



Ahsanullah University of Science and Technology

Department of Electrical and Electronic Engineering

LABORATORY MANUAL FOR ELECTRICAL AND ELECTRONIC SESSIONAL COURSES

Student Name:
Student ID:

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Course title: - Microwave Engineering Lab

For the students of
Department of Electrical and Electronic Engineering
4th Year, 1st Semester

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Experiment no: **1**

Name of the Experiment: **Microwave Oscillator Characterization and Power Measurement**

(a) Objective:

1. To understand the theory, operation and characteristics of microwave oscillators (Klystron and Gunn oscillator).
2. To learn about different ways of measuring microwave power.
3. To learn how to evaluate the accuracy of power measurement.

(b) Equipments:

1. Power supply

2. Microwave Oscillator

(a) Klystron Oscillator [set-up1]

The three most important parts are: Klystron tube, Klystron power supply and klystron mount. It works on the basis of interaction between an electron beam and an RF voltage.

(b) Gunn Oscillator[set-up2]

Work on the basis of Gunn effect. It generates microwave frequencies when a Gunn diode (which is loosely coupled to a cavity) is connected to a 8-10 V DC power source. It works with the aid of a *PIN-diode modulator* which utilizes the property of a PIN diode (material Si, GaAs etc.) which is passed across waveguide. When reverse bias across it is partially removed it begins to control the energy flow, thus creating an amplitude or pulse modulation effect.

3. Variable attenuator/Fixed attenuator

A variable attenuator provides attenuation of microwave signal by varying the degree of insertion of matched resistive strip into waveguide. Different types of variable attenuator and fixed attenuators (provides fixed attenuation) used in the experiment.

4. Coax cable with BNC (Bayonet Navy) connector

It provides a match between a waveguide and a 50 ohm coaxial. Coaxial cable is used as high frequency transmission line to carry high frequency or broadband signal. Sometimes DC bias is added to the signal to supply the equipment at other end, as in direct broadcast satellite receivers. Because electromagnetic field exist only in the space between inner and outer conductors, it cannot interfere or suffer interference from external electromagnetic field. The BNC (Bayonet Neil Connector) operates very well at frequencies up to about 4 GHz, beyond that it tends to radiate electromagnetic energy. The BNC can accept flexible cables with diameters of up to 6.35 mm and characteristics impedance of 50-75 ohms (Fig.1.1). *Waveguide to Coax adapter* was also used for the same purpose.

5. Waveguide to Coax adapter

It provides a match between a waveguide and a 50 ohm coaxial. The power flow can be in either direction. However SWR in the adaptor should be kept less than 1.2.

6. Power Meter

(a) Bolometer / Thermocouple mount [set-up1]

Bolometers are generally of two types – thermistor mount and waveguide mount. Figure 1.2 indicates the former type. The bolometer mount must be designed to satisfy the following requirements:

- i) Present a good impedance match to the transmission line over frequency of interest.
- ii) Keep I^2R and dielectric losses within the structure minimized so that power is not dissipated in electrical contacts, waveguide walls or insulators.
- iii) Provide isolation from thermal and physical shocks
- iv) Keep leakage small so that microwave power does not escape from the mount in a shunt path around the bolometer.

(b) Thermocouple Power Meter [set-up2]

A high quality thermocouple (high frequency material for thermo-junctions with low error rate) can convert the microwave energy to a readily measurable DC voltage which is generated as the wires conduct the high frequency current and heat is generated across the two different

metal contacts. The meter indication is calibrated to represent the power level in the waveguide. The power meter is provided with its 10 GHz DRO source. (Fig.1.3).

(c) Theory:

1. **Microwave oscillator**

There are two types of microwave signal source which generates microwave signal – (i) tube sources (such as klystron, magnetron, TWT etc.) and (ii) solid state sources (such as special diodes and transistors).

(a) **Klystron Oscillator [set-up1]**

It uses the transit time effect to an advantage. According to Fig. 1.4 of two cavity Klystron, a high velocity electron beam is obtained by the combined effect of cathode, focusing electrodes and collector. The electron beam passes through the gap 'A' of the buncher cavity, to which RF signal is coupled and result is interaction between electron beam and RF field across gap A. Then electron beam drifts in the drift space and reaches gap 'B' of catcher cavity where oscillation will start.

(b) **Gunn Oscillator [set-up2]**

To make a Gunn oscillator, we need an inductor to tune out capacitor and shunt local resistance (less than negative resistance). See Fig. 1.5 (b). It works on the basis of Gunn effect ("When a small DC voltage is applied across a thin slice of semiconductor material (GaAs or InP), it exhibits under negative resistance certain conditions"). So, oscillations can be started by connecting the negative resistance element to a tuned circuit. Gunn diode (Fig1.5) is a transferred electron device that uses bulk semiconductor (GaAs, InP), as opposed to a pn junction. This effect leads to negative resistance characteristics. Gunn diodes are grown epitaxially out of GaAs doped with silicon, selenium or tellurium. The substrate (used as ohmic contact) is highly doped for good conductivity, while the thin active layer (1-40 micrometer) is less highly doped. Normally Gunn diodes are available for frequency 4 GHz (1.5 W) to 7.5 GHz (50 mW).

