

MICROWAVE ENGINEERING

INTRODUCTION

Lecture Details:

Topic Name WAVE GUIDES

Subject/Branch, Semester:MWE & OC , ECE, 6th.

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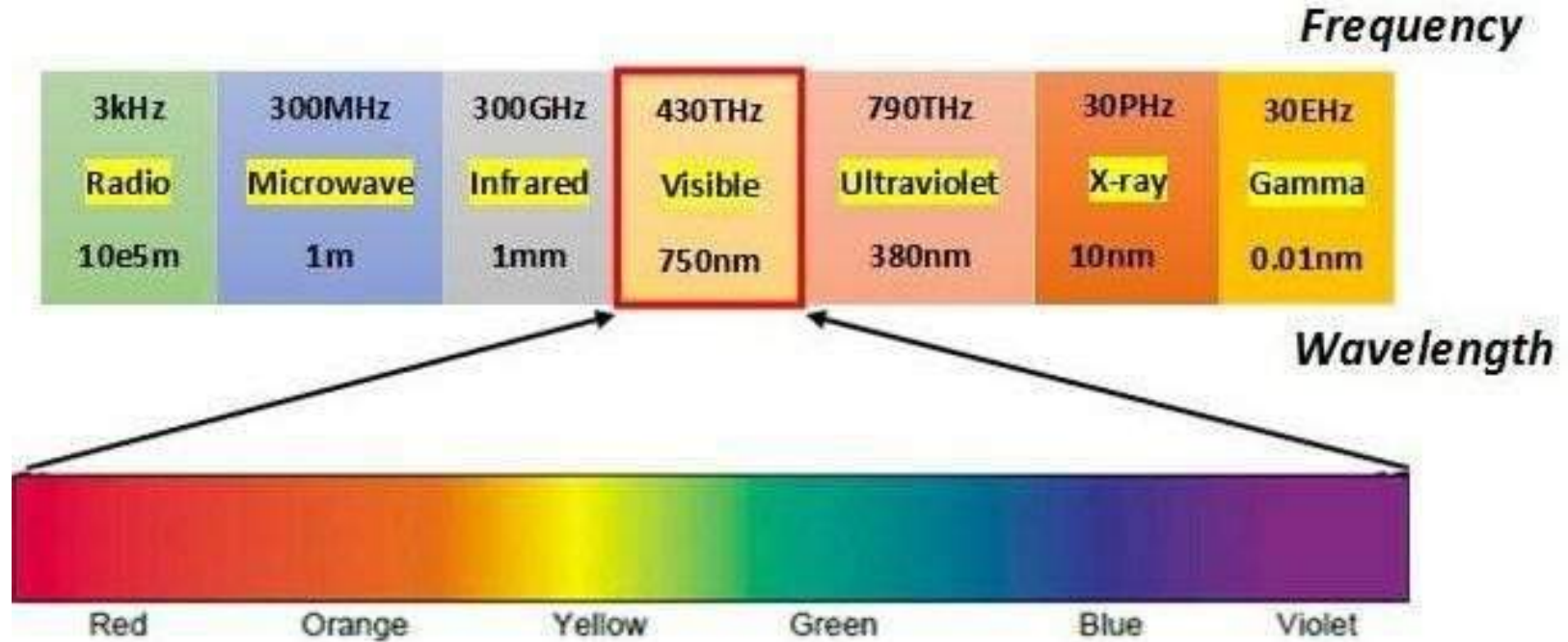
Department: ECE

College:GIET(A)

Introduction

- Microwaves are a form of electromagnetic radiation with wavelengths ranging from about one meter to one millimeter; with frequencies between 300 MHz (1 m) and 300 GHz (1 mm).
- In all cases, microwaves include the entire SHF band (3 to 30 GHz, or 10 to 1 cm) at minimum.
- Frequencies in the microwave range are often referred to by their IEEE radar band designations: S, C, X, K_u, K, or K_a band or by similar NATO or EU designations.

Microwave spectrum



Microwave frequency bands

Designation	Frequency range	Wavelength range	
L band	1 to 2 GHz	15 cm to 30 cm	
S band	2 to 4 GHz	7.5 cm to 15 cm	
C band	4 to 8 GHz	3.75 cm to 7.5 cm	
X band	8 to 12 GHz	25 mm to 37.5 mm	

K _u band	12 to 18 GHz	16.7 mm to 25 mm
K band	18 to 26.5 GHz	11.3 mm to 16.7 mm
K _a band	26.5 to 40 GHz	5.0 mm to 11.3 mm
Q band	33 to 50 GHz	6.0 mm to 9.0 mm
U band	40 to 60 GHz	5.0 mm to 7.5 mm

V band	50 to 75 GHz	4.0 mm to 6.0 mm
W band	75 to 110 GHz	2.7 mm to 4.0 mm
F band	90 to 140 GHz	2.1 mm to 3.3 mm
D band	110 to 170 GHz	1.8 mm to 2.7 mm

ADVANTAGES OF MICROWAVES

- **Large Bandwidth:** The Bandwidth of Microwaves is larger than the common low frequency radio waves.
- **Better Directivity:** At Microwave Frequencies, there are better directive properties.
- **Small Size Antenna:** Microwaves allows to decrease the size of antenna.
- **Low Power Consumption:** Microwaves have high frequency thus requires very less power.
- **Effect Of Fading:** The effect of fading is minimized by using Line Of Sight propagation technique at Microwave .

APPLICATIONS OF MICROWAVES

- Communication
- Military
- Medical Science

WAVE GUIDES

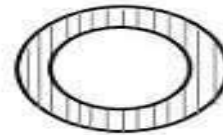
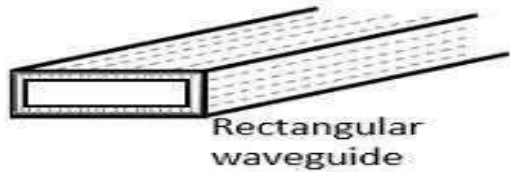
- A hollow metallic tube of the uniform cross section for transmitting electromagnetic waves by successive reflections from the inner walls of the tube is called as a Waveguide.
- Microwaves propagate through microwave circuits, components and devices, which act as a part of Microwave transmission lines, broadly called as Waveguides.

ADVANTAGES OF WAVEGUIDES

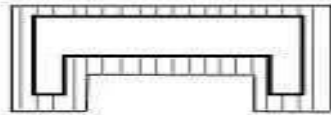
- Waveguides are easy to manufacture.
- They can handle very large power (in kilowatts)
- Power loss is very negligible in waveguides
- They offer very low loss

Types of waveguides

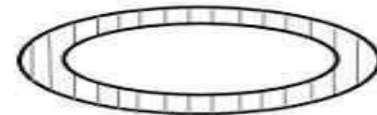
Types of Waveguides



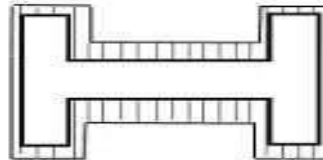
Circular waveguide



Single ridged waveguide



Elliptical waveguide



Double ridged waveguide

Transmission Lines Vs Waveguides

The main difference between a transmission line and a wave guide is –

- A two conductor structure that can support a TEM wave is a transmission line.
- A one conductor structure that can support a TE wave or a TM wave but not a TEM wave is called as a waveguide.

Rectangular Waveguides

- Rectangular waveguides are the one of the earliest type of the transmission lines.
- They are used in many applications. A lot of components such as isolators, detectors, attenuators, couplers and slotted lines are available for various standard waveguide bands between 1 GHz to above 220 GHz.
- A rectangular waveguide supports TM and TE modes but not TEM waves because we cannot define a unique voltage since there is only one conductor in a rectangular waveguide.
- The shape of a rectangular waveguide is as shown below. A material with permittivity ϵ and permeability μ fills the inside of the conductor.

Modes of wave guides

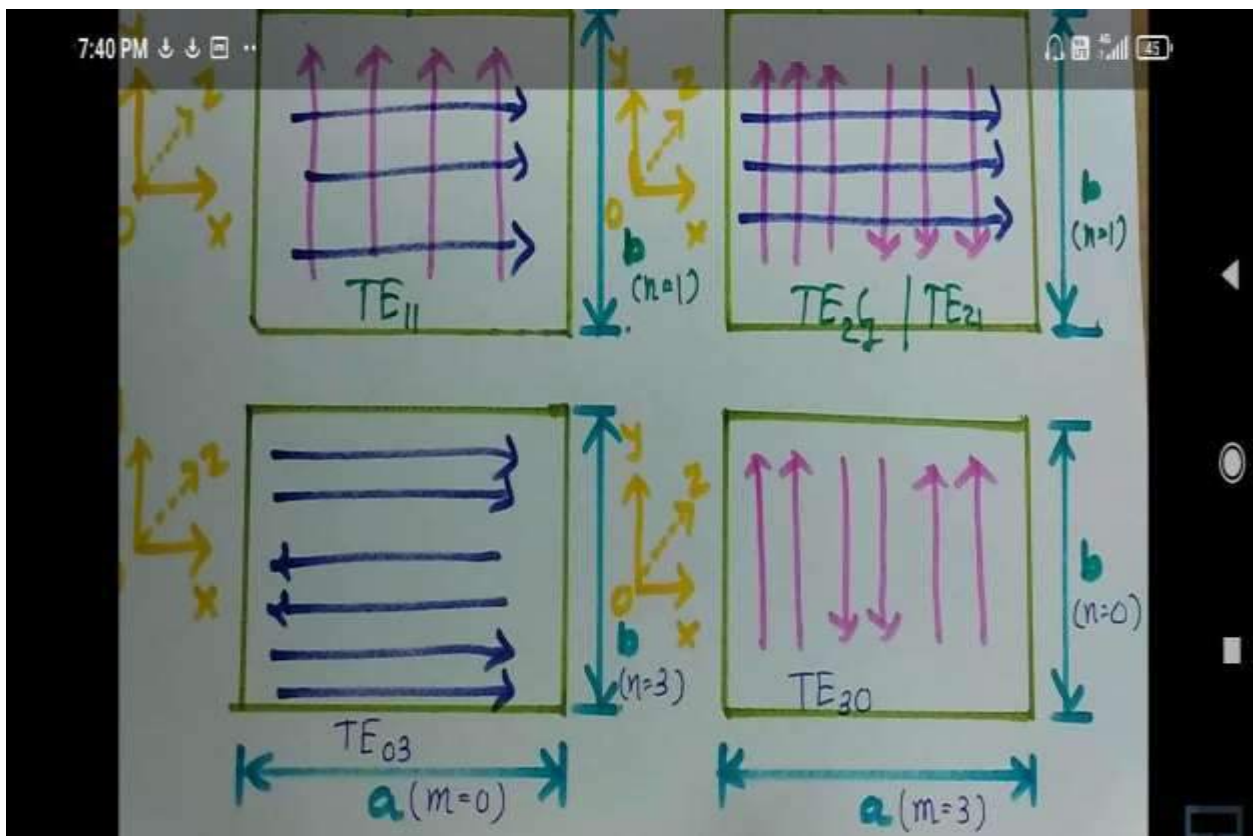
Waveguide modes

Looking at waveguide theory it is possible to calculate there are a number of formats in which an electromagnetic wave can propagate within the waveguide.

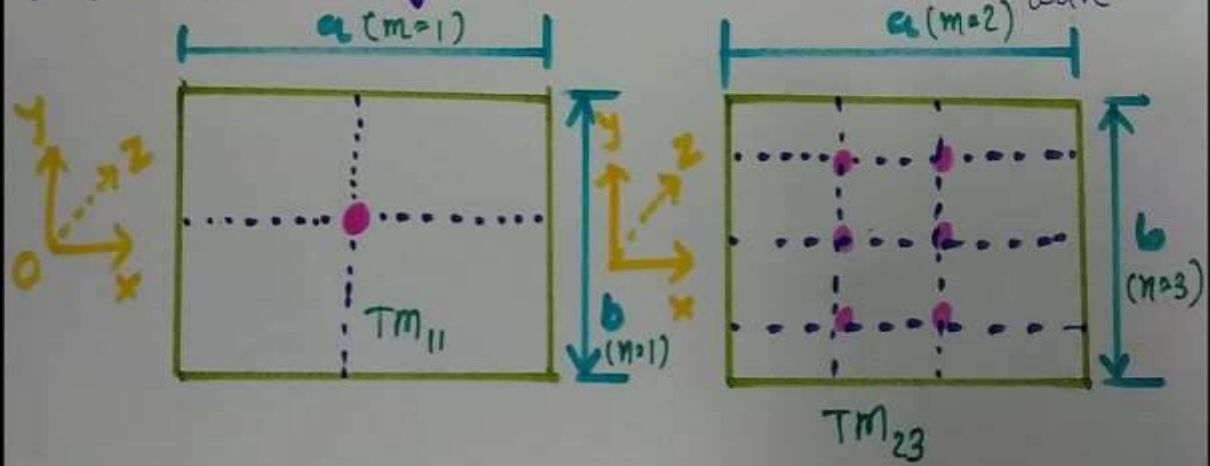
TE mode: In TE wave only the E field is purely transverse to the direction of propagation and the magnetic field is not purely transverse i.e. $E_z=0, H_z \neq 0$

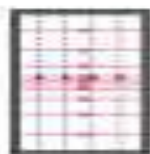
TM mode Transverse magnetic waves, also called E waves are characterised by the fact that the magnetic vector (H vector) is always perpendicular to the direction of propagation. :

TEM mode: The TEM wave is characterised by the fact that both the electric vector (E vector) and the magnetic vector (H vector) are perpendicular to the direction of propagation.

