MICROWAVE PASSIVE DEVICES

CO-AXIAL CABLES, CONNECTORS AND ADAPTERS

Coaxial Cables Microwave components and devices are interconnected using these co-axial cables of suitable length and operated at microwave frequencies. In this section let us consider some practical aspects of these co-axial cables. TEM mode is propagated through the co-axial line and the outer conductor guides these signals in the dielectric space between itself and inner conductor.

The outer conductor also acts as a shield to prevent the external signals to interfere with the internal signal. It also prevents the internal signal leakage. The co-axial cables usually possess characteristic impedance of either 50 ohms or 75 ohms Based on the structure of shielding, coaxial cables are classified into three basic types.

(i) Flexible co-axial Cable: Figure 5.1 shows the structure of flexible-type of co-axial cable consisting of low loss solid or foam type polyethylene dielectric. Electromagnetic shielding is provided for outer single braid or double braid of the flexible cable as shown, by using knitted metal wire mesh. The centre conductor usually consists of multi strand wire.

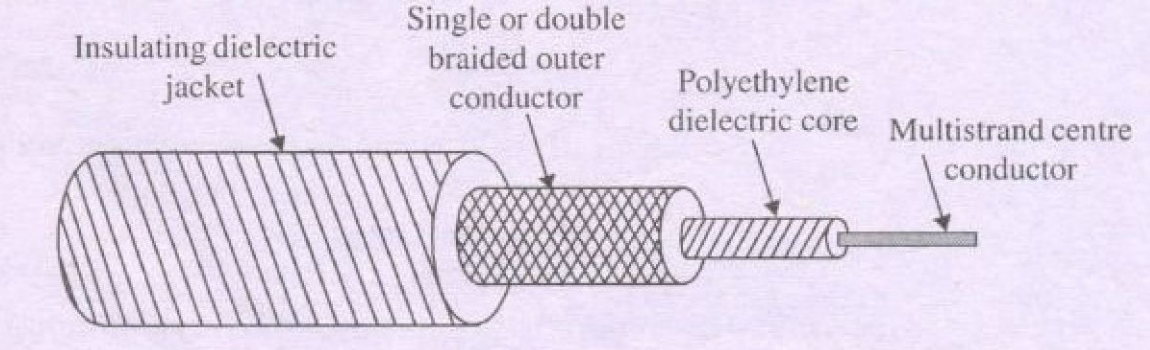


Figure 5.1 : Structure of flexible co-axial cable

(ii) Semi-rigid co-axial cable: Figure 5.2 shows the cross-sectional view of semi-rigid co-axial cable. Semi rigid co-axial cables make use of thin outer conductor made of copper and a strong inner conductor also made of copper. The region between the inner and outer conductor contains a solid dielectric. These cables can bent for convenient routing and are not as flexible as the first type.

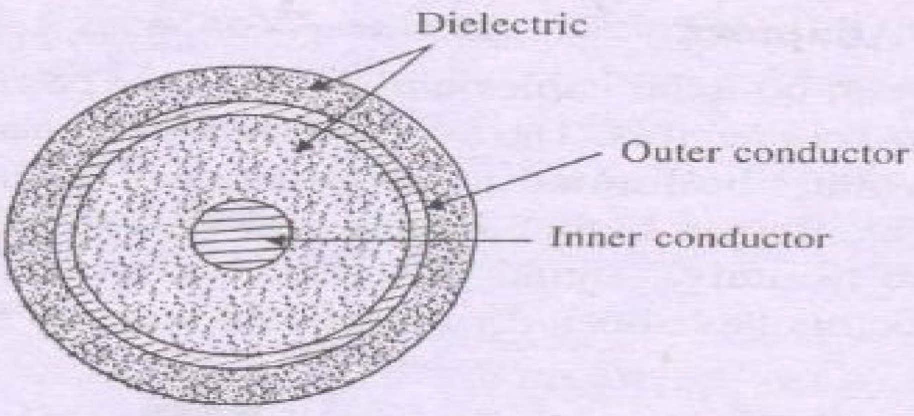


Figure 5.2 : Cross-section of semi-rigid co-axial cable

(ill) Rigid co-axial cable: Figure 5.3 shows the structure of a rigid co-axial cable consisting of inner and outer conductor with air as dielectric. To support the inner conductor at the centre dielectric spacers are introduced at regular intervals as shown. The thickness of these dielectric spacers is made small so that they do not produce significant discontinuities to the wave propagation.

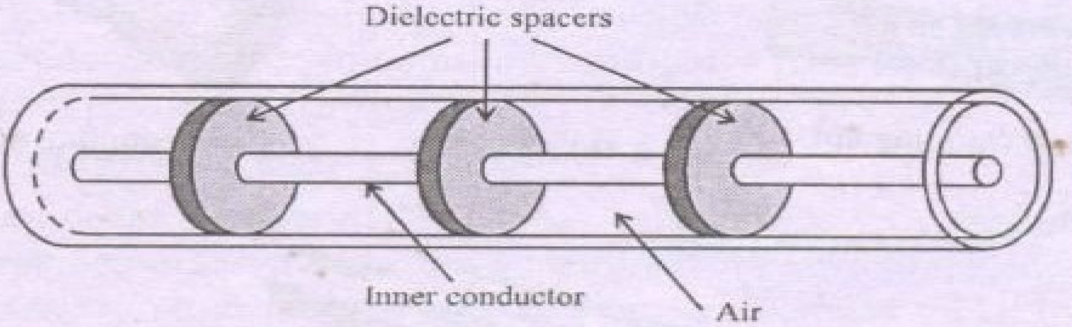


Figure 5.3 : Illustration of rigid co-axial cable

Co-axial cables can be used upto microwave -range of frequencies. Beyond these frequencies attenuation becomes very large (since attenuation increases with frequency) which makes co-axial cables unsuitable at higher frequencies. Some characteristics of standard coaxial cables with their radio guide (RG) and universal (U) numbers along with conductor (inner and outer) dimensions .

Coaxial Connectors and Adapters:

Interconnection between co-axial cables and microwave components is achieved with the help of shielded standard connectors. The average circumference of the co-axial cable, for mar high frequency operation must be limited to about one wavelength. This requirement is a VI necessary to reduce propagation at higher modes and also to eliminate erratic reflection coefficients (VSWR close to unity), signal distortion and power losses. Several types of co-axial connectors have been developed and some of them are described below.

(a) APC 3.5 (Amphenol Precision Connector - 3.5 mm)

HP (Hewlett - Packard) originally developed this connector, but it is now being manufactured by Amphenol. This connector can operate up to a frequency of 34 GHz and has a very low voltage standing wave ratio (VSWR). This connector provides repeatable connections and has 50 Q characteristic impedance. The male or female of SMA connector can be connected to the opposite type of APC 3.5 connector.

