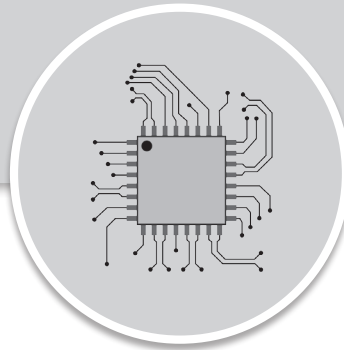


# ELECTRONICS ENGINEERING

## Microwave Engineering



Comprehensive Theory  
*with Solved Examples and Practice Questions*





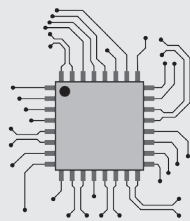
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## **Microwave Engineering**

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# CONTENTS

## Microwave Engineering

### CHAPTER 1

<b>Introduction .....</b>	<b>1</b>
1.1 Microwave Frequencies.....	2
1.2 Microwave Engineering .....	3
1.3 Microwave Properties and Advantages.....	3
1.4 Applications of Microwaves.....	4
<i>Student Assignments .....</i>	<i>6</i>

### CHAPTER 2

<b>Waveguides .....</b>	<b>7</b>
2.1 Waveguides .....	7
2.2 Rectangular Waveguides .....	10
2.3 Circular Waveguides (Cylindrical) .....	43
2.4 Other Waveguides.....	49
<i>Student Assignments .....</i>	<i>51</i>

### CHAPTER 3

<b>Microwave Components &amp; Circuits .....</b>	<b>53</b>
3.1 Introduction .....	53
3.2 S-Parameters .....	53
3.3 Waveguide Tees.....	60
3.4 Magic-Tee (Hybrid Tee) .....	66
3.5 Hybrid Ring (Rat-Race Circuit).....	70
3.6 Directional Coupler.....	71
3.7 Ferrite Devices .....	81
<i>Student Assignments .....</i>	<i>89</i>

### CHAPTER 4

<b>Microwave Tubes .....</b>	<b>91</b>
4.1 Introduction .....	91
4.2 Two Cavity Klystron Amplifier .....	92
4.3 Multicavity Klystron Amplifier .....	107
4.4 Reflex Klystron Oscillator .....	109
4.5 Travelling Wave Tube (TWT) .....	119
4.6 Magnetron .....	126
<i>Student Assignments .....</i>	<i>132</i>

### CHAPTER 5

<b>Microwave Solid State Devices .....</b>	<b>134</b>
5.1 Introduction .....	134
5.2 Microwave Bipolar Transistors .....	134
5.3 Tunnel Diodes .....	139
5.4 Transferred Electron Devices - Gunn Diodes .....	146
5.5 Avalanche Transit-Time Devices .....	156
5.6 Parametric Amplifiers.....	165
5.7 PIN Diode.....	171
5.8 MASER.....	172
<i>Student Assignments .....</i>	<i>173</i>

### CHAPTER 6

<b>Microwave Measurements .....</b>	<b>175</b>
6.1 Introduction .....	175
6.2 Frequency Measurement.....	176

6.3	Power Measurements .....	178
6.4	VSWR Measurements .....	181
6.5	Attenuation Measurement.....	186
6.6	Impedance Measurement .....	187
6.7	Phase Shift Measurement.....	188
6.8	Measurement of Q (Quality Factor).....	188
6.9	Microwave Antenna Gain Measurements .....	189
	<i>Student Assignments</i> .....	192

CHAPTER 7

<b>Miscellaneous Topics.....</b>		<b>194</b>
7.1	Cavity Resonators .....	194
7.2	Microstrip Lines.....	199
7.3	Microwave Communication System.....	202
7.4	Microwave Antennas.....	204
7.5	Friss Formula .....	206
7.6	Radar Equation .....	208
	<i>Student Assignments</i> .....	210



# Microwave Engineering

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## Microwave Engineering

After studying the basic electromagnetic field theory and its application in understanding waves and transmission lines, we are now ready to understand the guided wave propagation through waveguides. We shall start with the fields inside waveguide and its parameters like cut-off frequency, guide wavelength, phase velocity and dominant mode of wave propagation etc. Circular waveguides and other special purpose waveguides are also discussed. Further, we shall proceed to the microwave components which are sections of waveguides and their analysis using  $S$ -parameters followed by ferrite devices and their applications.

