Microwave:

Microwave is a form of electromagnetic radiation with wavelengths ranging from one meter to one millimeter; with frequencies between 300 MHz and 300 GHz.

Application of microwaves:

The application areas of microwaves can be categories in different ways:-

(i) point-to-point Communication, satellite, cellular access technologies,

(ii) Sensing communication, Radio astronomy,

(iii) Radar communication,

(iv) Diagnostics, imaging, and treatment applications,

(v) Navigation, positioning and measurement,

(vi) Telecom, GPS, Food, Heating, defense,

(vii) Air traffic security cameras, etc.

Rectangular WG
Circular WG
Elliptical WG
Flexible waveguide
Dielectric "

Microwave

- Microwave device
- Microwave Transmission Line
- Waveguide

Microwave device

- Microwave ovens
- WiFi Routers
- cell Phones
- Bluetooth devices
- Radar Systems
- sattellite
- ~~Rem~~ Some medical Machines
- Microwave Antenna, etc

Microwave Transmission Line

- Co-axial Cable
- Waveguide (hollow metalic tube)
- Micro strip line (PCB Board)
- Slotted Waveguide (radar)

Cavity Klystrone

Why are conventional electronic devices not behave satisfactory at μwave frequencies?

(1) Parasitic effect = At high f, resistor, inductor, capacitor, start showing unwanted behaviors. (wires → antenna)

(2) Increased signal loss → attenuation high at high f

(3) poor device speed → distortion

(4) Electromagnetic Interferrence (at high f → crosstalk

(1)

Microwave Device:

Microwave device is a device that is capable of generating, amplifying, modifying, detecting, or measuring microwaves, or voltages having microwave frequencies.

(এই সকল device high fre. এ কাজ করে)

Microwave solid-state devices – such as:

(1G computer) (I) Vacuume Tube, (rarely used → amplifier)

Not use today → (II) Tunnel diodes, ← oscilator/amplifier, motion detectors → automatic door open

Semiconductor → (III) Gunn diodes, → used as oscillators/MW amplifier

(Gunn) (osci + amp) (IV) Transferred Electron Devices (TEDs) etc.

App: Gunn, Collision avoidance Radar

Common characteristics of Microwave Devices:

The common characteristic of all microwave solid-state devices is the negative resistance that can be used for microwave oscillation and amplification.

(I) High Gain
(II) Small size & weight
(III) Wide Bandwidth
(IV) Negative Resistance

③

* Microwave Systems:

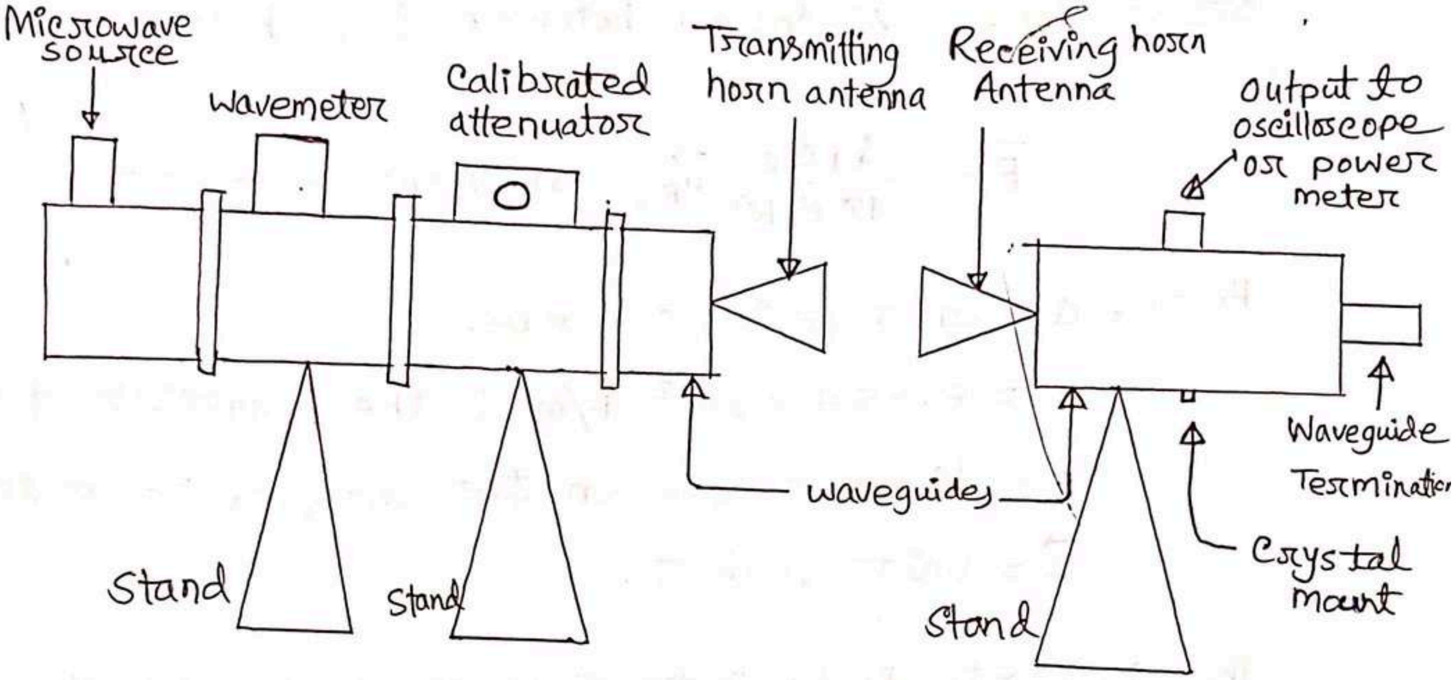


Fig: Generalized Block Diagram of Microwave system

A microwave system normally consists of a transmeter subsystem, including a microwave oscillator, waveguides, and a transmitting antenna, and a receiver subsystem that includes a receiving antenna, transmission line or wave-guide, a microwave amplifier, and a receiver.

(according fig)

* Electron Motion in an Electric Field:

We know from the coulomb's Law, the attractive or a repulsive force between two charges is:

$$\vec{F} = \frac{Q_1 Q_2}{4\pi\varepsilon_0 R^2} \vec{u}_{R_{12}} \text{ newtons} \quad \text{----(I)}$$

Here, Q = charge in coulombs.

$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the permittivity of free space

R = distance between the charges in meters.

$\vec{u}$ = unit vector.

The Electric Field intensity produced by the charges is defined as the force per unit charge – that is:

$$\vec{E} = \frac{\vec{F}}{Q} = \frac{Q}{4\pi\varepsilon_0 R^2} \vec{u}_R \quad V/m \quad \text{------(II)}$$

If there are n charges, the Electric Field becomes,

$$\vec{E} = \sum_{m=1}^{n} \frac{Q_m}{4\pi\varepsilon_0 R_m^2} \vec{u}_{R_m} \quad \text{------(III)}$$

We Know, $\vec{F} = -e\vec{E}$

and, $\vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt}$

$\therefore -e\vec{E} = m\frac{d\vec{v}}{dt}$

$\Rightarrow \vec{E} = -\frac{m}{e}\frac{d\vec{v}}{dt} \quad \text{------(IV)}$

$\therefore \frac{d\vec{v}}{dt} = -\frac{e}{m}\vec{E}$

Here,

$e = 1.602 \times 10^{-19}$ C

$m = 9.109 \times 10^{-31}$ kg

So, the differential equations of motion for an electron in an electric field in rectangular coordinates are given by,

$$\left.\begin{aligned}\frac{d^2x}{dt^2} &= -\frac{e}{m}E_x\\ \frac{d^2y}{dt^2} &= -\frac{e}{m}E_y\\ \frac{d^2z}{dt^2} &= -\frac{e}{m}E_z\end{aligned}\right\}$$

$$\vec{V} = \frac{dx}{dt}\hat{x} + \frac{dy}{dt}\hat{y} + \frac{dz}{dt}\hat{z}$$

$$\cancel{\frac{dv}{dt} = \frac{d^2x}{dt^2} = \frac{d^2y}{dt^2} = \frac{d^2z}{dt^2}}$$

$$\vec{E} = E_x\hat{x} + E_y\hat{y} + E_z\hat{z}$$

$$\frac{e}{m} = 1.759 \times 10^{11}\ c/kg$$

Now, The equation of motion for an electric field in cylindrical co-ordinates are given by,

$$\left.\begin{aligned}\frac{d^2r}{dt^2} - r\left(\frac{d\varphi}{dt}\right)^2 &= -\frac{e}{m}E_r\\ \frac{1}{r}\frac{d}{dt}\left(r^2\frac{d\varphi}{dt}\right) &= -\frac{e}{m}E_\varphi\\ \frac{d^2z}{dt^2} &= -\frac{e}{m}E_z\end{aligned}\right\}$$

From (N) No eq^n:

$$\vec{E} = -\frac{m}{e}\frac{d\vec{v}}{dt}$$

$$\Rightarrow -\vec{E} = \frac{m}{e}\frac{d\vec{v}}{dt}$$

If the work done by the field in carrying a unit positive charge from point A to point B is:-

(6)

$$\therefore -\int_A^B \vec{E}\cdot dl = \frac{m}{e}\int_{v_A}^{v_B} v\,dv \quad \text{------ (V)}$$

Here, $V = -\int_A^B \vec{E}\cdot dl$

$$\therefore V = \frac{m}{e}\int_{v_A}^{v_B} v\,dv = \frac{m}{e}\left[\frac{v^2}{2}\right]_{v_A}^{v_B}$$

$$\Rightarrow V = \frac{m}{e}\left(\frac{v_B^2}{2} - \frac{v_A^2}{2}\right)$$

$$\Rightarrow eV = \frac{m}{2}(v_B^2 - v_A^2) \quad \text{------ (VI)}$$

$1\ eV = 1.6\times10^{-19}\ J$

$$\Rightarrow eV = \frac{m}{2}v^2$$

Here, $v_B^2 - v_A^2 = v^2$

$$\Rightarrow v^2 = \frac{2eV}{m}$$

$$\Rightarrow v = \sqrt{\frac{2eV}{m}}$$

$$\therefore v = \left(\frac{2eV}{m}\right)^{1/2} \quad \text{------ (VII)}$$

It is the final velocity. #

$$\left\{ \begin{array}{l} * \; v = \left(\frac{2eV}{m}\right)^{1/2} \\ \therefore v = 0.593\times10^{6}\sqrt{V} \end{array} \right. \quad \Bigg\| \quad \frac{e}{m} = 1.759\times10^{11}\ C/kg$$

Electric and Magnetic Wave Equations:

The Electric and Magnetic wave equations can be derived from Maxwell's equations, which in time domain are expressed as,

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$
$$\vec{\nabla} \cdot \vec{D} = \rho_v$$
$$\vec{\nabla} \cdot \vec{B} = 0$$

Here, $\vec{E}$ = Electric field intensity
$\vec{H}$ = Magnetic field intensity
$\vec{D}$ = Electric flux Density
$\vec{B}$ = Magnetic flux Density
$\vec{J}$ = Electric Current Density
ρ_v = Electric charge Density
$\vec{\nabla} = \frac{\partial}{\partial x}\hat{x} + \frac{\partial}{\partial y}\hat{y} + \frac{\partial}{\partial z}\hat{z}$ (cartesian)

We know,

$$\vec{D} = \varepsilon \vec{E}$$
$$\vec{B} = \mu \vec{H}$$
$$\vec{J}_c = \sigma \vec{E}$$

Here,
ε = dielectric permittivity
μ = Magnetic permeability
σ = Conductivity of the medium.

And for the frequency domain $\frac{\partial}{\partial t} = j\omega$.

Now, the Maxwell's equations in frequency domain are given by,

$$\vec{\nabla} \times \vec{E} = -j\omega\mu\vec{H} \quad \text{--- (I)}$$
$$\vec{\nabla} \times \vec{H} = \sigma\vec{E} + j\omega\varepsilon\vec{E} = (\sigma + j\omega\varepsilon)\vec{E} \quad \text{--- (II)}$$
$$\vec{\nabla} \cdot \vec{D} = \rho_v$$
$$\vec{\nabla} \cdot \vec{B} = 0$$

In free space the space charge density is zero and perfect conductor in a static field do not exist, so,

$$\vec{\nabla} \cdot \vec{D} = 0$$
$$\vec{\nabla} \cdot \vec{E} = 0$$

from ① No equation,

$$\vec{\nabla} \times \vec{E} = -j\omega\mu \vec{H}$$

$$\Rightarrow \vec{\nabla} \times \vec{\nabla} \times \vec{E} = -j\omega\mu \vec{\nabla} \times \vec{H} \quad \text{(Taking curl on both side)}$$

$$\therefore \vec{\nabla} \times \vec{\nabla} \times \vec{E} = -j\omega\mu(\sigma + j\omega\epsilon)\vec{E} \quad [\because \vec{\nabla} \times \vec{H} = (\sigma + j\omega\epsilon)] \text{ --- (III)}$$

The vector identity for the curl of the curl of a vector quantity $\vec{E}$ is expressed as:

$$\vec{\nabla} \times \vec{\nabla} \times \vec{E} = -\nabla^2\vec{E} + \vec{\nabla}(\vec{\nabla} \cdot \vec{E})$$

$\nabla \times A \times B$
$= A \nabla B - B \nabla A$
$= \nabla \nabla E - E \cdot \nabla \nabla$
$= -\nabla^2 E + \nabla(\nabla \cdot E)$

(XX)

$$\therefore \vec{\nabla} \times \vec{\nabla} \times \vec{E} = -\nabla^2\vec{E} \text{ ----- (IV)} \quad [\because \vec{\nabla} \cdot \vec{E} = 0]$$

Now from (III) & (IV) No equations,

$$\nabla^2\vec{E} = j\omega\mu(\sigma + j\omega\epsilon)\vec{E} \text{ --- (V)}$$

$$\therefore \nabla^2\vec{E} = \gamma^2\vec{E} \text{ --- (VI)}$$

This is the electric wave eqn

Similarly, the magnetic wave eqn is given by, $\nabla^2\vec{H} = \gamma^2\vec{H}$ --- (VII)

(XX)

Here, $\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)}$
$= \alpha + j\beta$ is called intrinsic propagation

α = attenuation constant

β = phase constant.

