characteristic impedance of patch antenna

$$Z_P = \frac{Z_0}{n\sqrt{\epsilon_r}} \qquad ...(7.41)$$

If $\qquad n = 10$

$$Z_P = \frac{120\pi}{n\sqrt{\epsilon_r}} = \frac{120\pi}{10\sqrt{2}} = 26.63\Omega$$

As $n = w/t$, Z_P becomes

$$Z_P = \frac{Z_0\, t}{w\sqrt{\epsilon_r}} \qquad ...(7.42)$$

Expression (7.42) does not take care of fringing field at the edges.

As $w >> t$, this effect is small on the patch.

For **microstrip line** where w/t is small, the fringing effect is accounted for by approximately adding two cells. This gives more accurate formula for the impedance of the microstrip line. That is given by

$$Z_P \text{ (for microstrip line)} = \frac{\eta_0}{\sqrt{\epsilon_r}\left[\frac{w}{t} + 2\right]} \qquad ...(7.43)$$

Radiation pattern of the patch antenna is broad. Its typical value of beam area Ω_A is 1/2 of half space of or π sterradian.

Therefore, the directivity, D of the patch antenna,

$$D = \frac{4\pi}{\Omega_A} = \frac{4\pi}{\pi} = 4$$

$$D = 10 \log_{10} 4 = 6.021 \text{ dB}$$

The effective height h_e of the antenna is

$$h_e = \sqrt{\frac{2R_r A_e}{\eta_0}} \qquad ...(7.44)$$

Here, R_r = radiation resistance, Ω

A_e = effective aperture, λ^2

η_0 = intrinsic impedance of free space, Ω

$R_r = 50\Omega$ for a typical patch

$$A_e = \frac{D\lambda^2}{4\pi} = \frac{4\lambda^2}{4\pi} = \frac{\lambda^2}{\pi}$$

$$A_e = \frac{\lambda^2}{\pi} \qquad ...(7.45)$$

For matching purposes, feed point can be moved from the edge. Arrays of patches can be used to have more directivity.

Monolithic Microwave Integrated Circuit (MMIC) technology is used to manufacture patch antennas and associated circuitry in a compact form. These are used for frequencies ranging from 50 MHz to 100 GHz.

Printing technology is suitable for a variety of antenna elements like dipoles.

The conductance of the patch antennas is given by

$$g = \frac{1}{90}\left(\frac{w}{\lambda}\right)^2 \quad \text{for } w << \lambda$$

$$g = \frac{1}{120}\left(\frac{w}{\lambda}\right) \quad \text{for } w >> \lambda$$

Methods of band width control It is a narrow band width antenna. However, band width can be increased by:

1. increasing the thickness of parallel plate transmission line
2. cutting holes or slot in the patch. (These holes or slots increase its inductance)
3. using high dielectric constant ($\in_r$) substance
4. adding reactive component to the patch. (This reduces VSWR).

POINTS TO REMEMBER

1. Microwave region extends from 1 GHz to 100 GHz.
2. Parabolic dish antennas are popular to produce narrow beams in the microwave region.
3. Reflectors are used to modify the radiation of the primary antenna.
4. Cassegrain feed mechanism is very popular for low noise applications.
5. Half power beam width of paraboloid is $\phi = \frac{70\lambda}{D_a}$.
6. Beam width from null-to-null of paraboloid is $\phi_0 = \frac{140\lambda}{D_a}$.
7. Directivity, $D = 9.87 \left(\frac{D}{\lambda}\right)^2$.
8. Power gain of paraboloid is $g_p = 6.4 \left(\frac{D_a}{\lambda}\right)^2$.
9. Paraboloids are popular in TV reception and radars.
10. Shaped beam antennas are useful to produce desired shapes of the beam.
11. Narrow beams are useful for point-to-point communication and high angular resolution radars.
12. Sector beams are more useful in search radars.
13. Cosecant beams are useful for ground mapping and airport surveillance.
14. Horn is a flared out waveguide.
15. The efficiency of corrugated horn is more than that of conventional horn.
16. The directivity of horn is $D = \frac{7.5A}{\lambda^2}$.
17. The power gain of horn is $g_p = \frac{4.5A}{\lambda^2}$.
18. Slot antennas are compact and slot arrays are popular in marine radars.
19. The method of moment (MOM) is useful for finding field distribution in slots and other wire antennas.
20. Lens antennas are popular to convert spherical wave front to plane wave front.
21. Polystyrene and lucite are popular lens materials.
22. The shape of the lens is represented by $r = \frac{l\,(n-1)}{(n\cos\phi - 1)}$.

23. Microstrip antennas are popular in cellular phones and for installation on body of aircrafts and so on.

24. The desired polarisation can be obtained by different shapes of the microstrip antenna.

25. Characteristic impedance of patch antenna is $Z_p = \dfrac{Z_0}{n\sqrt{\epsilon_r}}$.

SOLVED PROBLEMS

Problem 7.1 Find the null-to-null main beam width of 2 m paraboloid reflector used at 5 GHz. Also find the half power beam width.

Solution Frequency, $f = 5$ GHz

$$\lambda = \frac{3 \times 10^8}{5 \times 10^9} = 0.06 \text{ m}$$

$$\text{BWFN} = 140 \times \left(\frac{\lambda}{D}\right) = 140 \times \frac{0.06}{2} = 4.2^\circ$$

$$\text{BWFN} = 4.2^\circ$$

$$\text{HPBW} = 70 \times \left(\frac{\lambda}{D}\right) = 70 \times \frac{0.06}{2.0} = 2.1^\circ$$

$$\text{HPBW} = 2.1^\circ.$$

Problem 7.2 Find the gain of a paraboloid of 2 m diameter operating at 5 GHz when half-wave dipole feed is used.

Solution Frequency, $f = 5$ GHz

$$\lambda = \frac{3 \times 10^8}{5 \times 10^9} = 0.06 \text{ m}$$

The gain of the paraboloid is

$$g_p = 6.4\left(\frac{D}{\lambda}\right)^2 = 6.4 \times \left(\frac{2}{0.06}\right)^2$$

$$g_p = 7111.1 = 38.51 \text{ dB}.$$

Problem 7.3 Find the band width between first nulls and half power points of the radiation pattern of a paraboloid operating at 10 GHz which has a mouth diameter of 0.15 m. Also find the power gain.

Solution Frequency, $f = 10$ GHz

Mouth diameter, $D_a = 0.15$ m

$$\lambda = \frac{3 \times 10^8}{10 \times 10^9} = 0.03 \text{ m}$$

$$\frac{\lambda}{D_a} = 0.2$$

$$\text{BWFN} = \phi_0 = 140 \times \left(\frac{\lambda}{D_a}\right) = 28^\circ$$

$$\text{HPBW} = \phi = 70 \times \left(\frac{\lambda}{D_a}\right) = 14^\circ$$

Power gain, $$g_p = 6.4\left(\frac{D_a}{\lambda}\right)^2 = 160 = 22.04 \text{ dB}$$

$$\phi_0 = 28^\circ,\ \phi = 14^\circ,\ g_p = 160 = 22.04 \text{ dB.}$$

Problem 7.4 For a paraboloid reflector antenna with 1.8 m diameter operating at 2 GHz, find the power gain in dB.

Solution Frequency, $f = 2$ GHz

Diameter, $D_a = 1.8$ m

$$\lambda = \frac{3 \times 10^8}{2 \times 10^9} = 0.15 \text{ m}$$

The power gain, $$g_p = 6.4\left(\frac{D_a}{\lambda}\right)^2 = 921.6$$

$$g_p\,(\text{dB}) = 10 \log_{10}(921.6)$$

$$g_p = 29.64 \text{ dB.}$$

Problem 7.5 A paraboloid operating at 5 GHz has a radiation pattern with Null-to-Null beam width of 10°. Find the mouth diameter of the paraboloid, half power beam width and power gain.

Solution Frequency, $f = 5$ GHz

$$\lambda = \frac{3 \times 10^8}{5 \times 10^9} = 0.06 \text{ m}$$

We have $$\phi_0 = \text{BWFN} = 140 \times \left(\frac{\lambda}{D_a}\right)$$

or $$D_a = 140 \times \left(\frac{\lambda}{\text{BWFN}}\right)$$

$$= 140 \times \left(\frac{0.06}{10} \right)$$

Mouth diameter, $D_a = 0.84$ m

$$\text{HPBW} = \phi = 70 \times \left(\frac{\lambda}{D_a} \right) = 5^{\circ}$$

Power gain, $g_p = 6.4 \left(\frac{D_a}{\lambda} \right)^2$

or $g_p = 1254.4$

$$D_a = 0.84 \text{ m}, \ \phi = 5^{\circ}, \ g_p = 1254.4.$$

Problem 7.6 For a paraboloid reflector of diameter 6 m, illumination efficiency, $b = 0.65$. The frequency of operation is 10 GHz. Find its beam width, directivity and capture area.

Solution Frequency, $f = 10$ GHz

$$\lambda = \frac{3 \times 10^8}{10 \times 10^9} = 0.03 \text{ m}$$

Mouth diameter, $D_a = 6$ m

Actual area, $A = \frac{\pi D_a^2}{4} = \pi \times \frac{36}{4} = 28.27 \text{ m}^2$

Capture area, $A_c = 0.65 \text{ A} = 18.378 \text{ m}^2$

Directivity, $D = 6.4 \times \left(\frac{D_a}{\lambda} \right)^2 = 2{,}56{,}000 = 54.1 \text{ dB}$

$$\text{HPBW} = \phi = 70 \times \left(\frac{\lambda}{D_a} \right) = 0.35^{\circ}$$

$$\text{BWFN} = \phi_0 = 2\phi = 0.70^{\circ}$$

$$\phi_0 = 0.7^{\circ}, \ \phi = 0.35^{\circ}, \ A_c = 18.378 \text{ m}^2$$

Directivity $= 54.1$ dB.

Problem 7.7 A paraboloid reflector operates at 4 GHz. Its mouth diameter is 6 m. It is required to measure far-field pattern of the paraboloid. Find the minimum distance required between the two antennas.

Solution The minimum distance required

$$r = \frac{2D_a^2}{\lambda}$$

where $D_a = 6.0$ m

$$f = 4 \text{ GHz}$$

$$\lambda = \frac{3 \times 10^8}{4 \times 10^9} = 0.075 \text{ m}$$

$$r = \frac{2D_a^2}{\lambda} = 960.0 \text{ m.}$$

Problem 7.8 A paraboloid reflector is required to have a power gain of 1,000 at a frequency of 3 GHz. Determine the mouth diameter and beam width of the antenna.

Solution Frequency, $f = 3$ GHz

$$\lambda = \frac{3 \times 10^8}{3 \times 10^9} = 0.1 \text{ m}$$

Required power gain,

$$g_p = 1{,}000$$

We have, $$g_p = 6.4 \times \left(\frac{D_a}{\lambda}\right)^2$$

Mouth diameter, $$D_a = \lambda \sqrt{\frac{g_p}{6.4}}$$

$$= 0.1 \sqrt{\frac{1{,}000}{6.4}} = 1.25 \text{ m}$$

$$\text{HPBW} = 70 \times \left(\frac{\lambda}{D_a}\right) = 5.6^\circ$$

$$\text{BWFN} = 140 \times \left(\frac{\lambda}{D_a}\right) = 11.2^\circ$$

$$D_a = 1.25 \text{ m}, \ \text{HPBW} = 5.6^\circ, \ \text{BWFN} = 11.2^\circ.$$

Problem 7.9 A paraboloid reflector operates at a frequency of 10 GHz and it provides a power gain of $g_p = 75$ dB. Find the capture area of the paraboloid and beam width.

Solution Frequency, $f = 10$ GHz

$$\lambda = \frac{3 \times 10^8}{10 \times 10^9} = 0.03 \text{ m}$$

Power gain, $$g_p = 6.4 \left(\frac{d_a}{\lambda}\right)^2$$

But, $$g_p = 75 \text{ dB}$$

That is, $g_p = 10 \log_{10} g = 75$

or $\log_{10} g = 75/10 = 7.5$

or $g = 10^{7.5} = 3.162 \times 10^7$

So, $g_p = 6.4\left(\dfrac{D_a}{\lambda}\right)^2 = 3.162 \times 10^7$

or $\left(\dfrac{D_a}{\lambda}\right)^2 = \dfrac{3.162 \times 10^7}{6.4}$

or $D_a = 0.03 \times \sqrt{\dfrac{3.162 \times 10^7}{6.4}}$

$$D_a = 0.03 \times 10^2 \sqrt{\frac{3162}{6.4}}$$

Mouth diameter, $D_a = 66.68$ m

Actual area, $A = \dfrac{\pi D_a^2}{4} = 3492 \text{ m}^2$

Capture area, $A_c = 0.65 \times A$

$$= 0.65 \times 3492 = 2269.83 \text{ m}^2$$

$$\text{BWFN} = \phi_0 = 140 \times \left(\frac{\lambda}{D_a}\right) = 0.062^\circ$$

$$\text{HPBW} = \phi = 70 \times \left(\frac{\lambda}{D_a}\right) = 0.031^\circ$$

$$A_c = 2269.83 \text{ m}^2,\ \phi_0 = 0.062^\circ,\ \phi = 0.031^\circ.$$

Problem 7.10 A parabolic reflector is operated at 2 GHz and it has mouth diameter of 60 m. If it is fed by non-directional antenna, find out HPBW, BWFN and power gain.

Solution Frequency, $f = 2$ GHz

$$\lambda = \frac{3 \times 10^8}{2 \times 10^9} = 1.5 \times 10^{-1} = 0.15 \text{ m}$$

Mouth diameter, $D_a = 60$ meters

Power gain, $g_p = 6.4\left(\dfrac{D_a}{\lambda}\right)^2 = 10{,}24{,}000$

or $g_p = 60.103$ dB

$$\text{HPBW} = \phi = 70 \times \left(\frac{\lambda}{D_a}\right) = 0.175^\circ$$

$$\text{BWFN} = \phi_0 = 140 \times \left(\frac{\lambda}{D_a}\right) = 0.35^\circ$$

$$g_p = 60.103 \text{ dB}, \ \phi = 0.175^\circ, \ \phi_0 = 0.35^\circ.$$

Problem 7.11 A parabolic reflector with a mouth diameter of 22 meters operates at $f = 5$ GHz. It has illumination efficiency of 0.6. Find the power gain.

Solution Mouth diameter, $D_a = 22$ m

Frequency, $f = 5$ GHz

$$\lambda = \frac{3 \times 10^8}{5 \times 10^9} = 0.06 \text{ m}$$

Illumination efficiency $= 0.6$

Power gain, $g_p = \text{illumination efficiency} \times \left(\frac{D_a}{\lambda}\right)^2$

$$= 0.6 \times \left(\frac{22}{0.06}\right)^2 = 80{,}666.6 \text{ or } 49.06 \text{ dB}$$

Power gain $g_p = 49.06$ dB.

Problem 7.12 For what mouth diameter and capture area of a paraboloid reflector is a BWFN of 12° obtained when it is operated at 2 GHz?

Solution Frequency, $f = 2$ GHz

$$\lambda = \frac{3 \times 10^8}{2 \times 10^9} = 0.15 \text{ m}$$

$$\text{BWFN} = 140 \times \left(\frac{\lambda}{D_a}\right) = 12^\circ$$

$$D_a = \frac{140\lambda}{12} = 1.75 \text{ m}$$

Capture area, $A_c = 0.65$ A

Here, $A = \dfrac{\pi D_a^2}{4} = 2.405 \text{ m}^2$

$$A_c = 1.5634 \text{ m}^2$$

Mouth diameter, $D_a = 1.75$ m

$A_c = 1.5634$ m^2.

Problem 7.13 A paraboloid reflector is required to produce a beam width between the first nulls equal to 3° at an operating frequency of 2.5 GHz. Find the mouth diameter and power gain.

Solution Frequency, $f = 2.5$ GHz

$$\text{BWFN} = 3^\circ$$

$$\lambda = \frac{3 \times 10^8}{2.5 \times 10^9} = 0.12 \text{ m}$$

But $$\text{BWFN} = 140 \times \left(\frac{\lambda}{D_a}\right) = 3^\circ$$

$$D_a = 140 \times \left(\frac{\lambda}{3}\right) = \left(\frac{140 \times 0.12}{3}\right) = 5.6 \text{ m}$$

Power gain, $$g_p = 6.4\left(\frac{D_a}{\lambda}\right)^2 = 13{,}937.7 \text{ or } 41.50 \text{ dB}$$

$D_a = 5.6$ m, $g_p = 41.44$ dB.

Problem 7.14 A paraboloid reflector has radiation characteristics whose half power beam width is 5°. Find out its Null-to-Null beam width and power gain.

Solution $\text{HPBW} = \phi = 5^\circ$

$$\text{BWFN} = \phi_0 = 2\phi = 10^\circ$$

But $$\phi = 70 \times \left(\frac{\lambda}{D_a}\right)$$

or $$\left(\frac{\lambda}{D_a}\right) = \frac{\phi}{70}$$

$$\left(\frac{D_a}{\lambda}\right) = \frac{70}{5} = 14.0$$

Power gain, $$g_p = 6.4\left(\frac{D_a}{\lambda}\right)^2 = 1254.4$$

or $$g_p = 30.98 \text{ dB}$$

$\text{BWFN} = 10^\circ$, $g_p = 30.98$ dB.

Problem 7.15 What is the power gain of a paraboloid reflector whose mouth diameter is equal to 8λ?

Solution Power gain, $g_p = 6.4\left(\frac{D_a}{\lambda}\right)^2$

Here $D_a = 8\lambda$

$$g_p = 6.4\left(\frac{8\lambda}{\lambda}\right)^2 = 409.6$$

$$g_p = 26.12 \text{ dB.}$$

Problem 7.16 Determine half power and Null-to-Null beam widths of a paraboloid reflector whose aperture diameter is 6λ. Also find its directivity.

Solution Aperture diameter, $= 6\lambda$

$$\text{HPBW} = \phi = 70 \times \left(\frac{\lambda}{D_a}\right) = 70 \times \left(\frac{\lambda}{6\lambda}\right) = 11.66^\circ$$

Null-to-Null beam width,

$$\phi_0 = 2\phi = 23.33^\circ$$

The directivity of the paraboloid,

$$D = 6.4 \times \left(\frac{6\lambda}{\lambda}\right)^2$$

$$= 6.4 \times 36 = 230.4$$

$$\phi = 11.6^\circ,\ \phi_0 = 23.33^\circ,\ D = 230.4.$$

Problem 7.17 The aperture dimensions of a pyramidal horn are 12×6 cm. It is operating at a frequency of 6 GHz. Find the beam width, power gain and directivity.

Solution Frequency, $f = 6$ GHz

$$\lambda = \frac{3 \times 10^8}{6 \times 10^9} = 0.05 \text{ m} = 5 \text{ cm}$$

$$d = 12 \text{ cm},\ w = 6 \text{ cm}$$

Half power beam width

$$= \text{HPBW}$$

$$\phi_E = 56\frac{\lambda}{d} = 56 \times \frac{5}{12} = 23.33^\circ$$

$$\phi_E = 67\frac{\lambda}{w} = 67 \times \frac{5}{6} = 55.83^\circ$$

Power gain, $g_p = \dfrac{4.5wd}{\lambda^2} = 12.96 = 11.12$ dB

Directivity, $D = \dfrac{7.5Wd}{\lambda^2} = \dfrac{7.5 \times 12 \times 6}{5^2} = 21.6$

$\phi_E = 23.33°$, $\phi_H = 55.83°$
$g_p = 11.12$ dB, $D = 21.6$.

Problem 7.18 Find the power gain of a square horn antenna whose aperture size is 8λ.

Solution The power gain, $g_p = \dfrac{4.5wd}{\lambda^2}$

$$= \frac{4.5 \times 8\lambda \times 8\lambda}{\lambda^2} = 288$$

$g_p = 24.59$ dB.

Problem 7.19 Find the power gain and directivity of a horn whose dimensions are 10×5 cm operating at a frequency of 6 GHz.

Solution The dimensions of horn are

$$d = 10 \text{ cm}, \; w = 5 \text{ cm}, \; f = 6 \text{ GHz}$$

$$\lambda = \frac{3 \times 10^8}{6 \times 10^9} = 0.05 \text{ m} = 5 \text{ cm}$$

Power gain, $g_p = \dfrac{4.5wd}{\lambda^2} = 9 = 9.54$ dB

Directivity, $D = \dfrac{7.5wd}{\lambda^2} = 15 = 11.76$ dB

$g_p = 9.54$ dB, $D = 11.76$ dB.