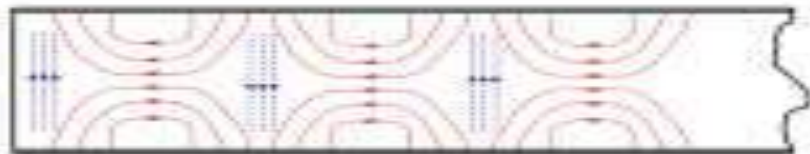


→ Transverse Magnetic mode (TM mode) ← current wave

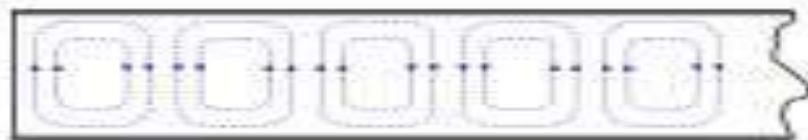




TE_{10}



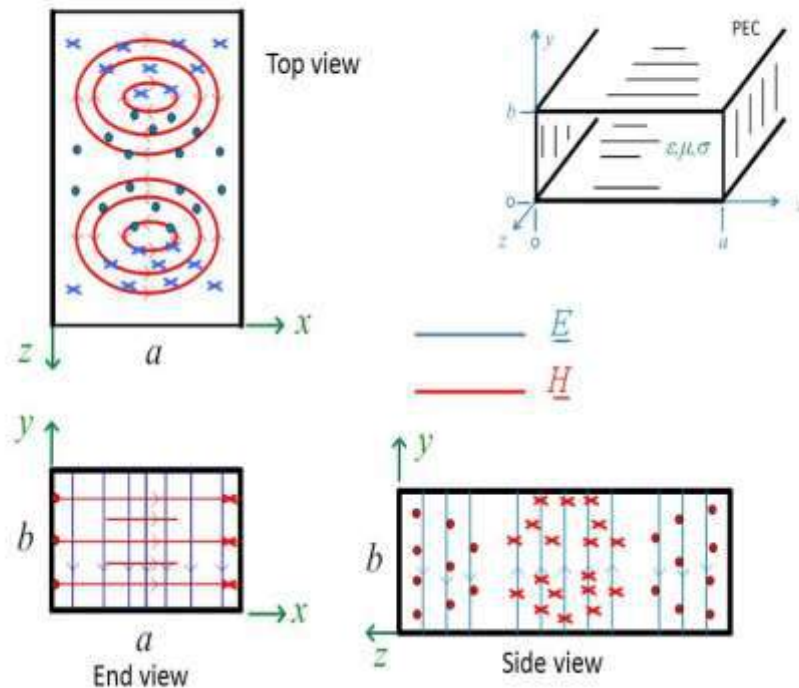
TM_{11}



TE_{11}

—•— E field
 —•— H field

Field Plots for TE_{10} Mode



Field equations in rectangular waveguides

WAVE EQUATIONS

Since we assumed that the wave direction is along z-direction then the wave equation are

$$\nabla^2 E_z = -\omega^2 \mu \epsilon E_z$$

for TM wave-----(1)

$$\nabla^2 H_z = -\omega^2 \mu \epsilon H_z$$

for TE wave -----(2)

$$\text{Where } E_z = E_0 e^{-\gamma z}, H_z = H_0 e^{-\gamma z} \text{-----(3)}$$

The condition for wave propagation is that γ must be imaginary. Differentiating eqn(3) w.r.t 'z' we get

$$\partial E_z / \partial z = E_0 e^{-\gamma z} (-\gamma) = -\gamma E_z \text{-----(4)}$$

$$\text{Hence we can define operator } \partial / \partial z = -\gamma \text{-----(5)}$$

We can define the operator

$$\partial^2/\partial z^2 = \gamma^2 \text{-----}(6)$$

From eqn(1) we can write

$$\nabla^2 E_z = -\omega^2 \mu \epsilon E_z$$

By expanding $\nabla^2 E_z$ in rectangular coordinate system

$$\partial^2 E_z / \partial x^2 + \partial^2 E_z / \partial y^2 + \partial^2 E_z / \partial z^2 = 0$$

For TM wave----- (7)

Similarly $\partial^2 H_z / \partial x^2 + \partial^2 H_z / \partial y^2 + \partial^2 H_z / \partial z^2 = 0$ for TE wave----

----- (8)

By solving above two partial differential equations we get solutions for E_z and H_z . Using Maxwell's equations. it is possible to find the various components along x and y-directions.

From Maxwell's first equation, we have

$$\nabla \times H = j\omega \epsilon E$$

$$\begin{matrix} a_x & a_y & a_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ H_x & H_y & H_z \end{matrix} = j\omega \epsilon [E_x a_x + E_y a_y + E_z a_z]$$

$$a_x \rightarrow \gamma H_y + \partial H_z / \partial y = j\omega \epsilon E_x \text{-----} (9)$$

$$a_y \rightarrow \gamma H_x + \partial H_z / \partial x = -j\omega \epsilon E_y \text{-----} (10)$$

$$a_z \rightarrow \partial H_y / \partial x + \partial H_x / \partial y = j\omega \epsilon E_z \text{-----} (11)$$

similarly from Maxwell's 2nd equation we have

$$\nabla \times E = -j\omega\mu H$$

By expanding

$$\begin{matrix} a_x & a_y & a_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E & E_z \end{matrix} = j\omega\epsilon^* [H_x a_x + H_y a_y + H_z a_z]$$

Since $\partial/\partial z = \gamma$

By comparing a_x, a_y, a_z components

$$a_x \rightarrow \gamma E_y + \partial E_z / \partial y = -j\omega\mu H_x \text{-----(12)}$$

$$a_y \rightarrow \gamma E_x + \partial E_z / \partial x = j\omega\mu H_y \text{-----(13)}$$

$$a_z \rightarrow \partial E_y / \partial x - \partial E_x / \partial y = -j\omega\epsilon H_z \text{-----(14)}$$

From eqn(13)

$$H_y = [\gamma E_x + \partial E_z / \partial x] / j\omega\mu \text{ -----(15)}$$

By substituting eqn(15) in eqn(9) we get

$$\gamma^2 / j\omega\mu E_x + \gamma / j\omega\epsilon \partial E_z / \partial x +$$

$$\partial H_z / \partial y = j\omega\epsilon E_x$$

$$\text{since } \gamma^2 + \omega^2\mu\epsilon = h^2$$

by dividing the above equation with h^2 we get

$$E_x = -\gamma / h^2 \partial E_z / \partial x - j\omega\mu / h^2 \partial H_z / \partial y$$

$$E_y = -\gamma / h^2 \partial E_z / \partial x + j\omega\epsilon / h^2 \partial E_z / \partial y$$

$$H_x = -\gamma / h^2 \partial H_z / \partial x + j\omega\mu / h^2 \partial E_z / \partial y$$

$$H_y = -\gamma / h^2 \partial H_z / \partial y - j\omega\mu / h^2 \partial E_z / \partial x$$

These equations give a general relationship for field components with in a waveguide.

Modes

- The electromagnetic wave inside a waveguide can have an infinite number of patterns which are called modes.
- The electric field cannot have a component parallel to the surface i.e. the electric field must always be perpendicular to the surface at the conductor.
- The magnetic field on the other hand always parallel to the surface of the conductor and cannot have a component perpendicular to it at the surface.

TE Mode Analysis

The TEM_{mn} modes in a rectangular waveguide are characterized by $E_z=0$. The z component of the magnetic field, H_z must exist in order to have energy transmission in the guide.

The wave equation for TE wave is given by

$$\nabla^2 H_z = -\omega^2 \mu \epsilon H_z \text{-----(1)}$$

i.e.

$$\frac{\partial^2 H_z}{\partial x^2} + \frac{\partial^2 H_z}{\partial y^2} + \frac{\partial^2 H_z}{\partial z^2} = -\omega^2 \mu \epsilon H_z$$

$$\frac{\partial^2 H_z}{\partial x^2} + \frac{\partial^2 H_z}{\partial y^2} + \gamma^2 H_z + \omega^2 \mu \epsilon H_z = 0$$

$$\frac{\partial^2 H_z}{\partial x^2} + \frac{\partial^2 H_z}{\partial y^2} + (\gamma^2 + \omega^2 \mu \epsilon) H_z = 0$$

$$\gamma^2 + \omega^2 \mu \epsilon = h^2$$

$$\frac{\partial^2 H_z}{\partial x^2} + \frac{\partial^2 H_z}{\partial y^2} + h^2 H_z = 0 \text{-----(2)}$$

This is a partial differential equation whose solution can be assumed.

Assume a solution

$$H_z = XY$$

Where X = pure function of x
only Y = pure function of y only

From equation 2

$$\frac{\partial^2 [XY]}{\partial x^2} + \frac{\partial^2 [XY]}{\partial y^2} + h^2 XY = 0$$

Dividing above equation with XY on both sides

$$\frac{1}{X} \frac{\partial^2 X}{\partial x^2} + \frac{1}{Y} \frac{\partial^2 Y}{\partial y^2} + h^2 = 0 \text{-----(3)}$$

Here $\frac{1}{X} \frac{\partial^2 X}{\partial x^2}$ is purely a function of x and $\frac{1}{Y} \frac{\partial^2 Y}{\partial y^2}$ is purely a function of y

$$\text{Let } \frac{1}{X} \frac{\partial^2 X}{\partial x^2} = -B^2 \text{ \& } \frac{1}{Y} \frac{\partial^2 Y}{\partial y^2} = -A^2$$

i.e. from equation (3)

$$-B^2-A^2+h^2=0$$

i.e. $h^2=A^2+B^2$ -----(4)

$$X=c_1\cos Bx+c_2\sin Bx$$

$$Y=c_3\cos Ay+c_4\sin Ay$$

i.e. the complete solution for $H_z=XY$ is

$$H_z= (c_1\cos Bx+c_2\sin Bx)(c_3\cos Ay+c_4\sin Ay)-----(5)$$

Where c_1, c_2, c_3 and c_4 are constants which can be evaluated by applying boundary conditions.

Boundary Conditions

Since we consider a TE wave propagating along z direction.

So $E_z=0$ but we have components along x and y direction.

$E_x=0$ waves along bottom and top walls of the waveguide
 $E_y=0$ waves along left and right walls of the waveguide

1st Boundary condition:

$E_x=0$ at $y=0 \forall x \rightarrow 0$ to a (bottom wall)

2nd Boundary condition

$E_x=0$ at $y=b \forall x \rightarrow 0$ to a (top wall)

3rd Boundary condition

$E_y=0$ at $x=0 \forall y \rightarrow 0$ to b

(left side wall)

4th Boundary
condition

$E_y=0$ at $x=a \forall y \rightarrow 0$ to b (right side wall)

Substituting the value of c_4 in eqn (5), the solution reduces to

$$H_z = (c_1 \cos Bx + c_2 \sin Bx)(c_3 \cos Ay) \text{-----(7)}$$

ii) from third boundary condition

$$E_y = 0 \text{ at } x=0 \quad \forall y \rightarrow 0 \text{ to } b$$

Since we

have

$$E_y = -\gamma/h^2 \partial E_z / \partial y + j\omega\mu/h^2 \partial H_z / \partial x \text{-----(8)}$$

Since $E_z=0$ and substituting the value of H_z in eqn(7), we get $E_y=$

$$j\omega\mu/h^2\partial[(c_1\cos Bx+c_2\sin Bx)(c_3\cos Ay)]/\partial x$$

$$E_y= j\omega\mu/h^2*(-Bc_1\sin Bx+Bc_2\sin Bx)(c_3\cos Ay)+$$

iii) From third

condition,

$$0=j\omega\mu/h^2(0+Bc_2)c_3\cos Ay$$

Since

$$\cos Ay \neq 0, B \neq 0, c_3 \neq 0$$

$$c_2=0$$

from eq (7) $H_z = c_1 c_3 \cos Bx \cos Ay$ ----- (9)

iii) 2nd Boundary condition since we have

$$E_x = -\gamma/h^2 \partial E_z / \partial x - j\omega\mu/h^2 \partial H_z / \partial y$$

$$= -j\omega\mu/h^2 \partial / \partial y [c_1 c_3 \cos Bx \cos Ay] \quad [E_z = 0] \quad E_x = j\omega\mu/h^2$$

$$c_1 c_3 \cos Bx \sin Ay$$

From the second boundary condition,

$$E_x = 0 \text{ at } y=b \quad \forall x \rightarrow 0 \text{ to } a$$

$$0 = j\omega\mu/h^2 c_1 c_3 \cos Bx \sin Ab$$

$$\cos Bx \neq 0, c_1 c_3 \neq 0$$

$$\sin Ab = 0 \text{ or } Ab = n\pi \text{ where } n=0,1,2,\dots$$

$$A = n\pi/b \text{----- (10)}$$

iv) 4th Boundary condition since

$E_y = -\frac{1}{h^2} \frac{\partial E}{\partial y} + j\omega\mu \frac{\partial H_z}{\partial x}$ $E_y = -$
 $j\omega\mu/h^2 \frac{\partial}{\partial x} [c_1 c_3 \cos Bx \cos Ay]$ $E_y = -$
 $j\omega\mu/h^2 c_1 c_3 \sin Bx \cdot B \cos Ay$ iv) From the 4th
 Boundary condition $E_y = 0$ at $x = a \forall y \rightarrow 0$ to b
 $0 = -j\omega\mu/h^2 B c_1 c_3 \sin Bx \cdot \cos Ay \forall y \rightarrow 0$ to b
 $\cos Ay \neq 0, c_1 c_3 \neq 0$
 $\sin Ba = 0$
 $B = m\pi/a$ ----- (11)
 From eq(9)
 $H_z = c_1 c_3 \cos(m\pi/a)x \cos(n\pi/b)y$
 Let $c_1 c_3 = c$
 $H_z = c \cos(m\pi/a)x \cos(n\pi/b)y e^{(j\omega t - \gamma z)}$ ----- (12)

