19ECCN1701 – RF and Microwave Engineering

Unit II – Microwave Passive Components

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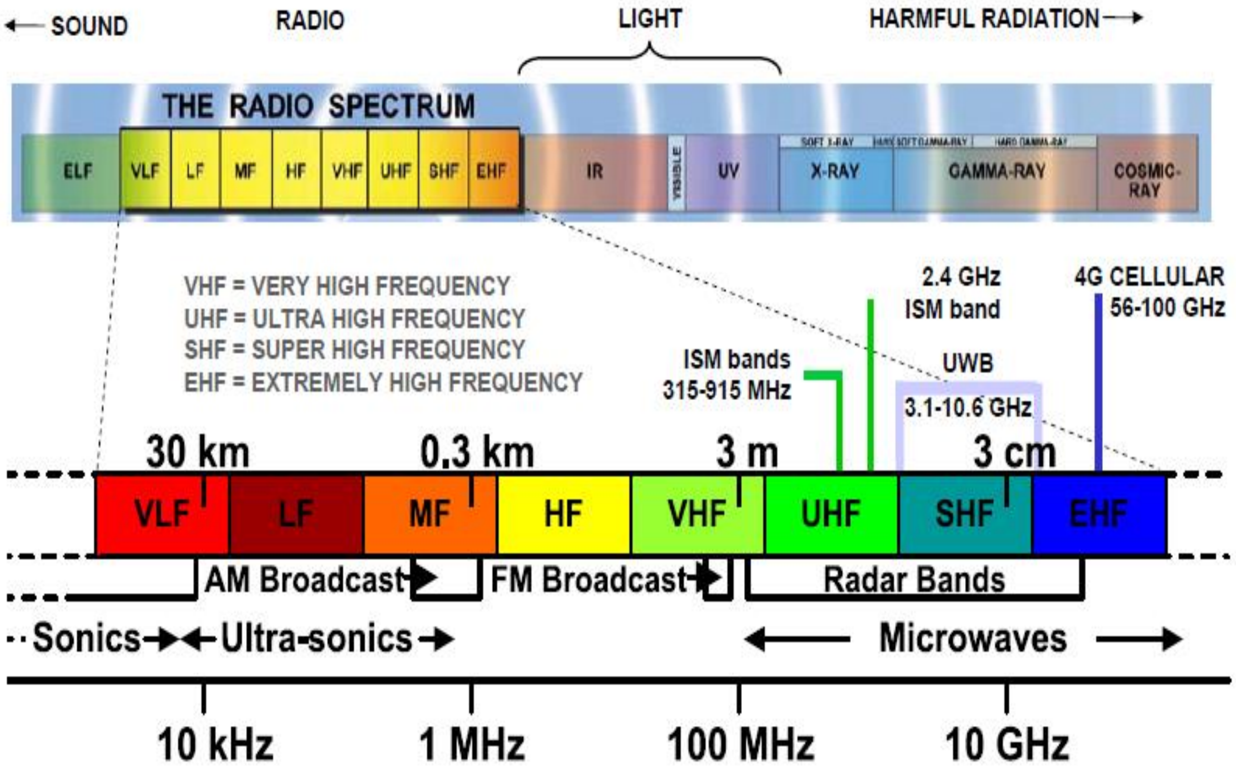
Microwave Frequency Range

The microwave spectrum is usually defined as a range of frequencies ranging from 300 MHz to 300 GHz.



Microwaves Frequency Bands

Band	Frequency range
HF Band	3 to 30 MHz
VHF Band	30 to 300 MHz
UHF Band	300 to 1000 MHz
L Band	1 to 2 GHz
S Band	2 to 4 GHz
C Band	4 to 8 GHz
X Band	8 to 12 GHz
Ku Band	12 to 18 GHz
K Band	18 to 27 GHz
Ka Band	27 to 40 GHz
V Band	40 to 75 GHz
W Band	75 to 110 GHz
mm Band	110 to 300 GHz

Microwave Applications: Overview

Civil

Wireless Communication

Vehicle Collision Avoidance

Remote Sensing

Military

Aircraft Safety and Navigation

RADAR

Missile Guidance and Control

Applications

Medical

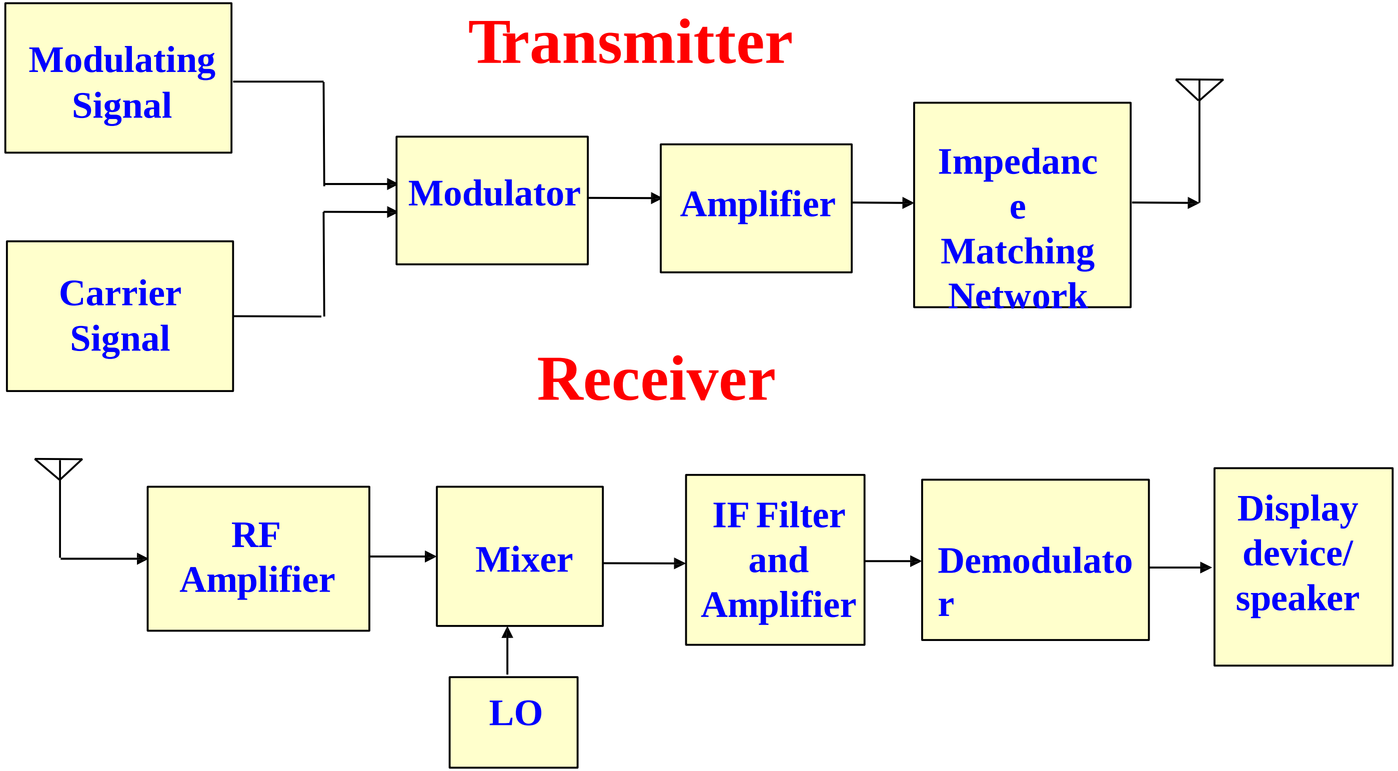
Cancer/Tumor Detection

Medical Diagnostics and Therapy

Applications and Frequency Bands

- FM Radio – Frequency: 88 to 108 MHz
- CDMA – 824 to 890 MHz
- GSM 900 - 890 to 915 and 935 to 960 MHz
- GPS – 1575 $\pm$ 10 MHz
- GSM1800 – 1710 to 1780 and 1810 to 1880 MHz
- 3G - 1920 to 1980 and 2110 to 2170 MHz
- 4G – 2300 to 2400 MHz
- Wi-Fi – 2400 to 2483 MHz and 5.2/5.8 GHz Band
- Satellite and Defense Communications (HF to mm wave)

Microwave Communication Systems



Properties of Microwaves

- Microwave is an electromagnetic radiation of short wavelength.
- They can reflect by conducting surfaces just like optical waves since they travel in straight line.
- Microwave currents flow through a thin outer layer of an ordinary cable.
- Microwaves are easily attenuated within short distances.
- They are not reflected by ionosphere

Advantages and Limitations

❑ Increased bandwidth availability:

- Microwaves have large bandwidths compared to the common bands like short waves (SW), ultrahigh frequency (UHF) waves, etc.
- For example, the microwaves extending from $\lambda = 1$ cm to $\lambda = 10$ cm (i.e) from 30,000 MHz – 3000 MHz, this region has a bandwidth of 27,000 MHz.

❑ Improved directive properties:

- The second advantage of microwaves is their ability to use high gain directive antennas, any EM wave can be focused in a specified direction (Just as the focusing of light rays with lenses or reflectors)

Advantages and Limitations

Fading effect and reliability:

- Fading effect due to the variation in the transmission medium is more effective at low frequency.
- Due to the Line of Sight (LOS) propagation and high frequencies, there is less fading effect and hence microwave communication is more reliable.

Power requirements:

- Transmitter / receiver power requirements are pretty low at microwave frequencies compared to that at short wave band.

Applications of Microwaves

- **Telecommunication:** Intercontinental Telephone and TV, space communication (Earth – to – space and space – to – Earth), telemetry communication link for railways etc.

- **Radars:** Detect aircraft, track / guide supersonic missiles, observe and track weather patterns, air traffic control (ATC), burglar alarms, garage door openers, police speed detectors etc.

- **Biomedical Applications (diagnostic / therapeutic) –** Diathermy for localized superficial heating, deep electromagnetic heating for treatment of cancer, hyperthermia (local, regional or whole body for cancer therapy).

Applications of Microwaves

❑ Commercial and Industrial applications of Microwaves :

- Microwave oven
- Drying machines – textile, food and paper industry for drying clothes, potato chips, printed matters etc.
- Food process industry – Pre cooling / cooking, pasteurization / sterility, hat frozen / refrigerated pre cooled meats, roasting of food grains / beans.
- Rubber industry / plastics / chemical / forest product industries
- Mining / public works, breaking rocks, tunnel boring, drying / breaking up concrete, breaking up coal seams, curing of cement.
- Drying inks / drying textiles, drying / sterilizing grains, drying / sterilizing pharmaceuticals, leather, tobacco, power transmission.

Applications of Microwaves

- Identifying objects or personnel by non – contact method.

- Light generated charge carriers in a microwave semiconductor make it possible to create a whole new world of microwave devices, fast jitter free switches, phase shifters, HF generators, etc.

Microwave Passive Components

- E-plane tee, H-plane tee, Magic tee
- Directional Coupler
- Circulator
- Corners, bends and twists

Microwave Tee Junction:

- The interconnection of two or more microwave devices may be regarded as a **microwave junction**.

- Three-Port Networks (T-Junctions): The simplest type of power divider is a T-junction, which is a three-port network with two inputs and one output.

Characteristics of a Three port Junction

1) A short circuit may always be placed in one of the arms of a three-port junction in such a way that no power can be transferred through the other two arms.
2) If the junction is symmetric about one of its arms, a short circuit can always be placed in that arm so that no reflections occur in power transmission between the other two arms. (i.e the arms present matched impedances.)
3) It is impossible for a general three-port junction of arbitrary symmetry to present matched impedances at all three arm

Three-Port Networks (T-Junctions)

- The scattering matrix of an arbitrary three-port network has nine independent elements:

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

- If the device is passive and contains no anisotropic materials, then it must be reciprocal and its scattering matrix will be symmetric $\boldsymbol{S_{ij} = S_{ji}}$

Three-Port Networks (T-Junctions)

- To avoid power loss - have a junction - lossless and matched at all ports.
- It is impossible to construct such a three-port lossless reciprocal network that is matched at all ports.
- If all ports are matched, then $S_{ii} = 0$, and if the network is reciprocal, the scattering matrix of (1) reduces to:

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix} \qquad \textbf{(2)}$$

Three-Port Networks (T-Junctions)

- If the network is also lossless, then energy conservation requires that the scattering matrix satisfy the unitary properties:

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix} \quad => \quad \begin{aligned} |S_{12}|^2 + |S_{13}|^2 &= 1 \\ |S_{12}|^2 + |S_{23}|^2 &= 1 \\ |S_{13}|^2 + |S_{23}|^2 &= 1 \end{aligned} \qquad (3)$$

For a Lossless network:

$$\sum_{k=1}^{N} S_{ki}\ S_{kj}{}^{*} = 1, for\ i = j$$

$$\sum_{k=1}^{N} S_{ki}\ S_{kj}{}^{*} = 0, for\ i \neq j$$

$$\begin{aligned} S_{13}{}^{*}S_{23} &= 0 \\ S_{23}{}^{*}S_{12} &= 0 \\ S_{12}{}^{*}S_{13} &= 0 \end{aligned} \qquad (4)$$

Three-Port Networks (T-Junctions)

- Eqn (4) shows that at least two of the three parameters (S_{12}, S_{13}, S_{23}) must be zero.
- This condition will always be inconsistent with one of equations in (3), implying that a three-port network cannot be simultaneously lossless, reciprocal and matched at all ports.
- If any one of these three conditions is relaxed, then a physically realizable device is possible.

Three-Port Networks (T-Junctions)

- If the three-port network is nonreciprocal, then $S_{ij} \neq S_{ji}$, and the conditions of input matching at all ports and energy conservation can be satisfied.

- It is known as a *circulator*, and generally relies on an anisotropic material, such as ferrite, to achieve nonreciprocal behaviour.

Three-Port Networks (T-Junctions)

- Any matched lossless three-port network must be nonreciprocal and thus a circulator.

- The scattering matrix of a matched three-port network has the following form:

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{21} & 0 & S_{23} \\ S_{31} & S_{32} & 0 \end{bmatrix} \qquad (5)$$

Three-Port Networks (T-Junctions)

➢If the network is lossless, [S] must be unitary, which implies the following conditions:

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{21} & 0 & S_{23} \\ S_{31} & S_{32} & 0 \end{bmatrix} \quad => \quad \begin{aligned} S_{31}{}^{*} S_{32} &= 0 \\ S_{21}{}^{*} S_{23} &= 0 \\ S_{12}{}^{*} S_{13} &= 0 \end{aligned} \qquad (6)$$

For a Lossless network:

$$\sum_{k=1}^{N} S_{ki}\, S_{kj}{}^{*} = 1, for\ i = j$$

$$\sum_{k=1}^{N} S_{ki}\, S_{kj}{}^{*} = 0, for\ i \neq j$$

$$\begin{aligned} |S_{12}|^2 + |S_{13}|^2 &= 1 \\ |S_{21}|^2 + |S_{23}|^2 &= 1 \\ |S_{31}|^2 + |S_{32}|^2 &= 1 \end{aligned} \qquad (7)$$

Three-Port Networks (T-Junctions)

- These equations can be satisfied in one of two ways. Either

$$S_{12} = S_{23} = S_{31} = 0, \qquad |S_{21}| = |S_{32}| = |S_{13}| = 1;$$

- Or

$$S_{21} = S_{32} = S_{13} = 0, \qquad |S_{12}| = |S_{23}| = |S_{31}| = 1;$$

- These results shows that $\boldsymbol{S_{ij}} \neq \boldsymbol{S_{ji}}$ for i ≠ j, which implies that the device must be nonreciprocal.

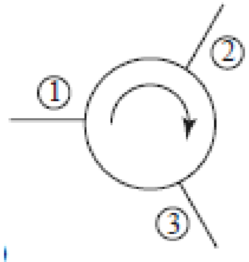
Three-Port Networks (T-Junctions)

$$S_{12} = S_{23} = S_{31} = 0 \quad \&$$
$$|S_{21}| = |S_{32}| = |S_{13}| = 1;$$

- The corresponding S Matrix is,

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

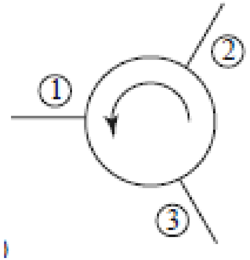
(a) Clockwise circulation



$$S_{21} = S_{32} = S_{13} = 0,$$
$$|S_{12}| = |S_{23}| = |S_{31}| = 1;$$

- The corresponding S Matrix is,

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



(b) Counter clockwise circulation

Three-Port Networks (T-Junctions)

- Alternatively, a lossless and reciprocal three-port network can be physically realized if only two of its ports are matched.
- If ports1and 2 are the matched ports, then the scattering matrix can be written as,

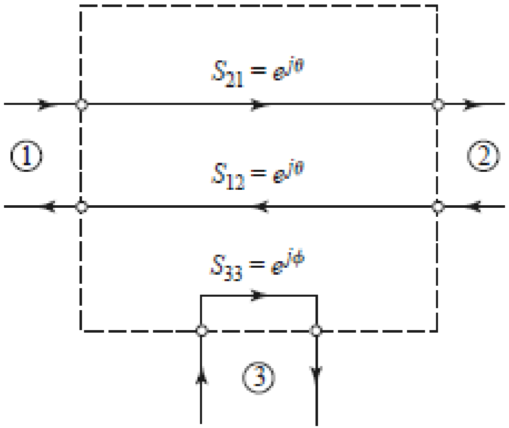
$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} \qquad (8)$$

Three-Port Networks (T-Junctions)

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} \quad => $$

$$\begin{aligned} S_{13}^* S_{23} &= 0, \\ S_{12}^* S_{13} + S_{23}^* S_{33} &= 0, \\ S_{23}^* S_{12} + S_{33}^* S_{13} &= 0, \end{aligned} \qquad (9)$$

$$[S] = \begin{bmatrix} 0 & e^{j\theta} & 0 \\ e^{j\theta} & 0 & 0 \\ 0 & 0 & e^{j\phi} \end{bmatrix}$$



A reciprocal lossless three-port network matched at ports 1 and 2.