Problem 7.20 Find the complementary slot impedance when the dipole impedance is:

(*a*) $Z_d = 73 + j42.5\Omega$

(*b*) $Z_d = 67\Omega$

(*c*) $Z_d = 710\Omega$

(*d*) $Z_d = 500\Omega$

(*e*) $Z_d = 50 + j20\Omega$

(*f*) $Z_d = 50 - j25\Omega$

(*g*) $Z_d = 300\Omega$.

Solution (*a*) We have

Z_s = slot impedance

$$= \frac{\eta_0^2}{4\,(R_d^2 + X_d^2)}\,(R_d - j\,X_d)$$

$$= \frac{35530.6}{(R_d^2 + X_d^2)}\,(R_d - j\,X_d)$$

If $\quad Z_d = R_d + j\,X_d = 73 + j\,42.5\,\Omega$

$$Z_s = 363.5 - j\,211.6,\ \Omega$$

(*b*) If $\quad Z_d = 67 + j\,0\,\Omega$

$$Z_s = 530.3\,\Omega$$

(*c*) If $\quad Z_d = 710 + j\,0\,\Omega$

$$Z_s = 50\,\Omega$$

(*d*) If $\quad Z_d = 500 + j\,0\,\Omega$

$$Z_s = 71\,\Omega$$

(*e*) If $\quad Z_d = 50 + j\,20\,\Omega$

$$Z_s = 612.6 - j\,245\,\Omega$$

(*f*) If $\quad Z_d = 50 - j\,25\,\Omega$

$$Z_s = 568.5 + j\,284.2\,\Omega$$

(*g*) If $\quad Z_d = 300\,\Omega$

$$Z_s = 118.4\,\Omega.$$

OBJECTIVE QUESTIONS

1. Ideally, reflector size is infinitely large. (Yes/No)
2. The polarisation and position of the primary antennas control the radiating properties of the complete system. (Yes/No)
3. Reflector is called primary antenna. (Yes/No)
4. Microwave frequency range is _______________.
5. Corner reflector is better than plane reflectors in collimating electromagnetic energy. (Yes/No)
6. Band width of corner reflector is more when elements are cylindrical dipoles rather than thin wires. (Yes/No)
7. A grid-wired corner reflector reduces the weight of the antenna system. (Yes/No)

8. Efficiency of corner reflector is reduced when spacing of feed element becomes small. (Yes/No)
9. Multiple lobes are produced when the spacing of feed element from the vertex is large. (Yes/No)
10. In corner reflectors, the spacing of the feed point should be greater than the length of the sides. (Yes/No)
11. If the main beam is narrow, the directivity is small. (Yes/No)
12. Collimation of electromagnetic energy means generation of parallel rays. (Yes/No)
13. Parabolic reflector is different from paraboloid. (Yes/No)
14. Dish antenna and paraboloid are one and the same. (Yes/No)
15. The gain of an antenna with a paraboloid reflector depends on (D_a/λ) and the illumination. (Yes/No)
16. In Cassegrain feed, the size of the hyperboloid reflector depends on its distance from the horn feed, mouth diameter of horn and frequency. (Yes/No)
17. The size of hyperboloid reflector is small if its distance from the feed antenna is small. (Yes/No)
18. Cassegrain feed is best suited for ______________.
19. The disadvantage of Cassegrain feed is the obstruction of electromagnetic energy by hyperbolic reflector. (Yes/No)
20. If half power band width is 10° in the radiation of pattern of paraboloid beam width from Null-to-Null is ______________.
21. The power gain of paraboloid is given by ______________.
22. Capture area of paraboloid is ______________ where $K = 0.65$ for dipole feed and A is actual area.
23. If the actual area of paraboloid reflector is 10 m^2, its capture area is ______________.
24. Sector beams are used in ______________ antennas.
25. Cosec beams are used for ______________.
26. Narrow beams are used for point-to-point communication purposes. (Yes/No)
27. For height finding, the antenna beam is ______________.
28. In pyramidal horn, flaring is done in only one plane. (Yes/No)
29. Power gain of horns is greater than that of paraboloid reflectors. (Yes/No)
30. Directivity of horns is greater than that of waveguide. (Yes/No)
31. Power gain of a horn is more than its directivity. (Yes/No)
32. Feed system with corrugated horn reduces spill over efficiency. (Yes/No)
33. Feed system with corrugated horn reduces cross-polarisation. (Yes/No)

34. Horizontal slot produces vertical polarised radiation fields. (Yes/No)

35. Horizontal dipole produces horizontal polarised radiation fields. (Yes/No)

36. If impedance of dipole is inductive, slot impedance is capacitive. (Yes/No)

37. If the impedance of the slot is capacitive, the impedance of complementary dipole is inductive. (Yes/No)

38. From slot antenna, in a conducting plane, its complementary dipole is formed by interchanging air and metallic regions in the slot. (Yes/No)

39. Impedance of the slot antenna can be changed by changing feed point. (Yes/No)

40. Back radiation from a slot in a conductive plane can be avoided by ______________.

41. Slot gain is increased by array of slots. (Yes/No)

42. The radiation pattern of annular slot antenna is ______________.

43. Array of slots is used in ______________.

44. An array of slots when excited with appropriate amplitude and phase is suitable in ______________.

45. Dipole of small length to diameter ratio increases the bandwidth. (Yes/No)

46. Slot of small length to width ratio increases the band width. (Yes/No)

47. Notch antennas are used in aircrafts. (Yes/No)

48. Notch antennas are used in edges of the wing surface of aircraft. (Yes/No)

49. Notch antenna is broad band. (Yes/No)

50. The purpose of dielectric filling of notch is ______________.

51. Microstrip antennas are used because of ______________.

52. Microstrip antennas are used for frequencies above ______________.

53. The band width of microstrip antenna is ______________.

54. In microstrip antennas, Beam width can be increased by ______________ the thickness of the strip.

55. If ϵ_r of substrate is high in microstrip antenna, Beamwidth increases. (Yes/No)

56. If reactive component is added in microstrip antenna, B.W. is increased. (Yes/No)

57. If reactive component is added in microstrip antennas Voltage standing wave ratio is increased. (Yes/No)

58. The radiation beam of microstrip antenna is ______________.

59. The characteristic impedance Z_0 of microstrip antenna is ______________.

60. Trihedral forms of corner reflectors are used as ______________.

61. Rod reflectors are nothing but parasitic elements. (Yes/No)

62. The length of the rod reflector is greater than $\lambda/2$. (Yes/No)

63. Rod reflector is an active radiating element. (Yes/No)
64. In Cassegrain feed, the dimension of the hyperboloid depends on its distance from the primary feed antenna. (Yes/No)
65. In Cassegrain feed, the dimension of the hyperboloid depends on mouth diameter of the horn. (Yes/No)
66. In Cassegrain feed the dimension of the hyperboloid depends on frequency of operation. (Yes/No)
67. Flare angle of the horn is related to axial length. (Yes/No)
68. The directivity of the paraboloid is greater than that of horn. (Yes/No)
69. The size of the horn becomes large if the flare angle is small. (Yes/No)
70. Horn antenna is called secondary antenna when used with paraboloid. (Yes/No)
71. The disadvantage of lens antenna at low frequencies is ______________.
72. The material of lens antenna is ______________.
73. Lens are preferred over parabolic reflectors at ______________.
74. Lens is used to correct the curved wavefront. (Yes/No)
75. The refractive index of lens material is different from unity. (Yes/No)
76. In fanned beams, the directivity is poor in one of the principal planes. (Yes/No)
77. If the beam width is small, target resolution is high. (Yes/No)
78. Fanned beams are used for ______________.
79. For feed systems using corrugated horns, the aperture efficiency is ______________.
80. Babinet's principle is applicable in electromagnetic problems. (Yes/No)
81. Babinet's principle is valid in optics. (Yes/No)
82. For a slot in conducting sheet, there exists a complementary dipole. (Yes/No)
83. The gain of the horn antenna is ______________.
84. Vertical slot in the narrow wall of rectangular waveguide does not radiate. (Yes/No)
85. Longitudinal centred slot in the broad wall of a rectangular waveguide does not radiate. (Yes/No)
86. The equivalent circuit of an inclined slot in the narrow wall of a rectangular waveguide is a ______________.
87. Resonant length of the slot is ______________.
88. Method of moments is useful to solve ______________.
89. Patch antennas are ______________.
90. Patch is made of dielectric material. (Yes/No)
91. Pyramidal horn is nothing but rectangular horn. (Yes/No)
92. Conical horn is excited conveniently by a circular waveguide. (Yes/No)

93. For lossless antenna, directivity is the same as gain. (Yes/No)

94. Aperture efficiency is given by ______________.

95. A slot can be excited by a waveguide. (Yes/No)

96. A slot can be excited by an energised cavity. (Yes/No)

97. A slot can be excited by a transmission line. (Yes/No)

98. The efficiency of patch antenna is ______________.

99. The equivalent circuit of symmetrical vertical slot in the broad wall of a rectangular waveguide is ______________.

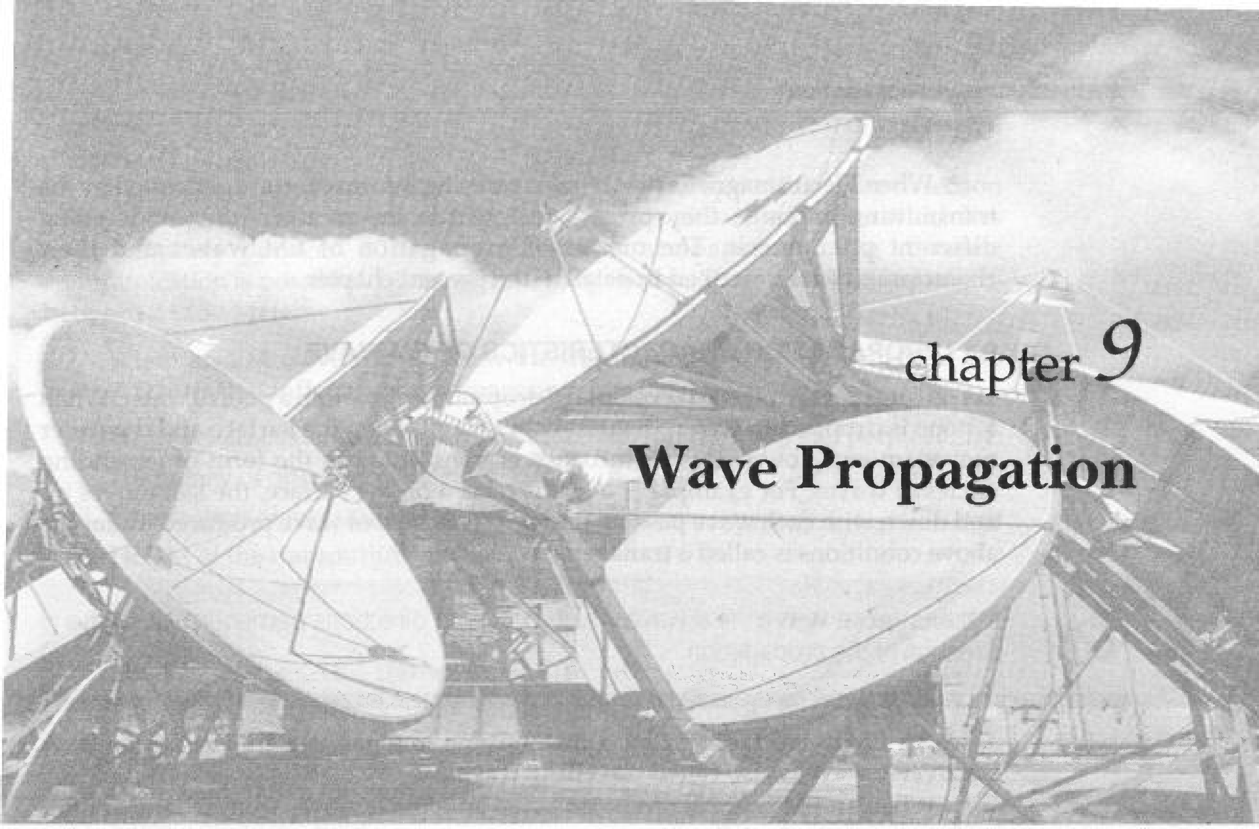
100. For producing circular polarised waves, the shape of the patch antenna is ______________.

ANSWERS

1. Yes **2.** Yes **3.** No **4.** 1 GHz – 100 GHz **5.** Yes
6. Yes **7.** Yes **8.** Yes **9.** Yes **10.** No **11.** No
12. Yes **13.** No **14.** Yes **15.** Yes **16.** Yes **17.** Yes
18. Low noise receiver applications **19.** Yes **20.** 20° **21.** $6.4\left(\frac{D}{\lambda}\right)^2$
22. *KA* **23.** 6.5 m^2 **24.** Surface search from ship-borne
25. Airport surveillance **26.** Yes **27.** Sharp in elevation **28.** No
29. No **30.** Yes **31.** No **32.** Yes **33.** Yes **34.** Yes
35. Yes **36.** Yes **37.** Yes **38.** Yes **39.** Yes
40. Boxing the slot suitably **41.** Yes **42.** Narrow beam **43.** Aircrafts
44. Scanning radars without antenna movement **45.** Yes **46.** Yes
47. Yes **48.** Yes **49.** Yes **50.** To eliminate aerodynamic drag in aircrafts
51. Small size, less weight, low cost and so on **52.** 100 MHz **53.** Small **54.** Increasing
55. Yes **56.** Yes **57.** No **58.** Broad **59.** $Z_0 = \eta\sqrt{\frac{\mu_r}{\epsilon_r}}\ \Omega$
60. Radar targets **61.** Yes **62.** Yes **63.** No **64.** Yes
65. Yes **66.** Yes **67.** Yes **68.** Yes **69.** No **70.** No
71. Bulkiness **72.** Lucite **73.** Millimeter and sub-millimeter frequencies **74.** Yes
75. Yes **76.** Yes **77.** Yes **78.** Air search from ground **79.** 75 – 80%
80. No **81.** Yes **82.** Yes **83.** Moderate **84.** Yes **85.** Yes
86. Shunt admittance **87.** $\lambda/2$ **88.** Integral equations
89. Very compact **90.** No **91.** Yes **92.** Yes **93.** Yes
94. Ratio of effective aperture and physical aperture **95.** Yes **96.** Yes
97. Yes **98.** Low **99.** Series impedance **100.** Circular

EXERCISE PROBLEMS

1. The power gain of transmitting antenna $A_p = 20$. The input power is $P_{in} = 200$ W. Find the effective isotropic radiated power EIRP in dB and dB_m.
2. Find the power density at a point at 12 km from the transmitting antenna. Its power gain is 10 and input power is 100 W.
3. The radiation resistance of a transmitting antenna dipole is 80 Ω, loss resistance is 10 Ω, directive gain is 15 and input power is 1 kW. Find antenna efficiency and radiated power.
4. The capture area of a receiving antenna is 10 cm^2 and available power density is 10μ W/cm^2. Find the capture power.
5. What is the band width in percentage of an antenna operating at a frequency of 100 MHz if 3dB frequencies are 300 MHz and 350 MHz.
6. The diameter of parabolic reflector is 2.0 m. It radiates a power of 100 W at an operating frequency of 3 GHz. Its efficiency is 60% and its aperture efficiency is 60%. Find the antenna power gain and beam width.
7. What is the free space path loss when the transmitting and receiving antennas are separated by 100 km, while operating at a frequency of 10 GHz?
8. A uniformly illuminated parabolic reflector whose aperture size is 2 m is operated at 6 GHz. Find the Null-to-Null beam width and power gain with reference to dipole of half wave length. Assume that the antenna is lossless.
9. A 2 m parabolic reflector operating at $f = 6$ GHz radiates a power of 100 W. It has efficiency of 60% and its aperture efficiency is 60%. Find the antenna power gain in dB.
10. A 3 m parabolic reflector operating at 8 GHz radiates a power of 10 W. It has an efficiency of 55% and its aperture efficiency is 60%. Find the receiver power gain. Also find the EIRP.
11. The power radiated by an antenna is 100 W and dissipated power is 10 W. The antenna has a directional gain of 250. Find antenna efficiency and power gain.



chapter 9

Wave Propagation

"The wave propagation characteristics between transmitter and receiver are controlled by the transmitting antenna, operating frequencies and media between them."

CHAPTER OBJECTIVES

This chapter discusses

- ✦ Different methods of wave propagation between transmitter and receiver
- ✦ Merits and demerits of each method
- ✦ Characteristics of Ground, Tropospheric and Ionospheric propagation
- ✦ Field strength estimation in each method
- ✦ The losses and attenuation
- ✦ Objective questions and solved problems useful for class tests, final examinations and also for competitive examinations
- ✦ Exercise problems to develop self problem solving skills

When Electromagnetic (EM) waves carrying information are generated by the transmitting antenna, they propagate towards the receiver after undergoing different phenomena. The modes of propagation of EM waves and their characteristics are described in detail in the present chapter.

9.1 PROPAGATION CHARACTERISTICS OF EM WAVE

Let us consider the physical example of dropping a stone into a pool of water. When a stone is dropped in water, disturbances take place on the surface and the water moves up and down. This disturbance is transmitted in the form of expanding circles of waves. For example, if a leaf is placed on the surface, the leaf moves up and down with each wave passing under it. This type of wave produced under the above conditions is called a **transverse wave**.

A **transverse wave** is a wave which occurs in directions perpendicular to the direction of the propagation.

An EM wave radiated by a transmitting antenna is a transverse wave. A **transverse wave** is also called **travelling wave**.

When an EM wave is produced by an antenna it moves from the transmitter to the receiver in the following ways:

1. A part of the wave travels along or near the surface of the earth. This wave is called the **ground wave** or **surface wave**.
2. Some waves travel directly from the transmitting to the receiving antenna. That is, these waves do no follow the earth and also do not move towards the sky. These waves are called **space waves**.
3. Some waves travel upwards into space towards the sky and get reflected back to the receiver. These waves are called **sky waves**.

9.2 FACTORS INVOLVED IN THE PROPAGATION OF RADIO WAVES

As explained above, an EM wave/Radio wave travels from the transmitter to the receiver in three different types of waves:

1. **Ground wave or surface wave**
2. **Space wave or tropospheric wave**
3. **Sky wave or ionospheric wave**.

Ground wave which is also called **surface wave** exists when the transmitting and receiving antennas are close to the earth and are **vertically polarised.** This type of wave propagation is useful at broadcast and low frequencies. The broadcast signals received during day-time are due to ground waves. It is useful for communication at VLF, LF and MF.

Space wave is also called **tropospheric wave**. Here, the wave propagates directly from the transmitter to the receiver in the tropospheric region. The portion of the atmosphere above the earth and within 16 km is called **troposphere**. This is useful above the frequency of 30 MHz. **FM reception** is normally by space wave propagation.

Sky wave is called **ionospheric wave**. The signal reception here is by reflection of the waves from the ionosphere. The **ionosphere** is an ionised region which lies approximately between 60 km to 450 km of atmosphere. Long distance communication is possible by this mode of propagation. It is useful for frequencies between 2 to 30 MHz.

When an EM wave travels from the transmitter to the receiver, there are several factors that influence the propagation. The factors are:

1. Earth's characteristics in terms of conductivity, permittivity and permeability.
2. Frequency of operation.
3. Polarisation of transmitting antenna.
4. Height of the transmitting antenna.
5. Transmitter power.
6. Curvature of the earth.
7. Obstacles between the transmitter and receiver.
8. Electrical characteristics of the atmosphere in the tropospheric region.
9. Moisture content in the troposphere.
10. Characteristics of the ionosphere.
11. Earth's magnetic field.
12. Refractive index of troposphere and ionosphere.
13. Permittivity of the tropospheric and ionospheric regions.
14. The distance between the transmitter and receiver.
15. Roughness of the earth.
16. Type of earth like hilly terrain, forest, sea water or river water.

9.3 GROUND WAVE

A wave is said to be **ground wave** or **surface wave** when it propagates from transmitter to receiver by gliding over the surface of the earth. This wave exists when,

- both transmitting and receiving antennas are close to the earth and
- the antennas are vertically polarised.

