UNIT 1

Low Frequency parameters

Name	Express	In terms of	Defining equations
Impedance	V_1, V_2	I_1, I_2	$V_1 = z_{11}I_1 + z_{12}I_2$ and $V_2 = z_{21}I_1 + z_{22}I_2$
Admittance	I_1, I_2	V_1, V_2	$I_1 = y_{11}V_1 + y_{12}V_2$ and $I_2 = y_{21}V_1 + y_{22}V_2$
Hybrid	V_1, I_2	I_1, V_2	$V_1 = h_{11}I_1 + h_{12}V_2$ and $I_2 = h_{21}I_1 + h_{22}V_2$
Transmission	V_1, I_1	$V_2, -I_2$	$V_1 = AV_2 - BI_2$ and $I_1 - CV_2 - DI_2$

Limitations of Low frequency Parameters

- Equipment is not readily available to measure total voltage and current at the ports of network
- Short circuit and open circuit are difficult of achieve in high frequencies
- Presence of active devices such as transistors and diodes make the system more unstable at high frequencies

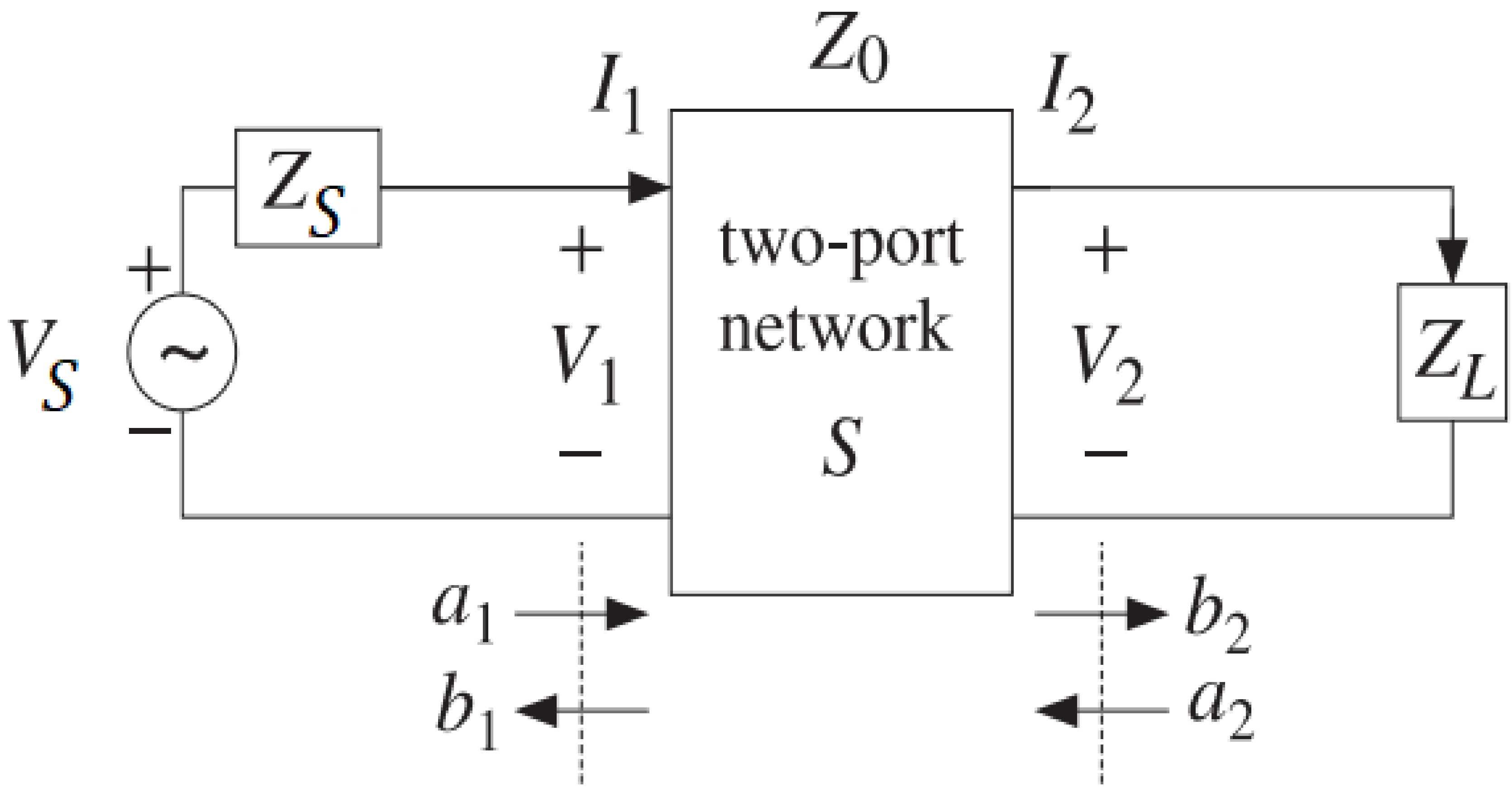
S-Parameters (Scattering Parameters)

- At high frequencies, rather than voltage and current, travelling waves are measured to identify the power relationships of the network.
- Scattering parameters describes the input-output relationships between ports in an electrical system.
- The essence of scattering parameters (or S-parameters) is that they relate forward- and backward-travelling waves on a transmission line.

Scattering Matrix

- Scattering matrix is a square matrix which gives all combinations of power relationships between the various input and output ports of a microwave junctions
- The elements of a scattering matrix are called as scattering co-efficients or s-parameters.
- S_{11}, S_{22} - Reflection Co-efficients at port 1 and 2 respectively.
- S_{12} – Reverse transmission co-efficient.
- S_{21} – Forward Transmission Co-efficient.

Formulation of S-Parameters



- The mathematical expression for 2-port microwave network is,

$$\mathbf{b_1 = S_{11}\, a_1 + S_{12}\, a_2}$$

$$\mathbf{b_2 = S_{21}\, a_1 + S_{22}\, a_2}$$

- a1 is the incident wave amplitude at port 1.
- b1 is the reflected wave amplitude at port 1.
- a2 is the incident wave amplitude at port 2
- b2 is the reflected wave amplitude at port 2.

$$s_{11} = \frac{b_1}{a_1}\Big|_{a_2 = 0}$$ = Input reflection coefficient Γin for case of $Z_L=Z_0$

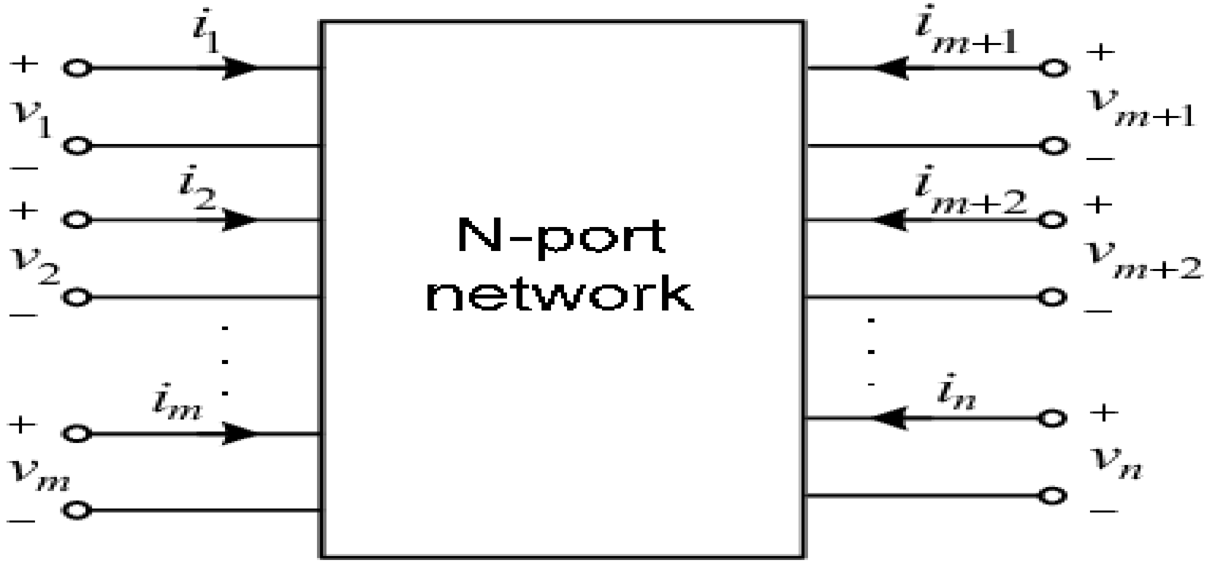
$$s_{21} = \frac{b_2}{a_1}\Big|_{a_2 = 0}$$ = Forward transmission (insertion) gain for case of $Z_L=Z_0$

$$s_{12} = \frac{b_1}{a_2}\Big|_{a_1 = 0}$$ = Reverse transmission (insertion) gain for case of $Z_s=Z_0$

$$s_{22} = \frac{b_2}{a_2}\Big|_{a_1 = 0}$$ = Output reflection coefficient Γout for case of $Z_s=Z_0$

N-Port network

$$\mathbf{V}_1 = (v_1,\ v_2,\ \cdots,\ v_m)^{\mathrm{T}}$$
$$\mathbf{I}_1 = (i_1,\ i_2,\ \cdots,\ i_m)^{\mathrm{T}}$$
$$\mathbf{V}_2 = (v_{m+1},\ v_{m+2},\ \cdots,\ v_n)^{\mathrm{T}}$$
$$\mathbf{I}_2 = (i_{m+1},\ i_{m+2},\ \cdots,\ i_n)^{\mathrm{T}}$$



-port network.

- Matrix form representation of incident wave and reflected wave amplitudes along with scattering co-efficients.

$$[b] = [S][a]$$

- For a multiport network The S parameters equation are expressed by

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

Properties of S-Parameters

1. **Zero diagonal elements for perfect matched network**

For an ideal N-port network with matched termination $S_{ii} = 0$

Since there is no reflection from any port. Therefore under perfect matched condition the diagonal elements of [S] are zero.

2. **Symmetry of [s] for a reciprocal network**

The reciprocal device has a same transmission characteristics in either direction of a pair of ports and is characterized by a symmetric scattering matrix

$$\mathbf{S_{ij} = S_{ji}\ ;\ i \neq j}$$

$$\mathbf{[S]_t = [S]}$$

3. **Unitary property of lossless network**

For any loss less network the sum of product of each term of any one row or any one column of s matrix multiplied by its complex conjugate is unity

$$\sum_{n=1}^{N} Sni\, Sni* = 1$$

4. **Phase shift property**

If any of the terminal or reference plane are moved away from the junction by an electric distance β_k,l_k. each of the coefficient S_{ij} involving K will be multiplied by the factor (e –jβ_k/k)

Components at high frequencies

WIRE

- A Wire is a passive device normally used for interconnecting several microwave components
- It is the simplest element having zero resistance at low frequencies
- Resistances, inductances, and capacitances are formed by wires, coils, and plates etc.
- Even a single wire or a copper line on a PCB possesses resistance and inductance.

Behavior of Passive Elements

- Resistance is frequency independent
- Inductor (L) is frequency dependant (XL = ωL)
- Capacitance (C) is frequency dependant (XC = $1/\omega C$)

At DC and low frequencies

- Capacitor behaves as open circuit at DC and low frequency
- An Inductor behaves as short circuit at DC and low frequencies

RF Behavior of Resistors

- At DC, current flows uniformly distributed over the entire conductor cross-sectional area.

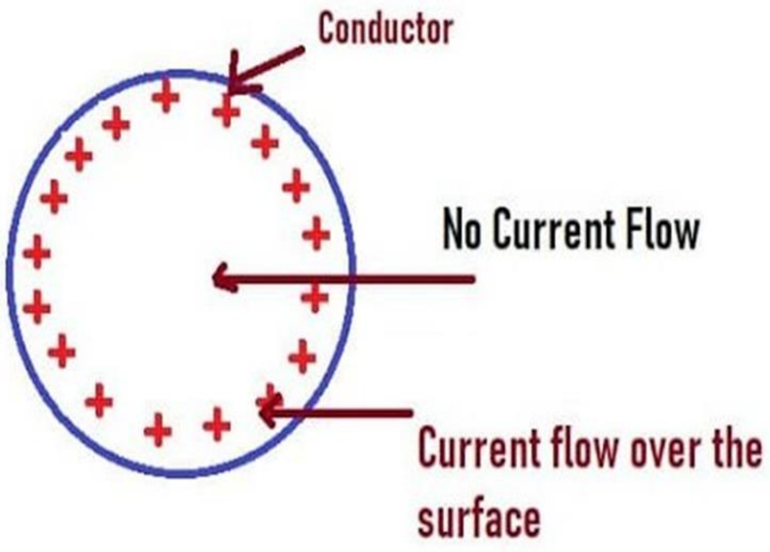
DC Current Density: $\boxed{J = \frac{I}{\pi a^2}}$

- At AC, The current density is given by,

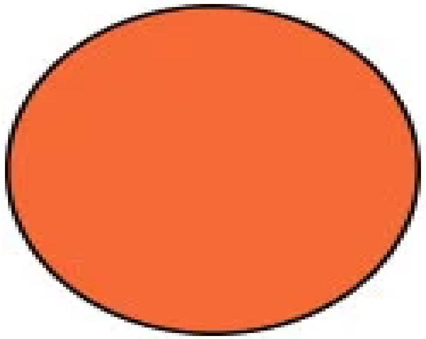
$$J_z = \frac{pI}{2\pi a j\sqrt{r}} \exp\left(-(1+j)\frac{a-r}{\delta}\right)$$

$$p^2 = -j\omega\mu\sigma_{cond}$$

$$\delta = \frac{1}{\sqrt{\pi f \mu\sigma_{cond}}}$$

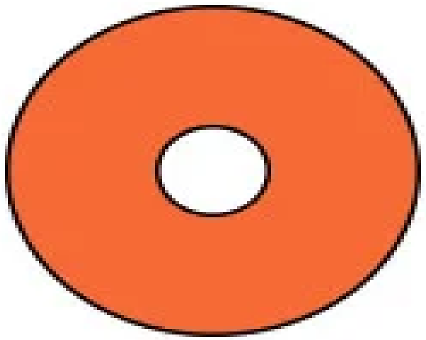


J_z drops with decrease in r (proximity to the center)
δ decreases with increase in frequency (skin depth from periphery reduces with increased frequency) $\rightarrow$ means the path for current conduction remains nearer to the periphery (skin effect) $\longrightarrow$ means, current density towards center decreases with increase in frequency and increase in conductivity



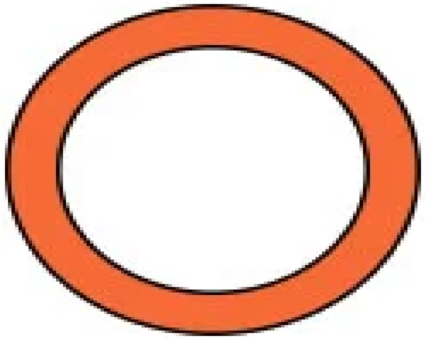
Cross-sectional area of a round conductor available for conducting DC current

“DC resistance”



Cross-sectional area of the same conductor available for conducting low-frequency AC

“AC resistance”



Cross-sectional area of the same conductor available for conducting high-frequency AC

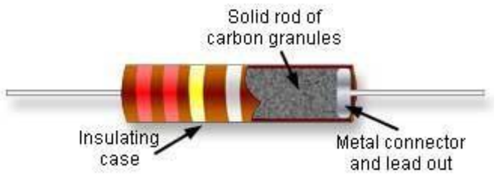
“AC resistance”

Skin Effect

- Skin effect is the tendency of an alternating electric current (AC) to become distributed within a conductor such that the current density is largest near the surface of the conductor and decreases exponentially with greater depths in the conductor
- The electric current flows mainly at the "skin" of the conductor, between the outer surface and a level called the skin depth. Skin depth depends on the frequency of the alternating current; as frequency increases, current flow becomes more concentrated near the surface, resulting in less skin depth.

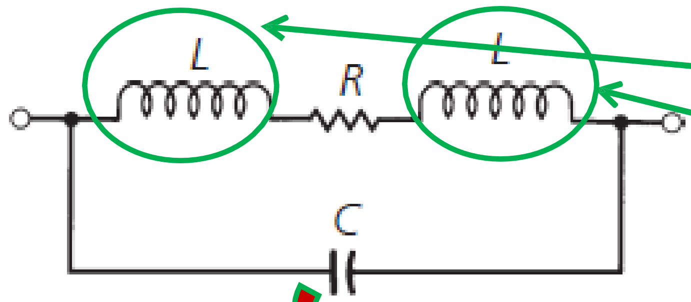
Resistors at High Frequencies

1. Carbon-composition resistors:



- Consists of densely packed dielectric particulates or carbon granules.
- **Between each pair of carbon granules <u>is</u> very small parasitic capacitor.**
- These parasitics, in aggregate, are significant → **primarily responsible for notoriously poor performance at high frequencies**

<u>Equivalent Ckt Model:</u>



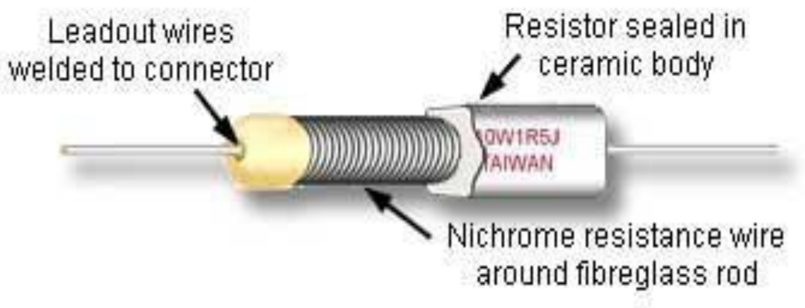
Lead Inductance

Combination of parasitic capacitances

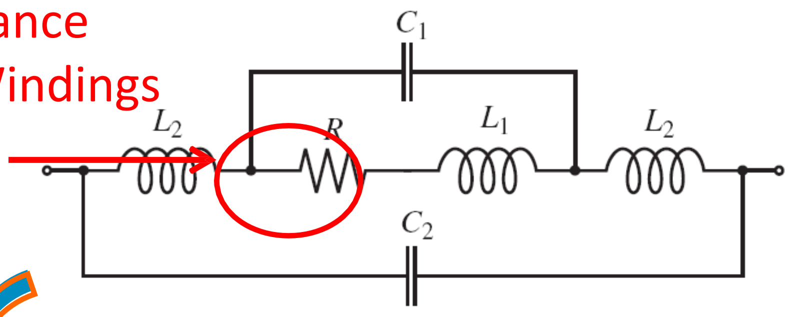
Resistors at High Frequencies

Equivalent Ckt Model:

2. Wire-wound Resistors:



Capacitance between Windings

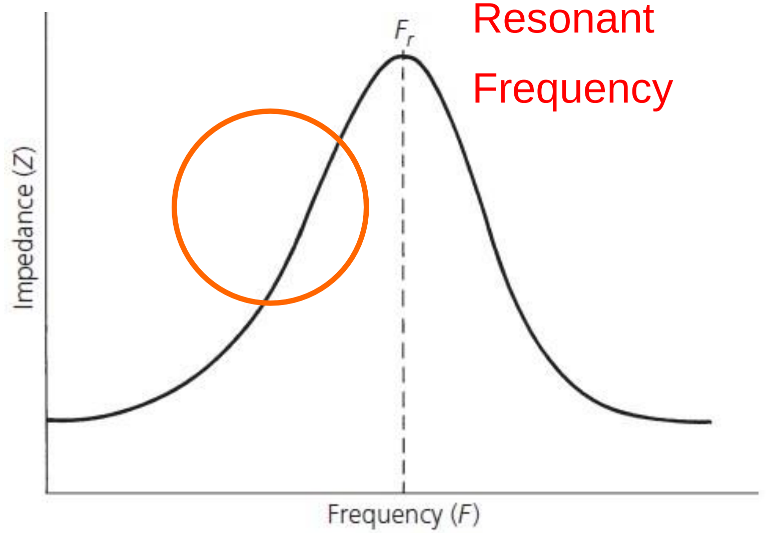


L_2: lead inductance

L_1: inductance of resistive wires

C_2: Interlead Capacitance

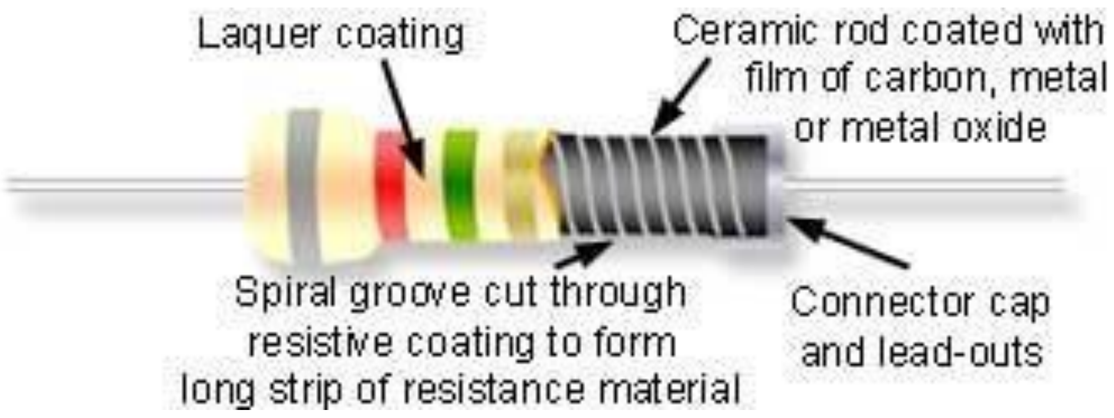
- Exhibit widely varying impedances over various frequencies.
- The inductor L is much larger here as compared to carbon-composition resistor.
- These resistors look like inductors → impedances will increase with increase in frequency.
- At some frequency F_r, the inductance will resonate with shunt capacitance →leads to decrease in impedance.