$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ (cartesian)

Waveguide:

In general, a waveguide consists of a hollow metalic tube of a rectangular or circular shape us to guide an electromagnetic wave.

Waveguides are used principally at frequencies i the microwave range; inconveniently large guides woul be required to transmit radio-frequency power a longer wavelengths.

The rectangular waveguide WR-90 has an inner width of 2.286 cm and an inner height of 1.016 cm; bu its outside dimensions are 2.54 cm wide and 1.27 cm high.

There are three mode of waveguide:

(i) TE Mode (Transverse Electric)
(ii) TM Mode (Transverse Magnetic)
(iii) TEM Mode (Transverse Electromag -tic)

(i) TE Mode: There is no E component ($E_z = 0$) present. Sometime call H-wa

(ii) TM Mode: there is no H component ($H_z = 0$) present + E w

(iii) TEM Mode: $E_z = 0$, $H_z = 0$.

◻ process of solving waveguide problems:

The process of solving the waveguide problems may involve three steps:

1// The desired wave equations are written in the form of either rectangular or cylindrical co-ordi-nate systems suitable to the problem at hand.

2// The boundary conditions are then applied to the wave equations set up in step 1.

3// The resultant equations usually are in the form of partial differential equations in either time or frequency domain. They can be solved by using the proper method.

Solutions of Wave Equations in Rectangular Co-ordinates:

A rectangular co-ordinate (waveguide) system is shown in below figure,

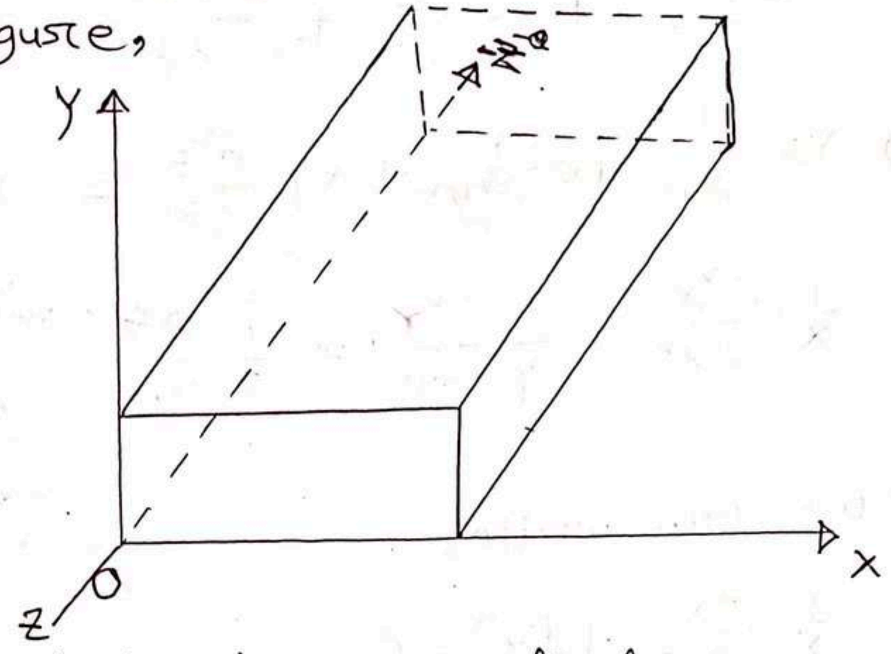


Fig: Rectangular co-ordinate.

The electric and magnetic wave equations in frequency domain are written by,

$$\nabla^2 \vec{E} = \gamma^2 \vec{E} \quad \text{—— (I)}$$

$$\nabla^2 \vec{H} = \gamma^2 \vec{H} \quad \text{—— (II)}$$

Here, $\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} = \alpha + j\beta$

α = attenuation constant

β = phase constant

Let us, consider a scalar Helmholtz equation (partial diff. eqn.) as,

actual $\nabla^2\psi = -k^2\psi \Leftarrow \nabla^2\psi = \gamma^2\psi$ —— (III) $\Rightarrow \frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2} = \gamma^2\psi$

This is linear & partial diff. eqn in three dimension

Let the solution of above equation (III) be,

$\psi = X(x)\, Y(y)\, Z(z)$ — function of x coordinate

2°

$\frac{1}{\cancel{}}\partial x^2$ [illegible]

Now (iii) No equation can be written as,

$$\frac{\partial^2 XYZ}{\partial x^2} + \frac{\partial^2 XYZ}{\partial y^2} + \frac{\partial^2 XYZ}{\partial z^2} = \gamma^2 XYZ$$

$$\Rightarrow YZ\frac{\partial^2 X}{\partial x^2} + XZ\frac{\partial^2 Y}{\partial y^2} + XY\frac{\partial^2 Z}{\partial z^2} = \gamma^2 XYZ$$

$$\therefore \frac{1}{X}\frac{\partial^2 X}{\partial x^2} + \frac{1}{Y}\frac{\partial^2 Y}{\partial y^2} + \frac{1}{Z}\frac{\partial^2 Z}{\partial z^2} = \underset{-k_x^2 - k_y^2 - k_z^2}{\underset{\downarrow}{\gamma^2}} \quad \text{--- (iv)}$$

Now we can write,

প্রতি সম:

$$\frac{1}{X}\frac{\partial^2 X}{\partial x^2} + k_x^2 = 0 \quad \text{--- (v)}$$

$$\frac{1}{Y}\frac{\partial^2 Y}{\partial y^2} + k_y^2 = 0 \quad \text{--- (vi)}$$

$-k^2 = \gamma^2$

$\Rightarrow -(k_x^2 + k_y^2 + k_z^2) = \gamma^2$

$$\frac{1}{Z}\frac{\partial^2 Z}{\partial z^2} + k_z^2 = 0 \quad \text{--- (vii)}$$

Here, $\gamma^2 = -(k_x^2 + k_y^2 + k_z^2)$

Equation (v), (vi) & (vii) can be written as,

$$\frac{\partial^2 X}{\partial x^2} + X k_x^2 = 0 \quad \text{--- (viii)}$$

$$\frac{\partial^2 Y}{\partial y^2} + Y k_y^2 = 0 \quad \text{--- (ix)}$$

$$\frac{\partial^2 Z}{\partial z^2} + Z k_z^2 = 0 \quad \text{--- (x)}$$

$$\frac{\partial^2 X}{\partial x^2} + X k_x^2 = 0 \quad \text{——— (1)}$$

let, $X(x) = e^{\alpha x}$ + choose exponential ~~for~~ cause, they are natural candidates for solving Second order diff. equation,

$$\frac{\partial X}{\partial x} = \frac{\partial}{\partial x}\left(e^{\alpha x}\right) = \alpha e^{\alpha x}$$

and, $\frac{\partial^2 X}{\partial x^2} = \frac{\partial}{\partial x}\left(\alpha e^{\alpha x}\right) = \alpha^2 e^{\alpha x}$

$$(1) \Rightarrow \frac{\partial^2 X}{\partial x^2} + X k_x^2 = 0$$

$$\Rightarrow \alpha^2 e^{\alpha x} + e^{\alpha x} k_x^2 = 0 \quad \text{——— (4)}$$

$$\Rightarrow \alpha^2 + k_x^2 = 0$$

$$\therefore \alpha = i k_x$$

$$\Rightarrow \cancel{i^2 k_x^2 e^{i k_x x} + e^{i k_x x} k_x^2} = 0$$

$$\Rightarrow X(x) = e^{i k_x x} = \cos(k_x x) + i \sin(k_x x)$$

$$= A \cos(k_x x) + B \sin(k_x x)$$

Solution of (VIII), (IX) & (X) equation is,

$$X = A\sin(k_x x) + B\cos(k_x x)$$

$$Y = C\sin(k_y y) + D\cos(k_y y)$$

$$Z = E\sin(k_z z) + F\cos(k_z z)$$

Now, solution of the Helmholtz equation is,

$$\psi = [A\sin(k_x x) + B\cos(k_x x)][C\sin(k_y y) + D\cos(k_y y)]$$
$$[E\sin(k_z z) + F\cos(k_z z)]$$

Now, writing the wave equation solution for Electric field,

$$E = [A\sin(k_x x) + B\cos(k_x x)][C\sin(k_y y) + D\cos(k_y y)]$$
$$[E\sin(k_z z) + F\cos(k_z z)]$$

Considering the propagation of wave in negative z direction (as Fig). So the solution becomes,

$$E_z = [A\sin(k_x x) + B\cos(k_x x)][C\sin(k_y y) + D\cos(k_y y)]\, e^{-j\beta_g z}$$

Similarly,

$$H_z = [A\sin(k_x x) + B\cos(k_x x)][C\sin(k_y y) + D\cos(k_y y)]\, e^{-j\beta_g z}$$

2^2

$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)}$

$\gamma = \alpha + j\beta_g$

Now, propagation constant.

$$\gamma_g^2 = \gamma^2 + k_x^2 + k_y^2$$

$$\therefore \gamma_g = \pm\sqrt{\gamma^2 + k_c^2}$$

Here, $k_c^2 = k_x^2 + k_y^2$

For a lossless dielectric,

$$\gamma^2 = -\omega^2\mu\epsilon$$

$$\therefore \gamma_g = \pm\sqrt{k_c^2 - \omega^2\mu\epsilon}$$

There are three cases for propagation constant γ_g in the waveguide:

Case I: There will be no wave propagation in the guide if $k_c^2 = \omega^2\mu\epsilon$ and $\gamma_g = 0$. This is the critical condition for cutoff propagation. The cutoff frequency is expressed as:

$$f_c = \frac{1}{2\pi\sqrt{\mu\epsilon}}\sqrt{k_x^2 + k_y^2}$$

Case II: The wave will be propagating in the guide if $\omega^2\mu\epsilon > k_c^2$ and,

$$\gamma_g = \pm j\beta_g = \pm j\omega\sqrt{\mu\epsilon}\sqrt{1 - \left(\frac{f_c}{f}\right)^2}$$

Here, f = operating
f_c = cutoff fr
$f > f_c$

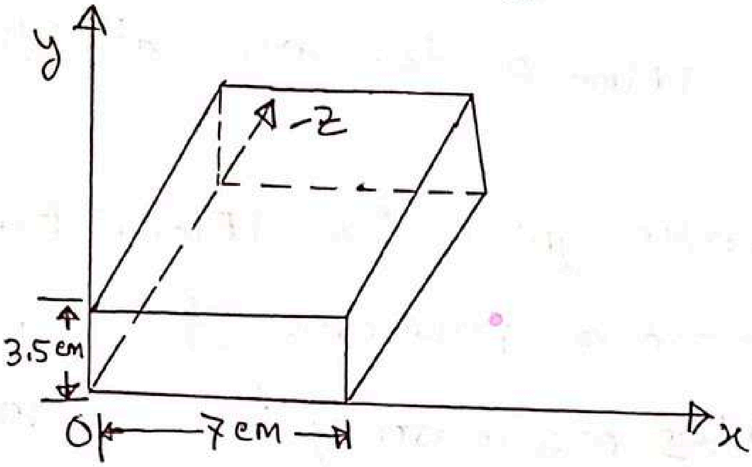
Case III: The wave will be attenuated if $\omega^2\mu\epsilon < k_c^2$ and,

$$\gamma_g = \pm\alpha_g = \pm\omega\sqrt{\mu\epsilon}\sqrt{\left(\frac{f_c}{f}\right)^2 - 1}$$

Here,
$f_c > f$

Example 4-1-1 : TE_{10} in Rectangular Waveguide:

An air-filled rectangular wave guide of inside dimensions 7 X 3.5 cm operates in the dominant TE10 mode as shown in below Fig:-



ⓐ Find the cutoff frequency ?

ⓑ Determine the phase velocity of the wave in the guide at a frequency of 3.5 GHz

ⓒ Determine the guided wavelength at the same frequency ?

Solution:

ⓐ $f_c = \dfrac{c}{2a} = \dfrac{3\times10^8}{2\times7\times10^{-2}} = 2.14$ GHz (Ans.)

ⓑ $v_g = \dfrac{c}{\sqrt{1-(f_c/f)^2}} = \dfrac{3\times10^8}{\sqrt{1-(2.14/3.5)^2}}$

$= 3.78\times10^8\ ms^{-1}$ (Ans.)

