Course Title: Microwave and Antennas	***Course Code: 20EC520***
Credits: 4	***Total Contact Hours (L:T:P): 52:0:0***
Type of Course: Theory	***Category: Professional Core course***
CIE Marks: 50	***SEE Marks: 100***

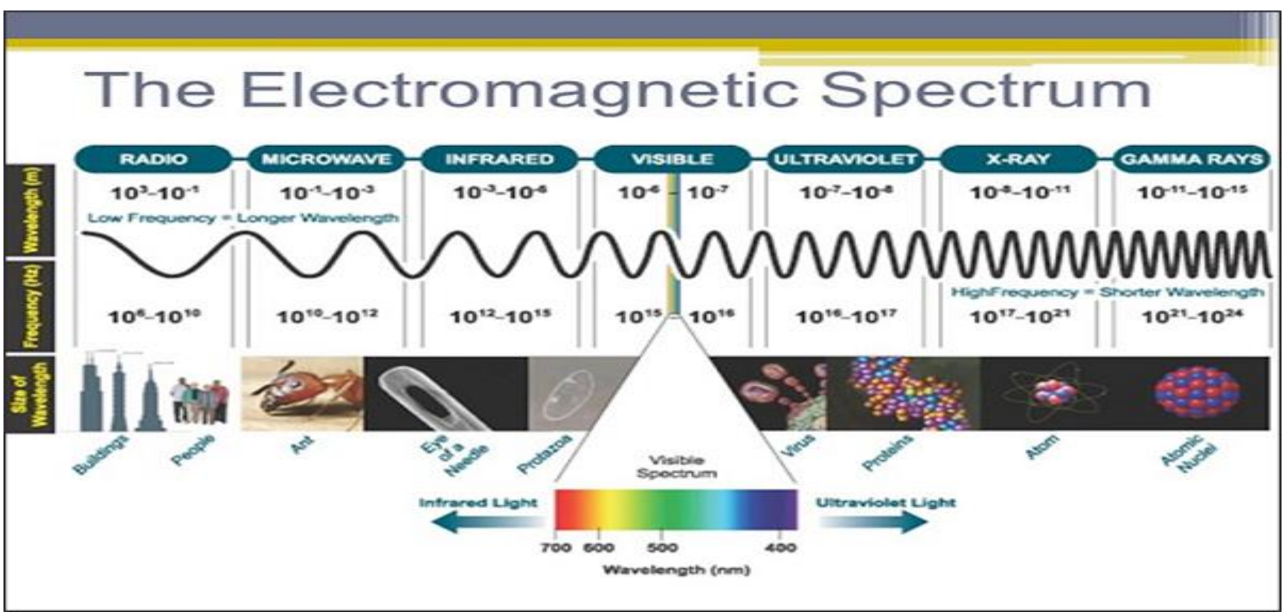
Course Outcomes: After completing this course, students should be able to:

CO1:	Explain the principles of microwave frequencies, sources, hazards of microwaves and system modeling using s-parameters.

Unit No.	Course Content	No. of Hours
1	**Introduction to Microwaves:** Introduction, bands, advantages, application and radiation hazards, S-parameters, Microwave filters, Microwave waveguides and components. Avalanche transit time devices – IMPATT diode, TRAPATT diode, Gunn diode, Tunnel diode, Varactor diodes. Microwave linear beam tubes – Klystrons, TWT, Microwave Cross field tubes – Magnetron, parametric amplifiers, Cross field amplifiers. **SLE:** Strip line fabrications	**11**

1. Introduction

Microwaves are generally defined as electromagnetic waves with a frequency between 300 MHz to 300 GHz. typically, the wavelengths of these electromagnetic waves are defined as well, with the range being from 1m to 1mm.shorter than that of a normal radio wave but longer than those of infrared radiation.



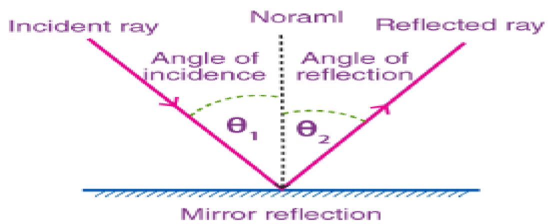
Microwaves obey the laws of optics, such as Snell's law and the law of reflection, and thus can be transferred, assimilated, or reflected, which is extremely important when considering how microwaves operate.

Snell's law, in optics, ***a relationship between the path taken by a ray of light in crossing the boundary or surface of separation between two contacting substances and the refractive index of each****.*

The law of reflection *formula is given as:*$\theta_i = \theta_r$

Where,

- θ_i is the angle of incidence
- θ_r is the angle of reflection



2. Bands:

Electromagnetic wave spectrum	Frequency band	Wavelength
Radio waves	**Very high frequency (VHF) (30–300 MHz)**	**10–1 m**
Microwaves	**Ultrahigh frequency (UHF) (300–3000 MHz)**	**(100–10 cm)**
	P band (230 MHz–1 GHz)	130–30 cm
	L band (1–2 GHz)	30–15 cm
	S band (2–4 GHz)	15–7.5 cm
	Super high frequency (SHF) (3–30 GHz)	**(10–1 cm)**
	S band (2–4 GHz)	15–7.5 cm
	C band (4–8 GHz)	7.5–3.75 cm
	X band (8–12.5 GHz)	3.75–2.4 cm
	Ku band (12.5–18 GHz)	2.4–1.67 cm
	K band (18–26.5 GHz)	1.67–1.13 cm
	Ka band (26.5–40 GHz)	1.13–0.75 cm

Electromagnetic wave spectrum	Frequency band	Wavelength
Millimeter waves	**Extremely high frequency (EHF) (30–300 GHz)**	**(10–1 mm)**
	Ka band (26.5–40 GHz)	1.13–0.75 cm
	V band (40–75 GHz)	7.5–4 mm
	W band (75–110 GHz)	4–2.73 mm
	Millimeter band (110–300 GHz)	2.73–1 mm

Name	Frequency range	Name origin	Common applications
VHF Band	30 to 300 MHz	Very High Frequency	• FM radio • Television broadcasts
UHF Band	300 to 3000 MHz	Ultra High Frequency	• Television broadcasts • Microwave oven • Microwave devices • Communications • Radio astronomy • Mobile phones • Wireless LAN • Bluetooth
L Band	1 to 2 GHz	Long	• Military telemetry • GPS • Air traffic control (ATC) radarS Band2 to 4 GHzShort• Weather radar • Surface ship radar • Microwave ovens • Microwave devices • Communications
C Band	4 to 8 GHz	Compromise(between S and X)	• Long-distance radio telecommunications
X Band	8 to 12 GHz	X for “crosshair” (used in WW2 for fire control radar	• Satellite communications • Radar • Terrestrial broadband • Space communications
Ku Band	12 to 18 GHz	Kurtz Under	• Satellite communications

Name	Frequency range	Name origin	Common applications
K Band	18 to 26.5 GHz	Kurtz (German for short)	• Radar • Satellite communications • Astronomical observations • Automotive radar
Ka Band26	5 to 40 GHz	Kurtz Above	• Satellite communications

Generally, microwave (MW) & radio frequency (RF) components are utilized in the following markets & applications:

1. Military & Defense Radar
2. Air Traffic Control Radar
3. Medical Imaging & Radiotherapy
4. Accelerator Science
5. High-Energy Physics Research
6. Fusion Energy Research
7. Industrial Microwave Systems
8. TV & Radio Broadcast
9. Materials Processing
10. Plasma Processing

3. Properties of Microwaves

Following are the main properties of Microwaves.

- Microwaves are the waves that radiate electromagnetic energy with shorter wavelength.
- Microwaves are not reflected by Ionosphere.
- Microwaves travel in a straight line and are reflected by the conducting surfaces.
- Microwaves are easily attenuated within shorter distances.
- Microwave currents can flow through a thin layer of a cable.

4. Advantages of Microwaves

There are many advantages of Microwaves such as the following –

- Supports larger bandwidth and hence more information is transmitted. For this reason, microwaves are used for point-to-point communications.
- More antenna gain is possible.
- Higher data rates are transmitted as the bandwidth is more.
- Antenna size gets reduced, as the frequencies are higher.
- Low power consumption as the signals are of higher frequencies.
- Effect of fading gets reduced by using line of sight propagation.
- Provides effective reflection area in the radar systems.
- Satellite and terrestrial communications with high capacities are possible.
- Low-cost miniature microwave components can be developed.
- Effective spectrum usage with wide variety of applications in all available frequency ranges of operation.

Disadvantages of Microwaves

There are a few disadvantages of Microwaves such as the following –

- Cost of equipment or installation cost is high.
- They are hefty and occupy more space.
- Electromagnetic interference may occur.
- Variations in dielectric properties with temperatures may occur.
- Inherent inefficiency of electric power.

5. Applications of Microwaves

There are a wide variety of applications for Microwaves, which are not possible for other radiations. They are –

Wireless Communications

- For long distance telephone calls
- Bluetooth
- WIMAX operations
- Outdoor broadcasting transmissions
- Broadcast auxiliary services
- Remote pickup unit

- Studio/transmitter link
- Direct Broadcast Satellite DBSDBS
- Personal Communication Systems PCSs
- Wireless Local Area Networks WLANs
- Cellular Video CVCV systems
- Automobile collision avoidance system

Electronics

- Fast jitter-free switches
- Phase shifters
- HF generation
- Tuning elements
- ECM/ECCM ElectronicCounterMeasureElectronicCounterMeasure systems
- Spread spectrum systems

Commercial Uses

- Burglar alarms
- Garage door openers
- Police speed detectors
- Identification by non-contact methods
- Cell phones, pagers, wireless LANs
- Satellite television, XM radio
- Motion detectors
- Remote sensing

Navigation

- Global navigation satellite systems
- Global Positioning System GPSGPS

Military and Radar

- Radars to detect the range and speed of the target.
- SONAR applications
- Air traffic control
- Weather forecasting
- Navigation of ships
- Minesweeping applications
- Speed limit enforcement
- Military uses microwave frequencies for communications and for the above-mentioned applications.

Research Applications

- Atomic resonances
- Nuclear resonances

Radio Astronomy

- Mark cosmic microwave background radiation
- Detection of powerful waves in the universe
- Detection of many radiations in the universe and earth's atmosphere

Food Industry

- Microwave ovens used for reheating and cooking
- Food processing applications
- Pre-heating applications

- Pre-cooking
- Roasting food grains/beans
- Drying potato chips
- Moisture levelling
- Absorbing water molecules

Industrial Uses

- Vulcanizing rubber
- Analytical chemistry applications
- Drying and reaction processes
- Processing ceramics
- Polymer matrix
- Surface modification
- Chemical vapor processing
- Powder processing
- Sterilizing pharmaceuticals
- Chemical synthesis
- Waste remediation
- Power transmission
- Tunnel boring
- Breaking rock/concrete
- Breaking up coal seams
- Curing of cement
- RF Lighting
- Fusion reactors
- Active denial systems

Semiconductor Processing Techniques

- Reactive ion etching
- Chemical vapor deposition

Spectroscopy

- Electron Paramagnetic Resonance
- To know about unpaired electrons in chemicals
- To know the free radicals in materials
- Electron chemistry

Medical Applications

- Monitoring heartbeat
- Lung water detection
- Tumor detection
- Regional hyperthermia
- Therapeutic applications
- Local heating
- Angioplasty
- Microwave tomography
- Microwave Acoustic imaging

For any wave to propagate, there is the need of a medium. The transmission lines, which are of different types, are used for the propagation of Microwaves.

6. Radiation hazards

A. Hazards of Electromagnetic Radiations to Personnel. (HERP)
B. Hazards of Electromagnetic Radiations to Ordnance (HERO)
C. Hazards of Electromagnetic Radiations to Fuel (HERF)

HERP is caused by thermal effect of radiated energy. Biological substances are : Blood, Muscles, Bone, Brain, Fat [These behave as conductive dielectric]
Microwave energy directed on to the body may be scattered, reflected, and absorbed, depending on the field strength, the frequency, dimension of the body and electrical properties of the tissue.

The absorbed microwave energy produces molecular vibrations and converts this energy into heat. If the organism can not dissipate, this heat energy as fast as heat is produced, the internal temperature of the body will increase. This heat may damage these biological substances permanently.

e.g. If the lens of the eye is exposed to microwaves, its circulatory system would be unable to provide sufficient flow of blood for cooling and may cause cataract.
Similarly, the stomach, intestines and bladder are specially sensitive to thermal damage from high power microwaves.

Microwave frequencies for which the wavelengths are of the same order of magnitude as the dimensions of the human body produce close coupling between the body and the microwave field and large amount of heat can be generated to cause severe damage in the body.

Significant energy absorption will occur even when the body size is at least 1/10 of a wavelength. Although the biological damage occurs mostly due to electric field coupling, low frequency magnitude field coupling can also produce damage when exposure time is large.

How to Protect from Radiations - Radiation protection can be practiced by preventing radiations from entering into the beam of the transmit antenna or
by preventing coming close to any microwave generator or propagating medium. - In areas where high power Radar are used, the service and maintenance personnel must wear microwave absorptive suit made out of stainless steel woven into a fire retardant synthetic fiber.

- The suit is light weight, comfortable and easy to put on.

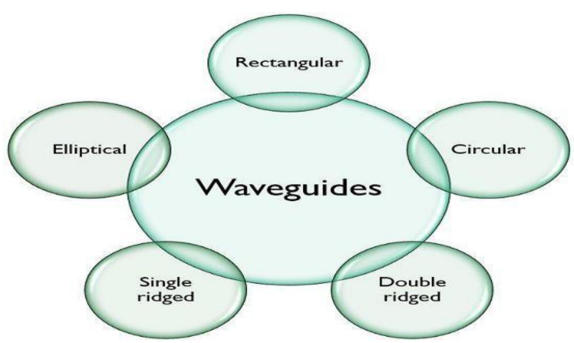
- The attenuation produces by such suit is above 20dB at 2450 MHz, 20-35 dB from 650-1150 MHz, and 35-40 dB from 1-11 GHz.

- **Hazard of Electromagnetic Radiation to Fuel (HERF)** is the hazard associated with the possibility of igniting fuel or other volatile materials through RF energy induced arcs or sparks. It takes a certain amount of arc energy to ignite a fuel and modern fuels like JP-5 are much safer than older fuels like JP-4. You can see how that might be a concern aboard and aircraft carrier. Fortunately there are many operational safeguards against this problem and many of the newer fuels such as JP-5 are much harder to ignite.
- **Hazard of Electromagnetic Radiation to Ordnance (HERO)** is defined as the danger of accidental actuation of electro-explosive devices or otherwise electrically activating ordnance because of radio frequency electromagnetic fields.

  This unintended actuation could have safety or reliability consequences such as duding. For HERO safety, we are concerned with any ordnance item containing electro-explosive devices (EEDs) or electrically initiated devices (EIDs). These devices can be adversely affected by RF energy to the point that the safety and/or reliability of the system is in jeopardy when the system is employed in the operational electromagnetic environment. Note that an EID cannot discriminate between an accidentally induced signal and a purposeful one

Types of waveguides

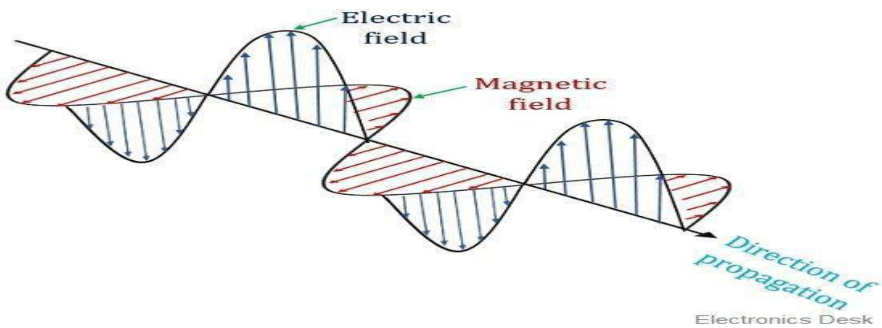
Waveguides are majorly classified as rectangular or circular but these are basically of 5 different types:



Modes of propagation in a Waveguide

When an electromagnetic wave is transmitted through a waveguide. Then it has two field components that oscillate mutually perpendicular to each other. Out of the two one is electric field and the other is a magnetic field.

The figure below represents the propagation of an electromagnetic wave in the z-direction with the two field components:



The propagation of wave inside the waveguide originates basically 2 modes.