GaAs possesses an empty energy band at the top of the energy level and a partially filled energy band is below the empty band. When the material is doped with n-type material, the excess electrons in the material are ready to flow when a voltage is applied across the diode. One of the requirements is to keep a voltage gradient across semiconductor material 3 KV/cm. When the applied voltage reaches a sufficiently high value, a bunch of electrons moves to a higher energy level which was previously empty (Fig. 1.5(c)) and becomes less mobile (transferred electron effect), not trying to move faster. So current (proportional to the voltage) flow decreases (negative resistance effect). These regions where negative resistance effect occurs are called *domains*. The frequency of oscillation is mainly determined by the time the *electron bunch* takes to transfer the slice of material. The domain electron is formed per cycle and it arrives at the positive end of the slice to excite oscillations in the associated tuned circuit. Other areas with fewer free electrons mean less conductivity and result in a potential difference. At higher voltage, electrons are taken out at first rate from these domains and those are behind the bunch (whole domain moves across the slice) and toward the positive end.

As a result, the amount of conduction band electron decreases and these areas become more less conductive and have a higher potential gradient. This process of electron transfer and domain travelling repeats itself and is said to be '*self perpetuating*.' When the domain reaches to the anode of the diode, a pulse is applied to the associated resonant tank circuit resulting in oscillation.

2. **Power Measurements:**

The power is defined as the time rate of transforming energy. In case of microwave, this energy is used in many different forms: exchange of information over long distance, heating a microwave oven or acceleration of particles in nuclear engineering etc.

For low frequency signals, power measurements are done from the voltage, current or lumped values of circuit parameters.

For microwave frequencies, the difficulty arises due to

1. Distributed nature of the circuit elements
2. Reflection of the signal, wherever there is an impedance mismatch.

There are two types of microwave power measurements-

1. Average power (time average of sum of the product of instantaneous voltage & current over the time period)
2. Peak power.

The average power in an alternating current circuit

$$P_{avg} = (1/T) \int_0^T e i dt ; T = \text{period, } e \text{ \& } I = \text{inst. voltage \& current}$$

$$P_{avg} = E_{rms} I_{rms} \cos(\theta)$$

Now consider a duty cycled pulse

Peak power of the pulse is related to the average power of the pulse by the duty cycle of the pulse

$$P_{peak} = P_{avg} / \text{duty cycle ; duty cycle} = t/T$$

Usually, average power is involved in the microwave circuit which has a continuous signal source. But, where pulsed signals serve as a signal source, peak power is more meaningful way of expressing power.

Microwave power measurements are basically of two types:

i) Bolometer method

This technique is based on devices such as detectors, bolometers and thermocouples (whose resistance changes with applied power). These devices can measure power in the range of mW and are very sensitive.

A bolometer is a square law device that produces current that is proportional to applied power. It is a simple circuit element whose resistance varies with temperature (Fig.1.6). Practically, a bolometer mount can be connected to the waveguide system and used as a load.

There are two different types of bolometers- barretter (a wire mounted in cartridge like ordinary fuse & its resistance increases with temperature), thermistor (a small semiconductor bead with connecting wire & its resistance decreases with temperature). Another power measurement technique using thermocouple is explained in the next section.

ii) Calorimeter method

Based on devices such as calorimeters in which temperature rise of known quantity of liquid (being used as a load) is measured. These devices can measure power in the range of hundreds of KW, are not so sensitive but are quite accurate.

3. Power measurement technique by bolometric method using wheatstone bridge [set-up1]:

One of the simplest methods for bolometric power measurement is to place a bolometer in one leg of wheatstone bridge (Fig.1.7). The bridge is excited by a regulated dc supply whose amplitude may be adjusted with R_1 . Since R_4 is a thermistor, its resistance may be controlled by the amount of current allowed to pass through it.

In operation, R_1 is adjusted until just enough current passes through the bridge to make the thermistor resistance equal to R_5 , bringing the bridge into balance and causing the meter to read zero.

In this case, half of the total current (i_T) will pass through R_1 .

$$I_4 = 0.5i_T$$

$$\text{Power, } P_T = i_4^2 R_4 = 0.25 i_T^2 R_4$$

Microwave power is then applied to the thermistor and heating effect causes the thermistor resistance to decrease, unbalancing the bridge in proportion to the power applied. The unbalance current is indicated on the meter, which is calibrated directly in mW. If we adjust R_1 to balance the bridge again, the total current changes. This dc power changes is equal to the rf power applied.

$$\text{DC power, } P_{dc} = 0.5 i_{dc}^2 R_4$$

$$\text{rf power, } P_{rf} = P_T - P_{dc} = 0.25 (i_T^2 - i_{dc}^2) R_4$$

$$P_{rf} = 0.25 (i_T - i_{dc}) (i_T + i_{dc}) R_4$$

$$P_{rf} = 0.25 (\Delta i)(i_T + i_{dc})R_4 = \text{proportional to current change}$$

This method is acceptable for power measurements when rf power is 1 mW or above. Otherwise, Δi becomes difficult to deal with.

4. Thermocouple Power Measurements [set-up2]:

The advantage of using thermocouple wires is the possibility of measuring the power by measuring the DC volts developed across the thermocouple wires (Fig. 1.8, Fig.1.9). The DC voltage is generated as the wires conduct the high frequency current and heat is generated across the two different metal contacts.