Ground wave is useful at low frequency broadcast applications. The broadcast signals received in the day-time are by ground waves. Ground wave signal is limited to only a few kilometers. The horizontally polarised antennas are not preferred as the horizontal component of the electric field in contact with the earth is short circuited by the earth. When the wave is in contact with the earth, it induces charges in the earth and constitute a current. The electric and magnetic fields of the wave over the earth are shown in Fig. 9.1.

The earth behaves like a leaky capacitance in carrying the induced current. **Equivalent circuit** of the earth is shown in Fig. 9.2.

The characteristics of the earth are described by its fundamental constants namely permittivity, conductivity and permeability.

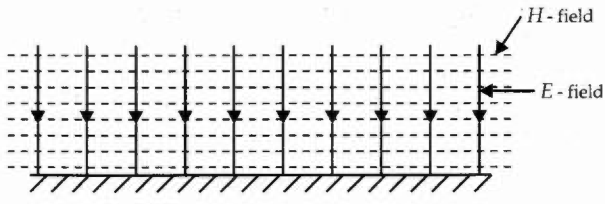


Fig. 9.1 *Vertically polarised wave*

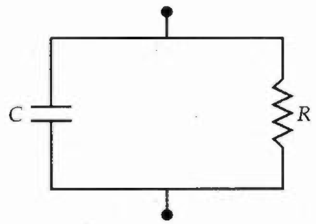


Fig. 9.2 *Equivalent circuit of the earth*

The wave is attenuated as it propagates due to imperfect nature of the earth (Fig. 9.3). The attenuation is mainly as a result of the absorption and reflection of EM energy by the earth. A part of this lost energy is compensated by the diffraction of additional energy coming from the atmospheric region above the earth.

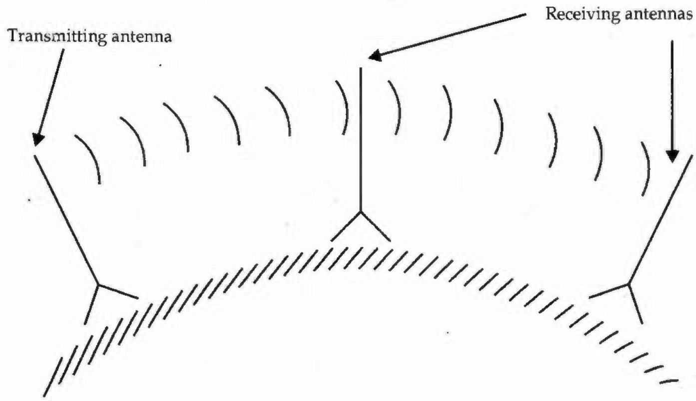


Fig. 9.3 *Ground wave between transmitting and receiving antennas*

9.4 GROUND WAVE FIELD STRENGTH

According to Somerfield analysis, the ground wave field strength for flat earth, is given by

$$E = \frac{AE_0}{d} \qquad \text{...(9.1)}$$

where E = field strength at a point, V/m

E_0 = field strength of the wave at a unit distance from the transmitting antenna, neglecting earth's losses (V/m)

A = factor of the ground losses

d = distance of the point from Transmitting antenna

E_0 depends on

1. Power radiated by the transmitting antenna.
2. Directivity of the antenna in vertical and horizontal planes.

Example Short vertical antenna is non-directional in horizontal plane. Its far-field is proportional to the cosine of the angle of elevation in vertical plane.

$$E_0 = 300 \text{ mV/m at } d = 1 \text{ km and for a radiated power} = 1 \text{ kW.}$$

For other radiated powers, E_0 is proportional to the square root of power or

$$E_0 = 300\sqrt{P_{kW}}, \text{ mV/m at 1 km.}$$

For antenna with vertical directivity, the field strength along the horizon is 1.41 times the field strength obtained with assumed cosine law.

The factor, A depends on

1. Conductivity, σ mho/m
2. Permittivity of the earth, ϵ_r
3. Frequency of the wave, f
4. Distance from the transmitter, d.

The determination of field strength due to Somerfield analysis mainly consists of determination of A.

This is found from the knowledge of **numerical distance**, p and **phase constant**, b. For vertical polarisation, these are given by

$$p = \frac{\pi}{D_f}\frac{d}{\lambda}\cos b \qquad \text{...(9.2)}$$

$$b = \tan^{-1}\left(\frac{\epsilon_r + 1}{D_f}\right) \qquad \text{...(9.3)}$$

where $$D_f = 1.80 \times 10^{12}\frac{\sigma}{f}$$

D_f is known as dissipation factor of the dielectric

σ = conductivity, (mho)/cm of earth

ϵ_r = relative permittivity of earth

f = frequency in Hz

$\frac{d}{\lambda}$ = normalised distance with respect to λ

λ = wavelength

The salient features of ground wave propagation

1. Ground wave propagates by gliding over the surface of the earth.
2. It exists for vertically polarised antennas.
3. It exists for antennas close to the earth.
4. It is suitable for VLF, LF and MF communications.
5. It can be used even at 15 kHz and upto 2 MHz.
6. Ground wave field strength is $E = \frac{AE_0}{d}$.
7. The ground wave field strength varies with characteristics of the earth.
8. Ground waves require relatively high transmitter power.
9. Ground wave propagation losses vary considerably with the type of earth.
10. Ground waves are not affected by the changes in atmospheric conditions.
11. Ground waves can be used to communicate between any two points on the globe if there is sufficient transmitter power.
12. It can be used for radio navigation, for ship-to-ship, ship-to-shore communication and maritime mobile communications.

A typical variation of A with numerical distance, p and phase constant, b is shown in Fig. 9.4.

The factor, A can be also calculated approximately from the following expression:

$$p = \frac{0.582 d_{\text{km}} f^2 \text{ (MHz)}}{\sigma \text{ (mho/m)}}$$

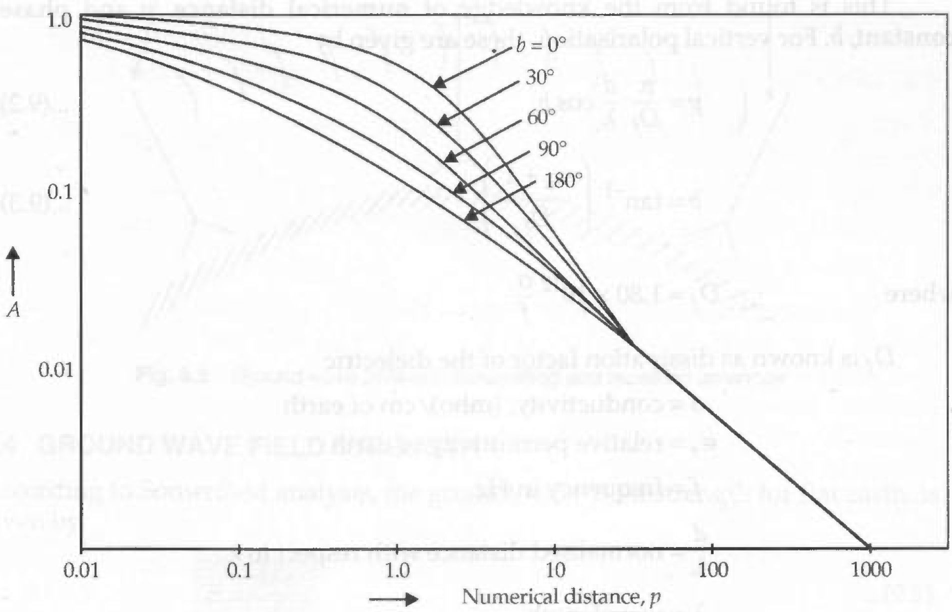


Fig. 9.4 *Variation of A with p and b*

and $$A \approx \frac{2+0.3p}{2+p+0.6p^2} \quad \text{for } b < 5^\circ$$

For all values of phase constant, b,

$$A = \frac{2+0.3p}{2+p+0.6p^2} - \sin b \sqrt{\frac{p}{2}}\, e^{-\left(\frac{5}{8}\right)p}$$

where p = numerical distance

However, for $b < 50^\circ$, $p < 4.5$, A is approximately given by $A = e^{-y}$

where $y = -0.43p + 0.01p^2$.

9.5 GROUND WAVE FIELD STRENGTH BY MAXWELL'S EQUATIONS

The field strength at a distance, d is given by

$$E = \frac{\eta_0 h_t I}{\lambda d} \text{ volts/m} \qquad \text{...(9.4)}$$

where h_t = effective height of transmitting antenna, m

η_0 = characteristics impedance of free space = $120\pi\Omega$

I = antenna current, A

d = distance from transmitter, m

λ = wavelength, m

When a receiving antenna of height, h_r is placed at a distance of d the **received signal** is given by

$$V = \frac{\eta_0 h_t h_r I}{\lambda d}, \text{ volts.} \qquad \text{...(9.5)}$$

9.6 REFLECTION OF RADIO WAVES BY THE SURFACE OF THE EARTH

If an EM wave is incident on the earth, it is reflected back. The angle of reflection is equal to the angle of incidence. The reflection coefficient is the ratio of the reflected wave to the incident wave. That is,

$$\rho = \frac{\text{Reflected wave}}{\text{Incident wave}}$$

The field strength near the earth is the vectorial sum of the incident and reflected fields.

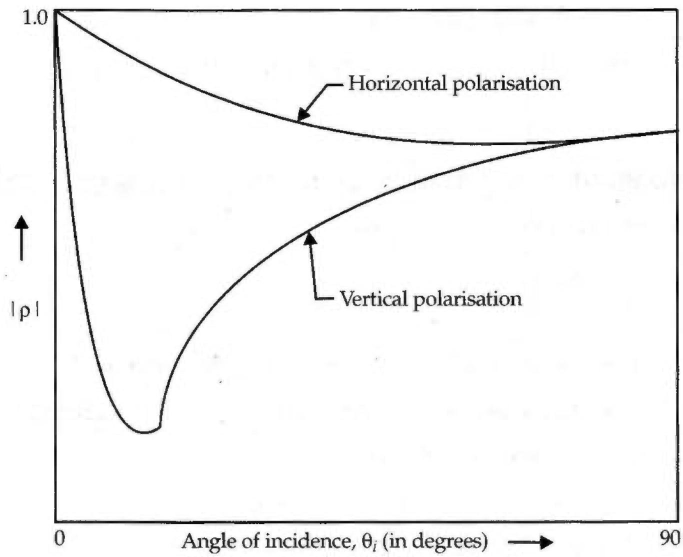
The **reflection coefficient**, ρ depends on

1. Dielectric constant, $\in_r$
2. Conductivity of the earth, σ
3. Frequency of the wave

4. Polarisation of the wave
5. Angle of incidence of the wave.

For perfect reflecting earth, $|\rho| = 1$ and for practical earth conditions, $|\rho| < 1$ and $\angle\rho \neq 0$.

Typical variations of magnitude of reflection coefficient and phase shift with the angle of incidence on the high conductivity earth at $f = 20$ MHz are shown in Fig. 9.5.



(a) Variation of ρ with θ_i

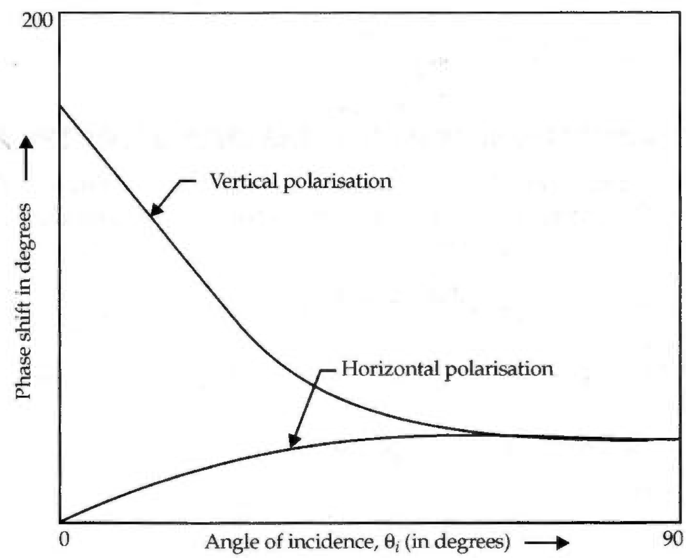


Fig. 9.5 *(b) Variation of $\angle\rho$ with θ_i*

It may be noted from Fig. 9.5, that for horizontally polarised waves, the reflection coefficient is the same as that of perfect earth for $\theta_i = 0$. That is, $\rho = 1 \angle 0$. When θ_i increases, $|\rho|$ reduces from 1 and the phase shift become small. The phase is found to be lagging with respect to that of perfect earth.

For vertically polarised wave, at $\theta_i = 0$, the reflection coefficient, ρ is $1 \angle 180^\circ$. At $\theta_i = 90^\circ$, the reflection coefficient for vertical and horizontally polarised waves are identical. The angle of incidence at which there is no reflection is known as **Brewster angle**.

$$\text{Brewester angle, } \theta_b = \theta_i = \tan^{-1}\sqrt{\frac{\epsilon_{r2}}{\epsilon_{r1}}}.$$

9.7 ROUGHNESS OF EARTH

Reflections of EM waves vary with the nature of the earth. Earth is classified as rough and smooth.

Roughness of earth According to the **Rayleigh criterion,** it is defined as:

$$R = \frac{4\pi\sigma_s \sin\theta_i}{\lambda} \qquad ...(9.6)$$

where σ_s = standard deviation of the surface irregularities relative to the mean surface height

θ_i = angle of incidence measured from earth's surface

λ = wavelength

If $R < 0.1$, the earth is considered **electrically smooth.**

If $R > 10$, it is said to be **electrically rough.**

9.8 REFLECTION FACTORS OF EARTH

Earth is neither a good conductor nor a good dielectric. It is a partially conducting dielectric medium and hence its dielectric constant can be considered to be complex. That is,

$$\epsilon' = \left(\epsilon + \frac{\sigma}{j\omega}\right)$$

Keeping this in mind, the reflection coefficient for horizontal polarisation is given by:

$$\rho_h = \frac{E_r}{E_i}$$

$$= \frac{\sin\theta_i - \sqrt{(\epsilon_r - jD_f) - \cos^2\theta_i}}{\sin\theta_i + \sqrt{(\epsilon_r - jD_f) - \cos^2\theta_i}} \qquad ...(9.7)$$

where $D_f = \dfrac{\sigma}{\omega\epsilon_0}$

θ_i = angle of incidence measured from earth's surface

For vertical polarisation,

$$\rho_v = \frac{(\epsilon_r - jD_f)\sin\theta_i - \sqrt{(\epsilon_r - jD_f) - \cos^2\theta_i}}{(\epsilon_r - jD_f)\sin\theta_i + \sqrt{(\epsilon_r - jD_f) - \cos^2\theta_i}} \quad \text{...(9.8)}$$

9.9 WAVE TILT OF THE GROUND WAVE

Wave tilt is defined as the change of orientation of the vertically polarised ground wave at the surface of the earth.

Salient features of wave tilt

1. Wave tilt occurs at the surface of the earth.
2. The tilt depends on conductivity and permittivity of the earth.
3. It causes power dissipation.
4. Due to tilt, there exists both horizontal and vertical components of the electric field.
5. These two components are not in phase.
6. The wave tilt changes the original vertically polarised wave into elliptically polarised wave.
7. The resultant typical electric field due to wave tilt is shown in Fig. 9.6.

Fig. 9.6 *Electric vector due to wave tilt*

8. The horizontal component of the electrical field, E_h is

$$E_h = J_s Z_s.$$

9. Vertical component of electric field, E_v is

$$E_v = H\eta_0$$

where Z_s = surface impedance of earth

$$= \sqrt{\frac{\omega\mu}{\sqrt{\sigma^2 + \omega^2 \epsilon^2}}} \angle \frac{1}{2}\tan^{-1}\frac{\sigma}{\omega\epsilon} \quad \text{...(9.9)}$$

σ = conductivity (mho/m)

$\in$ = permittivity (F/m)

μ = permeability of earth (H/m)

J_s = surface current density, (A/m)

η_0 = intrinsic impedance of free space (Ω).

10. The ratio of x and y components of E is given by

$$\frac{E_h}{E_v} = \frac{1}{377}\sqrt{\frac{\omega\mu}{\sqrt{\sigma^2+\omega^2\in^2}}}\;\angle\frac{1}{2}\tan^{-1} D_f \qquad \text{...(9.10)}$$

Example For a typical earth, with $\sigma = 5 \times 10^{-3}$ mho/m and $\in = 10\in_0$, $\mu = \mu_0$

$$\frac{E_h}{E_v} = 0.105 \angle 41.83^{\circ}$$

This means that the horizontal component of electric field is 10.5% of the vertical component and it leads E_y by 41.83°.

9.10 SPACE WAVE OR TROPOSPHERIC WAVE PROPAGATION

The EM wave that propagates from the transmitter to the receiver in the earth's **troposphere** is called **space wave** or **tropospheric wave**.

Troposphere is the region of the atmosphere within 16 km above the surface of the earth (Fig. 9.7).

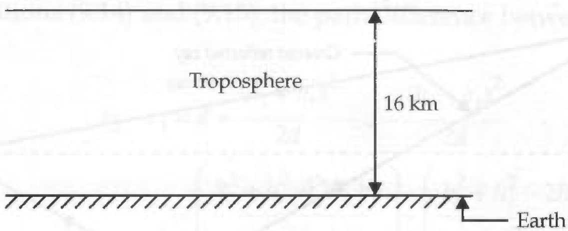


Fig. 9.7 *Troposphere*

In space wave propagation, the field strength at the receiver is contributed by

1. Direct ray from transmitter
2. Ground reflected ray
3. Reflected and refracted rays from the troposphere
4. Diffracted rays around the curvature of the earth, hills and so on.

However, the contribution of the first two rays is predominant.

Space wave propagation is useful at frequencies above 30 MHz. It is useful for FM, TV and radar applications. It is also used in VHF, UHF and higher frequency bands.

9.11 FIELD STRENGTH DUE TO SPACE WAVE

The **field strength** due to space wave,

$$E = \frac{2E_0}{d} \sin \frac{2\pi h_t h_r}{\lambda d} \qquad ...(9.11)$$

or

$$E \approx \frac{4\pi h_t h_r}{\lambda d^2} E_0 \qquad ...(9.12)$$

where E_0 = field strength due to direct ray at unit distance. This depends on directivity of transmitting antenna and transmitter power.

$E_0 = 137.6 \sqrt{P_{kW}}$ mV/m at one mile for half- wave transmitting antenna.

h_t = height of the transmitting antenna

h_r = height of the receiving antenna

d = distance between the two antennas.

Proof Assume flat earth.

Let h_t be the height of the transmitting antenna,

h_r be the height of the receiving antenna and

d be the distance between the two antennas.

The field strength at the receiver is mostly contributed by direct and ground reflected rays. These two rays are shown in Fig. 9.8.