However, overall basically 3 modes exist, which are as follows:

- **Transverse Electric wave**:
  In this mode of wave propagation, the electric field component is totally transverse to the direction of wave propagation whereas the magnetic field is not totally transverse to the direction of wave propagation. It is abbreviated as TE mode. $E_z \neq 0; H_z = 0$

- **Transverse Magnetic wave**:
  In this mode of wave propagation, the magnetic field component is totally transverse to the direction of wave propagation while the electric field is not totally transverse to the direction of wave propagation. It is abbreviated as TM mode. $E_z = 0; H_z \neq 0$

- **Transverse electromagnetic wave**:
  In this mode of wave propagation, both the field components i.e., electric and magnetic fields are totally transverse to the direction of wave propagation. It is abbreviated as TEM mode.

$$E_z = H_z = 0$$

It is to be noted here that, TEM mode is not supported in waveguides. As for the TEM mode, there is a need for the presence of two conductors and we already know that a waveguide is a single hollow conductor.

Parameters of a Waveguide:

- **Cut-off wavelength**: It the maximum signal wavelength of the transmitted signal that can be propagated within the waveguide without any attenuation. This means up to cut-off wavelength, a microwave signal can be easily transmitted through the waveguide. It is denoted by λc.

- **Group velocity**: Group velocity is the velocity with which wave propagates inside the waveguide. If the transmitted carrier is modulated, then the velocity of the modulation envelope is somewhat less as compare to the carrier signal. This velocity of the envelope is termed as group velocity. It is represented by Vg.

- **Phase velocity**: It is the velocity with which the transmitted wave changes its phase during propagation. Or we can say it is basically the velocity of a particular phase of the propagating wave. It is denoted by Vp.

- **Wave Impedance**: It is also known as the characteristic impedance. It is defined as the ratio of the transverse electric field to that of the transverse magnetic field during wave propagation at any point inside the waveguide. It is denoted by Zg.

Advantages of waveguides

1. In waveguides, the power loss during propagation is almost negligible.
2. Waveguides have the ability to manage large-signal power.
3. As waveguides possess a simple structure thus their installation is somewhat easy.

Disadvantages of waveguides

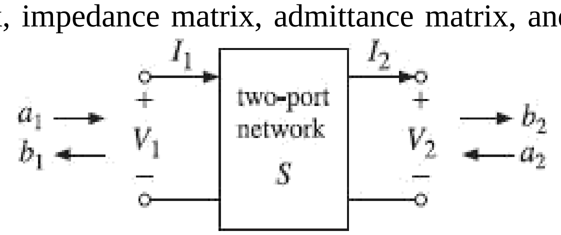
1. Its installation and manufacturing cost is high.
2. Waveguides are generally rigid in nature and hence sometimes causes difficulty in applications where tube flexibility is required.
3. It is somewhat large in size and bulkier as compared to other transmission lines.

It is noteworthy in the case of waveguides that their diameter must have some certain value in order to have proper signal propagation. This is so because if its diameter is very small and the wavelength of the signal to be propagated is large (or signal frequency is small) then it will not be propagated properly.

So, the signal frequency must be greater than the cutoff frequency in order to have a proper signal transmission.

7. S-parameters (Scattering Parameters)

Linear two-port (and multi-port) networks are characterized by a number of equivalent circuit parameters, such as their transfer matrix, impedance matrix, admittance matrix, and scattering matrix. Fig. shows a typical two-port network.



The transfer matrix, also known as the ABCD matrix, relates the voltage and current at port 1 to those at port 2, whereas the impedance matrix relates the two voltages V1,V2 to the two currents I1, I2.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad \text{(transfer matrix)}$$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ -I_2 \end{bmatrix} \quad \text{(impedance matrix)}$$

- Thus, the transfer and impedance matrices are the 2×2 matrices:
- The admittance matrix is simply the inverse of the impedance matrix, Y = Z−1.
- The scattering matrix relates the outgoing waves b1, b2 to the incoming waves a1, a2 that are incident on the two-port:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \quad S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \quad \text{(scattering matrix)}$$

The matrix elements S11, S12, S21, S22 are referred to as the scattering parameters or the S-parameters. The parameters S11, S22 have the meaning of reflection coefficients, and S21, S12, the meaning of transmission coefficients.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad \text{(transfer matrix)}$$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ -I_2 \end{bmatrix} \quad \text{(impedance matrix)}$$

S- the scattering matrix

The scattering matrix is defined as the relationship between the forward and backward moving waves. For a two-port network, like any other set of two-port parameters, the scattering matrix is a 2| matrix.

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}$$

$$T = \begin{bmatrix} A & B \\ C & D \end{bmatrix}, \quad Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$$

Properties of S matrix:

In general the scattering parameters are complex quantities having the following Properties:

Property (1) : When any Z port is perfectly matched to the junction, then there are no reflections from that S = 0. If all the ports are perfectly matched, then the leading diagonal II elements will all be zero.

Property (2): Symmetric Property of S-matrix: If a microwave junction satisfies reciprocity condition and if there are no active devices, then S parameters are equal to their corresponding transposes.

i.e., **Sij=Sji**

Property (3): Unitary property for a lossless junction - This property states that for any lossless network, the sum of the products of each term of anyone row or anyone column of the [SJ matrix with its complex conjugate is unity

Property (4) Phase - Shift Property: Complex S-parameters of a network are defined with respect to the positions of the port or reference planes. For a two-port network with unprimed reference planes 1 and 2

Reciprocal and Lossless Network

- A **reciprocal network** is one in which the power losses are same between any two ports regardless of direction of propagation.
- A network is known to be reciprocal if it is passive and contains only isotropic materials.
- A reciprocal network should satisfy reciprocity theorem.
- A reciprocal network always has a **symmetric S-parameter matrix** i.e. $S_{21} = S_{12}$; $S_{13} = S_{31}$

Two-port Reciprocal Network

- If the port 1 and 2 are interchanged for a two port network and the performance of the microwave device is still the same then we call that network as reciprocal network.

Lossless Network

- A passive network in which total power leaving the N ports is equal to total incident power to the network is called as **lossless network**.
- A lossless network always has a **unitary S-parameter** matrix i.e.

$$\boxed{\sum_{i=1}^{N} S_{ij} \ S_{ij}^{*} = 1}$$

- In a lossless network, no real power can be delivered to the network.

Symmetry of S-matrix for Reciprocal Network

- For a reciprocal junction the S - matrix is symmetrical i.e. $S_{ij} = S_{ji}$.
- The symmetry of scattering matrix is basically a consequence of reciprocity and assuming normalization.
- For a reciprocal network,

$$[V] = [Z][I] = [Z]([a] - [b]) = [a] + [b]$$

$$([Z] + [U])[b] = ([Z] - [U])[a]$$

$$[b] = ([Z]+[U])^{-1}([Z] - [[U])[a] \quad \ldots (2.3.1)$$

where [U] is unit matrix.

The S - matrix equation for the network is expressed as -

$$[b] = [S][a] \quad \ldots (2.3.2)$$

Comparing equation (2.3.1) and (2.3.2)

$$[S] = ([Z]+[U])^{-1}([Z]-[U])$$

Let $\quad [R] = [Z]-[U]$ and

$$[Q] = [Z]+[U]$$

For reciprocal network, the Z-matrix is symmetric

$$[R][Q] = [Q][R]$$

$$[Q]^{-1}[R][Q][Q]^{-1} = [Q]^{-1}[Q][R][Q]^{-1}$$

$$[Q]^{-1}[R] = [R][Q]^{-1} = S$$

Transpose of $[S] = [S]^T = ([Z]-[U])^T \left[[Z]+[U]^T\right]^{-1}$

Since Z-matrix is symmetrical

$$([Z]-[U])^T = [Z] - [U]$$

$$([Z]+[U])^T = [Z] + [U]$$

Hence, $\quad [S]^T = ([Z] - [U][Z] + [U])^{-1}$

$$[S]^T = [R][Q]^{-1}$$

$$\therefore \quad \boxed{[S]^T = [S]}$$

Hence proved that a reciprocal device has the same transmission characteristics in either direction of a pair of ports.

Scattering Matrix for Lossless Junction

Statement :

- The unitary property of S - matrix states that : For any lossless network, the sum of the products of each term of any one row or any one column of the [S] matrix with its complex conjugate is unity.

Proof :

- An n - port network can be described by an $n \times n$ S-parameter matrix :

$$\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ \vdots \\ b_n \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ \vdots \\ a_n \end{bmatrix}$$

$$b = Sa$$

- If the network is lossless, then the power entering the network must be equal to the power flowing out of the network.

i.e.
$$\sum_{n=1}^{N} |b_n|^2 = \sum_{n=1}^{N} |a_n|^2$$

$$\sum_{n=1}^{N} \left| \sum_{i=1}^{n} S_{ni} a_i \right|^2 = \sum_{n=1}^{N} |a_n|^2$$

If only i^{th} port is excited and remaining ports are matched terminated then $a_n = 0$ except a_i.

$\therefore$
$$\sum_{i=1}^{n} |S_{ni} a_i|^2 = \sum_{n=1}^{N} |a_i|^2$$

$$\sum_{n=1}^{n} |S_{ni}|^2 = \sum_{n=1}^{N} \left|S_{ni} S_{ni}^{*}\right| = 1$$

For a lossless junction
$$\sum_{n=1}^{N} \left|S_{ni} S_{ni}^{*}\right| = 1 \qquad \text{... (condition - 1)} \qquad \text{... (2.3.3)}$$

When all $a_n = 0$ except a_i and a_k

$$\sum_{n=1}^{N} S_{nk} \cdot S_{ni}^{*} = 0 \; (i \neq k) \qquad \text{... (condition - 2)} \qquad \text{...(2.3.4)}$$

In matrix form, this expression can be represented as,

$$[S^{*}][S]^{T} = [U]$$

$$[S^{*}] = \left([S]^{T}\right)^{-1} \qquad \text{... (condition - 3)} \qquad \text{... (2.3.5)}$$

Matrix [S] which satisfies above three condition is called unitary matrix and the network is lossless.

8. Microwave filters

- **The Basics of Lumped Element L-C Filter Construction**

In general, lumped element filters are passive filters constructed using the appropriate number of inductors (Ls), capacitors (Cs), and resistors (Rs) to meet the specific filtering needs of a particular application.

At the most basic level, lumped element filters can be constructed from a collection of simple L-C resonators as shown in Figure 1.

The resonators used in the filter will create poles and zeros in the frequency response. A zero occurs when the function tends to zero, and a pole occurs when the roots that make the function tend towards its maximum function.

By understanding how poles and zeros function (which you can learn more about in this post), we can construct resonators using Ls and Cs and place the poles and zeros where we need them to be to tightly control the frequency response.

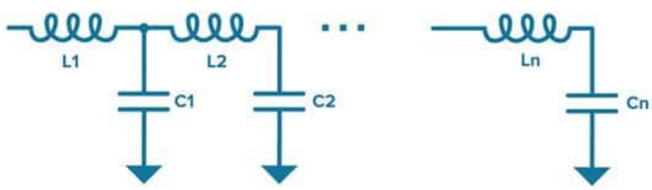


Figure 1. An example of a generic lumped element L-C filter structure

Lumped Element Filter Characteristics

Lumped element filters offer small size at low frequencies that are not achievable with common ceramic, cavity, or waveguide implementations. Additionally, lumped element filter designs are highly customizable both in terms of electrical performance and mechanical and thermal characteristics.

This is because we have a high level of control in terms of component and material choices as well as assembly techniques. For example, a lumped element filter can be constructed with withstand temperature and input power ranges that may not be possible with alternative resonator technologies.

What Filter Types Can Be Built Using a Lumped Element Construction?

All the usual filter types can be implemented in in a lumped element format including lowpass, high pass, bandpass, and band reject.

Lumped element filters can be customized to operate reliably in high-power, high-temperature, and harsh environmental conditions. More specifically, lumped element filters can be designed with the following specifications:

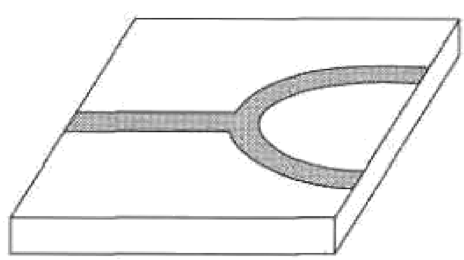
- Bandpass filters with narrow to moderate bandwidths (1 percent FBW to 70 percent FBW) and a Center Frequency (Fo) from 10 MHz to 7 GHz
- Bandpass filters with an extra wide bandpass bandwidth (70 percent FBW to 175 percent FBW) and a Fo of 20 MHz to 11 GHz
- Lowpass filters from 10 MHz to 22 GHz
- Highpass filters from 10 MHz to 10 GHz
- Bandreject filters from 20 MHz to 6 GHz that can be narrow band or wide band from 10 MHz to 6 GHz

9. Microwave waveguides and components

Waveguide multiport junctions:

T-junction power divider using waveguide:

- The T-junction power divider is a 3-port network that can be constructed either from a transmission line or from the waveguide depending upon the frequency of operation.



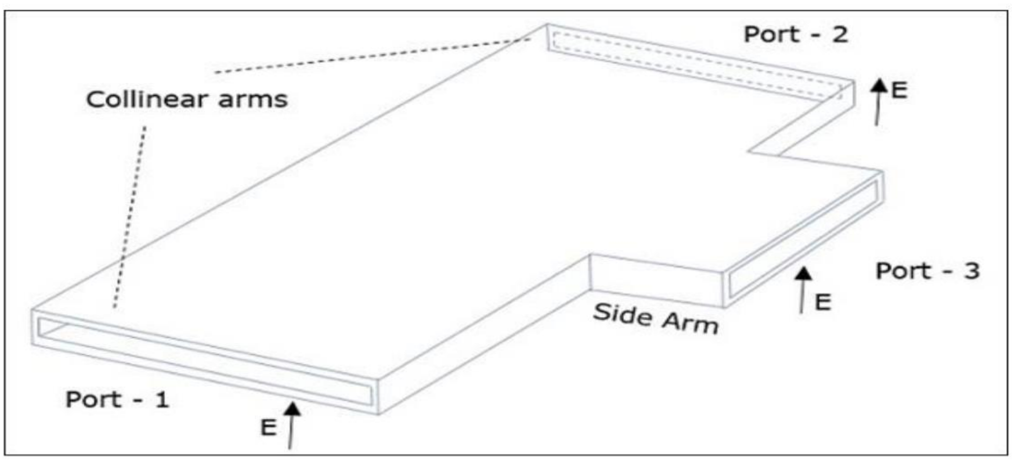
For very high frequency, power divider using waveguide is of 4 types

- H-Plane Tee
- E-Plane Tee
- E-H Plane Tee/Magic Tee
- Rat Race Tee

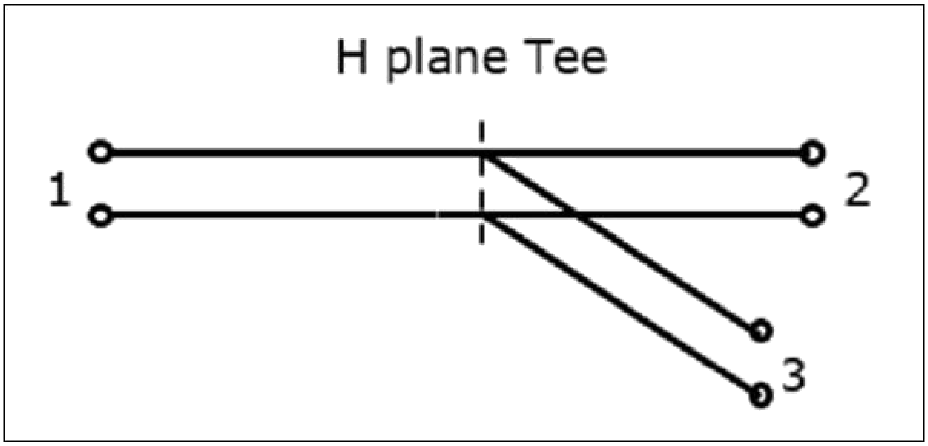
<u>H-Plane Tee</u>

An H-Plane Tee junction is designed by bestowing a simple waveguide to a rectangular waveguide which previously 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.

As the axis of the side arm is similar to the magnetic field, this junction is called H-Plane Tee junction. This is also called as Current junction, as the magnetic field splits itself into arms. The cross-sectional details of H-plane tee can be agreed by the resulting figure.



The following figure shows the connection made by the sidearm to the bi-directional waveguide to form the serial port.



Properties of H-Plane Tee

The properties of H-Plane Tee can be defined by its $[S]_{3\times3}$matrix.

1.It is a 3×3 matrix as there are 3 possible inputs and 3 possible outputs.