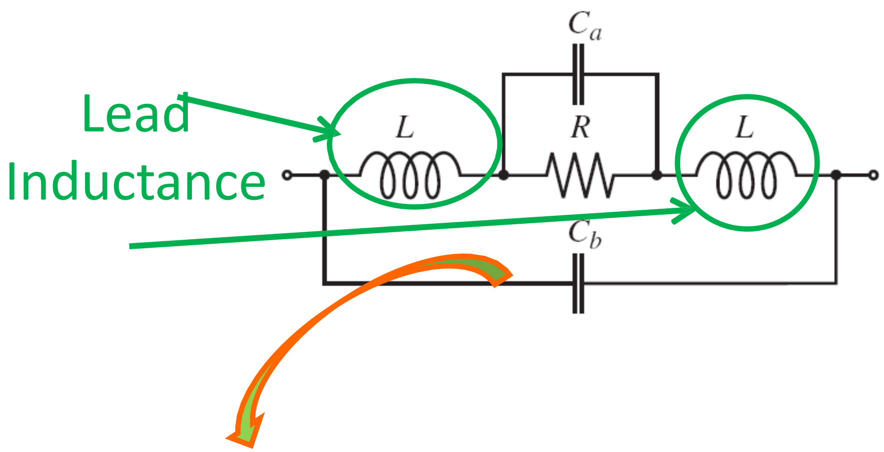
Resonant Frequency

Resistors at High Frequencies

3. Metal-film Resistors



Equivalent Ckt Model:



C_a models charge separation effects and C_b models interlead capacitance

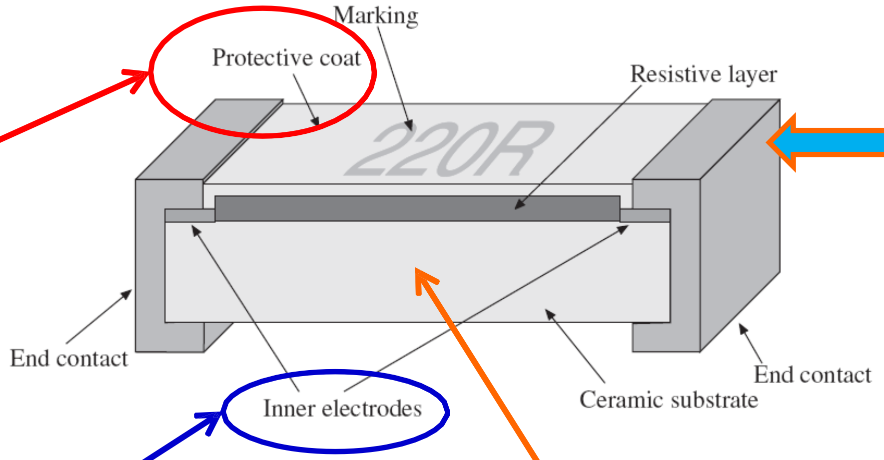
- Seem to exhibit very good characteristics over frequency.
- Values of L and C are much smaller as compared to wire-wound and carbon-composition resistors.
- It works well up to 10 MHz → useful up to 100 MHz

Resistors at High Frequencies

4. Thin-film Chip Resistors:

- The idea is to eliminate or reduce the stray capacitances associated with the resistors
- Good enough upto 2 GHz

Protective coat prevents variations from any environmental interferences



The end contacts are required for soldering purposes

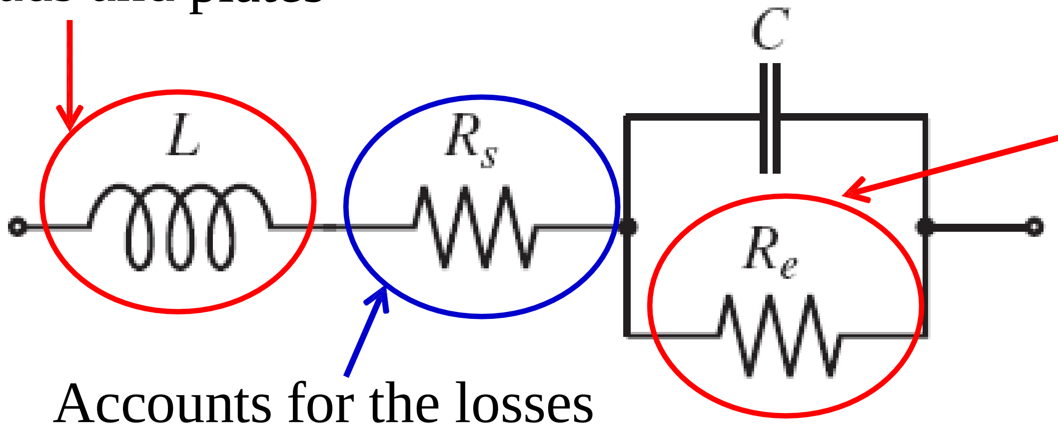
These electrodes are inserted after trimming the resistive layer to the desired value

A metal film (usually nichrome) layer is deposited on this ceramic substrate → this layer works as resistor

Capacitors at High Frequencies

Equivalent Circuit Representation of a capacitor → for a parallel plate

Inductance of the leads and plates



Represents Insulation Resistance

Accounts for the losses in the leads

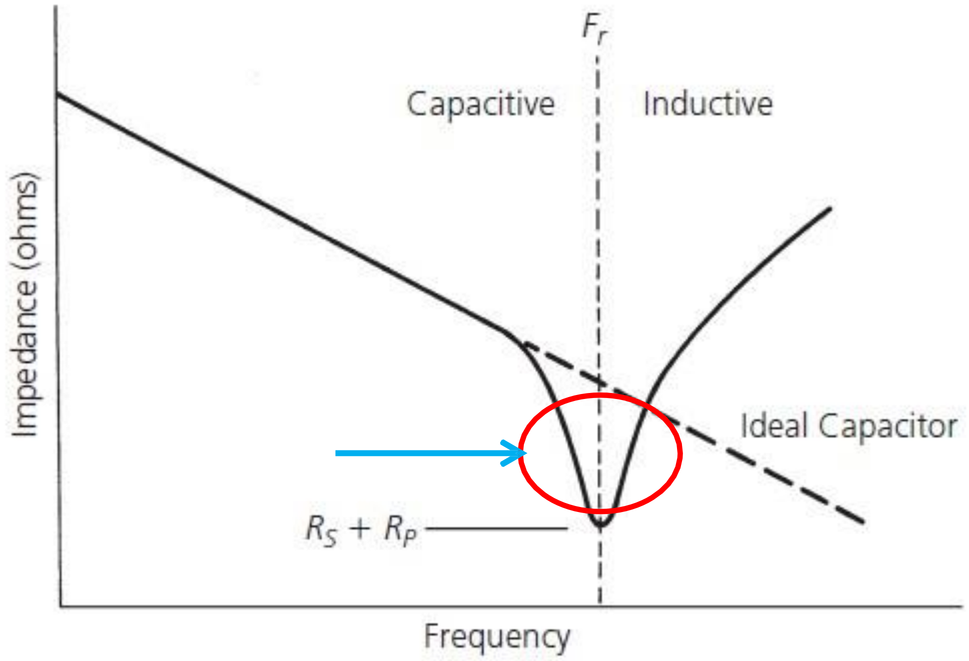
$$C = \frac{\varepsilon A}{d} = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

At high frequency, the dielectric become lossy i.e., there is conduction current through it

Then impedance of capacitor becomes a parallel combination of C and conductance G_e

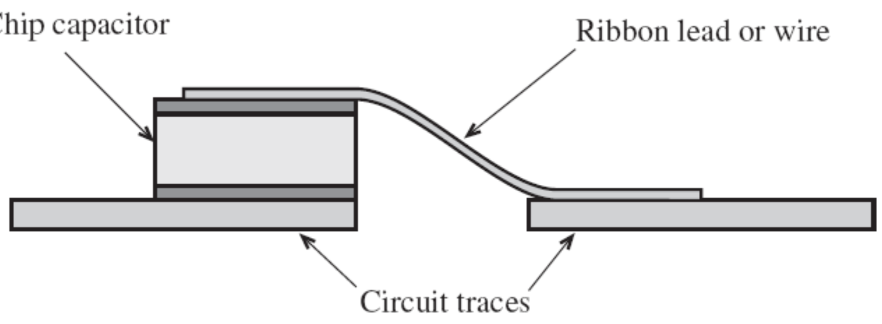
Capacitors at High Frequencies (contd)

Presence of resonance due to dielectric loss and finite lead wires

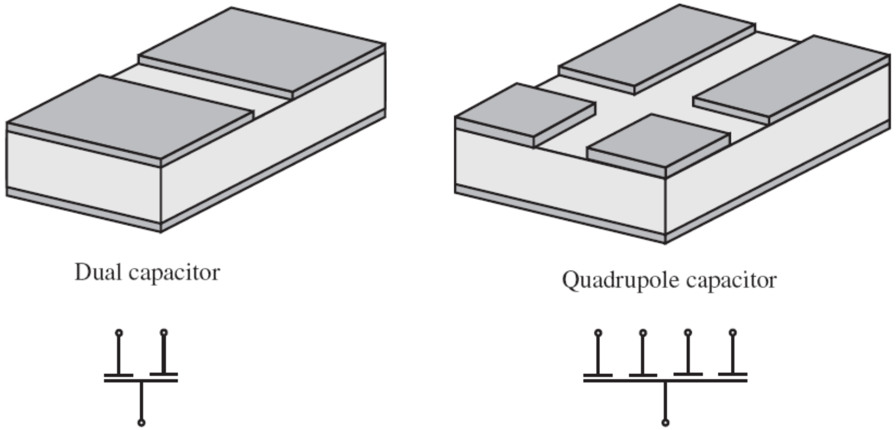


- Above F_r, the capacitor behaves as an inductor.
- In general, larger-value capacitors tend to exhibit more internal inductance than smaller-value capacitors.
- Therefore, it may happen that a $0.1\mu F$ may not be as a good as a $300pF$ capacitor in a bypass application at $250\ MHz$.
- The issue is due to significance of lead inductances at higher frequencies.

Capacitors at High Frequencies (contd)

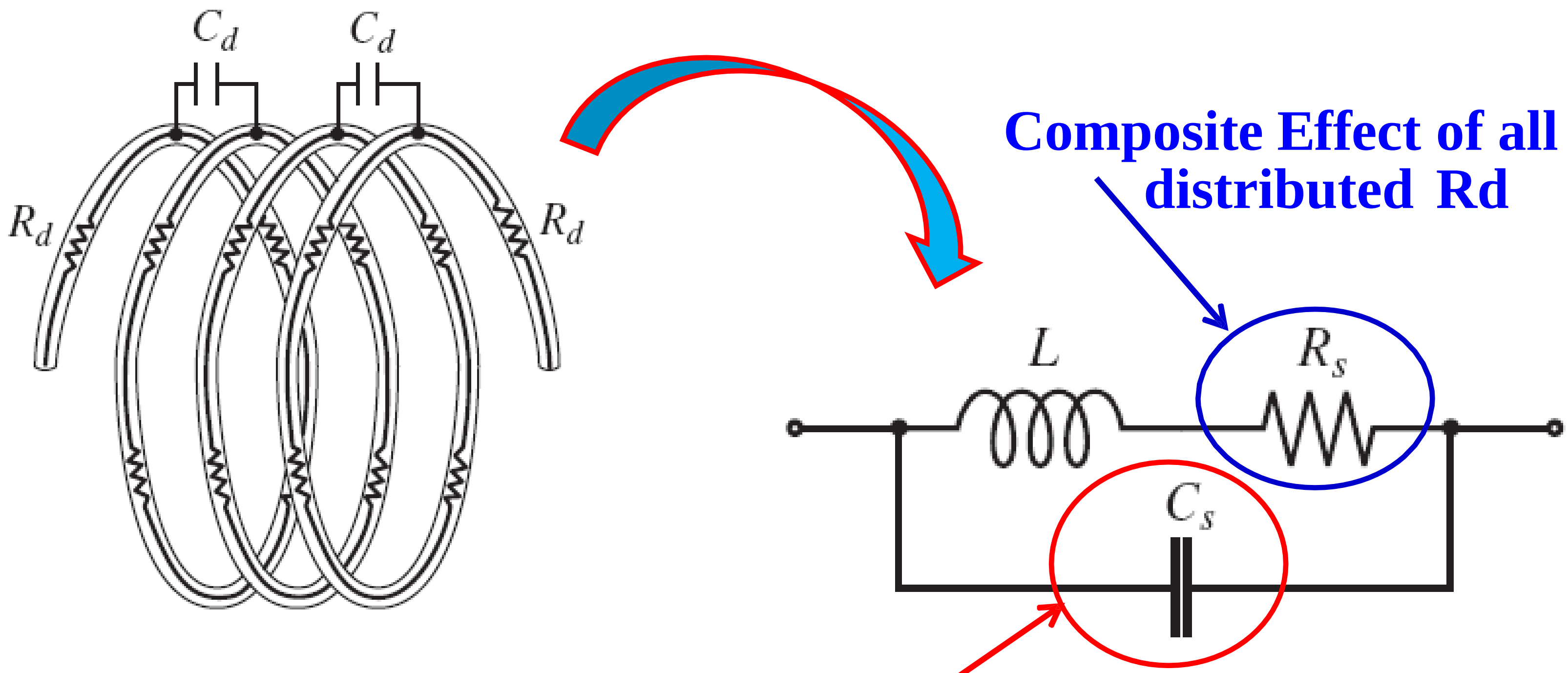


Cross-section of a single-plate capacitor connected to the board



Inductors at High Frequencies

Equivalent circuit representation of an inductor → coil type

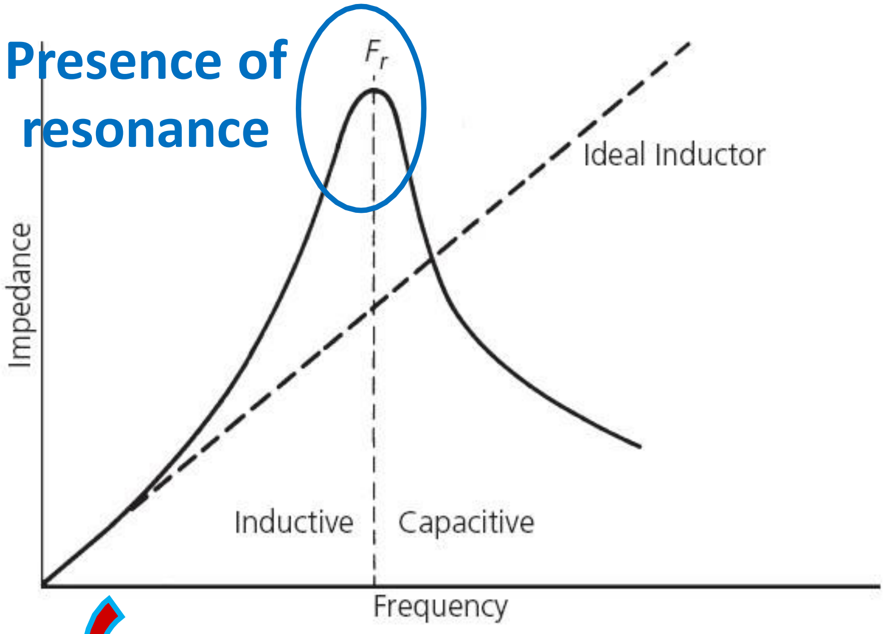


Composite Effect of all the distributed Rd

Composite Effect of all the distributed C_d

Inductors at High Frequencies (contd)

Presence of resonance

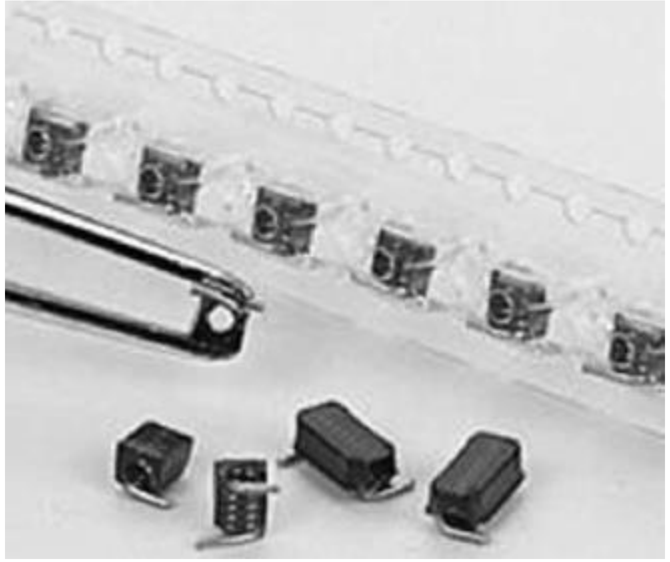


- Initially the reactance of inductor follows the ideal but soon departs from it and increases rapidly until it reaches a peak at the inductor's resonant frequency (F_r). **Why?**
- Above Fr, the inductor starts to behave as a capacitor.

Implement this in MATLAB or ADS

HW#0

Chip inductors



Surface mounted inductors still come as wire-wound coil →these are comparable in size to the resistors and capacitors

Properties of S- parameters.

(i) Zero diagonal elements for perfect matched network

For an ideal N- port network with matched termination, $\boxed{S_{ii} = 0,}$ since there is no reflection from any port. Therefore, under perfect matched conditions the diagonal elements of [S] are zero.

(ii) Symmetry of [S] for a reciprocal network

A reciprocal device has the same transmission characteristics in either direction of a pair of ports and is characterised by a symmetric scattering matrix, $S_{ij} = S_{ji}$ $(i \neq j)$, which results to,

$$[S]_t = [S] \rightarrow (\text{Transpose of } [S] = [S])$$

$$[S]^T = [S]$$

proof :-

For a reciprocal network, the impedance matrix equation is,

$$[V] = [Z][I]$$

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

$$[a] + [b] = [Z][a] - [Z][b]$$

$$[b] + [z][b] = [z][a] - [a]$$

$$[b](1 + [z]) = [a]([z] - 1)$$

$$[b] = \{(1 + [z])^{-1}([z] - 1)\}[a] \quad -①$$

General form of [S] equation,

$$[b] = [S][a] \quad -②$$

From ① and ②,

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

[1] can be replaced by [U], where [U] is unitary matrix.

$$[S] = ([U] + [z]^{-1})([z] - [U]) \quad -③$$

$$[R] = [z] - [U], \quad [Q] = [z] + [U]$$

For reciprocal network, the z-matrix is symmetric.

Hence,

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

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

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

Transpose of [S] is,

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

Since the Z-matrix is symmetrical,

$$([Z]-[U])_t = [Z]-[U]$$

$$([Z]+[U])_t = [Z]+[U]$$

Therefore,

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

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

$$= [S]$$

Thus, it is proved that $[S]_t = [S]$, for a symmetric junction.

(iii) Unitary property of a lossless junction

For any lossless network, the sum of products of each term of any one row or of any column of the S-matrix multiplied by its complex conjugate is unity

For a lossless n-port device, the total power leaving N-ports must be equal to the total power input to these ports, Hence,

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

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

If all $a_n = 0$ except a_i,

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

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

Therefore for a lossless junction

$$\boxed{\sum_{n=1}^{N} S_{ni} . S_{ni}^* = 1} \quad - \text{①}$$

If all $a_n = 0$, except a_i and a_k,

$$\boxed{\sum_{n=1}^{N} S_{nk} . S_{ni}^* = 0; \quad i \neq k} \quad - \text{②}$$

In matrix form,

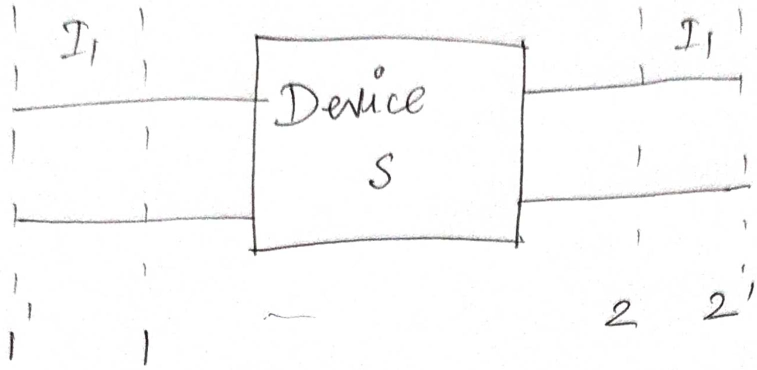
$$[S^*][S]_t = [U]$$

$$\boxed{[S^*] = [S]_t^{-1}} \quad - \text{③}$$

Where $[U]$ is the unitary matrix

A matrix $[S]$ for lossless network which satisfies the above ①, ② and ③ conditions is called as unitary matrix.

(iv) phase shift property



For the two-port network with unprimed reference planes 1 and 2, S-parameters will have definite complex values.