ⓒ $\lambda_g = \dfrac{\lambda}{\sqrt{1-(f_c/f)^2}} = \dfrac{(3\times10^8)/(3.5\times10^9)}{\sqrt{1-(2.14/3.5)^2}}$

Here,
$c = 3\times10^8\ ms^{-1}$
$a = 7$ cm
$= 7\times10^{-2}$ m
$f = 3.5$ GHz
$c = f\lambda$
$\therefore \lambda = \dfrac{c}{f} = \dfrac{3\times10^8}{3.5\times10^9}$

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(109-110 page)

Degenerate Modes and Dominant Modes:

Degenerate Mode

When two or more modes have the same cutoff frequency, then they are said to be degenerate mode. In a rectangular guide the corresponding TE_{mn} and TM_{mn} modes are always degenerate.

In a square guide, the TE_{mn}, TE_{nm}, TM_{mn}, and TM_{nm} modes form a foursome of degeneracy. Rectangular guides ordinarily have dimensions of $a = 2b$ ratio.

Dominant Mode

The mode with the lowest cuttoff frequency in a particular guide is called the dominant mode.

The TE_{101} is the Example of dominant mode.

4

// The mode having the lowest ~~cut~~ cutoff resonant frequency is known as the dominant mode.//

41

Properties of TEM modes in a lossless medium:

The properties of TEM modes in a lossless medium are as follows:

1. Its cutoff frequency is zero

2. Its transmission line is a two-conductor system.

Z_g 3. Its wave impedence is the impedence in an unbounded dielectric.

γ_g 4. Its propagation constant is the constant in an unbounded dielectric.

v_g 5. Its phase velocity is the velocity of light in an unbounded dielectric.

CT#2 start

Microwave cavities

A cavity resonator is a metallic enclosure that confines the electromagnetic energy. The stored electric and magnetic energies inside the cavity determine its equivalent inductance and capacitance.

In practice, the rectangular cavity resonator, circular-cavity resonator and reentrant-cavity resonator are commonly used in many microwave application.

Rectangular Cavity Resonator:

The geometry of a rectangular cavity is given below:

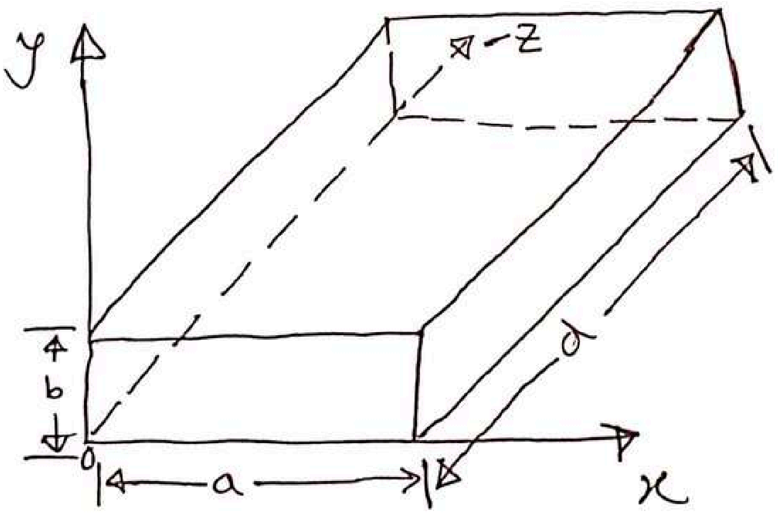

Fig: Co-ordinates of rectangular cavity

4-3-3 Q Factor of a Cavity Resonator:

V.V.I

→ The quality factor Q is a measure of the frequency selectivity of a resonant circuit, and it is defined as,

$$Q = 2\pi \frac{\text{maximum energy stored}}{\text{energy dissipated per cycle}} = \frac{\omega W}{P} \quad \text{---(i)}$$

where, W is the maximum stored energy and P is the average power loss.

At resonant frequency and in time quadrature, the electric and magnetic energies are equal. When the electric energy is maximum, then magnetic energy is zero and vice versa. Total energy is obtained by integrating the energy density over the volume of the resonator:

$$W_e = \int_V \frac{\epsilon}{2}|E|^2 dv = W_m = \int_V \frac{\mu}{2}|H|^2 dv = W \quad \text{---(ii)}$$

And the average power loss is obtained by integrating the power density over the inner surface of the resonator. Hence,

$$P = \frac{R_s}{2}\int_S |H_t|^2 da \quad \text{------(iii)}$$

Here, H_t is the peak value of the tangential magnetic intensity and R_s is the surface Resistance of the resonator.

From ① No equation we get:

$$Q = \frac{\omega W}{P}$$

$$\Rightarrow Q = \frac{\omega \int_v \frac{\mu}{2} |H|^2 dv}{\frac{R_s}{2} \int_s |H_t|^2 da}$$

$$\therefore Q = \frac{\omega \mu \int_v |H|^2 dv}{R_s \int_s |H_t|^2 da} \quad \text{(IV)}$$

Since peak value of the magnetic intensity is related to its tangential and normal component by,

$$|H|^2 = |H_t|^2 + |H_n|^2$$

Here, at the resonator walls, approximately $|H_t|^2 \cong 2|H|^2$. So from (IV) No equation,

$$Q = \frac{\omega \mu \,(\text{volume})}{2R_s\,(\text{surface areas})} \quad \text{(V)}$$

An unloaded resonator ~~to~~ can be represented by either a series or a parallel resonant circuit.

* The resonant frequency and the unloaded Q_0 of a cavity resonator are:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad \text{——— (VI)}$$

$$Q_0 = \frac{\omega_0 L}{R} \quad \text{——— (VII)}$$

If the cavity is coupled by an ideal N:1 transformer and a series inductance L_s to a generator having internal impedence Z_g, then coupling circuit and its equivalent are shown in below figure:

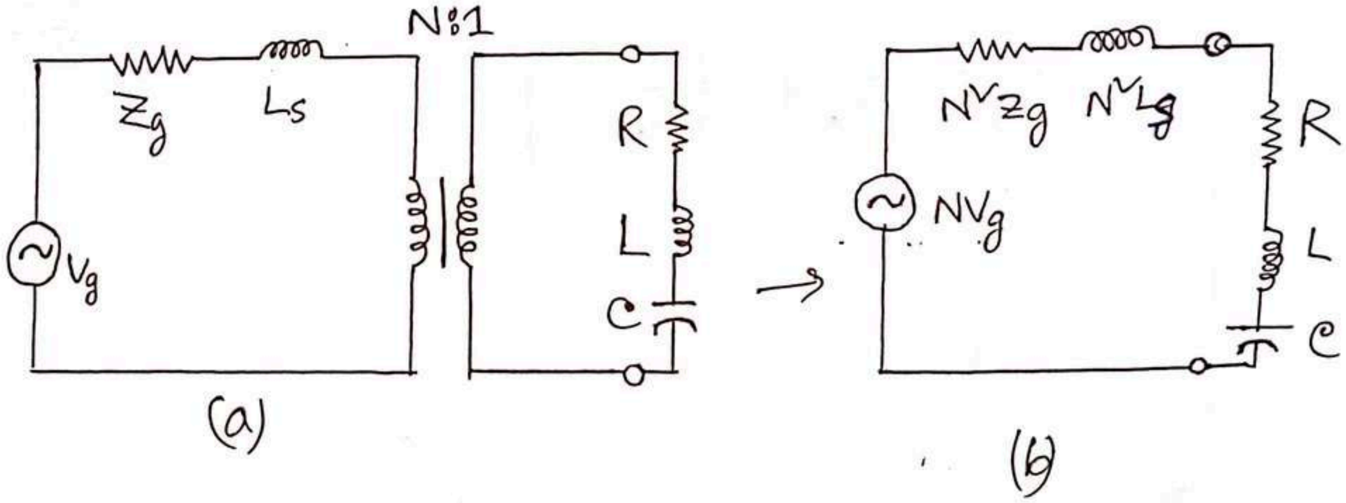

Fig: Cavity coupled to a generator (a) coupling circuit (b) Equivalent circuit

The loaded Q_l of the system is given by,

$$Q_l = \frac{\omega_0 L}{R + N^2 Z_g} \; ; \text{ for } |N^2 L_s| \ll |R + N^2 Z_g| \quad \text{--- (VIII)}$$

$$\Rightarrow Q_l = \frac{\omega_0 L}{R\left(1 + \frac{N^2 Z_g}{R}\right)}$$

$$\Rightarrow Q_l = \frac{\omega_0 L}{R(1+K)}$$

$$\therefore Q_l = \frac{Q_0}{1+K}$$

$$\frac{1}{Q_l} = \frac{1+K}{Q_0}$$

$$\Rightarrow \cancel{Q_l = Q_0 + \frac{Q_0}{K}}$$

$$\Rightarrow \frac{1}{Q_l} = \frac{1}{Q_0} + \frac{K}{Q_0}$$

$$\Rightarrow \frac{1}{Q_l} = \frac{1}{Q_0} + \frac{1}{\frac{Q_0}{K}}$$

$$\therefore \frac{1}{Q_l} = \frac{1}{Q_0} + \frac{1}{Q_{ext}}$$

Here,
coupling coefficient, $K = \frac{N^2 Z_g}{R}$

We know,

$$Q_0 = \frac{\omega_0 L}{R}$$

$$Q_{ext} = \text{external } Q = \frac{Q_0}{K} = \frac{\omega_0 L}{KR}$$

There are three types of coupling coefficents:
(1) Critical coupling
(2) Overcoupling
(3) Undercoupling

(1) Critical coupling :

If the resonator is matched to the generator, then $K = 1$.

So, the loaded Q_l is given by

$$Q_l = \frac{Q_0}{2}$$

(2) Over coupling :

If $K > 1$, the cavity terminals are at a voltage maximum in the input line at resonance. The normalized impedence at the voltage maximum is the standing-wave ratio ρ. That is, $K = \rho$

So, the loaded Q_l is given by

$$Q_l = \frac{Q_0}{1+\rho}$$

(3) Under coupling :

If $K < 1$, the cavity terminals are at a voltage minimum and the input terminal impedence is equal to the reciprocal of the standing-wave ratio. That is, $K = \frac{1}{\rho}$

So, the load Q_l is given by, $Q_l = \frac{\rho}{\rho+1} Q_0$

Pto

The relationship of the coupling coefficient K and the standing-wave ratio is shown in below figure,

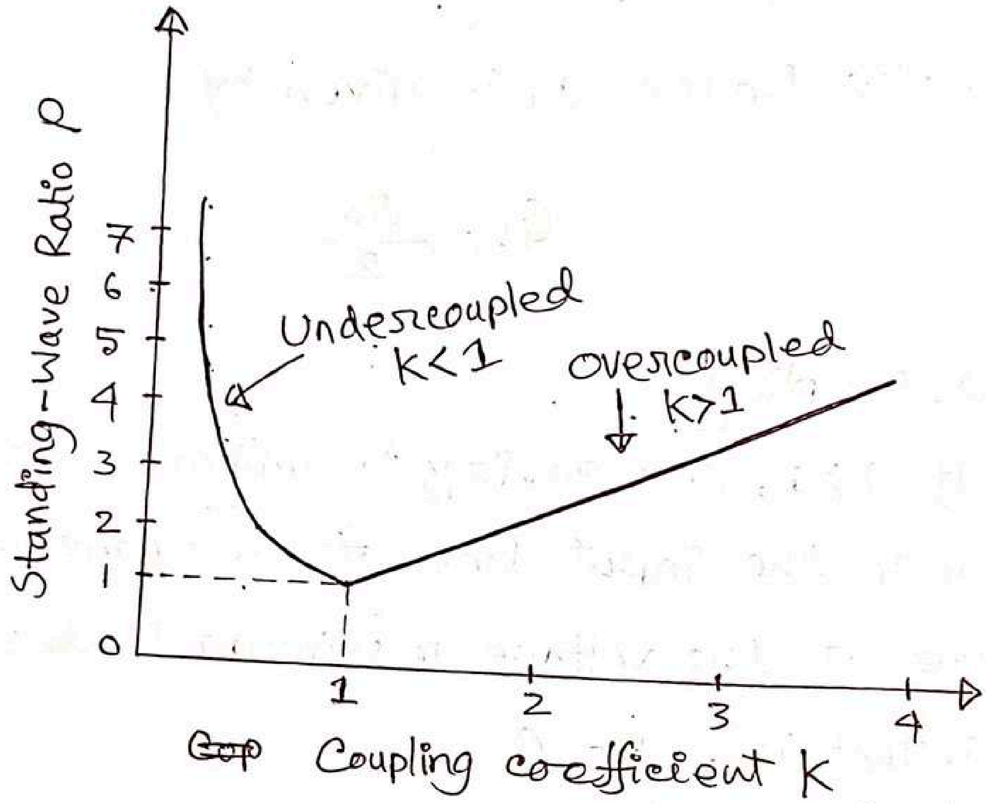

fig: Coupling coefficient versus standing wave ratio

Question:

\# Explain the Q Factor of a cavity Resonator.

\# Show that, a loaded cavity resonator quality Factor, $\frac{1}{Q_l} = \frac{1}{Q_0} + \frac{1}{Q_{ext}}$

\# Describe different types of coupling of a cavity resonator.