Field Components

$$E_x = -\gamma/h^2 \partial E_z / \partial x -$$

$$j\omega\mu/h^2 \partial H_z / \partial y \text{ Since } E_z=0 \text{ for}$$

TE wave

$$E_x = j\omega\mu/h^2 c (n\pi/b) \cos(m\pi/a) x \sin(n\pi/b) y e^{(j\omega t - \gamma z)} \text{----- (13) } E_y = -$$

$$\gamma/h^2 \partial E_z / \partial y + j\omega\mu/h^2 \partial H_z / \partial x$$

Since $E_z=0$ for TE wave

$$E_y = j\omega\mu/h^2 \partial H_z / \partial x$$

$$E_y = -j\omega\mu/h^2 c [m\pi/a] \sin(m\pi/a) x \cos(n\pi/b) y e^{(j\omega t - \gamma z)} \text{----- (14) Similarly}$$

$$H_x = -\gamma/h^2 \partial H_z / \partial x - j\omega\epsilon/h^2 \partial E_z / \partial y$$

$$H_x = \gamma/h^2 c (m\pi/a) \sin(m\pi/a) x \cos(n\pi/b) y e^{(j\omega t - \gamma z)} \text{----- (15) } H_y = -$$

$$\gamma/h^2 \partial H_z / \partial y + j\omega\epsilon/h^2 \partial E_z / \partial x$$

$$H_y = -\gamma/h^2 c (n\pi/b) 2 \cos(m\pi/a) x \sin(n\pi/b) y e^{(j\omega t - \gamma z)} \text{----- (16)}$$

TM Mode

For TM wave $H_z=0$ $E_z \neq 0$

$$\partial^2 E_z / \partial x^2 + \partial^2 E_z / \partial y^2 + h^2 E_z = 0 \text{-----(1)}$$

This is a partial differential equation which can be solved to get the different field components E_x, E_y, H_x and H_y by variable separable method.

Let us assume a solution $E_z = XY$ ------(2) Using these two equations from eqn(1)

we get

$$Y \partial^2 X / \partial x^2 + X \partial^2 Y / \partial y^2 + h^2 XY = 0 \text{-----(3)}$$

Dividing above equation with XY on both sides

$$1/X (\partial^2 X / \partial x^2) + 1/Y (\partial^2 Y / \partial y^2) + h^2 = 0 \text{-----(4)}$$

Here $1/X \partial^2 X / \partial x^2$ is purely a function of x and $1/Y \partial^2 Y / \partial y^2$ is purely a function of y

Let $\frac{1}{X}(\partial^2 X / \partial x^2) = -B^2$ -----(5)

$$\frac{1}{Y}(\partial^2 Y / \partial y^2) = -A^2$$
-----(6)

i.e. from equation (4),(5) and(6)

$$-B^2-A^2+h^2=0 \text{ i.e.}$$

$$h^2=A^2+B^2$$
-----(7)

the solution of eqn(5) and(6) are

$$X=c_1\cos Bx+c_2\sin Bx$$

$$Y=c_3\cos Ay+c_4\sin Ay$$

Where c_1, c_2, c_3 and c_4 are constants which can be evaluated by applying boundary conditions

From eqn(1)

$E_z = XY$

$$E_z = (c_1 \cos Bx + c_2 \sin Bx)(c_3 \cos Ay + c_4 \sin Ay) \text{----(8)}$$

Boundary Conditions

Since we consider a TE wave propagating along z direction. So $E_z=0$ but we have components along x and y direction.

1st Boundary condition: $E_z=0$ at $y=0 \forall x \rightarrow 0$ to a (bottom wall)

2nd Boundary condition $E_z=0$ at $y=b \forall x \rightarrow 0$ to a (top wall)

3rd Boundary condition $E_z=0$ at $x=0 \forall y \rightarrow 0$ to b (left side wall)

4th Boundary condition $E_z=0$ at $x=a \forall y \rightarrow 0$ to b (right side wall)

i) Substituting 1st Boundary condition in eqn(10) Since we have

$$0 = E_z = [c_1 \cos Bx + c_2 \sin Bx][c_3 \cos A_0 + c_4 \sin A_0]$$

$$[c_1 \cos Bx + c_2 \sin Bx] c_3 = 0$$

$$c_1 \cos Bx + c_2 \sin Bx \neq 0, c_3 = 0$$

$$\text{i.e. } E_z = [c_1 \cos Bx + c_2 \sin Bx] c_4 \sin A_y \text{-----(11)}$$

ii) Substituting 2nd Boundary condition in eqn(11),
we get

$$E_z = c_2 c_4 \sin Bx \sin A_y \text{-----(12)}$$

iii) Substituting 3rd Boundary condition in eqn(12),

$$\text{iv) we get } \sin A_b = 0 \quad A = n\pi/b \text{-----(13)}$$

v) Substituting 4th Boundary condition in eqn(12), we get $\sin B_a = 0$

$$B = m\pi/a \text{-----(14)}$$

From (12),(13),(14)

$$E_z = c \sin(m\pi/a)x \sin(n\pi/b)y e^{j(\omega t - \gamma z)}$$

----- (15)

$$E_x = -\gamma/h^2 \partial E_z / \partial x$$

$$E_x = -\gamma/h^2c(m\pi/a)\cos(m\pi/a)x\sin(n\pi/b) \gamma e^{j(\omega t - \gamma z)}$$

$$E_y = -\gamma/h^2c(n\pi/b)\sin(m\pi/a)x\cos(n\pi/b) \gamma e^{j(\omega t - \gamma z)} \quad \text{-----} \quad (17)$$

$$H_x = j\omega\epsilon/h^2c(n\pi/b)\sin(m\pi/a)x\cos(n\pi/b) \gamma e^{j(\omega t - \gamma z)} \quad \text{-----} \quad (18)$$

$$H_y = j\omega\epsilon/h^2c[m\pi/a]\cos(m\pi/a)x\sin(n\pi/b) \gamma e^{j(\omega t - \gamma z)} \quad \text{-----} \quad (19)$$

Power losses in Rectangular Waveguide

There are two types of power losses in a rectangular waveguide:

1. Losses in the dielectric
2. Losses in the guide walls

In a low-loss dielectric (that is, $\sigma \ll \omega\epsilon$), the propagation constant for a plane wave traveling in an unbounded lossy dielectric is given by :

$$\alpha = \frac{\sigma}{2} \sqrt{\frac{\mu}{\epsilon}} = \frac{\eta\sigma}{2}$$

$$\alpha_g = \frac{\sigma\eta}{2\sqrt{1 - (f_c/f)^2}} \quad \text{for TE mode}$$

$$\alpha_g = \frac{\sigma\eta}{2} \sqrt{1 - (f_c/f)^2} \quad \text{for TM mode}$$

Cut-off Frequency

Cut-off Frequency of a Waveguide

$$\gamma^2 + \omega^2 \mu \epsilon = h^2 = A^2 + B^2$$

$$A = n\pi/b, B = m\pi/a$$

$$\gamma^2 = (m\pi/a)^2 + (n\pi/b)^2 - \omega^2 \mu \epsilon$$

$$\gamma = \sqrt{(m\pi/a)^2 + (n\pi/b)^2 - \omega^2 \mu \epsilon} = \alpha + j\beta$$

At lower frequencies $\gamma > 0$

$$\sqrt{(m\pi/a)^2 + (n\pi/b)^2 - \omega^2 \mu \epsilon} > 0$$

γ then becomes real and positive

and equal to the attenuation

constant.

$$R_s \equiv \frac{\rho}{\delta} = \frac{1}{\sigma \delta} = \frac{\alpha_s}{\sigma} = \sqrt{\frac{\pi f \mu}{\sigma}} \quad \Omega/\text{square}$$

- The attenuation constant of the guide walls is equal to the ratio of the power loss per unit length to twice the power transmitted through the guide.
- Since the electric and magnetic field intensities established at the surface of a low-loss guide wall decay exponentially with respect to the skin depth while the waves progress into the walls, it is better to define a surface resistance of the guide walls as :
-
- where ρ = resistivity of the conducting wall in ohms-meter
 σ = conductivity in mhos per meter
 δ = skin depth or depth of penetration in meters

[Power transmission]

- The average Poynting vector for the waveguide fields is

$$\begin{aligned}\mathcal{P}_{ave} &= \frac{1}{2} \operatorname{Re}[E \times H^*] = \frac{1}{2} \operatorname{Re}[E_x H_y^* - E_y H_x^*] \\ &= \frac{|E_x|^2 + |E_y|^2}{2\eta} \hat{z} \quad [\text{W/m}^2]\end{aligned}$$

- where $\eta = \eta_{TE}$ or η_{TM} depending on the mode

$$P_{ave} = \int \mathcal{P}_{ave} \cdot dS = \int_{x=0}^a \int_{y=0}^b \frac{|E_x|^2 + |E_y|^2}{2\eta} dy dx \quad [\text{W}]$$

MICROWAVE ENGINEERING

INTRODUCTION

Lecture Details:

Topic Name Circular wave guides

Subject/Branch, Semester : MWE & OC ,ECE,6th

Presented By:

M.SARITHA DEVI

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Circular wave guide



A Hollow metallic tube of uniform circular cross section for transmitting electromagnetic waves by successive reflections from the inner walls of the tube is called *Circular waveguide.*

Applications of circular waveguide

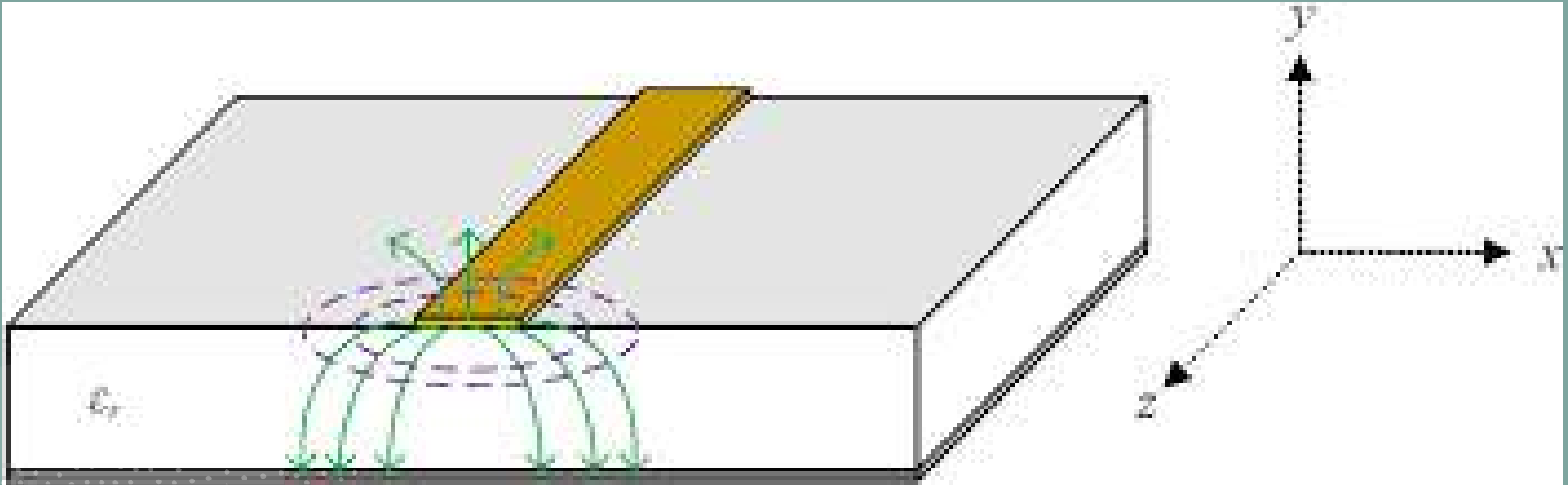
- Rotating joints in radars to connect the horn antenna feeding a parabolic reflector (which must rotate for tracking).
- TE_{01} mode suitable for long distance waveguide transmission above 10 GHz.
- Short and medium distance broad band communication (could replace / share coaxial and microwave links).
- To reduce attenuation loss.
- Can operate only above certain frequencies.