If the reference planes 1 and 2 are shifted outward to 1' and 2' by electrical phase shifts $\phi_1 = \beta_1 l_1$ and $\phi_2 = \beta_2 l_2$ respectively, then the new wave variables are $a_1 e^{j\phi_1}$, $b_1 e^{-j\phi_2}$, $a_2 e^{j\phi_2}$, $b_2 e^{-j\phi_2}$. The matrix S' is given by,

$$[S'] = \begin{bmatrix} e^{-j\phi_1} & 0 \\ 0 & e^{-j\phi_2} \end{bmatrix} [S] \begin{bmatrix} e^{-j\phi_1} & 0 \\ 0 & e^{-j\phi_2} \end{bmatrix}$$

This property is applicable to any no of ports.

Problems on S- parameters.

1. The S- Matrix of a two port network is given by, $[S] = \begin{bmatrix} 0.2\angle 0 & 0.9\angle 90 \\ 0.9\angle 90 & 0.1\angle 90 \end{bmatrix}$

Find whether the given network is reciprocal and loss less n/w.

i) Given,

$$[S] = \begin{bmatrix} 0.2\angle 0 & 0.9\angle 90 \\ 0.9\angle 90 & 0.1\angle 90 \end{bmatrix}$$

$$[S]^T = \begin{bmatrix} 0.2\angle 0 & 0.9\angle 90 \\ 0.9\angle 90 & 0.1\angle 90 \end{bmatrix}$$

$$= [S]$$

Hence, the given network is reciprocal.

(ii) For a lossless network,

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

This condition has to be checked for individual rows.

For 1st row,

$$|S_{11}|^2 + |S_{12}|^2 = 1.$$

$$(0.2)^2 + (0.9)^2 = 0.04 + 0.81 = 0.85 \neq 1$$

Hence, the given network is lossy network

Q. The S-~~param~~ Matrix of a four port network is given by,

$$[S] = \begin{bmatrix} 0.1\angle 90 & 0.8\angle 45 & 0.3\angle 90 & 0 \\ 0.8\angle 45 & 0 & 0 & 0.4\angle 45 \\ 0.3\angle 45 & 0 & 0 & 0.6\angle 45 \\ 0 & 0.4\angle 45 & 0.6\angle 45 & 0 \end{bmatrix}$$

Find given network is whether lossless and reciprocal.

(i) If $[S]^T = [S]$, the network is reciprocal network.

$$[S^T] = \begin{bmatrix} 0.1\angle 90 & 0.8\angle 45 & 0.3\angle 45 & 0 \\ 0.8\angle 45 & 0 & 0 & 0.4\angle 45 \\ 0.3\angle 90 & 0 & 0 & 0.6\angle 45 \\ 0 & 0.4\angle 45 & 0.6\angle 45 & 0 \end{bmatrix}$$

$$\neq [S].$$

Hence, the network is not reciprocal.

(ii) For lossless network,

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

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

Network is lossy network because, $\sum_{n=1}^{N} |S_{ni}|^2 \neq 1$.

$\therefore$ For 1st row,

$$|S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 + |S_{14}|^2 = 0.5 \neq 1$$

$$(0.1)^2 + (0.8)^2 + (0.3)^2 + 0 = 0.01 + 0.4 + 0.09 = 0.5 \neq 1$$

3. The S- Matrix of a two port network is given by,

$$[S] = \begin{bmatrix} 0.15\angle 0 & 0.85\angle -45 \\ 0.85\angle 45 & 0.2\angle 0 \end{bmatrix}$$

Find, whether the network is,

(i) Reciprocal

(ii) Lossless.

Also find,

(iii) If port 2 is terminated with matched load, find return loss at port 1.

(i) For a reciprocal network,

$$[S]^T = [S].$$

$$[S]^T = \begin{bmatrix} 0.15\angle 0 & 0.85\angle 45 \\ 0.85\angle -45 & 0.2\angle 0 \end{bmatrix}$$

$$\neq [S]$$

Hence, the network is not reciprocal.

(ii) For a lossless network.

$$\sum_{n=1}^{N} |S_{ni}|^2 = 1.$$

$$(0.15)^2 + (0.85)^2 = 0.745 \neq 1.$$

Hence, network is a lossy network.

(iii) If port 2 is terminated with matched load, find return loss at port 1.

For two port network,

$$b_1 = a_1 S_{11} + a_2 S_{12}$$

$$b_2 = a_1 S_{21} + a_2 S_{22}.$$

If port 2 is terminated with matched load, $a_2 = 0$ ($\because$ Diagonal elements of $[S]$ is zero for network with perfect matched termination).

$\therefore$ Return Loss $\Gamma_1 = \dfrac{b_1}{a_1} = S_{11} = 0.15$

$$RL = -20 \log |\Gamma_1|.$$

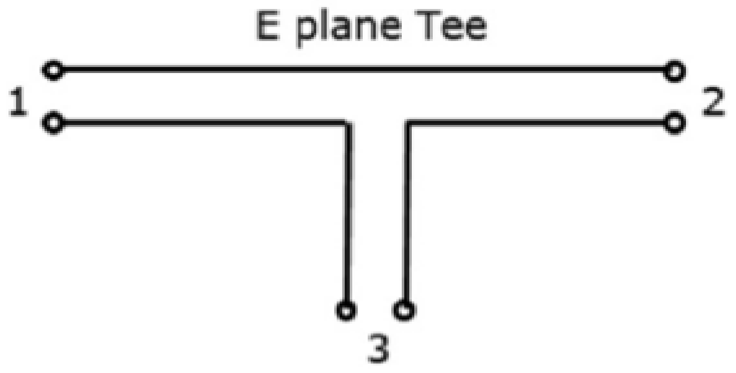
$$= -20 \log |0.15|$$

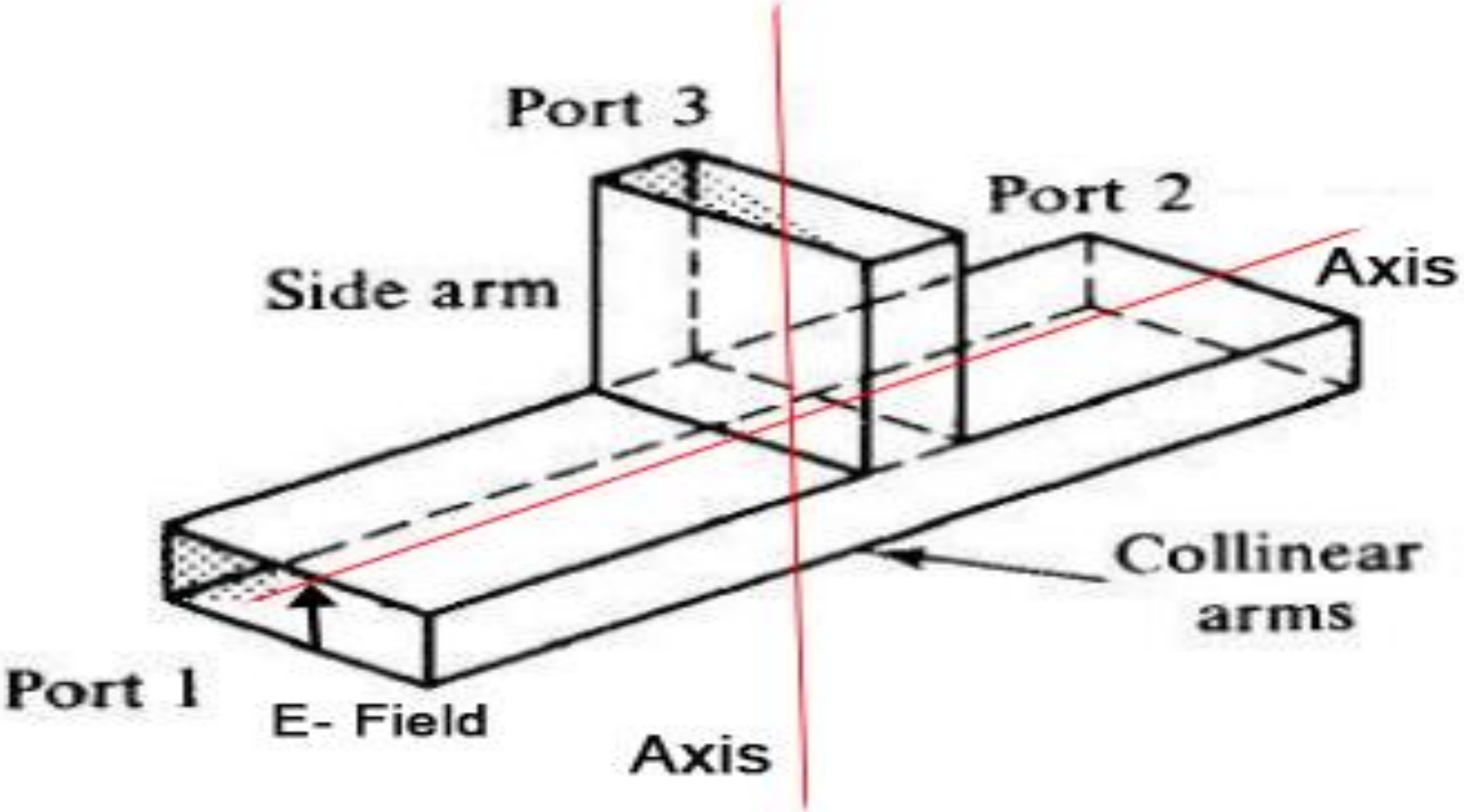
$$= 16.47 \text{ dB}.$$

UNIT 2

E-PLANE TEE – PRINCIPLE AND WORKING

- 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
- Port 1 and 2 of the rectangular waveguide is called as collinear arms
- Port 3 is called as side arm
- E-Plane tee is also called as series Tee.





Port 3
Port 2
Axis
Side arm
Collinear
arms
Port 1
E- Field
Axis

- 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.

S-MATRIX DERIVATION OF E-PLANE TEE

(i) The S-Matrix of an E-plane tee will be a 3x3 matrix since there are three ports.

$$[S] = \begin{bmatrix} S11 & S12 & S13 \\ S21 & S22 & S23 \\ S31 & S32 & S33 \end{bmatrix} \text{........ Equation 1}$$

(ii) According to phase shift of 180 deg between two collinear arms,

Scattering coefficients $S23 = -S13$ are out of phase by 180° with an input at port 3.

(iii) From the symmetric property, since all the three ports are symmetric,

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

Port 1 is symmetric to port 2,

$$S_{12}=S_{21}$$

Port 2 I symmetric to port 3,

$$S_{23}=S_{32}$$

Port 3 is symmetric to port 1,

$$S_{13}=S_{31}$$

(iv) Port 3 is perfectly matched,

Therefore, $S_{33} = 0.$

Hence, Now, the [S] matrix can be written as,

$$[S] = \begin{bmatrix} S11 & S12 & S13 \\ S12 & S22 & -S13 \\ S13 & -S13 & 0 \end{bmatrix} \text{........ Equation 2}$$

(v) From the Unitary property , $[S][S]^* = [I]$

$$\begin{bmatrix} S11 & S12 & S13 \\ S12 & S22 & -S13 \\ S13 & -S13 & 0 \end{bmatrix} \begin{bmatrix} S11^* & S12^* & S13^* \\ S12^* & S22^* & -S13^* \\ S13^* & -S13^* & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- Multiplying we get,

$$|S11|^2+|S12|^2+|S13|^2=1\text{........ ....}\textbf{Equation3}$$

$$|S12|^2+|S22|^2+|S13|^2=1\text{........ }\textbf{Equation4}$$

$$|S13|^2+|S13|^2=1\text{........................ }\textbf{Equation5}$$

$$:|S13||S11|^* - |S13||S12|^* = 0\text{...}\textbf{Equation6}$$

$$2|S13|^2=1 \quad \text{OR} \quad S13 = \frac{1}{\sqrt{2}}\text{....... ......}\textbf{Equation7}$$

$$|S11|^2=|S22|^2$$

$$S11=S22\text{....... }\textbf{Equation8}$$

From the Equation 6,

$$S13(S11^{*}\text{-}S12^{*})=0$$

Since,

$S13\neq 0 S11^{*}\text{-}S12^{*}=0$ $S11=S12=S22$....... **Equation9**

Using these in equation 3 and equation 9,

$|S11|^2+|S11|^2+\frac{1}{2}=1$

$$2\,|S11|^2 = 1\;\; S11 = \frac{1}{2} \qquad \text{......... \textbf{Equation 10}}$$

From equation 8 and 9,

$$S12=\frac{1}{2} \qquad \text{......... \textbf{Equation 11}}$$

$$S22=\frac{1}{2} \qquad \text{......... \textbf{Equation 12}}$$

Substituting for S13, S11, S12 and S22 from equation 7 and 10, 11 and 12 in equation 2,
We get,

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

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

$$\begin{bmatrix} b1 \\ b2 \\ b3 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \end{bmatrix} \begin{bmatrix} a1 \\ a2 \\ a3 \end{bmatrix} \text{......... } \textbf{Equation 13}$$

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

$$\text{b1} = \frac{1}{2} a1 + \frac{1}{2} a2 + \frac{1}{\sqrt{2}} a3 \text{......... } \textbf{Equation 14}$$

$$\text{b2} = \frac{1}{2} a1 + \frac{1}{2} a2 - \frac{1}{\sqrt{2}} a3 \text{......... } \textbf{Equation 15}$$

$$\text{b3} = \frac{1}{\sqrt{2}} a1 - \frac{1}{\sqrt{2}} a2 \text{ .... } \textbf{Equation 16}$$

CASE 1)

$a3 \neq 0$, $a1=a2=0$

Input at port3 is nonzero with other inputs are zero.

$b1=\frac{1}{\sqrt{2}}a3 \quad b2 = \frac{1}{\sqrt{2}}a3 \quad b3 = 0$

Let, P3=P1+P2=2P1=2P2

The amount of power coming out of port1 or port2 due to input at port3 is given by

$$P=10\log_{10}\frac{P1}{P2}$$

$$P=10\log_{10}\frac{P1}{2P1}$$

$$\boxed{\mathbf{P= -3db}}$$

CASE 2)

$$a3=0 \quad \& \quad a1=a2=a$$

i.e. input at port 3 is zero with same input at port1 &port2

Put in equation 14, 15, 16 we get,

b1=a b2=a & b3=0

Equal input at port1 and port2 results no output at port3.

CASE 3)

$$a1 \neq 0 a2=a3=0$$

Input at port1 is nonzero with other inputs are zero.

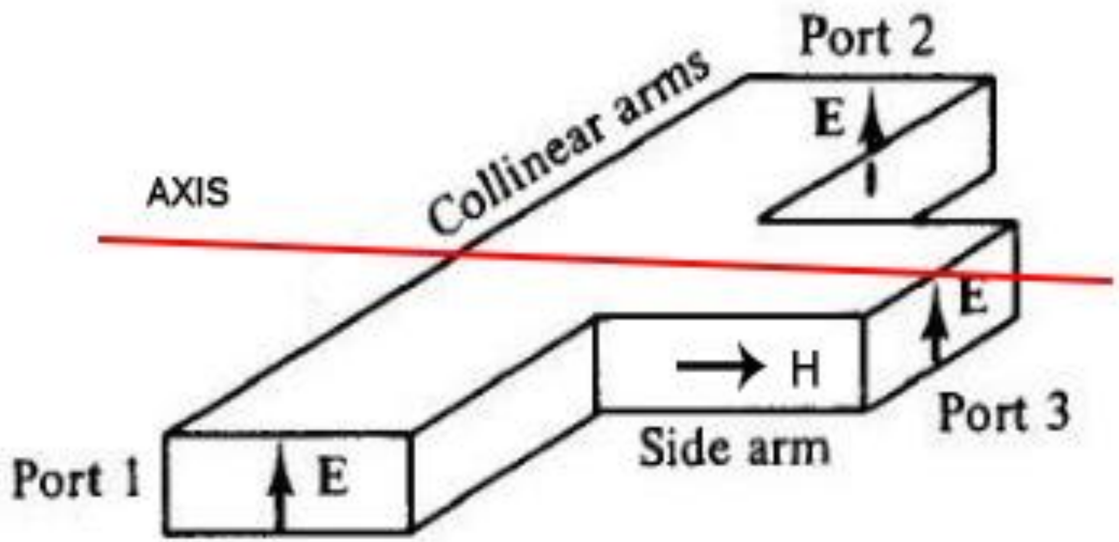
Putting these values in equation.

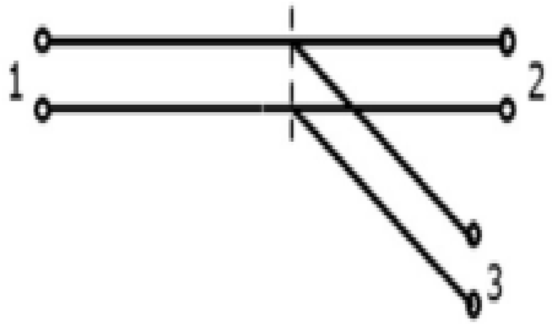
$$b1=\frac{1}{2}a1 \qquad b2=\frac{1}{2}a1 \qquad b3=\frac{1}{\sqrt{2}}a1$$

Similarly it can be taken for all possible combinations of input and output.

H-PLANE TEE

- An H-Plane Tee junction is formed by cutting narrower dimension of main waveguide and attaching a side arm.
- 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 parallel to the magnetic field, this junction is called H-Plane Tee junction.


Port 2
Collinear arms
AXIS
E
E
H
Side arm
Port 3
Port 1
E


1
2
3

The properties of H-Plane Tee can be defined by its [S] matrix.

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

$$[S] = \begin{bmatrix} S11 & S12 & S13 \\ S21 & S22 & S23 \\ S31 & S32 & S33 \end{bmatrix} \text{........ } \textbf{Equation 1}$$

- From the symmetric property,

$$Sij=Sji$$

$$S12=S21S23=S32=S13 \quad S13=S31$$

- Input given at port 3 will be equally split across port 1 and 2 with same phase difference.

$$S13 = S23$$

The port is perfectly matched

$$S33=0$$

Now, the [S] matrix can be written as,

$$[S] = \begin{bmatrix} S11 & S12 & S13 \\ S12 & S22 & S13 \\ S13 & S13 & 0 \end{bmatrix} \text{........ } \textbf{Equation 2}$$

From the Unitary property

$$[S][S]^{*}=[I]$$

$$[S] = \begin{bmatrix} S11 & S12 & S13 \\ S12 & S22 & S13 \\ S13 & S13 & 0 \end{bmatrix} \begin{bmatrix} S11^{*} & S12^{*} & S13^{*} \\ S12^{*} & S22^{*} & S13^{*} \\ S13^{*} & S13^{*} & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$|S11||S11|^{*}+|S12||S12|^{*}+|S13||S13|^{*}=1$$

$|S11|^2+|S12|^2+|S13|^2=1$........ **Equation3**

R2C2: $|S12|^2+|S22|^2+|S13|^2=1$........ **Equation4**

R3C3: $|S13|^2+|S13|^2=1$........ **Equation5**

R3C1: $|S13||S11|^{*}+|S13||S12|^{*}=0$....... **Equation6**

$2|S13|^2=1$ OR $S13=\frac{1}{\sqrt{2}}$....... **Equation7**

$|S11|^2=|S22|^2$

$S11=S22$....... **Equation8**

From the Equation 6,

$$S13(S11^{*}+S12^{*})=0$$

Since, $S13\neq0$, $S11^{*}+S12^{*}=0$ OR $S11^{*}=-S12^{*}$

OR

$S11=-S12 \text{ or } S12=-S11$ **Equation9**

Using these in equation 3,

Since, $S13\neq0$, $S11^{*}+S12^{*}=0$ OR $S11^{*}=-S12^{*}$

$|S11|^{2}+|S11|^{2}+\frac{1}{2}=1 \quad 2|S11|^{2}=1 \quad S11=\frac{1}{2}$......... **Equation 10**

From equation 8 and 9,

$S12=-\frac{1}{2}$......... **Equation 11**

$S22=\frac{1}{2}$......... **Equation 12**

- Substituting for S13, S11, S12 and S22 from equation 7 and 10, 11 and 12 in equation 2,We get

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

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

$$\begin{bmatrix} b1 \\ b2 \\ b3 \end{bmatrix}=\begin{bmatrix} \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \end{bmatrix}\begin{bmatrix} a1 \\ a2 \\ a3 \end{bmatrix} \text{......... } \textbf{Equation 13}$$

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

$$b1 = \frac{1}{2}a1 - \frac{1}{2}a2 - \frac{1}{\sqrt{2}}a3 \text{......... } \textbf{Equation 14}$$

$$b2 = -\frac{1}{2}a1 + \frac{1}{2}a2 + \frac{1}{\sqrt{2}}a3 \text{......... } \textbf{Equation 15}$$

$$b3 = \frac{1}{\sqrt{2}}a1 + \frac{1}{\sqrt{2}}a2 \text{......... } \textbf{Equation 16}$$

CASE 1) $a3 \neq 0$, $a1=a2=0$

$$\mathbf{b1} = -\frac{1}{\sqrt{2}}\mathbf{a3} \quad \mathbf{b2} = \frac{1}{\sqrt{2}}\mathbf{a3} \quad \mathbf{b3 = 0}$$

Let, P3=P1+P2=2P1=2P2

The amount of power coming out of port1 or port2 due to input at port3 is given by

$$P=10\log_{10}\frac{P1}{P2}; \quad P=10\log_{10}\frac{P1}{2P1}$$

$$\boxed{\mathbf{P = -3dB}}$$

This shows that, H-Plane tee acts as a 3dB power splitter. Power fed at port 3 is equally divided in port 1 and port 2.