Limitation of Conventional Vacuum Triodes, Tetrodes and pentrodes :

Conventional vacuum triodes, tetrodes and pentodes are less usefull signal sources at frequency above 1GHz because of :

(i) Lead-inductance and interelectrode-capaci--tance effects

(ii) Transit Angle Effects and,

(iii) Gain bandwidth product Limitations.

How reduce the Gain bandwidth product limitation?

** Reentrant cavities or slow-wave structures are used to obtain high gain **

Why conventional vacuum tubes are less usefull signal source for microwave circuits? How is it minimized? ④ (2015).

Ans:

conventional vacuum tubes are less useful signal sources at above 1 GHz because of :-

(i) Lead-inductance and interelectrode-capacitance effects,

(ii) Transit-angle effects, and

(iii). Gain-bandwidth product limitations.

There are several ways to minimize the inductance and capacitance effect, such as :

(1) Reduction lead length.

(2) Reduction electrode area.

Transit angle effect can be minimized by:

(1) First accelerating the electron beam with a very high dc voltage, and

(2) then velocity-modulating it.

In microwave devices, either reentrant cavities or slow-wave structure are used to obtain a possible overall high gain over a broad bandwidth.

Gain bandwidth product limitations can be minimized by:

(1) Using reentrant cavities or slow wave structure to obtain a possible overall high gain over a broad bandwidth.

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9-1-2 Transit-Angle Effects:

The electron transit angle is defined as,

$$\theta_g = \omega \tau_g = \frac{\omega d}{v_0}$$

$t = \frac{s}{v}$

$\tau_g = \frac{d}{v_0}$

where, $\tau_g = \frac{d}{v_0}$ = transit time

d = distance between cathode and grid

$v_0 = 0.593 \times 10^6 \sqrt{V_0}$ = velocity of Electron.

V_0 = dc voltage.

When the frequencies are below microwave range, the transit angle is negligible.

When the frequency is below 1 GHz, the output delay is negligible.

How we can minimize the transit-angle effect?

Ans: The transit angle effect can be minimized by:

(i) Accelerating the electron beam with a very high dc voltage.

(ii) and then velocity-modulating it.

9-1-3 Gain-Bandwidth product Limitation:

In ordinary vacuum tubes, the maximum gain is generally achieved by resonating the output circuit as shown in below figure:

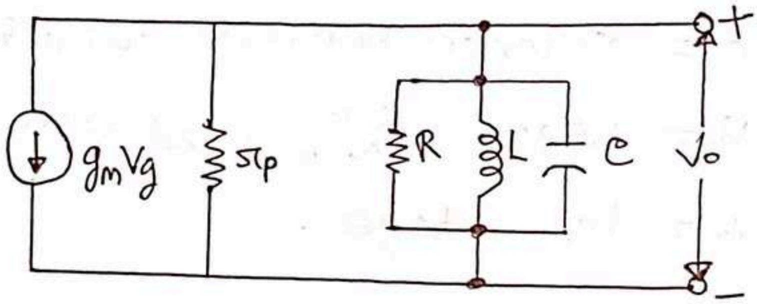

Fig: Output-tunned circuit of a pentode

In the figure, it is assumed that $r_p \gg \omega L_k$.

The load voltage is given by,

$$V_e = \frac{\overset{\text{Transconductance}}{g_m} \; V_g \rightarrow \text{grid voltage}}{G + j(\underset{\uparrow \text{ capacitive subsequence}}{\omega C} - 1/\omega L) \rightarrow \text{inductive subsequence}}$$

where, $G = \frac{1}{r_p} + \frac{1}{R}$ ← conductance

r_p = plate resistance

R = load resistance

L, C = tunning elements

[Reentrant cavities or slow wave structure]
are used to obtain high gain]

The resonant frequency is expressed by,

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

and maximum voltage gain is :

$$A_{max} = \frac{g_m}{G} \text{ ——— (I)}$$

and, $G = \omega C - \frac{1}{\omega L}$ $\Rightarrow G = \frac{\omega^2 LC - 1}{\omega L}$ $\Rightarrow \omega^2 LC - 1 = \omega G L$

$\Rightarrow \omega^2 LC - \omega G L - 1 = 0$

The roots of this quadratic equation are given by

$$\omega_1 = \frac{G}{2C} - \sqrt{\left(\frac{G}{2C}\right)^2 + \frac{1}{LC}}$$

$$\omega_2 = \frac{G}{2C} + \sqrt{\left(\frac{G}{2C}\right)^2 + \frac{1}{LC}}$$

$\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

[সূত্র প্রয়োগ করে]

The Bandwidth can be expressed as,

$$BW = \omega_2 - \omega_1$$

$$= \left(\frac{G}{2C} + \frac{G}{2C}\right) - \left(\frac{G}{2C} - \frac{G}{2C}\right) \quad ; \text{for } \left(\frac{G}{2C}\right)^2 \gg \frac{1}{LC}$$

$$= \frac{G}{2C} + \frac{G}{2C}$$

$$\therefore BW = \frac{G}{C} \text{ ——— (II)}$$

→ gain bandwidth product is independent of frequency.

Hence, the gain bandwidth product of above circuit is,

$$A_{max}(BW) = \frac{g_m}{G} \times \frac{G}{C} = \frac{g_m}{C}$$

[narrow Bandwidth এ High gain পাওয়া যায়]

9-2 Klystron :

A Klystron is a vacuum tube that can be used either as a generator or amplifier of power at low frequency.

Two-cavity klystron :

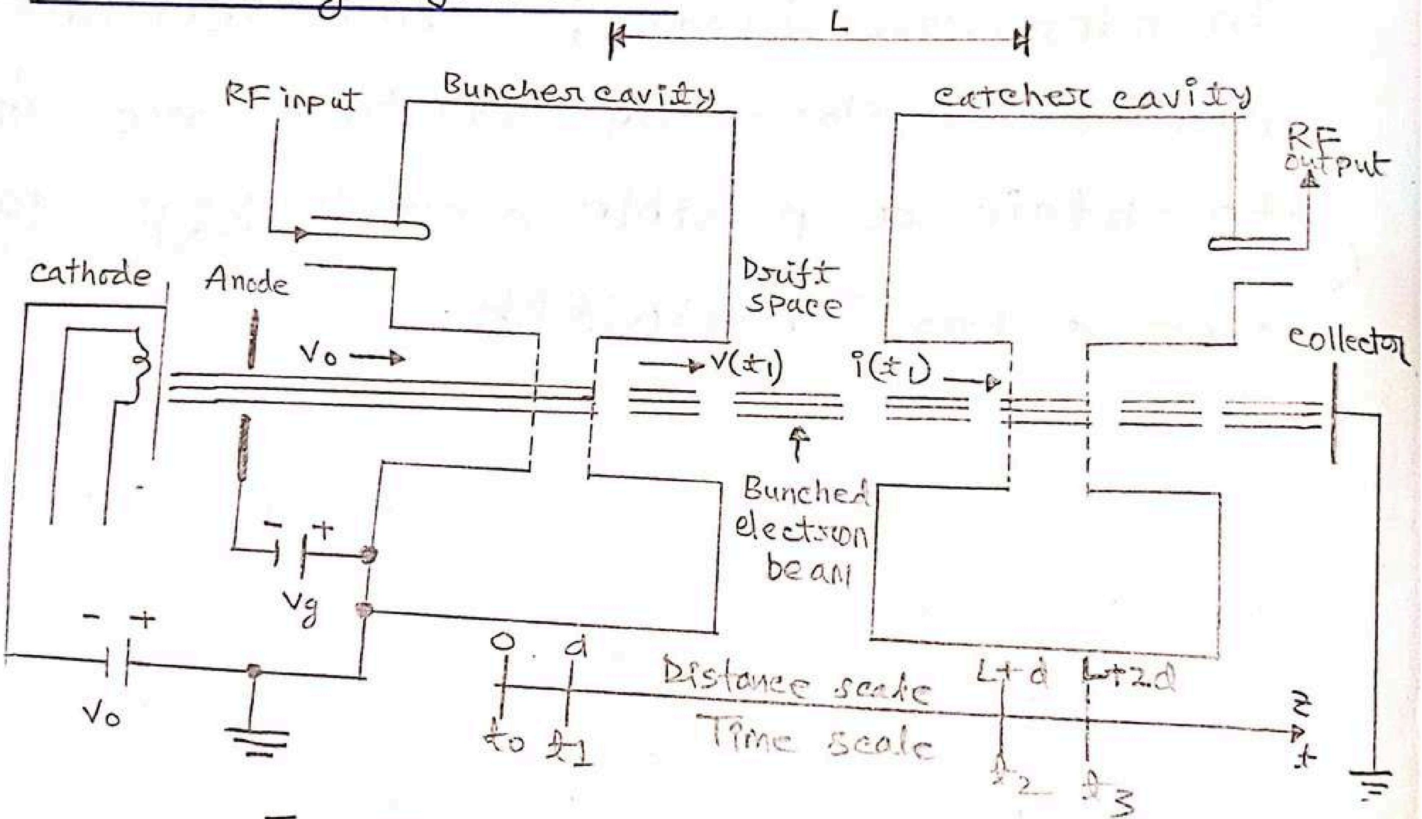

Fig : Two-cavity klystron amplifier.

Operating principle :

(i) The two cavity klystron is a microwave amplifier that is operated by the principle of velocity and current modulation.

(ii) All electrons arrive at the first cavity from the cathode with uniform velocity.

(iii) Those electrons passing the first cavity gap at zeros of the gap voltage pass through with unchanged velocity; those electron passing through the positive half cycles of the gap voltage undergo an increase in velocity; those electrons passing through the negative half cycles of the gap voltage undergo a decrease in velocity. This variation of electron velocity in the drift space is known as velocity modulation.

(iv) The density of the electrons in the second cavity gap varies cyclically with time. The electron beam contains an ac component and is said to be current modulation.

(v) The kinetic energy is transferred from the electrons to the field of the second cavity. The electrons then emerge from the second cavity with reduced velocity and finally terminate at the collector.

Characteristics of Two-cavity Klystron:

(i) Efficiency: about (20–40)%.

(ii) power gain: about 30 dB

(iii) power output: average power is up to 500 KW and pulsed power is up to 30 MW at 10 GHz.

(iv) Frequency = 1 GHz – 40 GHz

(v) Gain: 15-25 dB

(vi) Narrow Band amplification (1-2% of center frequency)

The quantitative analysis of two-cavity Klystron can be described in four parts under the following assumptions:

(i) The electron beam is assumed to have a uniform density in the cross section of the beam.

(ii) Space charge effects are negligible.

(iii) The magnitude of the microwave signal input is assumed to be much smaller than the dc accelerating voltage.

2-1 Reentrant Cavities:

The reentrant cavities are designed for use in klystrons and microwave triodes. A reentrant cavity is one in which the metallic boundaries extend into the interior of the cavity.

Several types of reentrant cavities are shown in below figure:-

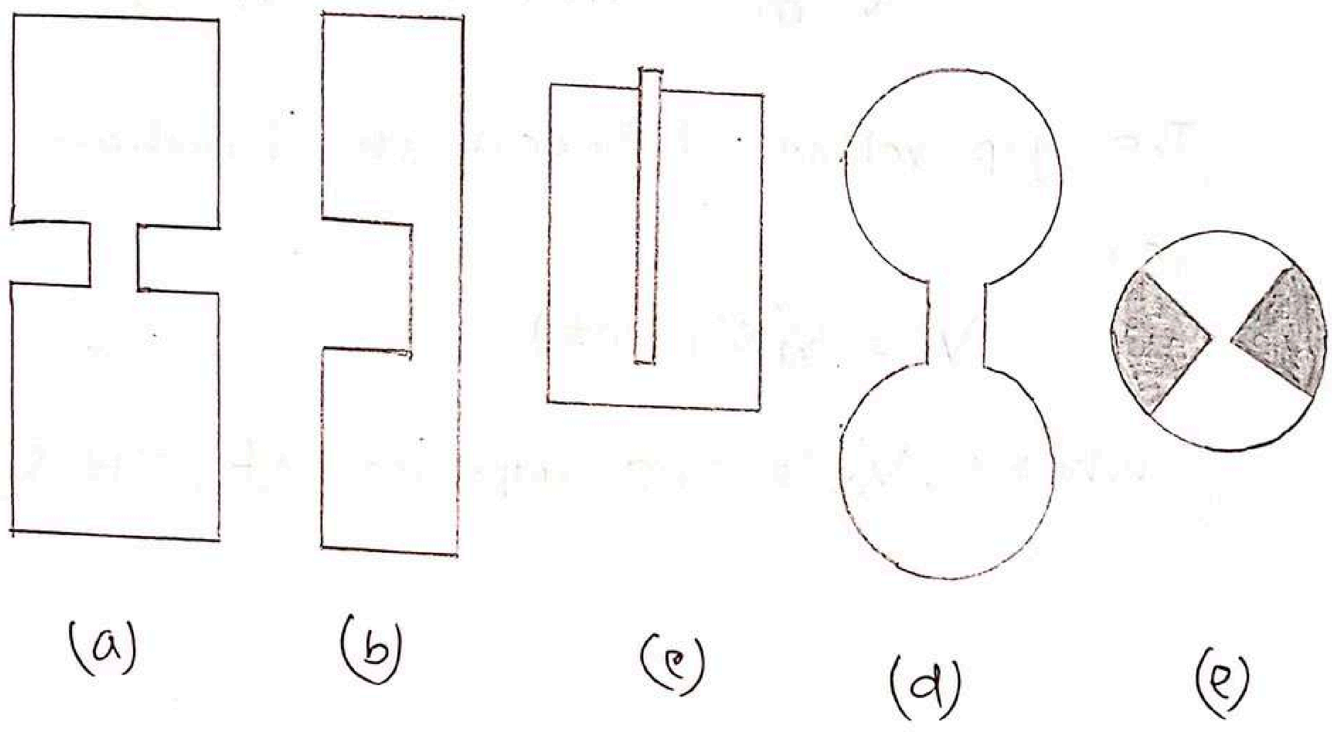

Figure: Reentrant cavities. (a) Coaxial cavity (b) Radial cavity (c) Tunable cavity (d) Toroidal cavity (e) Butterfly cavity.