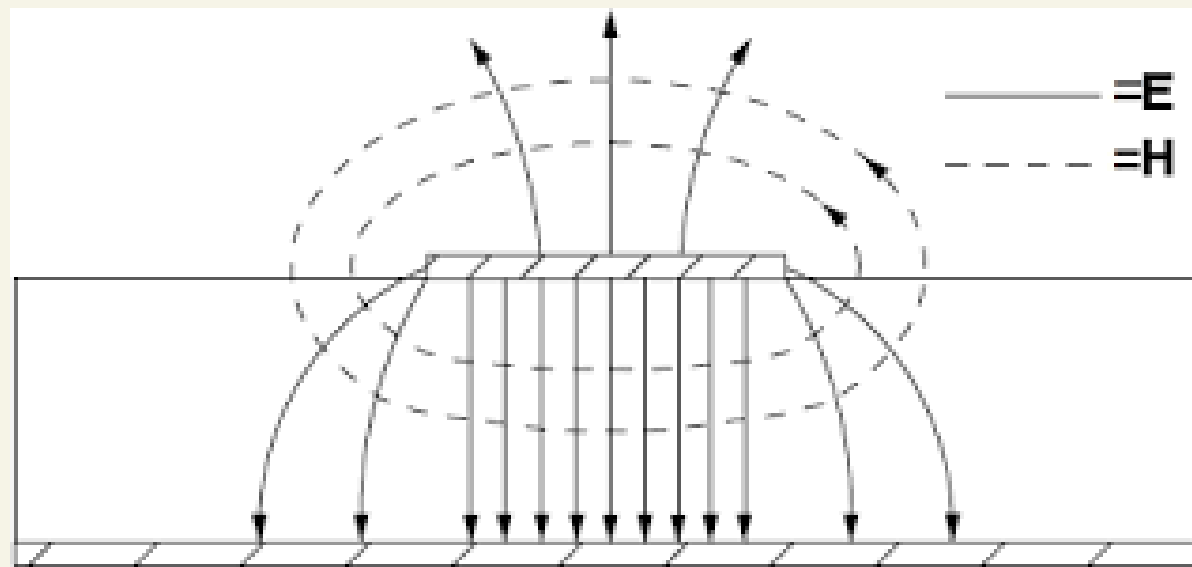
CIRCULAR WAVEGUIDES

- The circular waveguide is used in many special applications in microwave techniques.
- It has the advantage of greater power – handling capacity and lower attenuation for a given cutoff wavelength. However, the disadvantage of somewhat greater size and weight.
- The polarization of the transmitted wave can be altered due to the minor irregularities of the wall surface of the circular guide, whereas the rectangular wave guide the polarization is fixed.

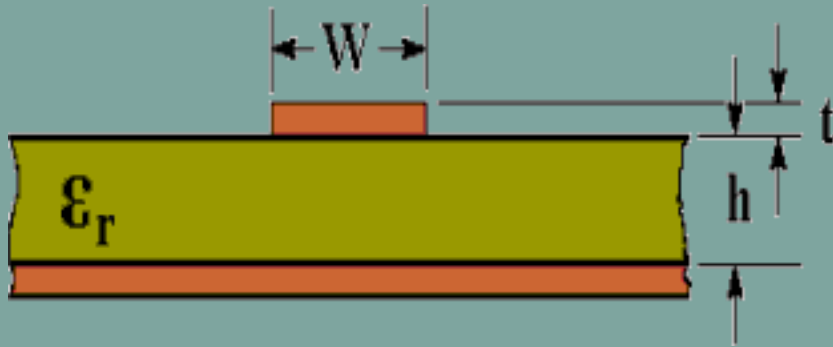
MICRO STRIP LINES: INTRODUCTION:

- Strip lines are essentially modifications of wire lines and coaxial lines. They are basically planar transmission lines widely used at frequencies 100MHz to 100 GHz





Characteristic Impedance Z_0 :



- The characteristic impedance of a micro strip line is a function of the strip line width, thickness, the distance between the line and the ground and the homogeneous dielectric constant of the board material

$$Z_o = (60/\text{sr}) \ln 4h/d \text{ for } h \gg d$$

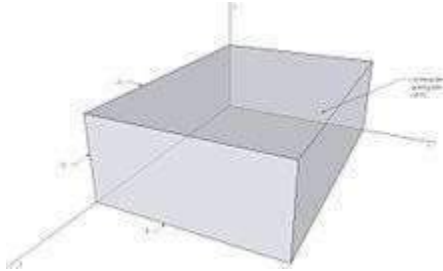
Losses in Micro strip Lines:

The attenuation constant of the dominant mode of the micro strip line depends on geometric factors, electrical properties of substrate and conductors and the frequency.

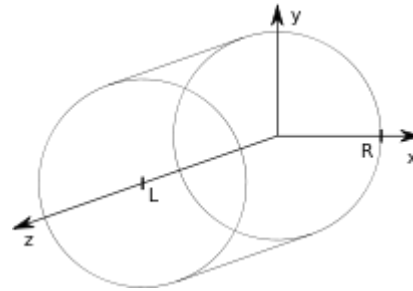
For non magnetic dielectric substrate, there occur two types of losses, one due to dielectric in the substrate and another due to ohmic skin loss in the strip conductor and the ground plate.

Cavity Resonators

- A cavity resonator is a metallic enclosure that confines the electromagnetic energy i.e.
- when one end of the waveguide is terminated in a shorting plate there will be reflections and hence standing waves
- When another shorting plate is kept at a distance of a multiple of $\lambda_g/2$ than the hollow space so formed can support a signal which bounces back and forth between the two shorting plates.
- This results in resonance and hence the hollow space is called “cavity” and the resonator as the ‘cavity resonator’



Rectangular Cavity resonator



Circular Cavity resonator

The stored electric and magnetic energies inside the cavity determine its equivalent inductance and capacitance.

- The energy dissipated by the finite conductivity of the cavity walls determines its equivalent resistance.
- A given resonator has an infinite number of resonant modes and each mode corresponds to a definite resonant frequency.
- When the frequency of an impressed signal is equal to a resonant frequency a maximum amplitude of the standing wave occurs and the peak energies stored in the electric and magnetic fields are equal.
- The mode having the lowest resonant frequency is called as the 'Dominant mode'

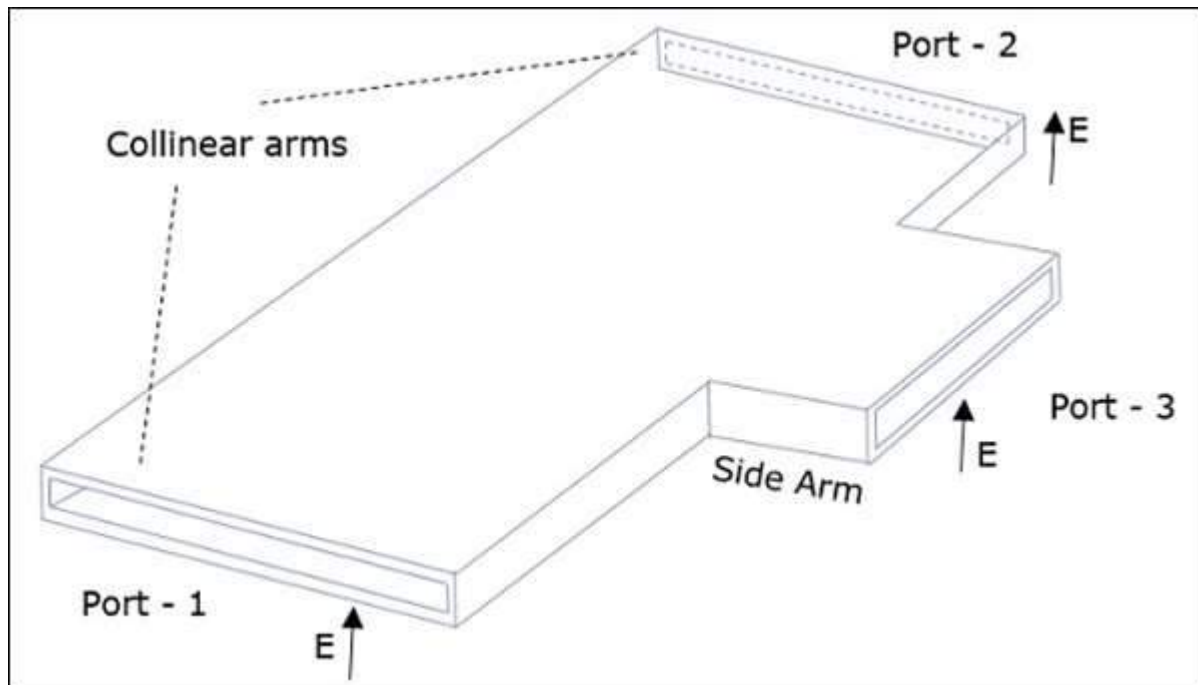
Rectangular cavity Resonator The electromagnetic field inside the cavity should satisfy Maxwell's equations subject to the boundary conditions that the electric field tangential to and the magnetic field normal to the metal walls must vanish.

The wave equations in the rectangular resonator should satisfy the boundary condition of the zero tangential 'E' At four of the walls.

H-PLANE TEE

An H-Plane Tee junction is formed by attaching a simple waveguide to a rectangular waveguide which already has two ports.

The arms of rectangular waveguides make two ports called collinear ports i.e., Port1 and Port2, while the new one, Port3 is called as Side arm or H-arm. This H-plane Tee is also called as Shunt Tee.

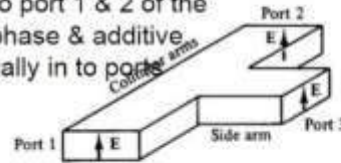


Properties of H-Plane Tee

H Plane Tee

An H plane tee is a waveguide tee in which the axis of its arm is shunting the E field or parallel the H field to main guide as shown .

- It can be seen that if two input waves are fed in to port 1 & 2 of the collinear arm the output wave at port 3 will be in phase & additive.
- If the input is fed to port 3 the wave will split equally in to ports 1 & 2 in phase & same magnitude.



The S matrix of H Plane tee is similar to that of E plane tee as shown

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{11} & -S_{13} \\ S_{13} & -S_{13} & S_{33} \end{bmatrix}$$

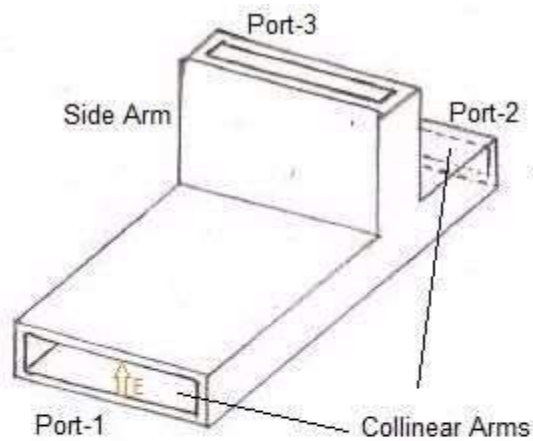
but $S_{13}=S_{23}$.

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{11} & S_{13} \\ S_{13} & S_{13} & S_{33} \end{bmatrix} \quad \text{If all ports are matched} \quad S = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{13} \\ S_{13} & S_{13} & 0 \end{bmatrix}$$

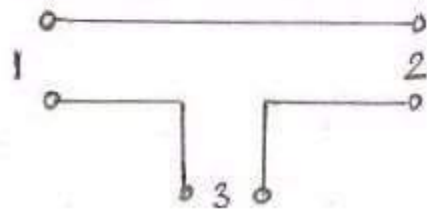
E-PLANE TEE

An E-Plane Tee junction is formed by attaching a simple waveguide to the broader dimension of a rectangular waveguide, which already has two ports.

The arms of rectangular waveguides make two ports called collinear ports i.e., Port1 and Port2, while the new one, Port3 is called as Side arm or E-arm. This E-plane Tee is also called as Series Tee.



E Plane Tee



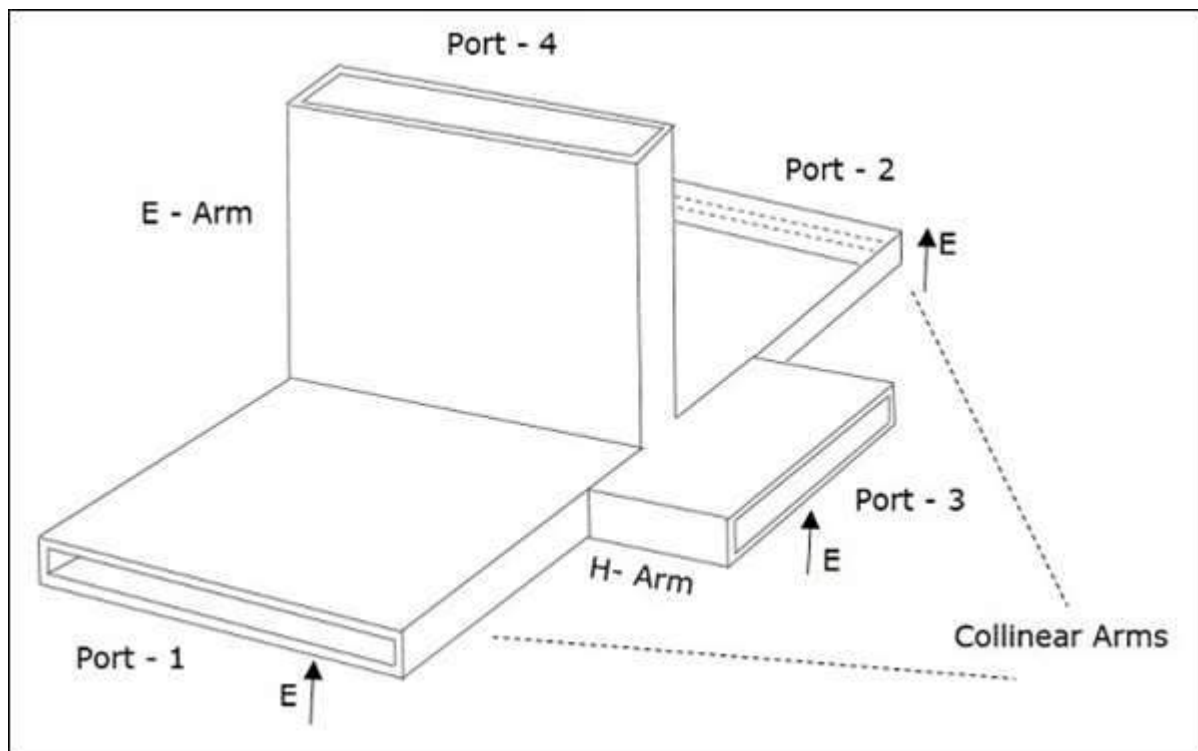
$$\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{21} & 0 & S_{23} \\ S_{31} & S_{32} & 0 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{11} & -S_{13} \\ S_{13} & -S_{13} & S_{33} \end{bmatrix} \quad (2)$$

E-H PLANE TEE

An E-H Plane Tee junction is formed by attaching two simple waveguides one parallel and the other series, to a rectangular waveguide which already has two ports.