(b) APC -7 (Amphenol Precision connector -7 mm)

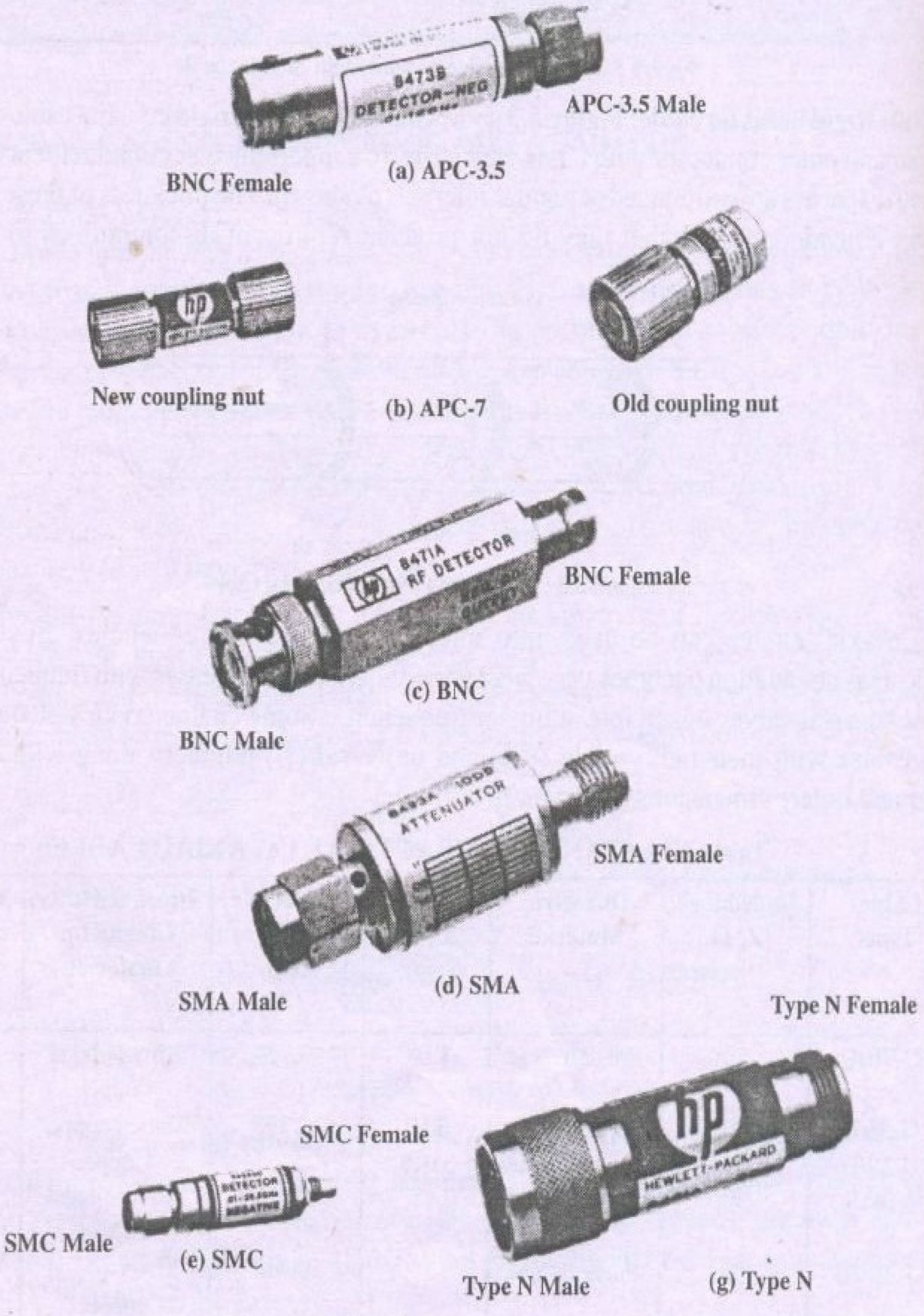
This connector was also developed by HP but improved later by Amphenol. This connector provides repeatable connections and used for very accurate 50 ohm measurement applications. This connector provides a coupling mechanism without male or female distinction (i.e., sexless) andits VSWR is extremely low, less than 1.02 in the frequency range upto 18 GHz.

(c) BNC (Bayonet Navy Connector)

This connector was developed during World War II and used for military applications. It has characteristic impedance 50 to 75 Q and is connected to flexible co-axial cable with diameters upto 0.635 cm. It is extensively used in almost all electronic measuring equipments upto 1 GHz of frequencies. BNC can be used even upto 4 GHz frequency and beyond that it starts radiating electromagnetic energy.

(d) SMA (Sub-Miniature A type)

This type of connector is also called OSM connector as it is manufactured by Omni-Spectra Inc. SMA connectors are used on components for microwave systems. The disadvantage with these connectors is that at high frequencies greater than 24 GHz, it introduces higher ordermodes and hence not used above 24 GHz.



(a) APC-3.5

(b) APC-7

(c) BNC

(d) SMA

(e) SMC

(g) Type N

Figure 5.4 : Co-axial microwave connectors

(e) SMC (Sub-Miniature C-type)

This connector is manufactured by Sealectro Corporation and its size is smaller than SMA connector. It is a 50 Q connector that connects flexible cables upto a diameter of 0.317 cm and used upto a frequency of 7 GHz.

(0 TNC (Threaded Navy Connector)

This connector is an improved version of BNC in the sense that it is threaded. This threading prevents radiation at high frequencies so that it can be used upto about 12 GHz frequency.

(g) Type-N (Type-Navy) connector

It is a 50 Q or 75 Q connector having a very low value of VSWR less than 1.02. This was developed during World War II and extensively used as a microwave measurement connector up to a frequency of 18 GHz.

ATTENUATORS:

In order to control power levels in a microwave system by partially absorbing the transmitted microwave signal, attenuators are employed. Resistive films (dielectric glass slab coated with aquadag) are used in the design of both fixed and variable attenuators.

A co-axial fixed attenuator uses the dielectric lossy material inside the centre conductor of the co-axial line to absorb some of the centre conductor microwave power propagating through it dielectric rod decides the amount of attenuation introduced. The microwave power absorbed by the lossy material is dissipated as heat.