CASE 2) $a3 = 0$, $a1=a2=a$

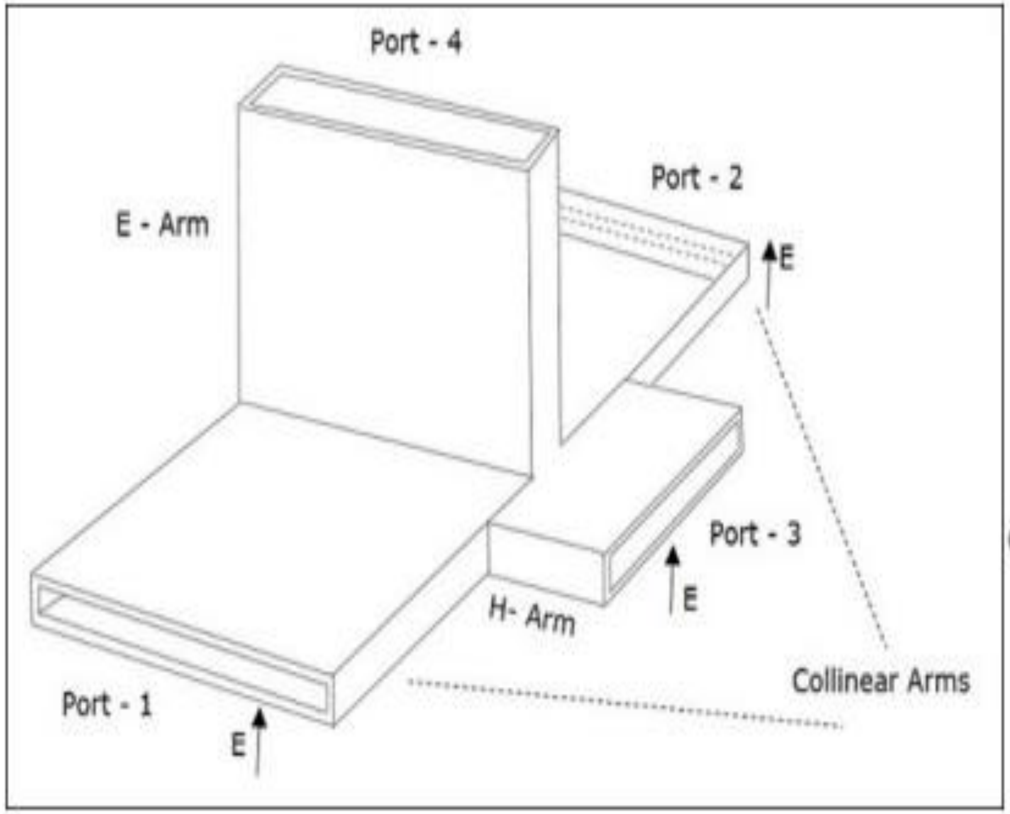
Input at port3 is zero with some input at port1 and port2.

Putting these values in equation.

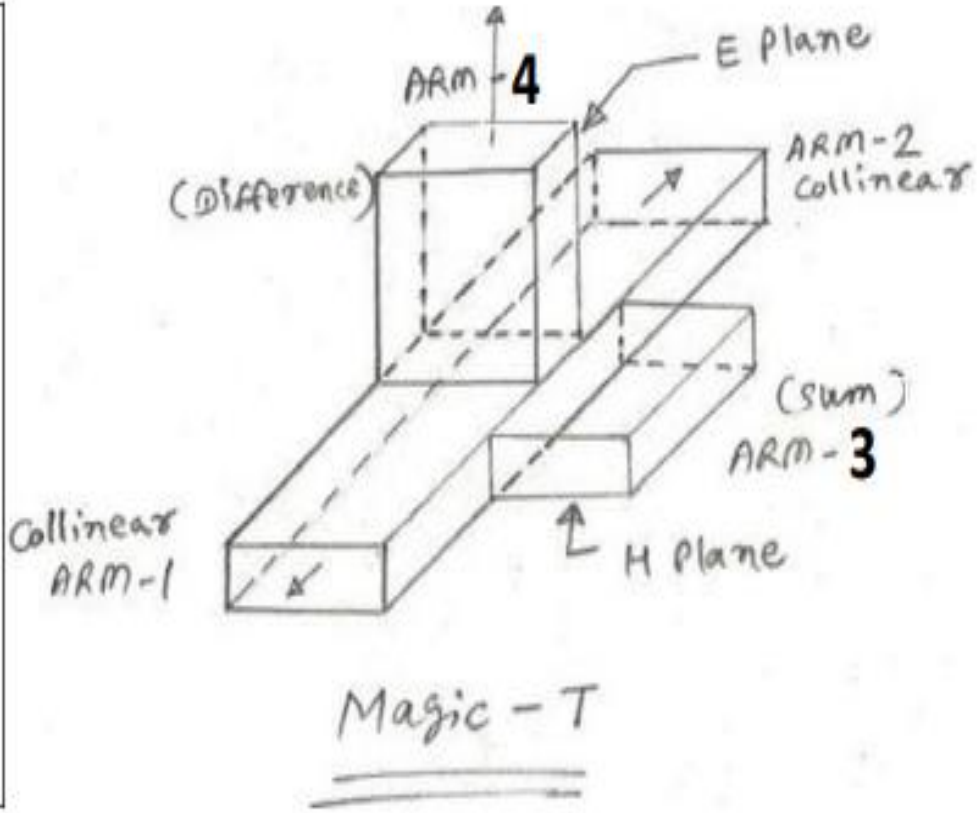
$$b1=0,\ b2=0\ ,\ b3 = \frac{1}{\sqrt{2}} a1 + \frac{1}{\sqrt{2}} a2$$

The output at port3 is addition of two input of port1 and port2.

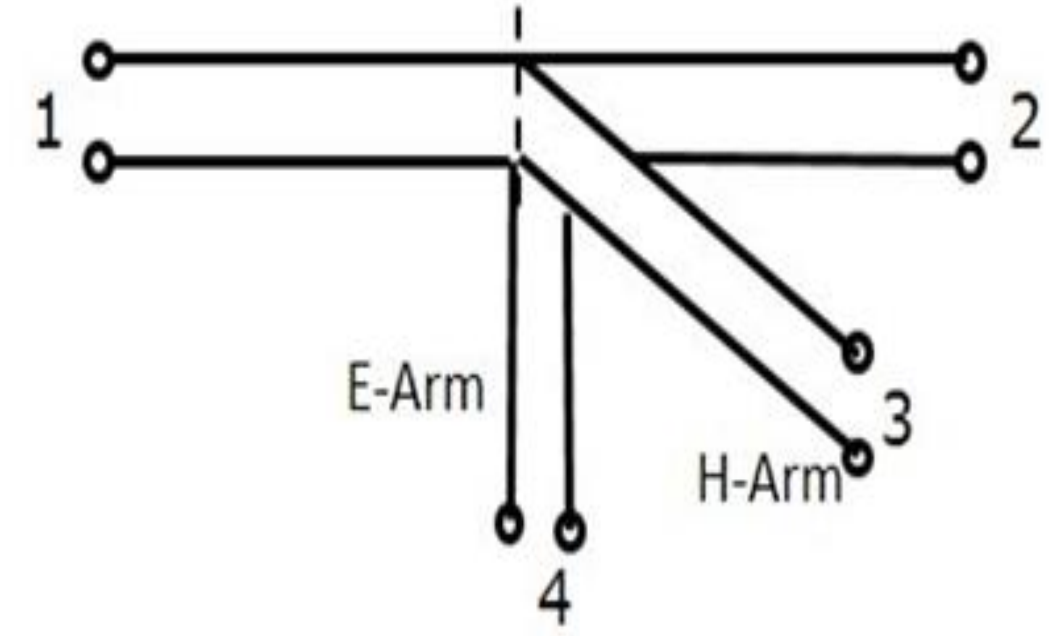
Magic Tee



Port - 4
E - Arm
Port - 2
E
Port - 3
E
H- Arm
Collinear Arms
Port - 1
E



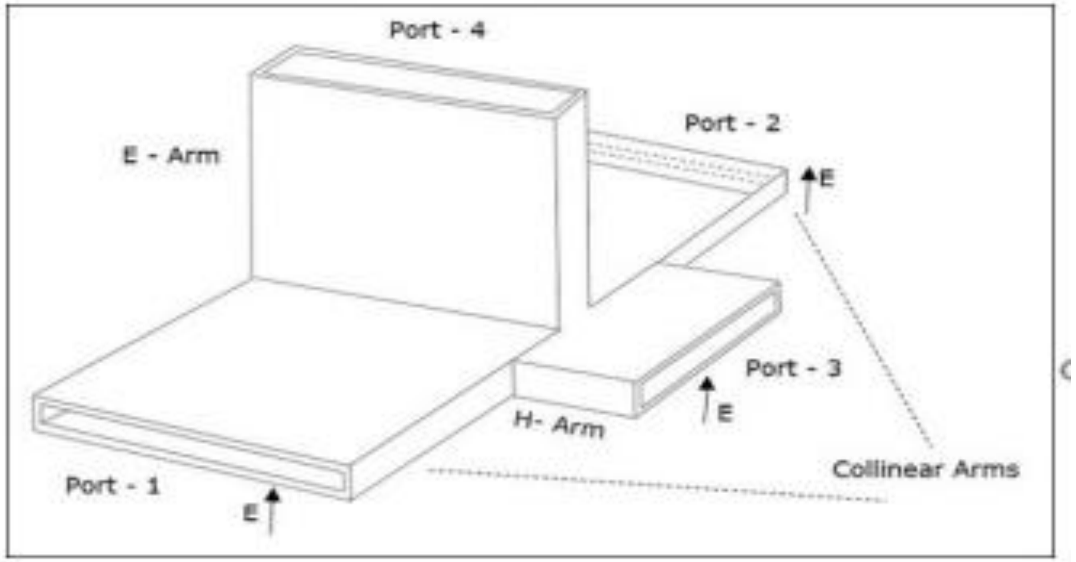
ARM 4
E Plane
ARM-2
collinear
(Difference)
(sum)
ARM-3
Collinear
ARM-1
H Plane
Magic - T



Magic Tee junction

Magic Tee

- Magic Tee is the combination of E and H Plane tee. Hence called as hybrid arm.
- Magic Tee will have the both E arm
- Hence magic tee will have four po



- Port 1 and 2 are collinear arms
- Port 3 is the difference arm
- Port 4 is the additive arm.

- E_H plane Tee is formed by cutting width and breadth of rectangular waveguide & attaching another waveguides
- Magic tee will four ports. Hence S-Matrix will be a square matrix of order 4.

$$[S]=\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} ---(1)$$

- Because of H-plane tee junction

$$S_{23} = S_{13}$$

- Because of E-plane tee junction

$$S_{24} = -S_{14}$$

- Outputs at ports 1 & 2 are phase shifted by 180 deg with respect to port 4
- Ports 3 and 4 are isolated out of each other.

$$S_{34} = S_{43} = 0 \quad \text{---(4)}$$

From symmetric property $S_{ij} = S_{ji}$, we have

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

$S_{24} = S_{42} = - S_{14}$; $S_{41} = S_{14}$ ----(5)

If ports 3 and 4 are perfectly matched then we have

$S_{33} = S_{44} = 0$ ----(6)

Putting above values of S parameters in matrix (1), we get,

$$[S]=\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{12} & S_{22} & S_{13} & -S_{14} \\ S_{13} & S_{13} & 0 & 0 \\ S_{14} & -S_{14} & 0 & 0 \end{bmatrix}---(7)$$

From unitary property [S][S]*=[I]

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{12} & S_{22} & S_{13} & -S_{14} \\ S_{13} & S_{13} & 0 & 0 \\ S_{14} & -S_{14} & 0 & 0 \end{bmatrix}\begin{bmatrix} S_{11}^* & S_{12}^* & S_{13}^* & S_{14}^* \\ S_{12}^* & S_{22}^* & S_{13}^* & -S_{14}^* \\ S_{13}^* & S_{13}^* & 0 & 0 \\ S_{14}^* & -S_{14}^* & 0 & 0 \end{bmatrix}=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Multiplying we get,

$$R_1C_1 : |S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 + |S_{14}|^2 = 1 --- (8)$$

$$R_2C_2 : |S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 + |S_{14}|^2 = 1 --- (9)$$

$$R_3C_3 : |S_{13}|^2 + |S_{13}|^2 = 1 --- (10)$$

$$R_4C_4 : |S_{14}|^2 + |S_{14}|^2 = 1 --- (11)$$

From eq'^{n} (10) and (11), we get

$$|S_{13}|^2 + |S_{13}|^2 = 1 --- (10)$$

$$\Rightarrow 2|S_{13}|^2 = 1$$

$$\Rightarrow \quad 2|S_{13}|^2 = 1$$

$$\Rightarrow S_{13} = \frac{1}{\sqrt{2}} ---(12)$$

$$|S_{14}|^2 + |S_{14}|^2 = 1 ---(11) \Rightarrow 2|S_{14}|^2 = 1$$

$$\Rightarrow S_{14} = \frac{1}{\sqrt{2}} ---(13)$$

Comparing eq'n (8) and (9), we get,

$$S_{11} = S_{22} ---(14)$$

R4C1: S14(S11* - S12*) = 0

S11* - S12*) = 0

S11 = S12 - Eqn 15

- Sub S11 = S12 in eqn 8,
- S11 =0.
- If S11 = 0, then S12= S21 = 0. (Which means port 1 and 2 are also isolated).

Putting all the values of scattering parameters, we get

$$[S] = \begin{bmatrix} 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 \end{bmatrix} --- (17)$$

We have [b]=[S][a]

$$\Rightarrow \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} --- (18)$$

$$b_1 = \frac{1}{\sqrt{2}}(a_3 + a_4) \,\&\, b_3 = \frac{1}{\sqrt{2}}(a_1 + a_2) \quad --- (19)$$

$$b_2 = \frac{1}{\sqrt{2}}(a_3 - a_4) \,\&\, b_4 = \frac{1}{\sqrt{2}}(a_1 - a_2)$$

Case 1. $a_3 \neq 0$ & $a_1 = a_2 = a_4 = 0$; Putting these values in eq'n (19), we get,

$$b_1 = \frac{1}{\sqrt{2}}(a_3 + a_4) \Rightarrow b_1 = \frac{a_3}{\sqrt{2}}$$

$$b_2 = \frac{1}{\sqrt{2}}(a_3 - a_4) \Rightarrow b_2 = \frac{a_3}{\sqrt{2}}$$

$$b_3 = \frac{1}{\sqrt{2}}(a_1 + a_2) \Rightarrow b_3 = 0$$

$$b_4 = \frac{1}{\sqrt{2}}(a_1 - a_2) \Rightarrow b_4 = 0$$

Case 2. $a_4 \neq 0$ & $a_1 = a_2 = a_3 = 0$

Putting these values in eq'n (19), we get

$$b_1 = \frac{a_4}{\sqrt{2}}; b_2 = -\frac{a_4}{\sqrt{2}}; b_3 = b_4 = 0$$

This gives property of E plane tee.

Case 3. $a_1 \neq 0$ & $a_2=a_3=a_4= 0$; Putting these values in eq'n(19), we get

$$b_1 = 0; b_2 = 0; b_3 = \frac{a_1}{\sqrt{2}}; b_4 = \frac{a_1}{\sqrt{2}}$$

i. When power is fed into port 1, nothing comes out of port 2 even though theyare collinear ports.
ii. Hence port 1 and 2 are called isolated ports.
iii. No output at collinear ports hence ***magic***.

Case 4. $a_3=a_4$ & $a_1= a_2 = 0$

Putting these values in eq'n (19), we get

$$b_1 = \frac{1}{\sqrt{2}}(2a_3); b_2 = 0; b_3 = b_4 = 0$$

a) Gives additive property.
b) Equal inputs at port 3 and 4 gives output at port 1 in phase and in equal magnitude.

Case 5. $a_1=a_2$ $a_3=a_4= 0$; Putting these values in eq'^n (19), we get

$$b_1 = 0 = b_2 = b_4 ; b_3 = \frac{1}{\sqrt{2}}(2a_1)$$

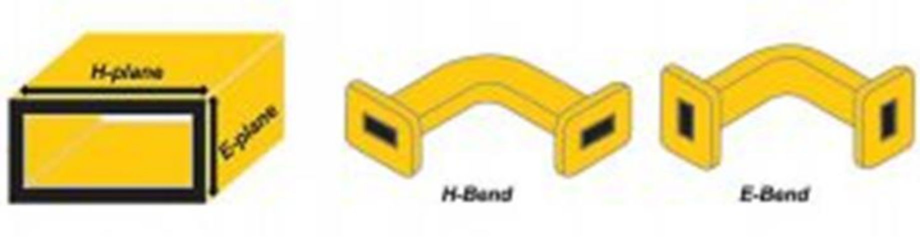
That is equal input at ports 1 and 2 results in an output at port 3 and no output at ports 1, 2 and 4.

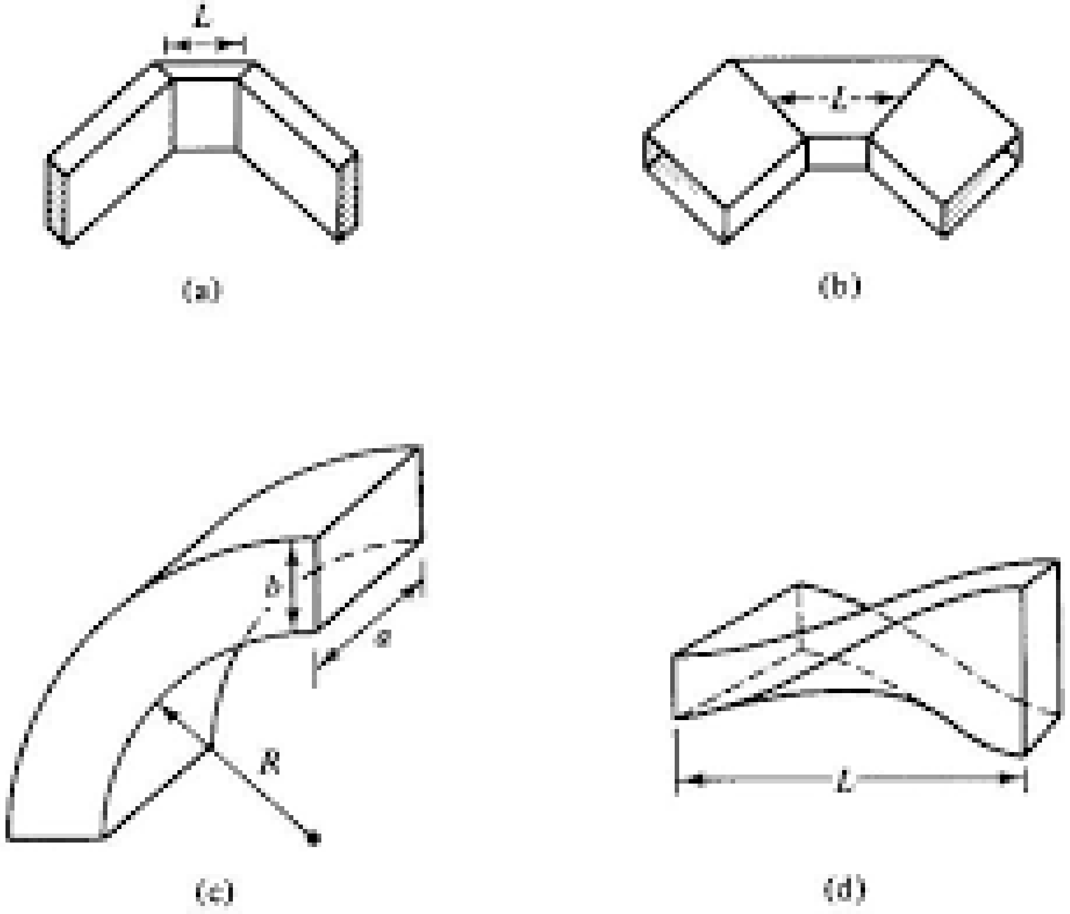
Applications

- Isolator
- Matching device
- Phase shifter
- Duplexer
- Mixer.