The next part of the book deals with microwave sources (amplifiers and oscillators) both high power (tubes) and low power (solid state devices). The operation of tubes like Klystrons, magnetron, and TWTs are discussed exhaustively followed by solid state devices like tunnel diode, IMPATT diodes, Gunn diodes and MASERs etc. The last part of the book discusses microwave measurements in detail. The major emphasis throughout the book is to developing a reader to understand and analyze principles of operation of various microwave devices and circuits, which are always an integral part of various competitive examinations. Throughout this book, a sequential and comprehensive approach has been used, so that a beginner with EMT basics can utilize this book in an efficient manner.

# Waveguides

## 2.1 Waveguides

Waveguides, like transmission lines, are structures used to guide Electromagnetic waves from one point (source) to another (load). Maxwell's equations predict that electromagnetic waves can also be guided through metallic tubes, like water is guided through pipes. Two common metallic waveguides, rectangular and circular cross section are shown in Figure 2.1

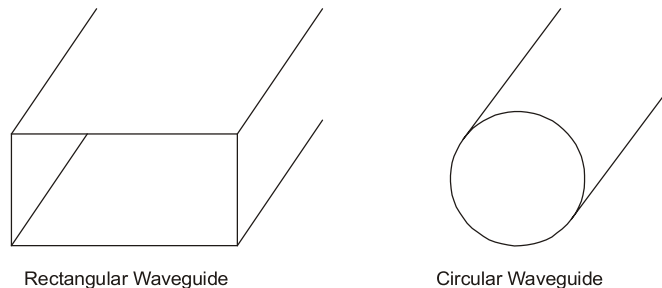


Figure-2.1

### Comparison of Waveguide and Transmission Line Characteristics

Transmission Line	Waveguide
<ul style="list-style-type: none"> <li>Two or more conductors separated by some insulating medium (Two wire, microstrip coaxial etc)</li> <li>Normal operating mode is the TEM or quasi-TEM mode (can support TE and TM modes but these modes are undesirable)</li> <li>No cutoff frequency for the TEM mode. Transmission lines can transmit signals from DC upto high frequency.</li> <li>Significant signal attenuation at high frequencies due to conductor and dielectric losses.</li> <li>Small cross section transmissions lines (like coaxial cables) can only transmit low power levels.</li> <li>Large cross section transmission lines (like power transmission lines) can transmit high power levels.</li> </ul>	<ul style="list-style-type: none"> <li>Metal waveguides are typically one enclosed conductor filled with an insulating medium (Rectangular, circular)</li> <li>Operating modes are TE or TM modes (cannot support a TEM mode)</li> <li>Must operate the waveguide at a frequency above the respective TE or TM mode cutoff frequency for that mode to propagate.</li> <li>Lower signal attenuation at high frequencies than transmission lines.</li> <li>Metal waveguides can transmit high power levels.</li> <li>Large cross section (low frequency) waveguides are impractical due to large size and high cost.</li> </ul>

**Example - 2.1**

The main difference between the operation of transmission lines and waveguides is that

- (a) the latter are not distributed, like transmission lines
- (b) the former can use stubs and quarter-wave transformers, unlike the latter
- (c) terms such as impedance matching and SWR cannot be applied to waveguides
- (d) Transmission lines use the principal mode of propagation and therefore do not suffer from low-frequency cut-off

**Solution : (d)**

Principal mode is TEM mode and this mode has zero cutoff frequency. Waveguides allows signals after particular range only.

**Example - 2.2**

Match List-I (Types of transmission line structures) with List-II (Modes of propagation) and select the correct answer using the code given below the lists:

List-I	List-II
A. Coaxial	1. Quasi TEM
B. Hollow rectangular waveguide	2. Pure TEM
C. Microstrip	3. TE/TM
D. Hollow cylindrical waveguide	4. Hybrid

Codes:

	A	B	C	D
(a)	2	1	3	4
(b)	4	3	1	3
(c)	2	3	1	3
(d)	2	3	1	2

**Solution : (c)****Example - 2.3**

Which of the following transmission line structures allow TEM mode of wave propagation?

- (a) Two wire transmission line
- (b) Coaxial cable
- (c) Rectangular waveguide
- (d) Both (a) and (b)

**Solution : (d)****Example - 2.4**

Statement (I): Coaxial cable is not preferred at microwave frequencies.  
Statement (II): At microwave frequencies, coaxial cable has high attenuation.

- (a) Both Statement (I) and Statement (II) are individually true and Statement (II) is the correct explanation of Statement (I)
- (b) Both Statement (I) and Statement (II) are individually true but Statement (II) is not the correct explanation of Statement (I)
- (c) Statement (I) is true but Statement (II) is false
- (d) Statement (I) is false but Statement (II) is true

**Solution : (a)**

At high frequencies (microwave frequencies) attenuation in coaxial cable is very high.