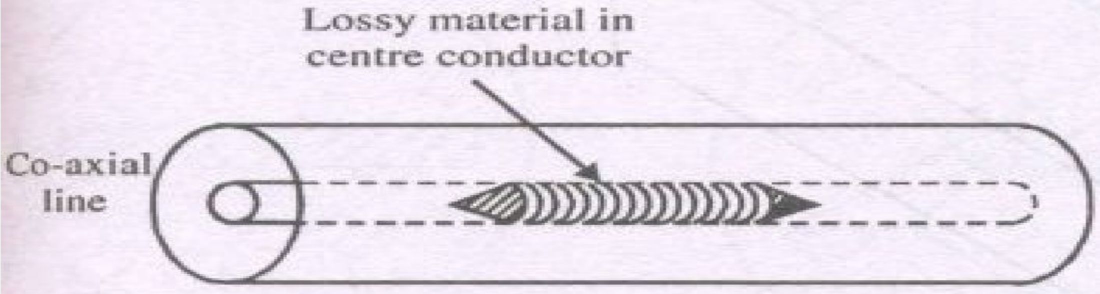


Figure 5.6 Co-axial line fixed attenuator

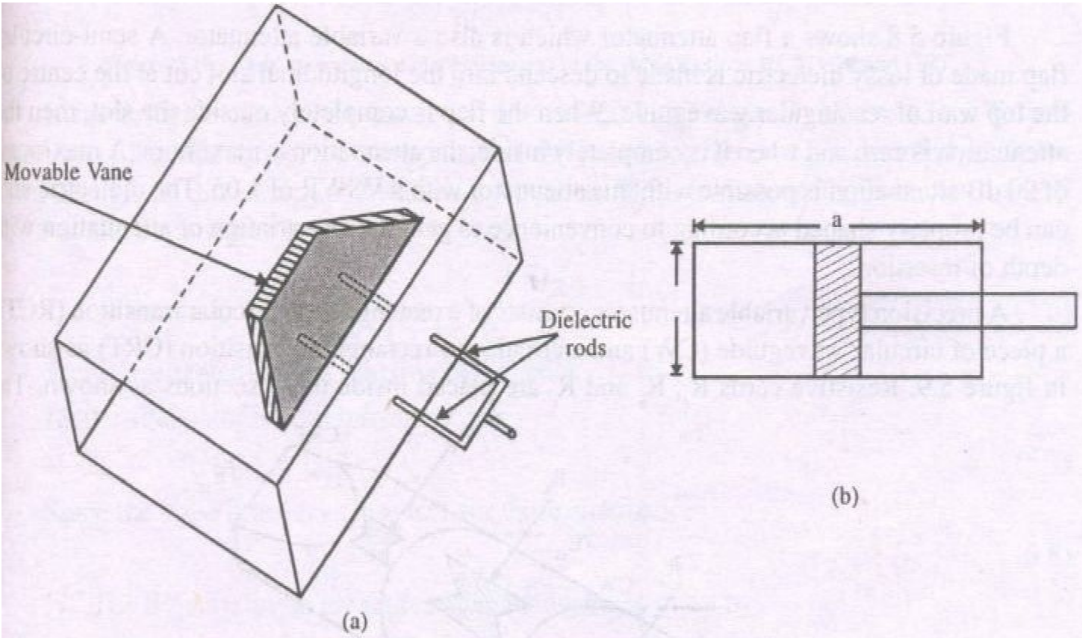


Figure 5.7 : Movable vane variable attenuator

In waveguides, the dielectric slab coated with aduadag is placed at the centre of the waveguide parallel to the maximum E-field for dominant TEIO mode. Induced current on the lossy material due to incoming microwave signal, results in power dissipation, leading to attenuation of the signal. The dielectric slab is tapered at both ends upto a length of more than half wavelength to reduce reflections as shown in figure 5.7. The dielectric slab may be made movable along the breadth of the waveguide by supporting it with two dielectric rods separated by an odd multiple of quarter guide wavelength and perpendicular to electric field. When the slab is at the centre, then the attenuation is maximum (since the electric field is concentrated at the centre for TEIO mode) and when it is moved towards one side-wall, the attenuation goes on decreasing thereby controlling the microwave power corning out of the other port.

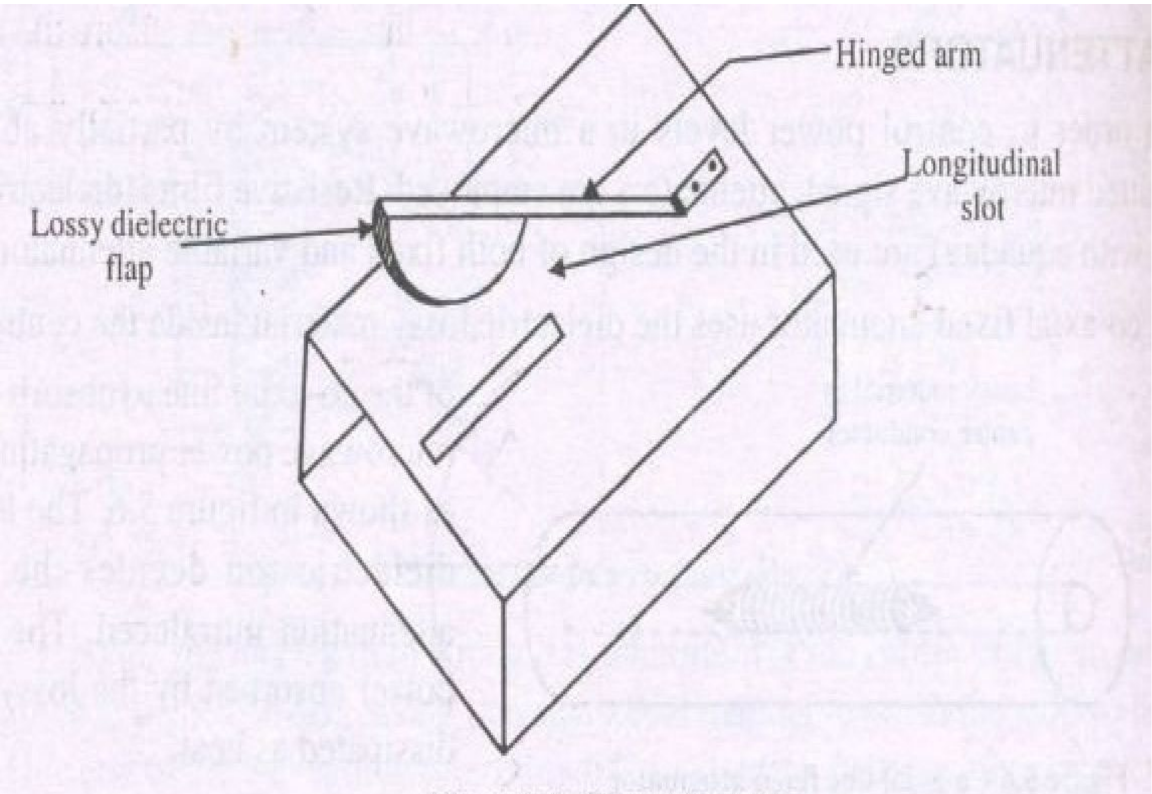


Figure 5.8 : Flap attenuator

Figure 5.8 shows a flap attenuator which is also a variable attenuator. A semi-circular flap made of lossy dielectric is made to descend into the longitudinal slot cut at the centre of the top wall of rectangular waveguide. When the flap is completely outside the slot, then the attenuation is zero and when it is completely inside, the attenuation is maximum. A maximum direction of 90 dB attenuation is possible with this attenuator with a VSWR of 1.05. The dielectric slab can be properly shaped according to convenience to get a linear variation of attenuation within the depth of insertion.

A precision type variable attenuator consists of a rectangular to circular transition (ReT), a piece of circular waveguide (CW) and a circular-to-rectangular transition (CRT) as shown in figure 5.9. Resistive cards R , Rand R are placed inside these sections as shown. The centre circular section containing the resistive card Rb can be precisely rotated by 3600 with respect to the two fixed resistive cards. The induced current on the resistive card R due to the incident signal is dissipated as heat producing attenuation of the transmitted signal. TE mode in RCT is converted into TE in circular waveguide. The resistive cards R and R a kept perpendicular to the electric field of TEIO mode so that it does not absorb the energy. But any component parallel to its plane will be readily absorbed. Hence, pure TE mode is excited in circular waveguide section. II

If the resistive card in the centre section is kept at an angle 8 relative to the E-field direction of the TEll mode, the component E cos8 parallel to the card get absorbed while the component E sin 8 is transmitted without attenuation. This component finally comes out as $E \sin 2\theta$ as shown in figure 5.10.