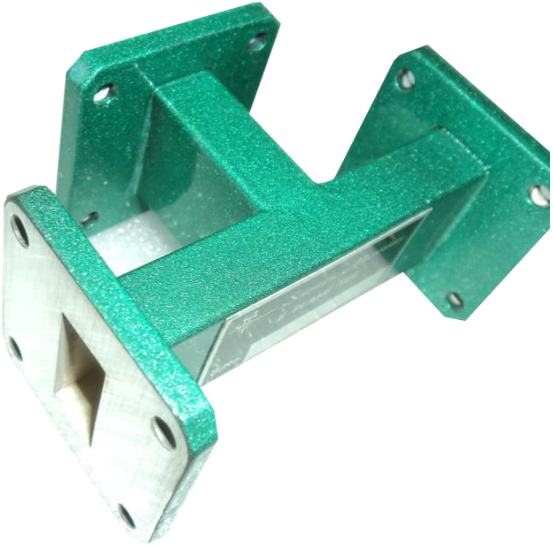
$$\begin{aligned} |S_{12}|^2 + |S_{13}|^2 &= 1, \\ |S_{12}|^2 + |S_{23}|^2 &= 1, \\ |S_{13}|^2 + |S_{23}|^2 + |S_{33}|^2 &= 1. \end{aligned} \qquad (10)$$

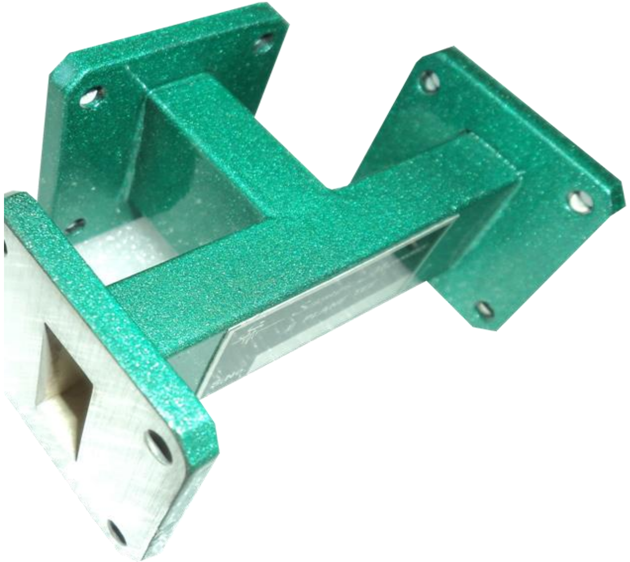
Waveguide Tee

- A Waveguide Tee is a 3-port device that can be used to either divide or combine power in a waveguide system. It is formed when three waveguides tubes are connected in the form of the English alphabet 'T'. This is where its name is derived from.
- Waveguide Tee junctions are used to split the line power into two or to combine the power from two lines with proper consideration of phase at Microwave Frequencies

E-plane Tee

- An E-plane TEE is a waveguide tee in which the axis of side arm is parallel to the E field of the main guide. If the collinear arms are symmetric about the side arms, there are two arm characteristics. When wave are fed into the side arms, the wave appear in the collinear arms will be in opposite phase and in the same magnitude.



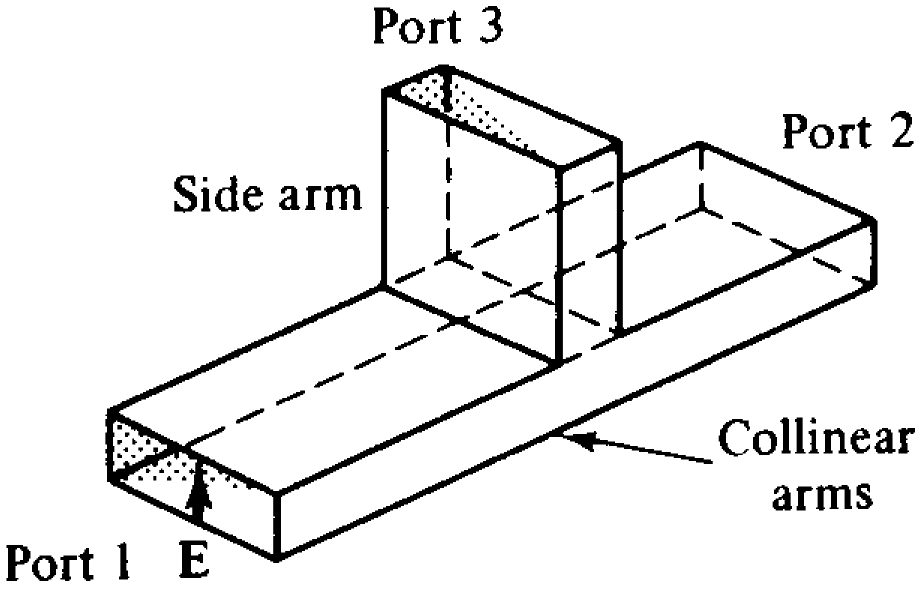


Specifications

Model	Band	Freq. Range(GHz)	Waveguide	VSWR
SET-154	S	2.60-3.95	WR-284	1.2
CET-154	C	3.95-5.85	WR-229	1.2
JET-154	J	5.85-8.20	WR-137	1.2
XET-154	X	8.20-12.40	WR-90	1.2
KuET-154	Ku	12.40-18.00	WR-62	1.2
KET-154	K	18.00-26.50	WR-42	1.2

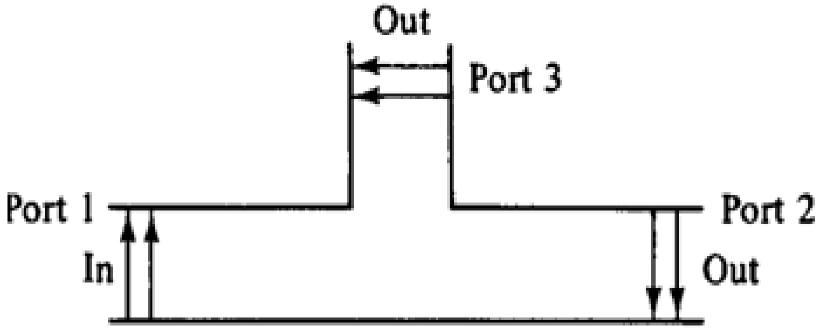
E-plane Tee

- A waveguide tee in which the **axis** of its side arm is **parallel to the E-field** of the main guide.



Series Tee

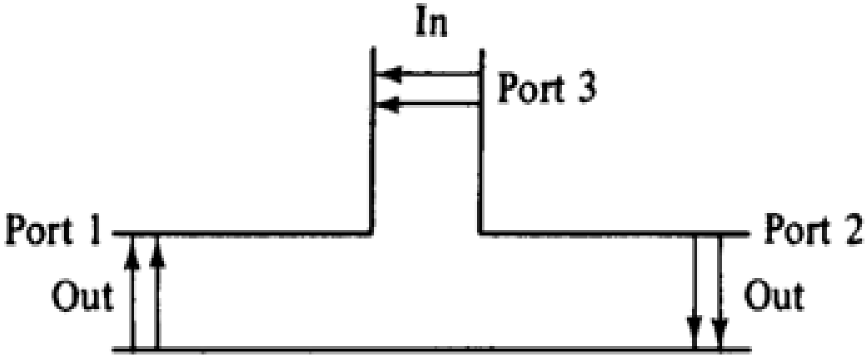
Transmission characteristics of E-plane Tee



(a)

When two inputs are fed into Port 1 and Port 2 of the collinear arm , the output wave at port 3 will be subtractive and opposite in phase. So the third port is called Difference arm

Transmission characteristics of E-plane Tee



(b)

When the waves are fed into the side arm (port 3), the waves appearing at port1 and port 2 of the collinear arm will be in the opposite phase and in the same magnitude.

S13= -S23

E-plane Tee

- The general S matrix of a Three port network is

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$

- If E-plane tee is perfectly matched with the aid of screw tuners or inductive or capacitive windows at the junction, the diagonal components of the S-matrix, S11, S22 and S33 **are zero** because there will be no reflection.

- Here let port 3 is matched,

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & 0 \end{bmatrix}$$

E-plane Tee

- Symmetry property : $S_{12} = S_{21}$, $S_{13} = S_{31}$ and $S_{23} = S_{32}$; WKT $S_{13}=-S_{23}$, then

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & 0 \end{bmatrix} \longrightarrow \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & -S_{13} \\ S_{13} & -S_{13} & 0 \end{bmatrix}$$

- From Unitary Property $[S][S]^* = [I]$,

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

- From Unitary Property,

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

from · $\underline{R_1C_1}$: $|S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = 1$ — (1)

$\underline{R_2C_2}$: $|S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1$ — (2)

$\underline{R_3C_3}$: $|S_{13}|^2 + |S_{13}|^2 = 1$ — (3)

$\boxed{S_{13} = \frac{1}{\sqrt{2}}}$ — (4)

Contd..,

from R_3C_1: $S_{13}S_{11}^* - S_{13}S_{12}^* = 0$

By equating we get

$$\boxed{S_{11} = S_{12}} \quad -⑤$$

from R_1C_1, R_2C_2: By equating R_1C_1 and R_2C_2

$$|S_{11}|^2 + \cancel{|S_{12}|^2} + \cancel{|S_{13}|^2} = \cancel{|S_{12}|^2} + |S_{22}|^2 + \cancel{|S_{13}|^2}$$

$$\boxed{S_{11} = S_{22}} \quad -⑥$$

from eq ⑤ & ⑥

$$S_{11} = S_{12} = S_{22}$$

Substitute $S_{12} = S_{11}$ in eq ①

$$|S_{11}|^2 + |S_{11}|^2 + |S_{13}|^2 = 1$$

$$2|S_{11}|^2 + \left(\frac{1}{\sqrt{2}}\right)^2 = 1$$

$$\boxed{S_{11} = 1/2}$$

S Matrix of E Plan Tee

Substitute the values in [S] matrix we get

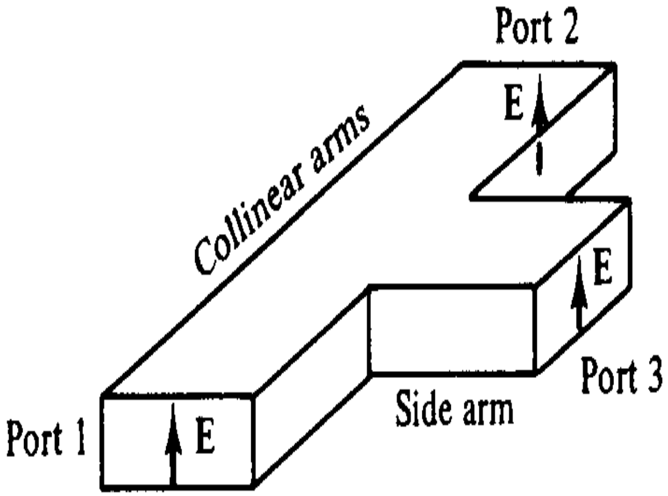
$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & -S_{13} \\ S_{13} & S_{13} & 0 \end{bmatrix} = \begin{bmatrix} 1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & 1/2 & -1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} & 0 \end{bmatrix}$$

Microwave Tee Junction:

- The interconnection of two or more microwave devices may be regarded as a **microwave junction**.

- Three-Port Networks (T-Junctions): The simplest type of power divider is a T-junction, which is a three-port network with two inputs and one output.

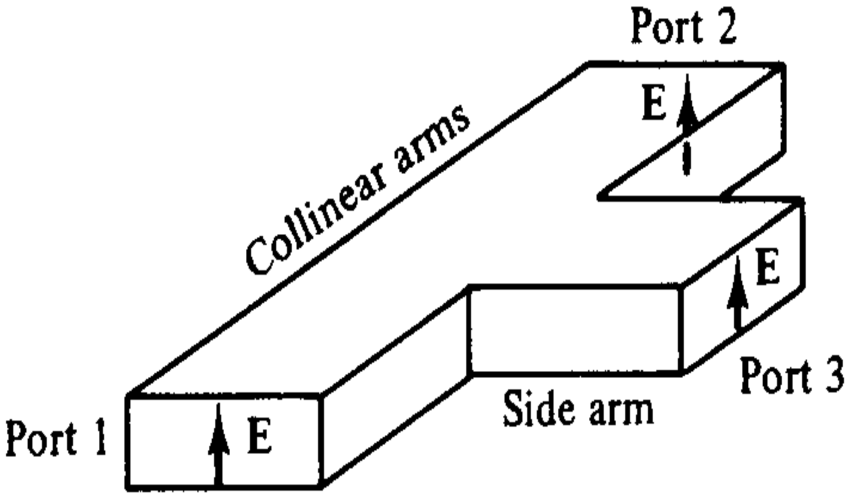
H-plane Tee:



Shunt Tee

- H-Plane Tee junction is formed by attaching a simple waveguide to a rectangular waveguide which already has two ports.
- The arms of rectangular waveguides make two ports called collinear ports i.e., Port 1 and Port 2, while the new one, Port 3 is called as Side arm or H-arm.
- This H-plane Tee is also called as Shunt Tee.

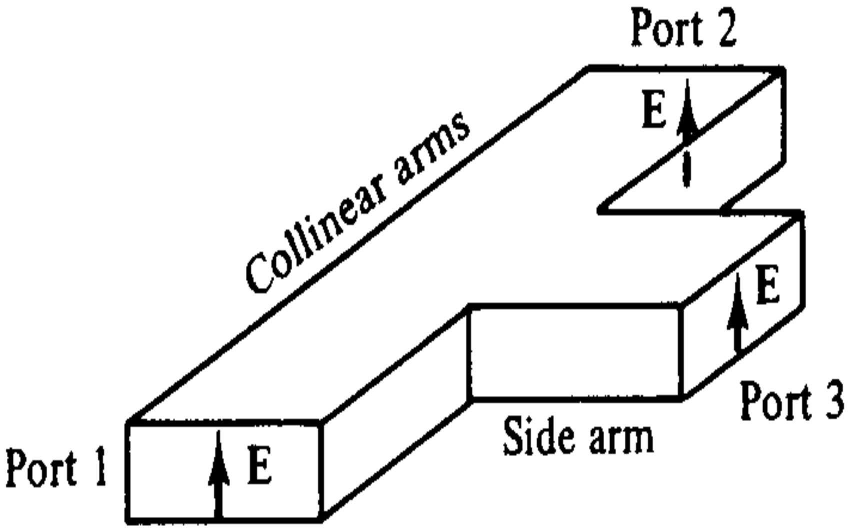
H-plane Tee



Shunt Tee

- As the axis of the side arm is parallel to the magnetic field, this junction is called as H-Plane Tee junction.
- Also called as Current junction, as the magnetic field divides itself into arms.

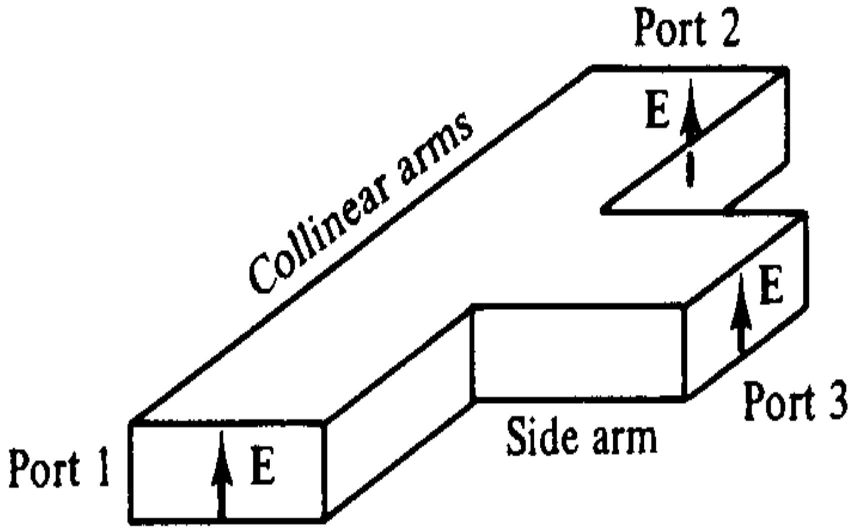
H-plane Tee



Shunt Tee

- A waveguide tee in which the axis of its side arm is “shunting” the E-field or parallel to the H-field of the main guide.