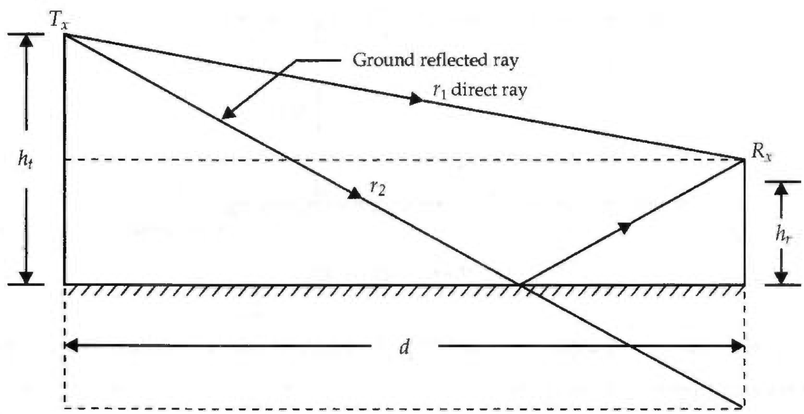


Fig. 9.8 *Direct and ground reflected rays in space wave*

From Fig. 9.8, we have

$$r_1^2 = (h_t - h_r)^2 + d^2$$

or

$$r_1 = d\left[1 + \left(\frac{h_t - h_r}{d}\right)^2\right]^{1/2} \qquad ...(9.13)$$

From Binomial series, we have

$$(1 \pm x)^{1/2} = 1 \pm \frac{1}{2}x - \frac{1}{2.4}x^2 + \ldots$$

If x is small, the higher order terms can be neglected. Then

$$(1 \pm x)^{1/2} \approx 1 \pm \frac{1}{2}x$$

Therefore Equation (9.13) can be written as

$$r_1 = d\left[1 + \frac{1}{2}\left(\frac{h_t - h_r}{d}\right)^2\right]$$

$$\approx \left[d + \frac{(h_t - h_r)^2}{2d}\right] \qquad \text{...(9.14)}$$

Similarly, $$r_2^2 = d^2 + (h_t + h_r)^2$$

or $$r_2^2 = d^2\left[1 + \frac{(h_t + h_r)^2}{d}\right]$$

So, $$r_2 \approx \left[d + \frac{(h_t + h_r)^2}{2d}\right] \qquad \text{...(9.15)}$$

From Equations (9.14) and (9.15), the path difference between the two ray is given by

$$r_2 - r_1 = d + \frac{(h_t + h_r)^2}{2d} - d - \frac{(h_t - h_r)^2}{2d}$$

$$= \left(\frac{h_t^2 + h_r^2 + 2h_t h_r}{2d}\right) - \left(\frac{h_t^2 + h_r^2 - 2h_t h_r}{2d}\right)$$

or $$r_2 - r_1 = \frac{4h_t h_r}{2d} = \frac{2h_t h_r}{d} \qquad \text{...(9.16)}$$

The phase difference due to path difference, α is

$$\alpha = \text{path difference} \times k$$

where $$k = \text{wave number} = 2\pi/\lambda$$

or $$\alpha = \frac{2h_t h_r}{d} \times \frac{2\pi}{\lambda}$$

Let E_d be the field due to direct ray and E_r be the field due to reflected ray. Then the resultant field E_R at the receiver is given by:

$$E_R = (E_d + E_r e^{-j\Psi}) \qquad \text{...(9.17)}$$

When a wave is incident on earth, it is reflected with the same amplitude but with phase reversal. Therefore, the total phase is

$$\psi = 180^\circ + \alpha$$

where α is phase difference due to path difference. Moreover,

$$E_d = E_r = E_s.$$

Now Equation (9.17) becomes

$$\begin{aligned} E_R &= E_s \{1 + e^{-j(180+\alpha)}\} \\ &= E_s [1 + \cos(180 + \alpha) - j \sin(180 + \alpha)] \\ &= E_s [1 - \cos\alpha + j \sin\alpha] \\ &= E_s \lfloor (1 - \cos\alpha)^2 + \sin^2\alpha \rfloor \\ &= E_s \lfloor \sqrt{2(1 - \cos\alpha)} \rfloor \\ &= E_s \sqrt{4 \sin^2 \frac{\alpha}{2}} \end{aligned}$$

$$E = 2E_s \sin\frac{\alpha}{2}$$

But $$E_s = \frac{E_0}{d}$$

So, $$E = \frac{2E_0}{d} \sin\frac{2\pi h_t h_r}{\lambda d} \qquad ...(9.18)$$

As $d >> h_t$ or h_r, Equation (9.18) becomes

$$E \approx \frac{4\pi h_t h_r}{\lambda d^2} E_0. \qquad ...(9.19)$$

9.12 CONSIDERATIONS IN SPACE WAVE PROPAGATION

The **space wave field strength** is affected by the following:

1. Curvature of the earth.
2. Earth's imperfections and roughness.
3. Hills, tall buildings and other obstacles.
4. Height above the earth.
5. Transition between ground and space wave.
6. Polarisation of the waves.

9.12.1 Effect of the Curvature of the Earth

The expression for space wave field strength, Equation (9.19) is derived assuming flat earth. However, when the distance between the transmitting and receiving antennas is considerably large, curvature of the earth has considerable effect on space wave propagation.

The main effects of earth's curvature are:

1. The field strength at the receiver becomes small as the direct ray may not be able to reach the receiving antenna (Fig. 9.9). The earth-reflected rays diverge after their incidence on the earth.

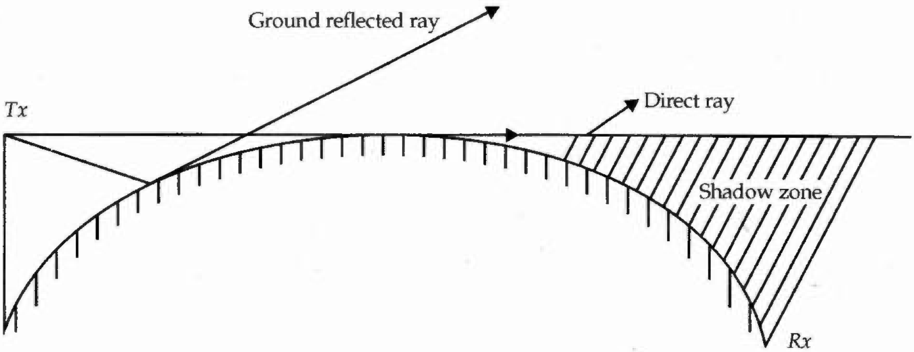


Fig. 9.9 *Effect of earth's curvature*

2. The curvature of the earth creates **shadow zones**. These are the regions where no signal reaches. Shadow zones are also called **diffraction zones**.
3. It reduces the possible distance of transmission.
4. The field strength that is available at the receiver becomes small.

When earth's curvature is considered, **the field strength at the receiver** becomes

$$E = \frac{2E_0}{d} \sin \frac{2\pi h'_t h'_r}{\lambda d} \qquad ...(9.20)$$

where h'_t and h'_r are the effective heights of transmitting and receiving antennas (Fig. 9.10). Here, effective height is the height of the antenna from the supposed flat earth.

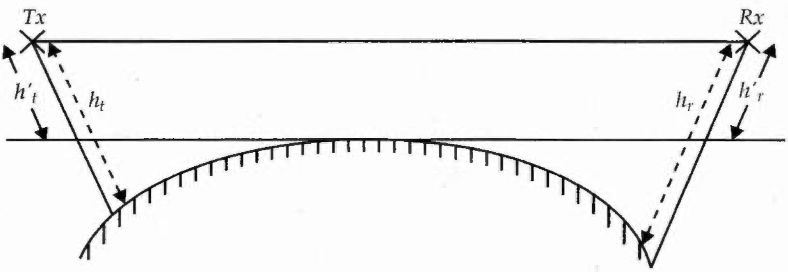


Fig. 9.10 *Effective and actual heights of antennas*

9.12.2 Effect of Earth's Imperfections and Roughness

Salient features

1. Earth is basically imperfect and electrically rough.

2. For perfect earth, reflection coefficient is unity. But actual earth makes it different from unity.
3. When a wave is reflected from perfect earth, its phase change is 180°. But actual earth makes the phase change different from 180°.
4. The amplitude of ground-reflected ray is smaller than that of direct ray.
5. The expression for the field is usually derived on the assumption of no change in amplitude and with a phase reversal after reflection.
6. Finally, the field at the receiving point due to space is reduced by earth's imperfection and roughness.

9.12.3 Effects of Hills, Buildings and Other Obstacles

Hills, buildings and other obstacles create shadow zones (Fig. 9.11). As a result, the possible distance of transmission is reduced.

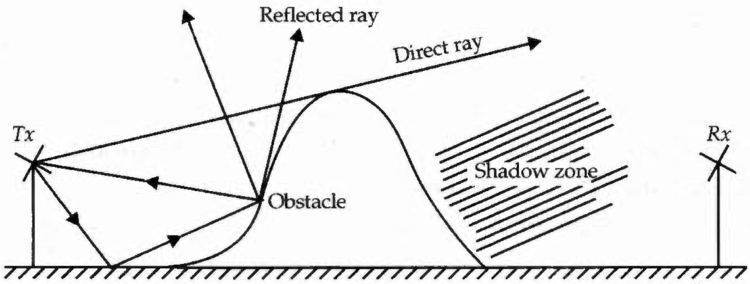


Fig. 9.11 *Effect of obstacles*

9.12.4 Effect of the Height Above the Earth

Salient features

1. The field varies with the height above the earth.
2. The field variation is characterised by the presence of maximas, minimas and nulls.

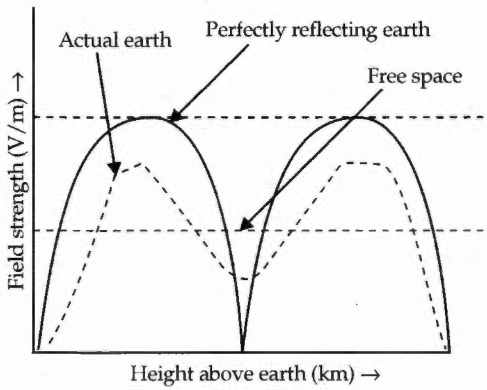


Fig. 9.12 *Typical variation of field strength with height*

3. The maximas and minimas depend on frequency, height of the transmitting antenna, ground characteristics and polarisation of the wave.
4. The variation of the field with height for perfect earth, actual earth and free space conditions is shown in Fig. 9.12.

9.12.5 Effect of Transition between Ground Wave and Space Wave

Salient features

1. When the transmitting antenna is close to earth, ground wave exists and the field strength is independent of the height of the antenna.
2. The antenna height has an effect on the field strength and direct and ground reflected rays predominate over the ground wave. Its effect depends on frequency, polarisation, and constants of the earth.
3. For vertically polarised wave, the ground wave does not dominate at heights of the order of λ or 2λ. That is, at higher heights of antennas, space wave dominates.
4. At heights $< \frac{\lambda}{10}$, transition between the ground wave and space wave takes place for horizontally polarised waves.

9.12.6 Effect of Polarisation

Salient features

1. For any angle of incidence other than $\theta_i = 0$ or 90°, the magnitude of the reflected wave will be less with vertical polarisation than with horizontal polarisation. This reduces the amplitude of the ground-reflected wave.
2. The height below which ground wave action is to be taken into account is much less with horizontal polarisation than with vertical polarisation. It is important at broadcast and lower frequencies.
3. The electromagnetic interference created by ignition systems, domestic and consumer electrical, electronic and communication equipment and so on is, in general, vertically polarised. Horizontal polarisation is useful for discrimination against these disturbances occurring in TV and FM broadcasting.

9.13 ATMOSPHERIC EFFECTS IN SPACE WAVE PROPAGATION

The atmosphere consists of gas molecules and water vapour. This causes the dielectric constant to be slightly greater than unity. The density of air and water vapour vary with height. As a result, the dielectric constant and hence refractive index of air depends on the height. Dielectric constant decreases with height. The variation of refractive index with height gives rise to different phenomena like refraction, reflection, scattering, duct propagation and fading.

By definition, the **refractive index**, n is the square root of the dielectric constant.

$$n \approx \sqrt{\epsilon_r}$$

In order to study some of the characteristics of the troposphere, a new term namely **modified refractive index**, M is introduced.

Modified refractive index (M) Modified refractive index in the troposphere is defined as the sum of the refractive indices at a given height above the mean geometrical surface and the ratio of the height to the mean geometrical radius. Mathematically, it is defined as

$$M = \left(n - 1 + \frac{h}{a}\right) \times 10^6 \qquad ...(9.21)$$

where n = refractive index

h = height above ground

a = radius of earth = 6.37×10^6 m

At high altitudes, ϵ_r or n is independent of height. Here, M increases by 0.048 units/ft. Near the earth, M increases linearly at a constant rate that is less than 0.048 units/ft.

For typical atmospheric conditions, $\frac{dM}{dh} = 0.036$ units/ft. This condition is called **standard atmosphere**.

The phenomenon of refraction in the troposphere due to change in refractive index is shown in Fig. 9.13.

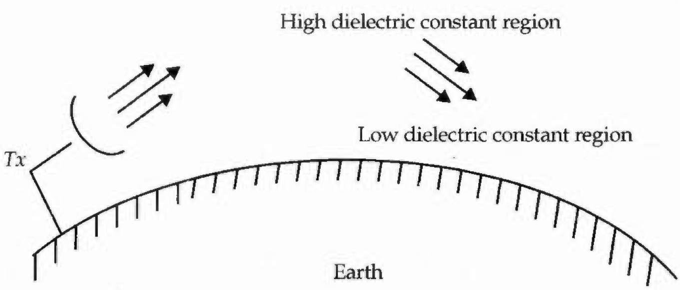


Fig. 9.13 *Refraction in troposphere*

The temperature inversion zone creates super refraction or duct phenomenon as shown in Fig. 9.14.

The EM rays bend away from one region to another region due to change in refractive index with height.

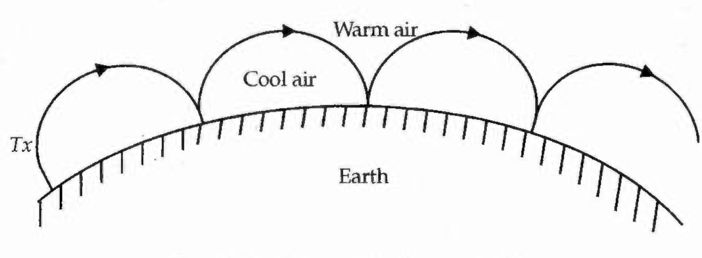


Fig. 9.14 *Super refraction or ducting*

In order to make a particular ray path like a straight line, the coordinates are changed. For this purpose, the **effective radius** of the earth is introduced in the following way.

$$K = \frac{\text{Effective radius of earth}}{\text{actual radius of earth}} = \frac{0.048}{dM/dh} \text{ for positive } \frac{dM}{dh} \qquad ...(9.22)$$

The **effective radius** of earth is also called **equivalent radius** of the earth.

Effective radius of the earth is defined as equivalent radius of the earth used to correct atmospheric refraction approximately, as refractive index of the atmosphere changes linearly with height.

For standard atmosphere, **effective radius of the earth** is equal to 4/3 times the actual radius of the earth. **Actual radius** of the earth is its **geometrical radius.**

When $\frac{dM}{dh} = 0.036$ units/ft for standard atmosphere, k becomes 4/3.

The equivalent radius of the earth becomes infinity for $\frac{dM}{dh} = 0$. Under these conditions, the ray path appears to be a straight line over a flat earth.

As radio waves exhibit curved ray paths, radio horizon differs from optical horizon.

9.14 DUCT PROPAGATION

Duct propagation is a phenomenon of propagation making use of the atmospheric duct region. The duct region exists between two levels where the variation of modified refractive index with height is minimum. It is also said to exist between a level, where the variation of modified refractive index with height is minimum, and a surface bounding the atmosphere.

In duct propagation, the ray which is parallel to the earth's surface travels round the earth in a series of hops with successive reflections from the earth. This is shown in Fig. 9.15.

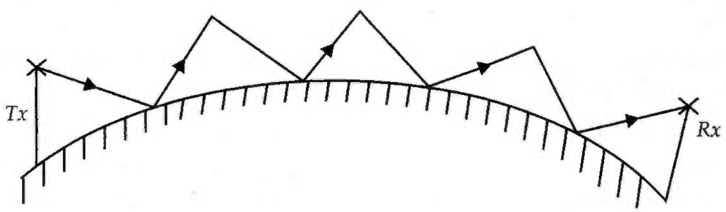


Fig. 9.15 *Duct propagation*

Salient features of duct propagation

1. It happens when $\frac{dM}{dh}$ is negative.

2. It happens when dielectric constant changes with height suddenly and rapidly.
3. It is a specific case of refraction of RF energy.
4. It takes place at VHF, UHF and microwave range and in areas contiguous to oceans.
5. It is similar to waveguide propagation of microwaves.
6. It is not a standard propagation.
7. It is a rare phenomenon.
8. It is not a dependable propagation.
9. It happens during monsoons.
10. Long distance communication is possible when duct phenomenon takes place.
11. The transmitting antenna should be within the duct. Otherwise, the signal, even if it is powerful, will not propagate.
12. It happens due to temperature inversion.
13. It occurs due to super refraction.
14. It takes place when low and high moisture regions exist.

9.15 RADIO HORIZON

Horizon means visible. It has another meaning, that is, a line at which earth and sky appear to meet.

> **Radio horizon of an antenna** is defined as the locus of the distant points at which direct rays from the antenna become tangential to a planetary surface. The horizon is a circle on a spherical surface.

The distance to the horizon is affected by the atmospheric refraction.

Salient features of radio horizon

1. Radio horizon is the range by which a direct ray from transmitting antenna reaches receiving antenna.
2. The earth's curvature exhibits a horizon to space-wave propagation. This is actually the radio horizon.
3. The radio horizon extends beyond optical horizon for standard atmosphere. This is due to bending or refraction of the radio wave.
4. Radio horizon is about 4/3 times the optical horizon.
5. The refraction of the wave takes place because of changes in density of troposphere, temperature, water-vapour content and relative conductivity.
6. The radio horizon can be increased by increasing antenna heights.

The radio horizon distance between transmitting and receiving antennas

$$\text{Radio horizon distance, } d_{\text{miles}} = \sqrt{2h_t\,(\text{feet})} + \sqrt{2h_r\,(\text{feet})}$$

$$\text{or radio horizon distance, } d_{\text{km}} = \sqrt{17h_t\,(\text{m})} + \sqrt{17h_r\,(\text{m})}$$

Proof We have

$$K = \frac{a'}{a} = \frac{\text{equivalent radius of earth}}{\text{actual radius}} = \frac{0.048}{dM/dh}$$

where K is called as **effective earth's radius factor.**

For standard atmosphere,

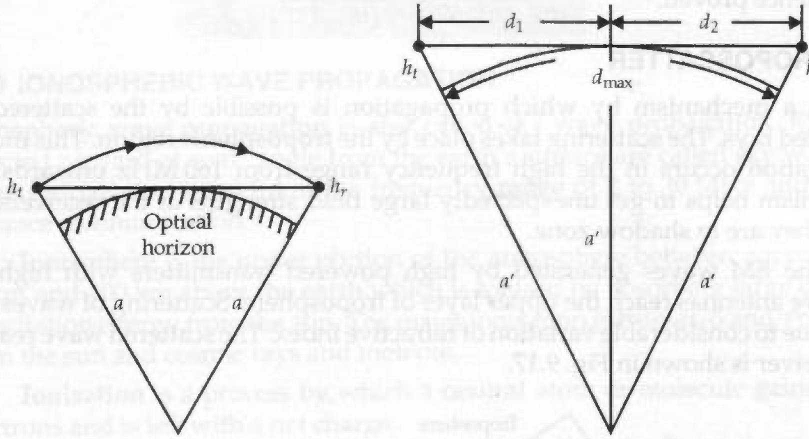
$$\frac{dM}{dh} = 0.036 \text{ units/ft}$$

$$\text{Equivalent radius, } a' = a \times \frac{0.048}{0.036}$$

$$a' = \frac{4}{3}a \qquad \text{...(9.23)}$$

Here a' is the equivalent radius of earth that accounts for refraction.

Consider Fig. 9.16.



(*a*) **Curvature of ray path as a result of refractive index of the air**

(*b*) **Equivalent straight line ray path for equivalent radius of earth, a'**

Fig. 9.16 *Equivalent radius of earth*

From Fig. 9.16 (*b*), we have

$$(a')^2 + d_1^2 = (a' + h_t)^2 \qquad \text{...(9.24)}$$

or

$$d_1^2 = a'^2 + h_t^2 + 2a'\,h_t - a'^2$$

$$d_1^2 = 2a'\,h_t + h_t^2$$

As $\quad a' >> h_t$

$$d_1^2 \approx 2a'\,h_t \qquad \text{...(9.25)}$$

Similarly, $\quad (a')^2 + d_2^2 = (a' + h_r)^2$

or

$$d_2^2 = 2a'\,h_r + h_r^2$$

As $\quad a' >> h_r,$

$$d_2^2 = 2a'\,h_r \qquad \text{...(9.26)}$$

The maximum distance of tropospheric propagation is

$$d_{max} = d_1 + d_2$$

$$d_{max} = \sqrt{2a' h_t} + \sqrt{2a' h_r} \quad ...(9.27)$$

As $$a' = \frac{4}{3} \times a, \quad a = 3{,}960 \text{ miles}$$

$$= \frac{4}{3} \times 3{,}960 \text{ miles}$$

$$d_{max} \text{ (miles)} = \sqrt{2h_t \text{ (feet)}} + \sqrt{2h_r \text{ (feet)}} \quad ...(9.28)$$

In metric units, $a = 6.37 \times 10^6$ m

$$d_{max} \text{ (km)} = \sqrt{17h_t \text{ (m)}} + \sqrt{17h_r \text{ (m)}} \quad ...(9.29)$$

Hence proved.