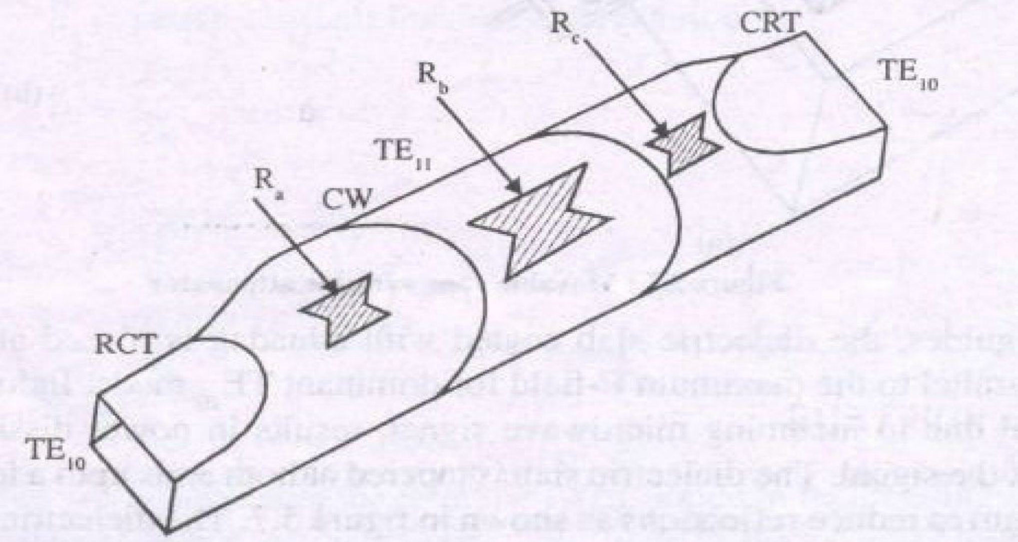


Figure 5.9 : Precision type variable attenuator

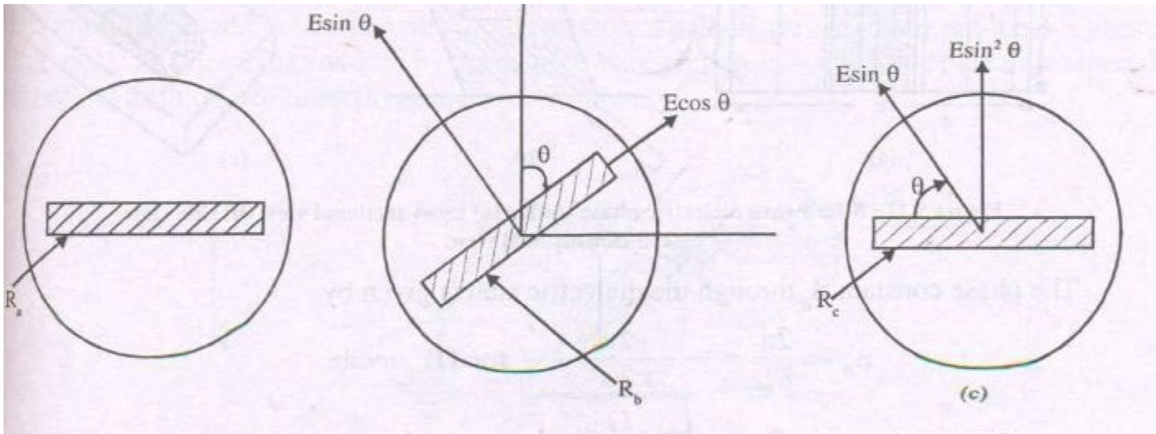


Figure 5.10 : Field components of electric field in the three sections RCT, CW and CRT

PHASE SHIFTERS:

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

PRECISION PHASE SHIFTER

The rotary type of precision phase shifter is shown in figure 5.12 which consists of a circular waveguide containing a lossless dielectric plate of length 2l called "half-wave section", a section of rectangular-to-circular transition containing a lossless dielectric plate of length l, called "quarter-wave section", oriented at an angle of 45° to the broader wall of the rectangular waveguide and a circular-to-rectangular transition again containing a lossless dielectric plate of same length 1 (quarter wave section) oriented at an angle 45°. The incident TEIO mode becomes TEll mode in circular waveguide section. The half-wave section produces a phase shift equal to twice that produced by the quarter wave section. The dielectric plates are tapered at both ends to reduce reflections due to discontinuity.

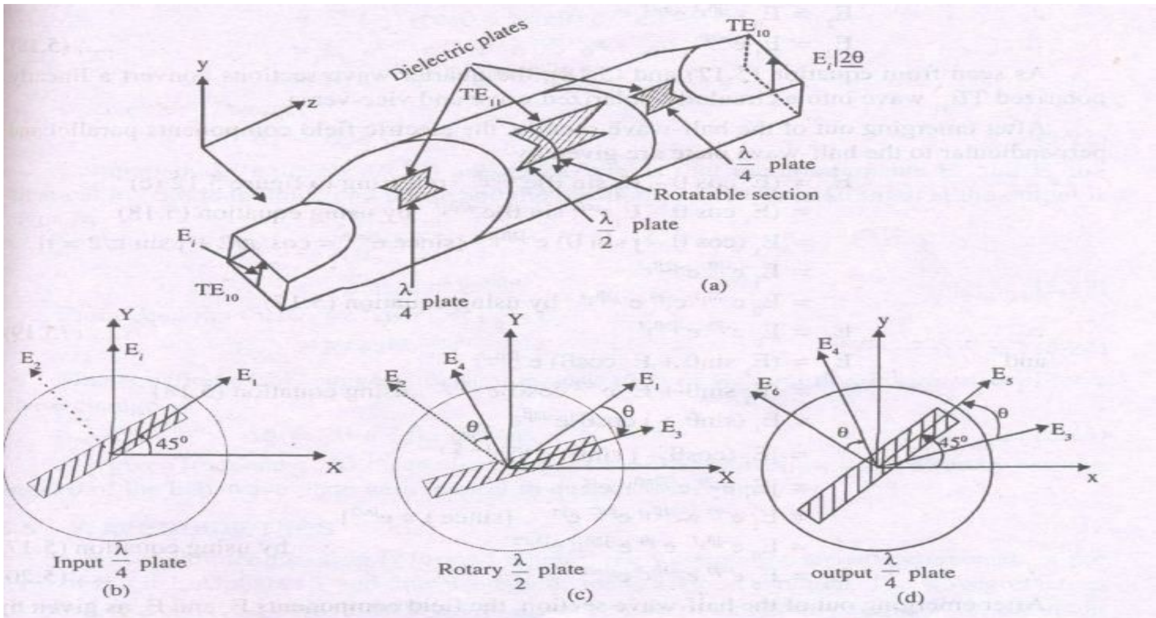


Figure 5.12 : Illustrating precision rotary phase shifter

When TEIO mode is propagated through the input rectangular waveguide of the rectangular to circular transition, then it is converted into TEll in the circular waveguide section. Let E; be the maximum electric field strength of this mode which is resolved into components, EI parallel to the plate and E2 perpendicular to El as shown in figure 5.12 (b). After propagation through the plate these components are given by

$$E_1 = (E_i \cos 45^0)\, e^{-j\beta_1 l} = E_0\, e^{-j\beta_1 l}$$

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

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

The length I is adjusted such that these two components E1 and Ez have equal amplitude but differing in phase by = 90°.