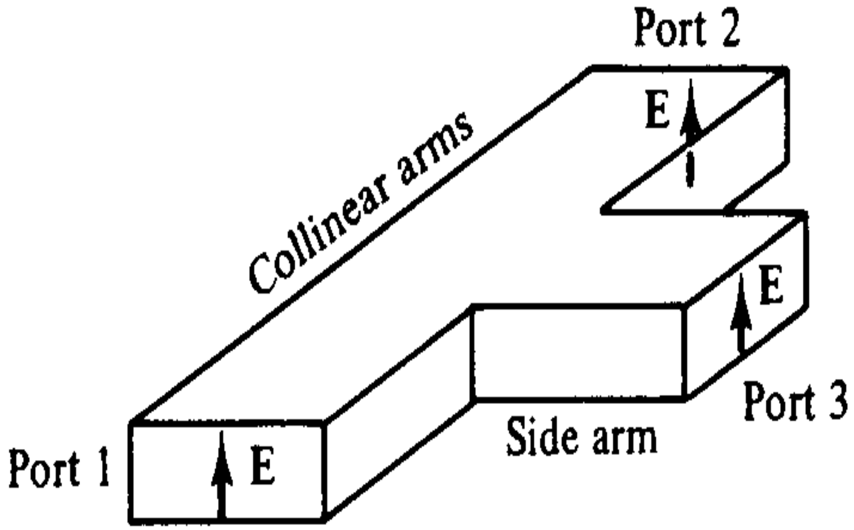
H-plane Tee – working principle



Shunt Tee

- If two input waves are fed into port 1 and port 2 of the collinear arm, the output wave at port 3 will be in phase and additive.
- The third port is called "Sum arm".

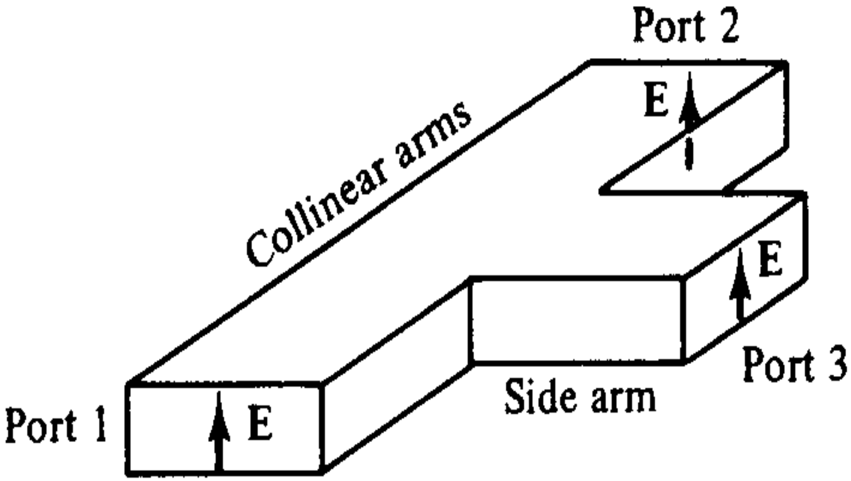
H-plane Tee – working principle



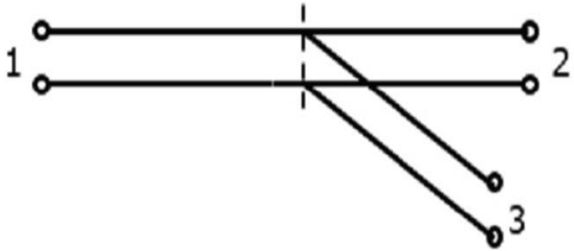
Shunt Tee

- If the input is fed into port 3, the wave will split equally into port 1 and port 2, which are in phase and in the same magnitude.
- i.e. $S_{13} = S_{23}$

H-plane Tee



Shunt Tee



- The connection made by the side arm to the bi-directional waveguide to form the serial port.

H-plane Tee

- It is a 3-port network. S matrix is given by,

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

- Since the junction is symmetrical in plane, $S_{13} = S_{23}$ (2)
- From symmetry property,

$$S_{12} = S_{21} \;\; S_{23} = S_{32} = S_{13} \;\; S_{13} = S_{31} \qquad (3)$$

- The third port is perfectly matched, i.e. $S_{33} = 0$

H-plane Tee

- The S matrix in (1) becomes,

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

$$S_{13} = S_{23}; \; S_{33} = 0$$

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

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & S_{13} \\ S_{13} & S_{13} & 0 \end{bmatrix} \qquad (4)$$

From the unitary property,

$$[S][S]^* = [I] \qquad (5)$$

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

H-plane Tee

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & S_{13} \\ S_{13} & S_{13} & 0 \end{bmatrix} \begin{bmatrix} S_{11}^* & S_{12}^* & S_{13}^* \\ S_{12}^* & S_{22}^* & S_{13}^* \\ S_{13}^* & S_{13}^* & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (6)$$

- Multiplying and Equating the elements,
- R_1C_1: $S_{11}S_{11}^* + S_{12}S_{12}^* + S_{13}S_{13}^* = 1$ => $|S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = 1$ (7)
- R_2C_2: => $|S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1$ (8)
- R_3C_3: => $|S_{13}|^2 + |S_{13}|^2 = 1$ (9)
- R_3C_1: => $S_{13}S_{11}^* + S_{13}S_{12}^* = 0$ (10)

H-plane Tee

From (9), $|S_{13}|^2 + |S_{13}|^2 = 1 \Rightarrow 2|S_{13}|^2 = 1 \Rightarrow |S_{13}|^2 = \frac{1}{2} \Rightarrow S_{13} = \frac{1}{\sqrt{2}}$ (11)

From (10), $S_{13}S_{11}^* + S_{13}S_{12}^* = 0 \Rightarrow S_{11} = -S_{12}\ (or)\ S_{12} = -S_{11}$ (12)

From (8), $|S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1$ & From (7), $|S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = 1$

When comparing (7) & (8) => $|S_{11}|^2 = |S_{22}|^2$ => $S_{11} = S_{22}$ (13)

Using eqns 11, 12, & 13 in (8), we get $S_{11} = \frac{1}{2} = S_{22}$; $S_{12} = \frac{-1}{2}$

H-plane Tee

- Substituting all values in (4)

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & S_{13} \\ S_{13} & S_{13} & 0 \end{bmatrix} \qquad (4)$$

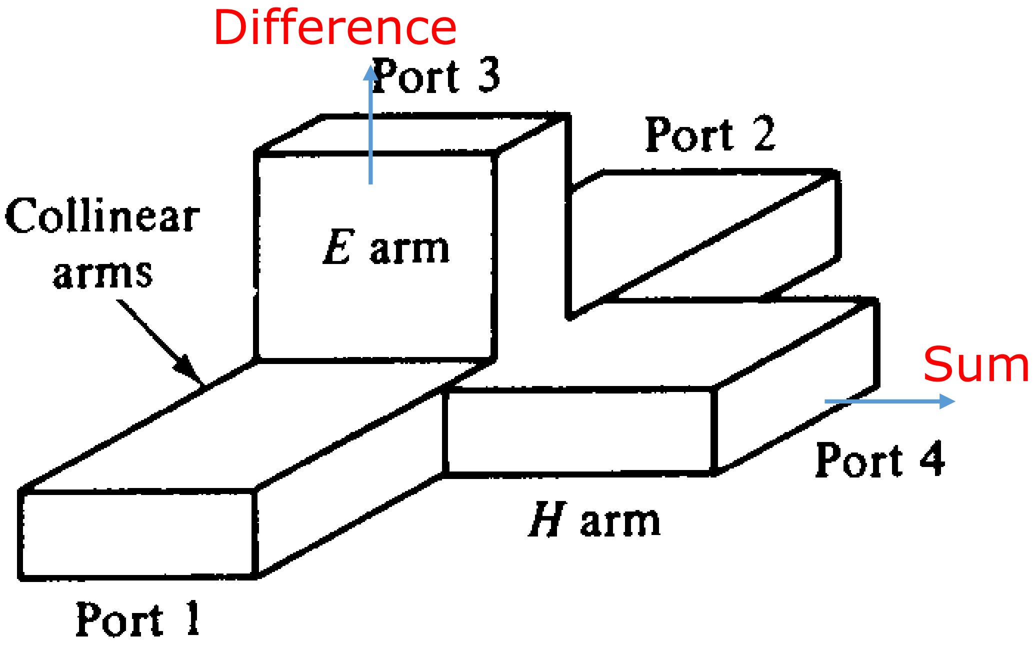
$$S_{11} = \frac{1}{2} = S_{22};$$

$$S_{12} = \frac{-1}{2} \;\&\; S_{13} = \frac{1}{\sqrt{2}}$$

The S matrix of H plane tee becomes,

$$[S] = \begin{bmatrix} \frac{1}{2} & \frac{-1}{2} & \frac{1}{\sqrt{2}} \\ \frac{-1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \end{bmatrix}$$ which explains its scattering properties.

Magic Tees (Hybrid Tees)



Combination of the E-plane and H-plane tees forms a hybrid tee, called Magic-T having 4 ports as shown

Magic Tees (Hybrid Tees)

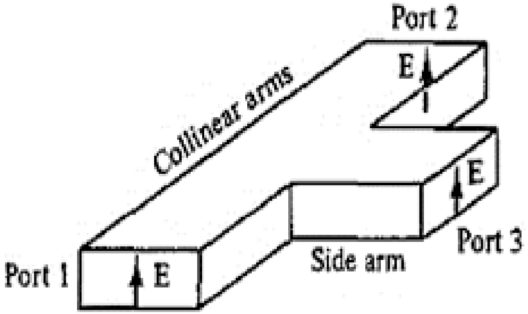
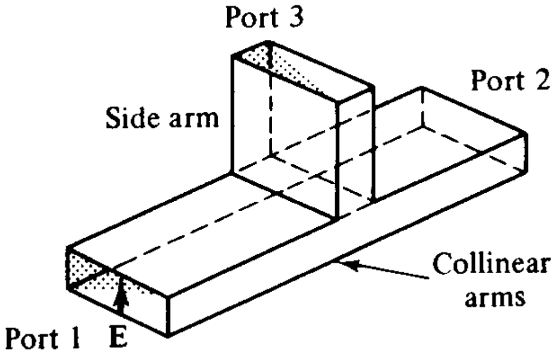
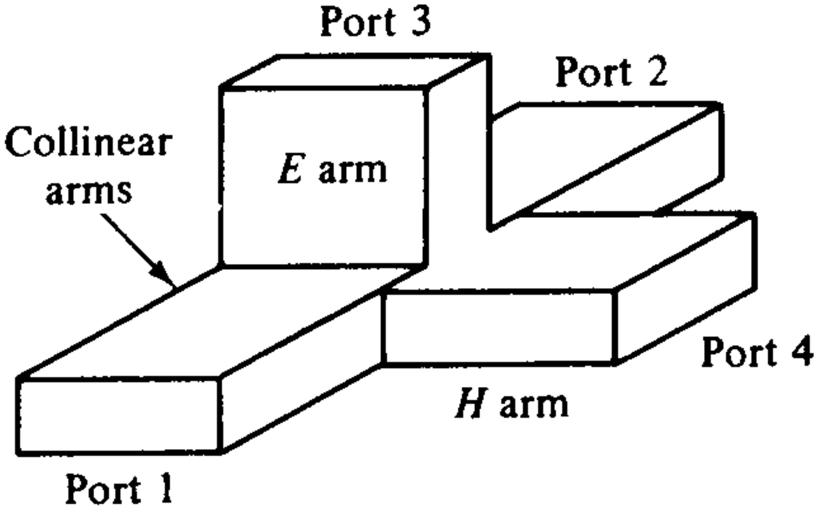
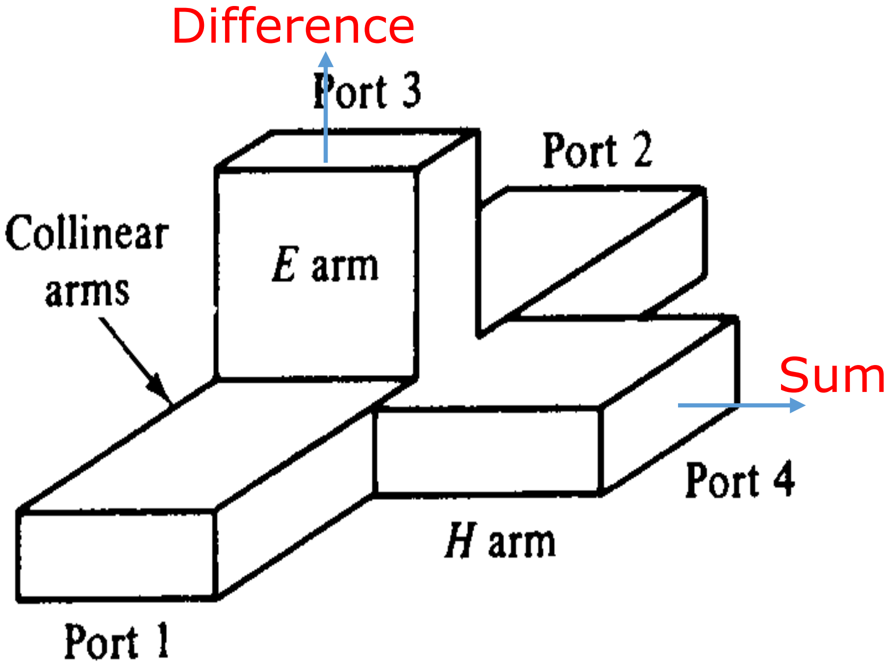


Fig. H-plane tee



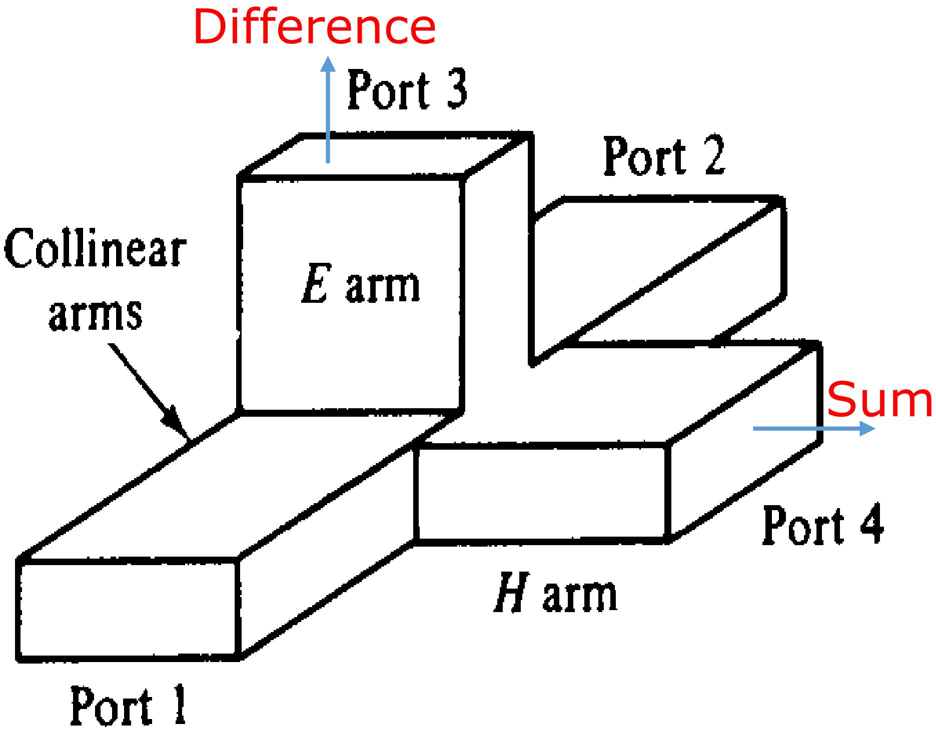


Magic Tees (Hybrid Tees)



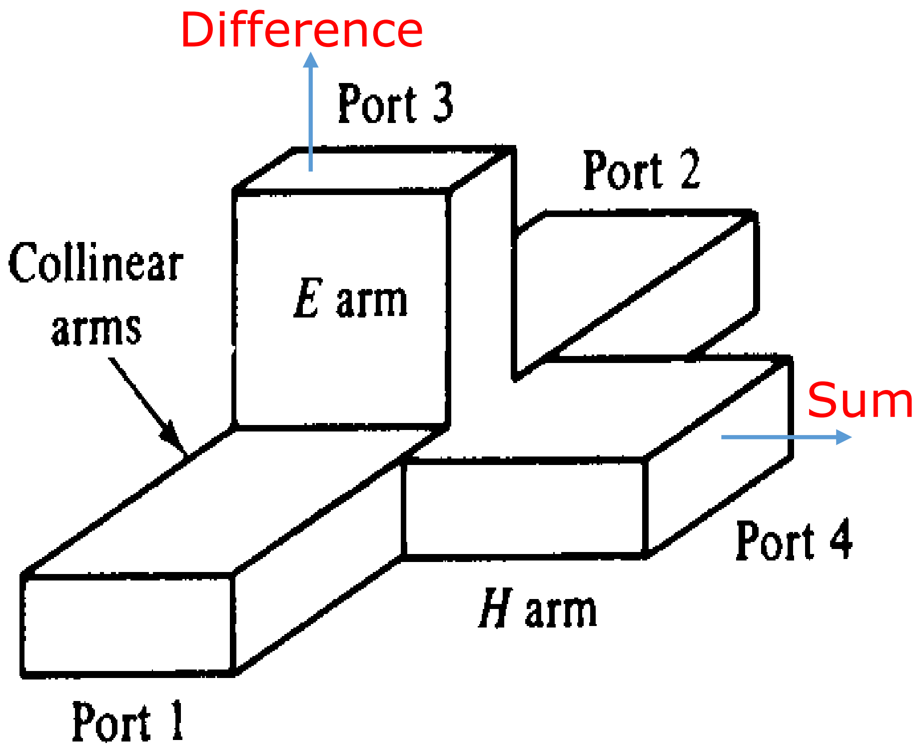
- If two waves of equal magnitude and the same phase are fed into port 1 and port 2, the output at port 3 is subtractive and hence zero. Total output power will appear additively at port 4.
- Hence Port 3 is called Difference or E-arm and Port 4 is called Sum or H-arm.

