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

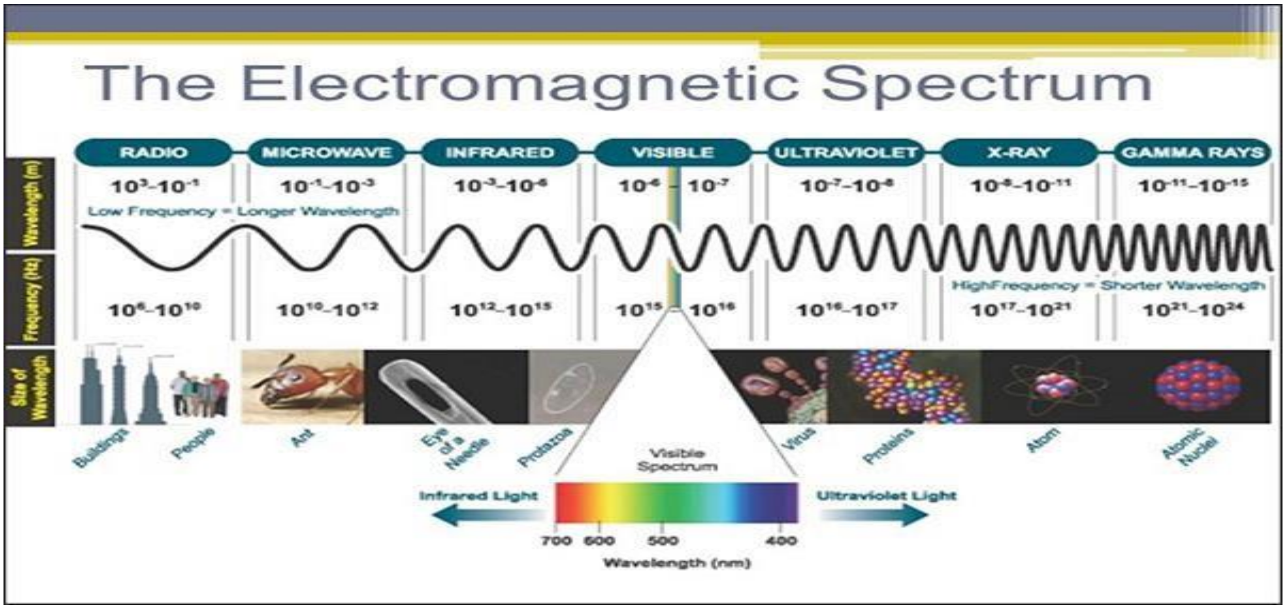
Course Outcomes: After completing this course, students should be able to:

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

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

1. Introduction

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



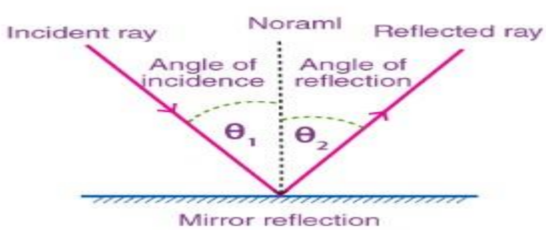
Microwaves obey the laws of optics, such as Snell's law and the law of reflection, and thus can be transferred, assimilated, or reflected, which is extremely important when considering how microwaves operate.

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

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

Where,

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



2. Bands:

Electromagnetic wave spectrum	**Frequency band**	**Wavelength**
Radio waves	**Very high frequency (VHF) (30–300 MHz)**	**10–1 m**
Microwaves	**Ultrahigh frequency (UHF) (300–3000 MHz)**	**(100–10 cm)**
	P band (230 MHz–1 GHz)	130–30 cm
	L band (1–2 GHz)	30–15 cm
	S band (2–4 GHz)	15–7.5 cm
	Super high frequency (SHF) (3–30 GHz)	**(10–1 cm)**
	S band (2–4 GHz)	15–7.5 cm
	C band (4–8 GHz)	7.5–3.75 cm
	X band (8–12.5 GHz)	3.75–2.4 cm
	Ku band (12.5–18 GHz)	2.4–1.67 cm
	K band (18–26.5 GHz)	1.67–1.13 cm
	Ka band (26.5–40 GHz)	1.13–0.75 cm
Electromagnetic wave spectrum	**Frequency band**	**Wavelength**
Millimeter waves	**Extremely high frequency (EHF) (30–300 GHz)**	**(10–1 mm)**
	Ka band (26.5–40 GHz)	1.13–0.75 cm
	V band (40–75 GHz)	7.5–4 mm
	W band (75–110 GHz)	4–2.73 mm
	Millimeter band (110–300 GHz)	2.73–1 mm