$$E_1 = E_0\, e^{-j\beta_1 l}$$

$$E_2 = E_0\, e^{-j(\beta_1 l - 90^0)} = E_0\, e^{-j(\beta_1 l - \frac{\pi}{2})}$$

$$\therefore \quad E_2 = E_0\, e^{-j\beta_1 l}\, e^{j\pi/2}$$

$$\therefore \quad E_2 = E_1\, e^{j\pi/2}$$

The quarter wave sections convert a linearly polarized TEll wave into a circularly polarized wave and vice-versa. After emerging out of the half-wave section, the electric field components parallel and perpendicular to the half-wave plate are given by

$$E_3 = (E_1 \cos\theta - E_2 \sin\theta)e^{-j2\beta_1 l} \quad \text{referring to figure 5.12 (c)}$$

$$= (E_1 \cos\theta - E_1 e^{j\pi/2} \sin\theta)e^{-j2\beta_1 l} \quad \text{by using equation (5.18)}$$

$$= E_1 (\cos\theta - j \sin\theta)\, e^{-j2\beta_1 l} \quad [\text{since } e^{j\pi/2} = \cos \pi/2 + j \sin \pi/2 = j]$$

$$= E_1\, e^{-j\theta}\, e^{-j2\beta_1 l}$$

$$= E_0\, e^{-j\beta_1 l}\, e^{-j\theta}\, e^{-j2\beta_1 l} \quad \text{by using equation (5.17)}$$

$$\therefore \quad E_3 = E_0\, e^{-j\theta}\, e^{-j3\beta_1 l} \qquad \text{..... (5.19)}$$

$$\text{and} \quad E_4 = (E_1 \sin\theta + E_2 \cos\theta)\, e^{-j2\beta_2 l}$$

$$= (E_1 \sin\theta + E_1\, e^{j\pi/2} \cos\theta)e^{-j2\beta_2 l} \quad \text{using equation (5.18)}$$

$$= E_1 (\sin\theta + j \cos\theta)e^{-j2\beta_2 l}$$

$$= jE_1 (\cos\theta - j \sin\theta)\, e^{-j2(\beta_1 l - \frac{\pi}{2})}$$

$$= jE_1\, e^{-j\theta}\, e^{-j2\pi\beta_1 l}\, e^{j\pi}$$

$$= E_1\, e^{-j\theta}\, e^{-j2\beta_1 l}\, e^{j\pi/2}\, e^{j\pi} \quad [\text{since } j = e^{j\pi/2}]$$

$$= E_0\, e^{-j\beta_1 l}\, e^{-j\theta}\, e^{-j2\beta_1 l}\, e^{j3\pi/2} \quad \text{by using equation (5.17)}$$

$$\therefore \quad E_4 = E_0\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{j3\pi/2} \qquad \text{..... (5.20)}$$

After emerging out of the half-wave section, the field components E3 and E4 as given by equations (5.19) and (5.20), may again be resolved into two TEll mQdes, polarized parallel and perpendicular to the output quarterwave plate. At the output end of this quarterwave plate, the field components parallel and perpendicular to the quarter wave plate, by referring to figure 5.12 (d), can be expressed as

$$E_5 = (E_3 \cos\theta + E_4 \sin\theta)\, e^{-j\beta_1 l}$$

$$= (E_0\, e^{-j\theta}\, e^{-j3\beta_1 l} \cos\theta + E_0\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{j3\pi/2} \sin\theta)e^{-j\beta_1 l}$$

$$= E_0 (\cos\theta + e^{j3\pi/2} \sin\theta)\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{-j\beta_1 l}$$

$$= E_o (\cos\theta - j \sin\theta)\, e^{-j\theta}.\, e^{-4\beta_1 l}$$

$$\therefore \quad E_5 = E_0\, e^{-j\theta}\, e^{-j\theta}\, e^{-j4\beta_1 l}$$

$$\therefore \quad E_5 = E_0\, e^{-j2\theta}\, e^{-j4\beta_1 l} \qquad \text{..... (5.21)}$$

$$\text{and} \quad E_6 = (E_4 \cos\theta - E_3 \sin\theta)\, e^{-j\beta_2 l}$$

$$\therefore \quad E_6 = (E_0\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{j3\pi/2} \cos\theta - E_o\, e^{-j\theta}\, e^{-j3\beta_1 l} \sin\theta)\, e^{-j\beta_2 l} \quad \text{by using equations (5.19) and (5.20)}$$

$$\therefore \quad E_6 = E_0 (e^{j3\pi/2} \cos\theta - \sin\theta)\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{-j(\beta_1 l - \frac{\pi}{2})}$$

$$= E_0 (-j \cos\theta - \sin\theta)\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{-j\beta_1 l}\, e^{j\pi/2}$$

$$= E_0 (-j) (\cos\theta - j \sin\theta)\, e^{-j\theta}\, e^{-j4\beta_1 l}\, e^{j\pi/2}$$

$$= E_0\, e^{j3\pi/2}\, e^{-j\theta}\, e^{-j\theta}\, e^{-j4\beta_1 l}\, e^{j\pi/2}$$

$$= E_0\, e^{-j2\theta}\, e^{-j4\beta_1 l}\, e^{j2\pi}$$

since $e^{j2\pi} = 1$, we get

$$E_6 = E_0\, e^{-j2\theta}\, e^{-j4\beta_1 l} \qquad \text{..... (5.22)}$$

Comparison of equation (5.21) and (5.22) yields that the components Es and E6 are identical in both magnitude and phase and the resultant electric field strength at the output is given by

$$\begin{aligned} E_{out} &= \sqrt{(E_5)^2 + (E_6)^2} \\ &= \sqrt{2}\ E_0\, e^{-j20}\, e^{-j4\beta_1 l} \end{aligned}$$

WAVE GUIDE TEE JUNCTIONS:

A waveguide Tee is formed when three waveguides are interconnected in the form of English alphabet T and thus waveguide tee is 3-port junction. The waveguide tees are used to connects a branch or section of waveguide in series or parallel with the main waveguide transmission line either for splitting or combining power in a waveguide system.

There are basically 2 types of tees namely

1.H- plane Tee junction
2.E-plane Tee junction

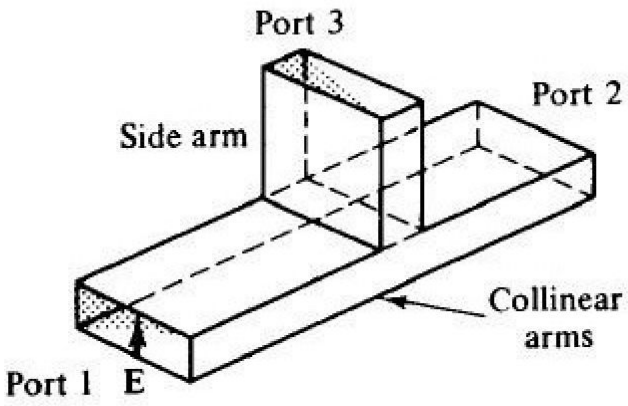
A combination of these two tee junctions is called a hybrid tee or “ Magic Tee”.