Magic Tees (Hybrid Tees)



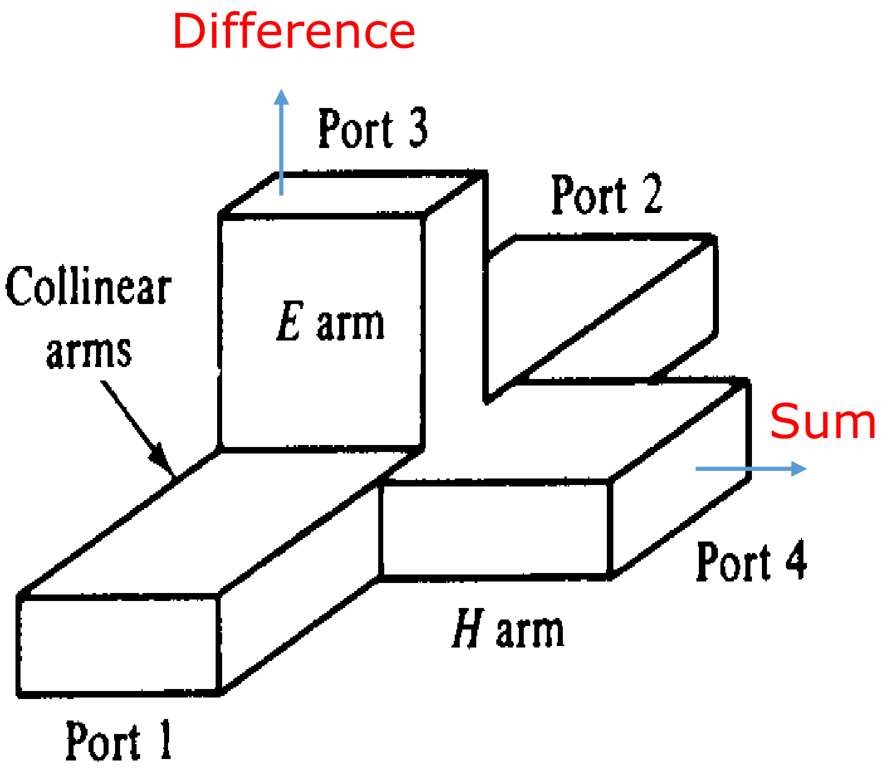
- If a wave is fed into port 4 (H arm), it will be divided equally between port 1 and port 2 of the collinear arms and will not appear at port 3 (E arm).

Magic Tees (Hybrid Tees)



- If a wave is fed into port 3 (E arm), it will produce an output of equal magnitude and opposite phase at port 1 and port 2. Output at port 4 is zero
- S43 = S34 = 0.

Magic Tees (Hybrid Tees)

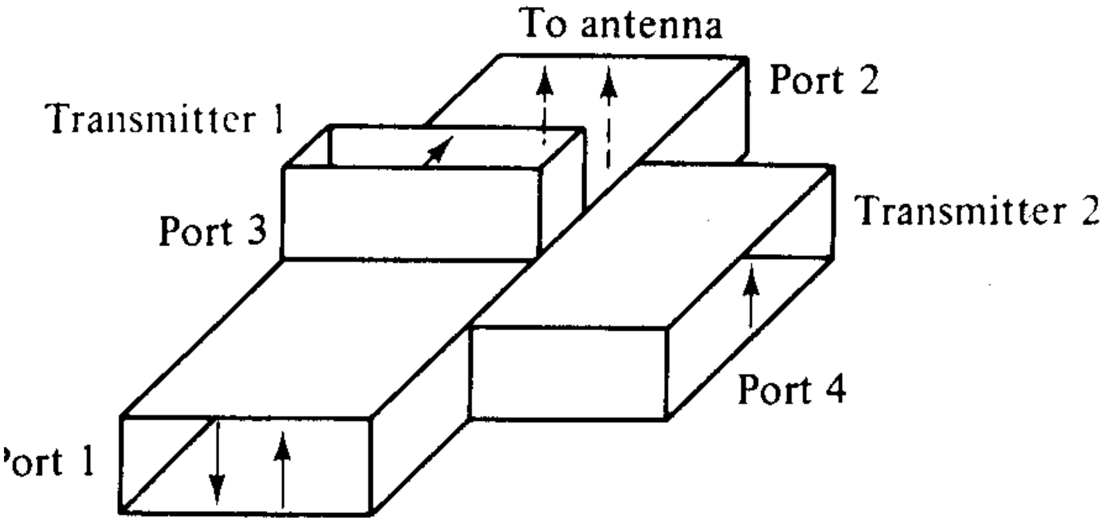


- If a wave is fed into one of the collinear arms at port 1 or port 2, it will not appear in the other collinear arm at port 2 or port 1 because the E arm causes a phase delay while the H arm causes the phase advance.
- S12 = S21 = 0.

Applications of Magic Tee

- As an Isolator
- As a Mixer
- As a Duplexer
- As a Matching device
- Impedance measurements.
- Radar transmitters

Applications of Magic Tee



Magic Tee coupled transmitters to antenna

Waveguide Corners, Bends, and Twists

- The size, shape, and dielectric material of a waveguide must be constant throughout its length for energy to move from one end to the other without reflections.
- Any abrupt change in its size or shape can cause reflections and a loss in overall efficiency.
- When such a change is necessary, the bends, twists, and joints of the waveguides must meet certain conditions to prevent reflections.

Waveguide Bends – E Bend

- Waveguides may be bent in several ways that do not cause reflections. One way is the gradual bend.
- This gradual bend is known as an E bend because it distorts the E fields.
- The E bend must have a radius greater than two wavelengths to prevent reflections.

Waveguide Bends - H Bend

- Another common bend is the gradual H bend shown in the left part of the figure. It is called an H bend because the H fields are distorted when a waveguide is bent in this manner. Again, the radius of the bend must be greater than two wavelengths to prevent reflections.
- A sharp bend in either dimension may be used if it meets certain requirements. Notice the two 45-degree bends in figure; the bends are $1/4 \cdot \lambda$ apart. The reflections that occur at the 45-degree bends cancel each other, leaving the fields as though no reflections have occurred.

Waveguide Bends- E Bend & H Bend

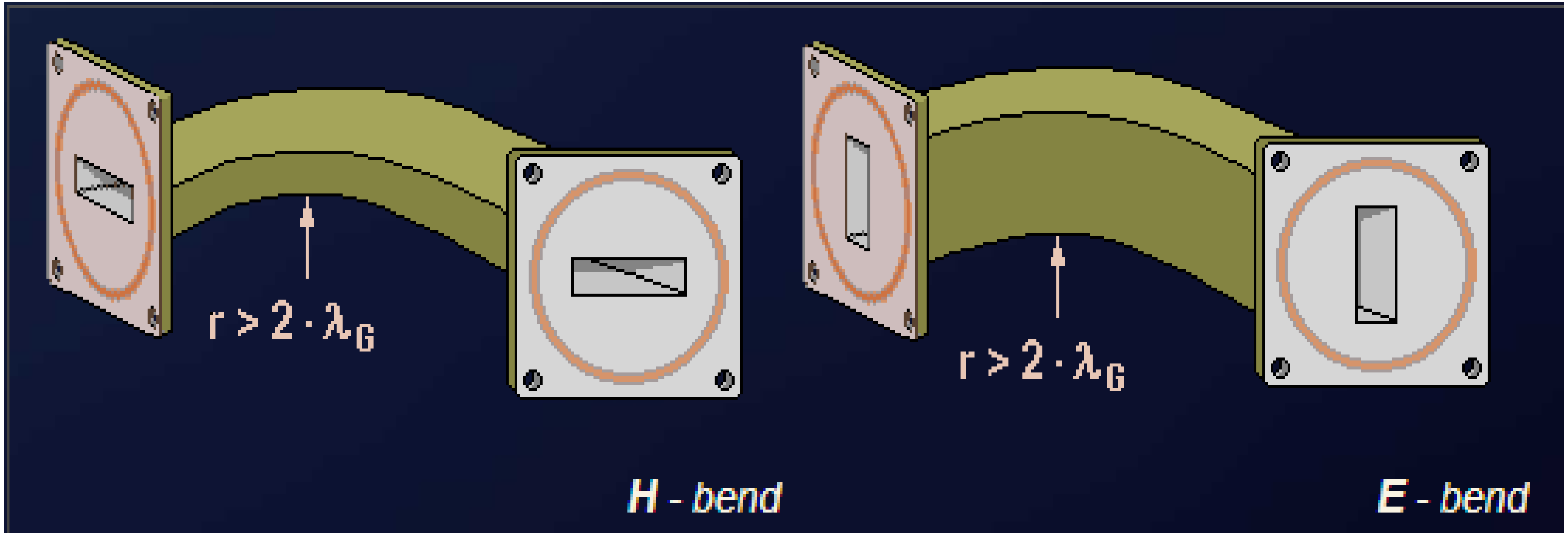
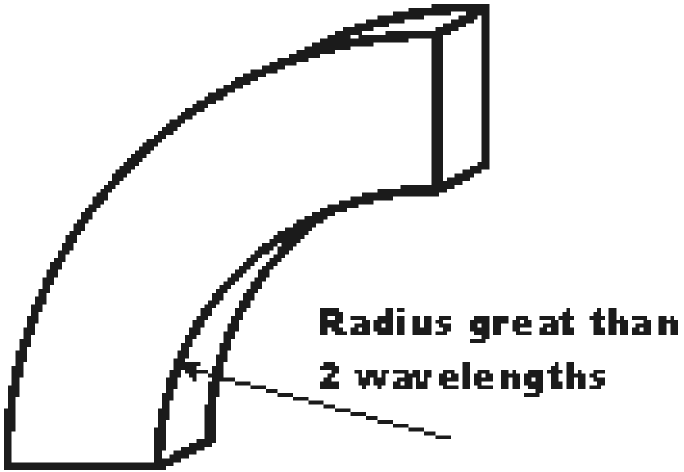
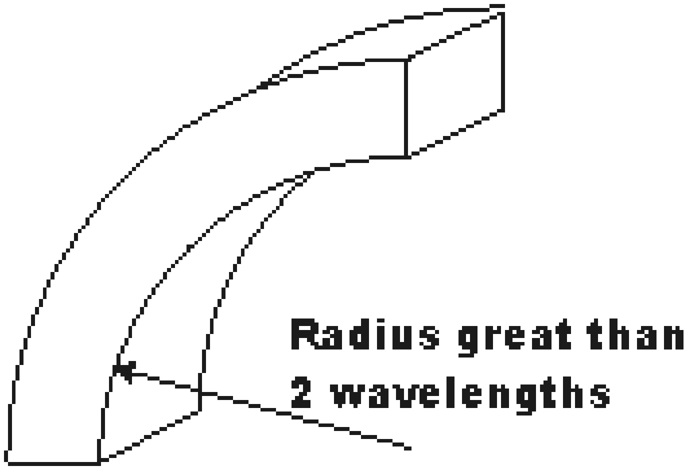


Figure 1: Waveguide bends

Waveguide Bends- E Bend & H Bend



Waveguide H bend



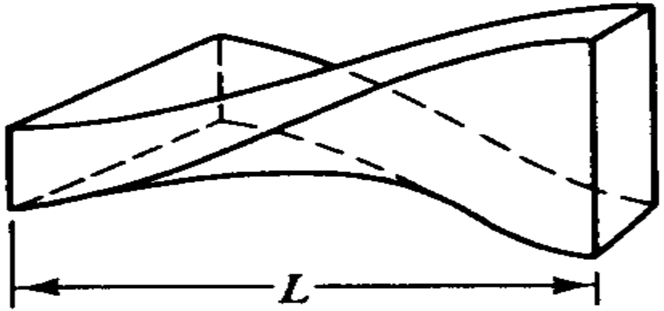
Waveguide E bend

Waveguide Twists

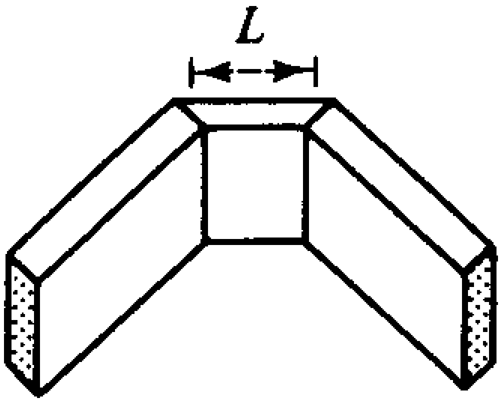
- Sometimes the electromagnetic fields must be rotated so that they are in the proper phase to match the phase of the load.
- This may be accomplished by twisting the waveguide as shown in the figure. The twist must be gradual and greater than two wavelengths ($2\cdot\lambda$).

Waveguide Corners, Bends, and Twists

- In order to prevent undue distortion on the waveform a 90° twist should be undertaken over a distance greater than two wavelengths of the frequency in use.
- If a complete inversion is required, e.g. for phasing requirements, the overall inversion or 180° twist should be undertaken over a four wavelength distance

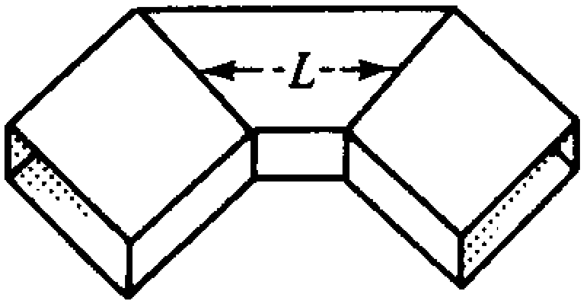


Waveguide Corners, Bends, and Twists



(a)

E plane Corner



(b)

H plane Corner

Waveguide Corners, Bends, and Twists

- These waveguide components are normally used to change the direction of the guide through an arbitrary angle.
- In order to minimize reflections from the discontinuities, it is desirable to have the mean length L between continuities equal to an odd number of quarter wavelengths.

i.e

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

where $n = 0, 1, 2, 3, \ldots$, and λ_g is the wavelength in the waveguide.

Waveguide Corners, Bends, and Twists

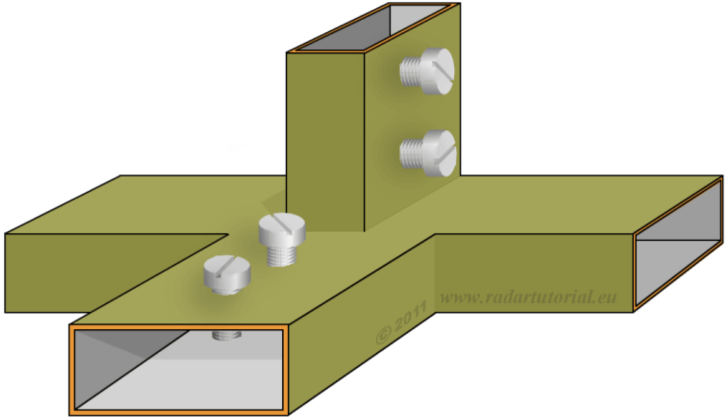
- If the mean length L is an odd number of quarter wavelengths, the reflected waves from both ends of the waveguide section are completely cancelled.
- For the waveguide bend, the minimum radius of curvature for a small reflection is given by

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

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

- Where a and b are the dimensions of the bend.

Waveguide Impedance Matching



Normally a magic-T needs an impedance matching shown in the figure as matching screws

Waveguide Summary

- The walls of the waveguide have only the function, to prevent that the electric magnetic waves deviate from the specified way.
- Waveguides have lower losses and are more charge as comparable coaxial cables.
- Waveguide haven't any practical meaning at frequencies by less than 1000 MHz because of the dependence of its geometric measurements of the transferred frequency.