9-2-2 Velocity-Modulation process:

The variation of electron velocity in the drift space is known as velocity modulation.
It is key principle of operation of a klystron

When electrons are first accelerated by the high dc voltage V_o, before entering the buncher grids, then their electron velocity is uniform:

$$v_o = \sqrt{\frac{2eV_o}{m}} = 0.593 \times 10^6 \sqrt{V_o} \ \ m/s \quad \text{---} (1)$$

The gap voltage between the buncher grids is:

$$V_s = V_1 \sin(\omega t) \quad \text{---} (2)$$

where, V_1 is the amplitude of the signal.

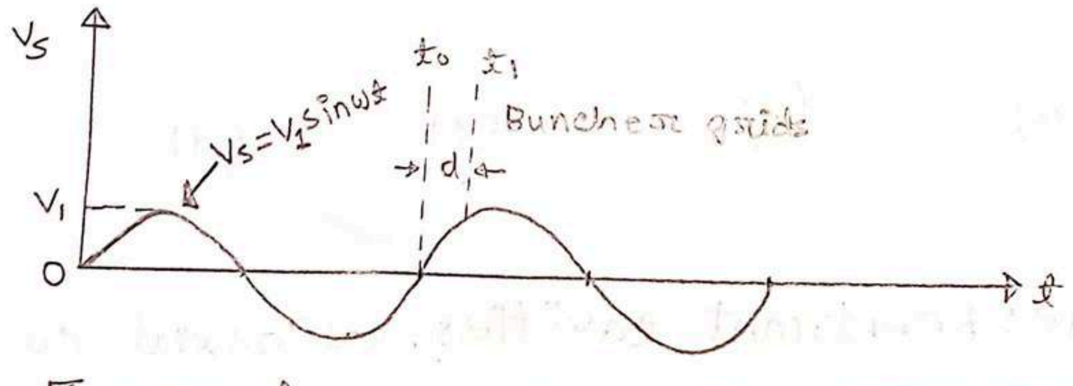

Fig: Signal voltage in the buncher gap.

The average transit time expressed as,

$$\tau = \frac{d}{V_0} = t_1 - t_0 \quad --- \quad (3)$$

here, d = buncher gap distance

t_0 = entering time

t_1 = exiting time.

v_0 = velocity of electrons

The average gap transit angle expressed as,

$$\boxed{\theta_g} = \omega\tau = \omega(t_1 - t_0) = \frac{\omega d}{V_0} \quad --- \quad (4) \quad \| \; \omega t_1 = \omega t_0 + \frac{\omega d}{V_0}$$

and, $\omega t_1 = \frac{\omega d}{V_0} + \omega t_0$

The average microwave voltage in the buncher gap is :

$$\langle V_s \rangle = \frac{1}{\tau}\int_{t_0}^{t_1} V_1 \sin(\omega t)\, dt$$

$$= \frac{1}{\tau}\left[-\frac{V_1 \cos(\omega t)}{\omega}\right]_{t_0}^{t_1}$$

$$= -\frac{V_1}{\omega\tau}\left[\cos(\omega t_1) - \cos(\omega t_0)\right]$$

$$= \frac{V_1}{\omega\tau}\left[\cos(\omega t_0) - \cos(\omega t_1)\right]$$

$$= \frac{V_1}{\omega\tau}\left[\cos(\omega t_0) - \cos\left(\omega t_0 + \frac{\omega d}{V_0}\right)\right]$$

$$= \frac{V_1}{\omega \tau} \cdot 2 \sin\left(\frac{2\omega t_0 + \frac{\omega d}{v_0}}{2}\right) \sin\left(\frac{\frac{\omega d}{v_0}}{2}\right)$$

$$= \frac{V_1}{\omega \tau} 2 \sin\left(\frac{\omega d}{2V_0}\right) \sin\left(\omega t_0 + \frac{\omega d}{2V_0}\right)$$

$$= \frac{V_1 \, 2 \sin\left(\frac{\omega d}{2V_0}\right)}{\frac{\omega d}{V_0}} \cdot \sin\left(\omega t_0 + \frac{\omega d}{2V_0}\right)$$

$$= \frac{V_1 \sin\left(\frac{\omega d}{2V_0}\right)}{\frac{\omega d}{2V_0}} \sin\left(\omega t_0 + \frac{\omega d}{2V_0}\right)$$

$$\Rightarrow \langle V_s \rangle = V_1 \frac{\sin(\theta_g/2)}{\theta_g/2} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)$$

$$\therefore \langle V_s \rangle = \beta_i V_1 \sin\left(\omega t_0 + \frac{\theta_g}{2}\right) \quad \text{———} \quad (5)$$

Here, $\beta_i = \dfrac{\sin(\theta_g/2)}{\theta_g/2}$ is known as the beam-coupling coefficient of the input cavity gap.

If increasing the gap transit angle θ_g, then decreases the beam coupling coefficient.

p.t.o

After velocity Modulation, the exit velocity is:

$$v(t_1) = \sqrt{\frac{2eV}{m}} = \sqrt{\frac{2e(V_0 + \langle V_s \rangle)}{m}}$$

$$= \sqrt{\frac{2e}{m}\left[V_0 + \beta_i V_1 \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)\right]}$$

$$= \sqrt{\frac{2eV_0}{m}\left[1 + \frac{\beta_i V_1}{V_0} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)\right]}$$

here, $\frac{\beta_i V_1}{V_0}$ is called the depth of velocity modulation

Now, $v(t_1) = V_0\left[1 + \frac{\beta_i V_1}{V_0} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)\right]^{1/2}$.

$$\Rightarrow v(t_1) = v_0\left[1 + \frac{1}{2}\frac{\beta_i V_1}{V_0} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right) + \frac{\frac{1}{2}\left(\frac{1}{2}-1\right)}{\lfloor 2}\left\{\frac{\beta_i V_1}{V_0} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)\right\}^2 + \text{----}\right]$$

for $\beta_i V_1 \ll V_0$

$$v(t_1) = V_0\left[1 + \frac{\beta_i V_1}{2V_0} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)\right] \text{------} (6)$$

This is the equation of velocity modulation.

Alternatively, the equation of velocity modulation is:

$$v(t_1) = v_0\left[1 + \frac{\beta_i V_1}{2V_0} \sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right] \text{---} (7)$$

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Necessary Formula of two-cavity Klystron

* $\boxed{v_0 = 0.593 \times 10^6 \times \sqrt{V_0}}$

here, v_0 = electron velocity

V_0 = dc voltage

* $$\theta_g = \frac{\omega d}{v_0}$$
$$\theta_0 = \frac{\omega L}{v_0} = 2\pi N$$

here, $\omega = 2\pi f$

θ_g = gap transit angle

θ_0 = dc transit angle between cavities.

d = buncher gap distance

N = no. of electron transit cycles in the dri[ft] space.

* $$\beta_i = \frac{\sin(\theta_g/2)}{(\theta_g/2)}$$

here, β_i = Beam coupling coefficient

θ_g = gap transit angle.

* $$X = \frac{\beta_i V_1 \theta_0}{2V_0}$$
$$V_1 = \frac{2V_0 X}{\beta_i \theta_0}$$

X = bunching parameter

V_1 = input voltage

$$* \boxed{A_v = \frac{|V_2|}{|V_1|} = \frac{\beta_0^2 \theta_0}{R_0} \frac{J_1(X)}{X} R_{sh}}$$

here, A_v = Voltage gain

$\beta_0 = \beta_i$ = beam coupling coefficient.

$R_0 = \frac{V_0}{I_0}$ = dc beam resistance

$J_1(X)$ = Bessel Function

Neglecting beam loading.

$$I_2 = 2 I_0 J_1(X)$$

$$V_2 = \beta_0 I_2 R_{sh}$$

$$\text{Efficiency} = \frac{P_{out}}{P_{in}} = \frac{\beta_0 I_2 V_2}{2 I_0 V_0}$$

here, I_2 = Current in the catcher

V_2 = Voltage in the catcher

For $X = 1.841$, $J_1(X) = 0.582$

R_{sh} = Shunt resistance

$$G_B = \frac{G_0}{2}\left(\beta_0^2 - \beta_0 \cos\frac{\theta_g}{2}\right)$$

$$R_B = \frac{1}{G_B}$$

here, $G_0 = \frac{1}{R_0}$

$\beta_0 = \beta_i$

Example 9-2-1:

A two-cavity Klystron amplifier has the following parameters:

$V_0 = 1000\ V$ $\quad$ $R_0 = 40\ k\Omega$

$I_0 = 25\ mA$ $\quad$ $f = 3\ GHz$

Gap spacing in either cavity: $d = 1\ mm$

Spacing between two cavities: $L = 4\ cm$

Effective shunt impedence, excluding beam loading: $R_{sh} = 30\ k\Omega$

(a) Find the input gap voltage to give maximum voltage V_2.

(b) Find the voltage gain, neglecting the beam loading in the output cavity.

(c) Find the efficiency of the amplifier, neglecting beam loading.

(d) Calculate the beam loading conductance and show that neglecting it was justified in the preceding calculations.

$$X = \frac{\beta_i V_1 \theta_0}{2V_0}$$

Solution:

(a) For maximum V_2, $J_1(X)$ must be maximum.

This means $J_1(X) = 0.582$ at $X = 1.841$.

We know,

$$V_{max} = \frac{2V_0 X}{\beta_i \theta_0}$$

here,

$V_0 = 1000\,V$

$X = 1.841$

$$\beta_i = \frac{\sin(\theta_g/2)}{(\theta_g/2)}$$

$$\theta_g = \frac{\omega d}{v_0}$$

$$v_0 = 0.593 \times 10^6 \sqrt{V_0} = 0.593 \times 10^6 \sqrt{1000}\ m/s$$

$$= 1.88 \times 10^7\ ms^{-1}$$

$$\theta_0 = \frac{\omega L}{v_0}$$

$\therefore$ $$\theta_0 = \frac{\omega L}{v_0}$$

$$= \frac{2\pi \times 3 \times 10^9 \times 0.04}{1.88 \times 10^7}$$

$$= 40\ rad$$

$\omega = 2\pi f$

$= 2\pi(3 \times 10^9)$

$L = 4\,cm = 0.04\,m$

$d = 1\,mm = 10^{-3}\,m$

$$\theta_g = \frac{\omega d}{v_0} = \frac{2\pi(3 \times 10^9) \times 10^{-3}}{1.88 \times 10^7}$$

$$= 1\ rad$$

$\therefore\ \cancel{\beta_i = \sin(\theta_g/2)}$

radian mode এ calculation

$$\therefore\ \beta_i = \frac{\sin(\theta_g/2)}{(\theta_g/2)} = \frac{\sin(1/2)}{(1/2)} = 0.952$$

0.958

$$\therefore\ V_{max} = \frac{2V_0X}{\beta_i\,\theta_0}$$

$$= \frac{2\times1000\times1.841}{0.952\times40}$$

$$= 96.5\,V$$ (Ans.)

ⓑ We know, voltage gain $A_v = \frac{\beta_0^2\theta_0}{R_0}\ \frac{J_1(X)}{X}\ R_{sh}$

$$\Rightarrow A_v = \frac{(0.952)^2\times40}{40\times10^3}\times\frac{0.582}{1.841}\times30\times10^3$$

$\therefore\ A_v = 8.595$ (Ans.)