In contrast, a power meter works when voltage is applied to a meter and meter is calibrated to indicate the power. There are also thin film thermocouple materials (bismuth and antimony) suitable for microwave applications. These materials develop heat by absorbing the input power resulting in an emf.

There are difficulties using thermocouple to measure power because of resistance change with temperature making matching difficult and very small diameter is required to remove skin effect and frequency dependence. Thermocouple has a use where constant power level monitoring has to be done.

d) Experiment procedure:

1. Characteristics of Gunn diode [set-up2].

(i) I-V characteristics

1. Set up the equipment as shown in Fig.1.10
2. Set up the voltage to 4 V. Set the variable attenuator o 10 dB. This will ensure proper isolation to Gunn oscillator.
3. Raise the voltage in 0.5 V increment. Measure and record the current each time according to Table 1

Table 1.1

Supply V	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
Supply mA													

Supply V	0	0.5	1	1.5	2	2.5	3	3.5	4
Supply mA									

4. Reduce the voltage to 0 V.
5. Plot the V-I characteristics curve from the measured data

(ii) Oscillator output power vs. supply voltage

1. In the previous set-up, turn the power meter on and wait for it to settle to zero.
2. Raise the gun diode voltage in 0.5 V increment and record the power indication on the power meter and the attenuator setting.
3. Convert the obtained reading in mw to dBm. Then add the attenuation to dBm. Then reconvert this gunn diode output power back to mw.

Example:

Assume supply = 8.5 V, power reading= 6.3 mW

Means power reading= $10 \log 6.3 = 8 \text{ dBm}$

Total power = 8 + attenuation (let 3)=11 dBm = 12.6 mW

4. Repeat the step (3) and complete the table below.
5. Draw a graph showing the relationship between supply voltage and output power.

Table 1.2

Supply V	4	4.5
Power meter reading (mw)		
Converted power (dBm)		
Attenuator setting (dB)		
Gunn diode output (dBm)		
Gunn diode output (mw)		

2. Power measurements

(i) **Direct measurement [set-up2]**

1. Set up the equipment as shown in Fig.1.9.
2. Without the signal activated, switch on the power meter and allow it to adjust the meter to zero.
3. Turn on the Gunn oscillator. Adjust the variable attenuator to 3 dB. Read the power meter and record the reading.

(ii) **Microwave power measurement [set-up1]**

1. Hook up the circuit as in Fig.1.11
2. Using multi-meter, measure the dc-voltage reading and corresponding μA meter reading at the output point of thermistor mount. Arrange them according to Table 1.3 and calculate power. Plot Power vs μA calibration graph.

Table 1.3

Multimeter reading (volt)	Current reading (μA)	Power reading (μW)

3. Withdraw the multimeter. Vary the attenuator setting according to Table.1.4, measure μA , convert the reading into relative power (proportional) and determine relative power (normalized) using the equation, power (in dB) = $10 \text{ Log}_{10}(P_{in}/P_{out})$.

Table 1.4

Power (dB))	Relative power (proportional)	Relative power (normaized)

0		
-3		
-6		
-12		
-24		

e) Report:

1. Draw respective block diagrams of experimental set-ups and briefly explain the function of each part.
2. Discuss the results.
3. Briefly explain different microwave signal generation techniques.
4. Briefly explain different microwave power measurement techniques.

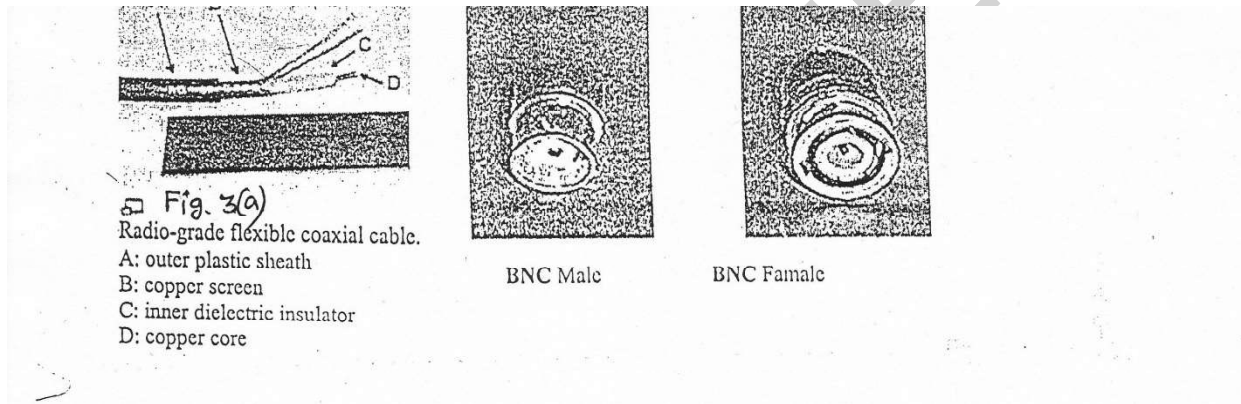


Fig. 1.1 Various types of connecting cables.