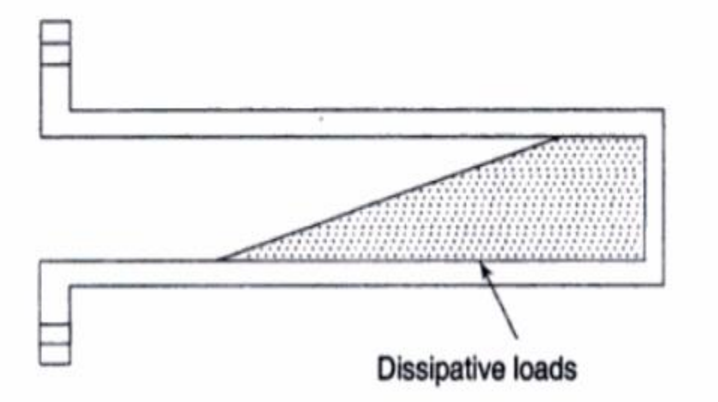
Waveguide Summary

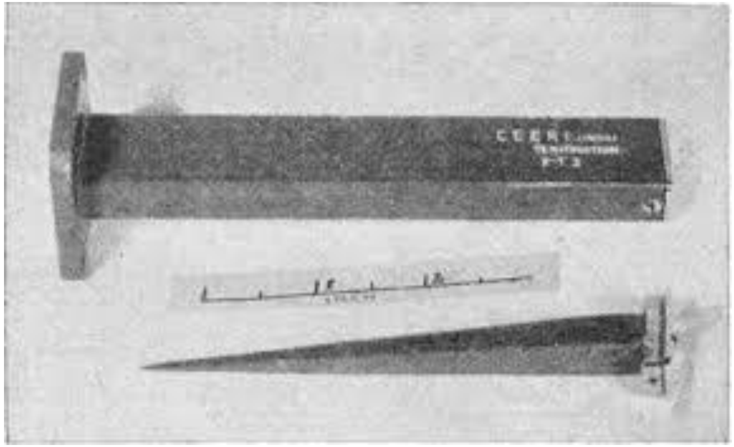
- There are electrical fields only vertically to conducting areas, magnetic fields can there be only parallelly to conducting areas
- The fields are moving by reflection between the covers of the waveguide.
- Waveguide being able to be operated only above the critical frequency. Applies to the cut off wavelength of rectangular waveguide: $\lambda_{cutoff} = 2 \cdot a$
- In the waveguide ongoing waves can only exist by exact termination with the impedance (E- and H-Feld in phase).

Matched Terminator

- Terminator is a device which is connected to the last peripheral device in a sequence or the last node in a network.
- Coaxial terminators and waveguide terminators are collectively known as radio frequency terminators or **microwave terminators**.
- They are used to absorb energy and prevent a signal from reflecting back from open-ended or unused ports.

Matched Terminator





Matched Termination

Problem

Example 6.2 A waveguide termination having VSWR of 1.1 is used to dissipate 100 watts of power. Find the reflected power.

Solution

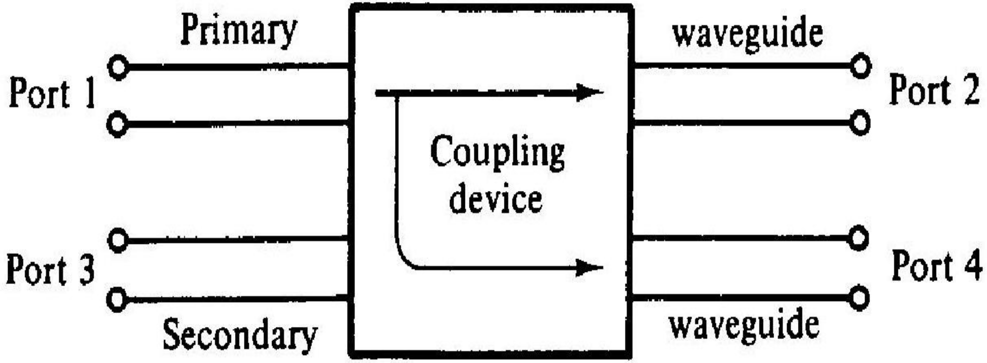
$$|\Gamma| = \frac{S-1}{S+1} = \frac{1.1-1}{1.1+1} = \frac{0.1}{2.1}$$

$$= 0.04762$$

$$P_{ref} = |\Gamma|^2 P_i = (0.04762)^2 \times 100 = 0.2268 \text{ W}$$

Directional Coupler:

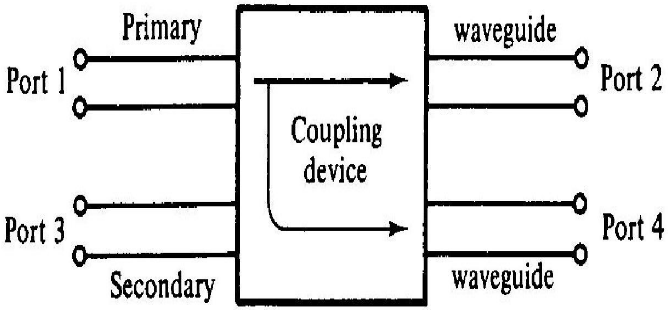
- It is a 4-port passive device used for coupling a known fraction of the microwave power to a port (coupled port) in the auxiliary line while flowing from input port to output port in the main line.
- Remaining port is ideally isolated port and matched port.



Directional Coupler:

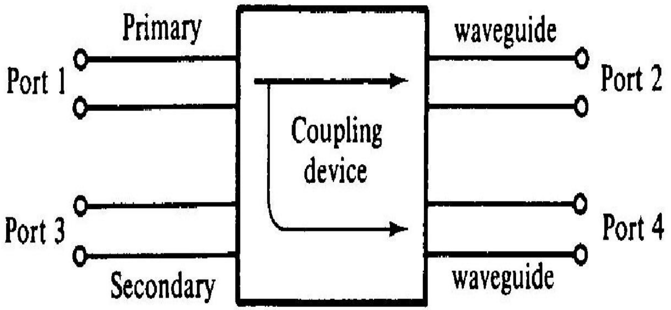
- Directional coupler is used to couple the Microwave power which may be unidirectional or bi-directional.
- A Directional coupler is a device that samples a small amount of Microwave power for measurement purposes.
- The power measurements include incident power, reflected power & VSWR values

Properties of Directional Couplers



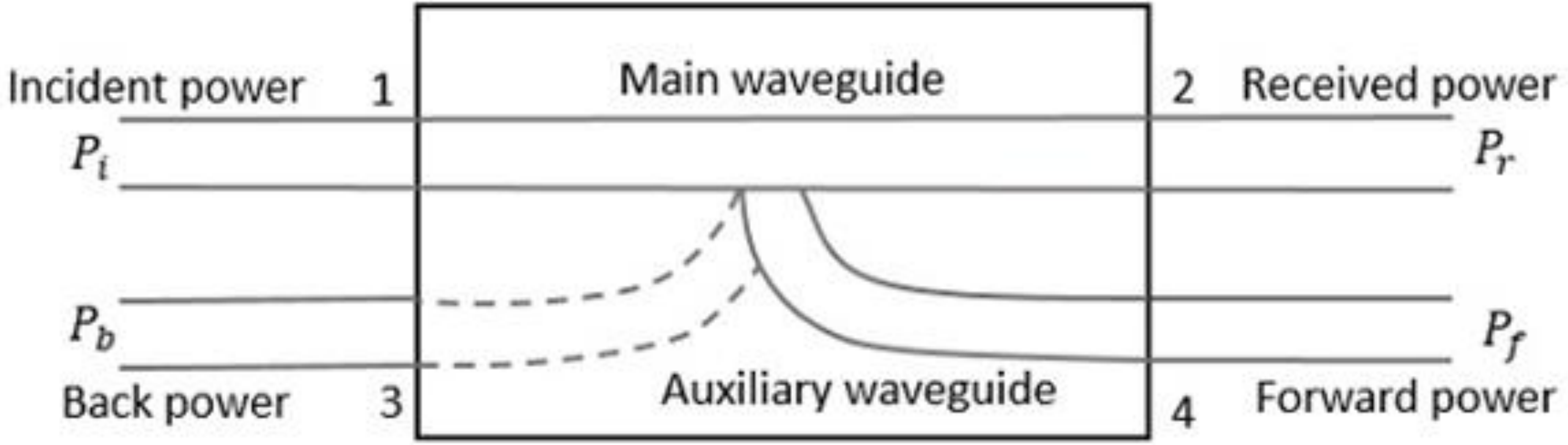
- All the terminations are matched to the ports.
- When the power travels from Port 1 to Port 2, some portion of it gets coupled to Port 4 but not to Port 3.
- As it is also a bi-directional coupler, when the power travels from Port 2 to Port 1, some portion of it gets coupled to Port 3 but not to Port 4.

Properties of Directional Couplers



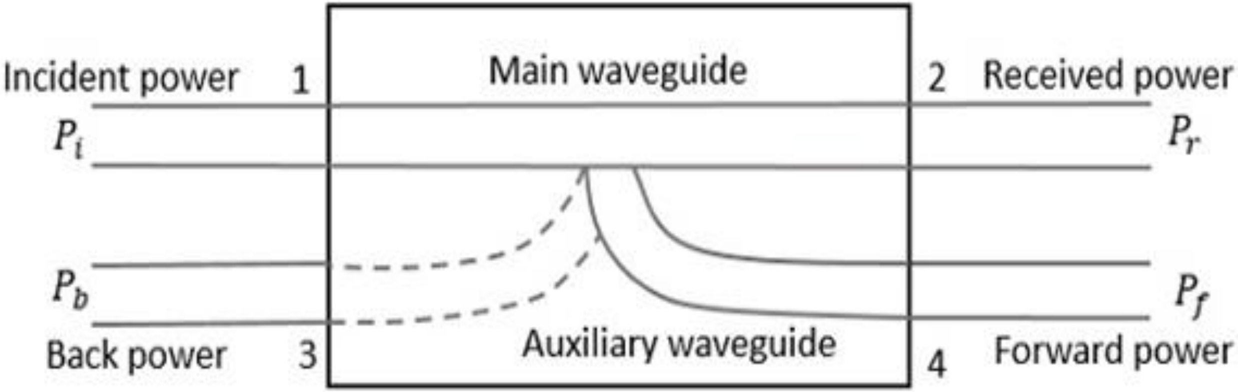
- If the power is incident through Port 3, a portion of it is coupled to Port 2, but not to Port 1.
- If the power is incident through Port 4, a portion of it is coupled to Port 1, but not to Port 2.
- Port 1 and 3 are decoupled as are Port 2 and Port 4

Power flow in a directional coupler



- ➢ Ideally, the output of Port 3 should be zero. However, practically, a small amount of power called back power is observed at Port 3.

Power flow in a directional coupler



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

Directional Coupler:

Parameters used to define the performance of a directional coupler:

- **Coupling factor, C:** It 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:** It is the ratio of forward power to the back power, measured in dB

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

Directional Coupler:

Parameters used to define the performance of a directional coupler:

➢Isolation, I:

- ✓ 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

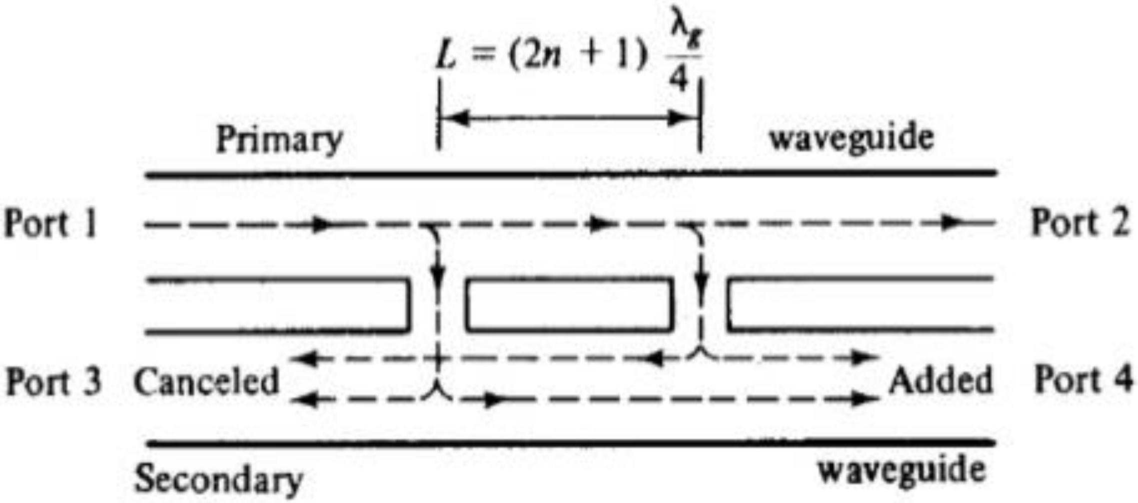
Types of Directional Couplers

- Two Hole Directional Coupler
- Four Hole Directional Coupler
- Schwinger Coupler
- Bethe-hole Directional Coupler

Applications of Directional Couplers

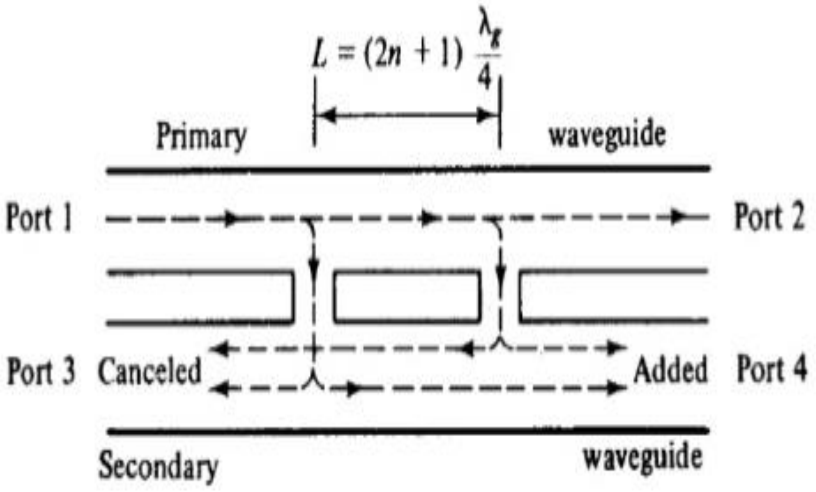
- Commercial applications
- Military applications
- Used for sampling a single direction of power which is propagating on a transmission line

Two Hole Directional Coupler:



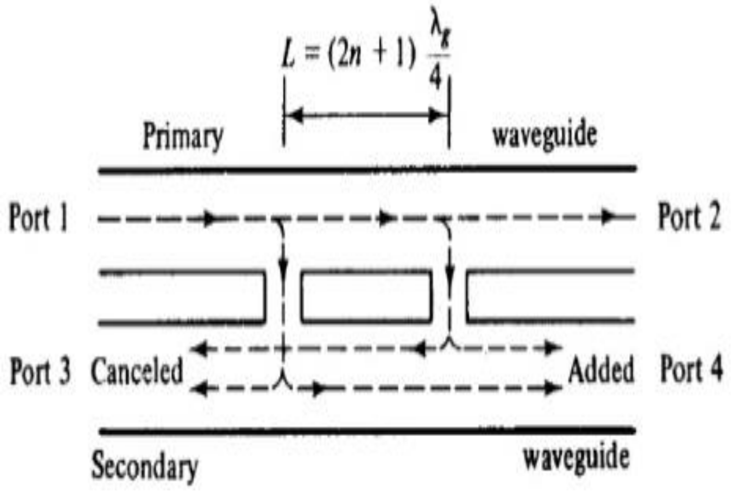
- Directional coupler with same main and auxiliary waveguides, but with two small holes that are common between them.
- These holes are $\lambda_g/4$ distance apart where λ_g is the guide wavelength

Two Hole Directional Coupler:



- A two-hole directional coupler is designed to meet the ideal requirement of directional coupler, which is to avoid back power.
- Some of the power while travelling between Port 1 and Port 2, escapes through the holes 1 and 2.

Two Hole Directional Coupler:



- The magnitude 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 contributing to the forward power P_f
- It is out of phase at hole 1, cancelling each other and preventing the back power to occur.
- The directivity of a directional coupler improves.

S Matrix of a Two Hole Directional Coupler:

- It is a 4 port network – size of S matrix is 4 x 4
- S matrix $$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \quad (1)$$
- Since, all ports are perfectly matched.