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \qquad \textbf{........ Equation 1}$$

2.Scattering coefficients S_{13} and S_{23} are equal here as the junction is symmetrical in plane

$$S_{ij} = S_{ji}$$

$$S_{12} = S_{21} \;\; S_{23} = S_{32} = S_{13} \;\; S_{13} = S_{31}$$

$$S_{33} = 0$$

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & S_{13} \\ S_{13} & S_{13} & 0 \end{bmatrix} \qquad \textbf{........ Equation 2}$$

4.We can say that we have four unknowns, considering the symmetry property.

$$[S][S]* = [I]$$

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & S_{13} \\ S_{13} & S_{13} & 0 \end{bmatrix} \begin{bmatrix} S^*_{11} & S^*_{12} & S^*_{13} \\ S^*_{12} & S^*_{22} & S^*_{13} \\ S^*_{13} & S^*_{13} & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

From the Unitary property

$$R_1C_1 : S_{11}S^*_{11} + S_{12}S^*_{12} + S_{13}S^*_{13} = 1$$

$$|S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = 1 \quad \text{......... Equation 3}$$

$$R_2C_2 : |S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1 \quad \text{......... Equation 4}$$

$$R_3C_3 : |S_{13}|^2 + |S_{13}|^2 = 1 \quad \text{......... Equation 5}$$

$$R_3C_1 : S_{13}S^*_{11} - S_{13}S^*_{12} = 0 \quad \text{......... Equation 6}$$

$$2|S_{13}|^2 = 1 \quad or \quad S_{13} = \frac{1}{\sqrt{2}} \quad \text{......... Equation 7}$$

$$|S_{11}|^2 = |S_{22}|^2$$

$$S_{11} = S_{22} \quad \text{......... Equation 8}$$

From the Equation 6,

$$S_{13}\left(S^*_{11} + S^*_{12}\right) = 0$$

$$S_{13} \neq 0, S_{11}^* + S_{12}^* = 0, \; or \; S_{11}^* = -S_{12}^*$$

$$S_{11} = -S_{12} \;\; or \;\; S_{12} = -S_{11} \quad \text{......... Equation 9}$$

$$|S_{11}|^2 + |S_{11}|^2 + \frac{1}{2} = 1 \quad or \quad 2|S_{11}|^2 = \frac{1}{2} \quad or \quad S_{11} = \frac{1}{2} \quad \text{..... Equation 10}$$

From equation 8 and 9,

$$[S] = \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \end{bmatrix}$$

We know that [b] = [s][a]

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

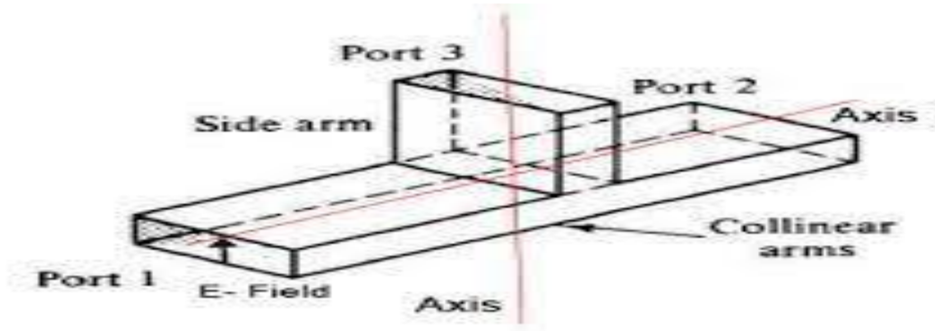
This is the scattering matrix for H-Plane Tee, which explains its scattering properties.

E-Plane Tee

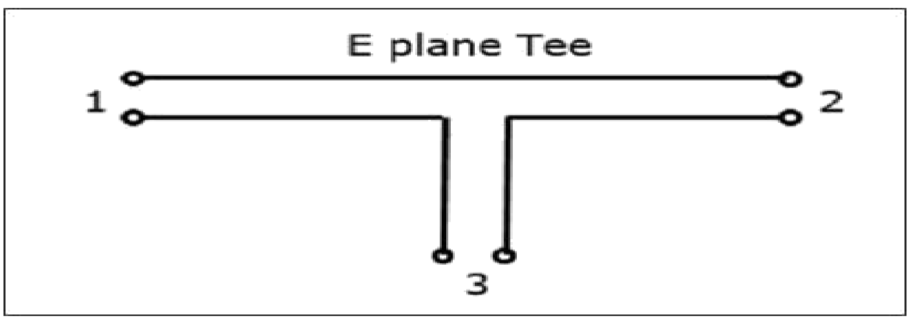
An E-Plane Tee junction is formed by attaching a simple waveguide to the broader dimension of a rectangular waveguide, which already has two ports. The arms of rectangular waveguides make two ports called **collinear ports** i.e., Port1 and Port2, while the new one, Port3 is called as Side arm or **E-arm**. T his E-plane Tee is also called as **Series Tee**.

As the axis of the side arm is parallel to the electric field, this junction is called E-Plane Tee junction. This is also called as **Voltage** or **Series junction**. The ports 1 and 2 are 180° out of phase with each other. The cross-sectional details of E-plane tee can be understood by the following figure. An E-Plane Tee junction is designed by assigning a simple waveguide to the broader dimension of a rectangular waveguide, which previously has two ports. The arms of rectangular waveguides create two ports called collinear ports i.e. Port1 and Port2, while the new one, Port3 is called as Side arm or E-arm. T his E-plane Tee is also called as Series Tee.

As the axis of the side arm is similar to the electric field, this junction is called E-Plane Tee junction. This is also called as Voltage or Series junction. The ports 1 and 2 are 180° out of phase with each other. The cross-sectional details of E-plane tee can be assumed by the resulting figure.



The resulting figure displays the connection made by the sidearm to the bi-directional waveguide to form the parallel port.



Properties of E-Plane Tee

The properties of E-Plane Tee can be defined by its $[S]_{3x3}[S]_{3x3}$ matrix.

1.It is a 3×3 matrix as there are 3 possible inputs and 3 possible outputs.

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \quad \text{........ Equation 1}$$

2.Scattering coefficients S_{13} and S_{23} are out of phase by 180° with an input at port 3

$$S_{23} = -S_{13}$$ **........ Equation 2**

3.The port is perfectly matched to the junction.

$$S_{33} = 0$$ **........ Equation 3**

4.From the symmetric property,

$$S_{ij} = S_{ji}$$

$$S_{12} = S_{21} \;\; S_{23} = S_{32} \;\; S_{13} = S_{31}$$ **........ Equation 4**

Considering equations 3 & 4, the [S] matrix can be written as,

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & -S_{13} \\ S_{13} & -S_{13} & 0 \end{bmatrix}$$ **........ Equation 5**

We can say that we have four unknowns, considering the symmetry property.

5.From the Unitary property

$$[S][S]* = [I]$$

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & -S_{13} \\ S_{13} & -S_{13} & 0 \end{bmatrix} \begin{bmatrix} S_{11}^* & S_{12}^* & S_{13}^* \\ S_{12}^* & S_{22}^* & -S_{13}^* \\ S_{13}^* & -S_{13}^* & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Multiplying we get, $R_1C_1 : S_{11}S_{11}^* + S_{12}S_{12}^* + S_{13}S_{13}^* = 1$

(Noting R as row and C as column) $|S_{11}|^2 + |S_{11}|^2 + |S_{11}|^2 = 1$ **........ Equation 6**

$R_2C_2 : |S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1$ **........ Equation 7**

$R_3C_3 : |S_{13}|^2 + |S_{13}|^2 = 1$ **........ Equation 8**

$R_3C_1 : S_{13}S_{11}^* - S_{13}S_{12}^* = 1$ **........ Equation 9**

Equating the equations 6 & 7, we get

$S_{11} = S_{22}$ .... **Equation 10**

From Equation 8,

$2|S_{13}|^2 \quad or \quad S_{13} = \frac{1}{\sqrt{2}}$ .... **Equation 11**

From Equation 9,

$S_{13}\left(S_{11}^* - S_{12}^*\right)$

Or $S_{11} = S_{12} = S_{22}$ .... **Equation 12**

Using the equations 10, 11, and 12 in the equation 6, we

get,

$$|S_{11}|^2 + |S_{11}|^2 + \frac{1}{2} = 1$$

$$2|S_{11}|^2 = \frac{1}{2}$$

Or $S_{11} = \frac{1}{2}$ .... **Equation 13**

Substituting the values from the above equations in [S][S] matrix, We

get,

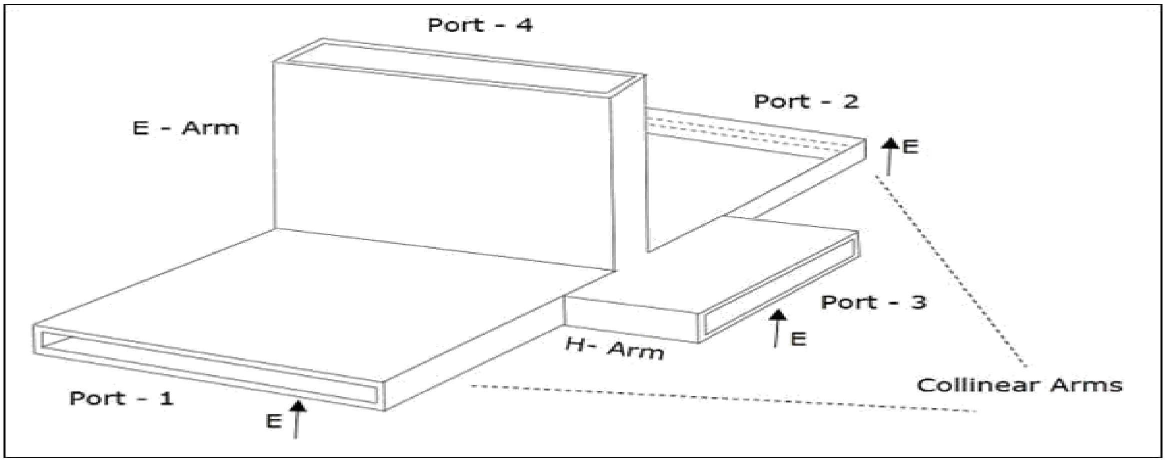
$$[S] = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{\sqrt{2}} & 0 \end{bmatrix}$$

We know that [b]= [S][a]

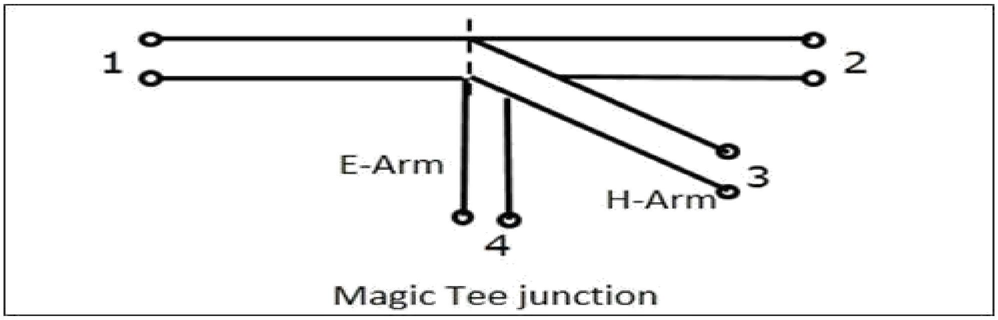
$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{\sqrt{2}} & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

This is the scattering matrix for E-Plane Tee, which explains its scattering properties.

E-H-Plane



The resulting figure shows the assembly made by the side arms to the bi-directional waveguide to form both parallel and serial ports.



Characteristics of E-H Plane Tee

- If a signal of equal phase and magnitude is sent to port 1 and port 2, then the output at port 4 is zero and the output at port 3 will be the additive of both the ports 1 and 2.
- If a signal is sent to port 4, (E-arm) then the power is divided between port 1 and 2 equally but in opposite phase, while there would be no output at port 3. Hence, $S_{34} = 0$.
- If a signal is fed at port 3, then the power is divided between port 1 and 2 equally, while there would be no output at port 4. Hence, $S_{43} = 0$.
- If a signal is fed at one of the collinear ports, then there appears no output at the other collinear port, as the E-arm produces a phase delay and the H-arm produces a phase advance. So, $S_{12} = S_{21} = 0$.

Now we understand that ports 1 and 2 are perfectly matched to the junction. As this is a 4 port junction, whenever two ports are perfectly matched, the other two ports are also perfectly matched to the junction. **The junction where all the four ports are perfectly matched is called as Magic Tee Junction.**

- Microwave source is linked to H-Arm port. The collinear ports composed with these ports make a bridge and the impedance measurement is done by balancing the bridge.

- E-H Plane Tee is used as a duplexer − A duplexer is a circuit which mechanisms as both the transmitter and the receiver, by means of a single antenna for both drives. Port 1 and 2 are used as receiver and transmitter where they are inaccessible and hence will not interfere. Antenna is connected to E-Arm port. A matched load is connected to H-Arm port, which provides no reflections. Currently, there exists transmission or reception without any problem.

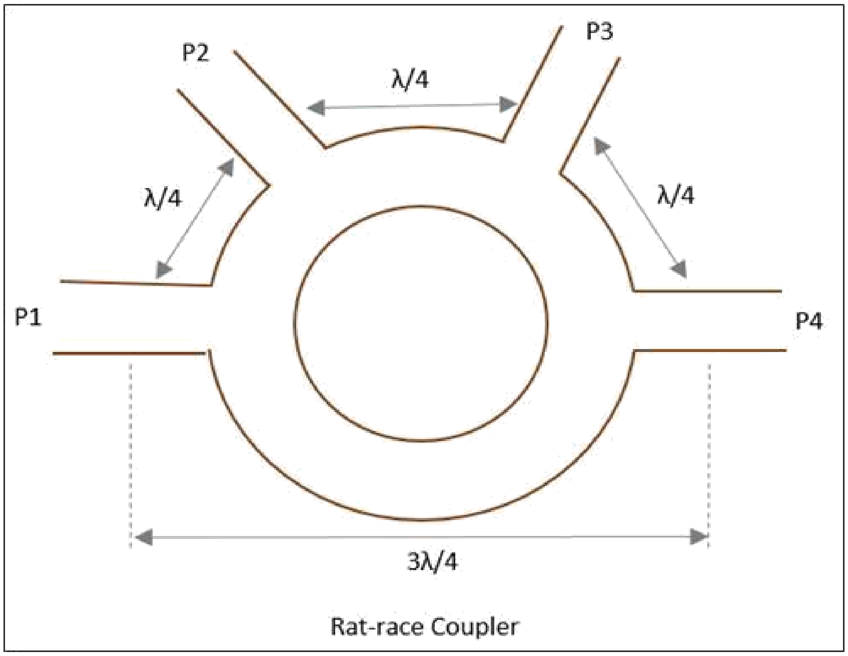
  E-H Plane Tee is used as a mixer − E-Arm port is connected with antenna and the H-Arm port is connected with local oscillator. Port 2 has a matched load which has noreflections and port 1 has the mixer circuit, which gets half of the signal power and half of the oscillator power to produce IF frequency.

- In addition to the above applications, an E-H Plane Tee junction is also used as Microwave bridge, Microwave discriminator, etc.

- If we need to association two signals with no phase modification and to avoid the

  signals with a path difference then we need microwave device. A usual three-port Tee junction is taken and a fourth port is added to it, to make it a ratrace junction. All of these ports are linked in angular ring forms at equal intervals using series or parallel junctions.

- The mean circumference of total race is 1.5λ and each of the four ports is detached by a distance of λ/4. The resulting figure shows the image of a Rat-race junction.

- 

Let us study a few cases to appreciate the operation of a Rat-race junction. **Case 1**

If the input power is applied at port 1, it gets similarly split into two ports, but in clockwise direction for port 2 and anti-clockwise direction for port 4. Port 3 has unconditionally no output.The reason being, at ports 2 and 4, the powers combine in phase, whereas at port 3, cancellation occurs due to λ/2 path difference.

Case 2

If the input power is applied at port 3, the power gets similarly separated between port 2 and port 4. But there will be no output at port 1.

Case 3

If two unequal signals are applied at port 1 itself, then the output will be relative to the sum of the two input signals, which is separated between port 2 and 4. Now at port 3, the differential output appears.