This is also called as Magic Tee, or Hybrid or 3dB coupler.



$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{12} & S_{22} & S_{13} & -S_{14} \\ S_{13} & S_{13} & 0 & 0 \\ S_{14} & -S_{14} & 0 & 0 \end{bmatrix} \begin{bmatrix} S_{11}^* & S_{12}^* & S_{13}^* & S_{14}^* \\ S_{12}^* & S_{22}^* & S_{13}^* & -S_{14}^* \\ S_{13} & S_{13} & 0 & 0 \\ S_{14} & -S_{14} & 0 & 0 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_1 C_1 : |S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = 1 + |S_{14}|^2 = 1 \quad \text{..... Equation 8}$$

$$R_2 C_2 : |S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1 + |S_{14}|^2 = 1 \quad \text{..... Equation 9}$$

$$R_3 C_3 : |S_{13}|^2 + |S_{13}|^2 = 1 \quad \text{..... Equation 10}$$

$$R_4 C_4 : |S_{14}|^2 + |S_{14}|^2 = 1 \quad \text{..... Equation 11}$$

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ 0 & 0 & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$

MICROWAVE ENGINEERING

MICROWAVE TUBES

Lecture Details:

Topic Name Reflex klystron

Subject/Branch, Semester:MWE & OC , ECE ,6th

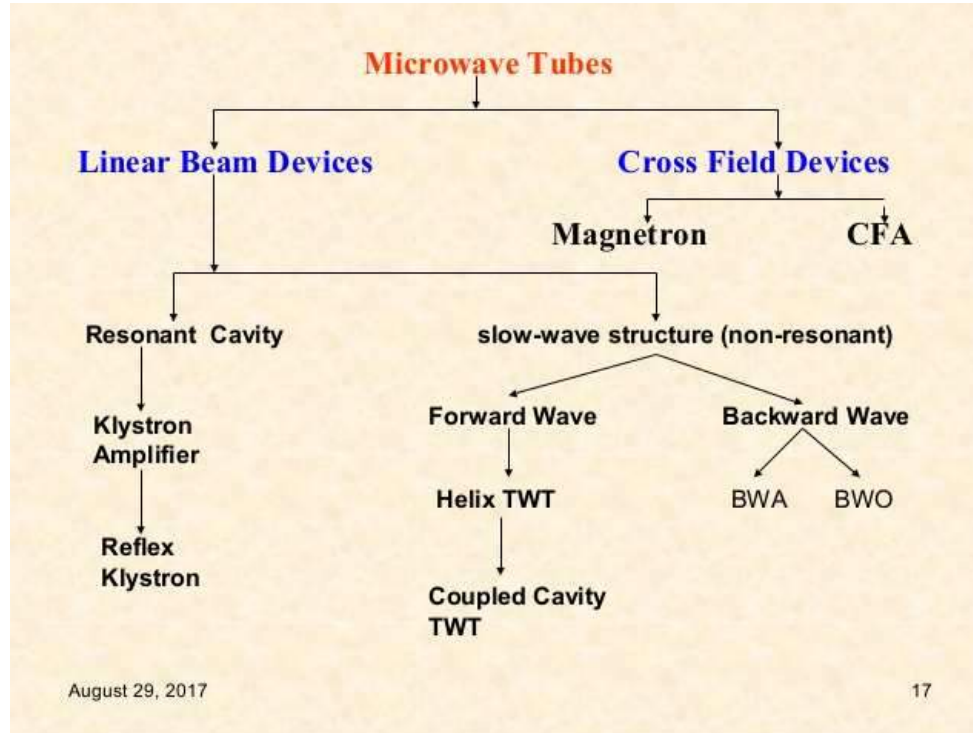
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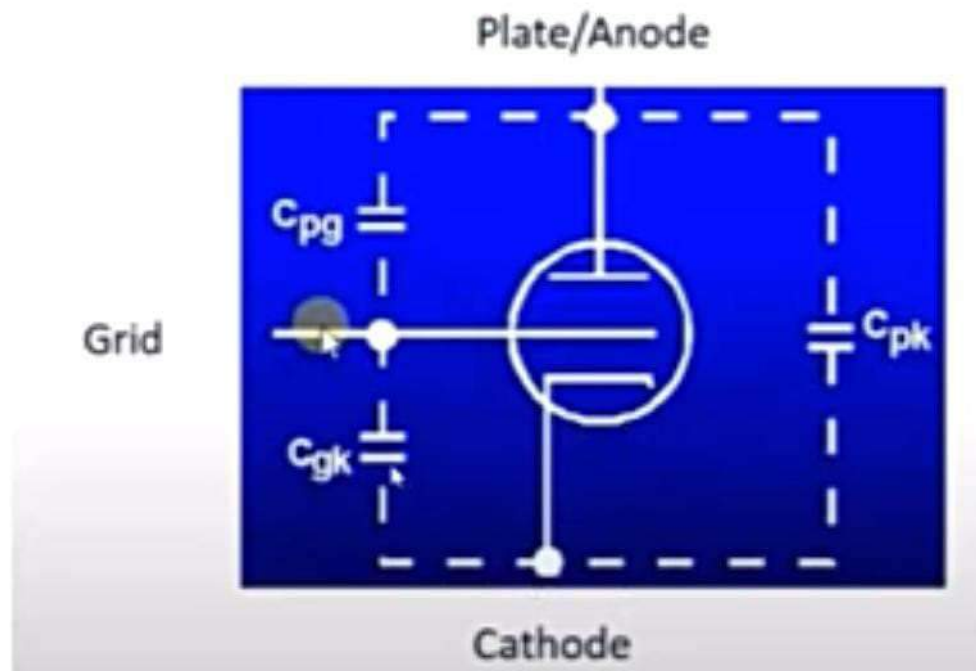


There are following reasons for that conventional tube cannot be used for microwave frequency or high frequency.

1. Inter electrode capacitance and lead inductance effect.
2. Transit time effect.
3. Gain-Bandwidth product limitation.
4. RF losses.
5. Radiation losses.

1. Inter electrode Capacitance : The inter electrode capacitances are the order of 1 to 2 pF. The shunt impedances due to inter electrode become very low become very high at the microwave or high frequency which makes these tube unstable.

2. Refinements have been done in the design and fabrication of these tubes with the result that these tubes, like disk seal tube, are still used up to the lower end of microwave spectrum.

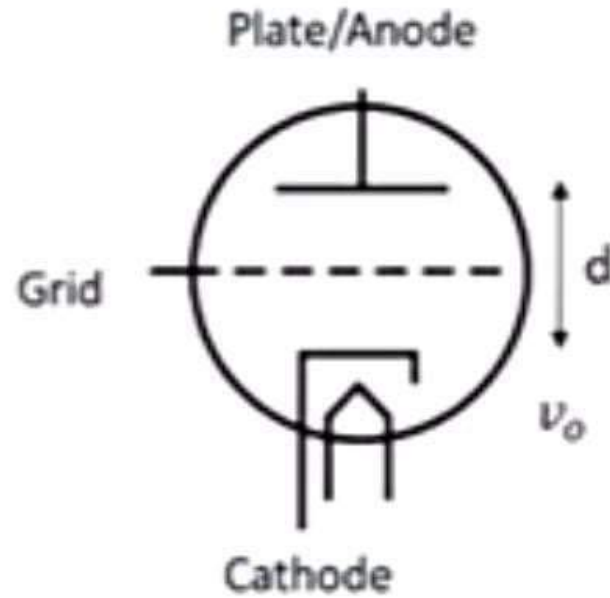


Lead Inductance Effect:

The inter electrode capacitances and lead inductances are the order of 1 to 2 pF and 15 to 20 nH respectively.

The shunt impedances due to inter electrode becomes very low and series impedances due to lead inductance become very high at the microwave or high frequency which makes these tube unstable.

TRANSIT TIME EFFECT



Gain-Bandwidth Product Limitation:

In ordinary vacuum tubes the maximum gain is generally achieved by resonating the output tuned circuit.

$$\text{Gain-bandwidth product} = A_{\text{max}} BW = (g_m / G) (G/C)$$

RF Losses:

RF losses include the skin effect losses and dielectric losses.

Radiation Losses:

At high frequency, when the dimensions of wire approaches near to the wavelength ($\lambda = c/f$). It will emit radiation called radiation losses.

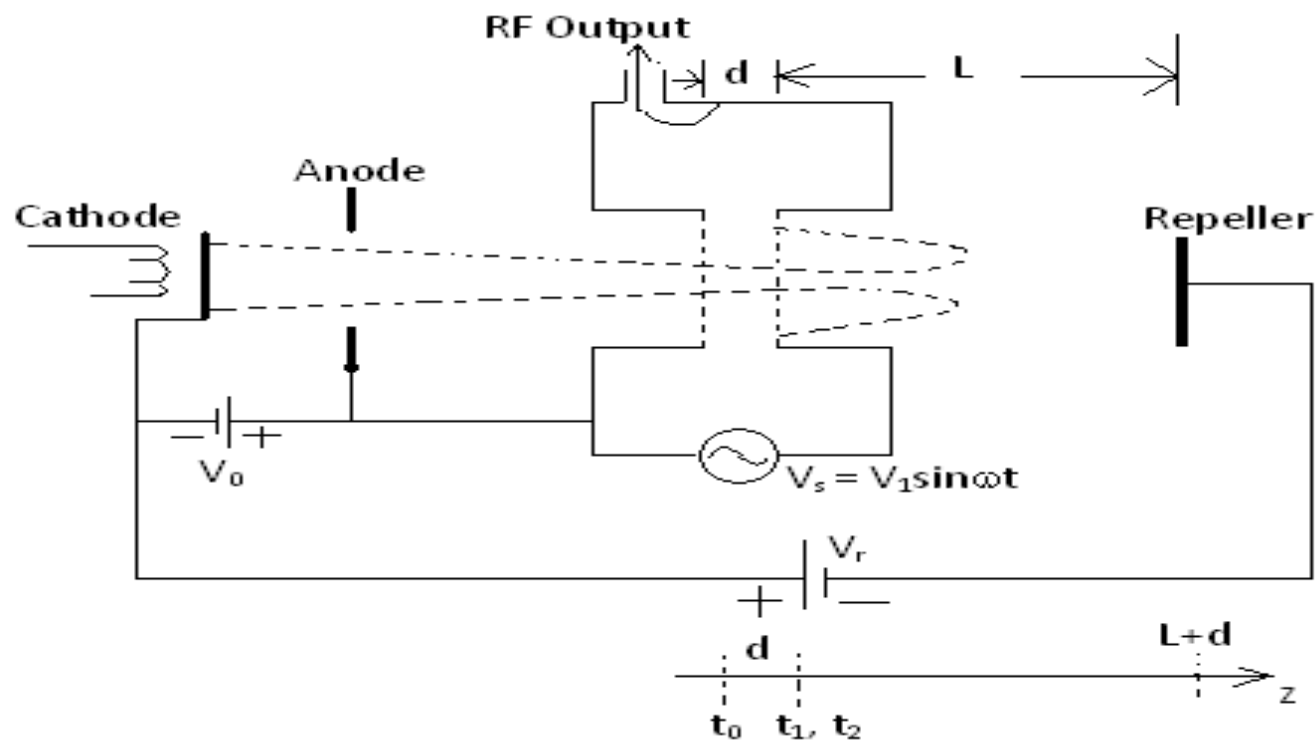
Radiation losses are increases with the increase in frequency.