WAVEGUIDE CORNERS BENDS AND TWISTS

- The Waveguide E and H plane corners and bends are used to alter the direction of the guide to any convenient angle.
- A Waveguide twists is used to change the polarization of propagating wave by 90 degrees.
- The length of the corners bends and twist will be equal to the odd multiple of quarter guide wavelength. It is chosen so to reduce the amount of reflections due to discontinuities.





$$R = 1.5b \qquad \text{for an } E \text{ bend}$$

$$R = 1.5a \qquad \text{for an } H \text{ bend}$$

$$L = (2n + 1)\frac{\lambda_g}{4}$$

Phase shifter

Definition

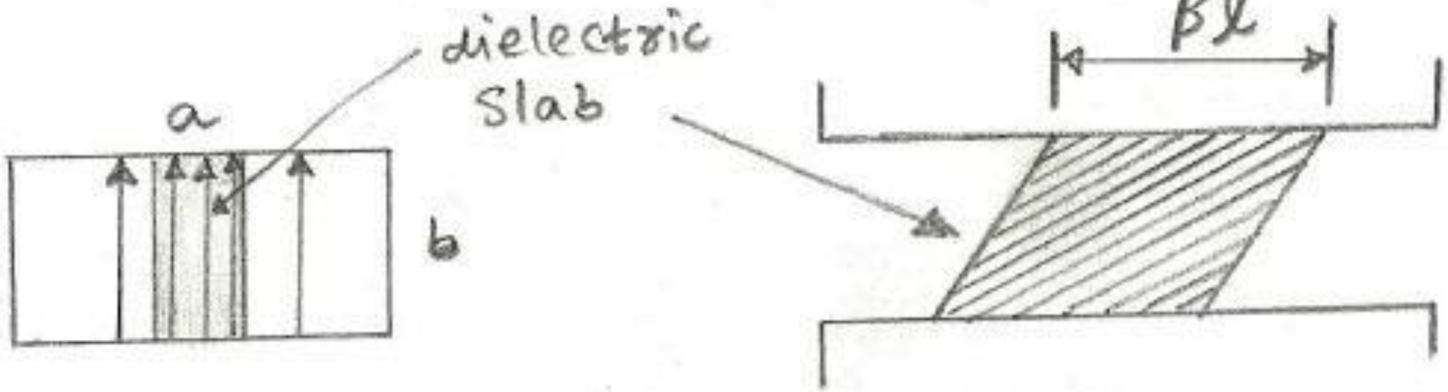
- A Phase shifter is a two port passive device that produces a variable change in phase of the wave transmitted through it.

Construction

- A Phase shifter can be realized by placing a lossless dielectric slab within a waveguide parallel to and at the position of maximum E-field.

Working

- A differential phase change is produced due to the change of wave velocity through the dielectric slab compared to that of the empty waveguide.



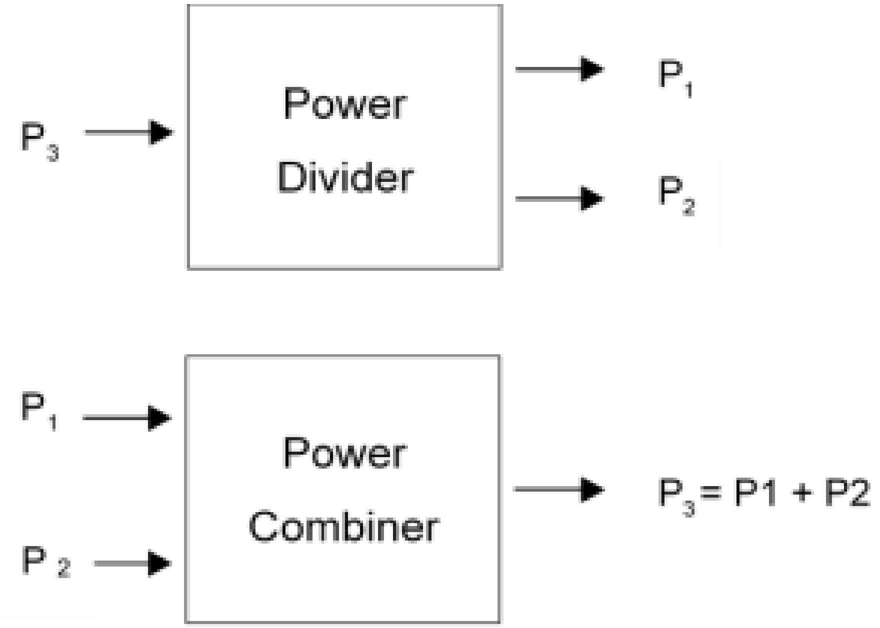
Phase shifter

Power divider

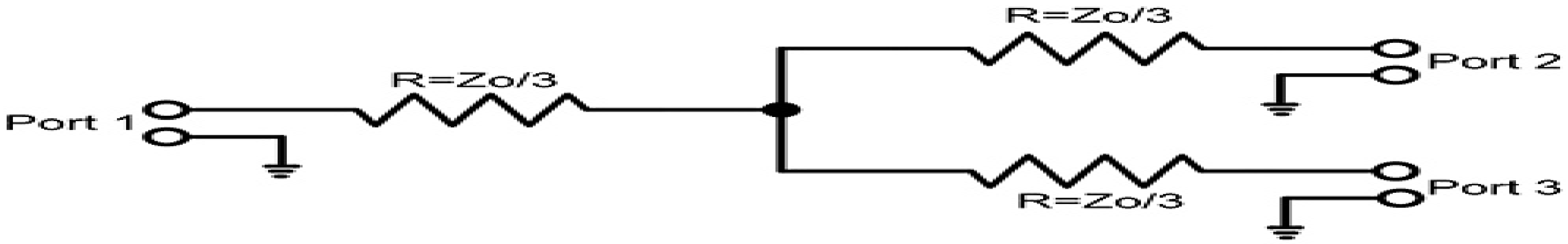
- A Power divider is a device used for splitting the input power into a number of smaller amounts of power at multiple ports. A Power divider can split the power input into either equal or unequal outputs.

Types of power dividers:

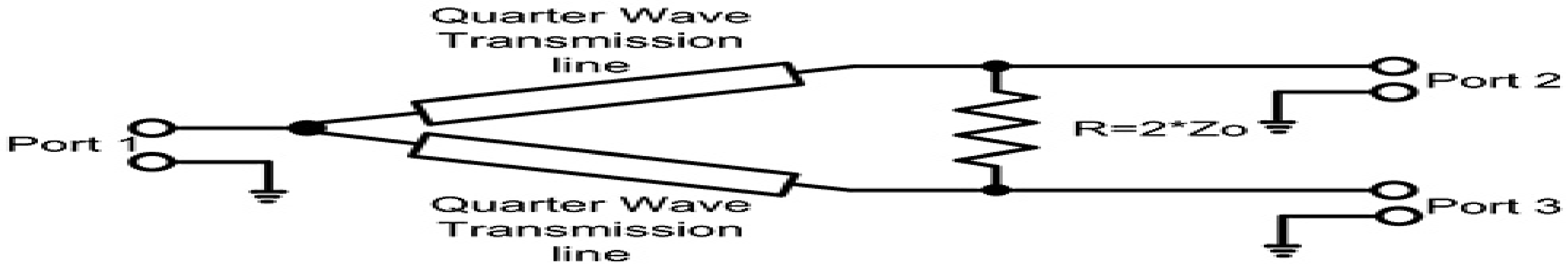
- T-junction
- Resistive
- Wilkinson
- Hybrid coupler



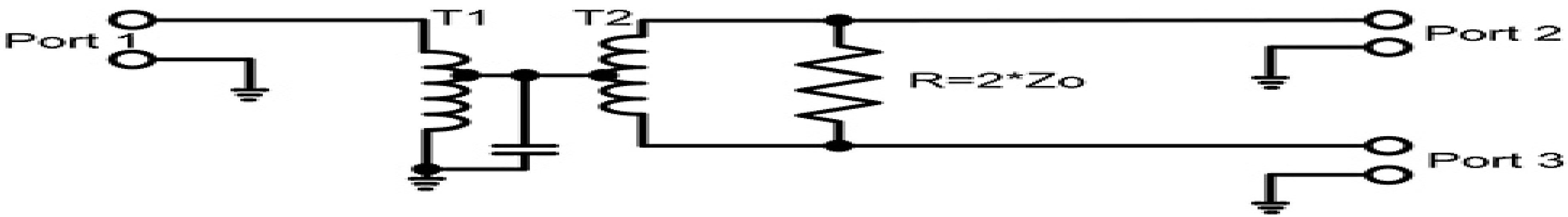
Resistive Divider



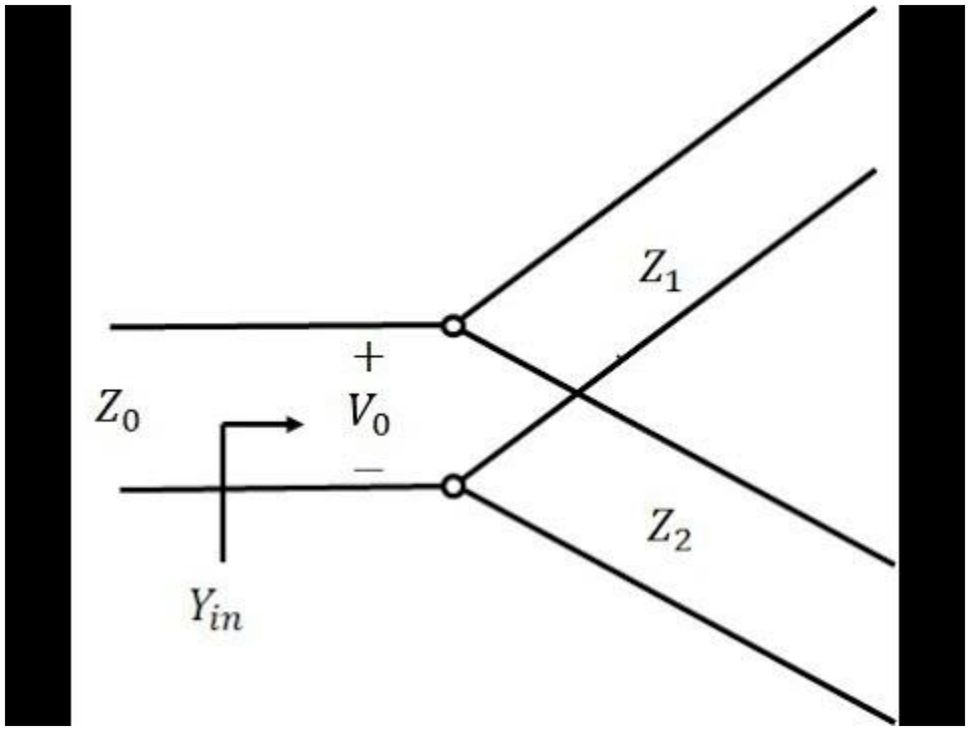
Wilkinson Divider



Hybrid Divider



T-junction power divider



T-JUNCTION POWER DIVIDER

- The T- Junction power divider is a simple 3-port network and can be implemented in any kind of transmission medium such as a microstrip, stripline, coplanar waveguide, etc.
- A 3-port network cannot be lossless, reciprocal, and matched at all the ports.
- Since a T-junction power divider is lossless and reciprocal, it cannot be perfectly matched at all of the ports.
- The T-Junction power divider can be modeled as a junction of three transmission lines

RESISTIVE POWER DIVIDER

- Resistive power dividers can be used to provide an RF split or division in any ratio, simply by choosing the correct values of resistor and configuration.
- There is a variety of different types of resistive RF divider or splitter.
- Resistive splitters are also able to provide an accurate impedance match over a wide band of frequencies provided the correct types of resistor and construction techniques are used.
- Resistive power dividers / splitters / combiners are cheap and easy to manufacture and they are often used in low cost television antenna splitters

WILKINSON POWER DIVIDER

- The Wilkinson Power Divider is a specific class of power divider circuit that can achieve isolation between the output ports while maintaining a matched condition on all ports.
- The Wilkinson design can also be used as a power combiner because it is made up of passive components and hence is reciprocal.
- It uses quarter wave transformers, which can be easily fabricated as quarter wave lines on printed circuit boards.
- One of the advantages of Wilkinson power divider is that unequal power splitting can also be implemented.

Isolator

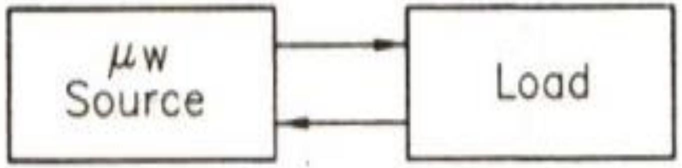
Definition

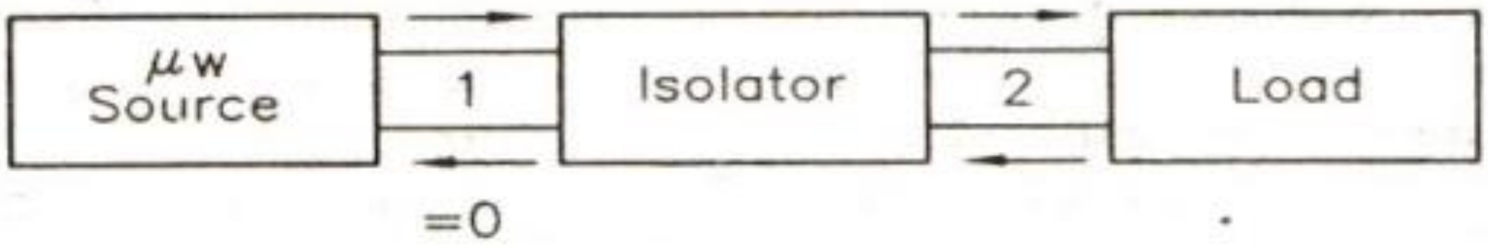
- An isolator is a two port non reciprocal device.
- An isolator is a 2 port device which provides very small amount of attenuation for transmission in one direction and provides maximum attenuation for transmission in other direction.

Need for isolator

- In most microwave generators, the output amplitude and frequency tends to fluctuate very significantly with changes in load impedance, this is due to mismatch of generator output to load resulting in reflected wave from load.
- These reflected waves should not be allowed to reach the microwave generator, which will cause amplitude and frequency instability of the microwave generator

- When isolator is Inserted between generator and load, all the signals from generator will get transmitted without any attenuation.
- Whereas in other direction, if any reflections arise from load, all get reflections will be attenuated.
- Thus, isolator provides one way of isolation of signals to maintain stability.

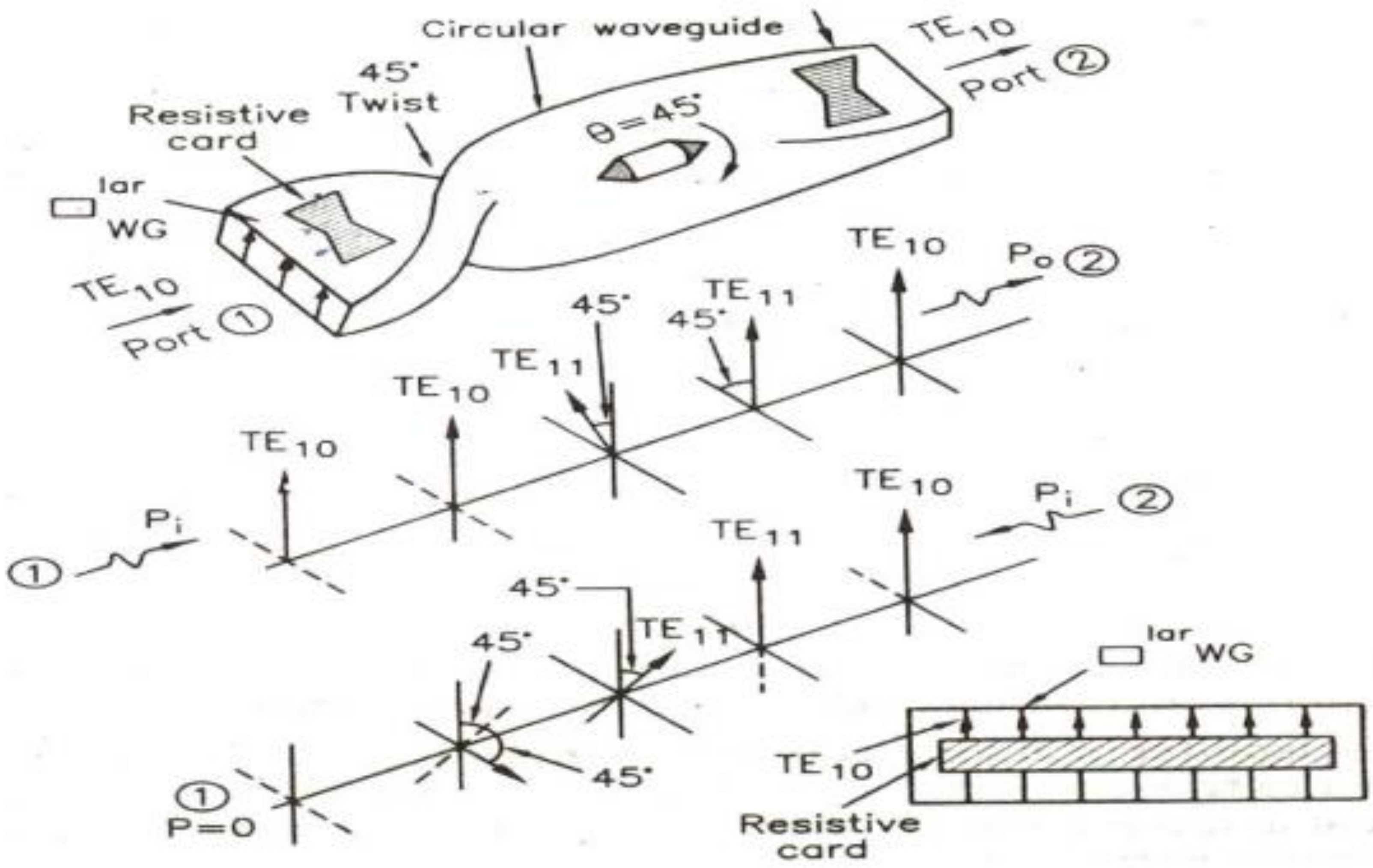




PRINCIPLE OF WORKING

Faraday’s rotation law

- When an electromagnetic wave passes through ferrites, plane of polarization continuous to rotate to angle θ in one particular direction (either clockwise or anticlockwise). This plane of polarization changes in the same direction whatever may be the direction of propagation of wave. This is called as Faraday rotation.



Circular waveguide
TE10
Port ②
45° Twist
Resistive card
θ=45°
lar WG
TE10
Port ①
TE10
Po ②
TE11
45°
45°
TE11
TE10
TE10
Pi
①
TE10
Pi ②
TE11
45°
TE11
45°
45°
lar WG
TE10
①
P=0
Resistive card

CONSTRUCTION

- Isolator is constructed using rectangular waveguide which is twisted by 45 degrees.
- And ferrite rod which will provide 45 degree rotation based on law.
- A resistive card is placed along the larger dimension of the rectangular waveguide, so as to absorb any wave whose plane of polarisation is similar to the plane of resistive card . the resistive card does not absorb any wave whose plane of polarization is perpendicular to its own plane.

ISOLATOR IS CALLED AS UNILINE

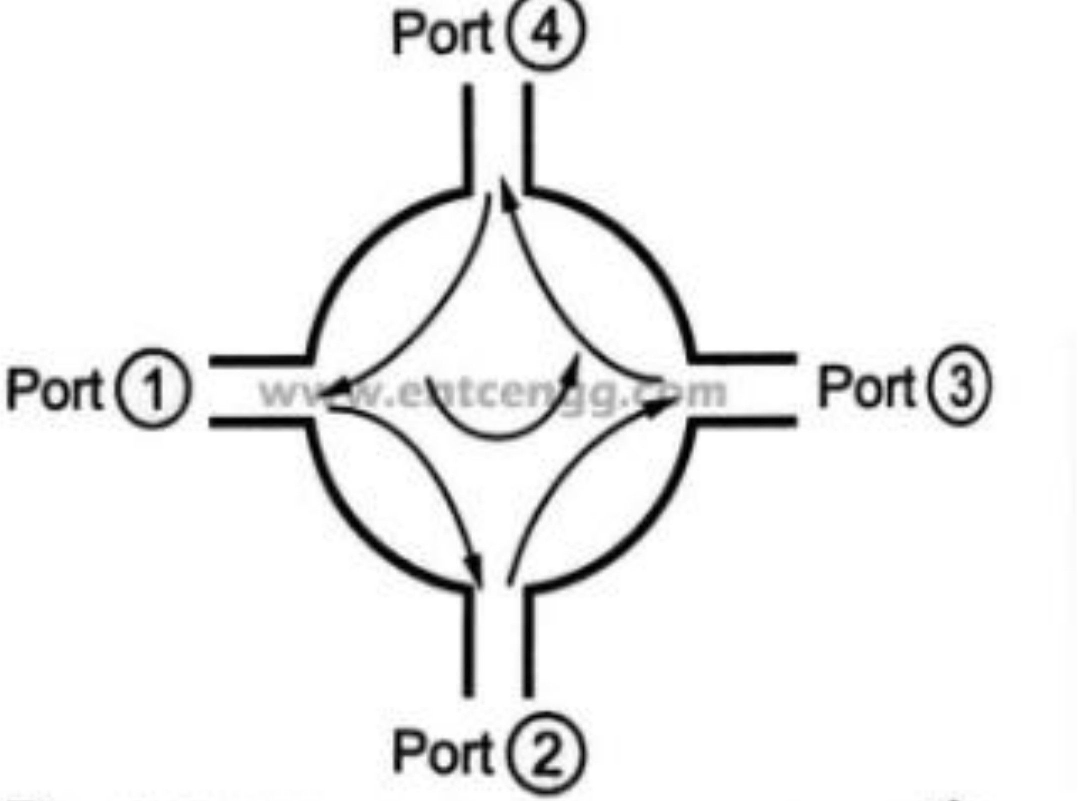
- Uniline means single line (only one direction)
- Since an isolator completely absorbs the power for propagation in one direction and provides lossless transmission in the opposite direction. Thus the isolator is usually called **uniline.**

CIRCULATOR

- A circulator is a passive, non-reciprocal, multi port device usually with three or four ports.
- In Circulator, a wave will travel from one port to the next immediate port in one direction only (clockwise or anticlockwise).
- Circulators works on the principle of faraday’s rotation law.
- Circulators are used to isolate signals transmitting from one port to all other ports. Input will be transmitted to next immediate port either in clockwise or anticlockwise direction only.