The Scattering Matrix for Rat-race junction is represented as

$$[S] = \begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{21} & 0 & S_{23} & 0 \\ 0 & S_{32} & 0 & S_{34} \\ S_{41} & 0 & S_{43} & 0 \end{bmatrix}$$

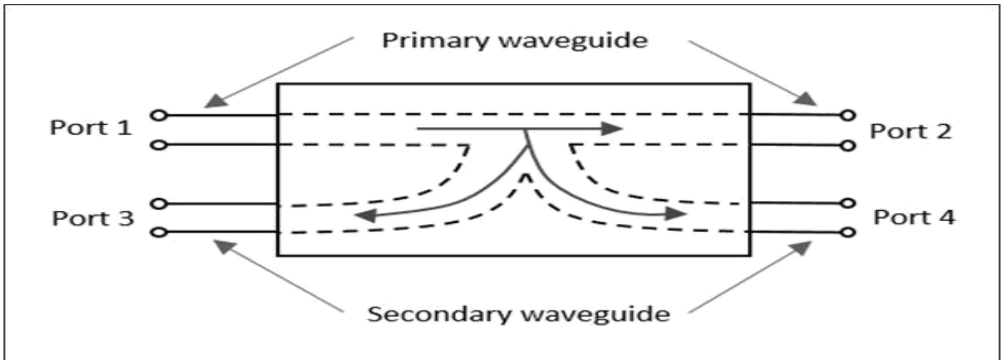
Applications:

Rat-race junction is used for uniting two signals and separating a signal into two halves.

Directional coupler

- A Directional coupler is a device that trials a minor amount of Microwave power for measurement tenacities. The power measurements comprise incident power, reflected power, VSWR values, etc.

- Directional Coupler is a 4-port waveguide junction comprising of a primary main waveguide and a secondary supporting waveguide. The resulting figure shows the image of a directional coupler.



Directional Coupler

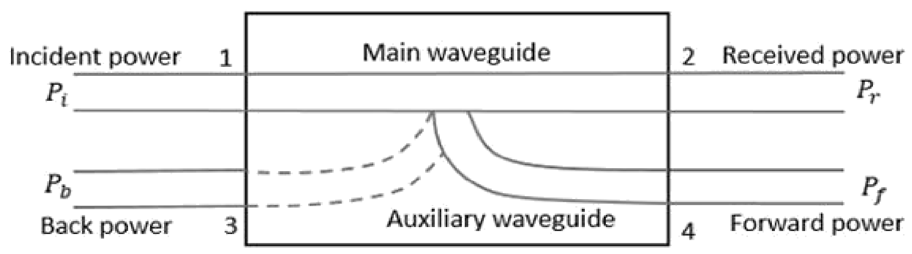
- Directional coupler is used to couple the Microwave power which may be unidirectional or bi-directional.

Properties of Directional Couplers:

The properties of an ideal directional coupler are as follows.

All the finishes are matched to the ports.

- When the power travels from Port 1 to Port 2, some portion of it gets coupled to Port 4 but not to Port 3.
- As it is also a bi-directional coupler, when the power travels from Port 2 to Port 1, some portion of it gets coupled to Port 3 but not to Port 4.
- If the power is incident through Port 3, a portion of it is coupled to Port 2, but not to Port 1.
- If the power is incident through Port 4, a portion of it is coupled to Port 1, but not to Port 2.
- Port 1 and 3 are decoupled as are Port 2 and Port 4.
    - Preferably, the output of Port 3 should be zero. Though, almost, a small amount of power called back power is practical at Port 3. The resulting figure specifies the power flow in a directional coupler.



Directional Coupler indicating powers

Where

- P_i = Incident power at Port 1
- P_r = Received power at Port 2
- P_f= Forward coupled power at Port 4
- P_b = Back power at Port 3

Resulting are the parameters used to define the performance of a directional coupler.

Coupling Factor (C)

The Coupling factor of a directional coupler is the ratio of incident power to the forward power, measured in dB.

$$C = 10\, log_{10} \frac{P_i}{P_f} dB$$

Directivity (D)

The Directivity of a directional coupler is the ratio of forward power to the back power, measured in dB.

$$D = 10\, log_{10} \frac{P_f}{P_b} dB$$

Isolation

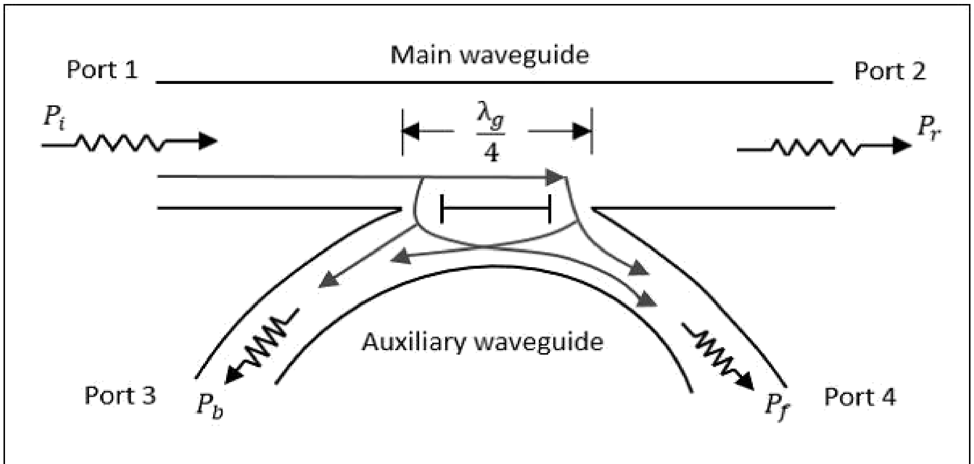
It defines the directive properties of a directional coupler. It is the ratio of incident power to the back power, measured in dB.

$$I = 10\, log_{10} \frac{P_i}{P_b} dB$$

Isolation in dB = Coupling factor + Directivity

Two-Hole Directional Coupler

This is a directional coupler with same main and auxiliary waveguides, but with two small holes that are common between them. These holes are λg/4 distance apart where λg is the guide wavelength. The following figure shows the image of a two-hole directional coupler.



Two-hole directional coupler

A two-hole directional coupler is planned to see the ideal condition of directional coupler, which is to evade back power. Some of the power while travelling between Port 1 and Port 2, escapes through the holes 1 and 2.

The greatness of the power depends upon the dimensions of the holes. This leakage power at both the holes are in phase at hole 2, adding up the power causal to the forward power Pf. Though, it is out of phase at hole 1, stopping each other and stopping the back power to occur. Therefore, the directivity of a directional coupler improves. The general S matrix of a directional coupler is,

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \end{bmatrix} \quad 1)$$

1.Since all ports in a directional coupler are matched.

$S_{11} = S_{22} = S_{33} = S_{44} = 0$ ----------------- (2)

2.Since there is no coupling between ports 1 & 3 and ports 2 & 4

$S_{13} = S_{31} = S_{24} = S_{42} = 0$ ------------- (3)

Apply equation (2) & (3) in (1)

$$S = \begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{12} & 0 & S_{23} & 0 \\ 0 & S_{23} & 0 & S_{34} \\ S_{14} & 0 & S_{34} & 0 \end{bmatrix}$$

3.By unitary property, [S][S]* = I

$$\begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{12} & 0 & S_{23} & 0 \\ 0 & S_{23} & 0 & S_{34} \\ S_{14} & 0 & S_{34} & 0 \end{bmatrix} \begin{bmatrix} 0 & S_{12}^* & 0 & S_{14}^* \\ S_{12}^* & 0 & S_{23}^* & 0 \\ 0 & S_{23}^* & 0 & S_{34}^* \\ S_{14}^* & 0 & S_{34}^* & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$R_1C_1 \Rightarrow |S_{12}|^2 + |S_{14}|^2 = 1$ ------------ (4)

$R_2C_2 \Rightarrow |S_{12}|^2 + |S_{23}|^2 = 1$ ------------ (5)

$R_3C_3 \Rightarrow |S_{23}|^2 + |S_{34}|^2 = 1$ ------------ (6)

$R_1C_3 \Rightarrow S_{12}\, S_{23}^* + S_{14}\, S_{34}^* = 0$ ----------- (7)

Comparing equations (4) and (5)

$|S_{12}|^2 + |S_{14}|^2 = |S_{12}|^2 + |S_{23}|^2$

$S_{14} = S_{23}$ --------------- (8)

Comparing equations (5) and (6)

$|S_{12}|^2 + |S_{23}|^2 = |S_{34}|^2 + |S_{23}|^2$

$S_{12} = S_{34}$ --------------- (9)

Let, S_{12} be real and positive,

i.e, $S_{12} = S_{34} = p$ -------------- (10)

applying equation (10) in (7)

Therefore, $p\, S_{23}^* + S_{14}\, p = 0$

$p\, [S_{23}^* + S_{14}] = 0$
$p\, [S_{23}^* + S_{23}] = 0$
$S_{23}^* + S_{23} = 0$

To satisfy the above condition, S_{23} should be a complex value.

Let $S_{23} = jq$

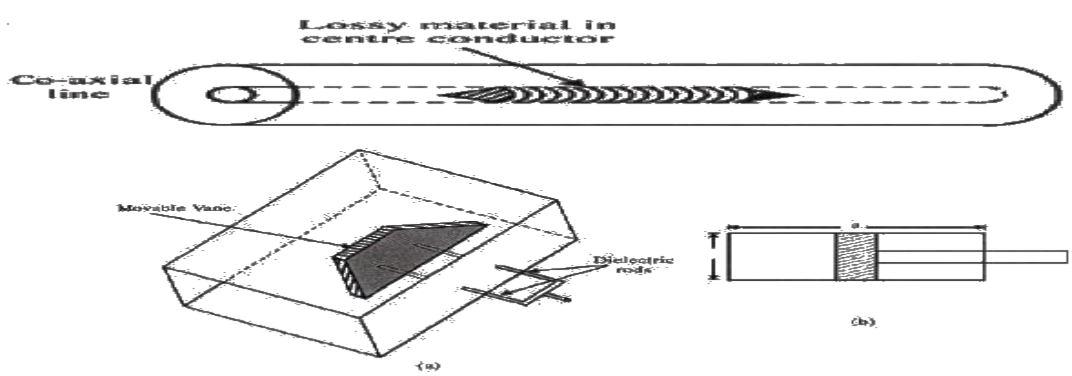
Therefore, the S matrix of directional coupler is,

$$S = \begin{bmatrix} 0 & p & 0 & jq \\ p & 0 & jq & 0 \\ 0 & jq & 0 & p \\ jq & 0 & p & 0 \end{bmatrix}$$

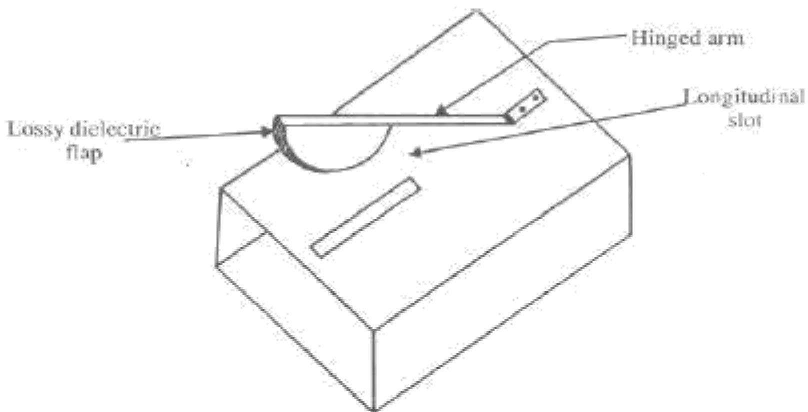
ATTENUATORS:

- In order to control power levels in a microwave system by partially absorbing the transmitted microwave signal, attenuators are employed. Resistive films (dielectric glass slab coated with aquadag) are used in the design of both fixed and variable attenuators.
- A co-axial fixed attenuator uses the dielectric lossy material inside the centre conductor of the co-axial line to absorb some of the centre conductor microwave po wer propagating through it dielectric rod decides the amount of attenuation introduced. The microwave power absorbed by the lossy material is dissipated as heat.
- In waveguides, the dielectric slab coated with aduadag is placed at the

centre of the waveguide parallel to the maximum E-field for dominant TE_{IO} mode. Inducedcurrent on the lossy material due to incoming microwave signal, results in power dissipation, leading to attenuation of the signal. The dielectric slab is tapered at both ends upto a length of more than half wavelength to reduce reflections as shown in figure 5.7. The dielectric slab may be made movable along the breadth of the waveguide by supporting it with two dielectric rods separated by an odd multiple of quarter guidewavelength and perpendicular to electricfield.



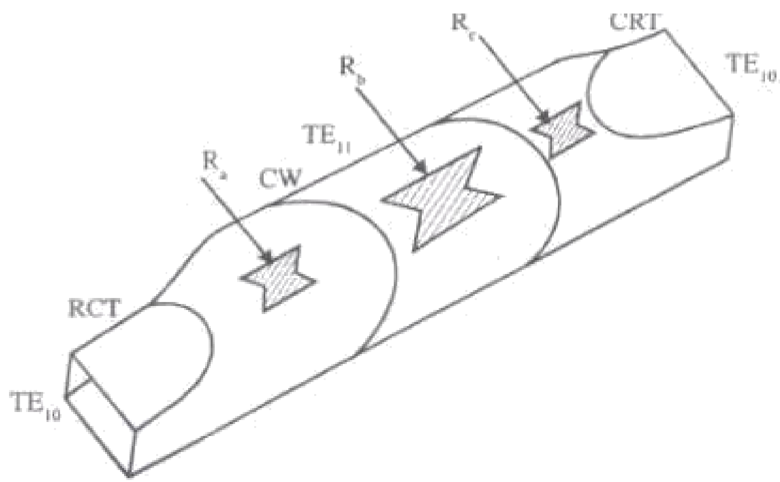
- When the slab is at the centre, then the attenuation is maximum (since the electric field is concentrated at the centre for TEIO mode) and when it is moved towards one side-wall, the attenuation goes on decreasing thereby controlling the microwave power corning outof the other port.

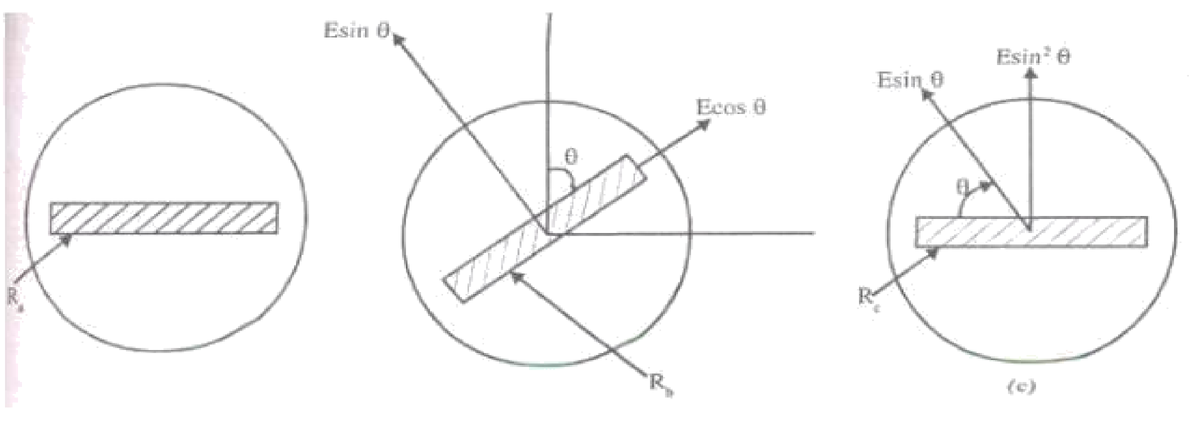


- Above figure shows a flap attenuator which is also a variable attenuator. A semi-circular flap made of lossy dielectric is made to descend into the longitude in slot cut at the center of the top wall of rectangular waveguide. When the flap is completely outside the slot, then the attenuation is zero and when it is completely inside, the attenuation is maximum. A maximum direction of 90 dB attenuation is possible with this attenuator with a VSWR of 1.05. The dielectric slab can be properly shaped according to convenience to get a linear variation of attenuation within the depth of insertion.

- A precision type variable attenuator consists of a rectangular to circular transition (ReT), a piece of circular waveguide (CW) and a circular-to-rectangular transition (CRT) as shown in below figure . Resistive cards Ra, Rb and Rc are placed inside these sections as shown. The centre circular section containing the resistive card Rb can be precisely rotated by 360 with respect to the two fixed resistive cards. The induced current on the resistive card R due to the incident signal is dissipated as heat producing attenuation of the transmitted signal. TE mode in RCT is converted into TE in circular waveguide. The resistive cards R and R a kept perpendicular to the electric field of TEIO mode so that it does not absorb the energy. But any component parallel to its plane will be readily abs orbed. Hence, pure TE mode is excited in circular waveguide section II.