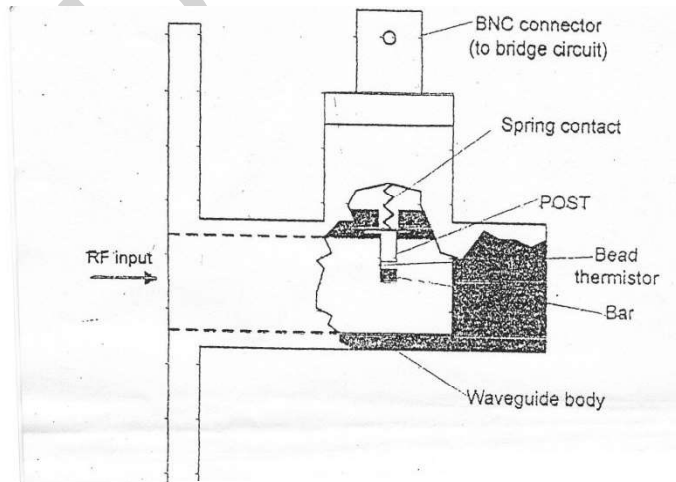


Fig. 1.2 Cutaway view of thermistor mount

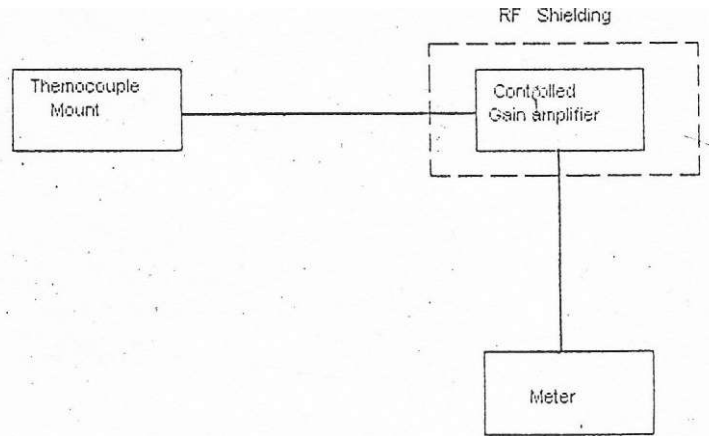


Fig.1.3 Construction of Thermocouple power meter

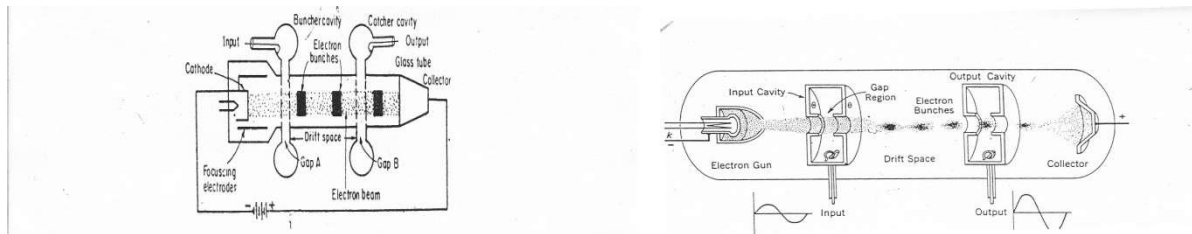


Fig. 1.4 Schematic Drawing of klystron Oscillator

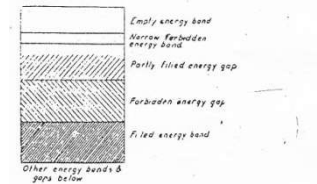
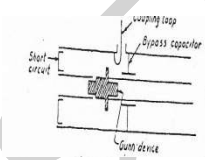
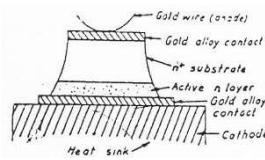


Fig. 1.5 (a) Epitaxial GaAs Gunn diode (b) Coaxial type Gunn oscillator (c) Energy levels

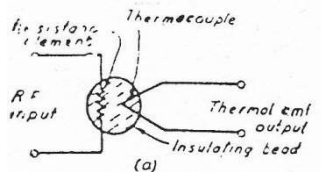
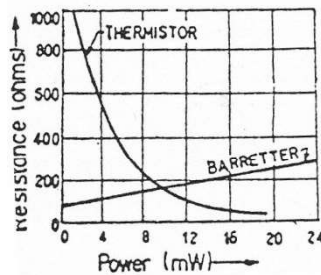