Hence $$S_{11} = S_{22} = S_{33} = S_{44} = 0 \quad (2)$$

- Port 1 and 3 are decoupled as well as port 2 and 4

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

S Matrix of a Two Hole Directional Coupler:

- Substitute (2) & (3) in (1)

$$S_{11} = S_{22} = S_{33} = S_{44} = 0 \qquad S_{13} = S_{31} = S_{24} = S_{42} = 0$$

- We will get

$$\begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{21} & 0 & S_{23} & 0 \\ 0 & S_{32} & 0 & S_{34} \\ S_{41} & 0 & S_{43} & 0 \end{bmatrix} \qquad (4)$$

- And [S] is a symmetric matrix. So $S_{ij} = S_{ji}$

S Matrix of a Two Hole Directional Coupler:

- From unitary property of [S] matrix: [S] [S]* = I

$$\begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{21} & 0 & S_{23} & 0 \\ 0 & S_{32} & 0 & S_{34} \\ S_{41} & 0 & S_{43} & 0 \end{bmatrix} \begin{bmatrix} 0 & S_{12}* & 0 & S_{14}* \\ S_{21}* & 0 & S_{23}* & 0 \\ 0 & S_{32}* & 0 & S_{34}* \\ S_{41}* & 0 & S_{43}* & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

- On multiplying [S] with [S]* and equating it to RHS,

$$R_1C_1 = |S_{12}|^2 + |S_{14}|^2 = 1 \quad (7)$$

$$R_3C_3 = |S_{23}|^2 + |S_{34}|^2 = 1 \quad (9)$$

$$R_2C_2 = |S_{12}|^2 + |S_{23}|^2 = 1 \quad (8)$$

$$R_4C_4 = |S_{14}|^2 + |S_{34}|^2 = 1 \quad (10)$$

$$R_1C_3 = S_{12}.S_{23}* + S_{14}.S_{34}* = 0 \quad (11)$$

S Matrix of a Two Hole Directional Coupler:

- From (7) & (8),

$R_1C_1 = |S_{12}|^2 + |S_{14}|^2 = 1$ & $R_2C_2 = |S_{12}|^2 + |S_{23}|^2 = 1$ => $S_{14} = S_{23}$

(Coupled power)

- From (9) , (10) & (7)

$R_3C_3 = |S_{23}|^2 + |S_{34}|^2 = 1$ $R_4C_4 = |S_{14}|^2 + |S_{34}|^2 = 1$ $S_{12} = S_{34}$

- Let, $S_{12} = S_{34}$ = P (Real No) => $S_{12}* = S_{34}* = P$ (Forward power)

- Eqn (11) becomes, $R_1C_3 = S_{12}.S_{23} * + S_{14}.S_{34}* = 0$

$P.S_{23} * + S_{14}P = 0$ => $P(S_{23} * + S_{14}) = 0$ => $P(S_{23} * + S_{23}) = 0$ => $S_{23}* = -S_{23}$

$$Let S_{23} = jq = S_{23}* = -jq$$

S Matrix of a Two Hole Directional Coupler:

- Applying symmetric property,

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

- S Matrix of a two hole directional coupler

$$[S] = \begin{bmatrix} 0 & P & 0 & jq \\ P & 0 & jq & 0 \\ 0 & jq & 0 & P \\ jq & 0 & P & 0 \end{bmatrix}$$

Microwave Isolator

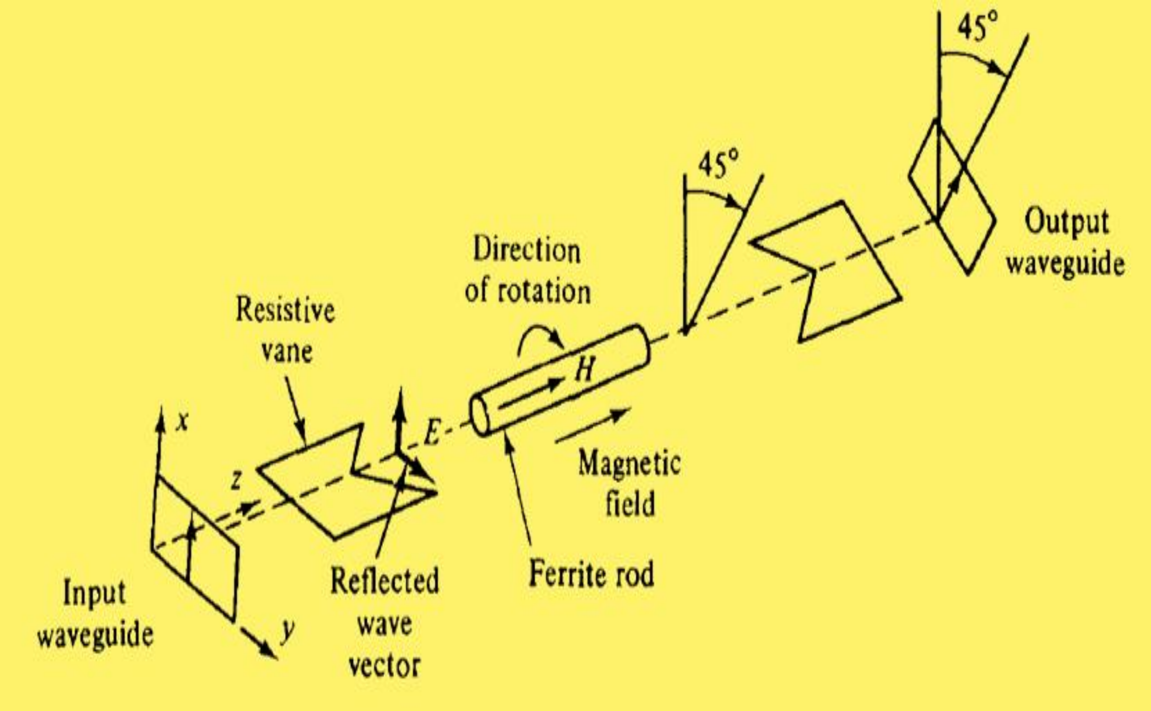
- An *isolator* is a nonreciprocal transmission device that is used to isolate one component from reflections of other components in the transmission line.
- An ideal isolator completely absorbs the power for propagation in one direction and provides lossless transmission in the opposite direction.
- Thus the isolator is usually called **Uniline.**

Microwave Isolator

- Isolators are generally used to improve the frequency stability of microwave generators, such as klystrons and magnetrons, in which the reflection from the load affects the generating frequency.
- In such cases, the isolator placed between the generator and load prevents the reflected power from the unmatched load from returning to the generator.
- As a result, the isolator maintains the frequency stability of the generator. Isolators can be constructed in many ways.

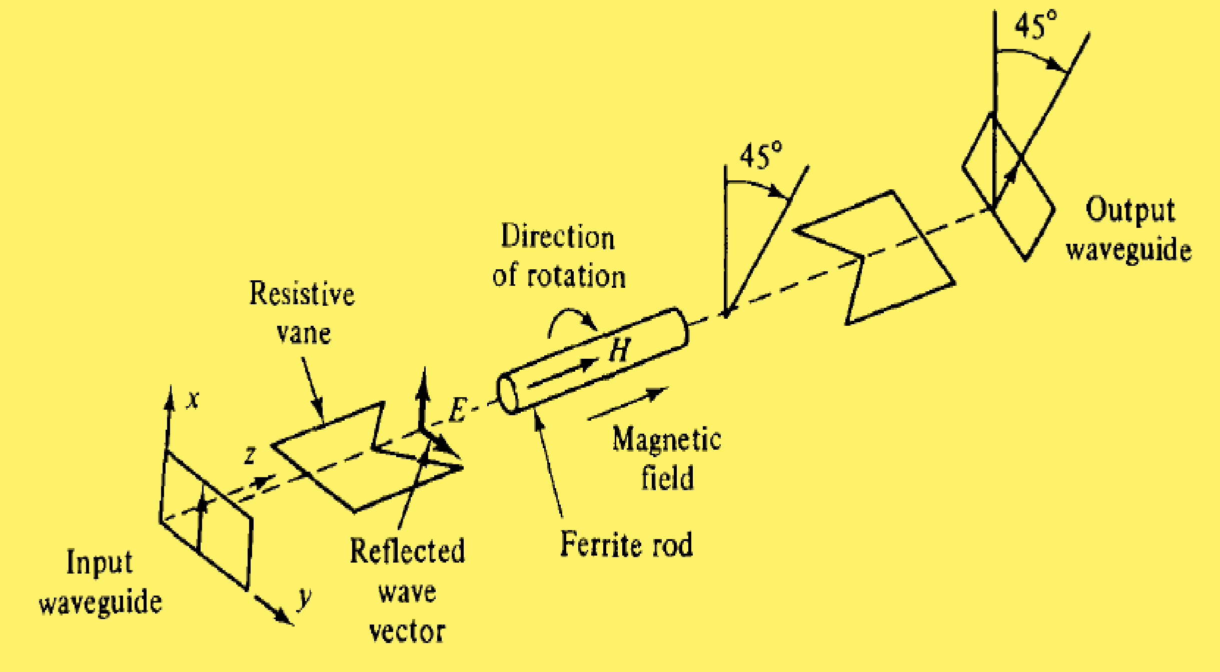
Microwave Isolator

- They can be made by terminating ports 3 and 4 of a four-port circulator with matched loads.
- On the other hand, isolators can be made by inserting a ferrite rod along the axis of a rectangular waveguide



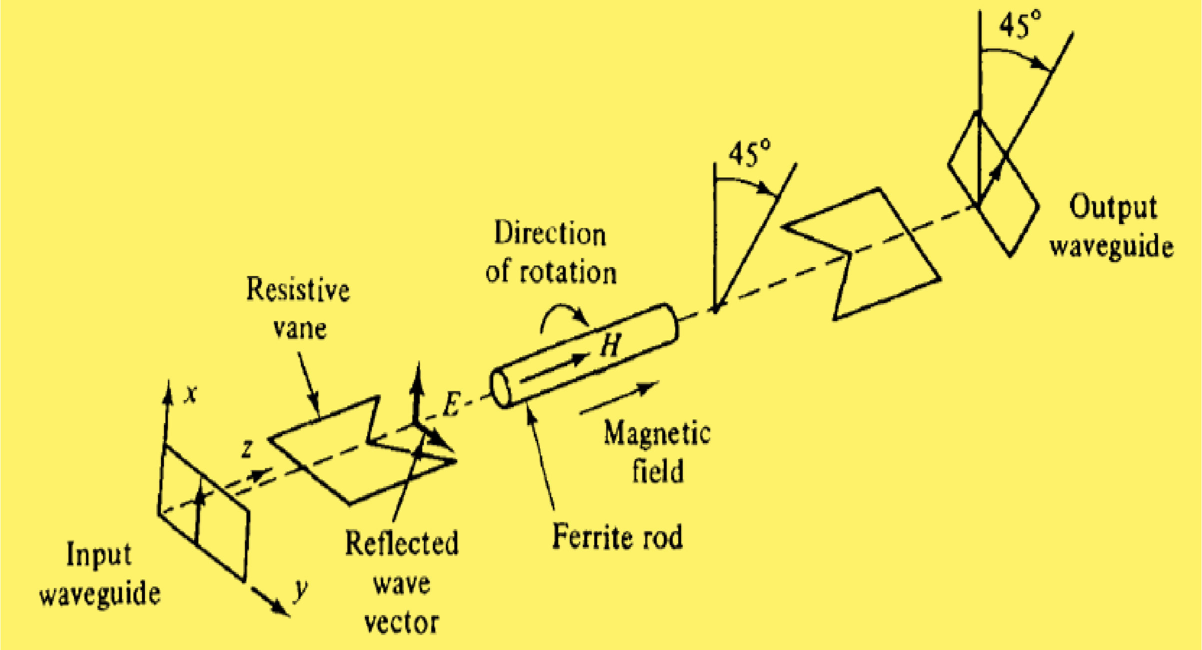
Microwave Isolator

- The input resistive card is in the *y*-*z* plane, and the output resistive card is displaced 45° with respect to the input card.
- The de magnetic field, which is applied longitudinally to the ferrite rod, rotates the wave plane of polarization by 45°.



Microwave Isolator

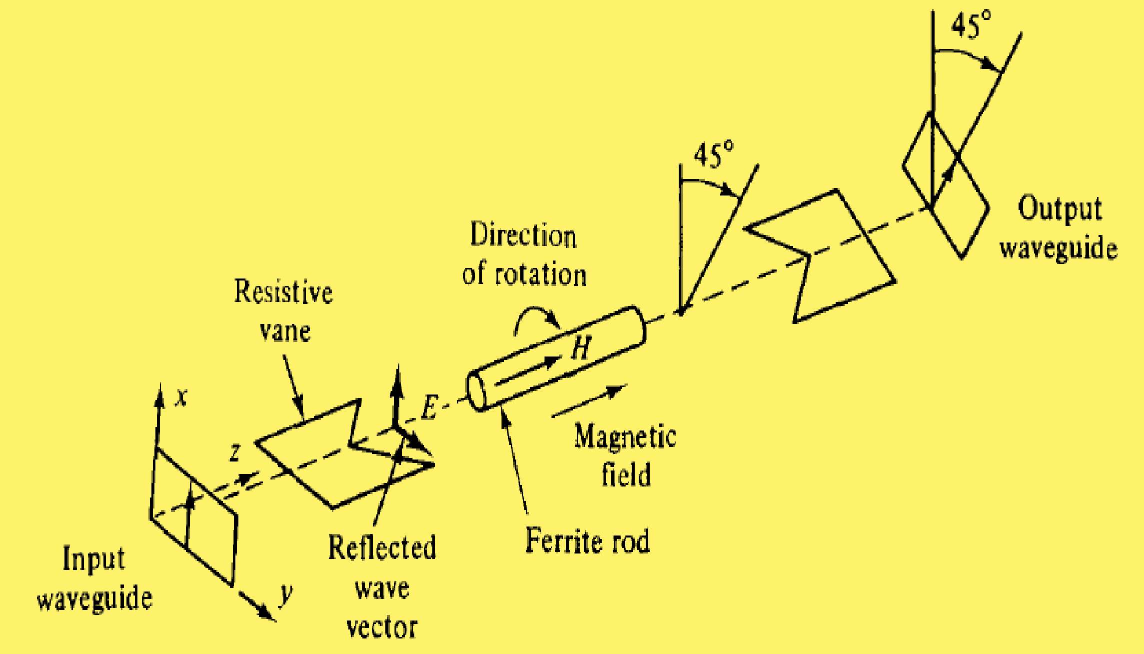
- The degrees of rotation depend on the length and diameter of the rod and on the applied de magnetic field.
- An input TE10 dominant mode is incident to the left end of the isolator.



Microwave Isolator

- Since the TE10 mode wave is perpendicular to the input resistive card, the wave passes through the ferrite rod without attenuation.

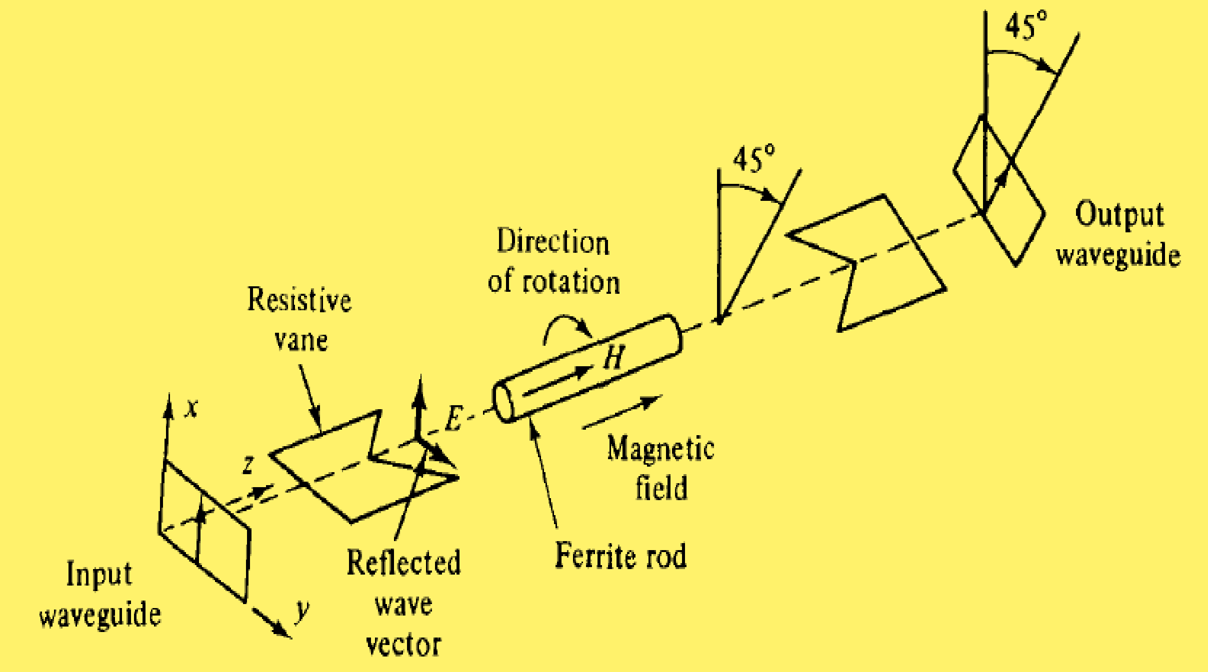
- The wave in the ferrite rod section is rotated clockwise by 45° and is normal to the output resistive card. As a result of rotation, the wave arrives at the output end without attenuation at all



Microwave Isolator

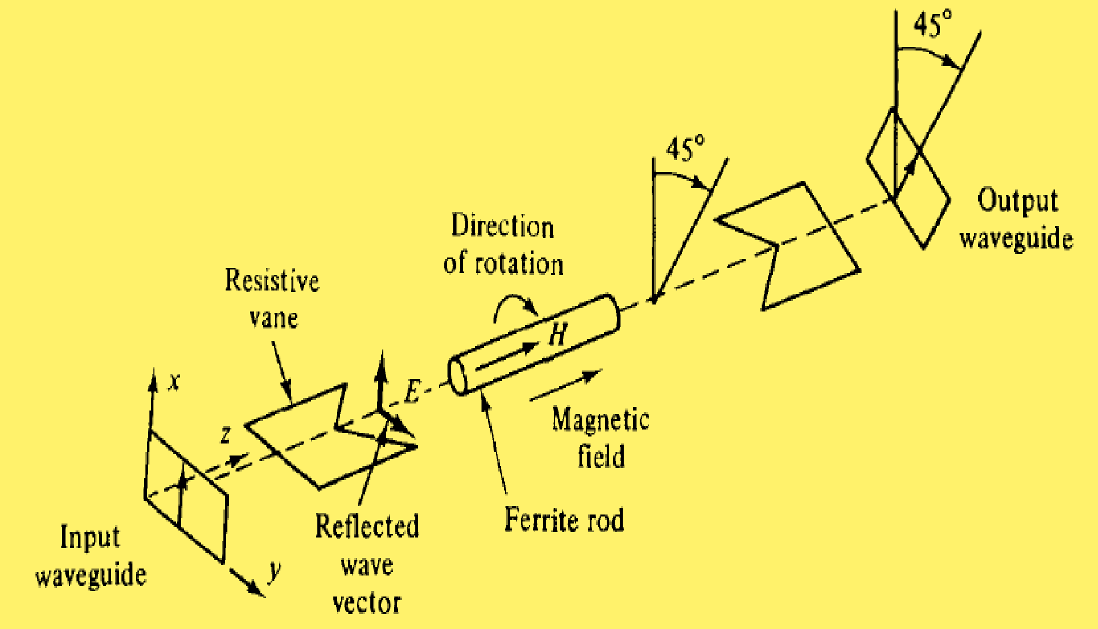
- On the contrary, a reflected wave from the output end is similarly rotated clockwise 45° by the ferrite rod.