- If the resistive card in the centre section is kept at an angle 8 relative to the E-field direction of the TEll mode, the component Ecos(θ) parallel to the card get absorbed while the component E sin θis transmitted without attenuation. This component finally comes out as E sin2θ as shown in figure below.



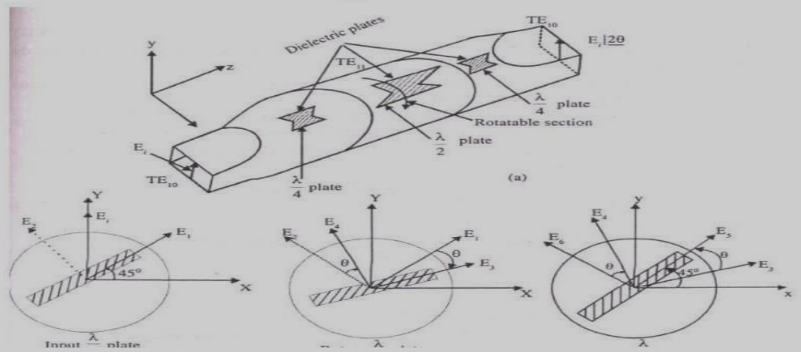


PHASE SHIFTERS:

$$E_t = (E_i \cos 45^0)\, e^{-j\beta_1 l} = E_0\, e^{-j\beta_1 l}$$

and $$E_2 = (E_i \sin 45^0)\, e^{-j\beta_2 l} = E_0\, e^{-j\beta_2 l}$$

Where $$E_0 = \frac{E_i}{\sqrt{2}}$$



- A microwave phase shifter is a two port device which produces a variable shift in phase of the incoming microwave signal. A lossless dielectric slab when placed inside the rectangular waveguide produces a phase shift.

PRECISION PHASE SHIFTER

- The rotary type of precision phase shifter is shown in figure below which consists of a circular waveguide containing a lossless dielectric plate of length 2lcalled "half-wave section", a section of rectangular-to-circular transition containing a lossless dielectric plate of length l, called "quarter-wave section", oriented at an angle of 45° to the broader wall of the rectangular waveguide and a circular-to-rectangular transition again containing a lossless dielectric plate of same length 1 (quarter wave section) oriented at an angle 45°.
- The incident TE10 mode becomes TEll mode in circular waveguide section. The half-wave section produces a phase shift equal to twice that produced by the quarter wave section. The dielectric plates are tapered at both ends to reduce reflections due to discontinuity.
- When TE10 mode is propagated through the input rectangular waveguide of the rectangular to circular transition, then it is converted into TEll in the circular waveguide section. Let E; be the maximum elelectric field strength of this mode which is resolved into components, EI parallel to the plate and E2 perpendicular to El as shown in figure 5.12 (b). After propagation through the plate these components are given by the length I is adjusted such that these two components E1 and Ez have equal amplitude but differing in phase by = 90.

- The quarter wave sections convert a linearly polarized TEll wave into a circularly polarized wave and vice-versa. After emerging out of the half-wave section,the electric field components parallel and perpendicular to the half-wave plate After emerging out of the half-wave section, the field components E3 and E4 as given in above equations, may again be resolved into two TEll modes, polarized parallel and perpendicular to the output quarter-wave plate. At the output end of this quarter-wave plate, the field components parallel and perpendicular to the quarter wave plate, by referring to figure above.

Waveguide Joints

As a waveguide system cannot be made in a single piece continuously, occasionally it is essential to join dissimilar waveguides. This joining must be sensibly done to stop problems such as − Reflection effects, creation of standing waves, and increasing the attenuation, etc.The waveguide joints also evading irregularities should also take care of E and H field patterns by not affecting them. There are many types of waveguide joints such as bolted flange, flange joint, choke joint, etc.

10. Avalanche transit time devices – IMPATT diode, TRAPATT diode, Gunn diode, Tunnel diode, Varactor diodes.

Microwave diodes are diodes that work in the microwave frequency band. It is a solid-state microwave device. Microwave band usually refers to the frequency from 300 MHz to 3000 GHz. After the discovery of the point contact diode effect at the end of the 19th century, microwave diodes such as PIN diodes, varactor diodes, and Schottky diode tubes appeared one after another. Microwave diodes have the advantages of small size and high reliability, and are used in microwave oscillation, amplification, frequency conversion, switching, phase shifting and modulation.

Diodes are used in electronic circuits, integrated circuits, and electronic devices in computers. For example, **diodes** and **transistors** are a combination of P-type and N-type **semiconductor** materials. Diodes are an example of the P-N type and are widely used in electronics.

Figure 1 shows the changes that occur when the P-type and N-type **semiconductor materials** are combined. A large number of electrons in the N-type material pass through the conduction band and enter the electron holes in the valence band of the P-type material.

Each electron eliminates an electron-hole, the N-type loses energy to the P-type and reaches a balance. The electrons must pass through the junction when flowing through the system, and the energy of a lower voltage can be applied to control the current.

Various diodes in the microwave field, including varactor diodes, step diodes, PIN diodes, limiting diodes, electrically modulated varactor diodes, solid noise diodes, and avalanche diodes. Various microwave diodes play the roles of low-noise amplification, power generation, frequency conversion, modulation, demodulation, and signal control in microwave circuits.

Microwave diodes are diodes that mainly work in the microwave frequency band. Such as barrier injection transit time **diode** (BARITT), impact avalanche transit time diode (IMPATT), limited space-charge accumulation diode (LSA), Gunn diode (Gunn), trapped plasma **avalanche diode** (TRAPATT), and **varactor diode** Wait. All of these diodes use the negative resistance effect to directly convert DC electrical energy into radiant microwave energy.

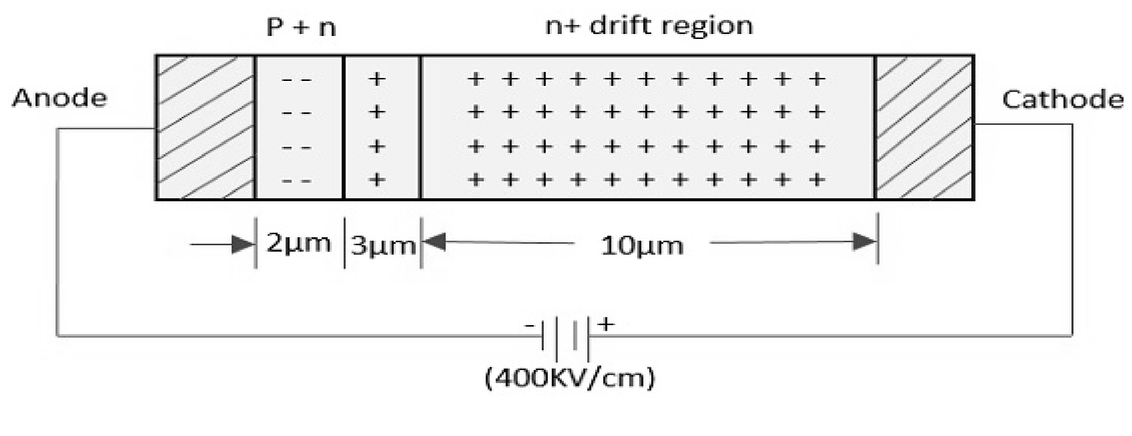
Types

IMPATT Diode

In high frequency microwave applications, the high-power semiconductor diode used is IMPATT Diode. The full form IMPATT is IMPact ionization Avalanche Transit Time diode.

A voltage gradient when applied to the IMPATT diode, results in a high current. A usual diode will finally breakdown by this. Though, IMPATT diode is developed to withstand all this. A high potential gradient is applied to back bias the diode and hence minority carriers flow across the junction.

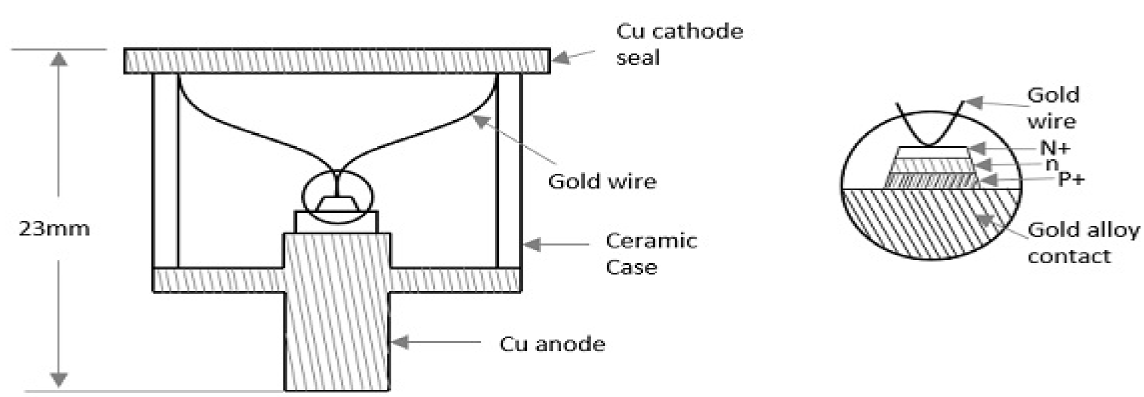
Application of a RF AC voltage if overlaid on a high DC voltage, the increased speed of holes and electrons outcomes in additional holes and electrons by beating them out of the crystal structure by Impact ionization. If the original DC field practical was at the threshold of developing this situation, then it leads to the fall current multiplication and this process continues. This can be assumed by the resulting figure.



IMPATT diode schematic

Due to this result, the current pulse takes a phase shift of 90°. On the other hand, instead of being there, it changes towards cathode due to the reverse bias applied. Based on the thickness of n+ layer the time taken for the pulse to reach cathode is stated, which is adjusted to make it 90° phase shift. Currently, a dynamic RF negative resistance is showed to exist. Therefore, IMPATT diode acts both as an oscillator and an amplifier.

The following figure shows the constructional details of an IMPATT diode.



Constructional details of IMPATT

The efficiency of IMPATT diode is represented as

$$\eta = \left[\frac{P_{ac}}{P_{dc}}\right] = \frac{V_a}{V_d}\left[\frac{I_a}{I_d}\right]$$

Where,

- P_{ac} = AC power
- P_{dc} = DC power
- V_a & I_a = AC voltage & current
- V_d & I_d = DC voltage & current

Disadvantages

Following are the disadvantages of IMPATT diode.

- It is noisy as avalanche is a noisy process
- Tuning range is not as good as in Gunn diodes

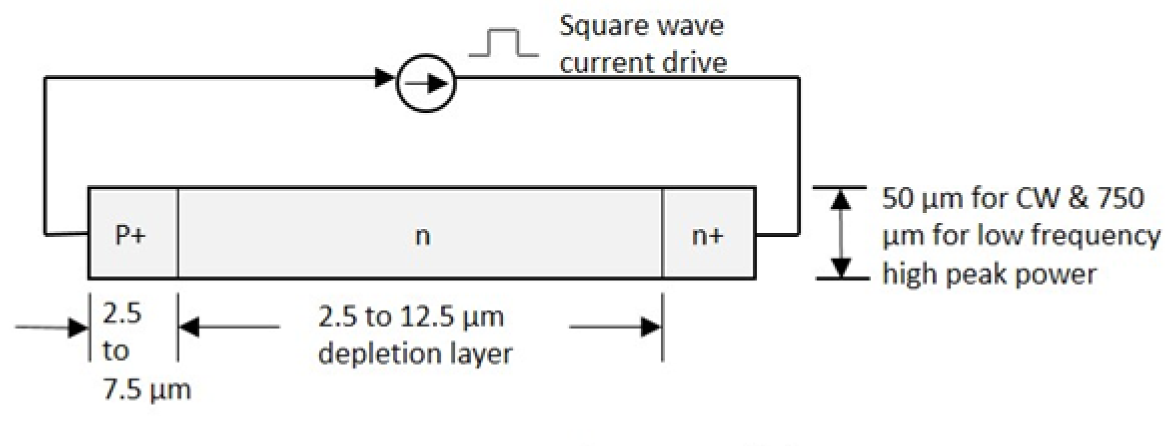
Applications

Following are the applications of IMPATT diode.

- Microwave oscillator
- Microwave generators
- Modulated output oscillator
- Receiver local oscillator
- Negative resistance amplifications
- Intrusion alarm networks (high Q IMPATT)
- Police radar (high Q IMPATT)
- Low power microwave transmitter (high Q IMPATT)
- FM telecom transmitter (low Q IMPATT)
- CW Doppler radar transmitter (low Q IMPATT)

TRAPATT Diode

The full form of TRAPATT diode is TRApped Plasma Avalanche Triggered Transit diode. A microwave generator which operates between hundreds of MHz to GHz. These are high peak power diodes usually n+- p-p+ or p+-n-n+structures with n-type depletion region, width varying from 2.5 to 1.25 Âµm. The following figure depicts this.



Arrangement in TRAPATT diode

The electrons and holes stuck in low field region behind the zone are made to fill the reduction region in the diode. This is complete by a high field fall region which spreads through the diode.

Applications

There are many applications of this diode.

- Low power Doppler radars
- Local oscillator for radars
- Microwave beacon landing system
- Radio altimeter
- Phased array radar, etc.
- **AVALANCHE TRANSIT TIME DEVICES**
-

	IMPATT	**TRAPPAT**
Operating Frequency	0.5-100 GHZ	1-10 GHZ
Noise Figure	30 dB	60 dB Not used as an amplifier
Power output	1W (CW), 400 W (Pulsed)	Several 100 W (Pulsed)

3. Gunn Diode

Gunn Diode, also known as body effect diode. The working mechanism of this type of device is based on an electron transfer effect. It uses the carriers in the semiconductor (electrons in N-type GaAs) to obtain energy in an external electric field, and transfers from the main energy band with high mobility to the sub-band with low mobility and high energy state, forming a differential resistance, thus producing Microwave oscillation. Gunn diodes have lower operating voltage and lower FM noise and are suitable for making local oscillator sources, signal sources, and low-power emission sources.

The materials used in Gunn diodes are III-V group compound semiconductors. At present, it is mainly GaAs and InP, but the GaAs Gunn diode operating frequency is below 100GHz millimeter-wave band, above which the output power will drop sharply. Because the speed-electric field characteristic of InP material has a higher peak-to-valley ratio and threshold electric field than GaAs, InP Gunn diodes have better frequency, power, efficiency, and noise performance.

4. Varactor Diode

Varactor diodes are made based on PN junction capacitance changing with reverse bias voltage. It can be roughly divided into two categories: **varactors** for low-noise parametric amplifiers and varactors for electrical tuning. The former is used for microwave parametric amplifiers, with a noise temperature as low as 30K, and has been widely used in satellite earth stations. The latter is mainly used for frequency tuning, voltage-controlled oscillators, electronic countermeasures, and rapid frequency agile radar frequency modulation. In addition, the varactor can also be used for phase shifting and amplitude limiting. In terms of production, there are certain differences between the two types of devices. The parametric varactor must have good capacitance nonlinearity and a high figure of merit; while the electrically tuned varactor must strictly control the doping concentration distribution of the semiconductor epitaxial layer in order to obtain a Large capacitance change area, and should have a higher figure of merit.

The characteristic of the varactor diode is that the junction capacitance that changes with the applied voltage provides variable reactance characteristics, and can be used as a lossless nonlinear element in the circuit. It is suitable for application in microwave signal modulation, harmonic generation (up-conversion), pulse generation and formation, etc., to make solid-state parametric amplifiers, harmonic generators, mixers, or frequency converters.