$\beta_0 = \beta_i = 0.952$

$\theta_0 = 40$ rad

$R_0 = 40\,k\Omega = 40\times10^3\,\Omega$

$J_1(X) = 0.582$

$X = 1.841$

$R_{sh} = 30\,k\Omega = 30\times10^3\,\Omega$

(c) We know, Efficiency $= \dfrac{\beta_0 I_2 V_2}{2 I_0 V_0}$

here,

$I_0 = 25\ mA$

$= 25 \times 10^{-3} A$

$V_0 = 1000\ V$

$J_1(X) = 0.582$

$R_{sh} = 30\ K\Omega$

$= 30 \times 10^3 \Omega$

$\beta_g = \beta_0 = 0.952$

$I_2 = 2 I_0 J_1(X)$

$= 2 \times 25 \times 10^{-3} \times 0.582$

$\therefore I_2 = 29.1 \times 10^{-3} A$

$V_2 = \beta_0 I_2 R_{sh}$

$= 0.952 \times 29.1 \times 10^{-3} \times 30 \times 10^3$

$\therefore V_2 = 831\ V$

$\therefore$ Efficiency $= \dfrac{\beta_0 I_2 V_2}{2 I_0 V_0}$

$= \dfrac{0.952 \times 29.1 \times 10^{-3} \times 831}{2 \times 25 \times 10^{-3} \times 1000}$

$= 0.4604$

$= 46.04\ \%$

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(d) We know, the beam loading conductance G_B is:

$$G_B = \frac{G_0}{2}\left(\beta_0^2 - \beta_0 \cos\frac{\theta_g}{2}\right)$$

$$\Rightarrow G_B = \frac{25\times10^{-6}}{2}\left(0.952^2 - 0.952\times\cos\frac{57.3}{2}\right)$$

$$= 8.85 \times 10^{-7} \text{ mho}$$ (Ans.)

here,

$G_0 = \frac{1}{R_0}$

$= \frac{1}{40\times10^3}$

$= 25\times10^{-6}$ mho

$\beta_0 = \beta_i = 0.952$

$\theta_g = 1$ rad

$= 57.3°$

$$\therefore R_B = \frac{1}{G_B} = \frac{1}{8.85\times10^{-7}}$$

$$\therefore R_B = 1.13\times10^{6}\,\Omega$$

In comparison with R_L and R_{sh}, the beam loading resistance is like an open circuit and thus can be neglected in the preceding calculations.

Example 9-3-3: Characteristics of two-cavity Klystron:-

A two cavity Klystron has the following parameters:

Beam voltage: $V_0 = 20\,KV$

Beam current: $I_0 = 2\,A$

Operating frequency: $f = 8\,GHz$

Beam coupling coefficient: $\beta_i = \beta_0 = 1$

dc electron beam current density: $\rho_0 = 10^{-6}\,C/m^3$

Signal voltage: $V_1 = 10\,V\,(rms)$

Total shunt resistance including load: $R = 30\,K\Omega$

Shunt resistance of the cavity: $R_{sh} = 10\,K\Omega$

Calculate:

(a) The plasma frequency

(b) The reduced plasma frequency for $R = 0.5$

(c) The induced current in the output cavity

(d) The induced voltage in the output cavity

(e) The output power delivered to the load

(f) The power gain

(g) The electronic efficiency.

Solution :-

(a) We know, the plasma frequency is :-

$$\omega_p = \sqrt{\frac{e\rho_o}{m\epsilon_o}}$$

$$\Rightarrow \omega_p = \sqrt{\frac{1.759 \times 10^{11} \times 10^{-6}}{8.854 \times 10^{-12}}}$$

$\frac{e}{m} = 1.759 \times 10^{11}$ c/kg
$\rho_o = 10^{-6}$ c/m³
$\epsilon_o = 8.854 \times 10^{-12}$ F/m
$\omega_p = ?$

$\therefore \omega_p = 1.41 \times 10^{8}$ rad/s (Ans.)

(b) We know, the reduced plasma frequency is :-

$$\omega_q = R\omega_p = 0.5 \times 1.41 \times 10^{8}$$

$$\Rightarrow \omega_q = 0.705 \times 10^{8} \text{ rad/s}$$

(Ans.)

$R = 0.5$
$\omega_p = 1.41 \times 10^{8}$ rad/s
$\omega_q = ?$

(c) We know, the induced current in the output cavity is:

$$|I_2| = \frac{1}{2}\left(\frac{I_o \omega}{V_o \omega_q}\right) \beta_o^2 |V_1|$$

$$= \frac{1}{2}\left(\frac{2 \times 2\pi \times 8 \times 10^{9}}{20 \times 10^{3} \times 0.705 \times 10^{8}}\right) \times 1^2 \times |10|$$

$\therefore |I_2| = 0.3565$ A (Ans.)

(d) We know, the induced voltage in the output cavity is:

$$|V_2| = |I_2| R_{sh} = 0.3565 \times 30 \times 10^{3}$$

$\therefore |V_2| = 10.695$ KV (Ans.)

$R_{sh} = R = 30$ kΩ
$= 30 \times 10^{3}$ Ω

(e) We know, output power delivered to the load is :-

$$P_{out} = |I_2|^2 R_{shl}$$

$$\Rightarrow P_{out} = (0.3565)^2 \times 30\times10^3$$

$$\therefore P_{out} = 3.813 \text{ KW}$$

(Ans.)

$|I_2| = 0.3565$ A
$R_{shl} = R = 30$ KΩ $= 30\times10^3\ \Omega$
$P_{out} = ?$

(f) We know, the power gain is :

$$\text{Gain} = \frac{1}{4}\left(\frac{I_0\omega}{V_0\omega_q}\right)^2 \beta_0^4\, R_{sh}\cdot R_{shl}$$

$$\Rightarrow \text{Gain} = \frac{1}{4}\left(\frac{2\times2\pi\times8\times10^9}{20\times10^3\times0.705\times10^8}\right)^2 \times 1^4 \times 10\times10^3 \times 30\times10^3$$

$$\Rightarrow \text{Gain} = 3.813\times10^5$$

$$\therefore \text{Gain} = 55.81 \text{ dB}$$

(Ans.)

$I_0 = 2A$
$\omega = 2\pi f = 2\pi\times8\times10^9$
$V_0 = 20$ KV $= 20\times10^3$ V
$\omega_q = 0.705\times10^8$ rad/s
$\beta_i = \beta_0 = 1$
$R_{sh1} = R = 30$ KΩ $= 30\times10^3\ \Omega$
$R_{sh} = 10$ kΩ $= 10\times10^3\ \Omega$

(g) We know, the electronic efficiency is :

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{V_0 I_0}$$

$$\Rightarrow \eta = \frac{3.813\times10^3}{20\times10^3\times2}$$

$$\therefore \eta = 0.0953$$

$$\therefore \eta = 9.53\%$$ (Ans.)

$P_{out} = 3.813$ kW $= 3.813\times10^3$ W
$V_0 = 20$ kV $= 20\times10^3$ V
$I_0 = 2A$
$\eta = ?$

Reflex klystron:

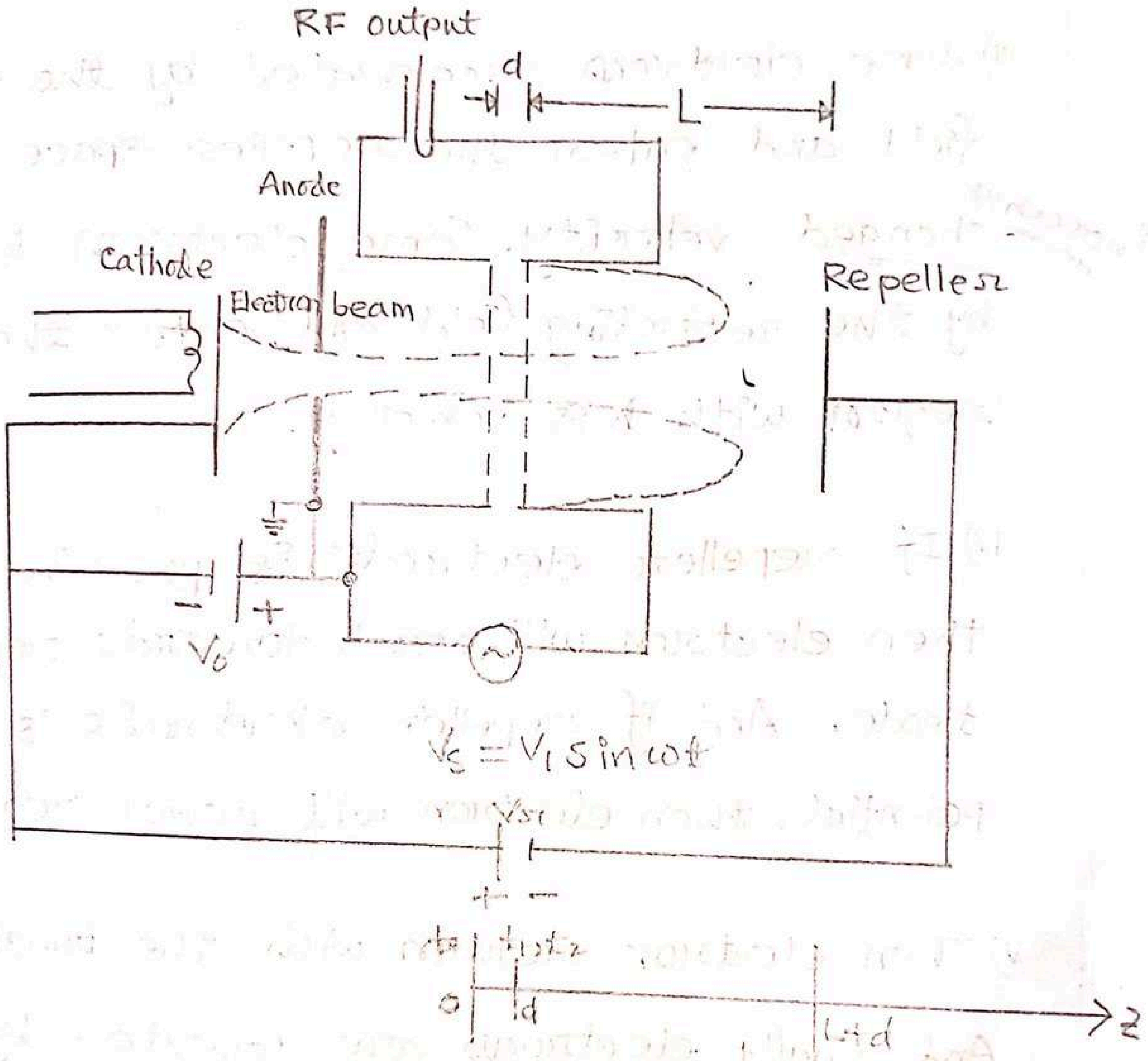
The reflex klystron is a single-cavity klystron that overcomes the disadvantages of the two-cavity klystron oscillator.

It is low-power generator of 10 to 500 mW at a frequency range of 1 to 25 GHz. The efficiency is about 10 to 30%.

It is used in the military: airborne doppler radars and missiles.

Operating principle of Reflex Klystron :

Operating principle of reflex Klystron is clearly shown in below figure :



(1) Reflex Klystron is a single cavity Klystron that works on the principle of velocity modulation and current modulation.

ii) The electron beam injected from cathode is first velocity modulated by the cavity gap voltage.

iii) Some electrons accelerated by the accelerating field and enter the repeller space with <u>un-</u> increasing <u>changed</u> velocity. Some electrons decelerated by the retarding field and enter the repeller region with less velocity.

iv) If repeller electrode is positive potential, then electron will reach towards repeller electrode. And if repeller electrode is negative potential, then electron will never reach towards.

v) Then electron return with the bunching process And finally electrons are collected by the walls of the cavity.

Why we use reflex klystron ?

Answer:

(I) A two-cavity klystron oscillator is usually not constructed, for this reason we use reflex klystron oscillator.

(II) Reflex klystron overcomes the disadvantage of the two-cavity klystron oscillator. For this reason we use reflex klystron oscillator.

Application of Reflex Klystron :

(I) Widely used in the labratory for microwave measurements.

(II) Used as local oscillators in receivers.

(III) Used in military, airborne doppler radars as well as missiles.

(IV) Signal source in microwave generators.

(V) pump oscillators in parametric amplifiers.

Necessary Formula of Reflex Klystron :

1/ $$\frac{V_0}{(V_r+V_0)^2} = \left(\frac{e}{m}\right)\frac{(2\pi n - \pi/2)^2}{8\omega^2 L^2}$$

Mode number

$N = n - \frac{1}{4}$

2/ $$I_2 = 2 I_0 \beta_i J_1(X')$$

3/ $$V_2 = I_2 R_{sh} = 2 I_0 \beta_i J_1(X') R_{sh}$$

4/ $$\text{Efficiency} = \frac{2X' J_1(X')}{2\pi n - \pi/2}$$

Here, V_0 = beam voltage

V_r = repeller voltage

$\frac{e}{m} = 1.759 \times 10^{11}$ C/kg

n = cycle number

X' = Bunching parameters of reflex Klystron $= 1.841$

V_2 = Microwave gap voltage

$J_1(X') = 0.582$

Example 9-4-1: Reflex klystron:

A reflex klystron operates under the following conditions:

$V_0 = 600\ V$ $\quad L = 1\ mm$

$R_{sh} = 15\ k\Omega$ $\quad \frac{e}{m} = 1.759 \times 10^{11}\ C/kg$

$f_r = 9\ GHz$

The tube is oscillating at f_r, at the peak of the $n=2$ mode or $1\frac{3}{4}$ mode. Assume that the transit time through the gap and beam loading can be neglected.

(a) Find the value of the repeller voltage V_r.

(b) Find the direct current necessary to give a Microwave gap voltage of 200 V.

(c) What is the electronic efficiency under this condition?