Fig.1.6 Typical bolometer characteristics

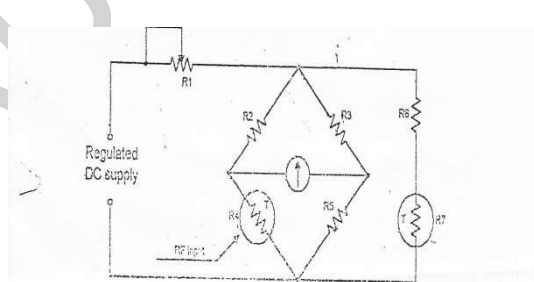


Fig. 1.7 Bridge assembly using thermistor

Fig. 1.8 Indirect heating type thermocouple

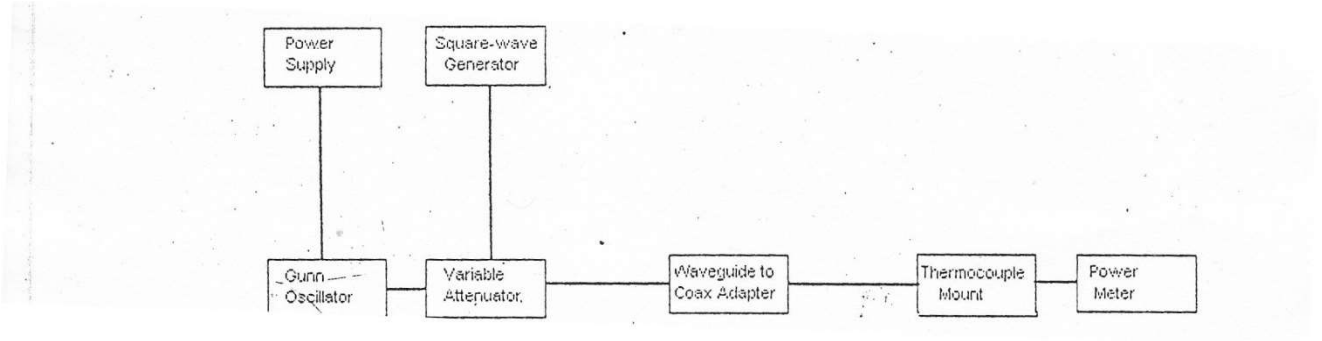


Fig. 1.9 Direct power measurement set-up

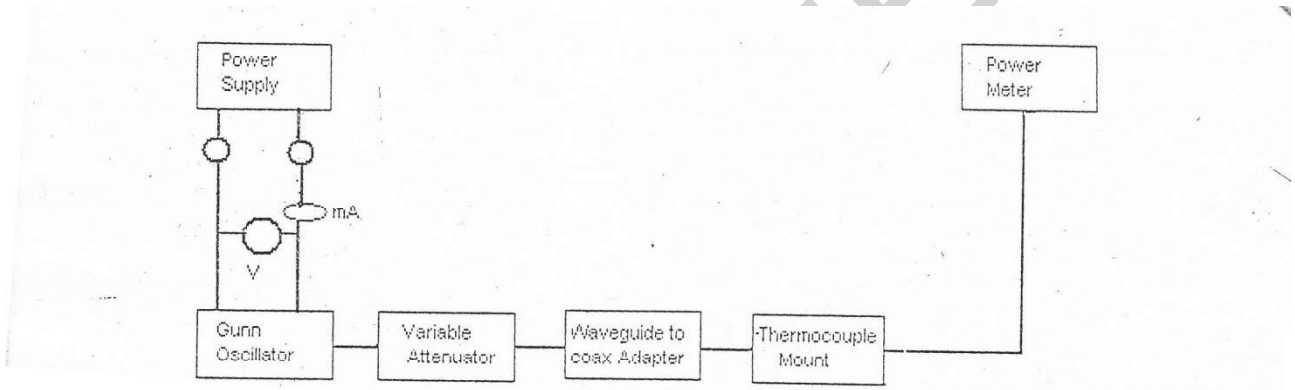


Fig. 1.10 Set-up for measuring I-V characteristics of Gunn diode.

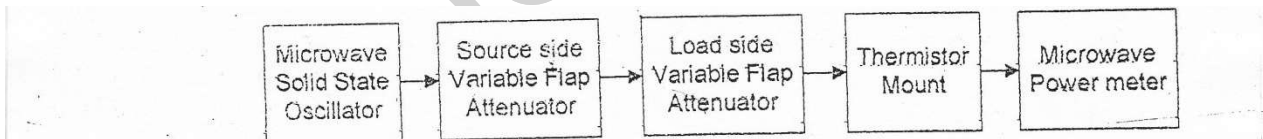


Fig. 1.11 Assembly used to measure microwave power

AUST/EEE

Experiment no: 2

Name of the Experiment: **Measurement of Standing Wave Ratio, frequency & Wavelength**

a) Objective:

1. To learn how to determine SWR using slotted line or SWR indicator.
2. To learn how measure frequency and wavelength of microwave signal.

b) Equipment & Waveguide component list:

1. **Gunn and Klystron power supply (see lab sheet of Expt. No.-1)**
2. **Gunn and Klystron oscillator(see lab sheet of Expt. No.-1)**
3. **PIN-diode modulator (see lab sheet of Expt. No.-1)**
4. **Variable attenuator (see lab sheet of Expt. No.-1)**
5. **Slotted line**

In measuring the standing wave inside a waveguide, a slotted line is used to probe the amplitude and phase of the standing wave pattern. A slotted line has a slot along the center inline of the broad side of the wall and it is an assembly consisting of a probe and a crystal along the open slot. Sliding the probe is required to sample the field in the waveguide and detector is needed to provide a rectified signal. The depth of the probe into the waveguide is adjustable and the strength of the detected signal is proportional to the depth.

6. **Slide screw tuner**

It consists of a probe mounted on a carriage which slides along a narrow and long on the feeding waveguide. When the adjusting micrometer is turned, depth of the probe varies. The depth and the position of the probe causes reflection in the waveguide at a specific amplitude and phase.

7. **Matched termination**

The matched terminator is essentially a matched to the microwave transmission line. As the standing waves occur due to impedance mismatches in the system, the matched termination is used to minimize the SWR in a system.

8. **Crystal Detector**

The crystal detector is basically a diode assembly which responds to the electromagnetic field inside the waveguide. The diode assembly consists of a small thin piece of silicon, a thin tungsten wire and a case. One side of the silicon is directly connected to the case and the other side is connected to the tip of tungsten wire.