- However, since the reflected wave is parallel to the input resistive card, the wave is thereby absorbed by the input card.

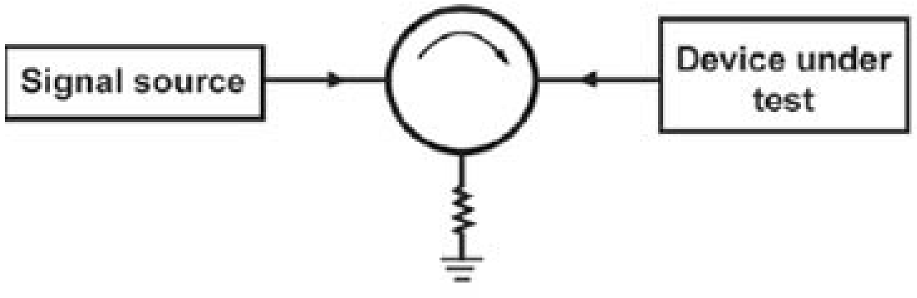


Microwave Isolator

The typical performance of these isolators is about 1-dB insertion loss in forward transmission and about 20- to 30-dB isolation in reverse attenuation.

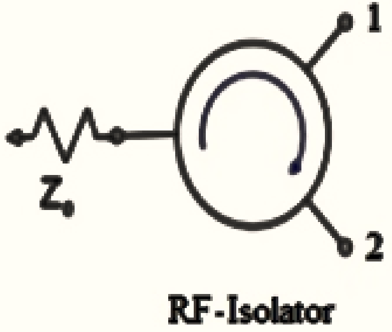


Microwave Isolator



One major use of the isolator is to prevent "backflow" of RF energy from a load back to the sensitive source, which may be due to impedance mismatch. (Image source: MECA Electronics, Inc.)

S Matrix of Isolator

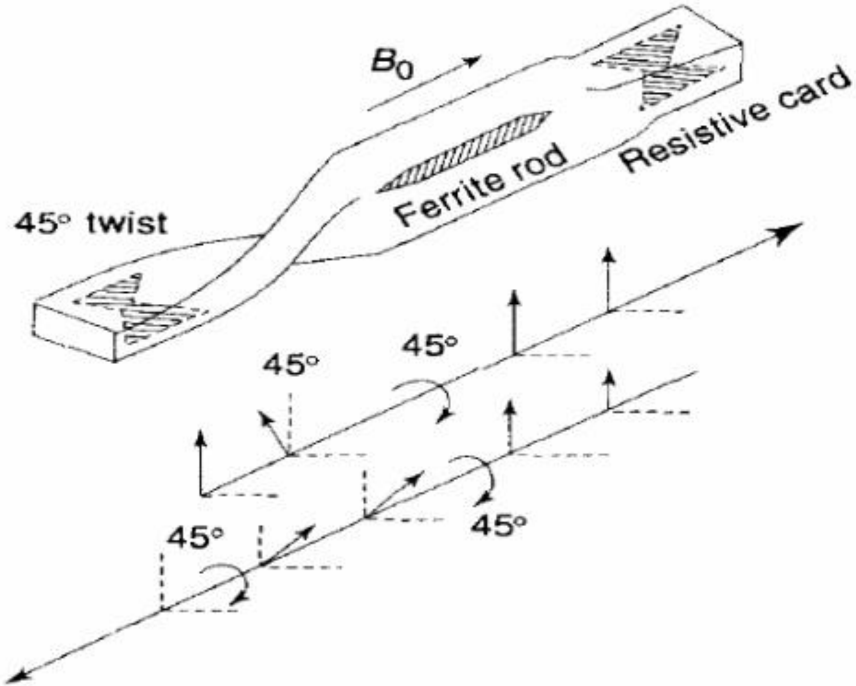


$$[S] = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$$

Isolator

An isolator is a two port, non-reciprocal device which produces a minimum attenuation to wave propagation in one direction and very high attenuation in the opposite direction.

Faraday rotation isolator



Properties of reciprocal and non-reciprocal networks

- A reciprocal network is one in which the transmission of a signal between any two ports does not depend on the direction of propagation- input and output ports are interchangeable (scattering parameter S21=S12, S13=S31, etc.)

- A network is known to be reciprocal if it is passive and contains only **isotropic** materials.

- Examples of reciprocal networks include cables and standard transmission lines, attenuators, and the common passive power splitters and couplers.

Properties of reciprocal and non-reciprocal networks

- Two classic examples of *non-reciprocal networks* are RF amplifiers and isolators. In both cases, scattering parameter S21 is much different from S12.
- In fact, almost all active circuits are non-reciprocal since transistors are inherently non-reciprocal devices.
- **Anisotropic** materials have different electrical properties depending on the direction a signal propagates through them. One example of an *anisotropic* material is the class of materials known as ferrites, from which circulators and isolators are made.
- Two classic examples of *non-reciprocal networks* are RF amplifiers and isolators. In both cases, the scattering parameter S21 is much different from S12. In fact, almost all active circuits are non-reciprocal since transistors are inherently non-reciprocal devices.

Properties of reciprocal and non-reciprocal networks

- A reciprocal network always has a symmetric S-parameter matrix. That means that S21=S12, S13=S31, etc. All values along the lower-left to upper right diagonal must be equal.
- A two-port S-parameter matrix (at a single frequency) is represented by:

$$\begin{bmatrix} S11 & S12 \\ S21 & S22 \end{bmatrix}$$

where S21 is identical to S12.

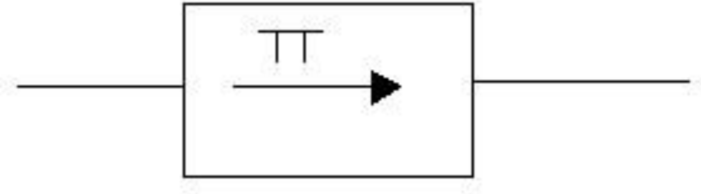
Microwave Phase shifter-Gyrator

- Anisotropic material will have different properties in different directions.
- The most common materials having anisotropic properties are ferromagnetic compound such as YIG and ferrites.
- A ferrite is basically a non metallic material.

Microwave Phase shifter-Gyrator

- When a circularly polarized wave is passed through a ferrite rod, under the influence of the axial magnetic field, the axis of polarization will get tilted in the clockwise direction.
- The amount of tilt depends on strength of the magnetic field as well as dimensions of the ferrite rod.
- The same principle is being used in the design of gyrator.

Gyrators

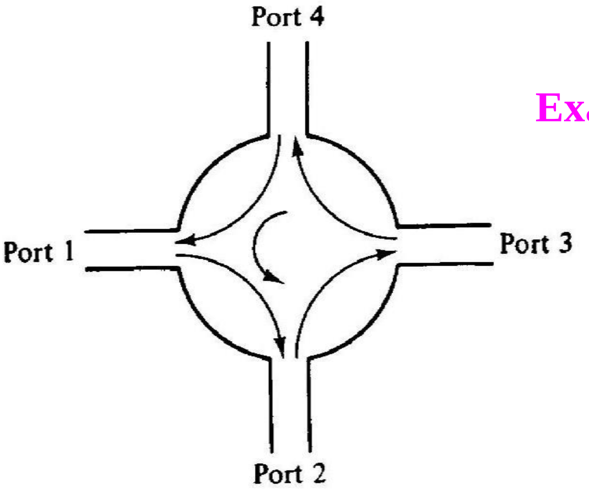


$$S=\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

gyrator

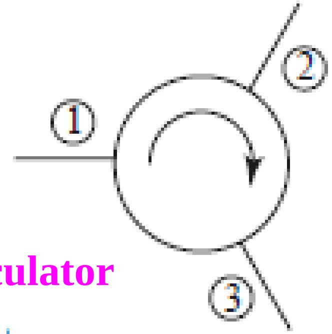
Circulator

- A circulator is a multi port junction in which the wave can travel from one port to the next immediate port in one direction only.



The symbol of a circulator.

Example: Four port Circulator



Example: Three port Circulator

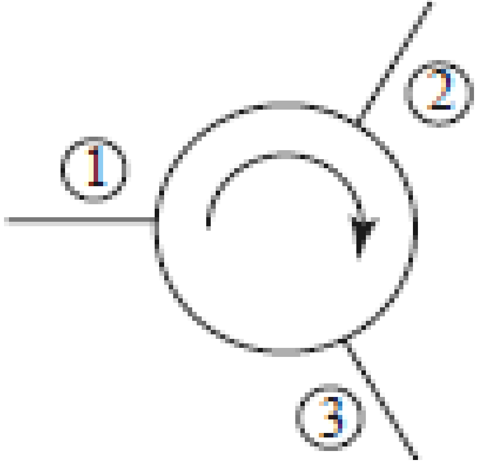
Circulator

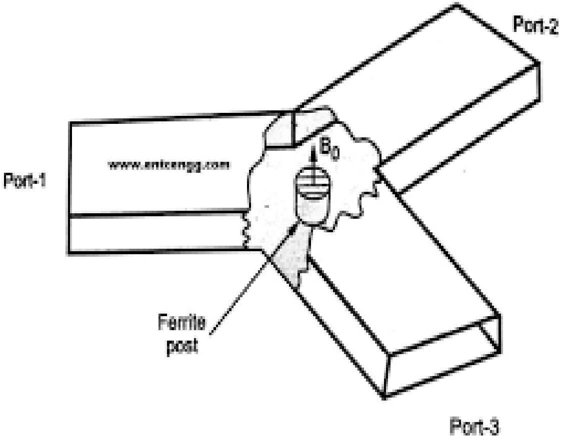
- The circulator is a ferrite device including two or more ports. When the input signal enters into any port then the signal will transmit in a particular direction
- There are different models of circulators available in the market from different manufacturing companies.
- These components are mainly used in different applications like radar systems, amplifier systems, transmitting or receiving from the antenna.
- The different models of these mainly include two port circulator; three port circulator with waveguide packages & frequency range will be up to 40 GHz

Circulator Characteristics

- Insertion loss is < 1 dB
- Isolation range is approximately from 30dB to 40 dB
- VSWR (voltage standing wave ratio) is <1.5

Three Port Circulator – Operating Principle





- It is formed by a 120^0 H-plane waveguide or strip line symmetrical Y-junction with a central ferrite post.

Circulator

- For a perfectly matched, lossless and non-reciprocal three port circulator, the S matrix is

$$[S] = \begin{bmatrix} 0 & 0 & S_{13} \\ S_{21} & 0 & 0 \\ 0 & S_{32} & 0 \end{bmatrix}$$

- If the terminal planes are properly chosen to make the phase angles of S_{13}, S_{21} and S_{32} zero. S_{13}= S_{21}= S_{32}= 1, so that,

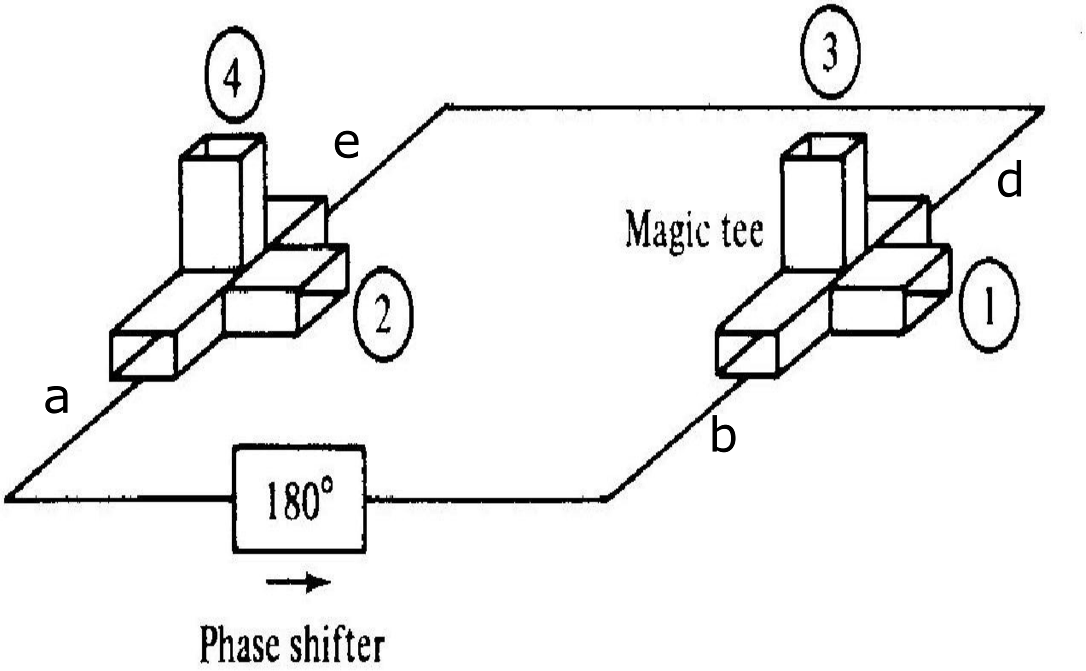
$$[S] = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

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

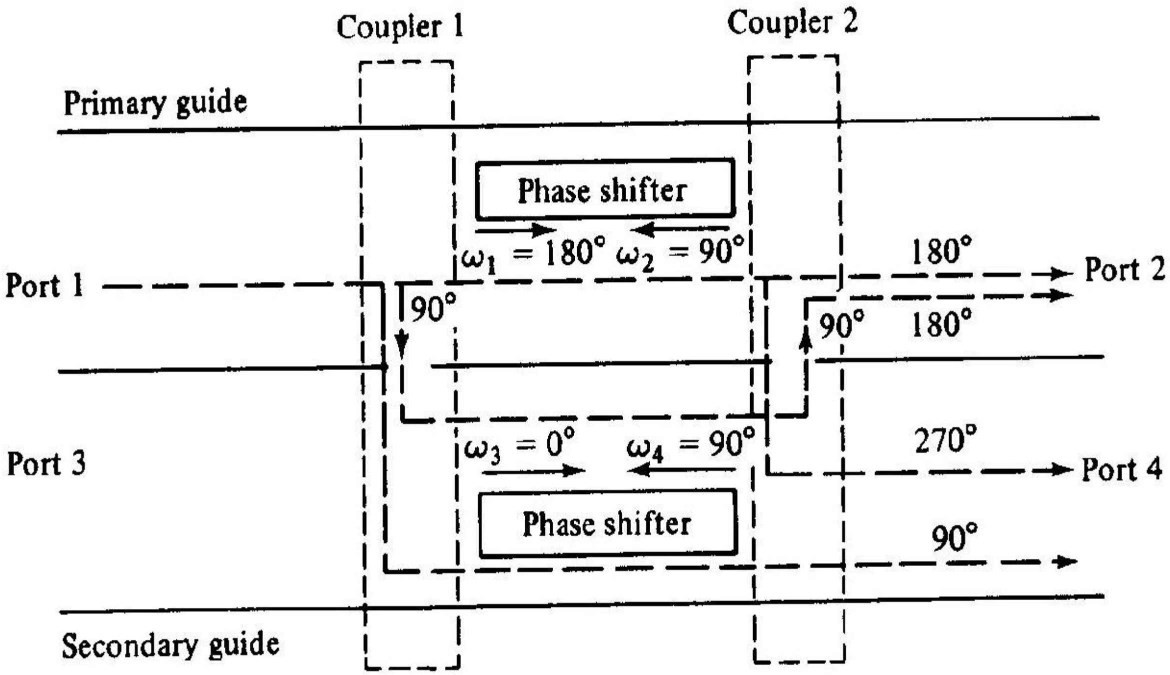
Four Port Circulator – Operating Principle

- A four port circulator can be constructed from
  a. Two Magic Tees and a non-reciprocal 180^0 phase shifter or
  b. A combination of two 3-dB side hole directional couplers and a rectangular waveguide with two non-reciprocal phase shifters.