Solution :

(a) We know that.

here,
$n=2$
$f=9GHz$
$=9\times10^{9}$ Hz
$\omega=2\pi f$
$L=1mm=10^{-3}$ m
$V_0=600V$

$$\frac{V_0}{(V_r+V_0)^2}=\frac{e}{m}\frac{(2\pi n-\pi/2)^2}{8\omega^2L^2}$$

$$\Rightarrow \frac{600}{(V_r+600)^2}=1.759\times10^{11}\times\frac{(2\pi\times2-\pi/2)^2}{8\times(2\pi\times9\times10^{9})^2(10^{-3})^2}$$

$$\Rightarrow \frac{600}{(V_r+600)^2}=8.313\times10^{-4}$$

$$\Rightarrow (V_r+600)^2=\frac{600}{8.313\times10^{-4}}$$

$$\Rightarrow (V_r+600)^2=721761.097$$

$$\Rightarrow V_r+600=849.57$$

$$\therefore V_r=249.57\ V$$ (Ans.)

(b) We know, $V_2=I_2R_{sh}=2I_0J_1(X')R_{sh}\beta_i$

Assum that,
$\beta_i=\beta_o=1$
$V_2=200V$
$J_1(X')=0.582$
$R_{sh}=15k\Omega$
$=15\times10^{3}\Omega$

$$\Rightarrow I_0=\frac{V_2}{2J_1(X')R_{sh}}$$

$$\Rightarrow I_0=\frac{200}{2\times0.582\times15\times10^{3}}$$

$$\therefore I_0=0.01145\ A=11.45\ mA$$

(Ans.)

(c) We know that, Electronic efficiency is :

$$\text{Efficiency} = \cancel{2\times 1}\; \frac{2X' J_1(X')}{2\pi n - \pi/2}$$

$X' = 1.841$

$J_1(X') = 0.582$

$n = 2$

Efficiency = ?

$$\Rightarrow \text{Efficiency} = \frac{2 \times 1.841 \times 0.582}{2\pi \times 2 - \pi/2}$$

$$\Rightarrow \text{Efficiency} = 0.1949$$

$\therefore$ Efficieney = 19.49 % (Ans)

Traveling-wave Tube (TWT) :

A traveling-wave tube is a vacuum tube that is used in electronics to amplify radio frequency (RF) signals in the microwave range.

It is a high-gain, low-noise, wide-bandwidth microwave amplifier. The TWT is primarily a voltage amplifier.

Characteristics of TWT :

The characteristics of the Traveling wave Tube (TWT) is :

1// Bandwidth : about 0.8 GHz .

2// Efficiency : 20 to 40 % .

3// Frequency Range : 3 GHz and higher .

4// power output : up to 10 KW average .

5// Power Gain : up to 60 dB .

Difference Between TWT and Klystron :

d.ofn

TWT	Klystron defn
1, The interaction of electron beam and RF field in the TWT is continuous over the entire length of the circuit	1, The interaction in the klystron occurs only at the gaps of a few resonant cavities.
2, The wave in the TWT is a propagating wave.	2, The wave in the Klystron is not a propagating wave.
3, In the coupled cavity TWT, there is a coupling effect between the cavities.	3, Each cavity in the Klystron operates independently.
4, The microwave circuit is non resonant.	4, The microwave circuit is resonant.
5, TWT is a wide band device	5, Klystron is a narrow band device.
6, High power output.	6, Low power output.
7, Long Life	7, short Life.

Helix Traveling-wave Tube :

Helix Traveling-wave Tube is a vacuum tube that consists of an electron beam and a slow wave structure. It is an O-type traveling-wave tube.

Slow-wave structure :

Slow-wave structures are special circuits that are used in microwave tubes to reduce the wave velocity.

Several slow-wave structures are shown in below :-

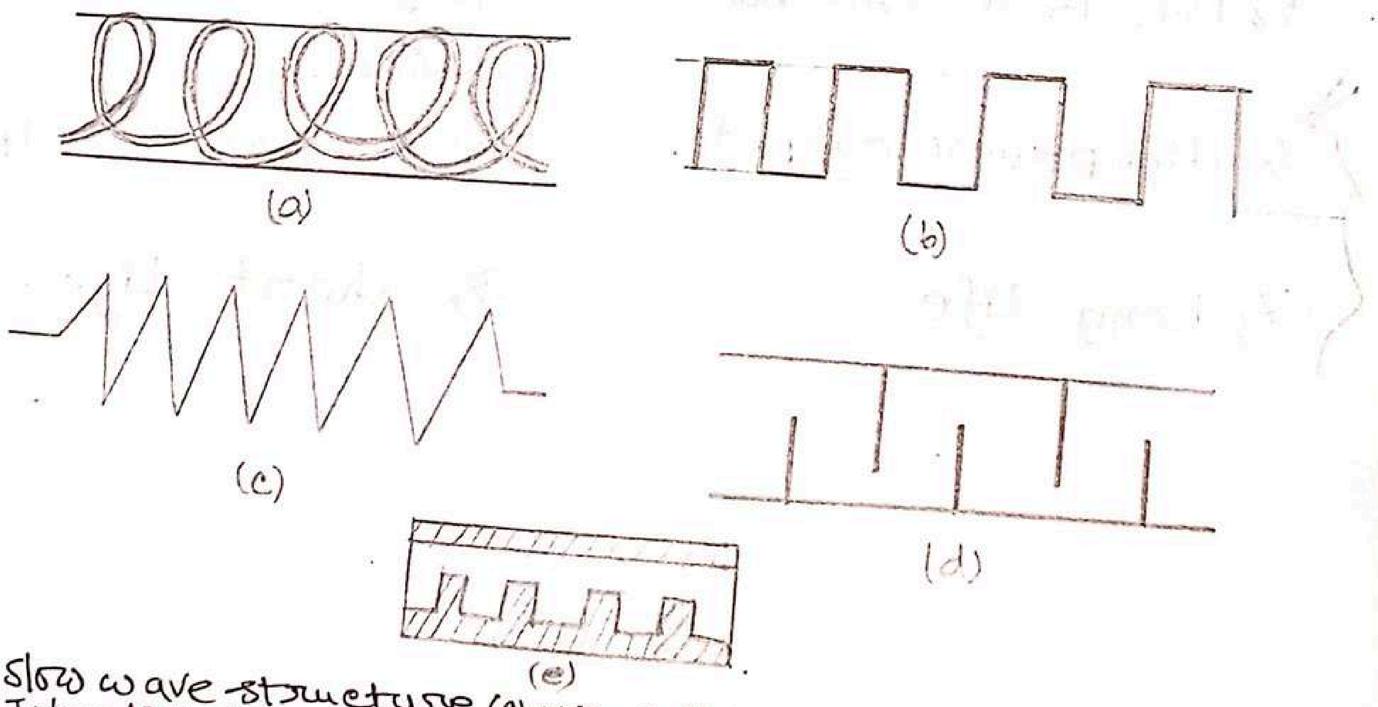


Fig: Slow wave structure (a) Helical line (b) Folded-back line (c) Zigzag Line (d) Interdigital line (e) Corrugated waveguide.

☐ Microstrip line :

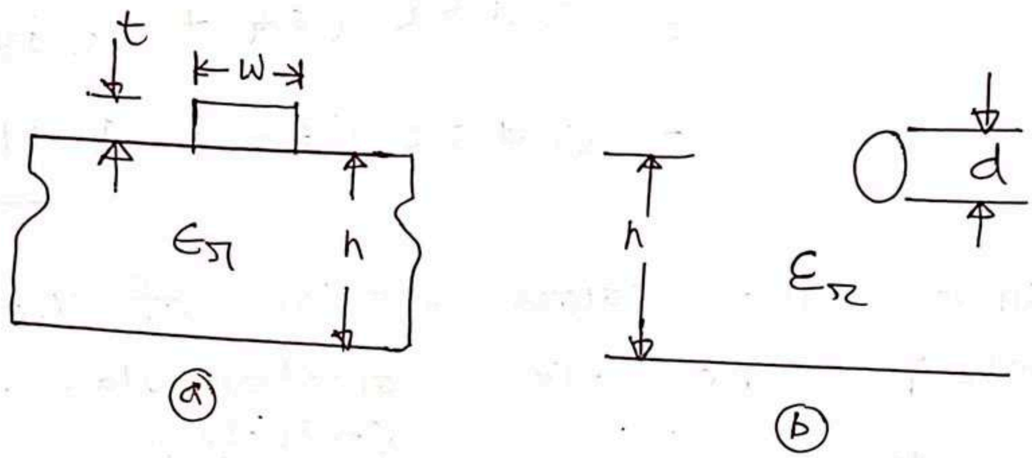
Microstrip line is a type of electrical transmission line which can be fabricated by using printed circuit board and used to convey microwave frequency signal.

Chapter # 11

Strip Lines :

☑ Characteristics Impedance of micro strip Line

The below figure shows the cross section of a microstrip line and a wire over ~~gou~~ ground line.



(Fig) 11.1.1 ⓐⓑ → Fig: cross section of ⓐ a micro strip Line ⓑ a wire over ground. line

The characteristic impedance of a wire-over-ground transmission line is given by

$$Z_0 = \frac{60}{\sqrt{\epsilon_{re}}} \ln \frac{4h}{d} \quad \text{for } h >> d \qquad (1)$$

where,

ϵ_{re} = dielectric ~~ong~~ constant of the ambient medium

h = height from the center of the wire to the ground plane

d = diameter of the ~~pla~~ wire

But the relative dielectric constant ϵ_r is related to the effective relative dielectric constant. The empirical equation is given by,

$$\epsilon_{re} = 0.475\,\epsilon_r + 0.67$$

$$= 0.475\left(\epsilon_r + \frac{0.67}{0.475}\right)$$

$$= 0.475\,(\epsilon_r + 1.41) \quad \text{——— (ii)}$$

Since, the cross section of the micro-strip line is rectangular.

So the rectangular conductor must be transformed into an equivallent circular conductor. The empirical equation is given by

$$d = 0.67\,W\left(0.8 + \frac{t}{W}\right) \quad \text{——— (iii)}$$

here,

d = diameter of the wire over ground

W = Width of the microstrip line

t = Thickness of the microstripline

put the value of ϵ_r and d in equation (1) we obtain —

$$Z_0 = \frac{60}{\sqrt{0.475(\epsilon_r + 1.41)}} \ln\left[\frac{4h}{0.67\, W(0.8+\frac{t}{W})}\right]$$

$$= \frac{60}{\sqrt{0.475}} \times \frac{1}{\sqrt{\epsilon_r + 1.41}} \ln\left(\frac{4}{0.67} \times \frac{h}{0.8W+t}\right)$$

$$= \frac{87}{\sqrt{\epsilon_r + 1.41}} \ln\left[\frac{5.98\,h}{0.8W+t}\right]$$

here, for $h < 0.8W$

ϵ_r = relative dielectric constant of the board material

h = height from the microstrip line to the ground

W = Width of the microstrip line

t = thickness of "

This is the ~~the~~ equation of characteristic impedance for a narrow micro stripline

Ex 11.1.1

Example : A certain microstrip Line has the following parameters :

$\epsilon_r = 5.23$

$h = 7$ mils

$t = 2.8$ mils

$W = 10$ mils

Calculate the characteristic impedance ~~of the~~ Z_0 of the line .

solution: We Know,

$$Z_0 = \frac{87}{\sqrt{\epsilon_r + 1.41}} \ln \left[\frac{5.98h}{0.8W + t} \right]$$

$$= \frac{87}{\sqrt{5.23 + 1.41}} \ln \left[\frac{5.98 \times 7}{0.8 \times 10 + 2.8} \right]$$

$$= 45.78\ \Omega$$

$45.74\ \Omega$

Radar range equation:

To determine the maximum range of a radar, it is necessary to determine the power of received echos and to compare it with the minimum power that the receiver can handle and display.

If the antenna is isotropic, then the power density P_D is:

$$P_D = \frac{P_t}{4\pi R^2} \quad \text{--- (i)}$$

P_t = Transmitted pulsed power

R = Distance from Antenna

For the maximum power gain A_p, the transmitted power density is:

$$P_D = \frac{A_p P_t}{4\pi R^2} \quad \text{--- (ii)}$$

Now, Total transmitted power is,

$$P = P_D S = \frac{A_p . P_t . S}{4\pi R^2} \quad \text{--- (iii)}$$

Here, S = surface area

The power density at the receiving antenna is,

$$P_D' = \frac{P}{4\pi R^2} = \frac{A_p . P_t . S}{(4\pi R^2)^2} \quad \text{--- (iv)}$$

Total received power is:

$$P' = P_D' A_o = \frac{A_p . P_t . S . A_o}{(4\pi R^2)^2} \quad \text{--- (v)}$$

Here, A_0 = Capture area of the receiving antenna.

If same antenna is used for both reception and transmission, then

$$A_p = \frac{4\pi A_0}{\lambda^2}$$

From (V) No equation,

$$p' = \frac{4\pi A_0}{\lambda^2} \cdot \frac{P_t . S . A_0}{16\pi^2 R^4}$$

$$\Rightarrow p' = \frac{P_t S A_0^2}{4\pi \lambda^2 R^4}$$

$$\Rightarrow R^4 = \frac{P_t S A_0^2}{4\pi \lambda^2 p'}$$

$$\therefore R = \left(\frac{P_t S A_0^2}{4\pi \lambda^2 p'}\right)^{1/4} \text{ ——— (VI)}$$

The maximum range will obtain for minimum received power,

$$\therefore R_{max} = \left(\frac{P_t . S . A_0^2}{4\pi \lambda^2 P_{min}}\right)^{\frac{1}{4}} \text{ — (VII)}$$

For R_{max}

$p' = P_{min}$

This is the radar range equation.