The diode action is due to the different properties of silicon and tungsten. Silicon has few surplus electrons but there are many free electrons in tungsten. Therefore, when a voltage is applied across diode in such a direction to force electrons to leave silicon and enter tungsten, a very small current result in. When direction of the voltage is reversed, a large current flows from tungsten into silicon. This is how the diode can be used for detection of microwave energy. For such diodes, output voltage/ current is proportional to square of input voltage (square law characteristics)

9. **SWR indicator**

The SWR meter has a tuned 1 KHz input BNC to read the SWR.

10. **Frequency meter**

It consists of a high Q resonant cavity and an attached wave-guide. The microwave signal in the waveguide is coupled to the resonant cavity through a small slot between the cavity and the waveguide. The effective size of the cavity and thus the resonant frequency of the cavity are varied by moving in and out an adjustable plunger. When the resonant frequency of the cavity is equal to the frequency of the waveguide, there is maximum energy transfer from the waveguide to the cavity. A large power drop on the power meter will indicate the condition.

c) Theory:

1. Standing wave ratio :

At any point along a transmission line, electromagnetic field is the sum of two waveforms: one travelling towards the load (transmitted wave) and another towards generator (reflected wave). It occurs because of impedance mismatch between left and right side of the observation point of transmission line. Any open spot on the line is responsible for another impedance mismatch and cause reflection. The amplitude and phase of the reflected wave depend on the load mismatch. The degree of attenuation of the line affects amplitude of the reflected wave also. The only way reflection can be eliminated is either the line is infinitely long or there is impedance match.

A standing wave results from two travelling waves in opposite direction. The vector sum of two waves creates minimum and maximum points on standing wave pattern in a lossless transmission line. Fig.2.1 shows standing wave pattern in a lossless line.

According to transmission line of Fig.2.2,

$$\text{Reflection coefficient, } \rho = (E_r / E_i) = (Z - Z_0) / (Z + Z_0)$$

For ' ρ ' evaluated at the load (Z_L),

$$\rho_L = (Z_L - Z_0) / (Z_L + Z_0)$$

$$\text{VSWR} = S = E_{\max} / E_{\min} = (E_i + E_r) / (E_i - E_r) = (1 + \rho) / (1 - \rho)$$

$$\rho = (S - 1) / (S + 1)$$

When r-f signal is transmitted down a line into a load, even one with a good match, some of the signal reflects back toward the source. The amount of signal sent vs. the amount of reflected back is compared and referred to as the standing wave ratio. When the pattern deals with measurements of voltage, it is called the voltage standing wave ratio (VSWR)- Fig.2.3

$$\text{VSWR} = (e_{\max} / e_{\min})$$

If e_{\max} and e_{\min} are the input of square law detector and i_{\max} and i_{\min} are the corresponding outputs, then

$$\text{VSWR} = \sqrt{(i_{\max} / i_{\min})} = \sqrt{(\text{maximum meter reading} / \text{minimum meter reading})}$$

This way the measurement of VSWR is by far the easiest, but if minimum reading cannot be measured with reliable degree of accuracy, the inherent flaws in the detector may create distortion increasing the chance of error.

When standing wave ratios are larger than ten to one, the 'double minimum' measurement system can be used to increase the accuracy and reduce the percentage error (Fig.2.4).

The mathematical expression of the curve is,

$$e = e_{\min}^2 + (e_{\max}^2 - e_{\min}^2) \sin^2(2\pi l / \lambda)$$

Starting at point 'A', we move to the right until the reading is twice what it was at point 'A'.

So,

$$2e_{\min}^2 = e_{\min}^2 + e_{\max}^2 \sin^2(\pi d / \lambda) - e_{\min}^2 \sin^2(\pi d / \lambda)$$

The relationship can be expressed as,

$$e_{\max}^2 / e_{\min}^2 = [1 + \sin^2(\pi d / \lambda)] / \sin^2(\pi d / \lambda)$$

Because in mathematics, $\sin^2 \theta = 1 - \cos^2 \theta$

$$e_{\max}^2 / e_{\min}^2 = [2 - \cos^2(\pi d / \lambda)] / \sin^2(\pi d / \lambda)$$

$$\text{VSWR} = e_{\max} / e_{\min} = \sqrt{[2 - \cos^2(\pi d / \lambda)] / \sin^2(\pi d / \lambda)}$$

VSWR's with ten or greater angle $\pi d / \lambda$ will be small,

$$1 + \sin^2(\pi d / \lambda) \approx 1$$

$$\text{VSWR} \approx 1 / \sin(\pi d / \lambda)$$

Because of the small angle,

$$\sin(\pi d / \lambda) \approx \pi d / \lambda$$

$$\text{VSWR} \approx \lambda / \pi d$$

2. Mathematical background of frequency measurement using slotted line:

The relationship of a rf wave could be seen as an equation between frequency, wavelength and velocity :

$$f \lambda = V$$

Frequency remains fixed, so that wavelength is directly affected by the velocity ($V = V_0 = 3 \times 10^{10}$ cm/sec if the wave travel through air). Otherwise, $V = V_0 / \sqrt{\mu_r \epsilon_r}$ where, μ_r and ϵ_r are the permeability and permittivity of the path. Consider Fig.2.4, the distance between two

minima X_1 and X_2 is, $d = \lambda_L/2$; λ_L = wavelength along the slotted line.