11. Microwave linear beam tubes – Klystrons, TWT,

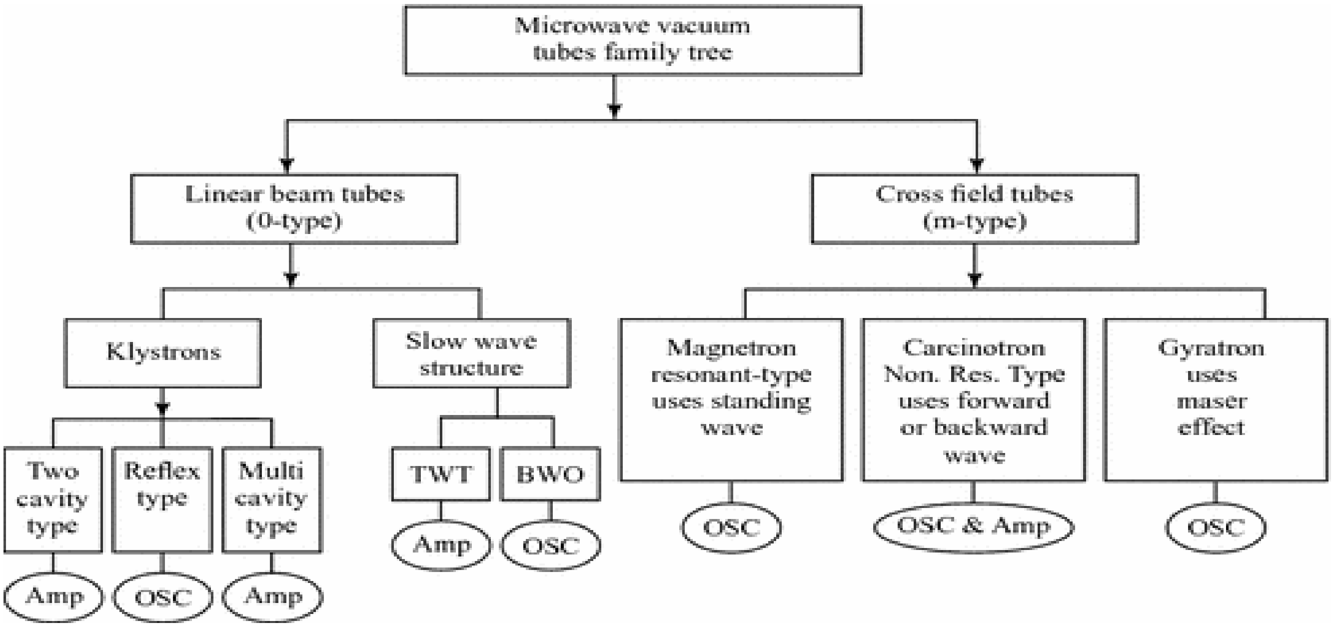
MICROWAVE TUBES

Limitations and losses of conventional Tubes at Microwave Frequencies

Conventional vacuum triodes, tetrodes and pentodes are less useful signal sources at frequencies above 1 G Hz because of

- lead inductance
- Inter-electrode capacitance effects,
- Transit angle effects
- Gain bandwidth product limitations.
- Power losses

Classification of Microwave tubes.



TWT-Travelling wave tube

BWO- Backward wave Oscillator

Klystron – Two-cavity Klystron Amplifier

Definition: Klystrons are a special type of vacuum tubes that find applications as amplifiers and oscillators at **microwave frequencies**. Its principle of operation is velocity modulation. Thus the device used for amplifying microwave signals is known as **Two-cavity Klystron**.

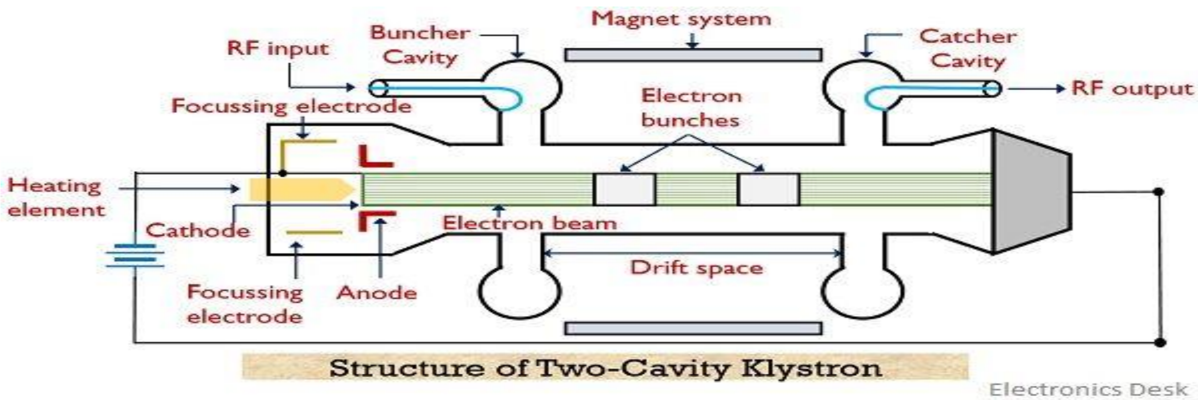
Operating Principle of Two-cavity Klystron

Klystron is based on the principle of velocity modulation. Thus two-cavity klystron amplifier utilizes the kinetic energy of moving electron beam for signal amplification.

The variation in the velocity of electrons while moving inside the tube is known as **velocity modulation**. This velocity modulation permits bunching of electrons while propagation. So, the combined energy of bunched electrons is transferred at the output thereby providing an amplified signal.

Construction

The figure below represents the structure of a two-cavity klystron:



As we can see that the above figure consists of 2 cavities namely the *buncher cavity* and *catcher cavity*. The RF signal to be amplified is provided at the buncher cavity. The electron gun comprises cathode, heating element and anode. The electron beam is produced by the cathode by making use of a heating element and the high positive potential at the anode provides the required acceleration to the electron beam initially. The region between two cavities is known as **drift space**.

To allow focussed propagation of electron beam inside the tube an external electromagnetic winding is used that generates a longitudinal magnetic field. This is done in order to prevent the spreading of the beam inside the tube. The amplified RF signal is achieved at the catcher cavity. Also, a collector is present near the second cavity that collects the electron bunch.

Working of Two-cavity Klystron Amplifier

Initially, electrons are emitted from the electron gun and the anode present in the structure provides the desired acceleration to the beam.

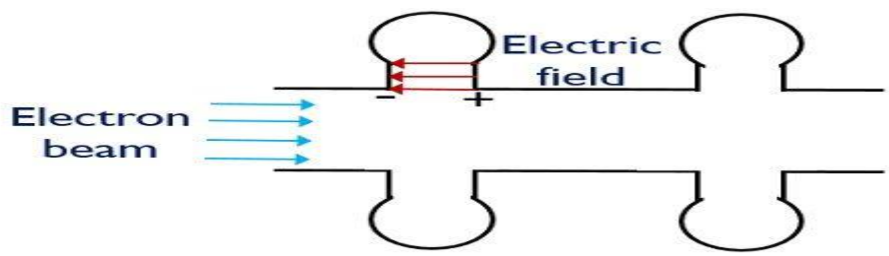
- In the absence of any RF input, the electron will tend to move with their respective uniform velocities to reach the catcher cavity and gets collected at the collector.
- But when external RF signal is applied at the input of the buncher cavity then this causes the generation of a local electric field inside the tube.

This electric field causes the bunching of electrons as the field applies acceleration and deceleration to the moving electron, according to the polarity of the signal by which the field is generated.

Basically, the reason for causing acceleration and deceleration is that when the direction of movement of an electron is opposite to the direction of the field, then, in this case, the electrons experience a decrease in their moving velocity. However, if the generated electric field and the direction of movement of the electron are the same then, in this case, the electrons experience increase in the velocity of their movement.

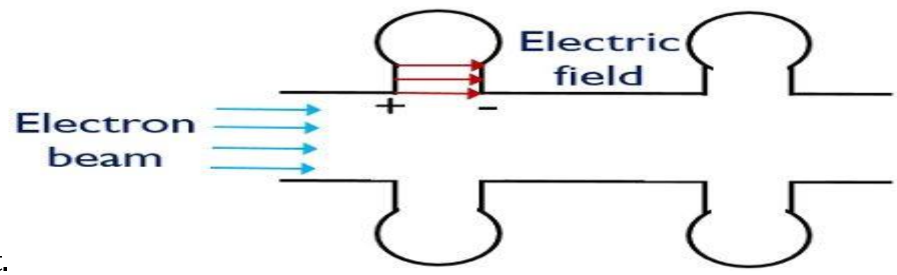
Let us now understand in detail how this increase and decrease in velocity causes bunching of electrons:

1. When the negative half of the RF signal is provided as input to the buncher cavity then the moving electrons experience a repulsive force due to the presence of a negative charge at the entering plate of the buncher cavity.



Or we can say, that due to the negative half of the input the generated field will be in a direction opposite to the direction of the movement of electrons. So, because of the opposition offered by the field, the moving velocity of electrons gets reduced.

2. Further when the positive half of the RF signal is provided then the positive potential at the first plate of the cavity applies attractive force to the moving electrons. More simply, for the positive half cycle of input, the generated electric field will be in a direction similar to the direction of electron



movement.

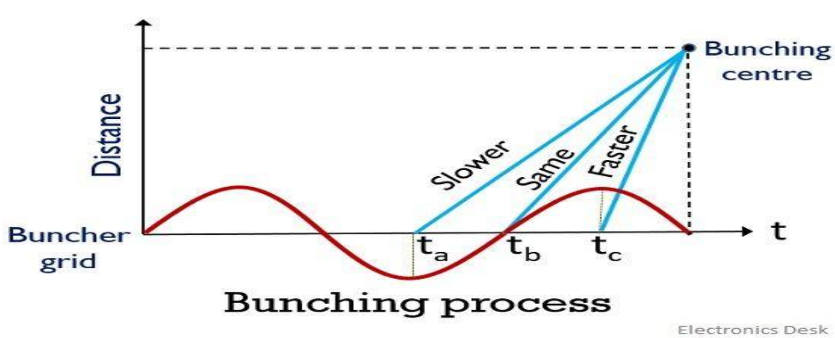
So, this leads to an increase in the moving velocity of the electrons.

Thus, combinely when we consider both the cases then the electrons that were emitted earlier by the gun will be decelerated. While the electrons emitted later will be accelerated. Thus all the electrons while moving with different velocities get bunched in the drift space. *This change in the velocity of electrons while moving due to RF input is known as velocity modulation*. Once the electron bunching is done then the catcher cavity present at another end of the tube absorbs the beam energy.

It is to be noted that to find the position of the catcher cavity **transit time** of the bunches must be considered. This is so because the *catcher cavity must be present at a sufficient distance from the buncher cavity* so that bunching can be attained in the drift space. Further, once the energy is transferred to the catcher cavity then electrons (now with low energy) gets collected at the collector.

Applegate Diagram

The figure below shows the Applegate diagram that represents the bunching of electrons moving with different velocities:



The electron travelling inside the tube under the absence of external fields acts as the bunching centre. Also, the electrons moving due to the influence of the positive half cycle of the signal reaches faster. While the movement due to the negative half cycle is retarded. Thus the figure represents the bunching process at a certain point and at a specific distance inside the tube.

Applications

The two-cavity Klystron finds application in satellite communication, UHF TV transmitters as well as radar systems, wideband high power communication and troposphere scatter transmitters etc.

Reflex Klystron

Definition: A Reflex Klystron is a specialized low-power vacuum tube used to **produce oscillations** at microwave frequency. Its principle of operation is velocity and current modulation.

Klystrons are basically specialized tubes used as amplifiers and oscillators at the microwave frequency range.

Need of Reflex Klystron

Basically, a two-cavity klystron can be converted into an oscillator, but some disadvantages are associated with it. As we know to design an oscillator, positive feedback must be provided to the input in a way to have a magnitude of loop gain as unity.
So, if we design a klystron oscillator using a two-cavity klystron then to have a change in oscillating frequency, the resonant frequency of the two-cavities is also required to be changed. Thereby leading to cause difficulty in generating oscillations. Thus to overcome the disadvantage, a reflex klystron having a single cavity was invented to have sustained oscillations at microwave frequency.

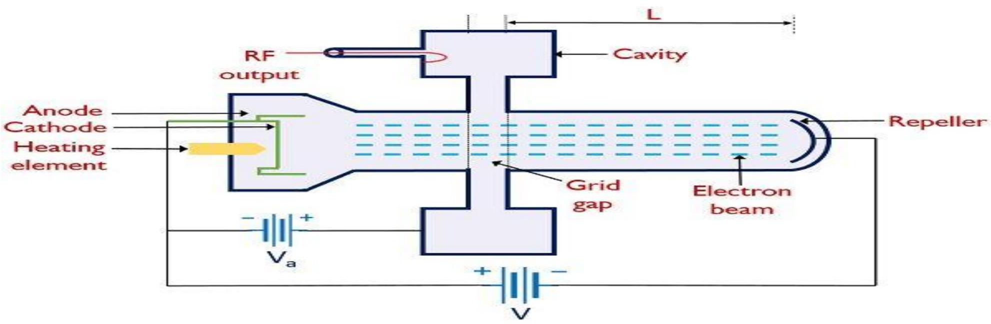
Operating Principle

Like a two-cavity klystron, a reflex klystron utilizes the phenomenon of **velocity and current modulation** to produce oscillations. However, there exist variation in constructional structure and the respective applications of the two. A reflex klystron consists of a **single cavity** that performs the action of both buncher and catcher cavity. As to have oscillations, feedback is needed to be applied at the input which is provided by the oscillator.

While moving electrons undergoes velocity modulation and the repeller applies repulsive forces on them. This leads to the formation of a bunch of electrons. Further, this bunching will lead to cause, current modulation.

Construction of Reflex Klystron

The basic schematic of a reflex klystron is shown below:



Structure of Reflex Klystron

The structure consists of a cathode and focusing anode that combinedly acts as an electron gun for the tube. The cathode emits the electron beam which is focussed inside the tube by the focusing anode. Also, a positive potential is provided as input which sets up an electric field inside the cavity.

- As it is a single cavity structure, thus single cavity act as buncher and catcher cavity separately. At the time of forward movement of the electron beam, it acts as a buncher cavity. While at the time of backward movement, it is a catcher cavity.

A repeller plate that causes backward movement of the electron beam is present at the opposite end of the electron gun. The potential at the repeller is made extremely negative in order to permit repulsion of like charges.

- Repulsion is necessary in order to build electrical oscillations, as output power must be fed to the input. So the velocity modulated electrons must have to travel a backward path in order to provide feedback. Thusrepeller is used in the structure of the klystron.

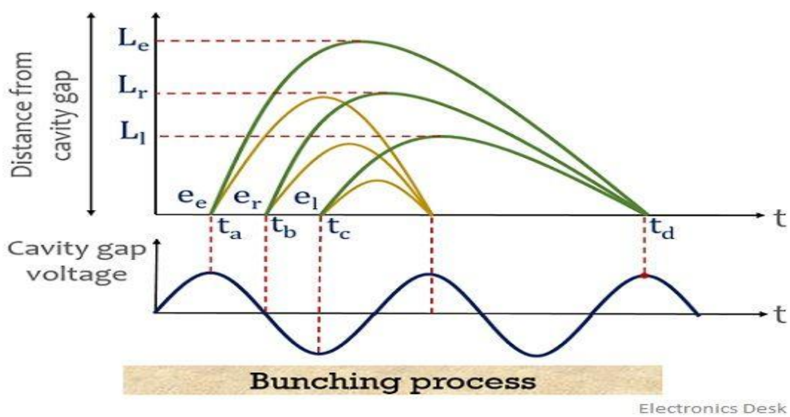
Working of Reflex Klystron

- Initially when the electron beam is emitted by the electron gun, then the early electrons, e_e experience a very high potential. Due to this, a strong electric field gets generated inside the cavity gap, leading to cause movement of electrons towards the repeller with a very high velocity.
- Due to high velocity, the electrons penetrate deeper into the region of the repeller and thus require greater time to repel back towards the catcher cavity.
- But when the externally applied potential is almost 0, then the electron moves with a uniform velocity with which it was emitted by the gun. These electrons are generally known as reference electrons e_r.
- So, in this case, e_r will not penetrate deeply into the repeller surface and gets repelled by the repeller in a lesser time than the early electron.
- Further, the electron that is emitted by the gun after the reference electron experiences a highly negative potential at the cavity. This electron is generally known as late electron e_l and moves with a very low velocity inside the tube. The penetration level of the late electron into the repeller space is least thus takes a minimal amount of time to get repelled back.

It is to be noted that due to deep penetration in the repeller region, e_e will take more time than e_r while returning towards the catcher. This change in the velocity of moving electrons is known as **velocity modulation**. And due to this velocity modulation, all the electrons get bunched while returning towards the catcher cavity.

So, in this way bunch of electrons reaches the catcher cavity. This bunching of electrons leads to cause, current modulation inside the tube. Therefore, at the time of returning, the *bunched electrons transfer the maximal of their energy* to the catcher cavity. Thereby leading to cause **oscillations** inside the tube.

- **Transit Time:** Transit time is defined as the time taken by the electrons to return to the cavity gap after getting repelled by the repeller. For sustained oscillations to take place, transit time is the most important factor. Basically, the optimum time for leaving the gun is centered around the reference electron, which is considered at a 180º phase difference from the sinusoidal applied potential across the gap.
- **Bunching Process:** The figure below shows the process of bunching on the return journey of all the 3 categories of electrons i.e., e_e, e_r, and e_l:



Here the x-axis represents the time and the y-axis shows the distance traveled by the electrons inside the tube.

As we have already discussed that bunching takes place at the time of the return journey of electrons. Thus it is represented in the figure that though e_e, e_r and e_l, are approaching the repeller with different velocities, yet while returning all of them are bunched at a respective time.