Reflex Klystron

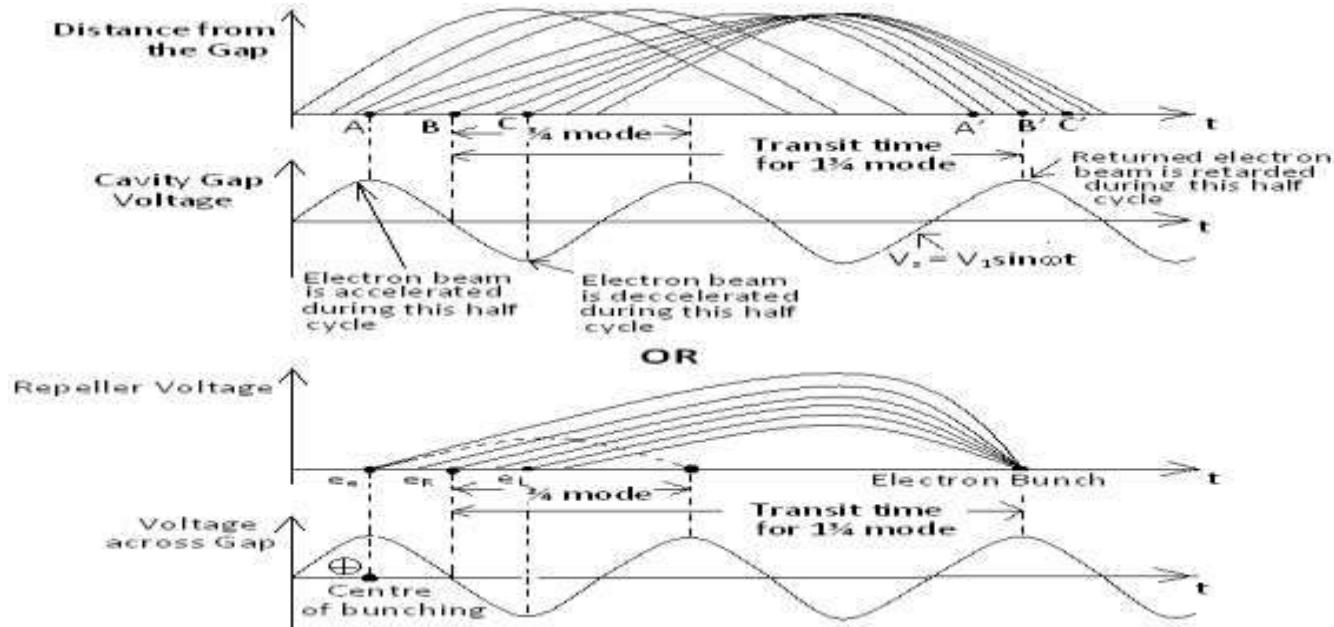
The suitable formed electron beam is accelerated towards the cavity, where a high positive voltage applied to it. This acts as anode and known as anode cavity.

After passing the gap in cavity electrons travel towards repeller which is at high negative potential. The electrons are repelled back from midway of the repeller space by the repeller electrode towards the anode.

If conditions are properly adjusted, then the returning electrons give more energy to the gap than they took from it on forward journey, thus leads to sustained oscillations



Applegate diagram



Operation through Applegate diagram-

The early electron e_e that passes through the gap, before the reference electron e_R , experiences a maximum +ve voltage across the gap and the electron is accelerated, it moves with greater velocity and penetrates deep into repeller space.

The return time for electron e_e is greater as the depth of penetration into the repeller space is more. Hence e_e and e_R appear at the gap for second time at the same instant.

Applications of Reflex Klystron

Reflex Klystron is used in applications where variable frequency is desirable,

- Radio receivers
- Portable microwave links
- Parametric amplifiers
- Local oscillators of microwave receivers
- As a signal source where variable frequency is desirable in microwave generators.

ELECTRONIC ADMITTANCE OF REFLEX KLYSTRON

The admittance of the klystron is the ratio of induced current to induced voltage. i.e., $Y_e = i_2/V_2$ Where,

$$i_2 = 2I_0\beta_i J_1(x')e^{-j\theta_0'}$$

$V_2 = I_2 R_{sh} = 2x'V_0 e^{-j\pi/2} / \beta_i(2\pi n - \pi/2)$ Substitute I_2 and V_2 ,

$$Y_e = (2I_0\beta_i J_1(x')e^{-j\theta_0'}) (\beta_i(2\pi n - \pi/2)) / 2x'V_0 e^{-j\pi/2}$$

$$= I_0\beta_i^2 J_1(x')e^{-j\theta_0'}(2\pi n - \pi/2) / x'V_0 e^{-j\pi/2}$$

Hence the admittance of the Reflex Klystron is obtained as:

$$Y_e = I_0\beta_i^2 J_1(x')e^{j(\pi/2 - \theta_0')} (2\pi n - \pi/2) / x'V_0$$

MICROWAVE ENGINEERING

MICROWAVE TUBES

Lecture Details:

Topic Name TWT & MAGNETRON

Subject/Branch, Semester :MWE & OC ,ECE 6th

Presented By:

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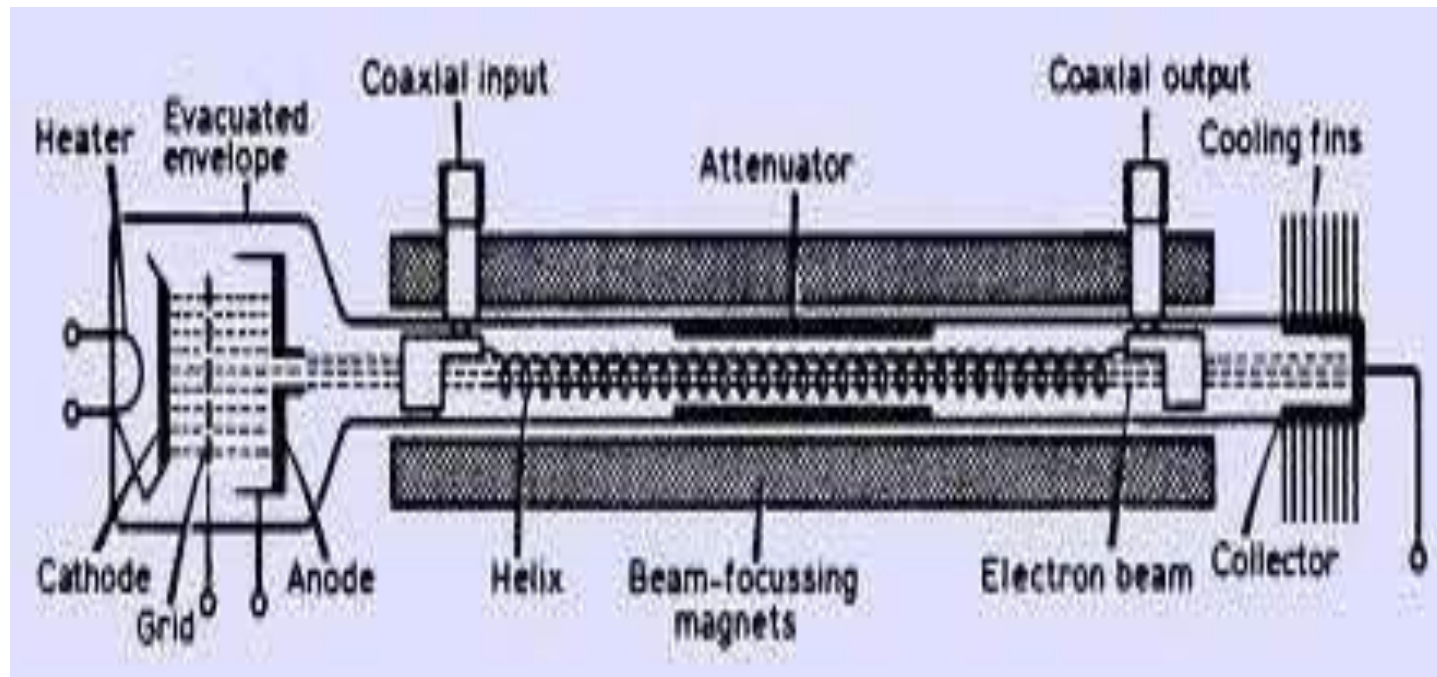
College:GIET(A)

Travelling wave tube

Travelling wave tube has been designed for frequencies as low as 300 MHz and high as 50 GHz. The wide bandwidth and low-noise characteristics makes the TWT ideal for used as an amplifier in microwave equipment.

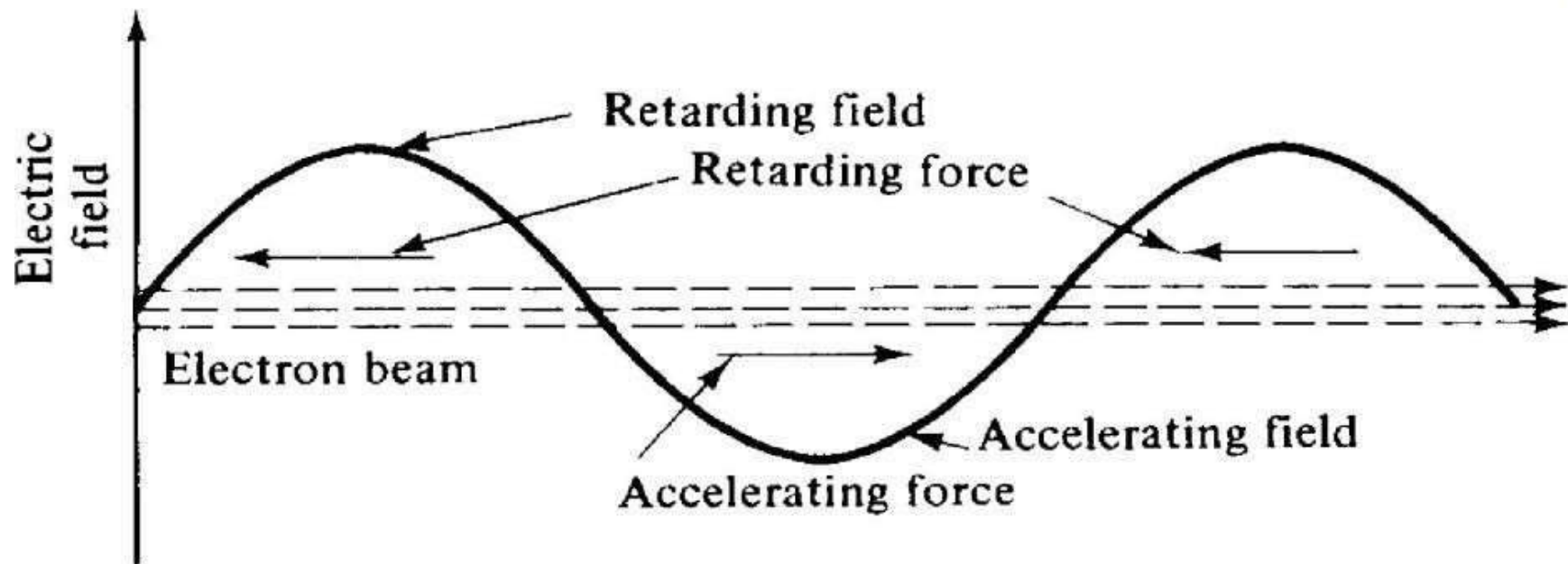
For broadband application, such as satellite, radar transmitter, the TWT are almost exclusively used.

If we compare the basic operating principles of TWT and klystron, in TWT, the microwave circuit is non-resonant and the wave propagates with same speed as the electrons in the beam. The initial effect on the beam is a small amount of velocity modulation caused by the weak electric field associated with the travelling wave.



Velocity Modulation- When the axial field is zero, electron velocity is unaffected. This happens at the point of node of the axial electric field. Those electrons entering the helix, when the axial field is positive antinode, at the accelerating field are accelerated.

At a later point where the axial RF field is -ve antinode, retarding field, the electrons are decelerated. The electrons get velocity modulated.

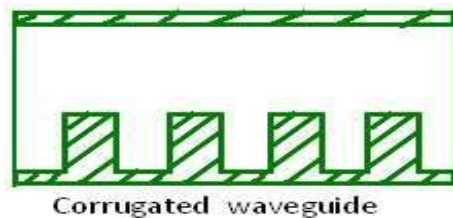
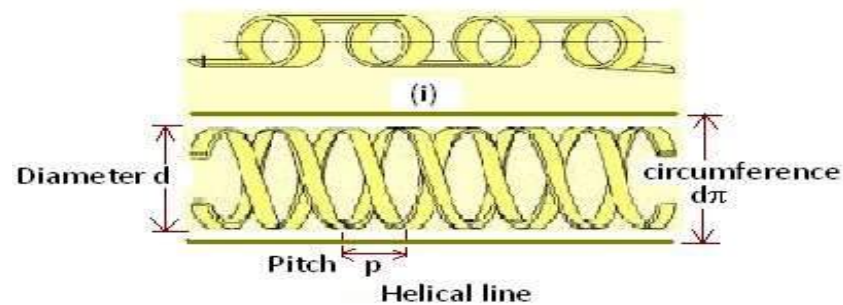


Slow Wave Structures (SWS)

SWSs are special circuits which are used in microwave tubes to reduce the velocity of wave in a certain direction so that the electron beam and the single wave can interact.

The phase velocity of a wave in ordinary waveguide is greater than the velocity of light in a vacuum.