When we use coaxial line, velocity $V_L = V_0$

When we use waveguide, velocity is determined by the larger dimension 'a' of waveguide.

$$\lambda_L = \lambda_0 / \sqrt{1 - (\lambda_0 / 2a)^2}$$

$$f = V_0 \sqrt{(\lambda_L^2 + 4a^2)} / (2a \lambda_L)$$

d) Experiment procedure

• SWR measurement [using set-up2]

1. Set up the equipment as shown in Fig 2.5.
2. Set the Gunn diode supply voltage to 9 V
3. Set the variable attenuator to 10 dB
4. Set the SWR indicator range to 20-40 dB. Turn on the indicator
5. Turn on the Gunn oscillator
6. Apply the modulation signal to the PIN diode modulator
7. Adjust the modulation frequency for maximum meter deflection.

i) **Measuring low and medium range SWR**

1. Move the probe of the slotted line and observe SWR indicator meter deflection.
2. Completely disengage the probe of slide screw tuner (VSWR reading should be less than 1.3)
3. Move the probe in slotted line until a maximum deflection is observed on SWR meter. Take the reading.
4. Repeat the procedure for three different probe depths.

Table 2.1

Probe depth				
VSWR				

Table 2.2 (Attenuator data)

μ -mm	dB	μ -mm	dB
13	0	12.5	1
12	2	11.5	4
11	7	10.5	10
10	13	9.5	15
9	17	8.5	20
8	21	7.5	22

ii) **Measuring high range SWR**

1. Maximize the depth of the probe of the slide screw tuner. Large depth of the probe is required for high SWR measurements.
2. Move the probe along the slotted line until a maximum is observed on the indicator.
3. Adjust the gain of the oscillator until 3 dB is shown on the dB scale. If required, then reduce attenuation.
4. Move the probe along the slotted line until 0 dB is obtained on dB scale.
5. Record the position of the probe under the d1 column in table.

Table 2.3

Probe	d1	d2	1 st min	2 nd min	λ_g	SWR
-------	----	----	---------------------	---------------------	-------------	-----

penetration	(mm)	(mm)	(mm)	(mm)	(mm)	

6. Repeat the procedure while moving the probe towards right and record the position of the probe under d2 column.
7. Repeat the measurement at three different probe depths.
8. Replace slide screw tuner with a shorting plate. Find the distance between two adjacent minimum. Calculate $\lambda_g = \text{twice the distance}$
9. Compute $SWR = [1 + (1/\sin^2 n(d1-d2)/ \lambda_g)^{0.5}]$
 $= \lambda_g / n (d1-d2)$

iii) Measuring high range SWR with calibrated attenuator

1. Maximize the depth of the probe of the slide screw tuner.
2. Move the probe along the slotted line until a minimum is observed.
3. Set the variable attenuator to 10 dB. Call this value A1. Adjust the gain of SWR indicator until 3 dB deviation is observed.
4. Move the probe along the slotted line and adjust the attenuator until the same maximum value as in the previous step. Read the dB value, call this A2 and record the table below.
5. Calculate the SWR using $S = 10 * (A2 - A1) / 20$
6. Repeat the procedure at different probe depths.

Table 2.4

Probe penetration	A1 dB	A2 dB	SWR

• SWR measurement [set-up1]

1. Set up the equipment as shown in Fig.2.6
2. Connect one of the video cable from the detector on the slotted line to the input marked VSWR on the power supply.
3. Turn on power supply and apply rf power.
4. Adjust the attenuator setting (eg. shorted attenuator set at maximum, adjust rf attenuator for full scale reading)
5. Move the probe on the slotted line for minimum reading
6. Adjust short feed attenuator for reading about 1/4 th scale.
7. Measure and record the reading at the points on Table 2.5.

Table 2.5

Distance along the line (cm)	Meter reading	Center measurement
	Y1	X1
	Y1'	
	Y2	X2
	Y2'	

8. Calculate, $d = X2 - X1$
9. Calculate VSWR, frequency and wavelength using corresponding equations and take value of $a = 2.2870 \text{ cm (waveguide type RG-()/U)}$

(iii) Oscillator output frequency vs. supply voltage (set-up2)

1. Set up the equipment as shown in Fig.2.7. Set the supply voltage to 9 V. Set the attenuator to maximum attenuation for maximum attenuation. Switch on the power meter. Reduce the attenuator until the power meter reading is close to 0.8-1 mW. Slowly turn the frequency meter. Observe a dip on the power meter when the frequency meter is exactly same as the frequency of Gunn oscillator.
2. From the lowest supply voltage at which oscillation occur to max of 10 V supply. Vary the voltage in increment of 1 V. Notice that the frequency meter is calibrated on 100 MHz increment. Interpolate.

Table 2.6

Supply V	
Measured frequency (MHz)	

Table 2.7 (Gunn Oscillator data, at 10.5 V)

μ -mm	Frequency (GHz)
0.5	12
1.5	11.5
2.5	11.3
3.5	10.9
4.5	10.6
5.5	10.2
6.5	10
7.5	9.7
8.5	9.5
9.5	9.4
10.5	9.2
11.5	9
12.5	8.7
13.5	8.4

e) Report:

1. Draw respective block diagrams of experimental set-ups and briefly explain the function of each part.
2. Briefly explain mathematical background of VSWR, frequency and wavelength measurement.
3. Discuss the results
4. Explain (a) Reflection coefficient, (b) Transmission coefficient, (c) Standing wave Ratio with respect to a microwave signal transmission line..