### 2.1.1 General Wave Equations in Rectangular Coordinates

Given any time-harmonic source of electromagnetic radiation, the phasor electric and magnetic fields associated with the electromagnetic waves that propagate away from the source through a medium characterized by  $(\mu, \epsilon)$  must satisfy the source free Maxwell's equations (in phasor form) given by

$$\nabla \times \bar{E} = -j\omega \mu \bar{H} \quad (2.1)$$

$$\nabla \times \bar{H} = j\omega \epsilon \bar{E} \quad (2.2)$$

$$\nabla \cdot \bar{E} = 0 \quad (2.3)$$

$$\nabla \cdot \bar{H} = 0 \quad (2.4)$$

Now, we manipulate source-free Maxwell's equations to get wave equations for electric and magnetic fields.

Taking the curl of equation (2.1)  $\nabla \times \nabla \times \bar{E} = -j\omega \mu (\nabla \times \bar{H})$

and inserting equation (2.2) gives  $\nabla \times \nabla \times \bar{E} = (-j\omega \mu)(j\omega \epsilon) \bar{E}$  (2.5)

Using the vector identity  $\nabla \times \nabla \times \bar{F} = \nabla(\nabla \cdot \bar{F}) - \nabla^2 \bar{F}$  (for any vector  $\bar{F}$ )

in equation (2.5) gives  $\nabla(\nabla \cdot \bar{E}) - \nabla^2 \bar{E} = \omega^2 \mu \epsilon \bar{E}$  (2.6)

From equation (2.3), we see that the divergence of electric field is zero in a source free region i.e.,  $\nabla \cdot \bar{E} = 0$

Inserting this result into equation (2.6) gives,  $\nabla^2 \bar{E} + \omega^2 \mu \epsilon \bar{E} = 0$  (2.7a)

Similarly for magnetic field,  $\nabla^2 \bar{H} + \omega^2 \mu \epsilon \bar{H} = 0$  (2.7b)

If we let  $-\omega^2 \mu \epsilon = \gamma^2$

We find that the electric and magnetic field phasors satisfy vector wave equations given by

$$\boxed{\nabla^2 \bar{E} - \gamma^2 \bar{E} = 0} \quad (2.8a)$$

$$\boxed{\nabla^2 \bar{H} - \gamma^2 \bar{H} = 0} \quad (2.8b)$$

where  $\gamma$  is intrinsic propagation constant of medium generally given by

$$\boxed{\gamma = \alpha + j\beta} \quad \begin{array}{l} \alpha\text{-attenuation constant (Nep/m)} \\ \beta\text{-phase constant (rad/m)} \end{array}$$

For source free and loss less medium  $\boxed{\gamma = j\beta = j\omega\sqrt{\mu\epsilon}}$

**Example - 2.5** For lossless propagation of EM waves through an unbounded dielectric, the propagation constant is

- |             |                   |
|-------------|-------------------|
| (a) real    | (b) imaginary     |
| (c) complex | (d) None of these |

**Solution : (b)**

For lossless transmission  $\alpha = 0$ .



## 2.2 Rectangular Waveguides

Consider the geometry of a rectangular waveguide shown in Fig. 2.2, where  $a$  and  $b$  are the inner dimensions of the waveguide.

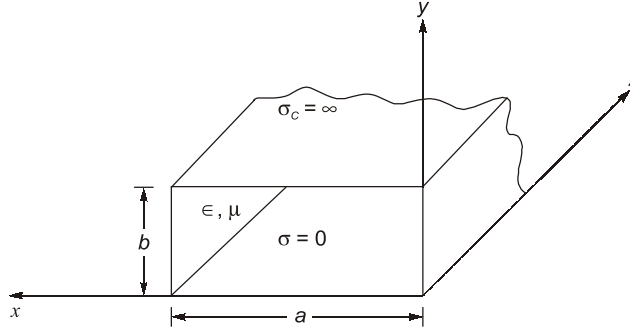


Figure-2.2

### Assumptions:

- The waveguide is infinitely long, oriented along  $z$ -axis, and uniform along its length.
- The waveguide is filled with a source free ( $\rho_v = 0$ ) lossless dielectric ( $\epsilon, \mu, \sigma = 0$ ) and guide walls are perfectly conducting ( $\sigma_c = \infty$ ).
- Fields are time harmonic i.e.  $e^{j\omega t}$  dependence.