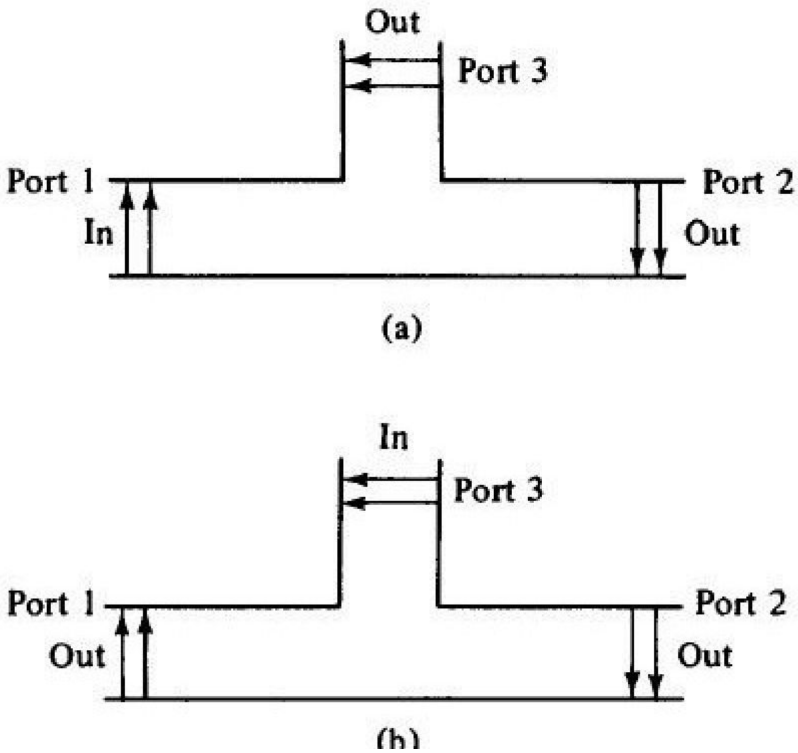
E-plane Tee(series tee):

An E-plane tee is a waveguide tee in which the axis of its side arm is parallel to the E field of the main guide . if the collinear arms are symmetric about the side arm.

If the E-plane tee is perfectly matched with the aid of screw tuners at the junction , the diagonal components of the scattering matrix are zero because there will be no reflection.

When the waves are fed into side arm, the waves appearing at port 1 and port 2 of the collinear arm will be in opposite phase and in same magnitude.



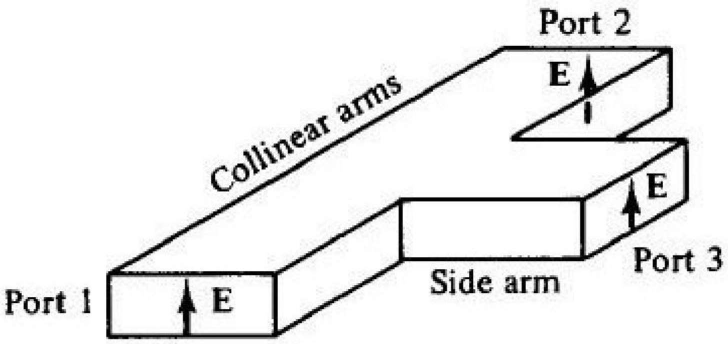


(a)

(b)

H-plane tee: (shunt tee)

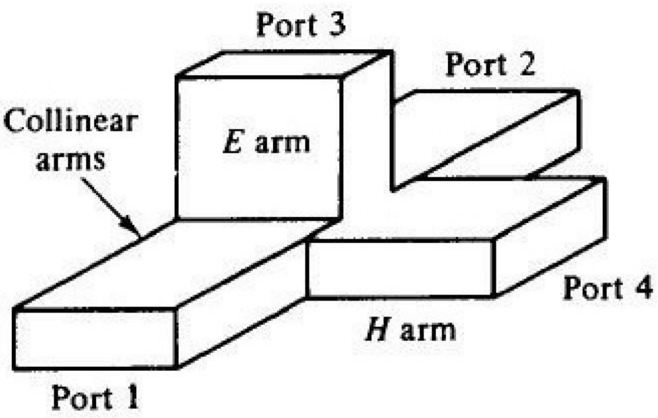
An H-plane tee is a waveguide tee in which the axis of its side arm is shunting the E field or parallel to the H-field of the main guide.



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 .
If the input is fed into port 3, the wave will split equally into port 1 and port 2 in phase and in same magnitude .

Magic Tee (Hybrid Tees)

A magic tee is a combination of E-plane and H-plane tee. The characteristics of magic tee are:



1. If two waves of equal magnitude and same phase are fed into port 1 and port 2 the output will be zero at port 3 and additive at port 4.

1. If a wave is fed into port 4 it will be divided equally between port 1 and port 2 of the collinear arms and will not appear at port 3.
2. If a wave is fed into port 3 , it will produce an output of equal magnitude and opposite phase at port 1 and port 2. the output at port 4 is zero.
3. If a wave is fed into one of the collinear arms at port 1 and port 2, it will not appear in the other collinear arm at port 2 or 1 because the E-arm causes a phase delay while H arm causes a phase advance.

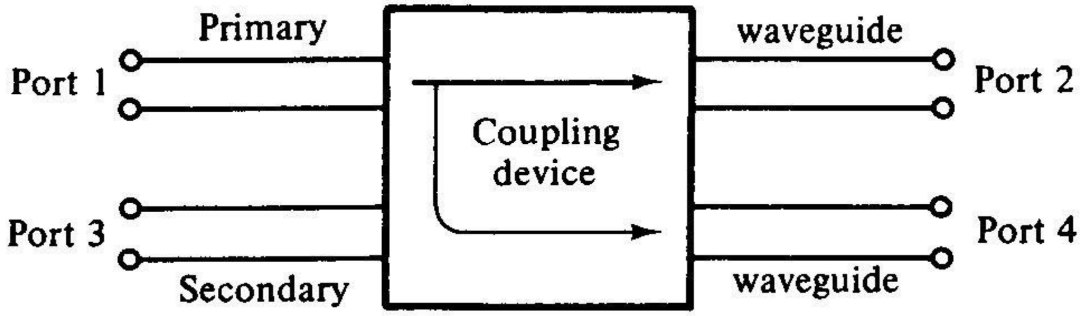
Therefore the **S** matrix of a magic tee can be expressed as

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

DIRECTIONAL COUPLERS:

A directional coupler is a four-port waveguide junction as shown below. It Consists of a primary waveguide 1-2 and a secondary waveguide 3-4. When all Ports are terminated in their characteristic impedances, there is free transmission of the waves without reflection, between port 1 and port 2, and there is no transmission of power between port I and port 3 or between port 2 and port 4 because no coupling exists between these two pairs of ports. The degree of coupling between port 1 and port4 and between port 2 and port 3 depends on the structure of the coupler.