FOUR PORT CIRCULATOR

PORTS CONNECTIVITY



CONSTRUCTION

- A four port circulator can be constructed in many ways

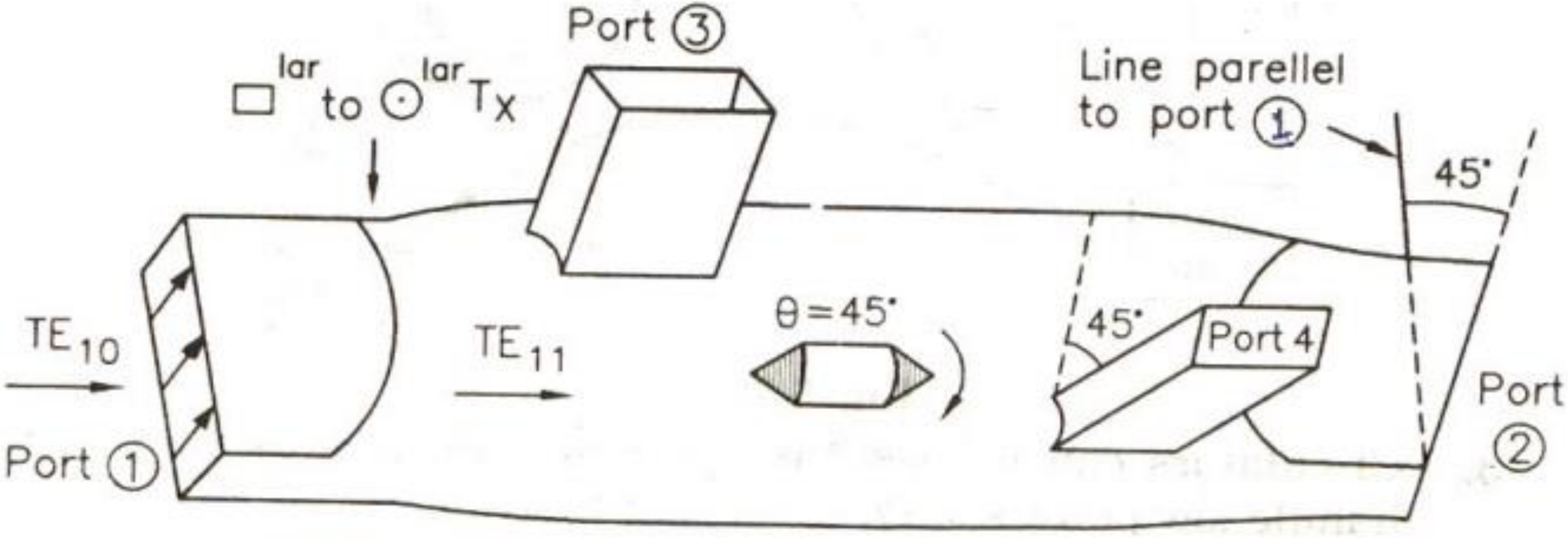


Fig. Four port circulator

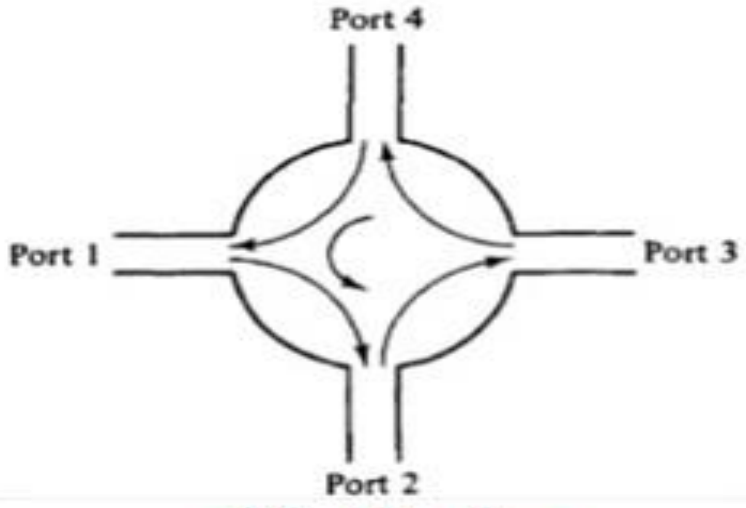
- The power input given at port 1 is in TE_{10} mode. Since rectangular form is varied to circular at the centre, the propagating mode is changed to TE_{11} mode.
- Power entering port 1 will travel along the magnetized ferrite and will receive at port 2. Port 3 cannot receive power sent by port 1 because port 1 is isolated from port 3 by phase varied alignment of port 3 arm.
- Power from port 2 is transmitted to port 4. Port 3 cannot receive power from port 2 as port 2 and 4 are isolated by phase varied alignment of port 4 arm.
- Power from port 4 is transmitted to port 1.

S-MATRIX DERIVATION

$$[S]=\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} ---(1)$$

- If all ports are perfectly matched then, S11 =S22=S33=S44=0.
- By non reciprocity and principle of ports connectivity in only one direction.
- Port 1 is connected to port 2. **(S12 = 1)**
- Port 2 is connected to port 3. **(S32=1)**
- Port 3 is connected to port 4. **(S43=1)**
- Port 4 is connected to port 1. **(S14=1)**

- Remaining all transmission co-efficients are zero as there is further no inter connections between ports. All are isolated from each other except P 1 to 2, P2 to 3, P3 to 4, P4 to 1.



4-Port Circulator

$$\mathbf{S} = \begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{21} & 0 & S_{23} & S_{24} \\ S_{31} & S_{32} & 0 & S_{34} \\ S_{41} & S_{42} & S_{43} & 0 \end{bmatrix}$$

$$\Downarrow$$

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

Three port circulator

- A Three port circulator is a three port non reciprocal asymmetrical network.
- A three port circulator can be constructed in two ways:

(i) By using a 120 degree H-plane waveguide with a central ferrite post

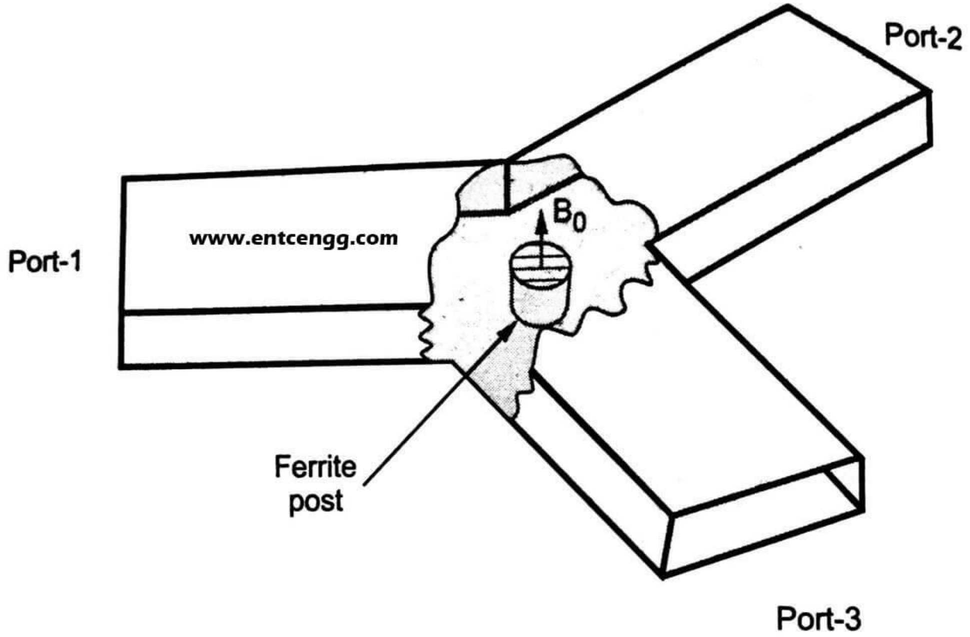
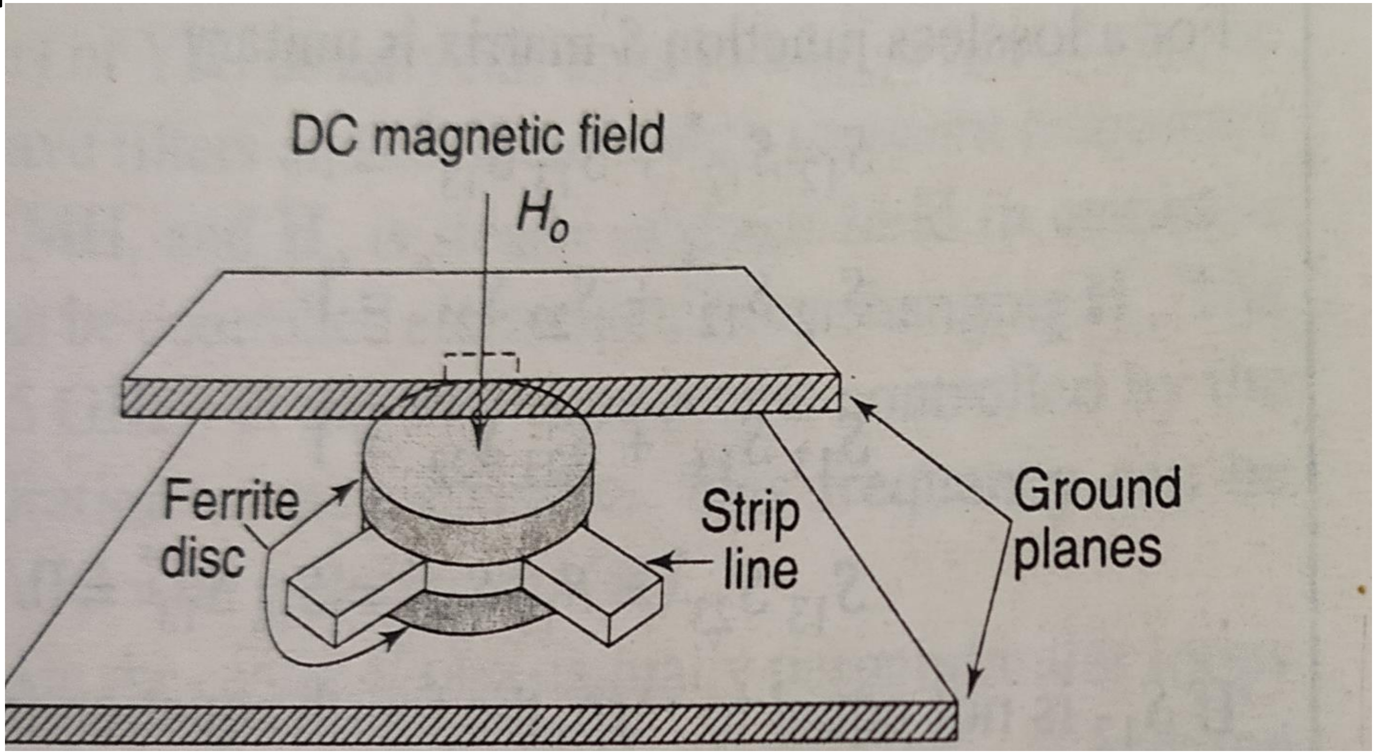


Fig. 2.6.4 Three port circulator

- The signal that is to be transmitted travels from 1-port to 2-port and signal received at antenna travels from 2-port to 3-port
- The ferrite post is magnetized by a static B field along the axis. It provides the necessary nonreciprocal property.

(ii) By using a strip line symmetrical Y-junction with a central ferrite post



- For a perfectly matched , lossless, non-reciprocal three port circulator, the S-matrix will be

$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

- The matching of the junction can be achieved by placing suitable tuning elements

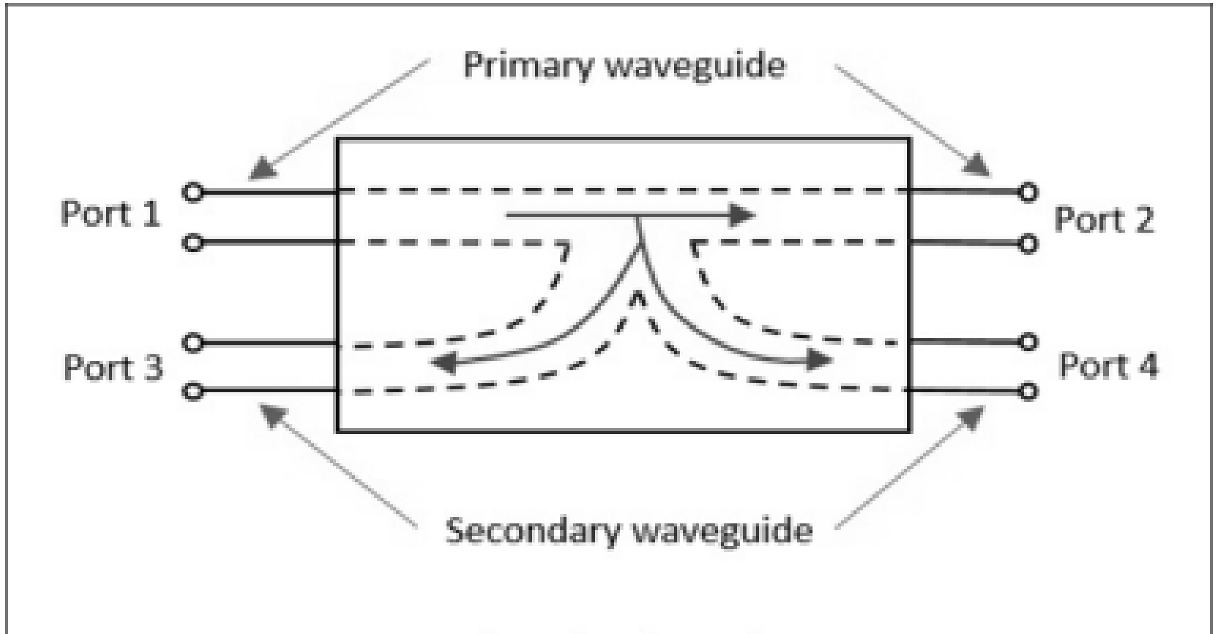
Characteristics of Circulators:

- Insertion loss < 1 dB
- Isolation approx =30-40 dB
- VSWR <1.5

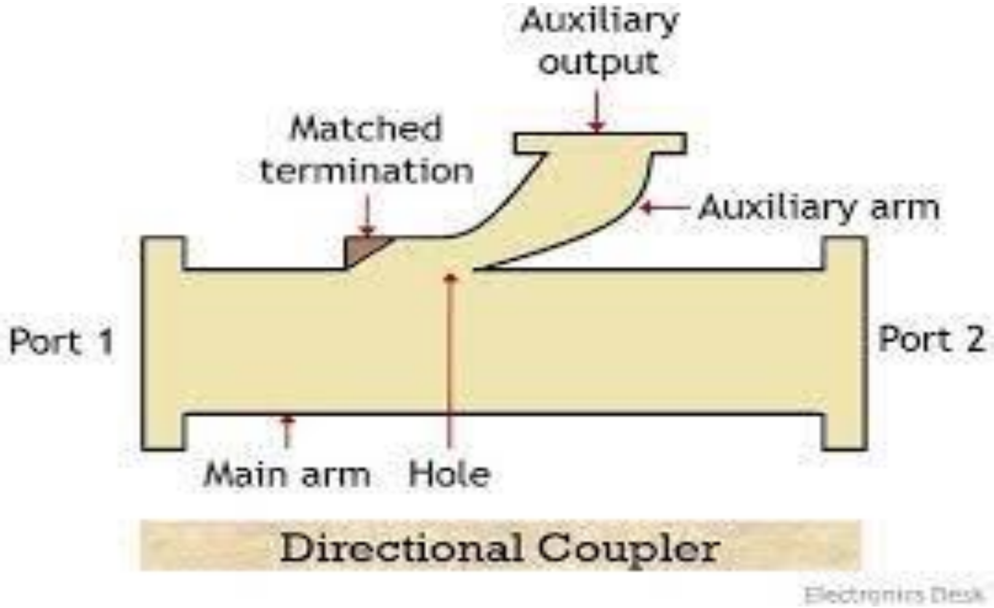
DIRECTIONAL COUPLER

- Directional couplers are passive reciprocal four port passive device.
- A directional coupler has four ports, where one is regarded as the input,
- One is regarded as the **"through" port** (where most of the incident signal exits),
- One is regarded as the "**coupled**" port (where a fixed fraction of the input signal appears, usually expressed in dB),
- And one is regarded as the "**isolated**" port, which is usually terminated.

- Directional Coupler is a 4-port waveguide junction consisting of a primary main waveguide and a secondary auxiliary waveguide

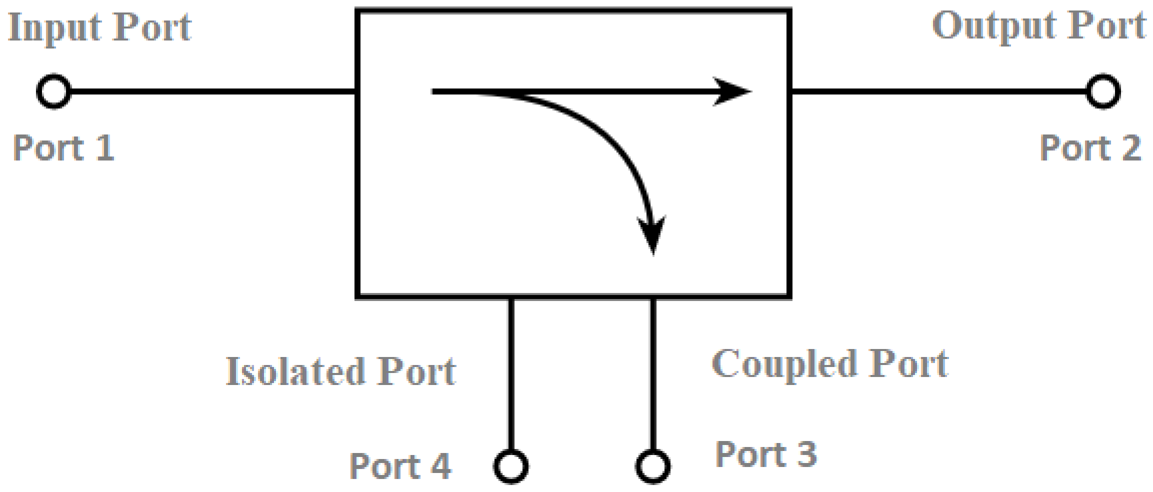


Directional Coupler



DIRECTIONAL COUPLER WORKING

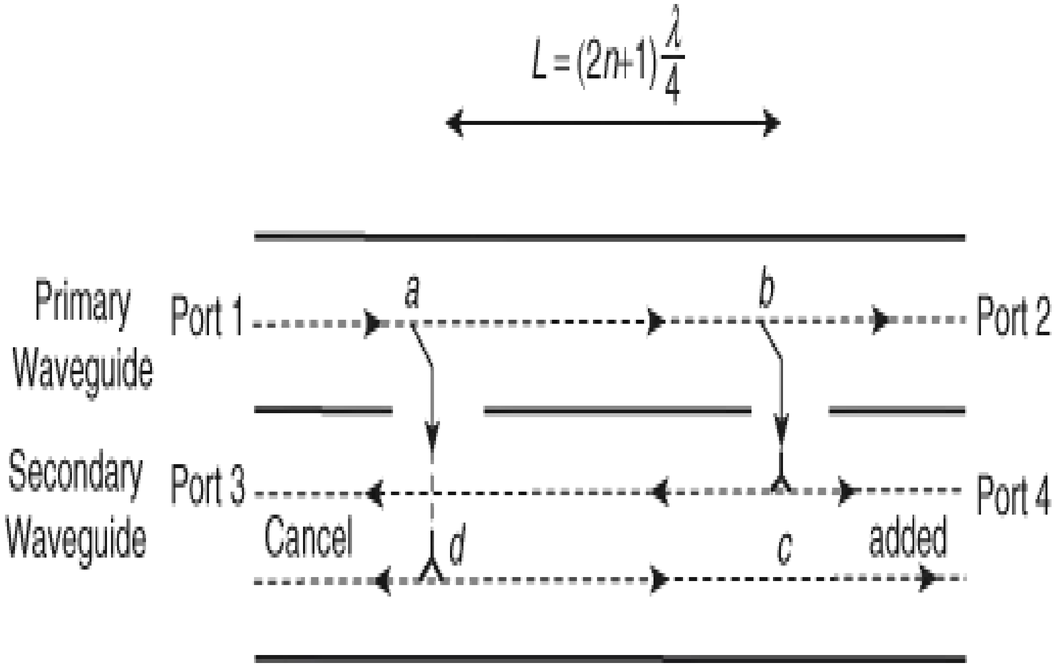
- Directional couplers are devices that will pass signal across one path while passing a much smaller signal along another path
- Directional coupler functions are utilized in RF and microwave circuits to isolate, separate, or combine electromagnetic power.