The electric and magnetic fields of a general wave propagating in  $+z$ -direction through waveguide with guide propagation constant  $\gamma_g$  are characterised by a  $z$ -dependence of  $e^{-\gamma_g z}$ . Then general field ( $E$  &  $H$ ) expressions inside the guide are given by

$$\vec{E}(x, y, z) = \vec{E}(x, y)e^{-\gamma_g z} = [E_x(x, y)\hat{x} + E_y(x, y)\hat{y} + E_z(x, y)\hat{z}]e^{-\gamma_g z} \quad (2.9a)$$

$$\vec{H}(x, y, z) = \vec{H}(x, y)e^{-\gamma_g z} = [H_x(x, y)\hat{x} + H_y(x, y)\hat{y} + H_z(x, y)\hat{z}]e^{-\gamma_g z} \quad (2.9b)$$

where  $\gamma_g = \alpha_g + j\beta_g$

$\alpha_g$  = waveguide attenuation constant (Nep/m)

$\beta_g$  = waveguide phase constant (rad/m)

The propagation constant is purely imaginary ( $\alpha_g = 0, \gamma_g = j\beta_g$ ) when the wave travels without attenuation (no losses) or complex-valued when losses are present.

### Task

To obtain complete  $E$  and  $H$  field of a wave propagating in  $+z$  direction inside a rectangular waveguide of infinite length.

### Method of Solution

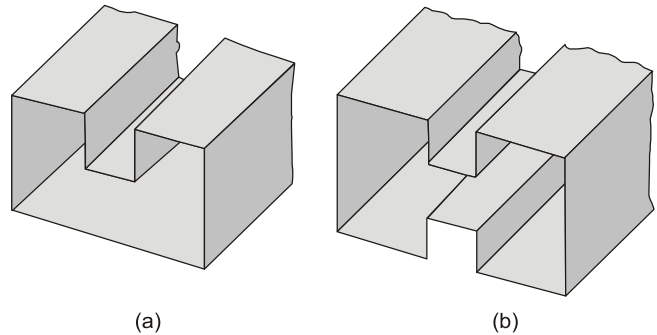
1. Express transverse field components ( $E_x, E_y, H_x, H_y$ ) in terms of Axial field components ( $E_z, H_z$ ).
2. Obtain solution for the Axial/ Longitudinal fields ( $E_z, H_z$ ) from the wave equations.
3. Obtain  $E_x, E_y, H_x, H_y$  from  $E_z$  and  $H_z$ .

**Ridged Waveguides**

Rectangular waveguides can be made with single or double ridges, as shown in figure (2.15).

**Benefits**

1. Ridges lower the value of cutoff wavelength ( $\lambda_c$ ). Thus allows a guide with smaller dimensions to be used for any given frequency.
2. Ridge in waveguide increase the useful frequency range of the guide, that is dominant mode propagate in the ridged guide over a wider frequency range than in any other waveguide.
3. Ridged guide has greater Bandwidth than an equivalent rectangular guide.



**Figure-2.15: Ridged waveguides**  
(a) Single ridge (b) Double ridge

**Disadvantages**

More attenuation per unit length than in rectangular waveguides.

**Flexible Waveguides**

These are required when there is need of movement of a waveguide section. This may be bending, twisting, stitching or vibration etc. Popular types are copper or aluminium tube having elliptical cross section. This waveguide is of continuous in construction and joints of separate bends are not required. It may have polyethylene or rubber outer cover.

Power handling ability and SWR are similar to those of rectangular waveguides of same size but attenuation in dB/m is about 5 times as much.

**Summary**

- Waveguides are metallic structures used to guide EM waves at very high frequencies.
- Two modes of propagation (or field patterns) are  $TE_{mn}$  ( $m = 0, 1, 2, \dots$ , and  $n = 0, 1, 2, \dots$ ,  $m = n \neq 0$ ) and  $TM_{mn}$  ( $m = 1, 2, \dots$ , and  $n = 1, 2, \dots$ )
- Each mode of propagation has associated guide propagation constant  $\gamma_g = \alpha_g + j\beta_g$  and cutoff frequency.
- The guide propagation constant not only depends on material parameters ( $\epsilon, \mu, \sigma$ ) but also depends on dimensions of the waveguide.
- Cut-off frequency is the transition frequency at which  $\gamma_g$  changes from real (attenuation) to imaginary (wave propagation)
- The lowest mode possible is called dominant mode.
- For rectangular waveguide ( $a \times b$ ,  $a > b$ ), the dominant mode is  $TE_{10}$ .
- The group velocity  $v_g$  (velocity of energy flow) phase velocity  $v_p$  and medium (unbounded) velocity  $v$  are related through

$$v_g v_p = v^2 \text{ where, } v = \frac{1}{\sqrt{\mu \epsilon}}$$

- The method of excitation decides the mode of operation of waveguide.