9.16 TROPOSCATTER

This is a mechanism by which propagation is possible by the scattered and diffracted rays. The scattering takes place by the **tropospheric region**. This mode of propagation occurs in the high frequency range from 160 MHz onwards. This mechanism helps to get unexpectedly large field strengths at the receivers even when they are in shadow zone.

The EM waves generated by high powered transmitters with high gain directive antennas reach the upper layer of troposphere. Scattering of waves takes place due to considerable variation of refractive index. The scattered wave reaching the receiver is shown in Fig. 9.17.

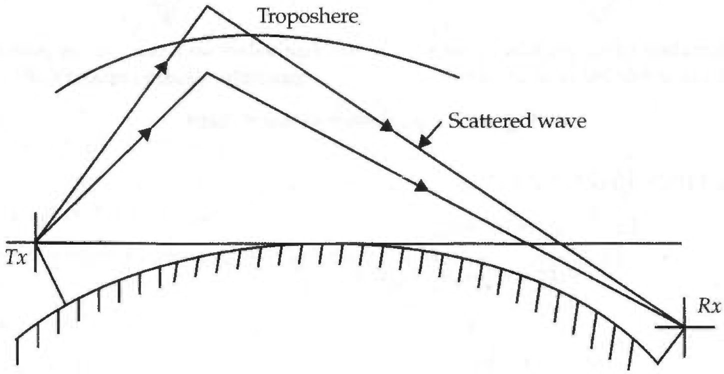


Fig. 9.17 *Troposcatter*

9.17 FADING OF EM WAVES IN TROPOSPHERE

Fading is a loss of signal due to change in electrical characteristics of troposphere. It is mainly due to the following:

1. Variation of dielectric constant.

2. Presence of eddies.
3. Uneven variations of refractive index.
4. Variation of effective earth radius factor, K.

9.18 LINE OF SIGHT (LOS)

It is defined as the distance that is covered by a direct space wave from the transmitting antenna to the receiving antenna.

It depends on:

1. Height of the receiving antenna.
2. Height of the transmitting antenna.
3. Effective earth's radius factor, K.

For standard atmosphere, $K = 4/3$.

The **line of sight distance,** d_{LOS} is given by

$$d_{LOS} = \sqrt{17h_t \text{ (m)}} + \sqrt{17h_r \text{ (m)}} \text{ km.} \qquad ...(9.30)$$

9.19 IONOSPHERIC WAVE PROPAGATION

Ionospheric wave propagation is also called sky wave propagation. EM waves directed upward at some angle from the earth's surface are called sky waves. Sky wave propagation is useful in the frequency range of 2 to 30 MHz and for long distance communication.

Ionosphere is the upper portion of the atmosphere between approximately 60 km and 400 km above the earth which is ionised by absorbing large quantities of radiation energy from the sun. The major ionisation is from α, β and γ radiations from the sun and cosmic rays and meteors.

Ionisation is a process by which a neutral atom or molecule gains or loses electrons and is left with a net charge.

9.20 CHARACTERISTICS OF IONOSPHERE

The physical properties of the ionosphere vary from time to time as the temperature, ionisation density and composition change regularly. As a result, ionosphere tends to be stratified and it does not have regular and constant distribution.

Ionosphere is divided meteorologically into different regions or layers and each layer exhibits different characteristics.

The layers of the ionosphere are:

1. D-Layer
2. E-Layer
3. E_s-Layer
4. F_1-Layer
5. F_2-Layer.

1. **Characteristics of D-Layer**

(*a*) It is the lowest layer of the ionosphere.
(*b*) It exists at an average height of 70 km.
(*c*) Its thickness is 10 km.

(*d*) It exists only in day-time.
(*e*) Its ionisation properties depend on the altitude of the sun above the horizon.
(*f*) It is not a useful layer for HF communication.
(*g*) It reflects some VLF and LF waves.
(*h*) It absorbs MF and HF waves to some extent.
(*i*) Its electron density, $N = 400$ electrons/cc.
(*j*) Its virtual height is 60 to 80 km.
(*k*) Critical frequency of the layer, $f_c = 180$ kHz.

2. **Characteristics of *E*-Layer**

(*a*) It exists next to *D*-Layer.
(*b*) It exists at an average height of 100 km.
(*c*) Its thickness is about 25 km.
(*d*) It exists only in day-time.
(*e*) The ions are recombined into molecules due to the absence of sun at night.
(*f*) It reflects some HF waves in day-time.
(*g*) It disappears at nights.
(*h*) Its electron density, $N = 5 \times 10^5$ electrons/cc.
(*i*) Its virtual height, $h_v = 110$ km.
(*j*) Its critical frequency, $f_c \approx 4$ MHz.
(*k*) Maximum single-hop range $\approx$ 2350 km.

3. **Characteristics of E_s-Layer**

(*a*) It is a sporadic *E*-Layer.
(*b*) Its appearance is sporadic in nature.
(*c*) If at all it appears, it exists in both day and night.
(*d*) It is a thin layer.
(*e*) Its ionisation density is high.
(*f*) It appears close to *E*-Layer.
(*g*) If it appears, it provides good reception.
(*h*) It is not a dependable layer for communication.

4. **Characteristics of F_1-Layer**

(*a*) It exists at a height of about 180 km in day-time.
(*b*) Its thickness is about 20 km.
(*c*) It combines with F_2-Layer during nights.
(*d*) HF waves are reflected to some extent.
(*e*) It absorbs HF to a considerable extent.
(*f*) It passes on some HF waves towards F_2-layer.
(*g*) Its virtual height, $h_v \approx 180$ km.
(*h*) Its critical frequency, $f_c \approx 5$ MHz.
(*i*) Maximum single-hop range $\approx$ 3,000 km.

5. **Characteristics of F_2-Layer**

(*a*) It is the most import layer for HF communication.
(*b*) Its average height is about 325 km in day-time.
(*c*) Its thickness is about 200 km.
(*d*) It falls to a height of 300 km at nights as it combines with the F_1-Layer.
(*e*) The height of F_2-Layer varies drastically with the time of the day, the average ambient temperature and sunspot cycle.
(*f*) It exists at nights also.
(*g*) It is the topmost layer of the ionosphere.
(*h*) It is highly ionised.
(*i*) It offers better HF reflection and hence reception.
(*j*) Electron density of F-Layer, $N = 2 \times 10^6$ electrons/cc.
(*k*) Its virtual height, $h_v = 300$ km in day-time and 350 km in night.
(*l*) Its critical frequency, $f_c \approx 8$ MHz in day-time and $f_c \approx 6$ MHz at nights.
(*m*) Maximum single-hop range $\approx 3{,}800$ km during day-time and 4,100 km at night.

The heights of the ionospheric layers and their electron densities are shown in Table 9.1.

Table 9.1 Ionospheric layer heights and their electron densities

Layer	*Approximate height above earth*	*Electron density (electrons/cc)*	*Day*	*Night*
D	70 km	400	Exists	Absent
E	100 km	5×10^5	Exists	Absent
F_1	180 km	—	Exists	Merges with F_2
F_2	325 km	—	Exists	Exists
F	300 km	2×10^6	Exists	Exists

9.21 REFRACTIVE INDEX OF IONOSPHERE

Refractive index of the ionosphere is defined as the ratio of phase velocity of a wave in vacuum to the velocity in the ionosphere. That is, **refractive index** of ionosphere,

$$n \equiv \frac{v_0}{v_p} = \frac{\dfrac{1}{\sqrt{\mu_0 \epsilon_0}}}{\dfrac{1}{\sqrt{\mu_0 \epsilon}}}$$

$$= \frac{\dfrac{1}{\sqrt{\mu_0 \epsilon_0}}}{\dfrac{1}{\sqrt{\mu_0 \epsilon_0 \epsilon_r}}} \equiv \sqrt{\epsilon_r}$$

When an EM wave enters an ionised region at vertical incidence as in Fig. 9.18, the electric field exerts a force on the charged particles namely electrons and ions. The charges are displaced by this force and hence current flows. Magnitude of the charge of a positive ion is the same as that of an electron but its mass is 100 times that of an electron. Due to its high mass, velocity of the ion is very small and its current contribution is negligible.

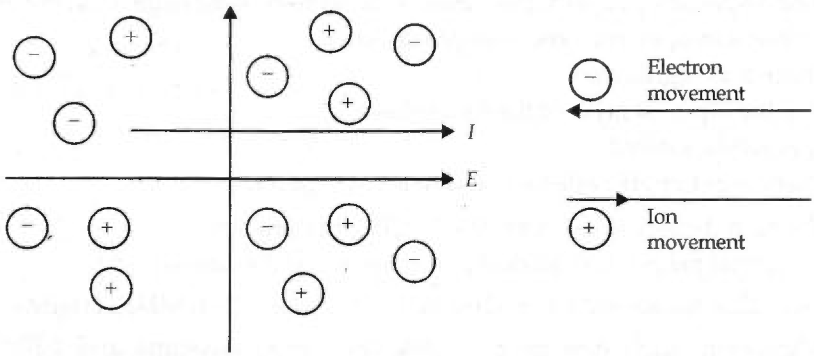


Fig. 9.18 *Effect of electric field of EM wave on the charged particles in the ionosphere*

In the presence of an electric field, electron cloud oscillates but with a phase retardation of 90°. This motion of the electron cloud produces a space current. Moreover, electric field has its own capacitive displacement current which leads the field by 90°. It is, therefore, obvious that the space and displacement currents are out of phase. This is found to reduce the relative permittivity of the ionosphere and it is given by

$$\epsilon_r = 1 - \frac{NQ_e^2}{\epsilon_0 m\omega^2} \qquad ...(9.31)$$

Here, ϵ_r = relative permittivity of ionosphere

N = electron density (m^{-3})

m = mass of electron at rest = 9.11×10^{-31} kg

$\omega = 2\pi f$ = angular frequency of the wave

Q_e = magnitude of electron charge = 1.6×10^{-19} C

At $\omega = \omega_p$, $$\epsilon_r = 1 - \frac{NQ_e^2}{\epsilon_0 m\omega_p^2} = 0$$

or $$\omega_p^2 = \frac{NQ_e^2}{\epsilon_0 m}$$

$$f_p^2 = \frac{NQ_e^2}{(2\pi)^2 \epsilon_0 m} \qquad ...(9.32)$$

Substituting the following values:

$$Q_e = 1.6 \times 10^{-19}\text{ C}$$

$$m = 9.11 \times 10^{-31}\text{ kg}$$

$$\epsilon_0 = 8.854 \times 10^{-12}\text{ F/m}$$

$$f_p = 9\sqrt{N} \qquad \text{...(9.33)}$$

The Equation (9.32) for ϵ_r becomes

$$\epsilon_r = 1 - \frac{f_p^2}{f^2} \qquad \text{...(9.34)}$$

As the refractive index, n by definition is equal to $\sqrt{\epsilon_r}$,

$$n = \epsilon_r = \sqrt{1 - \frac{f_p^2}{f^2}} \qquad \text{...(9.35)}$$

Here, f_p is the plasma frequency at which $\epsilon_r = 0$.

Plasma frequency is defined as the natural frequency of oscillation of charged particles in plasma region. It is given by $f_p = \frac{1}{2\pi}\sqrt{\frac{NQ_e^2}{\varepsilon_0 m}}$

Plasma is a completely ionised gas at very high temperature consisting of the charged nuclei and negative electrons.

The highest frequency of the wave that is reflected back from ionospheric layer is determined by the maximum electron density of that layer. This is called critical frequency of the wave and it is given by

$$\text{Critical frequency, } f_c = 9\sqrt{N_{max}} \qquad \text{...(9.36)}$$

where N_{max} = maximum electron density of the layer.

9.22 PHASE AND GROUP VELOCITIES

Phase velocity, v_p It is defined as the rate at which the EM wave changes phase. It is also defined as the velocity of an equiphase surface along the wave normal of a travelling wave. The wave normal of a travelling wave is the direction normal to an equiphase surface taken in the direction of increasing phase.

$$v_p = \frac{1}{\sqrt{\mu \epsilon}}$$

For the ionosphere, $\mu \approx \mu_0$.

Then $$v_p = \frac{1}{\sqrt{\mu_0 \epsilon_0 \epsilon_r}}$$

or $$v_p = \frac{v_0}{\sqrt{\epsilon_r}} \qquad \text{...(9.37)}$$

where v_0 = free space velocity

Phase velocity is also defined as

$$v_p \equiv \frac{\text{free space velocity}}{\text{refractive index}}$$

So, $$v_p = \frac{v_0}{n}$$

When a wave reaches a height where $\epsilon_r = 0$, phase velocity becomes infinite. The charge in a wave travels at the group velocity, v_g and it is given by

$$v_0^2 = v_p\, v_g \qquad \text{...(9.38)}$$

It is obvious that when $v_p = \infty$, v_g becomes zero. This means that the energy ceases to propagate upwards.

Group velocity, v_g The group velocity of a wave is defined as the velocity of propagation of the envelope. The magnitude of the group velocity is the reciprocal of the rate of change of phase constant with angular frequency. This definition is valid if the envelope moves without considerable change of its shape.

If the phase velocity varies with frequency the magnitudes of group and phase velocities are different.

The group and phase velocities have different directions if the phase velocity varies with direction.

9.23 MECHANISM OF IONOSPHERIC PROPAGATION—REFLECTION AND REFRACTION

Ionospheric propagation involves the reflection of the wave by the ionosphere. In actual mechanism, refraction takes place as shown in Fig. 9.19.

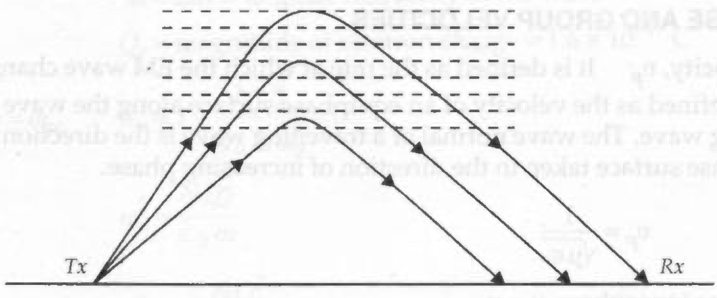


Fig. 9.19 *Ionospheric wave propagation and ray paths*

As ionisation density increases at an angle for the incoming wave, the refractive index of the layer decreases and the dielectric constant also decreases. Hence, the incident wave is gradually bent away from the normal.

If the rate of change of refractive index per unit height in terms of wavelength is sufficient, the refracted ray finally becomes parallel to the layer. Then it bends downwards and returns from the ionised layer at an angle equal to the angle of incidence. Although, some absorption takes place depending on the frequency, the wave is returned by the ionosphere to the receiver on earth. As a result, ionospheric propagation takes place through reflection and refraction of EM waves in the ionospheric layers.

The bending of a wave produced by the ionosphere follows optical laws. The direction of propagating wave at a point in the ionosphere is given by **Snell's law**. That is,

$$n = \frac{\sin \theta_i}{\sin \theta_r}$$

where θ_i = angle of incidence at lower edge of ionosphere

θ_r = angle of refraction at point P (Fig. 9.20).

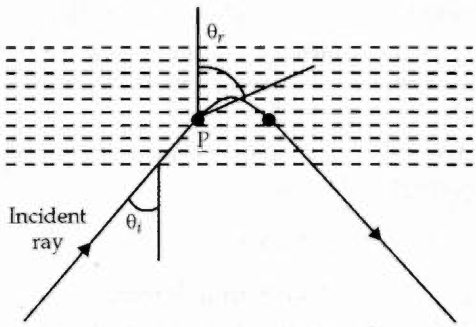


Fig. 9.20 *Refraction of EM wave in ionosphere*

9.24 CHARACTERISTIC PARAMETERS OF IONOSPHERIC PROPAGATION

Generally, propagation characteristics of the layers are described in terms of the following parameters:

1. Virtual height, h_v
2. Critical frequency, f_c
3. Maximum Usable Frequency, MUF
4. Skip distance
5. Lowest Usable Frequency, LUF
6. Critical angle, θ_c
7. Optimum working frequency, OWF or frequency of optimum traffic (FOT).

1. **Virtual height, h_v** It is defined as the height that is reached by a short pulse of energy which has the same time delay as the original wave. Virtual height of the layer is always greater than the actual height. (Fig. 9.21).

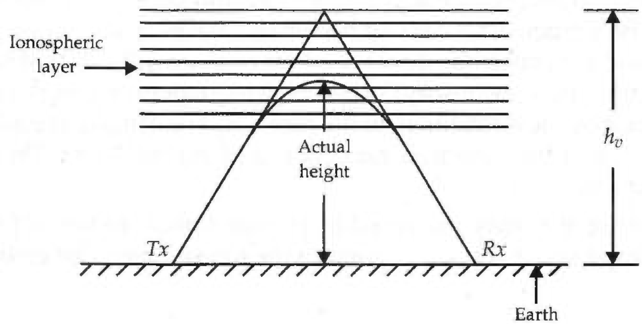


Fig. 9.21 *Actual and virtual heights of ionospheric layer*

Virtual height of the layer is useful to find the angle of incidence required for the wave to return to earth at a specified point.

2. **Critical frequency, f_c** f_c for a given layer is defined as the highest frequency that will be reflected to earth by that layer at vertical incidence.

   It is also defined as the limiting frequency below which a wave is reflected and above which it penetrates through an ionospheric layer, when the waves are incident on the layer normally.

   Frequencies above the critical frequencies will penetrate through the layer. The critical frequency, f_c is given by,

$$f_c = 9\sqrt{N}$$

   Here N = electron density

   It may be noted that f_c is not fixed but depends on electron density. It also differs from time to time during the day.

3. **Maximum usable frequency, MUF** It is the highest frequency of wave that is reflected by the layer at an angle of incidence other than normal. MUF depends on time of day, distance, direction, season and solar activity.

   MUF is the highest frequency that can be used for sky-wave communication between transmitter and receiver. The common values of MUF range between 8 to 30 MHz. However, it may even be 50 MHz at times. The ray paths corresponding to critical and maximum usable frequencies are shown in Figs. 9.22 and 9.23.

   From Fig. 9.23, we have,

$$\cos\theta_i = \frac{f_c}{\text{MUF}}$$

or

$$\text{MUF} = \frac{f_c}{\cos\theta_i} = f_c \sec\theta_i \qquad ...(9.39)$$

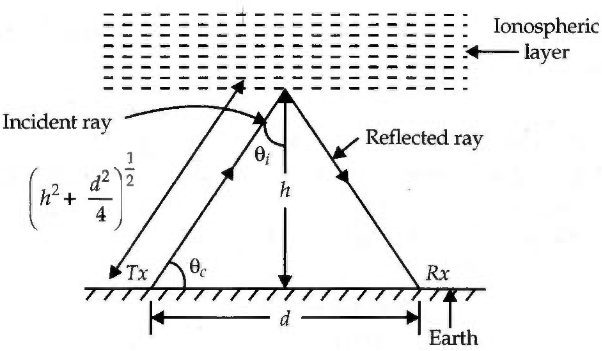


Fig. 9.22 *Ray geometry to find MUF*

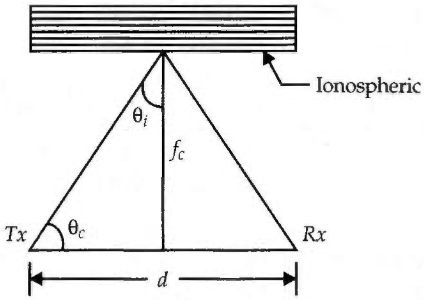


Fig. 9.23 *Ray paths of MUF and f_c*

where θ_i = angle of incidence between the incident ray and normal

θ_c = critical angle

Equation (9.39) represents the **secant law**. Secant law is useful to find MUF. In fact, it is applicable for flat earth and ionospheric layer. From Fig. 9.22, we have

$$\text{MUF} = \frac{f_c}{\sin \theta_c} \quad \text{...(9.40)}$$

But
$$\sin \theta_c = \frac{h}{\left(h^2 + \frac{d^2}{4}\right)^{1/2}} \quad \text{...(9.41)}$$

where h = height of the layer

d = distance between transmitting and receiving antennas.

From Equations (9.40) and (9.41), we have

$$\text{MUF} = f_c \left(\frac{d^2}{4h^2} + 1\right)^{1/2} \quad \text{...(9.42)}$$

4. **Skip distance (d_s)** It is defined as the shortest distance from the transmitter that is covered by a fixed frequency ($> f_c$).