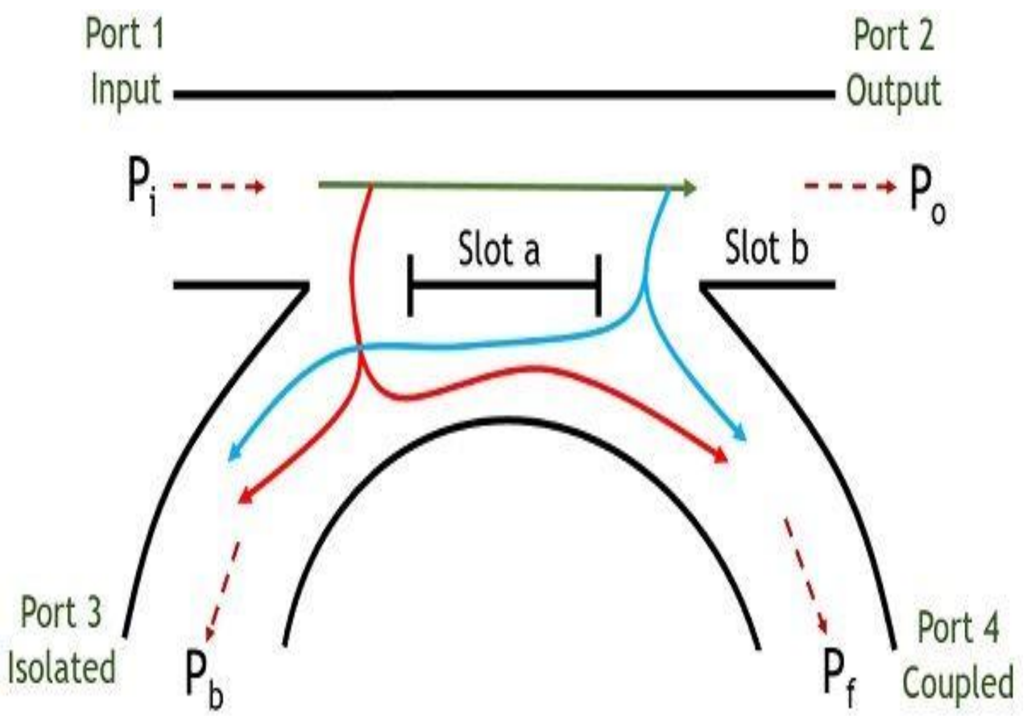
TYPES OF DIRECTIONAL COUPLERS

- **Two-hole directional coupler**
- **Single-hole or Bethe-hole directional couple**

TWO HOLE DIRECTIONAL COUPLER



Two-Hole Directional Couplers



Two-hole Directional Coupler

Electronics Desk

CONSTRUCTION

- The directional coupler consists of two waveguides referred to as the main waveguide (ports 1 and 2) and an auxiliary waveguide (ports 3 and 4).
- To have the directional property of a coupler, the spacing between the centers of two holes should be $L = (2n + 1)\, \lambda/4$, where n is any positive integer.

WORKING

- When power is applied at port 1 of the main waveguide, the output is will reach port 2 of the main waveguide.
- A fraction of the power is coupled into port 4 of the auxiliary waveguide, and no power flows in port 3 of the auxiliary waveguide
- This is because, the power leaks out of 1^{st} hole and power leaks out of 2^{nd} hole will cancel out at port 3 because, the power is 180 deg out of phase with each other. Hence , no net power will reach port 3.
- Thus, port 3 is isolated.

- In port 4, both power leak from hole 1 and 2 added up each other because power is in phase with each other at port 4.
- Since the device is reciprocal, the port 2 can be used as input port. If so used, port 3 will be coupled port and port 4 will be isolated.

S-MATRIX DERIVATION

- $$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

- Since, all ports are perfectly matched. Hence,

  S11=S22=S33=S44=0
- Port 1 and 3 are decoupled as well as port 2 and 4

  S13=S31=S24=S42=0
- Also, [s] is symmetric matrix i.e. **Sij = Sji**

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

From unitary property of [S] matrix.

[S] [S]* = I

$$\begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{21} & 0 & S_{23} & 0 \\ 0 & S_{32} & 0 & S_{34} \\ S_{41} & 0 & S_{43} & 0 \end{bmatrix} \begin{bmatrix} 0 & S_{12}* & 0 & S_{14}* \\ S_{21}* & 0 & S_{23}* & 0 \\ 0 & S_{32}* & 0 & S_{34}* \\ S_{41}* & 0 & S_{43}* & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_1C_1 = |S_{12}|^2 + |S_{14}|^2 = 1 ------ 1)$$

$$R_2C_2 = |S_{12}|^2 + |S_{23}|^2 = 1 ------ 2)$$

$$R_3C_3 = |S_{23}|^2 + |S_{34}|^2 = 1 ------ 3)$$

$$R_4C_4 = |S_{14}|^2 + |S_{34}|^2 = 1 ------ 4)$$

$$R_1C_3 = S_{12}.\, S_{23} * + S_{14}.\, S_{34}* = 0 ------ 5)$$

From equation 1) and 2)

$$S_{14} = S_{23}$$

From equation 1) and 4)

$$S_{12} = S_{34}$$

Let $S_{12} = S_{34} – P$ (Real no.)

Hence, $S_{12}* = S_{34}* = P$

Equation 5) becomes

$$P.S_{23}*+S_{14}P=0$$
$$P(S_{23}*+S_{14})=0$$
$$But, S_{14}=S_{23}$$
$$P(S_{23}*+S_{23})=0$$
$$S_{23}*=-S_{23}$$
$$Let S_{23}=jq=S_{23}*=-jq$$
$$[S]=\begin{bmatrix} 0 & P & 0 & jq \\ P & 0 & jq & 0 \\ 0 & jq & 0 & P \\ jq & 0 & P & 0 \end{bmatrix}$$

ATTENUATOR

- The attenuators are basically passive devices which control power levels in microwave system by absorpsion of the signal
- It reduces the power of a signal without degrading its integrity appreciably (**without distorting its waveform**).
- Practical use of a power attenuator would be to reduce the power of an amplifier to match the power rating of the speaker.

TYPES OF ATTENUATOR

- Fixed type attenuator
- Variable attenuator
- Fixed step attenuator

Fixed Attenuators

- As the name implies, fixed value attenuator's attenuation value cannot be varied.
- Fixed attenuators are placed in signal paths to reduce power transmission and are set at a fixed attenuation by symmetrical resistive networks that follows a T, L or Pi configuration.
- Their configuration can either be in waveguide, in surface mount or coaxial, and depending on their application, they can either be directional or bidirectional.

Variable attenuators

- Variable attenuators can be used to provide a different attenuation level as there as an option to regulate and get required attenuation level.
- This can be achieved by varying the input voltage applied to the control line.

Fixed step attenuator

- Step attenuators are used to provide fixed steps of attenuation levels.
- These are almost similar to fixed attenuators but with an extra advantage of facility to provide different fixed attenuation levels in pre-calibrated steps.

Precision type variable attenuator:

- It contains circular section containing a very thin tapered resistive card on both sides
- Precision Variable Attenuators can be used to adjust power level in automated test systems.
- Applications include bit error rate testing of transmitters and receivers as well as channel equalization in testing of WDM systems.
- All Specifications at room temperature, without connectors.

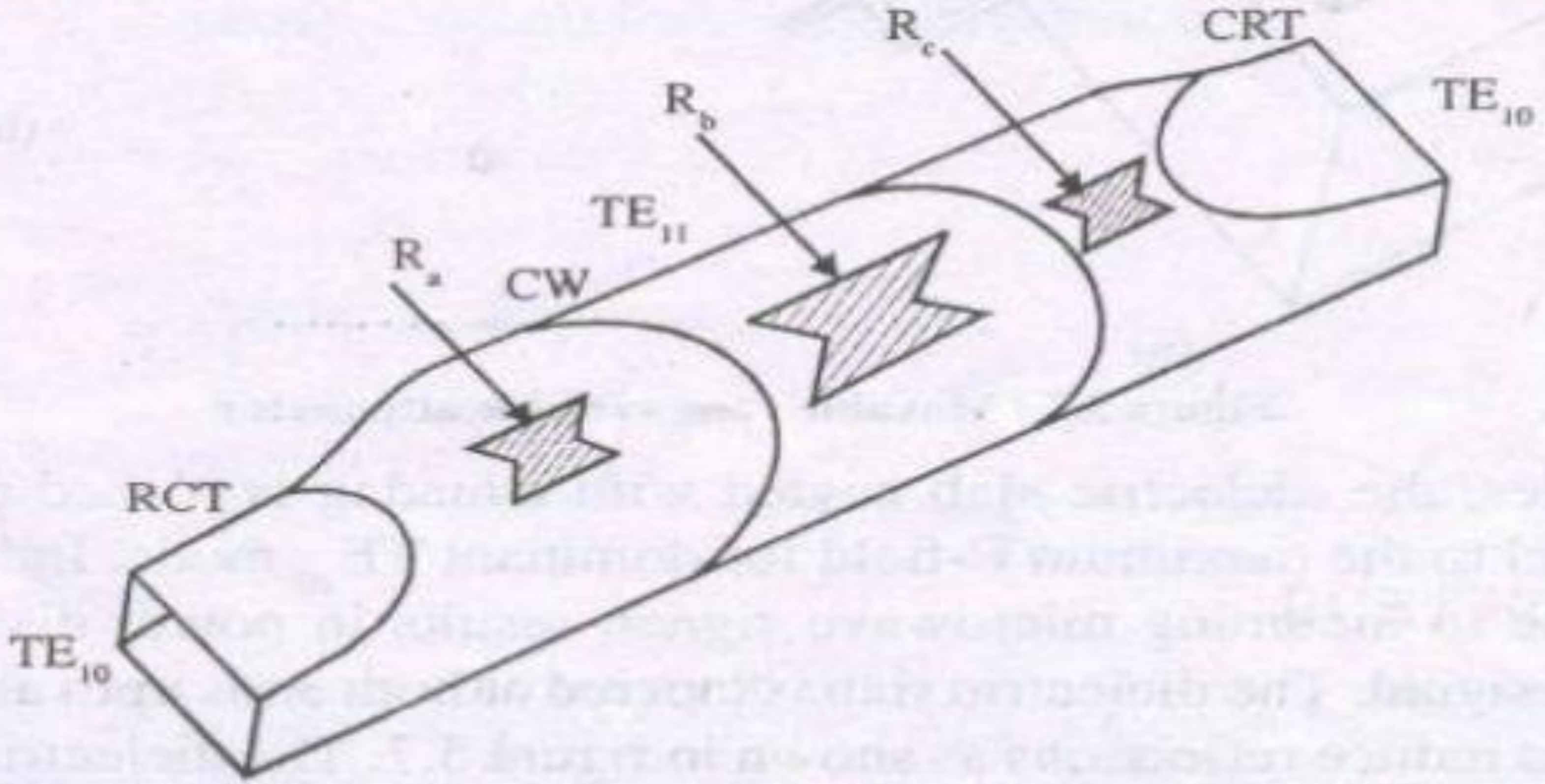


Figure 5.9 : Precision type variable attenuator

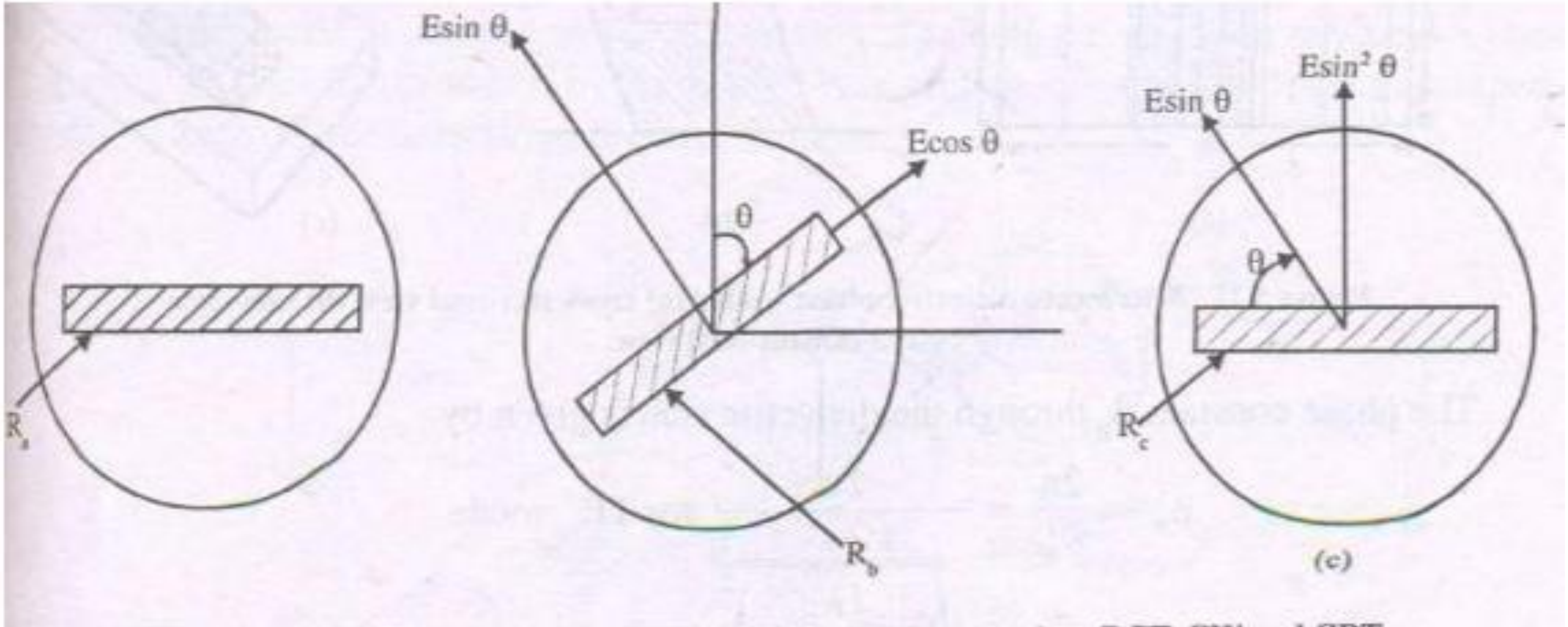


Figure 5.10 : Field components of electric field in the three sections RCT, CW and CRT

Applications

- Attenuators are generally used in radio, communication and transmission line applications to weaken a stronger signal.
- Resistive attenuators are used as volume controls in broadcasting stations and also can be used for matching circuits of different resistive impedances.
- Variable attenuators are used in laboratories, when it is necessary to obtain small value of voltage or current for testing purposes.

UNIT - 3

MICROWAVE TRANSISTOR

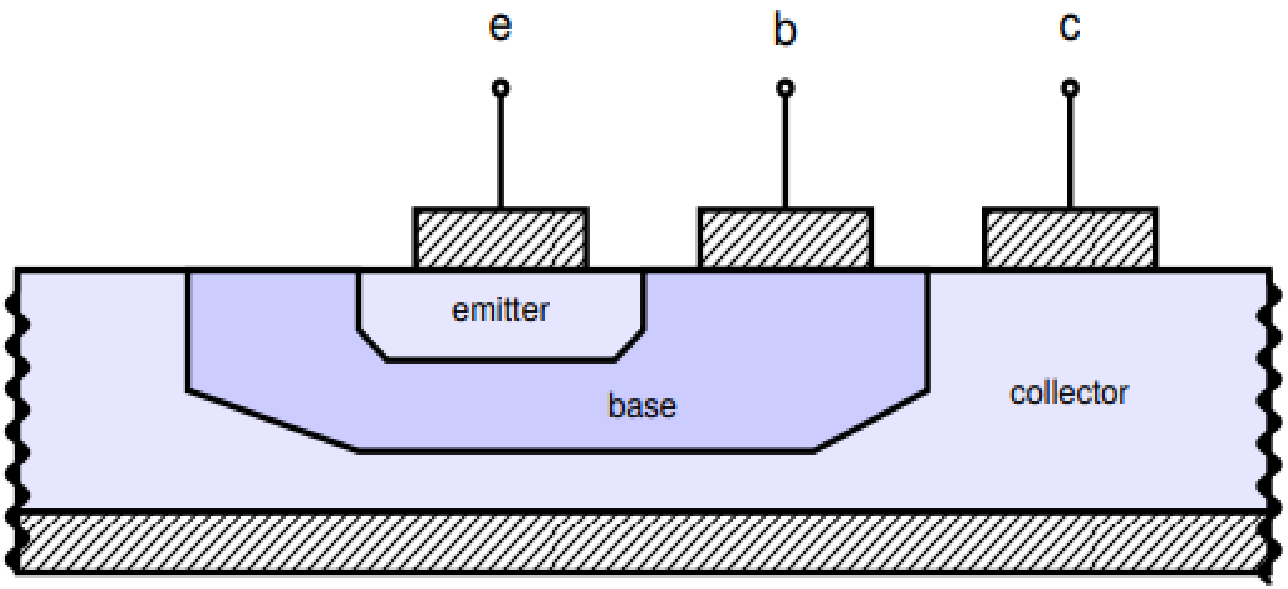
- A microwave transistor is a type of electronic device that amplifies or switches electronic signals in the microwave
- There are two types of microwave transistor

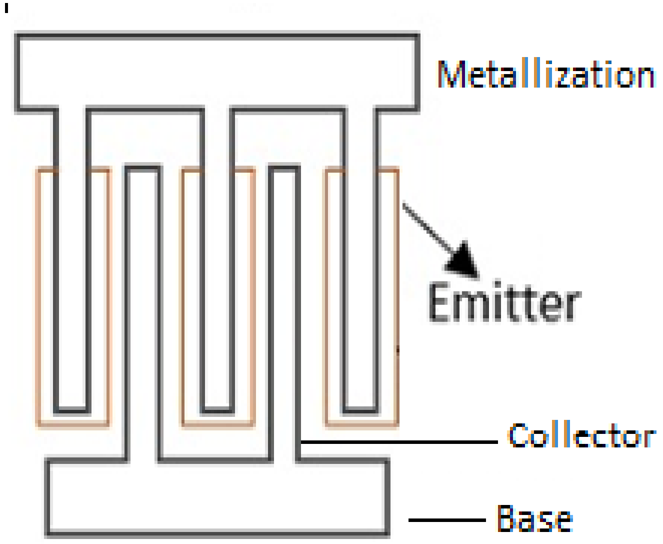
  BJT – Bipolar junction transistor (Microwave bipolar)

  FET – Field effect transistor (Microwave FET)

Microwave bipolar transistor

- The microwave bipolar transistor is a non linear device , with Silicon as the semiconductor material .
- Mostly npn type are used which operates up to ‘5 GHz’





Interdigitated Geometry

CONSTRUCTION AND WORKING

- The device consists of three differently doped semiconductor regions, the emitter region, the base region and the collector region.
- The emitter region of the transistor is heavily doped and has thin area of cross section.
- The base of the transistor is moderate and lightly doped to reduce the recombination rate.
- The collector region of the transistor is large and moderately doped

- The charge carriers from the emitter are supplied to the collector through the base.
- When the charge carriers from the emitter reach the base some of them recombine with the charge carriers in the base.
- The remaining charge carriers are directed towards the collector constituting the collector current or output current.

MODES OF OPERATION

- The microwave transistors have four modes of operation depending on the polarity of the applied voltage.

1. **Normal Mode:** In this mode, the emitter base junction of the npn transistor is forward biased and collector base junction is reverse biased. Most transistor amplifiers is operate in normal mode.

2. **Saturation Mode:** When both the emitter base junction and collector base junction are forward biased, the transistor is in saturation mode with low resistance and acts like a short circuit.

3. **Cut Off Mode:** When both the Tr junctions are reverse biased, the Tr is operated in Cut Off mode. The Tr acts like an open circuit. Both the saturation and cut off modes are used when transistor acts as a switch.

4. **Inverted Active Mode**: In this mode, the emitter base junction is reverse biased and collector base junction is forward biased.

Microwave Field Effect Transistors

- Field effect transistors (FETs) are unipolar device, with only one carrier type (holes or electrons). Only majority carriers contributes to current flow.
- n-channel FETs employ electrons, while p-channel devices use holes
- FET is a voltage-controlled device where the input gate to source voltage controls the output drain current.
- The output current (IDS) is controlled by the input voltage (VGS)

TYPES OF FET’S

- MESFET (metal semiconductor FET),
- MOSFET (metal oxide semiconductor FET),
- **HEMT (high electron mobility transistor)**,
- the PHEMT (pseudomorphic HEMT).

HEMT (High electron mobility transistor)

- The name HEMT stands for High Electron Mobility Transistor
- This device has an unusual properly of a very narrow channel - enabling it to operate at exceedingly high frequencies.
- In addition to the very high frequency performance, the HEMT also offers a very attractive low noise performance.