Name	**Frequency range**	**Name origin**	**Common applications**
VHF Band	30 to 300 MHz	Very High Frequency	• FM radio • Television broadcasts

UHF Band	300 to 3000 MHz	Ultra High Frequency	• Television broadcasts • Microwave oven • Microwave devices • Communications • Radio astronomy • Mobile phones • Wireless LAN • Bluetooth
L Band	1 to 2 GHz	Long	• Military telemetry • GPS • Air traffic control (ATC) radarS Band2 to 4 GHzShort• Weather radar • Surface ship radar • Microwave ovens • Microwave devices • Communications
C Band	4 to 8 GHz	Compromise(between S and X)	• Long-distance radio telecommunications
X Band	8 to 12 GHz	X for “crosshair” (used in WW2 for fire control radar	• Satellite communications • Radar • Terrestrial broadband • Space communications
Ku Band	12 to 18 GHz	Kurtz Under	• Satellite communications
Name	**Frequency range**	**Name origin**	**Common applications**
K Band	18 to 26.5 GHz	Kurtz (German for short)	• Radar • Satellite communications • Astronomical observations • Automotive radar
Ka Band26	5 to 40 GHz	Kurtz Above	• Satellite communications

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

1. Military & Defense Radar

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

3. Properties of Microwaves

Following are the main properties of Microwaves.

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

4. Advantages of Microwaves

There are many advantages of Microwaves such as the following –

- Supports larger bandwidth and hence more information is transmitted. For this reason, microwaves are used for point-to-point communications.
- More antenna gain is possible.
- Higher data rates are transmitted as the bandwidth is more.
- Antenna size gets reduced, as the frequencies are higher.
- Low power consumption as the signals are of higher frequencies.
- Effect of fading gets reduced by using line of sight propagation.

- Provides effective reflection area in the radar systems.
- Satellite and terrestrial communications with high capacities are possible.
- Low-cost miniature microwave components can be developed.
- Effective spectrum usage with wide variety of applications in all available frequency ranges of operation.

Disadvantages of Microwaves

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

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

5. Applications of Microwaves

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

- For long distance telephone calls
- Bluetooth
- WIMAX operations
- Outdoor broadcasting transmissions
- Broadcast auxiliary services
- Remote pickup unit
- Studio/transmitter link
- Direct Broadcast Satellite DBSDBS
- Personal Communication Systems PCSs
- Wireless Local Area Networks WLANs
- Cellular Video CVCV systems
- Automobile collision avoidance system

Electronics

- Fast jitter-free switches
- Phase shifters
- HF generation
- Tuning elements
- ECM/ECCM ElectronicCounterMea

sureElectronicCounterMeasure sy stems

- Spread spectrum systems

Commercial Uses

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

Navigation

- Global navigation satellite systems
- Global Positioning System GPSGPS

Military and Radar

- Radars to detect the range and speed of the target.
- SONAR applications
- Air traffic control
- Weather forecasting
- Navigation of ships
- Minesweeping applications
- Pre-cooking • To know about unpaired electrons
- Roasting food grains/beans in chemicals
- Drying potato chips • To know the free radicals in
- Moisture levelling materials
- Speed limit enforcement
- Military uses microwave frequencies for communications and for the above-mentioned applications.

Research Applications

- Atomic resonances
- Nuclear resonances

Radio Astronomy

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

Food Industry

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

- Absorbing water molecules • Electron chemistry

Industrial Uses **Medical Applications**

- Vulcanizing rubber • Monitoring heartbeat
- Analytical chemistry applications • Lung water detection
- Drying and reaction processes • Tumor detection
- Processing ceramics • Regional hyperthermia
- Polymer matrix • Therapeutic applications
- Surface modification • Local heating
- Chemical vapor processing • Angioplasty
- Powder processing • Microwave tomography
- Sterilizing pharmaceuticals • Microwave Acoustic imaging
- Chemical synthesis
- Waste remediation
- Power transmission
- Tunnel boring
- Breaking rock/concrete
- Breaking up coal seams
- Curing of cement
- RF Lighting
- Fusion reactors
- Active denial systems

Semiconductor Processing Techniques

- Reactive ion etching
- Chemical vapor deposition **Spectroscopy**
- Electron Paramagnetic Resonance

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

6. Radiation hazards

A. Hazards of Electromagnetic Radiations to Personnel. (HERP)

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

HERP is caused by thermal effect of radiated energy. Biological substances are : Blood, Muscles, Bone, Brain, Fat [These behave as conductive dielectric]

Microwave energy directed on to the body may be scattered, reflected, and absorbed, depending on the field strength, the frequency, dimension of the body and electrical properties of the tissue.