Since the electron beam can be accelerated only to velocities that are about a fraction of the velocity of light, thus the electron beam must keep in step with the microwave signal and a slow wave structure must be incorporated in the microwave devices

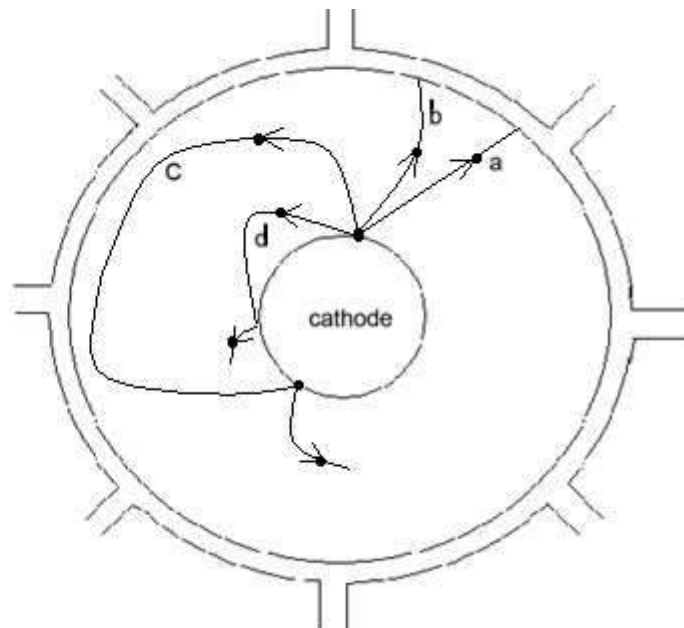
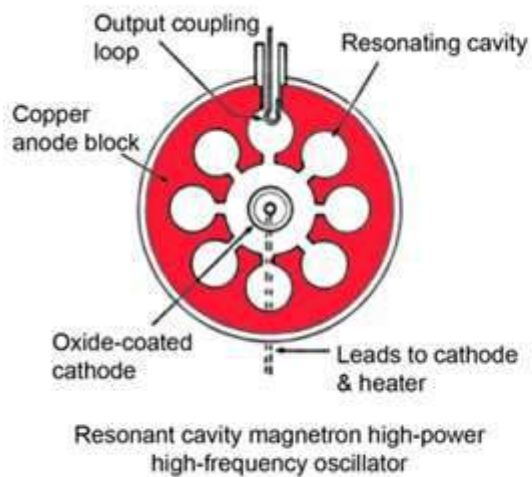


Magnetron

Mechanism of oscillations in Magnetron- The magnetron requires an external magnetic field with flux lines parallel to the axis of cathode. This field is provided by a permanent magnet or electromagnet.

The dc magnetic field is normal to the dc electric field between the cathode and anode. Because of the cross-field between the cathode and anode, the electrons emitted from the cathode are affected by the cross-field to move in curved paths.

If the dc magnetic field is strong enough, the electrons will not arrive in the anode but return back to the cathode.



π -Mode Oscillations

- Let the cavity magnetron has 8 cavities, by which it supports varieties of modes depending upon the phase difference between fields in two adjacent cavities.
- Boundary conditions are satisfied when total phase shift around the eight cavities is multiplied by 2π radians.
- However, the most important mode for magnetron operation is one where in the phase shift between the fields of adjacent cavities is π radians. This is known as *π -Mode*

Hull cut- off voltage & Hartee condition



- In a cylindrical magnetron, several re-entrant cavities are connected to the gaps. Thus it is also called as Cavity Magnetron. Assume the radius of cathode is 'a' and anode is 'b'.
- The dc voltage V_0 is applied between the cathode and anode. When the dc voltage and the magnetic flux (i.e. which is in the +ve z-direction) are adjusted properly, the electrons will follow parabolic path in the presence of cross field.

For the Hull's cut-off voltage V_c , if $B_c = B$ then $V_0 = V_c$ and thus cut-off voltage for a given B is found from the equation ,

$$V_c = (eB_0^2 b^2 / 8m)(1 - a^2 / b^2) \dots\dots\dots(x)$$

If $V_0 < V_c$ for given B , the electrons will not reach the anode.
Equation (x) is referred to as *Hull's cut-off voltage equation*

OPTICAL COMMUNICATION

Presented By:
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Lecture Details:
Overview of optical fiber communication
Optical Communication/ECE, 6th Semester.

INTRODUCTION

- Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information.

- **Optical Fiber -**

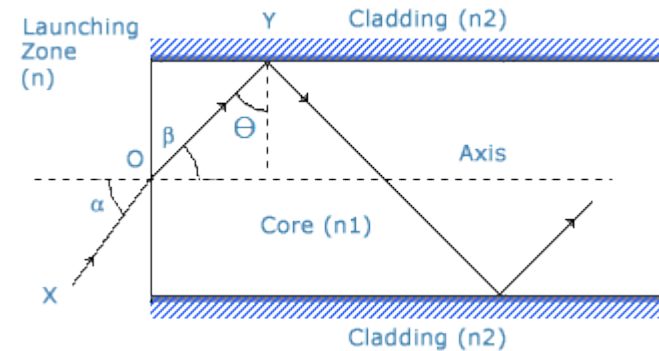
An optical fibre is a dielectric wave guide that operates at optical frequencies. This fibre wave guide is normally cylindrical in form.

- **Function -**

It confines electro magnetic energy in the form of light to within its surfaces and guides the light in a direction parallel to its axis.

PRINCIPLE OF LIGHT PROPAGATION THROUGH A FIBER

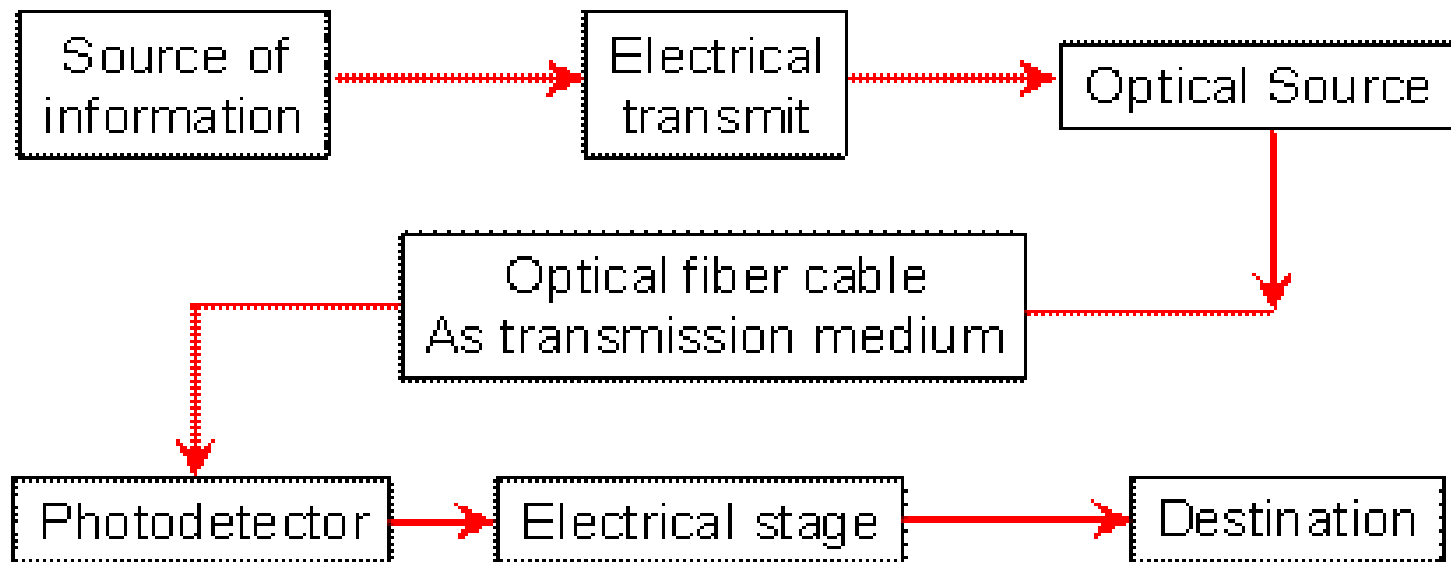
- When the light ray is incident on the interface between two medium having different indices at an angle greater than critical angle, the light gets totally internally reflected within the medium of higher refractive index.



GENERAL OVERVIEW OF OPTICAL FIBER COMMUNICATION SYSTEM

- Like all other communication system, the primary objective of optical fiber communication system also is to transfer the signal containing information (voice, data, video) from the source to the destination. The general block diagram of optical fiber communication system is shown in the figure.

GENERAL BLOCK DIAGRAM OF OPTICAL COMMUNICATION SYSTEM



PRIMARY ELEMENTS OF OPTICAL FIBER COMMUNICATION SYSTEM

- The Block diagram shows the major elements used in an optical fiber communication system , as we can see transmitter stage consists of a light source and associated drive circuitary . Again the receiver section includes photodetector, signal amplifier .
- Optical sources examples : LED, LASER , etc.,
- Optical Detectors examples : Photo Diode, Photo Transistor , etc.,

BENEFITS OF OPTICAL FIBER COMMUNICATION SYSTEM

Some of the innumerable benefits of optical fiber communication system are:

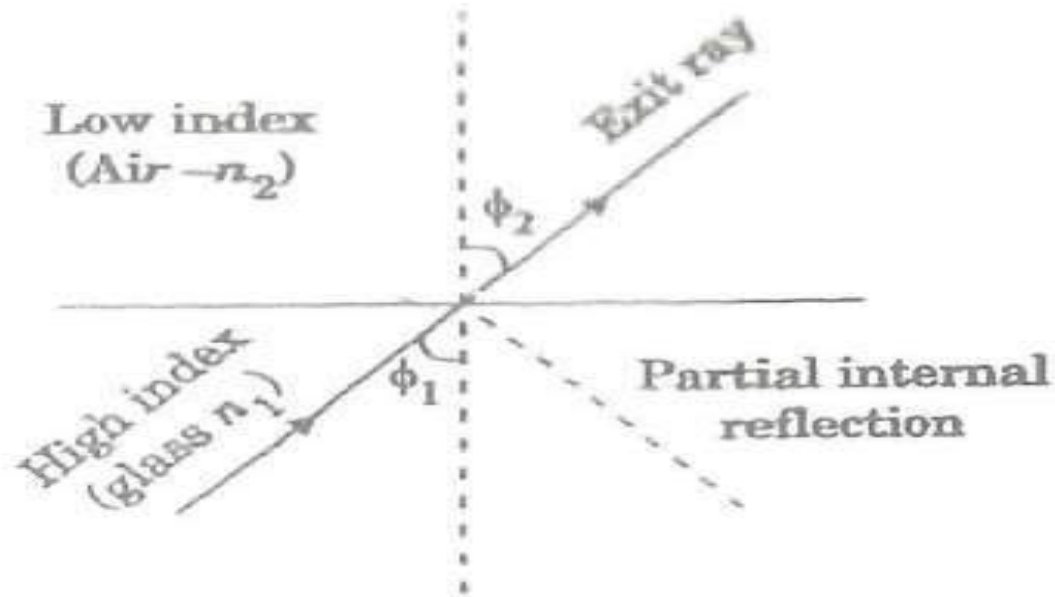
- Immense bandwidth to utilize
- Total electrical isolation in the transmission medium
- Very low transmission loss
- Small size and light weight
- High signal security
- Immunity to interference and crosstalk
- Very low power consumption and wide scope of system expansion etc.

APPLICATIONS

Due to its variety of advantages optical fiber communication system has a wide range of application in different fields namely:

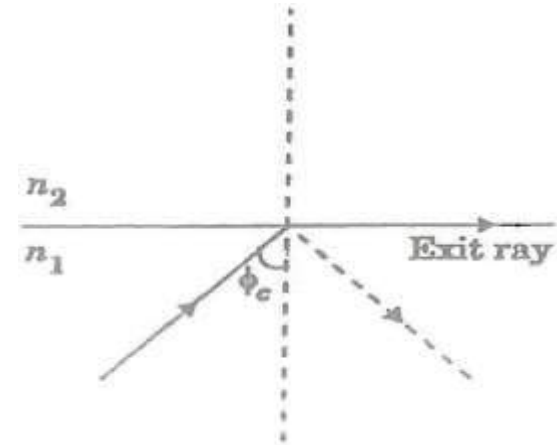
- Public network field which includes trunk networks, junction networks, local access networks, submerged systems, synchronous systems etc.
- Field of military applications
- Civil, consumer and industrial applications
- Field of computers which is the center of research right now.

- **Refractive Index** – The refractive index of a medium is defined as the ratio of velocity of light in vacuum to the velocity of light in the medium



- The propagation of light within an optical fiber is explained using the Ray Theory model –
 1. A Ray of light travels more slowly in an optically dense medium than in one that is less dense
 2. When a ray is incident at an angle Φ_1 normal at the surface of the interface between two dielectrics of different refractive indices (e.g.glass-air), reflection occurs as shown the figure .
 3. If the dielectric on other side of interface has the refractive index n_2 which is less than n_1 , then the refraction is such that the ray path in this index medium is at an angle Φ_2 to the normal where $\Phi_2 > \Phi_1$.
 4. The angle of incidence Φ_1 and the refraction Φ_2 are related to each other and to the refractive indices of dielectric by Snell's law of refraction which states that
$$n_1 \sin \Phi_1 = n_2 \sin \Phi_2$$
 5. When the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90° .

6. This is the limiting case of refraction, and the angle of incidence is known as the critical angle Φ_c as shown in the figure.
7. At angle of incidence greater than the critical angle , the light is reflected back into the originating dielectric medium with high efficiency (around 99.9%). This phenomenon is called total internal reflection.



CONDITIONS TO ACHIEVE TOTAL INTERNAL REFLECTION

- The phenomenon of total internal reflection occurs at the interface between two dielectrics of different refractive indices only when,
 - Light is incident on the dielectric of lower index from the dielectric of higher index.
 - The angle of incidence exceeds the critical value.