A Four port circulator from two Magic Tees



Four Port Circulator – Operating Principle



Schematic Diagram

Circulator

- A perfectly matched, lossless and non-reciprocal four-port circulator has S-matrix

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

Applications of Circulators

- Duplexer
- Isolator
- Reflection amplifier
- Radar systems
- Amplifier systems
- Antenna transmitting or receiving

Microwave Attenuator

- The attenuators are basically passive devices which control power levels in microwave system by absorption of the signal.
- Attenuator which attenuates the RF signal in a waveguide system is referred as **waveguide attenuator**.
- They are achieved by insertion of resistive films (aquadag).

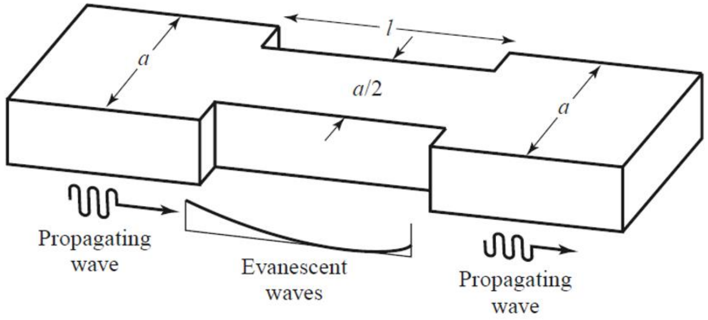
Waveguide Attenuation

The “cut off” Principle

- Waveguide attenuation is often based on the cut off principle where a section of the waveguide is operating frequency far below the cut off frequency — a frequency that directly correlated with the dimensions of the waveguide, below which the waveguide is unable to carry signals.
- For a rectangular waveguide, the length of the broadwall is generally equal ½ wavelength of the lower cut off frequency.

Waveguide Attenuation

- Microwave energy will therefore dissipate very rapidly in sections where the H-plane is shunted as shown in ***Figure 1***.
- This rate of decay is exponential along the transmission path of the signal.
- As the cut off frequency increases, so does the rate of attenuation of the modes below cut off frequency.
- And since waveguides can operate with many modes existing simultaneously, the dominant mode is used; the mode with the lowest decay rate and lowest cut off frequency



Attenuators

There are two main types of attenuators

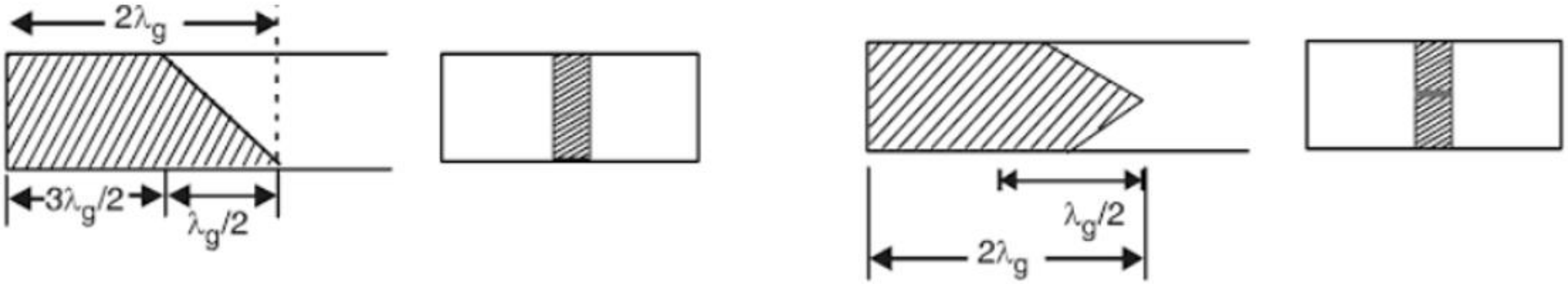
- Fixed Attenuator
- Variable Attenuator

Fixed Attenuators

- Fixed attenuator consists of a dissipative element called **pad** which is placed in a waveguide.
- The pad is placed in such a way that its plane is parallel to the electric field, for this two thin metal rods are used
- The pad is tapered for providing a gradual transition from the waveguide medium to the absorbing medium of the pad.

Fixed Attenuators

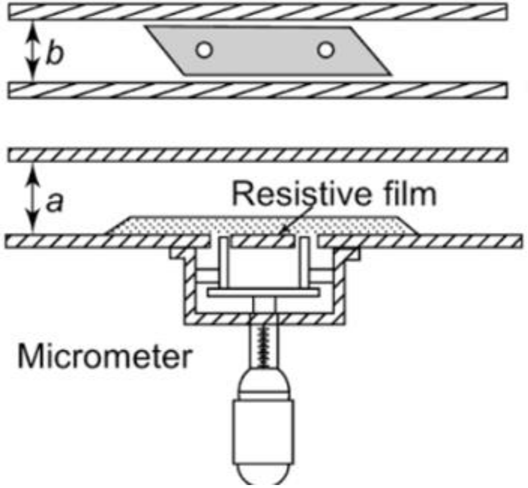
- The resistive element causes attenuations while the taper minimizes reflections.
- The taper shape can vary with a single taper or a double taper.



Continuously variable Attenuators

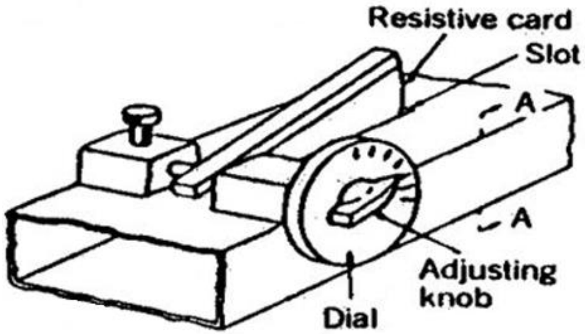
- A continuously variable attenuation is accomplished in a waveguide by means of vertically adjusting the lossy dielectric fins to incrementally reduce the energy level of the signal at the output.

- This can be done with either a micrometer screw or with a flap-type adjustment where the attenuating material is mounted to a movable arm



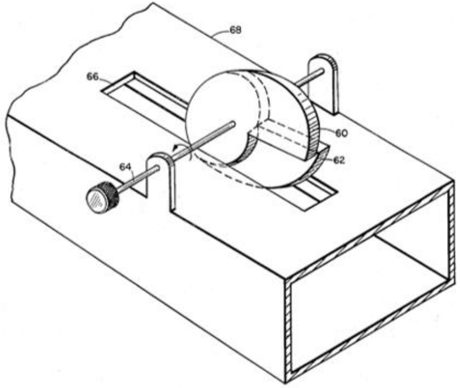
Continuously variable Attenuators

- This can be done with either a micrometer screw or with a flap-type adjustment where the attenuating material is mounted to a movable arm.
- The greater the penetration of the lossy vane, the greater the attenuation.
- The dielectric slab can be specifically shaped (and is often disc-shaped) so that the attenuation can vary linearly with insertion.



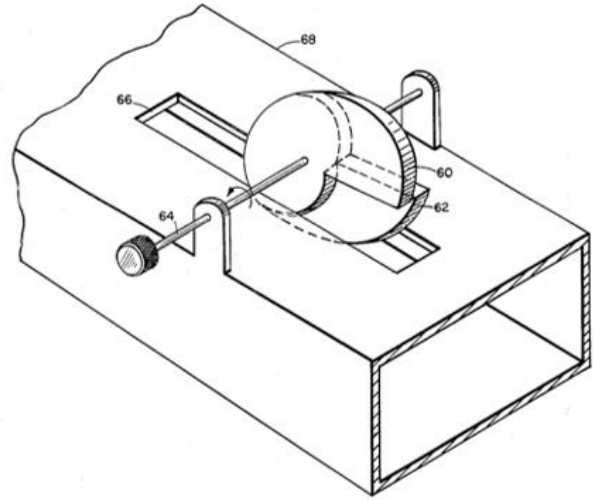
Flat Type Attenuators

- The flap-type waveguide attenuator has gone through several iterations to improve the linearity of the insertion loss over mechanical positions.
- Older constructions involved suspending the element manually to preset fixed positions that could vary over time with wear and tear thereby risking oscillations.



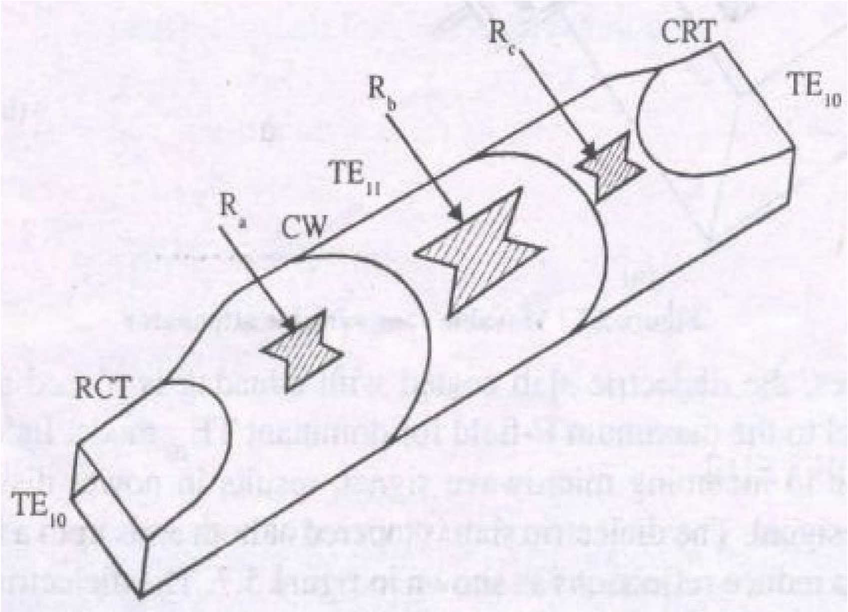
Flat Type Attenuators

- More precision flap-type attenuators are adjusted via a plane orthogonal to the moving arm so that the element is inserted into the waveguide as a function of angular position.
- These attenuators are not designed specifically for high powers due to the poor thermal management of the resistive component.
- For instance, high powered coaxial attenuators contain resistive elements on a ceramic insulating substrate that are in direct contact with a heat sink where heat can be carried away rapidly by the anodized aluminium fins



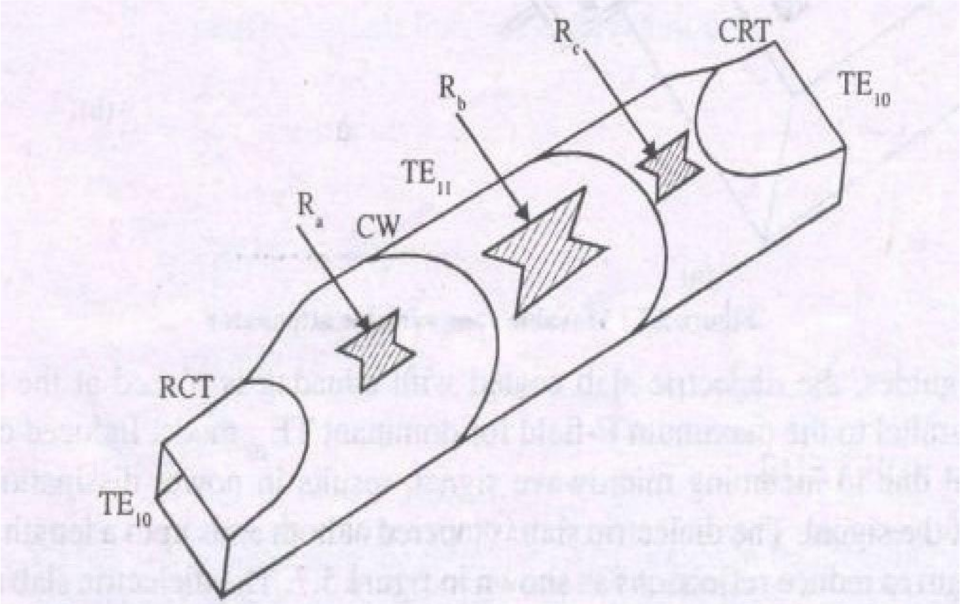
Precision type Variable Attenuators

- 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 figure .



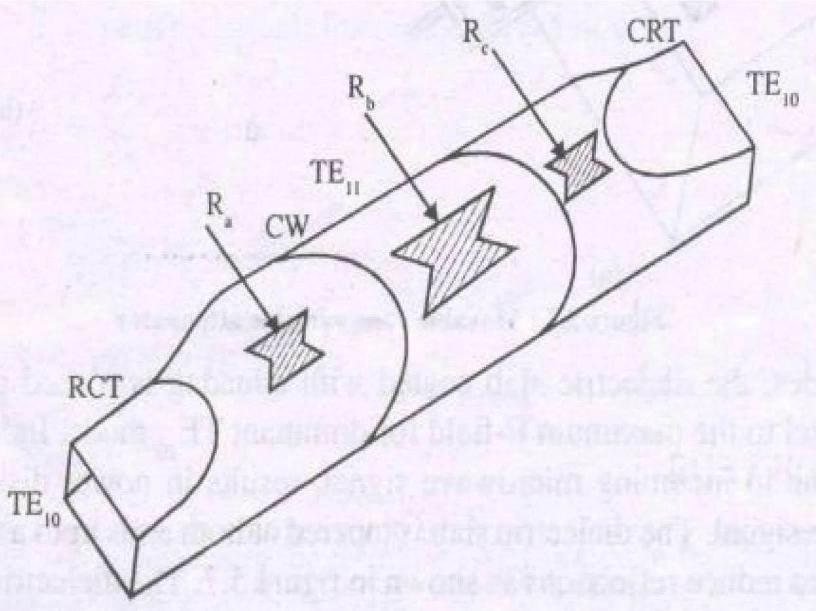
Precision type Variable Attenuators

- Resistive cards Ra , Rb and Re are placed inside these sections as shown. The centre circular section containing the resistive card Rb can be precisely rotated by 360 degree 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



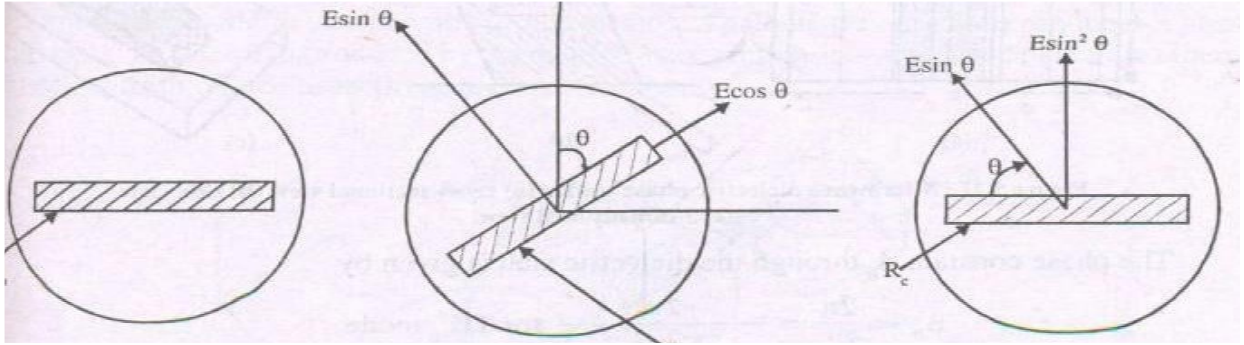
Precision type Variable Attenuators

- TE10 mode in RCT is converted into TE11 in circular waveguide.
- The resistive cards Rb and Re a kept perpendicular to the electric field of TE10 mode so that it does not absorb the energy.
- But any component parallel to its plane will be readily absorbed. Hence, pure TE11 mode is excited in circular waveguide section.



Precision type Variable Attenuators

- If the resistive card in the centre section is kept at an angle θ relative to the E-field direction of the TE11 mode, the component E cos θ parallel to the card get absorbed while the component E sin θ is transmitted without attenuation.
- This component finally comes out as E $\sin^2\theta$



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Thank you