Factors Influencing the maximum range:

We know from the Radar range equation:

$$r_{max} = \left(\frac{A_0^2 P_t S}{4\pi \lambda^2 P_{min}} \right)^{\frac{1}{4}}$$

(i) $r_{max} \propto (P_t)^{\frac{1}{4}}$

$\therefore r_{max} \propto \sqrt[4]{P_t}$

So, maximum range is proportional to the fourth root of the peak transmitted pulse power.

(ii) $r_{max} \propto \left(\frac{1}{P_{min}} \right)^{\frac{1}{4}}$

$\therefore r_{max} \propto \frac{1}{\sqrt[4]{P_{min}}}$

So, maximum range is inversely proportional to the fourth root of the minimum receiving power.

(iii) $r_{max} \propto (A_0^2)^{\frac{1}{4}} \Rightarrow r_{max} \propto \sqrt{A_0}$

$4\pi r^2$

$= \sqrt{\pi}\, 2r$

So, maximum range is proportional to the square root of the capture area and directly proportional to the diameter of the capture area.

$$\boxed{\begin{aligned} &\text{Rest time} = PRT - PW \\ &\text{Duty cycle} = \frac{PW}{PRT} \\ &r_{max} = \left(\frac{P_t A_o^2 S}{4\pi\lambda^2 P_{min}}\right)^{\frac{1}{4}} \end{aligned}}$$

~~16.2~~

~~$R.T. = PRT - PW$~~

~~$\Rightarrow PRT = RT + PW$~~

~~$= 997 + 3\times10^{-6}$~~

~~$=$~~

Example 16-1: What is the duty cycle of Radar with a PW of 3 μs and a PRT of 6 ms?

Solution:

We know, ~~dy~~ duty cycle $= \frac{PW}{PRT}$

$$= \frac{3\times10^{-6}}{6\times10^{-3}}$$

$$= 0.5\times10^{-3}$$

$$= 0.0005 \text{ (Ans.)}$$

$PW = 3\ \mu s$
$= 3\times10^{-6}\ s$

$PRT = 6\ ms$
$= 6\times10^{-3}\ s$

Example 16-4:

Calculate the maximum range of a radar which operates at 3 cm with a peak pulse power of 500KW. If minimum receiable power is 10^{-13} W, the capture area is 5 m^2, and the radar cross section area of the target is 20 m^2.

Solution:

$$r_{max} = \left(\frac{P_t A_o^2 S}{4\pi\lambda^2 P_{min}}\right)^{\frac{1}{4}} = \left[\frac{5\times10^5 \times 5^2 \times 20}{4\times\pi\times(0.03)^2\times10^{-13}}\right]^{\frac{1}{4}}$$

$$= 6.86\times10^5\ m$$

$$= 686\ km \text{ (Ans.)}$$

$P_t = 500\ KW$
$= 5\times10^5\ W$

$A_o = 5\ m^2$

$S = 20\ m^2$

$\lambda = 3\ cm$
$= 0.03\ m$

Antenna:

Antenna is usually a metalic device for radiating or receiving radio waves. Antenna converts Electrical signals into Electromagnetic signals and vice versa.

Antenna is a device that ~~device~~ generate or collect electromagnetic energy. In two way commn, the same antenna can be used for both transmission and reception.

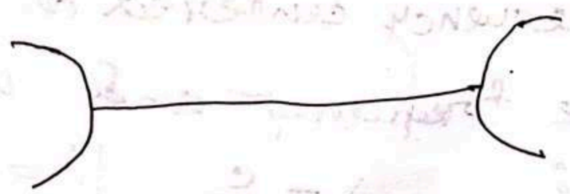
Application:

(I) point-to-point communication.

(II) Satellite communication.

(III) Radar communication.

(IV) Broadcasting applications.



Radiation pattern

The radiation pattern of an antenna is a graph which shows the variation in actual field strength of electromagnetic field at all points which are at equal distances from the antenna. If the radiation is expressed in terms of field strength (E), it is known as 'field pattern'. If it is given in power, then it is denoted as 'power pattern'. Radiation pattern is generally a three dimensional one. They are following spherical coordinate system. Certain methods are followed to represent radiation pattern into two dimensional patterns. Two dimensional patterns are drawn as elevation and azimuthal patterns, vertical and horizontal patterns, 'E' plane and 'H' plane patterns.

Impedance or Radiation Resistance

Antenna as a transmitter is connected at the last part of a communication system. Antenna provides a series resistance to the communication network. This resistance is known as the radiation resistance. For a dipole, radiation resistance is 73 Ω. As signal from source travels through different parts of the communication system, it may encounter differences in impedance. At each interface, depending on the impedance match, some fraction of the wave's energy will reflect back to the source, forming a standing wave in the transmission line. The ratio of maximum power to minimum power of the wave can be measured and is called the standing wave ratio (SWR). A SWR of 1:1 is ideal. It means the entire power is radiated through antenna. Practically, part of transmitted power gets reflected back into the transmission line and is measured as SWR. A SWR of 1.5:1 is considered to be acceptable. Matching impedances at each interface reduces SWR and maximize power transfer through each part of the communication system.

Efficiency

Efficiency of an antenna is defined as the ratio of power actually radiated to the total input power into the antenna terminals.

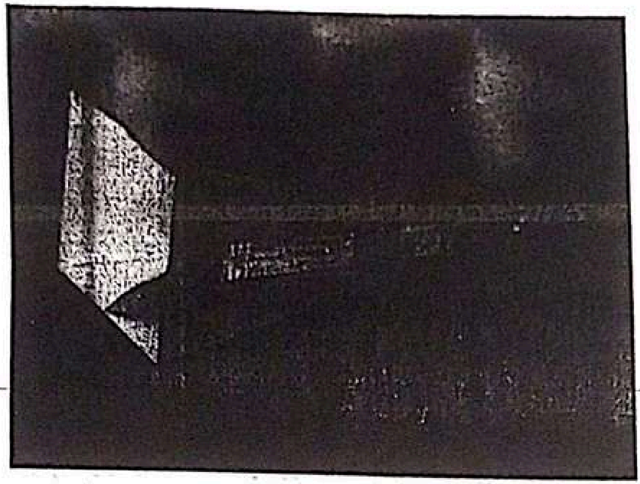


Fig 5.8 Horn Antenna

Reflector Antenna

The antennas which can have higher gain by reflecting EM waves on a surface are known as 'Reflector Antenna'. Depending on the shape of surface, this antenna is classified such as parabolic reflector antenna. This antenna is used for satellite reception and has been used for satellite Television signal reception. 'Direct to Home [DTH] Service' is also utilizing this antenna. At the focal point of this antenna, a feed antenna is placed. Dipole or horn antenna is used as feeder for this antenna. To increase efficiency of this antenna, feeder is placed at the back side of reflector. This is known as 'Cassegrain feed'. Similarly the feeder is placed at one end is known as 'Offset feed'. This antenna acts as excellent microwave reflector and concentrates signal in a particular direction. So, this antenna can provide better directivity. An image of parabolic reflector is given in fig 5.9.

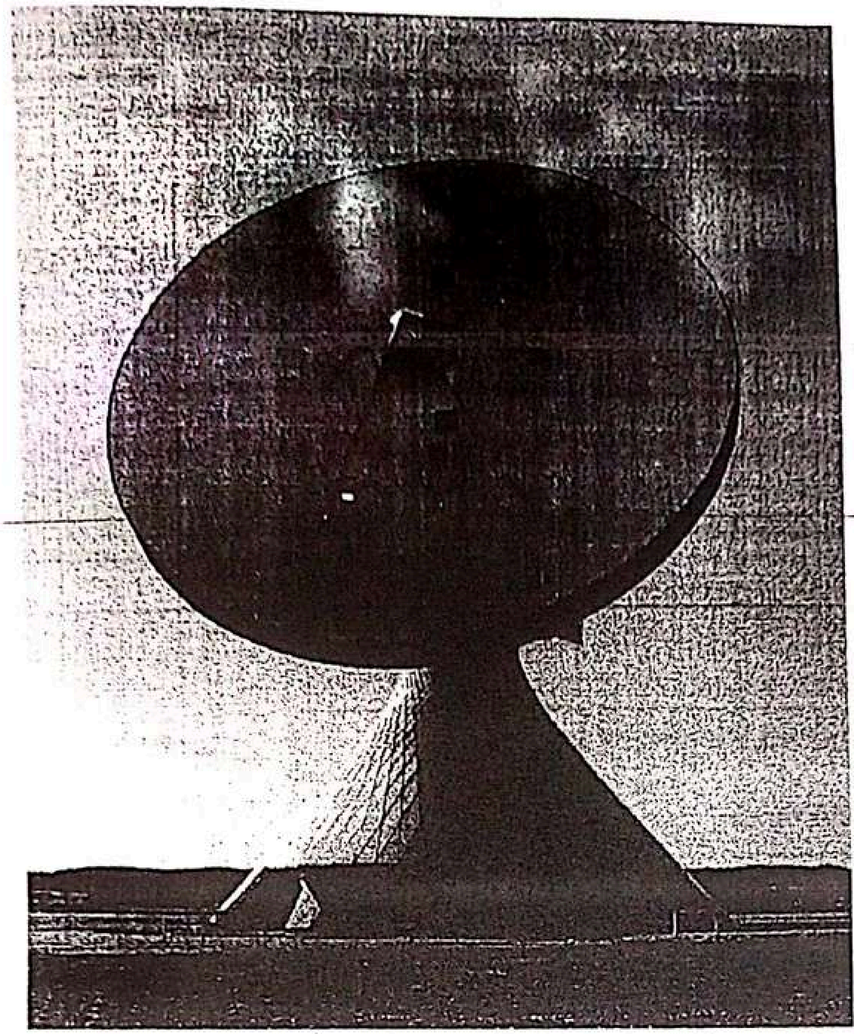


Fig 5.9 Parabolic Reflector Antenna

Array Antenna – Yagi Antenna

The most easiest and efficient directional antenna is the 'Yagi – Uda' Antenna. It is named after its inventors Prof. Uda and Prof. Yagi. This antenna has been successfully used for VHF band terrestrial home Television reception. The directivity is increased by increasing the number of directors which are known as 'Parasitic Elements' as they are not directly fed. Only the dipole or folded dipole is directly fed. There is one reflector which used to reflect EM signal. A sample yagi array is given in the following diagram.

Antenna

Problem-I

For a transmitter antenna with a power gain $G_t = 10$ and input power $P_t = 100$ W.

Determine : (1) EIRP in Watt, dBm, dBw.

(2) PD at 10 km

(3) P_D for isotropic antenna

Solution: In watt,

(1) $EIRP = P_t G_t$

$= (100 \times 10)$ W

$= 1000$ W (Ans)

here, $P_t = 100$W

$G_t = 10$

EIRP = Effective isotropic radiated power.

In dBw,

$EIRP = 10 \log (1000)$

$= 30$ dBw (Ans)

In dBm,

$EIRP = 10 \log (1000) + 10 \log (1000)$

$= 30$ dBm $+ 30$ dBm

$= 60$ dBm

(2) $P_D = \frac{P_t G_t}{4\pi R^2}$

$P_t = 100$ W

$G_t = 10$

$R = 10$ KM

$= 10 \times 10^3$ m

$= \frac{100 \times 10}{4 \times \pi \times (10 \times 10^3)^2}$

$= 7.96 \times 10^{-7}$ W/m²

$= 0.796 \times 10^{-6}$ W/m²

$= 0.796\ \mu$ W/m² (Ans.)

(3) For isotropic antenna,

$P_D = \frac{P_t}{4\pi R^2}$

$= \frac{100}{4 \times \pi \times (10 \times 10^3)^2}$

$= 7.96 \times 10^{-8}$ W/m²

$= 0.0796 \times 10^{-6}$ W/m²

$= 0.0796\ \mu$ W/m² (Ans.)

Sub
SAT SUN MON TUE WED THU FRI
DATE

Civil, military and weather application of Radar:

Civil application:

(i) Air Traffic Control:

- Ensure safe takeoff, landing of aircraft.
- prevent collisions of aircraft.

(ii) Marine Navigation:

- used in ships ~~and~~ to avoid collision and detect obstacles.

(iii) Search and Rescue operations:

- Help to locate lost aircraft or others.

Military application:

(i) Target detection and tracking:

- Identify and track enemy aircraft, ships, etc.
- Guide missile to target.

(ii) Surveillance:

- Detect Stealth objects

(iii)

Sub

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Weather Applications:

(i) Weather Forecasting:

- Detects rain, storm, etc.
- Monitor rainfall intensity, Wind speed, etc

(ii) Tornado & Cyclone Detection:

- Track the formation, movement, and strength of tornadoes, cyclones, hurricanes, etc.

(iii) Meteorological Research:

- Gather data for research

(iv) Aviation Weather Monitoring:

- provide real-time updates on weather to pilots ensuring safe navigation, etc