**Student's  
Assignments****1**

**Q.1** A dielectric filled ( $\epsilon_r = 2.5$ ) rectangular waveguide has dimensions  $a = 3$  cm and  $b = 1.5$  cm. The signal frequency is 10 GHz. Compute the following for  $TE_{11}$  mode.

(i) Cut-off wave number

[Ans: 234.16 rad/m]

(ii) Cut-off frequency

[Ans:  $5\sqrt{2}$  GHz]

(iii) Cut-off wavelength

[Ans:  $\frac{6}{\sqrt{5}}$  cm]

(iv) Guide phase constant

[Ans: 140.5/m]

(v) Guide attenuation constant

[Ans: 0]

(vi) Guide propagation constant

[Ans:  $j140.5/\text{m}$ ]

(vii) Guide wavelength

[Ans: 4.47 cm]

(viii) Phase velocity

[Ans:  $2.68 \times 10^8$  m/s]

(ix) Wave impedance

[Ans: 337.2  $\Omega$ ]

**Q.2** An air filled rectangular waveguide has dimensions 2 cm  $\times$  4 cm. Determine the frequency at which  $TE_{11}$  mode has an attenuation of  $20\pi$  nepers/m.

[Ans: 8.9 GHz]

**Q.3** A microwave signal of 8 GHz is propagating in dominant mode through a rectangular waveguide filled with air. If inside dimensions of the waveguide are 2 cm  $\times$  4 cm, calculate following:

(i) cut of frequency

[Ans: 3.75 GHz]

(ii) guide wave length

[Ans: 4.245 cm]

(iii) phase velocity

[Ans:  $3.396 \times 10^8$  m/sec]

(iv) characteristic impedance

[Ans: 426.8  $\Omega$ ]

**Q.4** An air filled rectangular waveguide has dimensions  $a = 3$  cm and  $b = 1.5$  cm

(i) Over what range of frequencies will the guide operate in single mode.

[Ans:  $5 < f < 10$  GHz]

(ii) Decay rates for  $TE_{10}$ ,  $TE_{01}$  at 2 GHz.

[Ans: exponentially decays w.r.t.  $-95.97$  z Np/m, and  $-205.2$  z Np/m]

**Q.5** The dominant  $TE_{10}$  is propagated inside an air filled rectangular waveguide of dimensions 4 cm  $\times$  2 cm. The waveguide is perfectly matched and maximum  $E$  field existing every where in the guide is 2 kV/m. Determine the average power passing through the guide and assume operating frequency of 12 GHz.

[Ans: 4 W]

**Q.6** A  $TE_{11}$  mode is propagating through an air filled circular waveguide. The diameter of the guide is 5 cm, and the guide contains an air dielectric. Operating frequency is 12 GHz. Determine:

(i) the cutoff frequency ( $f_c$ )

[Ans: 3.516 GHz]

(ii) the guide wavelength ( $\lambda_g$ )

[Ans: 2.614 cm]

(iii) wave impedance ( $Z_g$ )

[Ans: 394.35  $\Omega$ ]

(iv) phase velocity ( $v_p$ )

[Ans:  $3.138 \times 10^8$  m/s]

**Q.7** Show that  $TM_{01}$  and  $TM_{10}$  modes in rectangular waveguide do not exist.

**Student's  
Assignments****2**

**Q.1** The propagation velocity of the signal in a waveguide is

(a) Greater than speed of light

(b) Less than speed of light

(c) Equal to the speed of light

(d) None of these

- Q.2** The primary advantage of ridged waveguide over rectangular waveguide is its  
(a) Simple construction  
(b) Cost  
(c) Attenuation  
(d) Ability to work at lower frequency
- Q.3** The wavelength of EM wave inside the waveguide is  
(a) Greater than the free space wavelength  
(b) Less than the free space wavelength  
(c) Equal to the free space wavelength  
(d) None of these
- Q.4** The characteristic wave impedance for an air filled rectangular waveguide is  
(a)  $120\pi\Omega$   
(b) Dependent on frequency  
(c) Dependent on dimensions of waveguide  
(d) Both (b) and (c)
- Q.5** The coupling of microwave energy into and out of a waveguide can be accomplished by  
(a) Loops (b) Probes  
(c) Both (a) and (b) (d) None of these
- Answers : (Objective)**  
1. (b) 2. (d) 3. (a) 4. (d) 5. (c)