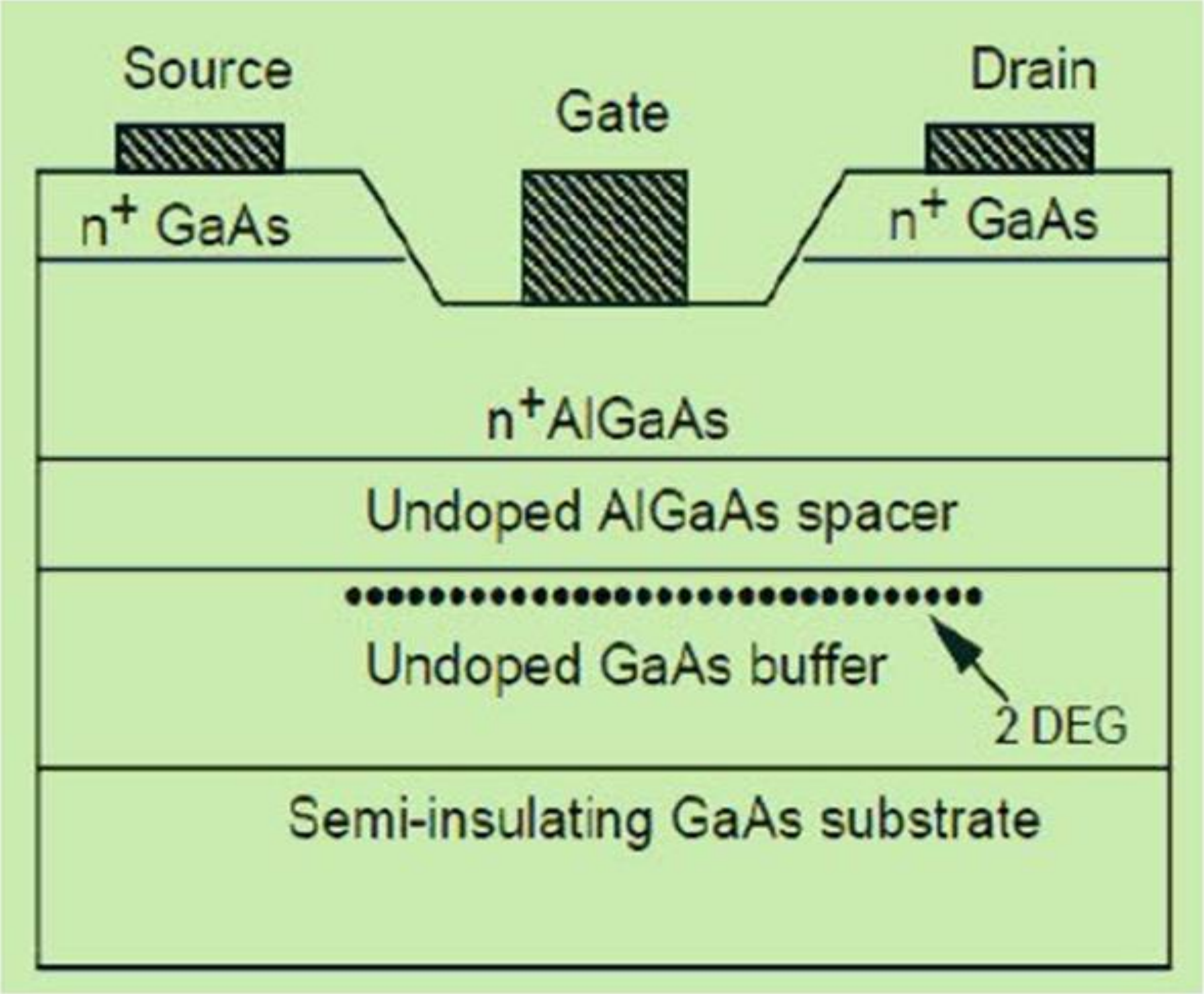
High-electron-mobility transistor

- A high-electron-mobility transistor (HEMT or HEM FET) is also known as heterostructure FET (HFET) because, it incorporates a junction between two materials with different band gaps (heterojunction)
- The most common materials used are Aluminium Gallium Arsenide (AlGaAs) and Gallium Arsenide (GaAs).
- Gallium Arsenide is generally used because it provides a high level of basic electron mobility which has higher mobilities and carrier drift velocities than Si.

CONSTRUCTION

- The key element that is used to construct an HEMT is the specialised PN junction
- It is known as a hetero-junction and consists of a junction that uses different materials either side of the junction.
- HEMTs are made up of a thin layer of semiconductor material called the channel, which is sandwiched between two layers of a material with a wider bandgap.

- First an intrinsic layer of Gallium Arsenide is set down on the semi-insulating Gallium Arsenide layer.
- After that, a very thin layer of intrinsic Aluminium Gallium Arsenide is set down on top of this layer.
- The main purpose of this layer is to ensure the separation of the Hetero-junction interface from the doped Aluminium Gallium Arsenide region.


Source
Gate
Drain
n+ GaAs
n+ GaAs
n+AlGaAs
Undoped AlGaAs spacer
Undoped GaAs buffer
2 DEG
Semi-insulating GaAs substrate

- Electrons from the n-type region move through the crystal lattice and many remain close to the hetero-junction. Within this region the electrons are able to move freely because there are no other donor electrons or other items with which electrons will collide and the mobility of the electrons in the gas is very high

SOLID STATE DEVICES

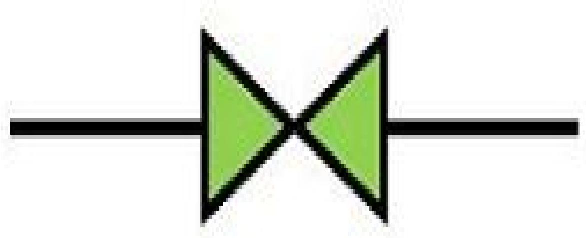
- A solid-state device is an electrical component or system that's based largely or entirely on a semiconductor.
- In solid-state devices, the current flowing through a circuit is confined to the solid compounds specially designed to amplify and switch it.
- The Microwave solid state devices are Tunnel Diode, Gunn Diode, IMPATT Diode, BARITT Diode, TRAPATT Diode, Varactor Diode, etc.
- Theses solid state devices are widely used in microwave system for generation, amplification, or detection of microwave signal. These devices are compact and integrated in a printed circuit board.

GUNN DIODE - CONSTRUCTION

- A Gunn diode, also known as a transferred electron device (TED), is a form of two-terminal semiconductor electronic component with negative resistance which used in high-frequencies.

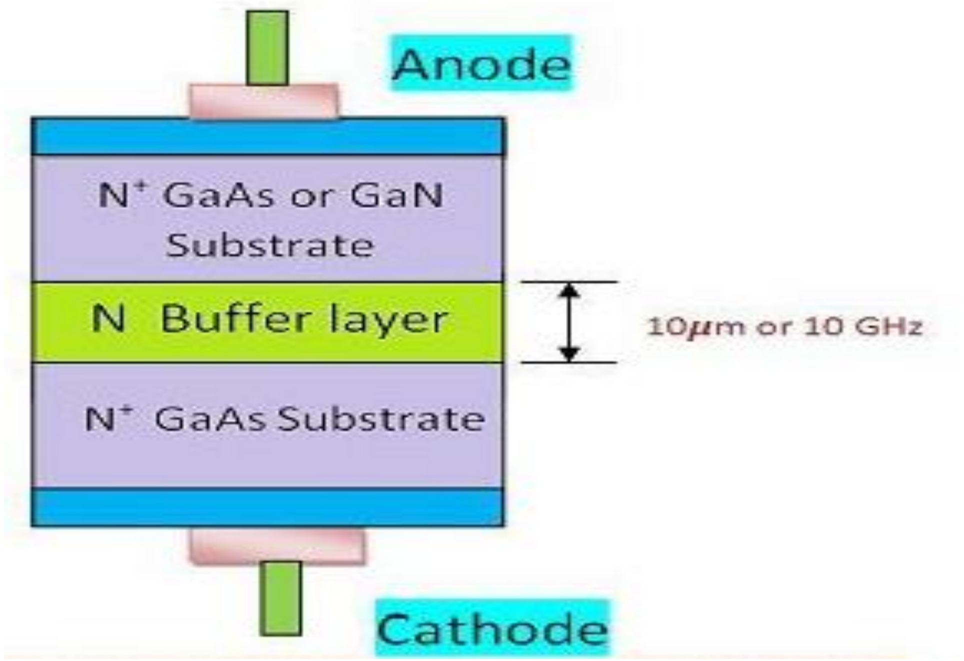
- It is composed of only N-type semiconductor because N-type semiconductor has electrons as majority carriers. And transferred electron devices use such materials which have electrons as majority charge carrier.

- It is made up of three layers of N-type semiconductor.



CONSTRUCTION

- The semiconductors used in Gunn diodes are Gallium Arsenide (GaAs), Gallium Nitride (GaN), Cadmium Telluride (CdTe), Cadmium Sulphide (CdS), Indium Phosphide (InP), Indium Arsenide (InAs), Indium Antimonide (InSb) and Zinc Selenide (ZnSe).
- Among these three layers the top most and the bottom most are heavily doped while the middle layer is lightly doped in comparison to the extreme layers.



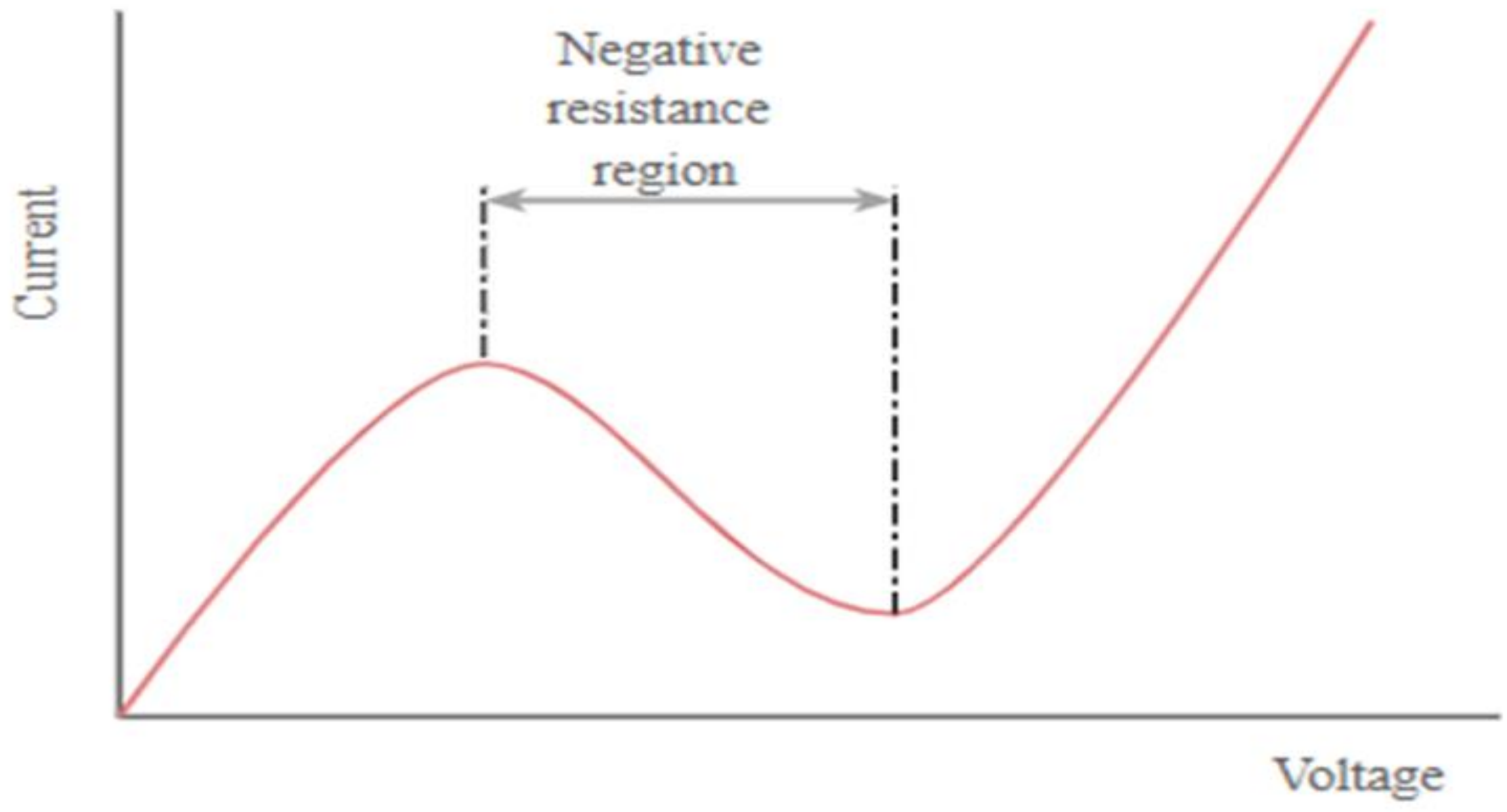
WORKING

- The Gunn diode operation depends on the fact that it has a **voltage controlled negative resistance**
- **Negative resistance** is exhibited through **transferred electron effect**.
- When a voltage is applied to the device, electric current increases to certain point, after reaching the threshold voltage, the current starts to decrease, this is called **negative resistance effect**.
- This is due to **transferred electron effect(TEE).** So called, transferred electron device.

TEE

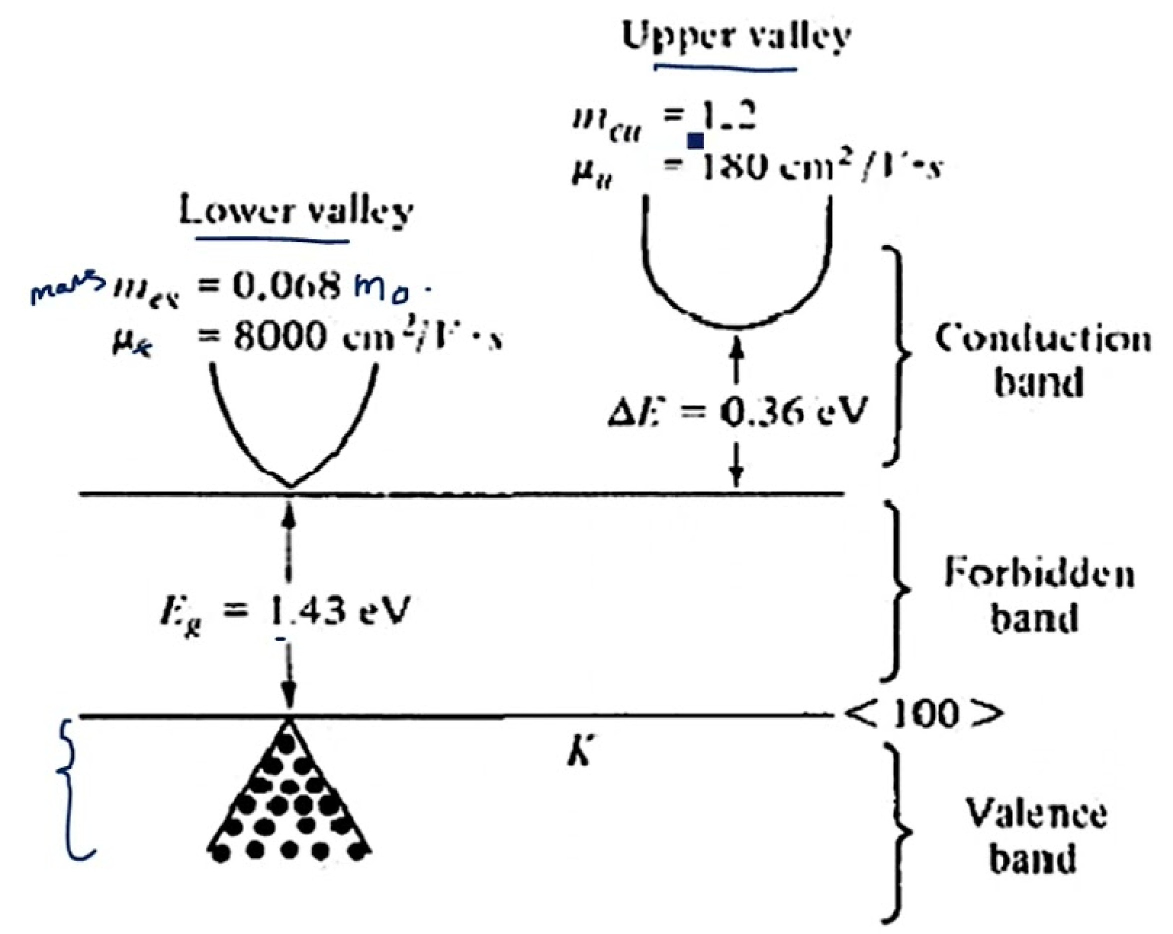
Movement of electrons from one valley point to another valley (lower energy to higher energy) in conduction band due to applied voltage is called transferred electron effect.

V-I Characteristics



Gunn diode characteristic

TWO VALLEY THEORY



- Only Certain semiconductor materials exhibit transferred electron effect.
- In which the conduction band is further classified as two valleys –sub conduction bands.
- The electrons in lower valley will have high electron mobility with low energy level.
- The electrons in the upper valley will have low mobility with high energy level.

- When a low electric field is applied at beginning, the electrons in the lower valley will gain energy through applied electric field and move to upper valley.
- At certain threshold point, all the electrons would have moved to upper valley.
- In upper valley, the mobility is low. So current will also be reduced.
- Since, current decrease with increase in voltage , it is called negative resistance region.
- This causes the negative resistance effect.

MODES OF GUNN DIODE

Modes of gunn diode based on doping,

1. Gunn oscillation mode,
2. Limited space charge accumulation mode,
3. Stable amplification mode
4. Bias circuit oscillation mode.

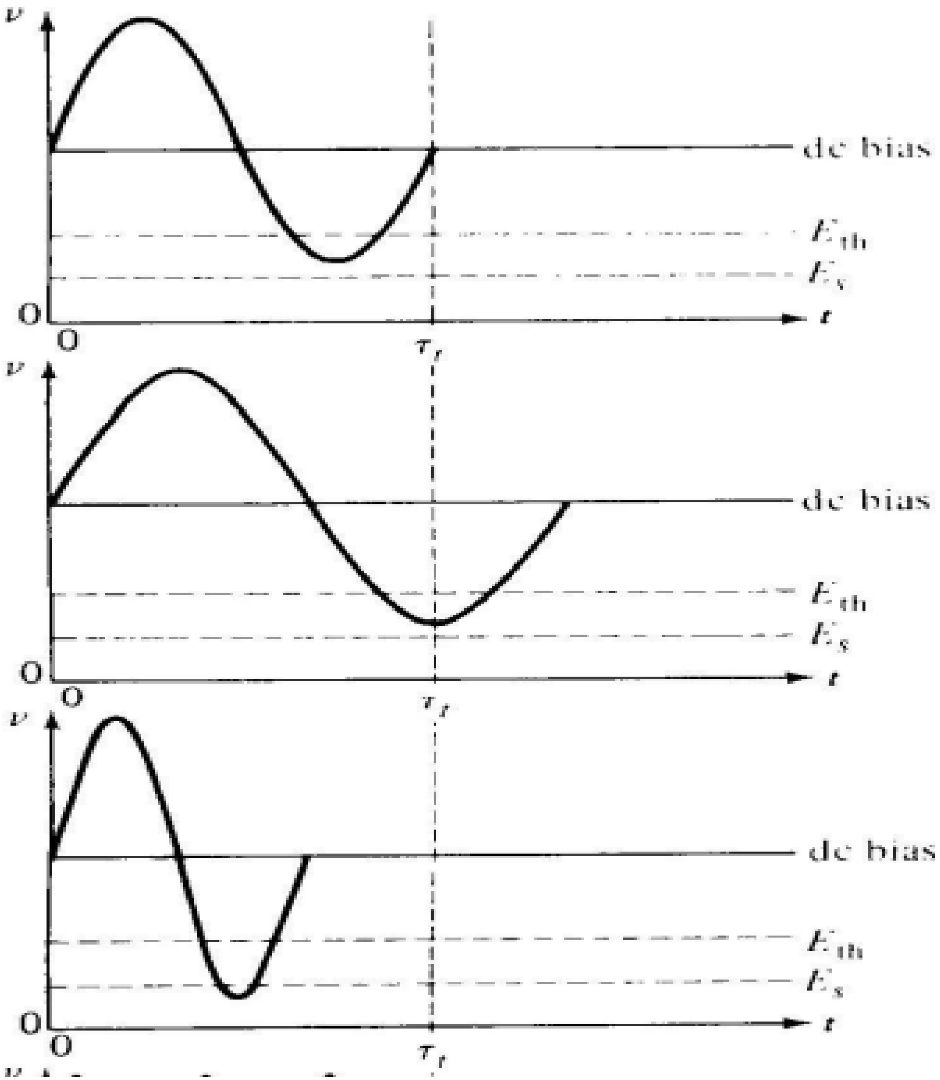
GUNN OSCILLATION MODE

- Gunn oscillation mode can be defined as the mode which produces microwave oscillations.
- In this region, the diode is not stable due to the formation of cyclic high field domain due to accumulation of electrons in low mobility valley.
- The time taken by high field domain to transit from cathode to anode is called as transit time.
- The gunn oscillation mode has three sub-modes namely.

a) Transit time domain mode

b) Delayed domain mode

c) Quenched domain mode.



(a) Transit-time mode $\tau_0 = \tau_t$

(b) Delayed mode $\tau_0 > \tau_t$

(c) Quenched mode $\tau_0 < \tau_t$

Stable Amplification Mode

- In stable amplification mode, the gunn diode produces stable oscillations with respect to the given input bias voltage.

LSA (Limited space charge accumulation) Mode

- This kind of mode can be defined as resonant mode.
- Maximum oscillations can be generated in this mode.
- It uses negative resistance region.

Bias Circuit Oscillation Mode

- This kind of mode happens simply once there is either LSA or Gunn oscillation takes place.
- Once the biasing of a bulk diode is done to the threshold then the average current drops suddenly when the oscillation of Gunn starts.