Specifications

1. The operating frequency range generally offered is **1 to 20 GHz**.
2. It delivers output power in the range of **10mW to 2.5 W**.
3. The tuning range of klystron lies between **5 GHz at 2W** to **30 GHz at 10 mW**.

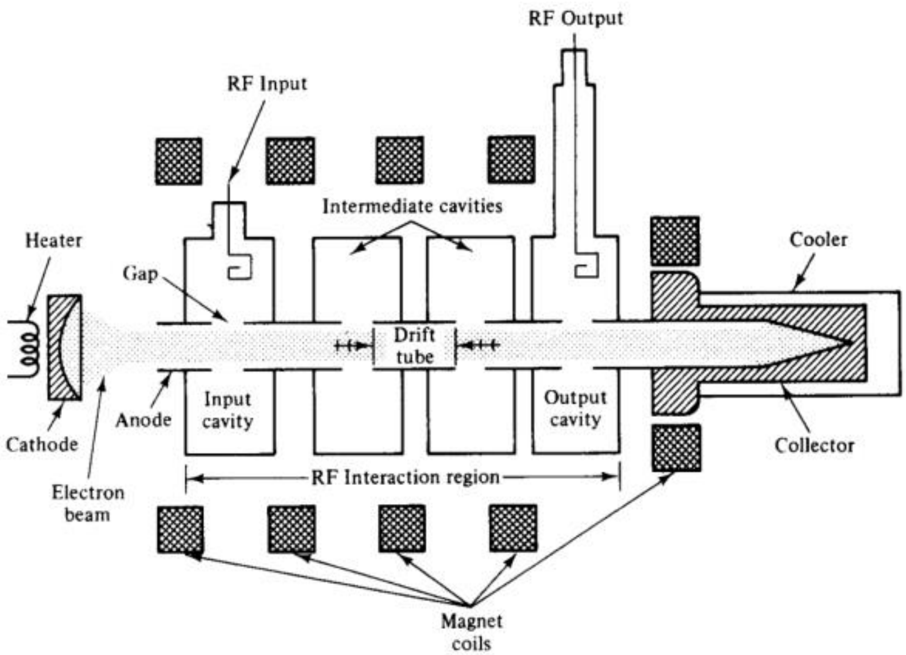
4. Theoretically, the efficiency is considered **22.78%** while practically the achieved efficiency is only **10 to 20%**.

Applications

As reflex klystrons are oscillators thus find applications in local oscillators receivers, radar receivers, radio receivers. Also utilized as signal sources in microwave generators and pump oscillators of parametric amplifiers.

Multi Cavity Klystron

- Typical gain of 2-cavity klystron is 30 dB. This gain is not adequate in many applications
- In order to achieve higher gain, several two cavity resonant tubes are connected in cascade in which output of each of the tubes is fed as input to the following tube.
- The intermediate cavities are place at a distance so that the bunching parameter X = 1.841 with respect to the previous cavity.
- The intermediate cavity acts as a buncher with the passing electron beam inducing a more enhanced RF voltage than the previous cavity, which in turn sets up an increased velocity modulation.
- Typical gain achievable by a multi cavity klystron is of the order of 50 dB with bandwidth of about 80 M Hz.
- A multi cavity klystron amplifier produces high gain and narrow bandwidth if all the cavities are tuned to the same frequency.
- When each of the cavities are tuned to slightly different frequencies (Staggered tuning), the bandwidth will appreciably increase but at the cost of the gain



Schematic diagram of a 4 –cavity klystron

Travelling Wave Tube (TWT)

A travelling wave tube is a high power amplifier used for the **amplification of microwave signals** up to a wide range. It is a special type of vacuum tube that offers an operating frequency ranging between **300 MHz to 50 GHz**.

Travelling wave tubes are **non-resonant structures** that offer continuous interaction of applied RF field with the electron beam over the entire length of the tube. Due to this reason, it provides wider operating bandwidth.

Basic Concept

Travelling wave tubes are abbreviated as **TWT**. It is majorly used in the amplification of RF signals. Basically a travelling wave tube is nothing but an elongated vacuum tube that allows the movement of electron beam inside it by the action of applied RF input.

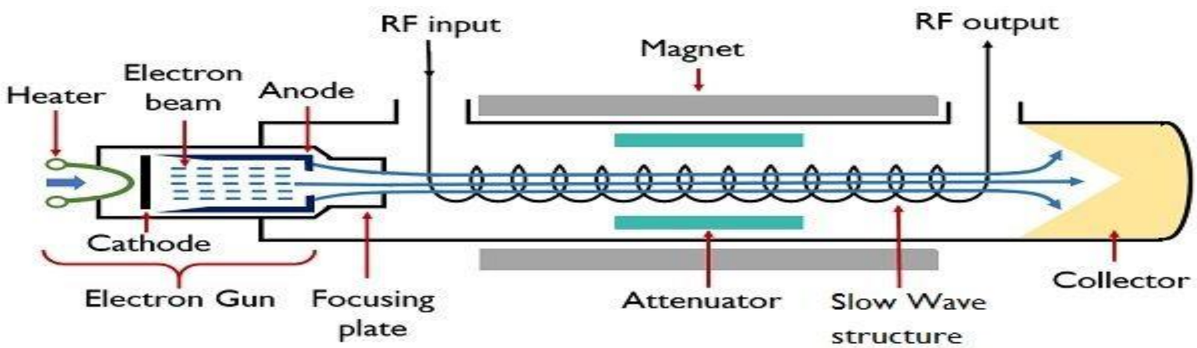
The movement of an electron inside the tube permits the amplification of applied RF input. As it offers amplification to a wide range of frequency thus is considered more advantageous for microwave applications than other tubes.

It offers average power gain of around **60 dB**. The output power lies in the range of few watts to several megawatts.

A travelling wave tube is basically of two types one is helix type and the other is coupled cavity. Here in this section, we will discuss the detailed construction and working of a helical travelling wave tube.

Construction of Travelling Wave Tube

The figure here shows the constructional structure of a TWT:



Constructional Structure of Travelling Wave Tube

As we can see that the helical travelling wave tube consists of an **electron gun** and a **slow-wave structure**. The electron gun produces a narrow beam of the electron. A focusing plate is used that focuses the electron beam inside the tube.

A positive potential is provided to the coil (helix) with respect to the cathode terminal. While the collector is more positive than the coil (helix). In order to restrict beam spreading inside the tube. A dc magnetic field is applied between the travelling path by the help of magnets.

The signal which is needed to be amplified is provided at one of the ends of the helix, present adjacent to the electron gun. While the amplified signal is achieved at the opposite end of the helix.

In the figure, we can clearly see that attenuator is present along both the sides of the travelling wave tube. This is so because travelling wave amplifiers are high gain devices, so in case of poor load matching conditions, oscillations get build up inside the tube due to reflection.

Thus in order to restrict the generation of oscillations inside the tube attenuators are used.

Attenuators are basically formed by providing a metallic coating over the surface of the glass tube. **Aquadag** or **Kanthal** are majorly used for this.

It is to be noteworthy that a slow-wave structure is considered here, the reason is to maintain continuous interaction between the travelling wave and electron beam.

Need of Slow-Wave Structure

We know that the velocity of the electromagnetic wave is very much higher when compared with the phase velocity of the electron beam emitted by the electron gun.

Basically the RF wave applied at the input of TWT propagates with the speed of light (i.e., $\mathbf{3 * 10^8\, m/s}$). While the propagating velocity of the electron beam inside the tube is comparatively smaller than the velocity of RF wave.

If we try to somehow accelerate the velocity of the electron beam, then it can be accelerated only to a fraction of velocity of light. So it is better to reduce the velocity of the applied RF input in order to match the velocity of the electron beam.

Therefore, a slow-wave structure is used that causes a reduction in the phase velocity of the RF wave inside the TWT.

The slow-wave structures can be of different types like a single helix, double helix, zigzag line, corrugated, coupled-cavity or ring bar type etc.

A single helix slow-wave structure is formed by wounding a wire of element like tungsten and molybdenum in the form of a coil. The helical shape of the structure slows the velocity of the wave travelling along its axis to a fraction of about one-tenth of c.

This is so because due to the helical shape of the structure, the **wave travels a much larger distance** than the distance travelled by the beam inside the tube. So, in this way, the speed of wave propagation depends on the number of turns or diameter of the turns.

More specifically we can say that change in pitch can vary the speed of wave propagation inside the tube.

The equation given below shows the relation of phase velocity of the wave with the pitch of the helix:

$$V_P = \frac{cP}{\sqrt{(P)^2 + (\pi d)^2}}$$

: *c = velocity of light (3 * 10^8 m/s)*

V_P = phase velocity in m/s

P = pitch of helix in m

d = diameter of the helix in m

Therefore, this causes continuous interaction between the RF input wave and the electron beam as the velocity of propagation of the two is not highly different. As such interaction is the basis of working of TWT thus slow-wave structures are used.

Working of Travelling Wave Tube

The applied RF signal produces an electric field inside the tube. Due to the applied positive half, the moving electron beam experiences accelerative force. However, the negative half of the input applies a de-accelerative force on the moving electrons.

This is said to be **velocity modulation** because the electrons of the beam are experiencing different velocity inside the tube.

However, the slowly travelling wave inside the tube exhibits continuous interaction with the electron beam.

Due to the continuous interaction, the electrons moving with high velocity transfer their energy to the wave inside the tube and thus slow down. So with the rise in the amplitude of the wave, the velocity of electrons reduces and this causes bunching of electrons inside the tube.

The growing amplitude of the wave resultantly causes more bunching of electrons while reaching the end from the beginning. Thereby causing further **amplification of the RF wave** inside the tube.

More specifically we can say that forward progression of the field along the axis of the tube gives rise to amplification of the RF wave. Thus at the end of the tube an amplified signal is achieved.

The positive potential provided at the other end causes collection of electron bunch at the collector.

The magnetic field inside the tube restricts the spreading of the beam as the electrons possess repulsive nature.

However, as the TWT is a **bidirectional device**. Therefore, the reflected signal causes oscillations inside the tube. But as we have already discussed earlier that the presence of attenuators reduces the generation of oscillations due to reflected backwave.

Sometimes despite using attenuators, internal impedance terminals are used that puts less lossy effects on the forward signal.

Applications of TWT

1. Travelling wave tubes are highly used in continuous wave radar systems.
2. These amplifying tubes also find application in broadband receivers for RF amplification.
3. TWT's are also used to get high power output in satellite transponders.

12. Microwave Cross field tubes – Magnetron

Definition: A magnetron is a device that generates high power electromagnetic wave. It is basically considered as a self-excited microwave oscillator. And is also known as a *crossed-field device*.

The reason behind calling it so is that the electric and magnetic field produced inside the tube are mutually perpendicular to each other thus the two crosses each other.

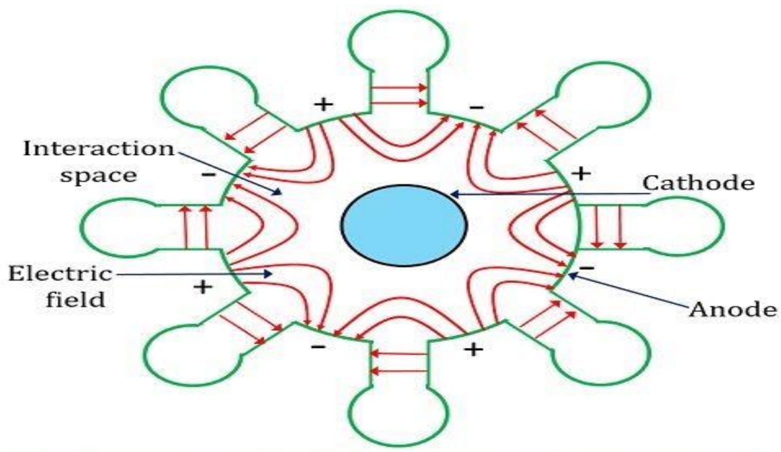
Operating Principle

A magnetron is basically a vacuum tube of high power having multiple cavities. It is also known as **cavity magnetron** because of the presence of anode in the resonant cavity of the tube.

The operating principle of a magnetron is such that when electrons interact with electric and magnetic field in the cavity then high power oscillations get generated.

Construction of Magnetrons

The figure here shows a magnetron with 8 cavities:



Structure of Magnetron

A cylindrical magnetron has a cylindrical cathode of a certain length and radius present at the centre around which a cylindrical anode is present. The cavities are present at the circumference of the anode at equal spacing.

Also, the area existing between anode and cathode of the tube is known as *interaction space/region*.

It is to be noted here that there exists a phase difference of 180^0 between adjacent cavities. Therefore, cavities will transfer their excitation from one cavity to another with a phase shift of 180^0.

Thus we can say that if one plate is positive then automatically its adjacent plate will be negative. And this is clearly shown in the figure given above.

More specifically we can say that edges and cavities show180^0 phase apart relationship.

As we have already discussed that here the electric and magnetic field are perpendicular to each other. And the magnetic field is generated by using a permanent magnet.

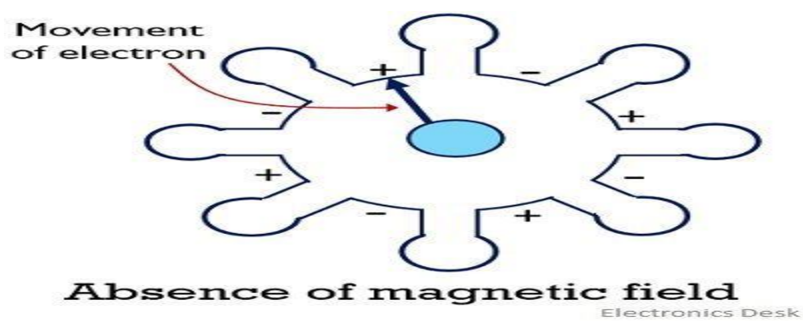
Working of Magnetron

The excitation to the cathode of the magnetron is provided by a dc supply which causes the emergence of electrons from it.

1. When RF input is not present

Case I: When the magnetic field is 0 or absent

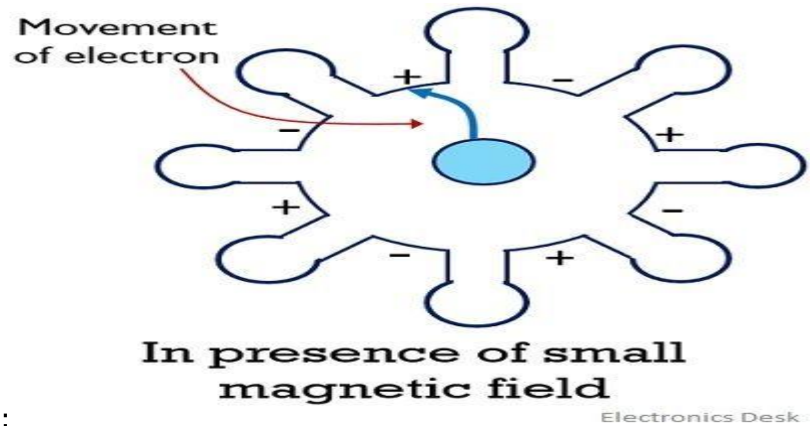
When the magnetic field is absent then the electron emerging from the cathode radially moves towards the anode. This is shown in the figure below:



This is so because the moving electron does not experience the effect of the magnetic field and moves in a straight path.