The characteristics of a directional coupler can be expressed in terms of its Coupling factor and its directivity. Assuming that the wave is propagating from port to port2 in the primary line, the coupling factor and the directivity are defined,



Directional coupler.

where PI = power input to port I

P3 = power output from port 3

P4 = power output from port 4

$$\text{Coupling factor (dB)} = 10 \log_{10} \frac{P_1}{P_4}$$

$$\text{Directivity (dB)} = 10 \log_{10} \frac{P_4}{P_3}$$

It should be noted that port 2, port 3, and port 4 are terminated in their characteristic impedances. The coupling factor is a measure of the ratio of power levels in the primary and secondary lines. Hence if the coupling factor is known, a fraction of power measured at port 4 may be used to determine the power input at port 1 .

This significance is desirable for microwave power measurements because no disturbance, which may be caused by the power measurements, occurs in the primary line. The directivity is a measure of how well the forward traveling wave in the primary waveguide couples only to a specific port of the secondary waveguide ideal directional coupler should have infinite directivity. In other words, the power at port 3 must be zero because port 2 and portA are perfectly matched. Actually well-designed directional couplers have a directivity of only 30 to 35 dB.

Several types of directional couplers exist, such as a two-hole direct couler, four-hole directional coupler, reverse-coupling directional coupler , and Bethe-hole directional coupler the very commonly used two-hole directional coupler is described here.

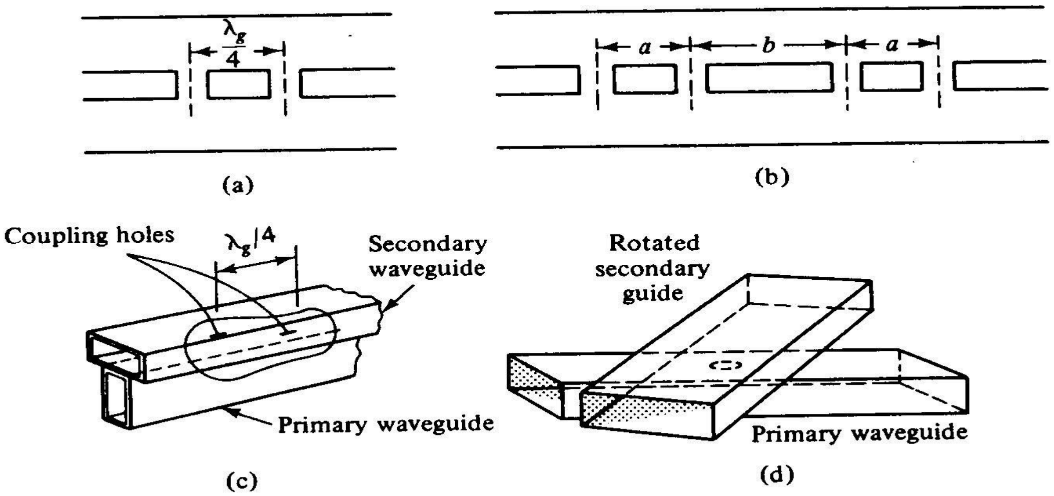


Figure 4-5-2 Different directional couplers. (a) Two-hole directional coupler. (b) Four-hole directional coupler. (c) Schwinger coupler. (d) Bethe-hole directional coupler.

TWO HOLE DIRECTIONAL COUPLERS:

A two hole directional coupler with traveling wave propagating in it is illustrated . the spacing between the centers of two holes is

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

A fraction of the wave energy entered into port 1 passes through the holes and is radiated into the secondary guide as he holes act as slot antennas. The forward waves in the secondary guide are in same phase , regardless of the hole space and are added at port 4. the backward waves in the secondary guide are out of phase and are cancelled in port 3.

S-matrix for Directional coupler:

The following characteristics arc observed in an ideal Directional Coupler:

1. Since the directional coupler is a 4-portjunction, the order or (S I matrix is 4 x 4 givcn by

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

2. Microwave power fed into port (I) cannot comc out of port (3) as port (3) is the back port. Therefore the scattering co-efficient S13 is zero...'

$$S_{13} = 0$$

3. Because of the symmetry of the junction, an input power at port (2) cannot couple to port (4) as port (4) is the back-port for port (2)

$$S_{24} = 0$$

4. Let us assume that port (3) and (4) are perfectly matched to the junction so that

$$S_{33} = S_{44} = 0$$

Then, the remaining two ports will be "automatically" matched to the junction

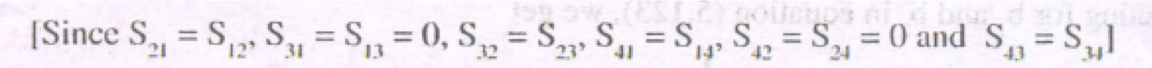
$$S_{11} = S_{22} = 0$$

From the symmetric property of ISI matrix, we have

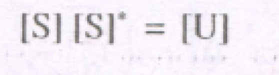
$$S_{ij} = S_{ji}$$

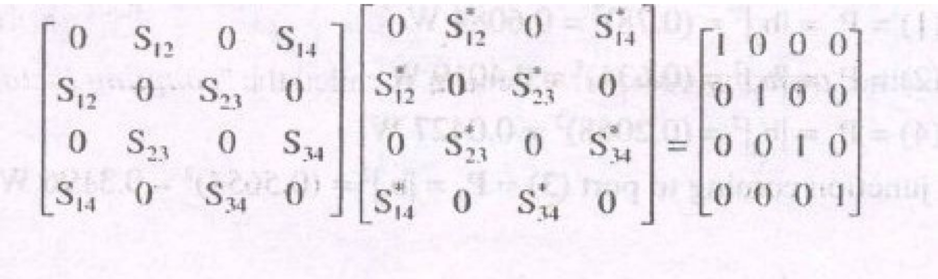
With the above characteristic values for S-parameters, the matrix of (5.125) becomes