Total Internal Reflection

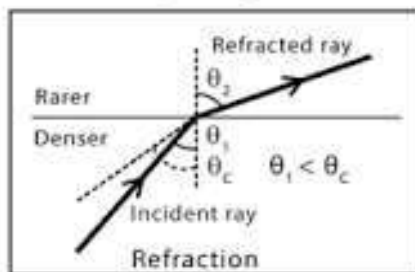
n_1 = refractive index of the denser medium

n_2 = refractive index of the rarer medium

θ_1 = angle of incidence

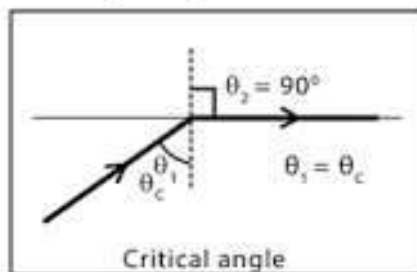
θ_2 = angle of refraction

θ_c = critical angle



Snell's law of refraction

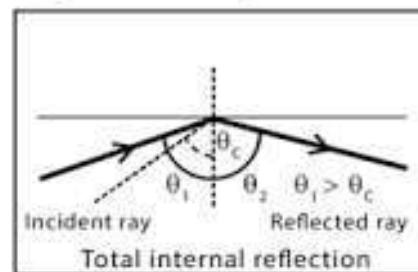
$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$



For critical angle, $\theta_2 = 90^\circ$

$$n_1 \sin \theta_1 = n_2 \sin 90^\circ = n_2 \times 1$$

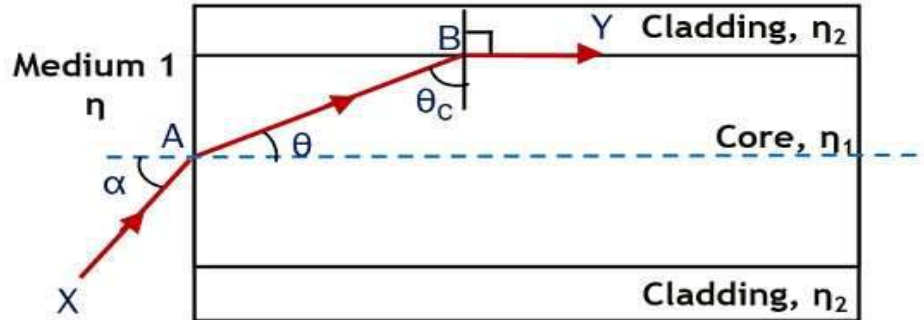
$$\theta_1 = \theta_c = \arcsin(n_2/n_1)$$



For total internal reflection

to occur, $\theta_1 > \theta_c$

Numerical Aperture



Ray propagation through Optical Fiber

Circuit Globe

Numerical Aperture(NA)



- **Numerical Aperture** is the measure of the ability of an **optical fiber** to collect or confine the incident light ray inside it. As acceptance angle is that max angle through which light enters the **fiber**. Hence the acceptance angle and **numerical aperture** are related to each other.

$$NA = \sqrt{n_1^2 - n_2^2}$$

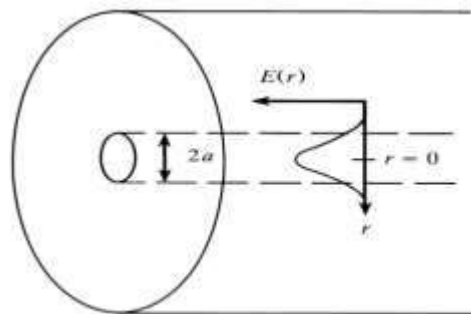
V-NUMBER

- An optical fiber is characterized by one more important parameter known as V number more commonly called as normalized frequency. It is expressed as $V = (2\pi a/\lambda) NA$, where a is radius of core
- It signifies the no of modes propagated in the fiber
- $V < 2.405$, the fiber can support only one mode $V > 2.405$ the fiber can support many modes $V = 2.405$ corresponds to cut off wavelength
- For a step index fiber, no. of modes supported by the fiber is $M = (V^2)/2$
- For a Graded index fiber, no. of modes supported by the fiber is $M = (V^2)/4$

Mode field diameter

- In optical fibers, the mode field diameter (MFD) is an expression of distribution of the irradiance i.e., the optical power per unit area, across the end face of a single-mode fiber.
- For a Gaussian intensity (i.e., power density, W/m^2) distribution in a single mode optical fiber, the mode field diameter is that at which the electric and magnetic field strengths are reduced to $1/e$ of their maximum values, i.e., the diameter at which power density is reduced to $1/e^2$ of the maximum power density, because the power density is proportional to the square of the field strength. $1/e^2$ is 0.135 times the power or a loss of -8.68 dB.
- Mode Field Diameter''' is also defined as the maximum area, where the light signal resides. It consists of the core and some part of the cladding. It is slightly larger than the Core (optical fiber) as the light travels through the core and few of the cladding as well

Mode-field Diameter ($2W_0$)

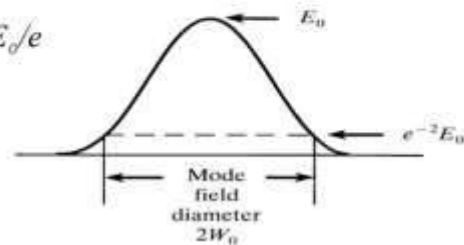


In a Single Mode Fiber,

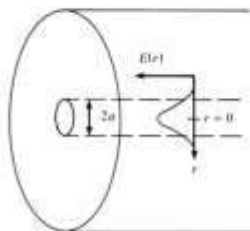
$$E(r) = E_0 \exp(-r^2 / w_0^2)$$

$$\text{At } r = w_0, \quad E(W_0) = E_0 / e$$

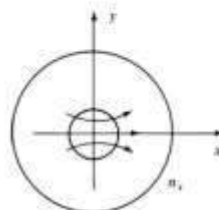
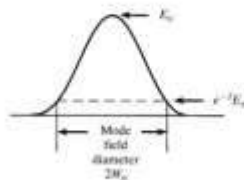
Typically $W_0 > a$



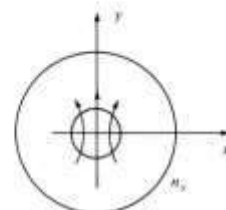
Fundamental Mode Field Distribution



Mode field diameter



Horizontal mode



Vertical mode

Polarizations of fundamental mode

Cutoff wavelength

- The cutoff wavelength for any mode is defined as the maximum wavelength at which that mode propagates.
- For a standard rectangular waveguide , the cutoff wavelength is given by

$$\lambda_c = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}}$$

Where a and b are measured in centimeters

Theoretical cutoff wavelength

$$\lambda_c = \frac{2\pi a n_1}{V_c} (2\Delta)^{\frac{1}{2}}$$

λ_c = theoretical cutoff wavelength

a = radius of the core

n_1 = refractive index of core

V_c = normalized frequency

Δ = Relative Refractive Index Difference (between core and cladding)

Typical cutoff wavelength for 1.3um single mode fibers = from 1.1 to 1.28 μm .

Effective Refractive Index



- The rate of change of phase of the fundamental LP01 mode propagating along a straight fiber is determined by the phase propagation constant β .

$$\beta\lambda_{01} = 2\pi$$

DIFFERENT TYPES OF FIBERS AND THEIR PROPERTIES

- Based on fibers used in communication they are classified into:
 1. Step index fiber
 - a. Single mode
 - b. Multimode
 2. Graded index fiber
 - a. Multimode

Step Index Fibre

- The refractive index of core is maximum and constant throughout the core.
- There is a stepwise decrease of refractive cladding.
- The refractive index of cladding is given by,

$$n_2 = n_1 (1 - \Delta)$$

n_1 - refractive index of core

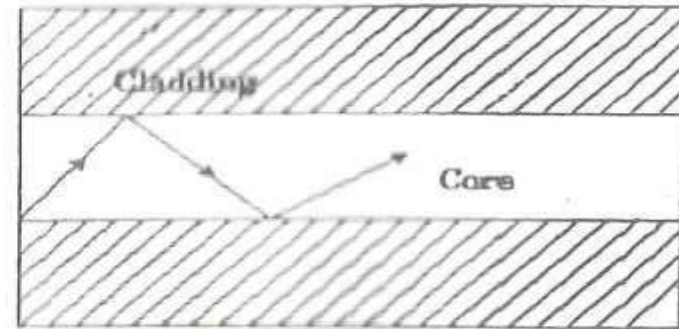
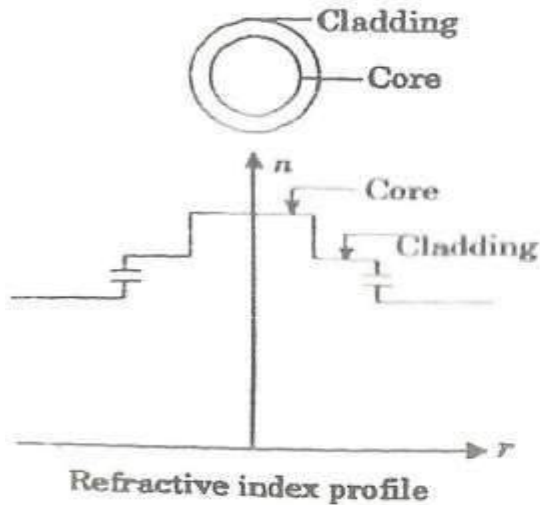
Δ - Relative refractive index difference between core and cladding.

Step index multimode fiber



- The difference between refractive indices of core and cladding is more.
- Its core has large diameter.
- It is used in short distance communication because attenuation is large.

Step index multimode fiber

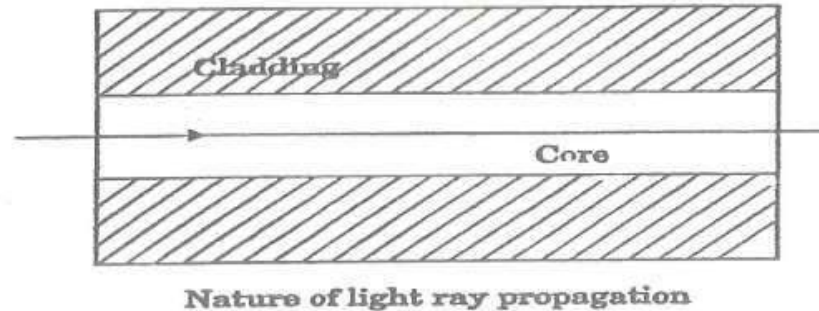
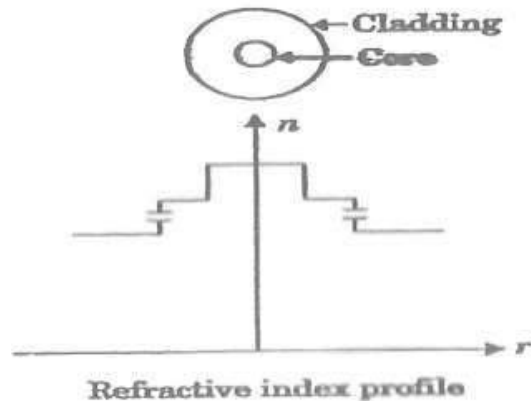


Nature of light ray propagation

Step index single mode fiber

- The difference between refractive indices of core and cladding is very less.
- Its core diameter is also very small.
- It has low attenuation and very high bandwidth.
- It has low numerical aperture(NA). So these are used in long distance communication.

Step index single mode fiber



2. Graded Index Fiber-

- The refractive index of core varies parabolically such that its maximum at the core axis and minimum at the core cladding boundary.
- The refractive index of a graded index fiber is given by,

2. Graded Index Fiber-

where, r - radical distance from the fiber axis

a - Core radius

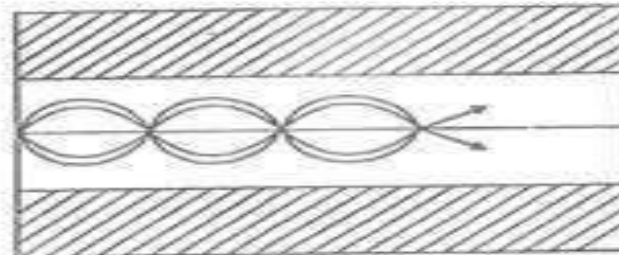
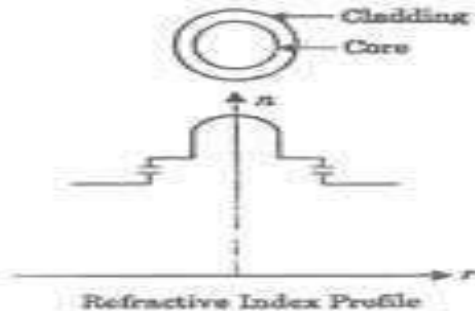
n_2 - refractive index of cladding

n_1 - refractive index of core

Δ - refractive index difference

α - Refractive index profile $\left(\frac{n_1^2 - n_2^2}{2n_1^2} \right)$

- For parabolic type graded index fibers, $\alpha = 2$.
- When $\alpha = \infty$, $n(r) = n_1$



Nature of light ray propagation

Step index fiber	Graded index fiber
Index difference is given by , $\Delta = [n_1 - n_2] / n_1$	Index difference is given by , $\Delta = [(n_1)^2 - (n_2)^2] / 2(n_1)^2$
Spreading of pulse is high	Spreading of pulse is low
Attenuation of light is less, generally 0.34dB/km at 1.3micro meter	Attenuation of light is high, generally 0.6 to 1dB/km at 1.3micro meter
It has high coupling efficiency	It has low coupling efficiency
It is used for the subscriber local network communication	It is used for the local and wide area networks