When the angle of incidence is large, ray 1 (Fig. 9.24) returns to ground at a long distance from the transmitter. If the angle is reduced, ray 2 returns to a point closer to the transmitter. So there is always a possibility that short distances may not be covered by sky-wave propagation under certain conditions. Skip distance is shown in Fig. 9.24.

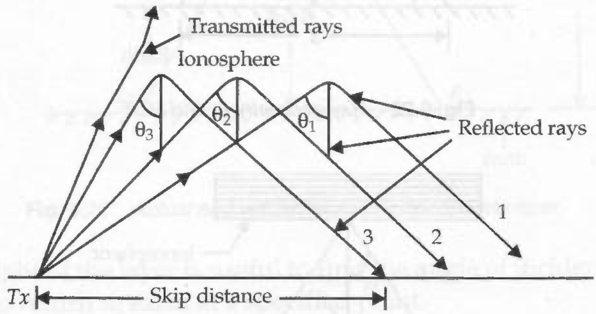


Fig. 9.24 *Skip distance*

If the operating frequency is low, it is possible to receive the ray by two different paths after one or two hops (Fig. 9.25).

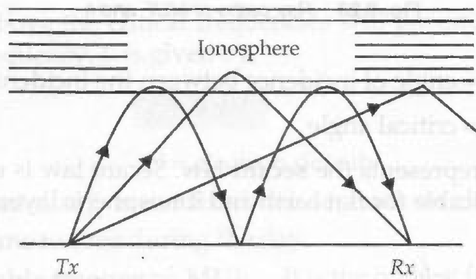


Fig. 9.25 *Multi path sky-wave propagation*

The transmission path is limited by the skip distance and curvature of the earth. The longest single-hop distance is achieved when the transmitted ray is tangential to the surface of the earth.

The skip distance, d_s is found from

$$d_s = \frac{2h}{\tan \theta_c}$$

where h = height of the layer

θ_c = critical angle

When the operating frequency, $f = f_{\text{MUF}}$, the skip distance is expressed in terms of f_{MUF}, f_c and the height of the layer and it is given by

$$d_s = 2h\left[\left(\frac{f_{\text{MUF}}}{f_c}\right)^2 - 1\right]^{1/2}.$$

5. **Lowest usable frequency, LUF** At certain low frequencies, the combination of ionospheric absorption, atmospheric noise, miscellaneous static and receiver $\frac{S}{N}$ requirements conspire to reduce radio communications. The lowest frequency that can be used for communication is called LUF.
6. **Critical angle, θ_c** Critical angle, θ_c is defined as the angle of incidence of a wave at which the wave will not be reflected when $\theta > \theta_c$ and it will be reflected when $\theta < \theta_c$. It depends on the thickness of layer, height and frequency of the wave.

   The concept of critical angle is illustrated in Fig. 9.26. When $\theta > \theta_c$, the wave is not reflected and when $\theta < \theta_c$, it is reflected.

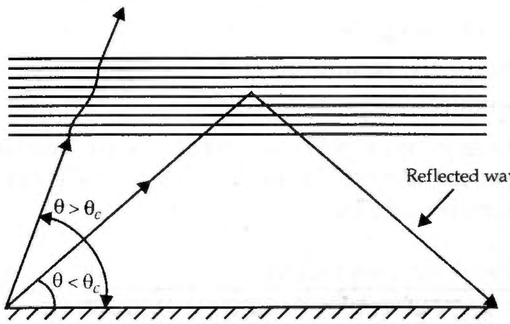


Fig. 9.26 *Effect of critical angle*

7. **Optimum working frequency (OWF) or frequency of optimum traffic (FOT)** The frequency of wave which is normally used for ionospheric communication is known as **optimum working frequency**.

   It is generally chosen to be about 15% less than the MUF. It is always desirable to use as high a frequency as possible since the attenuation is inversely proportional to the square of the frequency.

9.25 SKY WAVE FIELD STRENGTH

The sky wave field strength is reduced with distance because of the following facts:

1. Due to spreading of rays during propagation.
2. Due to collisions of vibrating electrons in ionised regions.
3. The signal strength is inversely proportional to distance.
4. Sky wave absorption increases with increase in distance between the transmitter and receiver.
5. At high frequencies, there is loss of energy due to collisions at the top of the D-layer. Here the product of collisional frequency and electron density is a

maximum. This type of loss is called non-deviative absorption when the ray is moving through the absorbing regions.

6. The attenuation constant due to absorption is given by

$$\alpha = K\left(\frac{f_E}{f}\right)^2 \text{ dB/m} \qquad \text{...(9.44)}$$

f_E = critical frequency of E-Layer

f = frequency of EM wave

K = constant which is a function of collisional frequency.

9.26 FADING AND DIVERSITY TECHNIQUES

Fading is the change in signal strength at the receiver. Most of the receivers are designed with an automatic volume control (AVC) circuit which reduces the effect of fading if the change in signal strength is small. Fading up to 20 dB is common.

The main causes of fading are:

1. Variation in ionospheric conditions and
2. Multi path reception.

As the ionosphere is not stable and electron density changes, signal path length changes and hence there will be a change in phase. This causes the received field strength to change. (Fig. 9.27).

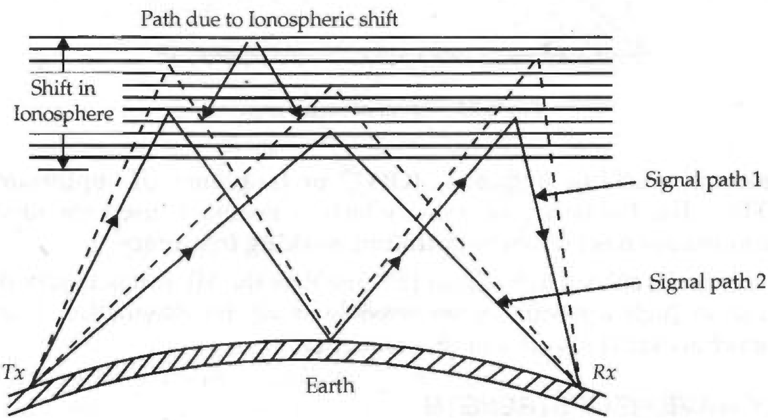


Fig. 9.27 *Fading*

Fading is classified in terms of the duration of the variation in signal strength. They are:

1. **Rapid fluctuations** These are due to multi-path interference and they occur for a few seconds.
2. **Short-term fluctuations** These are due to variation in the characteristics of the propagating medium and they occur for a few hours.

3. **Long-term fluctuations** These are due to seasonal variations in the propagation medium and they occur for a few days.

Fade out (total fading) occurs during sudden ionospheric disturbances, ionospheric storms, sun spot cycle and so on.

Types of fading are:

1. Selective fading
2. Interference fading
3. Absorption fading
4. Polarisation fading
5. Skip fading

The features of these fadings are given below :

1. **Selective fading:**

(*a*) It produces serious distortion of modulated signal.

(*b*) It is more prominent at high frequencies at which sky-wave propagation is used.

(*c*) It is large with AM signals at high percentage of modulation.

(*d*) AM signals are more distorted by selective fading than SSB signals.

(*e*) Selective fading can be reduced by the use of SSB system.

2. **Interference fading:**

(*a*) It is produced by the interference between rays.

(*b*) It is also produced by the interference between waves reaching the receiver by different paths.

(*c*) It is also produced by the interference between a ground wave and sky wave.

(*d*) It occurs due to fluctuations of layer height at a fixed frequency.

(*e*) As the path length of the wave varies, the relative phase of waves reaching the receiver also varies.

(*f*) Interference fading can be minimised by different diversity techniques.

3. **Absorption fading** This takes place due to absorption of waves by the ionosphere.

4. **Polarisation fading:**

(*a*) This takes place due to change of polarisation of EM wave.

(*b*) This is caused by cross-polarised waves.

(*c*) When polarisation changes, the signal amplitude changes in the receiver.

(*d*) This type of fading is reduced by polarisation diversity.

5. **Skip fading:**

(*a*) This occurs near the skip distance.

(*b*) The variation of height of density of the layer causes skip fading.

(*c*) This is minimised by AVC and AGC in the receiver.

It is difficult to control short and long term fluctuations. But the fading due to rapid fluctuations can be reduced by different diversity techniques.

The diversity techniques are:

1. Frequency diversity
2. Space diversity
3. Polarity diversity
4. Time diversity

1. **Frequency diversity** In this, the transmitter will send two or more frequencies simultaneously with the same modulating information. As the different frequencies will fade differently, one will always be strong. This scheme is shown in Fig. 9.28.

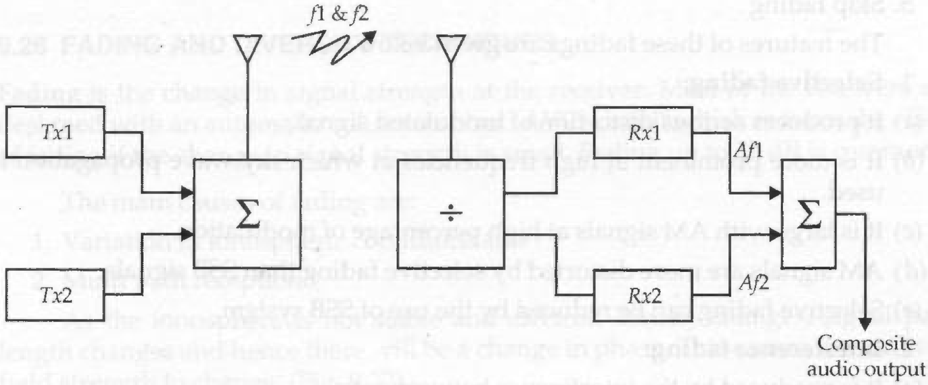


Fig. 9.28 *Frequency diversity to reduce fading*

2. **Space diversity technique** A single transmitter frequency is used. At the receiving site, two or more receiving antennas spaced at one-half wavelength apart are used. The signal will fade at one antenna while it increases at the

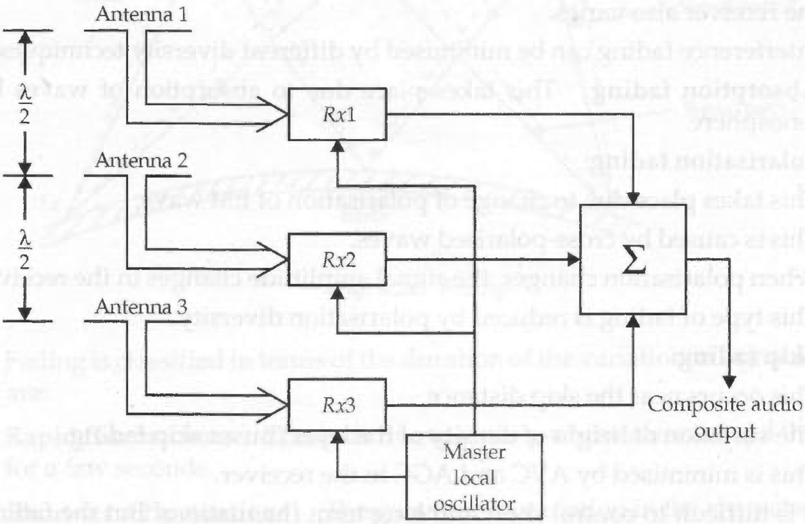


Fig. 9.29 *Space diversity*

other antenna. A three antenna system may be used. Three separate but identical receivers tuned by the same master local oscillator are connected to three antennas. Audio mixing on the basis of the strongest signal keeps the audio output constant while RF signal fades. This scheme is shown in Fig. 9.29.

3. **Polarity diversity system** In this, vertical and horizontal polarisation antennas are used to receive the signal. As in the case of space diversity system, the two receivers are combined to produce constant output. This scheme is shown in Fig. 9.30.

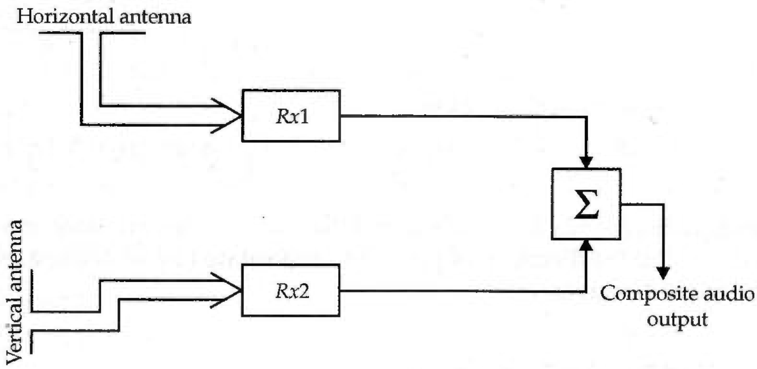


Fig. 9.30 *Polarity diversity*

4. **Time diversity** In this, the same signals are transmitted at different times. As fading is time-dependent, some signals may be strong and fading is less.

9.27 FARADAY ROTATION

Rotation of the plane of polarisation is defined as **Faraday rotation**. It is also defined as the process of rotation of polarisation ellipse of EM wave in a magneto-ionic medium. This process occurs in the ionospheric regions when a plane wave enters the ionosphere.

It is a variable effect and leads to loss of signal power at the receiving antenna due to polarisation mismatch.

A linearly polarised EM wave can be regarded as the vector sum of two counter-rotating circularly polarised waves. If such a wave propagates in the direction of the magnetic field in a loss-less plasma region, the two circularly polarised components travel with different phase velocities and hence the plane of polarisation rotates with distance.

On an ionospheric layer of L meters, let the incident plane wave along z-direction be represented by

$$E = 2E_0\, e^{-j\beta z} \qquad ...(9.45)$$

Decomposing this into left and right circularly polarised waves, Equation (9.45) can be written as

$$E = E_0\,(\mathbf{a}_x + j\,\mathbf{a}_y)\, e^{-j\beta z} + E_0\,(\mathbf{a}_x - j\,\mathbf{a}_y)\, e^{-j\beta z} \qquad ...(9.46)$$

This wave enters the ionospheric layer at $z = 0$ and travels as two circularly polarised waves with different propagation constants. Neglecting reflections at each interface, the electric field at the exit plane is given by

$$E = E_0 (\mathbf{a}_x - j\,\mathbf{a}_y)\, e^{-j\beta_1 L} + E_0 (\mathbf{a}_x + j\,\mathbf{a}_y)\, e^{-j\beta_2 L}$$

$$= E_0\, e^{-j(\beta_1+\beta_2)\frac{L}{2}} \left[\mathbf{a}_x \left(e^{j(\beta_2-\beta_1)\frac{L}{2}} + e^{-j(\beta_2-\beta_1)\frac{L}{2}} \right) - j\,\mathbf{a}_y \left(e^{j(\beta_2-\beta_1)\frac{L}{2}} - e^{-j(\beta_2-\beta_1)\frac{L}{2}} \right) \right]$$

$$= 2E_0\, e^{-j(\beta_1+\beta_2)\frac{L}{2}} \left[\mathbf{a}_x \cos(\beta_2 - \beta_1)\frac{L}{2} + \mathbf{a}_y \sin(\beta_2 - \beta_1)\frac{L}{2} \right] \qquad ...(9.47)$$

From Equation (9.47), it is evident that the wave at the exit plane is a linearly polarised wave. But the direction of polarisation is rotated by an angle ϕ relative to x- axis. The angle ϕ is given by

$$\tan \phi = \frac{E_y}{E_x} = \tan(\beta_2 - \beta_1)\frac{L}{2}$$

or

$$\phi = (\beta_2 - \beta_1)\frac{L}{2} \qquad ...(9.48)$$

Faraday rotation is most pronounced when f is close to f_c. Here, f_c is called cyclotron frequency and it is given by

$$f_c = -\frac{Q_e B}{2\pi m} \qquad ...(9.49)$$

where Q_e = electron charge

m = mass of the electron

B = earth's magnetic flux density = 5×10^{-5} Wb/m^2

f_c = 1.4 MHz.

Here, $(\beta_2 - \beta_1)$ is the largest. At high frequencies, β_1 and β_2 have almost the same values and hence the magnitude of rotation is much smaller. The rotation angle depends on many unpredictable variables. This leads to a loss in received signal power at the receiving antenna due to mismatched polarisation. At frequencies of hundreds of megahertz, most of Faraday rotation occurs in 90-1,000 km altitude range.

9.28 IONOSPHERIC ABNORMALITIES

The electrical characteristics of the ionosphere depend on solar radiation and hence they vary continuously. The variations of the ionosphere are classified as follows.

9.28.1 Normal

The normal variation in the characteristics of the ionosphere occur due to the following:

1. Diurnal
2. Seasonal
3. Thickness and
4. Height variations of the ionospheric layers.

9.28.2 Abnormal

The abnormal variations in the characteristics of the ionosphere occur mainly due to changes in solar activity. The common abnormal variations are:

1. Ionospheric storms
2. Sudden ionospheric disturbances
3. Sunspot cycle
4. Fading
5. Whistlers
6. Tides and winds.

9.29 IONOSPHERIC STORMS

These are due to the high absorption of sky waves and abnormal changes at the critical frequencies of E and F_2 layers. These storms usually persist for a few days.

9.30 SUDDEN IONOSPHERIC DISTURBANCES (SID)

The sudden appearance of solar flares causes **SIDs**. The solar flares occur suddenly and sporadically. These occur during solar peak activity. SIDs block out the signals completely. They persist for a few minutes to an hour. SID causes complete fading and it is called Dellinger fade-out. Ultraviolet radiation is intensive due to solar flares in D-Layer. SID does not occur in the layer of low air density and hence it is not found in E, F_1 and F_2 layers.

9.31 SUN SPOT CYCLE

Sun spot cycle is a eleven years cycle during which radiation varies drastically. The variation due to ultraviolet rays, flares, particle radiation and sun spots is very high and it is low due to light. During sun spot maxima, the critical frequencies are the highest and they are lowest during sun spot minima. To minimise the effect of sun spot cycle, the operating frequency is carefully chosen.

9.32 WHISTLERS

Whistlers are the transient electromagnetic disturbances which occur naturally. Whistlers consist of EM pulses of audio frequency radiation along the direction of the magnetic field of the earth between conjugate points in the northern and southern hemispheres.

Long whistlers, short whistlers and noise whistlers are a few types of whistlers. The composition of the upper atmosphere can be provided by whistlers.

9.33 TIDES AND WINDS IN THE IONOSPHERE

Tides and winds are common in the atmosphere. Solar tide effects are more pronounced. The winds in the ionosphere are caused by the tides. The presence of ionospheric winds are due to the motion of turbulence in F_2-layer. Tidal effect introduces a small peak of maximum ionisation density in the layer at mid-night.

9.34 EFFECT OF EARTH'S MAGNETIC FIELD

The average magnetic field of earth is about 40 A/m. This makes the ionosphere to behave like an anisotropic medium, that is, permittivity varies in different directions.

The earth's magnetic field causes the electrons to trace complicated trajectories with cyclotron or gyro frequency $f_c = 1.4$ MHz at $H = 40$ A/m.

> **Gyro frequency** is defined as the lowest natural frequency at which charged particles spiral in a fixed magnetic field.

It is a vector quantity and it is defined mathematically as

$$f_g = \frac{1}{2\pi}\frac{Q_e\,\mathbf{B}}{m}$$

where Q = charge of the particles, coloumbs

$\mathbf{B}$ = magnetic flux density, Wb/m^2

m = mass of the particle, kg.

> **Cyclotron frequency** is defined as the lowest natural frequency of a wave at which charged particles spiral in a fixed magnetic field.

It is obvious that the cyclotron frequency is same as gyro frequency.

Specific effects of earth's magnetic field

1. The earth's magnetic field exerts a deflecting force on the moving electrons. This force is given by

$$\mathbf{F} = Q_e\,(\mathbf{V} \times \mathbf{B})$$

where $\mathbf{F}$ = force on the electron in the ionosphere whose charge is Q_e (Newton)

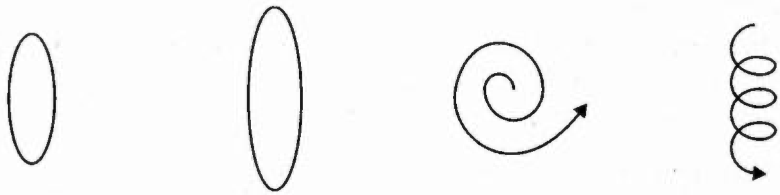
$\mathbf{V}$ = velocity of the electron, m/s

$\mathbf{B}$ = magnetic flux density, Wb/m^2

$= \mu_0\,\mathbf{H}$, $\mathbf{H}$ is the magnetic field intensity of earth (A/m).