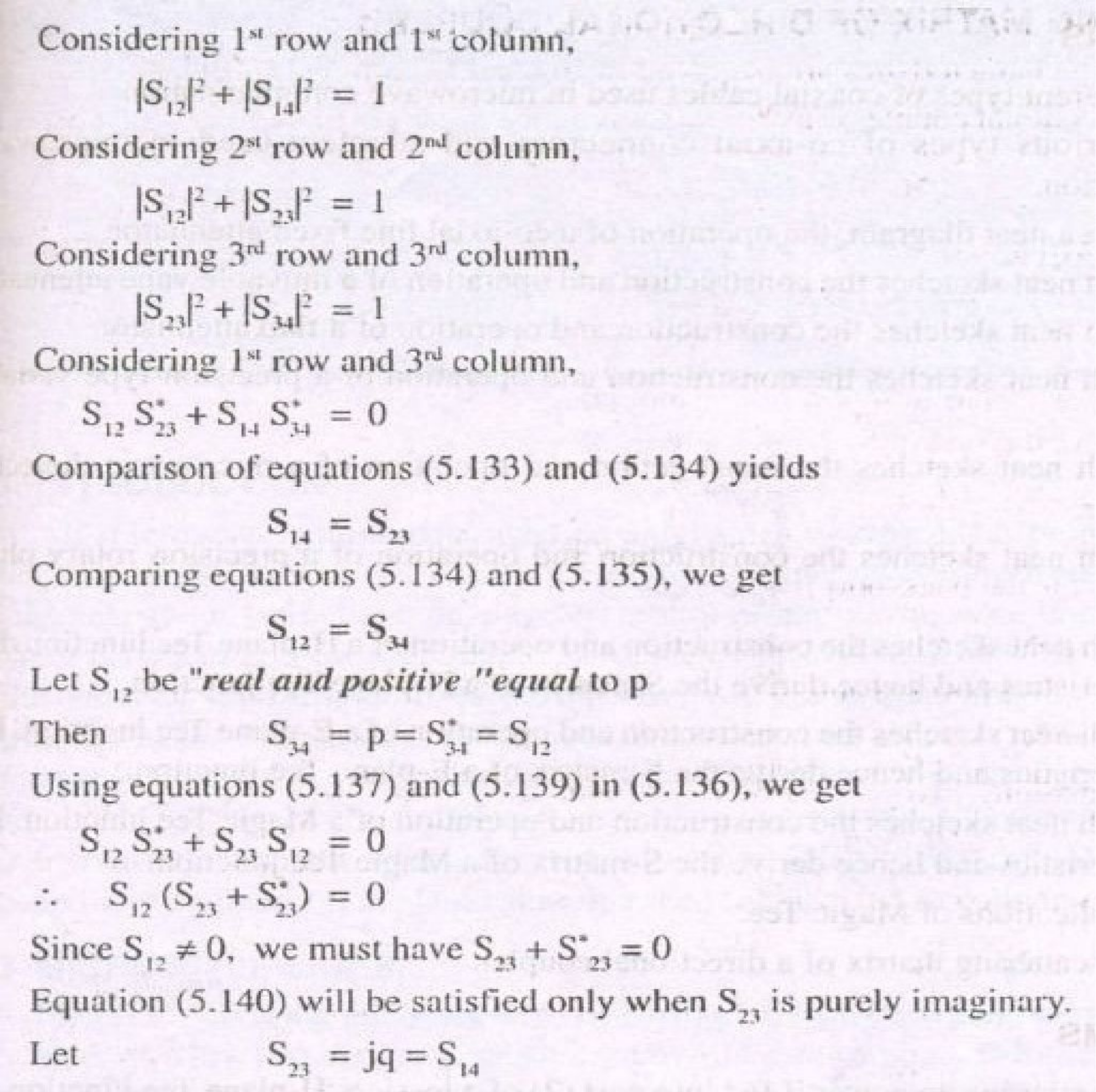
$$[S]_x = \begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{12} & 0 & S_{23} & 0 \\ 0 & S_{23} & 0 & S_{34} \\ S_{14} & 0 & S_{34} & 0 \end{bmatrix}$$


[Since $S_{21} = S_{12}$, $S_{31} = S_{13} = 0$, $S_{32} = S_{23}$, $S_{41} = S_{14}$, $S_{42} = S_{24} = 0$ and $S_{43} = S_{34}$]

From unitary property of equation we have


$$[S]\,[S]^* = [U]$$


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


Considering 1st row and 1st column,

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

Considering 2nd row and 2nd column,

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

Considering 3rd row and 3rd column,

$$|S_{23}|^2 + |S_{34}|^2 = 1$$

Considering 1st row and 3rd column,

$$S_{12}\, S_{23}^* + S_{14}\, S_{34}^* = 0$$

Comparison of equations (5.133) and (5.134) yields

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

Comparing equations (5.134) and (5.135), we get

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

Let S_{12} be "*real and positive* "*equal* to p

Then $S_{34} = p = S_{34}^* = S_{12}$

Using equations (5.137) and (5.139) in (5.136), we get

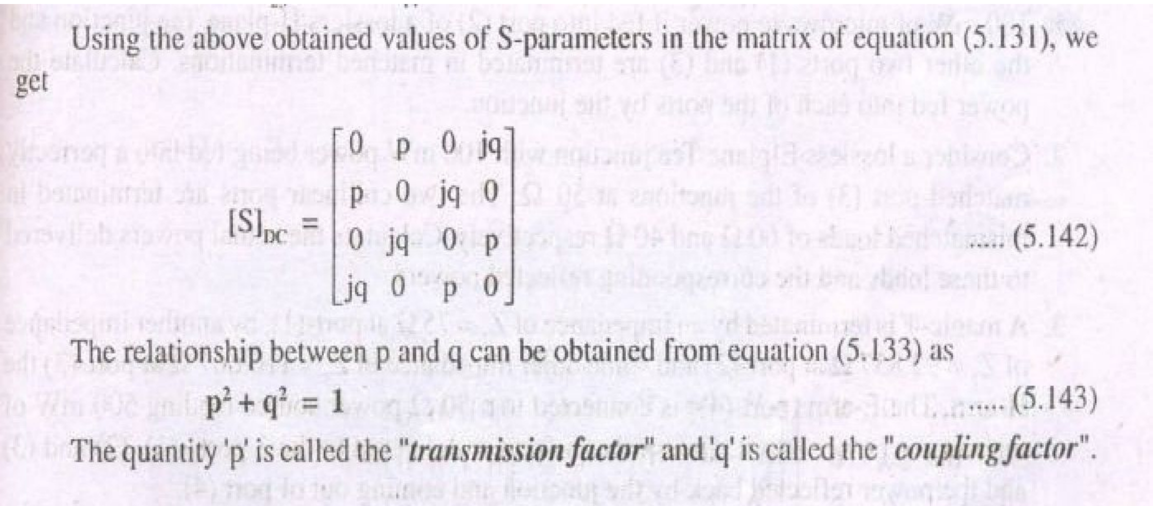
$$S_{12}\, S_{23}^* + S_{23}\, S_{12} = 0$$

$$\therefore \quad S_{12}\,(S_{23} + S_{23}^*) = 0$$

Since $S_{12} \neq 0$, we must have $S_{23} + S^*_{23} = 0$

Equation (5.140) will be satisfied only when S_{23} is purely imaginary.

Let $S_{23} = jq = S_{14}$



Using the above obtained values of S-parameters in the matrix of equation (5.131), we get

$$[S]_{DC} = \begin{bmatrix} 0 & p & 0 & jq \\ p & 0 & jq & 0 \\ 0 & jq & 0 & p \\ jq & 0 & p & 0 \end{bmatrix} \quad \text{..... (5.142)}$$

The relationship between p and q can be obtained from equation (5.133) as

$$p^2 + q^2 = 1 \quad \text{..... (5.143)}$$

The quantity 'p' is called the "***transmission factor***" and 'q' is called the "***coupling factor***".

RECOMMENDED QUESTIONS FOR UNIT -5

1. **Explain the different co-axial connectors and adapters used for microwave applications.**
2. **Explain the different co-axial cables used for microwave applications.**
3. **Explain with a neat sketch a precision type variable attenuator**
4. **Explain with a neat sketch a flap type variable attenuator**
5. **Explain with a neat sketch a precision resistive type attenuator**
6. **With a neat sketch explain a precision rotary phase shifter**
7. Explain with neat sketch the construction and operation of H-plane Tee junction .
8. Explain with neat sketch the construction and operation of E-plane Tee junction .
9. Explain with neat sketch the construction and operation of Magic Tee
10. Explain the characteristics and S- matrix of H-plane Tee junction .
11. Explain the characteristics and S- matrix of E-plane Tee junction .
12. Explain the characteristics and S- matrix of Magic Tee junction .
13. Derive the scattering parameter of a directional coupler.