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

e.g. If the lens of the eye is exposed to microwaves, its circulatory system would be unable to provide sufficient flow of blood for cooling and may cause cataract.

Similarly, the stomach, intestines and bladder are specially sensitive to thermal damage from high power microwaves.

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

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

How to Protect from Radiations - Radiation protection can be practiced by preventing radiations from entering into the beam of the transmit antenna or

by preventing coming close to any microwave generator or propagating medium. - In areas where high power Radar are used, the service and maintenance personnel must wear microwave absorptive suit made out of stainless steel woven into a fire retardant synthetic fiber.

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

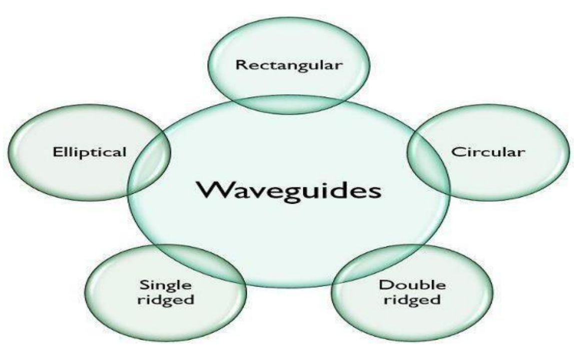
- The attenuation produces by such suit is above 20dB at 2450 MHz, 20-35 dB from 650-1150 MHz, and 35-40 dB from 1-11 GHz.

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

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

Types of waveguides

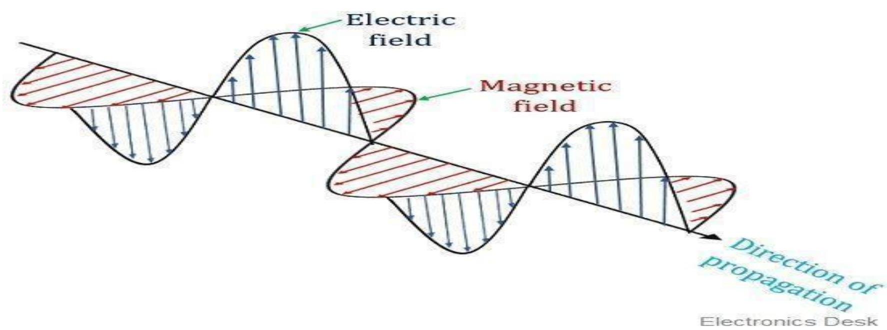
Waveguides are majorly classified as rectangular or circular but these are basically of 5 different types:



Modes of propagation in a Waveguide

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

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



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

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

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

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

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

$$E_z = H_z = 0$$

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

Parameters of a Waveguide:

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

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

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

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

Advantages of waveguides

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

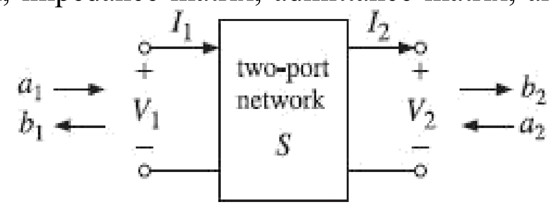
1. Its installation and manufacturing cost is high.
2. Waveguides are generally rigid in nature and hence sometimes causes difficulty in applications where tube flexibility is required.
3. It is somewhat large in size and bulkier as compared to other transmission lines.

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

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

7. S-parameters (Scattering Parameters)

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



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

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

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

- Thus, the transfer and impedance matrices are the 2×2 matrices:

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

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

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

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

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

S- the scattering matrix

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

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

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

Properties of S matrix:

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

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

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

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

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

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

8. *State and explain the properties of S-matrix.*

VTU : Jan.-19, Marks 7

9. *Discuss the following properties of S-parameters :*
   i) Symmetry of [S] for a reciprocal network.
   ii) Unitary property for a lossless junction

VTU : July-19, Marks 8

2.3 Reciprocal and Lossless Network

VTU : July-16, 17, Jan.-19, July-19, Jan.-20

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

Two-port Reciprocal Network

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

Lossless Network

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

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

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

2.3.1 Symmetry of S-matrix for Reciprocal Network

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

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

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

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

where [U] is unit matrix.

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

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

Comparing equation (2.3.1) and (2.3.2)

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

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

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

For reciprocal network, the Z-matrix is symmetric

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

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

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

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

Since Z-matrix is symmetrical

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

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

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

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

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

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

2.3.2 Scattering Matrix for Lossless Junction

Statement :

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

Proof :

- An n - port network can be described by an n × n S-parameter matrix :