It is clear from this equation, that the direction of the force is perpendicular to the velocity of the electron and also to the magnetic field.

2. The magnetic field component of the earth which is perpendicular to the electric field of the incident wave makes vibrating electrons to follow elliptical paths as in Fig. 9.31.



(*a*) High frequency (*b*) Medium frequency (*c*) Gyro frequency (*d*) Lower frequency

Fig. 9.31 *Effect of earth's magnetic field*

3. The electrons of the ionosphere absorb some energy from the EM wave. This absorbed energy is re-radiated with a polarisation that is rotated by 90° in space with respect to that of the incident EM wave. This re-radiated cross polarised component also differs in time phase from the field of the incident wave. As a result, the plane polarised wave is changed to elliptically polarised wave.
4. As the average velocity of the electrons is inversely proportional to the frequency, the effect of earth's magnetic field is more pronounced at low frequencies.
5. At high frequency, electrons vibrate in narrow elliptical paths under the influence of earth's magnetic field.
6. As the frequency is decreased, the minor axis of the ellipse increases and electron vibration amplitude also increases.
7. When the frequency is reduced to cyclotron resonant frequency 1.4 MHz, the electrons follow a spiral path of steadily increasing radius as in Fig. 9.31 (*c*), along with increase in velocity.
8. This frequency is given by

$$f_g = \frac{Q_e B}{2\pi m} = \frac{\mu_0 Q_e H}{2\pi m}$$

Here μ_0 permeability of ionosphere, H/m

Q_e = electron charge, (C)

m = mass of electron (gm)

H = earth's magnetic field, (A/m)

B = magnetic flux density of the earth, (Wb/m^2).

The average value of

$$B = 0.5 \times 10^{-4} \text{ Wb/m}^2 \text{ or Tesla.}$$

POINTS TO REMEMBER

1. Electromagnetic wave in free space is a transverse wave.
2. The basic modes of wave propagation between transmitter and receiver are ground wave, space wave and ionospheric wave.
3. The propagation characteristics of EM wave depend upon the type of earth, electrical characteristics of troposphere and ionosphere.
4. Ground wave is useful at VLF, LF and MF.
5. Space wave is useful for frequencies above 30 MHz.
6. Ionospheric wave propagation is useful between 2 MHz and 30 MHz.
7. Equivalent circuit of earth is a capacitance in parallel with a resistance.
8. The field strength due to ground wave is $E = \frac{AE_0}{d}$ volt/m.
9. The value of the factor of earth's losses lies between 0 and 1.
10. Ground wave field strength is $E = \frac{\eta_0 h_t I}{\lambda d}$ volt/m.
11. The received voltage due to ground wave is $V = \frac{\eta_0 h_t h_r I}{\lambda d}$ volts.
12. The roughness of earth is $R = \frac{4\pi\sigma_s \sin\theta_i}{\lambda}$.
13. Wave tilt is the change of orientation of the vertically polarised ground wave at the surface of the earth.
14. Troposphere is the region of atmosphere less than 16 km above the earth.
15. The field strength due to space wave is $E = \frac{4\pi h_t h_r}{\lambda d^2} E_0$.
16. The curvature of the earth creates shadow zones.
17. The refractive index of a medium is $\sqrt{\epsilon_r}$.
18. Modified refractive index of troposphere is $M = \left(n - 1 + \frac{h}{a}\right) \times 10^6$.
19. For standard atmosphere, $\frac{dM}{dh} = 0.036$ units/ft.
20. Radio horizon is always greater than optical horizon.
21. Radio horizon, $d_{\text{miles}} = \sqrt{2h_{f\,(\text{feet})}} + \sqrt{2h_{r\,(\text{feet})}}$.

22. Radio horizon, $d_{km} = \sqrt{17h_{t\,(m)}} + \sqrt{17h_{r\,(m)}}$.
23. The effective earth radius factor, K is 4/3 for standard atmosphere.
24. The line of sight distance $d_{LOS} = \sqrt{17h_{t\,(m)}} + \sqrt{17h_{r\,(m)}}$.
25. D is the lowest layer and F_2 is the highest layer in the ionosphere.
26. F-layer has the highest electron density.
27. D-layer has the lowest electron density.
28. The critical frequency of the layer is $f_c = 9\sqrt{N_{max}}$.
29. The relation between group velocity, phase velocity and free space velocity is $\upsilon_0^2 = \upsilon_p\,\upsilon_g$.
30. The phase velocity, $\upsilon_p = \dfrac{\upsilon_0}{n}$.
31. MUF $= f_c \sec\theta_i$.
32. The skip distance, $d_s = \dfrac{2h}{\tan\theta_c}$.
33. Faraday rotation is the rotation of plane of polarisation.
34. Gyro frequency is the lowest natural frequency at which charged particles spiral in a fixed magnetic field.
35. Gyro frequency is given by $f_g = \dfrac{\mu_0 Q_e H}{2\pi m}$.

SOLVED PROBLEMS

Problem 9.1 A transmitter operating at a frequency of 1.7 MHz is required to provide a ground wave field strength of 0.5 mV/m at a distance of 10 km. A short vertical transmitting antenna has an efficiency of 50%. The conductivity of the ground is 5×10^{-5} (mho)/cm and its relative permittivity is 10. Find the transmitter power required.

Solution The phase constant,

$$b = \tan^{-1}\left(\frac{\epsilon_r + 1}{D_f}\right)$$

$$f = 1.7 \times 10^6 \text{ Hz}, \quad \lambda = 1.764 \times 10^2 \text{ m}$$

$$D_f = 1.80 \times 10^{12}\frac{\sigma}{f} = \text{dissipation factor}$$

$$= \frac{1.80 \times 10^{12} \times 5 \times 10^{-5}}{1.7 \times 10^6}$$

$$= 52.9$$

$$b = \tan^{-1}\left(\frac{10+1}{52.9}\right) = \tan^{-1}(0.2079) = 11.74^\circ$$

The numerical distance, p is

$$p = \frac{\pi}{D_f}\frac{d}{\lambda}\cos b$$

$$= \frac{\pi}{52.9}\frac{10 \times 10^3}{1.764 \times 10^2}\cos(11.74^\circ) = 3.296$$

Formula method for A

$$A = \frac{2+0.3p}{2+p+0.6p^2} - \sin b\sqrt{\frac{p}{2}}\, e^{-\left(\frac{5}{8}\right)p}$$

$$= 0.21075$$

For $b = 11.74^\circ$, $p = 3.296$, the value of A is taken from standard plot of Fig. 9.4. That is,

$$A \approx 0.21$$

But the field strength at 10 km

$$E = \frac{AE_0}{d}$$

Here $\quad E_0 = 300\sqrt{P_{\text{kW}}},\ d = 10 \text{ km}$

or $$0.5 \times 10^{-3} = \frac{0.21 \times 300 \times 10^{-3}\sqrt{P_{\text{kW}}}}{10}$$

or $$\sqrt{P_{\text{kW}}} = \frac{0.5 \times 10}{300 \times 0.21} = \frac{5}{63} = 0.07936$$

$$P_{\text{kW}} = 0.0063$$

The efficiency of the antenna is only 50%.

The transmitter power required

$$= 2 \times P_{\text{kW}} = 2 \times 0.0063$$

$$= 0.0126 \text{ kW}$$

$$P_{TX} = 12.6 \text{ W.}$$

Problem 9.2 A broadcast transmitter supplies 100 kW to an antenna that radiates 50% of this power. The antenna has directional characteristic such that the field strength without ground losses is given by $E_0 = 300 \times 1.28\sqrt{P_{\text{kW}}}$ mV/m at 1 km. Find the field strength of the ground wave at 100 km for the following types of earth conditions (*i*) for $f = 500$ kHz, (*ii*) for $f = 1500$ kHz.

(*a*) Sea water earth: $\epsilon_r = 81$, $\sigma = 45 \times 10^{-3}$ (mho)/cm

(*b*) Good soil: $\epsilon_r = 20$, $\sigma = 10^{-4}$ (mho)/cm

(*c*) Poor soil: $\epsilon_r = 10$, $\sigma = 0.2 \times 10^{-4}$ (mho)/cm (*d*) Cities, industrial areas: $\in_r = 5$, $\sigma = 10^{-5}$ (mho)/cm

(*e*) Rockey soil, flat sandy: $\in_r = 10$, $\sigma = 2 \times 10^{-5}$ (mho)/cm

(*f*) Medium hills, forestation: $\in_r = 13$, $\sigma = 50 \times 10^{-5}$ (mho)/cm

Solution (*i*) Transmitter power, $P_T = 100$ kW

Efficiency of antenna $= 50\%$

So, radiated power $= 50$ kW

The field strength without ground losses is

$$E_0 = 300 \times 1.28 \sqrt{P_{kW}} \text{ mV/m at 1 km}$$

$$= 2{,}715.29 \text{ mV/m}$$

Frequency, $f = 500$ kHz.

(*a*) **Sea water earth**

$$\sigma = 45 \times 10^{-3} \text{ (mho)/cm}$$

$$\in_r = 81$$

$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f}$$

$$= \frac{1.8 \times 10^{12} \times 45 \times 10^{-3}}{500 \times 10^3}$$

$$= 162 \times 10^3$$

Phase constant, $b = \tan^{-1}\left(\dfrac{\in_r + 1}{D_f}\right) = 0.029^\circ$

Numerical distance

$$p = \frac{\pi}{D_f} \frac{d}{\lambda} \cos b$$

$$= \frac{\pi}{1{,}62{,}000} \times \frac{100 \times 10^3 \times 500 \times 10^3}{3 \times 10^8} \cos(0.029)$$

$$= 0.0032$$

$$A = \frac{2 + 0.3p}{2 + p + 0.6p^2} - \sin b \sqrt{\frac{p}{2}}\, e^{-\left(\frac{5}{8}\right)p}$$

Subtracting the values of p and b, we get

$$A = 0.9988$$

The field strength,

$$E = \frac{AE_0}{d}$$

$$= \frac{0.9988 \times 2{,}715.29}{100}$$

$$E = 27.1 \text{ mV/m.}$$

(*b*) **For good soil**

$$\sigma = 10^{-4} \text{ (mho)/cm}, \ \in_r = 20$$

$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f} = 360$$

Phase constant, $$b = \tan^{-1}\left(\frac{\in_r + 1}{D_f}\right) = 3.33^\circ$$

Numerical distance, $$p = \frac{\pi}{D_f} \frac{d}{\lambda} \cos b = 1.452$$

$$A = 0.4963$$

The field strength at 100 km

$$= \frac{AE_0}{d}$$

$$= \frac{0.4963 \times 2{,}715.29}{100}$$

$$E = 13.5 \text{ mV/m.}$$

(*c*) **For poor soil**

$$\sigma = 0.2 \times 10^{-4} \text{ (mho)/cm}, \ \in_r = 10$$

$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f} = 72.0, \ b = 8.68^\circ, \ p = 7.18$$

$$A = 0.01002$$

$$E = \frac{AE_0}{d} = \frac{0.1002 \times 2{,}715.29}{100}$$

$$E = 2.7 \text{ mV/m.}$$

(*d*) **For cities, industrial areas**

$$\in_r = 5, \ \sigma = 10^{-5} \text{ (mho)/cm}$$

$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f} = 36$$

$$b = 9.46^\circ$$

$$p = 14.34$$

$$A = 0.045$$

$$E = \frac{AE_0}{d} = \frac{0.045 \times 2{,}715.29}{100}$$

$$E = 1.222 \text{ mV/m.}$$

(*e*) **For rocky soil, flat sand earth**

$$\epsilon_r = 10, \;\; \sigma = 2 \times 10^{-5} \text{ (mho)/cm}$$

$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f} = 7{,}200$$

Phase constant, $$b = \tan^{-1}\left(\frac{\epsilon_r + 1}{D_f}\right) = 0.0875°$$

$$p = \frac{\pi}{D_f} \frac{d}{\lambda} \cos b = 0.0727$$

$$A = \frac{2 + 0.3p}{2 + p + 0.6p^2} - \sin b \sqrt{\frac{p}{2}}\, e^{-\frac{5}{8}p} = 0.9737$$

$$E = \frac{AE_0}{d} = \frac{0.9737 \times 2{,}715.29}{100}$$

$$E = 26.4 \text{ mV/m.}$$

(*f*) **For medium hills and forestation earth**

$$\sigma = 5 \times 10^{-5} \text{ (mho)/cm}$$

$$\epsilon_r = 13$$

$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f} = \frac{1.8 \times 10^{12} \times 5 \times 10^{-5}}{500 \times 10^3} = 180$$

$$b = \tan^{-1}\left(\frac{\epsilon_r + 1}{D_f}\right) = 4.44°$$

$$p = \frac{\pi}{D_f} \frac{d}{\lambda} \cos b = 2.90$$

$$A = 0.2733$$

Now $$E = \frac{AE_0}{d} = \frac{0.2733 \times 2{,}715.29}{100}$$

$$E = 7.4 \text{ mV/m.}$$

(*ii*) Frequency, $f = 1{,}500$ kHz

$$E_0 = 300 \times 1.28 \sqrt{P_{\text{kW}}}$$

$$= 2{,}715.29 \text{ mV/m.}$$

(*a*) **Sea water earth**

$$\in_r = 81$$

$$\sigma = 45 \times 10^{-3} \text{ (mho)/cm}$$

$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f} = 54{,}000.00$$

$$b = \tan^{-1}\left(\frac{\in_r + 1}{D_f}\right) = 0.087^\circ$$

$$p = \frac{\pi}{D_f}\frac{d}{\lambda}\cos b = 0.0291$$

$$A = \frac{2 + 0.3p}{2 + p + 0.6p^2} - \sin b\sqrt{\frac{p}{2}}\, e^{-\frac{5}{8}p}$$

$$= 0.9895$$

$$E = \frac{AE_0}{d} = 26.9 \text{ mV/m.}$$

(*b*) **Good soil**

$$\in_r = 20.0$$

$$\sigma = 1.0 \times 10^{-4} \text{ (mho)/cm}$$

$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f} = 120.0$$

$$b = \tan^{-1}\left(\frac{\in_r + 1}{D_f}\right) = 9.92^\circ$$

$$p = \frac{\pi}{D_f}\frac{d}{\lambda}\cos b = 12.89$$

$$A = \frac{2 + 0.3p}{2 + p + 0.6p^2} - \sin b\sqrt{\frac{p}{2}}\, e^{-\frac{5}{8}p}$$

$$= 0.0510$$

$$E = \frac{AE_0}{d} = 1.4 \text{ mV/m.}$$

(*c*) **Poor soil**

$$\in_r = 10$$

$$\sigma = 0.2 \times 10^{-4} \text{ (mho)/cm}$$

$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f} = 24.0$$

$$b = \tan^{-1}\left(\frac{\epsilon_r + 1}{D_f}\right) = 24.62^\circ$$

$$p = \frac{\pi}{D_f}\,\frac{d}{\lambda}\cos b = 59.49$$

$$A = \frac{2 + 0.3p}{2 + p + 0.6p^2} - \sin b\,\sqrt{\frac{p}{2}}\,e^{-\frac{5}{8}p}$$

$$= 0.0091$$

$$E = \frac{AE_0}{d} = 0.2\ \text{mV/m.}$$

(*d*) **Cities, industrial area**

$$\epsilon_r = 5$$

$$\sigma = 1.0 \times 10^{-4}\ \text{(mho)/cm}$$

$$D_f = 1.8 \times 10^{12}\,\frac{\sigma}{f} = 12.0$$

$$b = \tan^{-1}\left(\frac{\epsilon_r + 1}{D_f}\right) = 26.56^\circ$$

$$p = \frac{\pi}{D_f}\,\frac{d}{\lambda}\cos b = 117.08$$

$$A = \frac{2 + 0.3p}{2 + p + 0.6p^2} - \sin b\,\sqrt{\frac{p}{2}}\,e^{-\frac{5}{8}p}$$

$$= 0.0044$$

$$E = \frac{AE_0}{d} = 0.1\ \text{mV/m.}$$

(*e*) **Rocky soil, flat sandy**

$$\epsilon_r = 10$$

$$\sigma = 2 \times 10^{-3}\ \text{(mho)/cm}$$

$$D_f = 1.8 \times 10^{12}\,\frac{\sigma}{f} = 2{,}400.0$$

$$b = \tan^{-1}\left(\frac{\epsilon_r + 1}{D_f}\right) = 26.26^\circ$$

$$p = \frac{\pi}{D_f}\,\frac{d}{\lambda}\cos b = 0.6545$$

$$A = \frac{2+0.3p}{2+p+0.6p^2} - \sin b \sqrt{\frac{p}{2}}\, e^{-\frac{5}{8}p}$$
$$= 0.7526$$

$$E = \frac{AE_0}{d} = 20.4 \text{ mV/m.}$$

(*f*) **Medium hills, forestation**

$$\in_r = 13$$
$$\sigma = 5 \times 10^{-5} \text{ (mho)/cm}$$
$$D_f = 1.8 \times 10^{12} \frac{\sigma}{f} = 60.00$$
$$b = \tan^{-1}\left(\frac{\in_r + 1}{D_f}\right) = 13.13°$$
$$p = \frac{\pi}{D_f} \frac{d}{\lambda} \cos b = 25.49$$
$$A = \frac{2+0.3p}{2+p+0.6p^2} - \sin b \sqrt{\frac{p}{2}}\, e^{-\frac{5}{8}p}$$
$$= 0.2331$$

$$E = \frac{AE_0}{d} = 0.6 \text{ mV/m.}$$

Problem 9.3 Find the maximum range of tropospheric transmission for which the height of the transmitting antenna is 100 ft and that of the receiving antenna is 50 ft.

Solution We have

$$d_{max} \text{ (miles)} = \sqrt{2h_t \text{ (feet)}} + \sqrt{2h_r \text{ (feet)}}$$
$$= \sqrt{2 \times 100} + \sqrt{2 \times 50}$$
$$d_{max} = 14.142 + 10$$
$$d_{max} = 24.142 \text{ miles.}$$

Problem 9.4 Find the radio horizon distance of a transmitting antenna whose height is 80 m.

Solution

$$d \text{ (km)} = \sqrt{17h_t \text{ (m)}}$$
$$= \sqrt{17 \times 80}$$
$$= 36.88$$

Radio horizon distance $d = 36.88$ km.

Problem 9.5 Find the maximum distance that can be covered by a space wave when the antenna heights are 80 m and 50 m.

Solution $$d_{max} = \sqrt{17h_t} + \sqrt{17h_r}$$

$$= \sqrt{17 \times 80} + \sqrt{17 \times 50}$$

or $$d_{max} = 36.88 + 29.15$$

$$d_{max} = 66.03 \text{ km.}$$

Problem 9.6 A receiving antenna is located at 80 km from the transmitting antenna. The height of the transmitting antenna is 100 m. What is the required height of the receiving antenna?

Solution We have

$$d_{max} = \sqrt{17h_t} + \sqrt{17h_r}$$

or $$\sqrt{17h_r} = d_{max} - \sqrt{17h_t}$$

or $$17h_r = (d_{max} - \sqrt{17h_t})^2$$

$$h_r = \frac{(d_{max} - \sqrt{17h_t})^2}{17}$$

$$h_r = \frac{(80 - \sqrt{17 \times 100})^2}{17}$$

The height of the receiving antenna, h_r is 88.41 m.

Problem 9.7 Determine (*a*) the radio horizon distance for a transmitting antenna height of 300 feet (*b*) the radio horizon distance of a receiving antenna with a height of 100 feet (*c*) the maximum range of space wave communication for the above antenna heights.

Solution (*a*) Radio horizon distance for the transmitting antenna in miles,

$$d_t \text{ (miles)} = \sqrt{2h_t} = \sqrt{2 \times 300}$$

or $$d_t = 24.49 \text{ miles.}$$

(*b*) Radio horizon distance for receiving antenna in miles

$$d_r \text{ (miles)} = \sqrt{2h_r} = \sqrt{2 \times 100}$$

$$d_r = 14.142 \text{ miles.}$$

(*c*) The maximum range

$$= d_t + d_r = 24.49 + 14.142$$

$$d_{max} = 38.63 \text{ miles.}$$

Problem 9.8 A communication system is to be established at a frequency of 60 MHz with a transmitter power of 1 kW watts. The field strength of the directive antenna is 3 times that of a half-wave antenna. $h_t = 50$ m, $h_r = 5$ m. A field strength of 80μ V/m is required to give satisfactory reception. Find the range of the system.