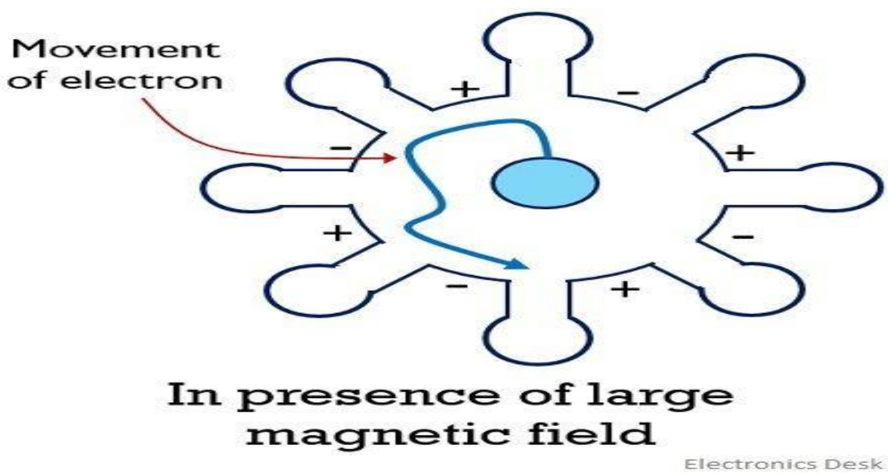
Case II: When a small magnetic field is present

In case a small magnetic field exists inside the magnetron then the electron emerging from the cathode will slightly deviate from its straight path. And this will cause a curvy motion of the electron from cathode to anode as shown in the figure:



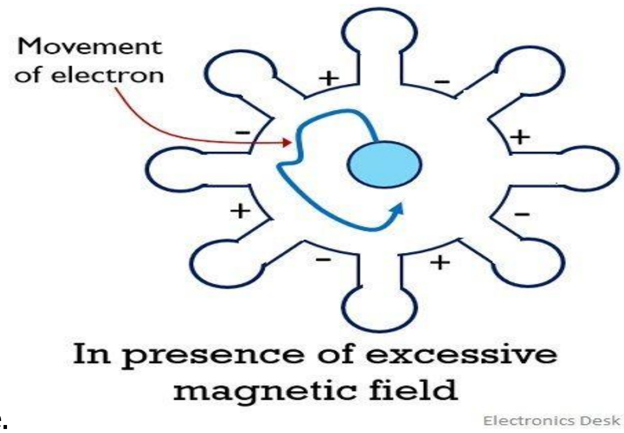
This motion of the electron is the result of the action of electric as well as magnetic force over it.

Case III: In case when the magnetic field is further increased then electrons emerging from the cathode gets highly deflected by the magnetic field. And graze along the surface of the cathode, as shown below:



This causes the anode current to be 0. The value of the magnetic field that causes the anode current to become 0 is known as the *critical magnetic field*.

If the magnetic field is increased beyond the critical magnetic field. Then the electron will bounce back to the cathode itself without reaching the



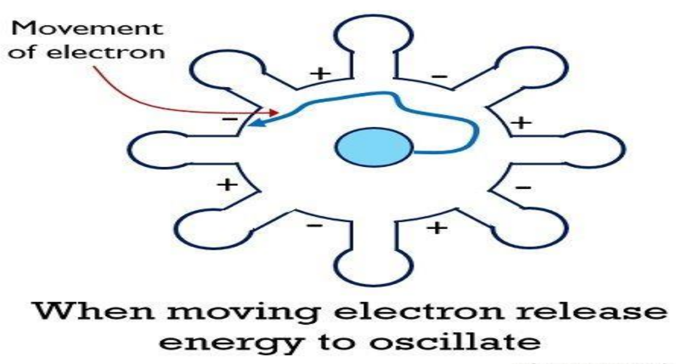
anode.

The reaching of the emitted electrons from the cathode back to it is known as **back heating**. So to avoid this the electric supply provided to the cathode must be cut-off after oscillations have been set up in the tube.

2. When the RF field is present

Case I: In case an active RF input is provided to the anode of the magnetron then oscillations are set up in the interaction space of the magnetron. So, when an electron is emitted from the cathode to anode then it transfers its energy in order to oscillate.

Such electrons are called **favoured electrons**. In this condition, the electrons will have a low velocity and thus will take a considerably high amount of time to reach from cathode to anode.

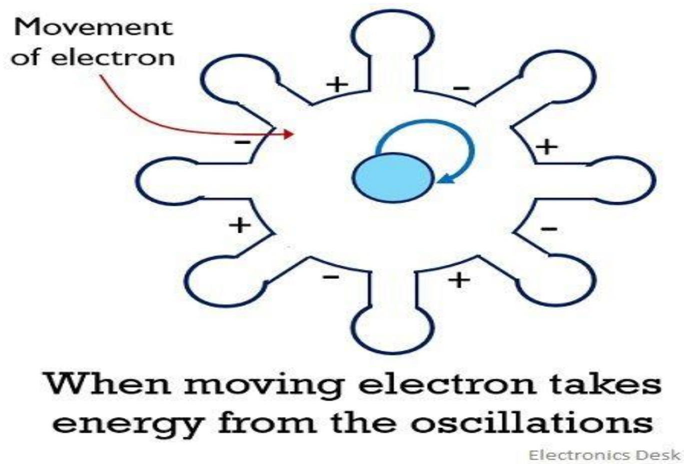


This is given in the figure below:

Case II: Another condition arises in the presence of RF input. In this case, the emitted electron from the cathode while travelling takes energy from the oscillations thereby resultantly increasing its velocity.

So despite reaching the anode, the electrons will bounce back to the cathode and these electrons are known as **unfavoured electrons**.

The propagation of unfavoured electrons is shown below:



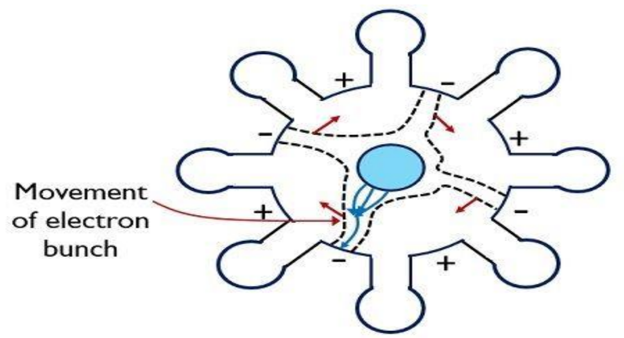
Case III: When the RF input is further increased then the electron emitted while travelling increases its velocity in order to catch up the electron emitted earlier with comparatively lower velocity.

So, all those electrons that do not take energy from the oscillations for their movement are known as favoured electrons. And these favoured electrons form **electron bunch** or **electron cloud** and reaches anode from the cathode.

The formation of electron bunch inside the tube is known as **phase focusing effect**.

Due to this, the orbit of the electron gets confined into spokes. These spokes rotate according to some fractional value of electron emitted by the cathode until it reaches anode while delivering their energy to oscillations.

However, the electrons released from the region of cathode between spokes, will take the energy of the field and get back to the cathode very quickly. But this energy is very small in comparison to the energy delivered to the oscillations. This is shown in the figure below:



Path of electron cloud according to the rotation of spokes

The movement of these favoured electrons inside the tube enhances the field existing between the gaps in the cavity. This leads to sustained oscillations inside the magnetron thereby providing high power at the output.

Frequency Pushing and Pulling

The variation in the oscillating frequency of the magnetron give rise to the term *frequency pushing and pulling*.
When the voltage applied at the anode of the magnetron is varied then this causes the variation in the velocity of the electrons moving from cathode to anode. This resultantly changes the frequency of oscillations.

Therefore, we can say when the resonant frequency of the magnetron shows variation due to the change in the anode voltage then it is known as **frequency pushing**.
The change in resonant frequency is sometimes a result of the change in the load impedance of the magnetron. The load impedance varies when the change is purely resistive or reactive. This frequency variation is known as **frequency pulling**. A steady

power supply can provide a reduction in this frequency variation.

Advantages

- Magnetrons are a highly efficient device used for generation of the high power microwave signal.
- The use of magnetrons in radar can produce radar system of better quality for tracking purpose.
- It is usually small in size thus less bulky.

Disadvantages

- It is quite expensive.
- Despite producing a wide range of frequency, there exists a drawback in controllability of the generated frequency.
- It offers average power of around 1 to 2 kilowatts.
- Magnetrons are quite noisy.

Applications of Magnetron

- A major application of magnetron is present in a pulsed radar system in order to produce a high-power microwave signal.
- Magnetrons are also used in heating appliances likes microwave ovens so as to produce fixed frequency oscillations.
- Tunable magnetrons find their applications in sweep oscillators.

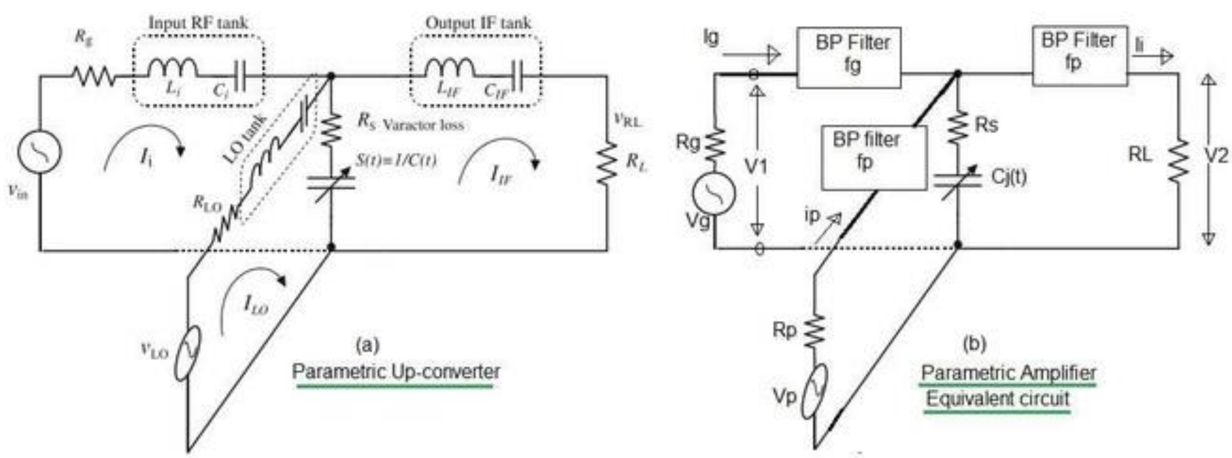
It is noteworthy here that this mode of operation of the magnetron is also known as π mode. This is so because a proper phase shift of 180^0 is maintained between two adjacent plates. Also, it is to be noted that oscillations are only built-up in π mode.

13. parametric amplifiers

It is the device in which periodic variation of the it's parameters e.g. capacitance of the varactor diode under the influence of suitable pump signal. Due to this. it is known as **parametric amplifier**.

If a small input signal with frequency fg and AC power with frequency fp are applied to varoctor diode, linear amplification of small input signal occurs. This happens due to time varying capacitance of the varactor diode.

Here pump signal (fp) provides power needed for amplification. The power output is either at the input frequency (fg) or at the idler frequency (fi=fp-fg).



A set of relations are obtained by Manley-Rowe in order to determine maximum gain of parametric amplifier. The power gain of signal is expressed as follows:

Power Gain = fo/fg = (fg+fp)/fg = 1 + fp/fg

Manley Rowe relations provides maximum gain theoretically. But practically, gain is less than 1+(fp/fg) due to losses. This type of parametric amplifier is referred as up converter.

When the output frequency is equal to fg-fp, the parametric device is referred as down converter. In this condition it provides loss instead of gain.

The figure-part (b) depicts equivalent circuit of parametric amplifier. The varactor diode represents negative resistance at signal frequency to provide amplification of the input signal.

The figure-part (a) depicts equivalent circuit of parametric up converter. As shown fp and fg are applied through tuned circuits to the varactor diode. Output is taken at frequency fi equal to fp + fg. The series tuned circuits will allow only currents with respective frequencies (fg,fp and fi) in each of the loops.

Parametric Amplifier Advantages

Following are advantages of Parametric amplifier:

- Noise Figure: Because of minimum resistive elements, thermal noise in parametric amplifier is very less in comparison to transistor amplifier. Hence noise figure is less and will be in the range 1-2 dB.

- Frequency Range: The upper freqency limit (about 40 to 200GHz) is set by the difficulty of obtaining a source power at pump frequency and also by the frequency at which the varactor capacitance can be pumped. The lower frequency limit is set by the cut-off frequency of the microwave components used in circuit
- Bacause of its low noise, parametric smplifiers are used in space communications systems, tropo-receivers and radio telescopes.

Parametric Amplifier Disadvantages

Following are disadvantages of Parametric amplifier

- Bandwidth: Parametric amplyfier bandwidth is small due to the presence of tuned circuits. Bandwidth can be increased by stagger tuning.
- Gain: It is limited by the stabilities of pump source and the time varying capacitance. It is usually in the rane of 20 to 80 dB.

14. Cross field amplifiers.

The Crossed Field Amplifier is a microwave power amplifier based on the magnetron and looking very much like it. It is a cross between the TWT and the magnetron in its operation. It uses an essentially magnetron structure to provide an interaction between crossed dc electric and magnetic fields and an RF field. It uses a slow-wave structure similar to that of the TWT to provide a continuous interaction between the electron beam and a moving RF field. (It will be noted that in the magnetron, interaction is with a stationary RF field.) The Crossed Field Amplifier is more recent than most other microwave tubes, having been first proposed in the early 1960s.

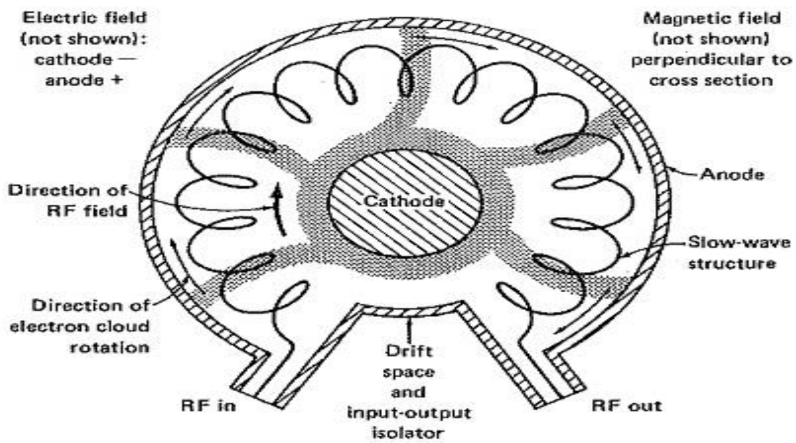


FIGURE **Simplified cross section of continuous-cathode, forward-wave crossed-field amplifier.**

Operation:

The cross section of a typical Crossed Field Amplifier is shown in Figure; the similarity to a coaxial magnetron is striking in its appearance. It would have been even more striking if, as used in practice, a vane slow-wave structure had been shown, with waveguide connections. The helix is illustrated here purely to simplify the explanation. Practical CFAs and magnetrons are very difficult to tell apart by mere looks, except for one unmistakable giveaway: unlike magnetrons, CFAs have RF input connections.

As in the magnetron, the interaction of the various fields results in the formation of bunched electron clouds. An input signal is supplied and receives energy from electron clouds traveling in the same direction as the RF field. In the TWT, signal strength grows along the slow-wave structure, and gain results. It will be seen in Figure 11-22 that there is an area free of the slow-wave structure. This provides a space in which electrons drift freely, isolating the input from the output to prevent feedback and hence oscillations. An attenuator is sometimes used also, similar to the TWT arrangement.

In the tube shown, the direction of the RF field and the electron bunches is the same; this is a forward-wave Crossed Field Amplifier. Backward-wave CFAs also exist, in which the two directions are opposed. There are also CFAs which have a grid located near the cathode in the drift-space area, with an accelerating anode nearby. They are known as injected-beam CFAs.

Practical considerations:

The majority of Crossed Field Amplifier are pulsed devices. CW and dual-mode CFAs are also available, although their performance and other details tend to be shrouded in military secrecy. However, dual-mode operation is easier for CFAs than for TWTs, because here both the electric and the magnetic fields can be switched to alter power output. Thus 10:1 or higher power ratios for dual-mode operations are feasible.

Pulsed CFAs are available for the frequency range from 1 to 50 GHz, but the upper frequency is a limit of existing requirements rather than tube design. CFAs are quite small for the power they produce (like magnetrons), and that is a significant advantage for airborne radars. The maximum powers available are well over 10 MW in the UHF range (with an excellent efficiency of up to 70 percent), 1 MW at 10 GHz (efficiency up to 55 percent) and 400 kW CW in the S-band. The excellent efficiency contributes to the small relative size of this device and of course to its use. Duty cycles are up to about 5 percent, better than magnetrons but not as high as TWTs. Bandwidths are quite good at up to 25 percent of center frequency (and one octave for some injected-beam CFAs). The relatively low gains available, typically 10 to 20 dB, are a disadvantage, in that the small size of the tube is offset by the size of the driver, which the klystron or TWT, with their much higher gains, would not have required.

A typical forward-wave Crossed Field Amplifier is the Varian SFD257. It operates over the range 5.4 to 5.9 GHz, producing a peak power of I MW with a duty cycle of 0.1 percent. The efficiency is 50 percent, gain 13 dB, and noise figure approximately 36 dB, a little higher than for a corresponding klystron. The anode voltage is 30 kV dc, and the peak anode current is 70 A. The tube, like a number of magnetrons, uses back-heating for the cathode, and indeed both it and the anode are liquid-cooled. The whole package, with magnet, weighs 95 kg and looks just like a high-power magnetron with an extra set of RF terminals. Crossed Field Amplifier are used almost entirely for radar and electronic countermeasures.