Solution Frequency, $f = 60$ MHz

Transmitter power$P_{TX} = 1$ kW

$$h_t = 50 \text{ m}, \; h_r = 5 \text{ m}$$

Required field strength, $E = 80\mu$ V/m

$$E_0 = 3 \times 137.6 \sqrt{P_{kW}} \text{ mV/m at one mile}$$

$$E_0 = 3 \times 137.6 \sqrt{P_{kW}} \times \frac{8}{5} \times 10^3 \text{ mV/m at 1 m}$$

$$= 660.48 \times 10^3 \text{ mV/m}$$

The field strength due to a space wave is

$$E = \frac{4\pi h_t h_r}{\lambda d^2} E_0$$

or

$$d^2 = \frac{4\pi h_t h_r}{\lambda E} E_0$$

$$= \frac{4\pi \times 50 \times 5 \times 660.48 \times 10^3 \times 10^{-3}}{5 \times 80 \times 10^{-6}}$$

$$= \frac{200\pi \times 660.48 \times 10^6}{80}$$

$$= 5187.39 \times 10^6$$

$$d = 72.023 \times 10^3 \text{ m}$$

or

$$d = 72.023 \text{ km}$$

The range of the space wave is $d = 72.023$ km.

Problem 9.9 Find the maximum wavelength at which propagation is possible by means of a ground-based duct 30 m high when $\Delta M = 30$.

Solution Height of the duct,

$$h_d = 30 \text{ m}, \ \Delta M = 30$$

The maximum wavelength at which duct propagation is possible is given by

$$\lambda_{max} = 2.5 h_d \sqrt{\Delta M \times 10^{-6}}$$

$$= 2.5 \times 30 \sqrt{30 \times 10^{-6}}$$

$$= 410.79 \times 10^{-3}$$

$$\lambda_{max} = 0.410 \text{ m.}$$

Problem 9.10 If the critical frequency of an ionised layer is 1.5 MHz, find the electron density of the layer.

Solution We have

$$f_c = 9\sqrt{N}$$

where

$$f_c = 1.5 \text{ MHz}$$

$$N_{max} = \frac{f_c^2}{81}$$

$$= \frac{1.5^2 \times 10^{12}}{81}$$

$$N_{max} = 2.777 \times 10^{10} \text{ electrons/m}^3.$$

Problem 9.11 When the maximum electron density of the ionospheric layer corresponds to refractive index of 0.92 at the frequency of 10 MHz, find the range if the frequency is MUF itself. The height of the ray reflection point on the ionospheric layer is 400 km. Assume flat earth and negligible effect of earth's magnetic field.

Solution We have the relation of refractive index, n

$$n = \sqrt{1 - \frac{81 N_{max}}{f^2}}$$

Here $n = 0.92$, $f = 10$ MHz

The above equation is rewritten as

$$N_{max} = \frac{(1-n^2) f^2}{81}$$

$$= \frac{0.1536}{81} \times 10^{14}$$

$$N_{max} = 18.96 \times 10^{10} \text{ electrons/m}^3$$

The critical frequency,

$$f_c = 9\sqrt{N_{max}}$$

$$= 9 \times \sqrt{18.96 \times 10^{10}}$$

$$= 3.92 \times 10^6 \text{ Hz}$$

$$\text{MUF} = f_c \sec \theta_i = 10 \times 10^6 \text{ Hz}$$

or

$$\sec \theta_i = \frac{\text{MUF}}{f_c}$$

$$= 2.55$$

$$= \frac{\left(h^2 + \frac{d^2}{4}\right)^{1/2}}{h}$$

$$d = 1{,}876.59 \text{ km.}$$

Problem 9.12 Find out the relative permittivity of D, E and F-layers of the ionosphere for an EM wave of frequency 50 MHz.

The electron density of D layer = 400 electrons/cm^3

The electron density of E layer = 5×10^5 electrons/cm^3

The electron density of F layer = 2×10^6 electrons/cm^3.

Solution We have

$$n = \sqrt{\in_r} = \left(1 - \frac{81N}{f^2}\right)^{1/2}$$

or $$\in_r = \left(1 - \frac{81N}{f_{\text{kHz}}^2}\right)$$

$$N = 400 \text{ electrons/cm}^3$$

$$\in_r = 1 - \frac{81 \times 400}{(5 \times 10^4)^2}$$

$$= 1 - 1.29 \times 10^{-5}$$

$$\in_r \approx 1.0$$

For *E* layer, $$N = 5 \times 10^5 \text{ electrons/cm}^3$$

$\therefore$ $$\in_r = 1 - \frac{81N}{f_{\text{kHz}}^2}$$

$$= 1 - \frac{81 \times 5 \times 10^5}{(5 \times 10^4)^2}$$

$$= 1 - \frac{405 \times 10^5}{25 \times 10^8}$$

$$= 1 - 0.0162$$

$$\in_r = 0.9838 \text{ for } E\text{-layer}$$

For *F* layer, $$N = 2 \times 10^6 \text{ electrons/cm}^3$$

$$\in_r = 1 - \frac{81N}{f_{\text{kHz}}^2}$$

$$= 1 - \frac{81 \times 2 \times 10^6}{25 \times 10^8}$$

$$\in_r = 0.9345 \text{ for } F\text{-layer}$$

Problem 9.13 A sky-wave is incident on *D*-layer at an angle of 30°. Find the angle of refraction if the frequency of the transmitted wave is 50 MHz.

Solution For *D*-layer, $N = 400$ electrons/cm^3 and we have

$$\sqrt{\in_r} = \left(1 - \frac{81N}{f_{\text{kHz}}^2}\right)^{1/2}$$

$$\sqrt{\epsilon_r} = \left(1 - \frac{81 \times 400}{(5 \times 10^4)}\right)^{1/2}$$

$$\epsilon_r \approx 1.0$$

As refractive index, $n = \sqrt{\epsilon_r}$

$$n = 1.0$$

According to Snell's law

$$n \sin \theta_r = \sin \theta_i$$

$$\sin \theta_r = \sin \theta_i$$

$$= \sin 30^\circ$$

The angle of refraction $\theta_r = 30^\circ$.

Problem 9.14 Determine the critical frequency of EM wave for D ($N = 400$ electrons/cm^3), E (5×10^5 electrons/cm^3) and F (2×10^6 electrons/cm^3) layers.

Solution The expression for critical frequency is given by

$$f_c = 9\sqrt{N}$$

For D-layer,

$$f_c = 9 \times \sqrt{400} = 180 \text{ kHz}$$

For E-layer

$$f_c = 9 \times \sqrt{5 \times 10^5}$$

$$= 63.64 \times 10^2 \text{ kHz}$$

$$= 6.364 \text{ MHz}$$

For F-layer

$$f_c = 9 \times \sqrt{2 \times 10^6}$$

$$= 12.8 \text{ MHz}.$$

Problem 9.15 Find the critical frequency if the maximum electron density is

$$1.3 \times 10^6 \text{ electrons/cm}^3.$$

Solution $(f_c)_{\text{kHz}} = 9\sqrt{N_{\max}}$

$$= 9 \times \sqrt{1.3 \times 10^6}$$

$$= 10.26 \times 10^3 \text{ kHz}$$

$$f_c = 10.26 \text{ MHz}.$$

Problem 9.16 An HF radio communication is to be established between two points on the earth's surface. The points are at a distance of 2,600 km. The height of the ionospheric layer is 200 km and critical frequency is 4 MHz. Find MUF.

Solution $$\text{MUF} = f_c\left[\left(1+\frac{d}{2h}\right)^2\right]^{1/2}$$

$$d = 2{,}600 \text{ km}$$

$$f_c = 4 \text{ MHz and } h = 200 \text{ km}$$

$$\text{MUF} = 10.95 \text{ MHz.}$$

Problem 9.17 Find the frequency of the propagating wave for *D*-Layer to have refractive index of 0.5.

Solution For *D*-Layer, $N = 400$ electrons/cm^3

We have refractive index, $n = \left(1-\dfrac{81N}{f_{\text{kHz}}^2}\right)^{1/2}$

$$(0.5)^2 = 1-\frac{81N}{f_{\text{kHz}}^2}$$

or $$f^2 = \frac{81\times 400}{0.75}$$

$$f = 207.84 \text{ kHz.}$$

Problem 9.18 Determine the range of line of sight if the height of the transmitting antenna is 60 m and the height of the receiving antenna is 6 m. Assume standard atmosphere.

Solution The range of LOS, in km is given by

$$d = \sqrt{17h_t}+\sqrt{17h_r}$$

Here $h_t = 60$ m, $h_r = 6$ m

$\therefore$ $$d = 31.94 + 10.1$$

$$d = 42.04 \text{ km.}$$

Problem 9.19 What is the critical angle of propagation for *D*-Layer if the transmitter and receiver are separated by 500 km?

Solution Height of the *D*-Layer

$$= 70 \text{ km}$$

The distance between transmitter and receiver

$$= 500 \text{ km}$$

The critical angle,

$$\theta_c = \sin^{-1}\left\{\frac{h}{\left[h^2+\left(\dfrac{d^2}{4}\right)\right]^{1/2}}\right\}$$

$$= \sin^{-1}\left\{\frac{70}{\left[4{,}900 + \left(\frac{500^2}{4}\right)\right]^{1/2}}\right\}$$

$$\theta_c = 15.64°$$

It can also be calculated from

$$\theta_c = \tan^{-1}\left(\frac{2h}{d}\right)$$

$$\theta_c = \tan^{-1}\left(\frac{2 \times 70}{500}\right)$$

$$\theta_c = 15.64°.$$

OBJECTIVE QUESTIONS

1. Ground wave is effective when the transmitting and receiving antennas are:
(*a*) vertically polarised (*b*) horizontally polarised
(*c*) elliptically polarised (*d*) circularly polarised

2. Ground wave propagation is used when:
(*a*) f is in UHF range (*b*) f is in microwave range
(*c*) f is in LF range (*d*) f is in VHF range

3. The equivalent circuit of earth is:
(*a*) a capacitance in shunt with a conductance
(*b*) series R-C circuit
(*c*) series R-L circuit
(*d*) series R-L-C circuit

4. The factor, A that takes care of earth's losses in ground wave propagation depends on:
(*a*) σ, ϵ, f, d and polarisation (*b*) σ, ϵ
(*c*) f, d (*d*) d

5. The factor, A depends on d as
(*a*) inversely proportional to d^2 (*b*) inversely proportional to d
(*c*) inversely proportional to d^3 (*d*) proportional to d

6. Ground wave field strength depends on:
(*a*) the height of transmitting antenna
(*b*) the height of receiving antenna
(*c*) the heights of transmitting and receiving antennas
(*d*) none of these

7. The reflection coefficient of incident EM wave on the earth depends on the angle of incidence. (Yes/No)

8. The reflection coefficient of incident wave on the earth depends on polarisation of the wave. (Yes/No)

9. The reflection coefficient of the incident wave on the earth depends on $\in_r$, σ, f. (Yes/No)

10. Roughness of earth depends on
    (*a*) angle of incidence, θ_i only
    (*b*) frequency, f only
    (*c*) standard deviation of earth's irregularities, σ_s only
    (*d*) θ_i, f and σ_s

11. Earth is considered to be smooth if the roughness is ______________.

12. Earth is considered to be rough if the roughness is ______________.

13. Space wave field strength depends on ______________.

14. Space wave field strength depends on ______________.
    (*a*) h_t only (*b*) h_r only
    (*c*) h_t and h_r only (*d*) h_t, h_r, d, f, P

15. Curvature of earth creates ______________.

16. Hills and tall buildings affect space wave field strength. (Yes/No)

17. Atmosphere is said to be standard atmosphere when $\frac{dM}{dh}$ = ______________.

18. For standard atmosphere, the ratio of equivalent radius and actual radius of the earth is ______________.

19. Refractive index in terms of relative permittivity is ______________.

20. Duct propagation takes place when ______________.

21. Radio horizon distance for standard atmosphere when $h_t = 50$ m and h_r is 5 m is
    (*a*) 38.37 km (*b*) 38.37 miles
    (*c*) 383.7 km (*d*) 383.7 miles

22. Maximum wavelength at which duct propagation is possible, is ______________.

23. *E*-Layer of ionosphere is the lowest layer. (Yes/No)

24. *D*-Layer of the ionosphere is best suited for HF communication. (Yes/No)

25. The thickness of *D*-Layer is the smallest. (Yes/No)

26. The thickness of *F*-Layer is the highest. (Yes/No)

27. Actual height of the ionospheric layers is greater than virtual height. (Yes/No)

28. *D*-Layer exists at all times. (Yes/No)

29. *F*-Layer exists at nights. (Yes/No)

30. The electron density of *D*-Layer is the highest. (Yes/No)

31. Phase velocity of EM wave in ionosphere is ______________.

32. Phase velocity, group velocity and free space velocity are related by ______________.

33. The relation between MUF and f_c is ______________.

34. The skip distance, d_s in terms of height of the layer and critical angle is ______________.

35. If the critical frequency of the ionospheric layer is 1.5 MHz, the maximum electron density of the layer in electrons/m^3 is

(*a*) 2.777×10^{10} (*b*) 27.77×10^{10}
(*c*) 0.2777×10^{10} (*d*) 277.7×10^{10}

36. Fading is nothing but

(*a*) amplification of field (*b*) multiplication of field
(*c*) subtraction of two fields (*d*) change of field strength

37. Fading is usually compensated by ______________.

38. Troposcatter propagation is related to ______________.

(*a*) SIDS (*b*) Faraday rotation
(*c*) Fading (*d*) Atmospheric storms

39. EM waves of UHF range normally propagate by means of

(*a*) ground waves (*b*) space waves
(*c*) sky waves (*d*) surface waves

40. The absorption of EM waves by the atmosphere depends on

(*a*) the distance of the transmitter (*b*) their frequency
(*c*) the polarisation of the waves (*d*) strength of EM wave

41. Short-waves for long distance communication depend on

(*a*) ionospheric waves (*b*) ground waves
(*c*) direct waves (*d*) space waves

42. Troposcatter propagation is used at frequency range of

(*a*) VHF only (*b*) VLF only
(*c*) MF only (*d*) UHF and VHF

43. *D*-Layer lies approximately between

(*a*) 65 to 75 km (*b*) 100 to 110 km
(*c*) 40 to 50 km (*d*) 150 to 160 km

44. Attenuation in atmosphere is inversely proportional to the square of the frequency. (Yes/No)

45. The relative permittivity of ionospheric layer is

(a) $\epsilon_r = \left(1 - \frac{81N}{f^2}\right)$ (b) $\epsilon_r = \sqrt{1 - \frac{81N}{f^2}}$

(c) $\epsilon_r = \left(1 - \frac{f^2}{81N}\right)$ (d) $\epsilon_r = 9\sqrt{N}$

46. Wave unaffected by night or day is

(a) ground wave (b) sky wave
(c) space wave (d) tropospheric wave

47. When an EM wave propagates from air into ionosphere, its velocity

(a) decreases (b) increases
(c) remains the same (d) reduces to zero

48. During day-time the ionospheric layer that does not exist is

(a) F (b) F_1
(c) F_2 (d) D

49. Critical frequency of the ionospheric layer is

(a) $f_c = 81\sqrt{N_{max}}$ (b) $f_c = 81N_{max}$
(c) $f_c = 9\sqrt{N_{max}}$ (d) $f_c = 9N_{max}$

50. If an EM wave whose frequency is 30 MHz is incident with an angle of 60°. MUF is

(a) 60 MHz (b) 20 MHz
(c) 30 MHz (d) 10 MHz

51. When an EM wave of frequency 20 MHz is incident at angle of 30°, MUF is

(a) 10 MHz (b) 15 MHz
(c) 23 MHz (d) 43 MHz

52. When an EM wave whose MUF is 25 MHz is incident at 40°, the critical frequency is

(a) 19.15 MHz (b) 1.915 MHz
(c) 2 MHz (d) 30 MHz

53. If the critical frequency of an ionized layer is 15 MHz, the electron density of the layer is

(a) 2.78×10^6 electrons/m^3 (b) 0.278×10^6 electrons/m^3
(c) 27.8×10^6 electrons/m^3 (d) 3.2×10^6 electrons/m^3

54. The critical angle of an EM wave for an ionospheric layer of height h when the distance between the transmitter and receiver is d, is given by ______________.

55. Critical frequency, f_c is determined from ______________.

56. Frequency of optimum traffic, FOT is the frequency at which ______________.

57. Frequency of optimum traffic, FOT is ______________.

58. OWF is the same as ______________.
59. The Horizon distance is affected by atmospheric refraction. (Yes/No)
60. On a spherical surface Horizon is ______________.
61. Radio Horizon of an antenna is the locus of the farthest points at which direct rays become ______________ to the planetary surface.
62. Faraday rotation takes place in all media. (Yes/No)
63. The effective radius of the earth for a standard atmosphere is ______________ times the actual radius of the earth.
64. Gyro-frequency is a vector. (Yes/No)
65. Gyro-frequency depends on the magnetic field. (Yes/No)
66. Gyro frequency depends on the mass of the charged particles. (Yes/No)
67. Gyro-frequency depends on the charges of the particles. (Yes/No)
68. LOS distance is affected by atmospheric refraction. (Yes/No)
69. Group and phase velocities have equal magnitudes even when phase velocity varies with frequency. (Yes/No)
70. Group and phase velocities have the same directions even when the phase velocity varies with direction. (Yes/No)

ANSWERS

1. (a)	2. (c)	3. (a)	4. (a)	5. (a)	6. (a)
7. Yes	8. Yes	9. Yes	10. (d)	11. Less then 0.1	
12. Greater then 10		13. Direct and ground reflected rays			14. (d)
15. Shadow zones		16. Yes	17. $\frac{dM}{dh} = 0.036$ units/ft		18. $\frac{4}{3}$
19. $\sqrt{\epsilon_r}$	20. $\frac{dM}{dh}$ = negative		21. (a)	22. $2.5h_d\sqrt{\Delta M \times 10^{-6}}$	
23. Yes	24. No	25. Yes	26. Yes	27. No	28. No
29. No	30. No	31. v_0/n	32. $v_0^2 = v_p\, v_g$	33. MUF $= f_c \sec \theta_i$	
34. $d_s = 2h/\tan \theta_c$		35. (a)	36. (d)	37. Diversity schemes	
38. (c)	39. (b)	40. (b)	41. (a)	42. (d)	43. (a)
44. Yes	45. (a)	46. (a)	47. (b)	48. (a)	49. (c)
50. (a)	51. (c)	52. (a)	53. (a)	54. $\theta_c = \tan^{-1} \frac{2h}{d}$	
55. Ionogram	56. The signal strength is strong			57. About 85% of MUF	
58. FOT	59. Yes	60. Circle	61. Tangential	62. No	63. 4/3
64. Yes	65. Yes	66. Yes	67. Yes	68. Yes	69. No
70. No					

EXERCISE PROBLEMS

1. A transmitter operating at $f = 1.0$ MHz is required to provide a ground wave field strength of 1.0 mV/m at a distance of 20 km. A short vertical transmitting antenna has an efficiency of 60%. $\sigma = 4 \times 10^5$ mho/cm, $\epsilon_r = 15$. Determine the transmitter power required.
2. Find the field strength due to space wave at a distance of 100 km when the transmitting and receiving antennas are 100 m and 20 m respectively. $E_0 = 137.6 \sqrt{P_{kW}}$ mV/m at one mile. The radiated power is 100 kW. It operates at a frequency of 50 MHz.
3. Determine the Radio horizon distance of a transmitting antenna if its height is 100 m.
4. Find the maximum wavelength at which duct propagation is possible by means of a ground based duct of height $h = 2.5$ km when the modified refractive index is 20.
5. Determine the electron density of a layer if the critical frequency of the ionised layer is 2.0 MHz.
6. Communication by ionospheric propagation is required for a distance of 2,000 km. Height of the layer is 220 km and critical frequency is 5 MHz. Find MUF.
7. What is the maximum distance that can be covered by space wave communication if transmitting and receiving antenna heights are 300 feet and 100 feet respectively?
8. Find the Radio horizon distances if receiving antenna height is (*a*) 80 m (*b*) 120 m.
9. Determine the transmitting antenna height if (*a*) the receiving antenna is at a distance of 50 km and its height is 50 m, (*b*) the receiving antenna is at a distance of 60 km and the its height is 30 m.