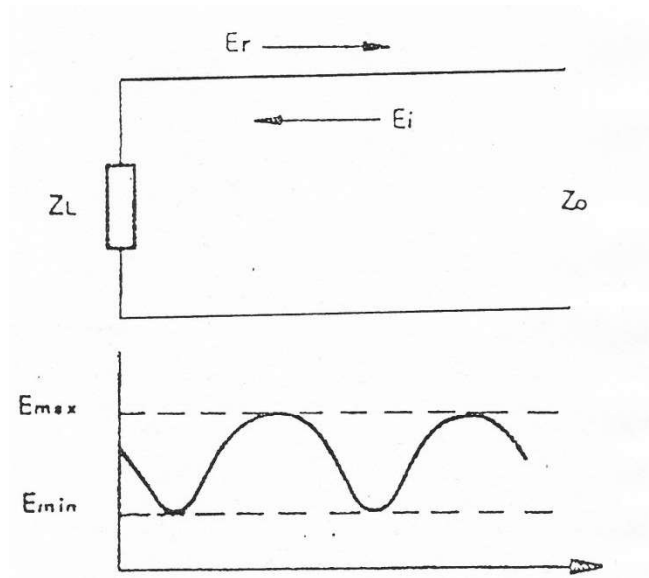
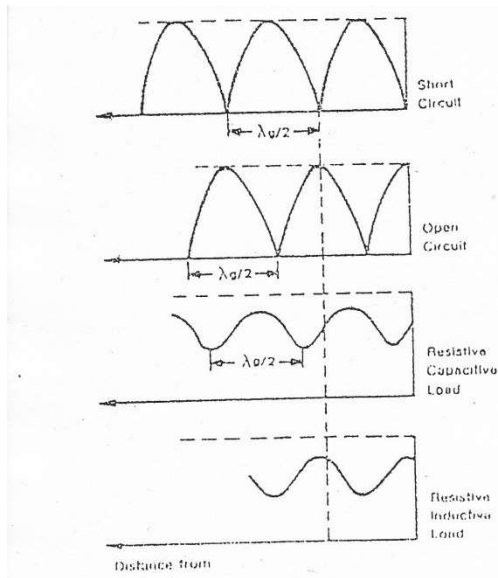


Fig. 2.1 Standing wave pattern in a lossless line

Fig. 2.2 Microwave line (Z_0) terminated by load (Z_L)

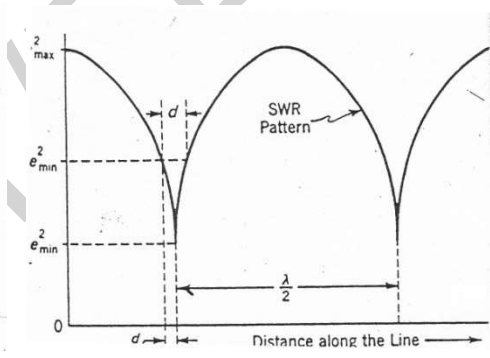
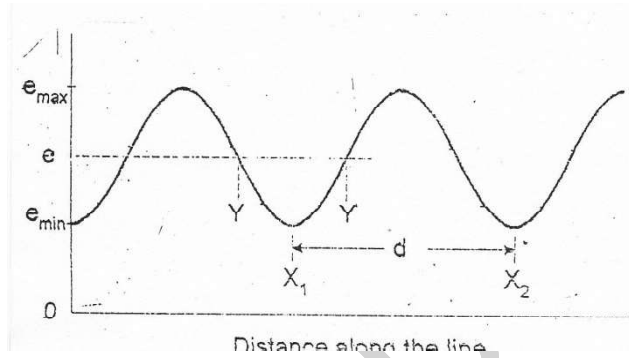


Fig. 2.3 Microwave along transmission line

Fig. 2.4 Double minimum method

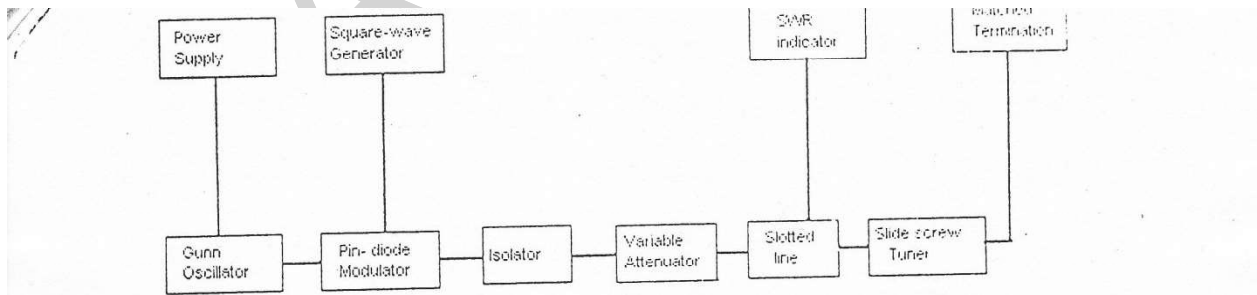


Fig. 2.5 Set-up diagram for SWR measurement

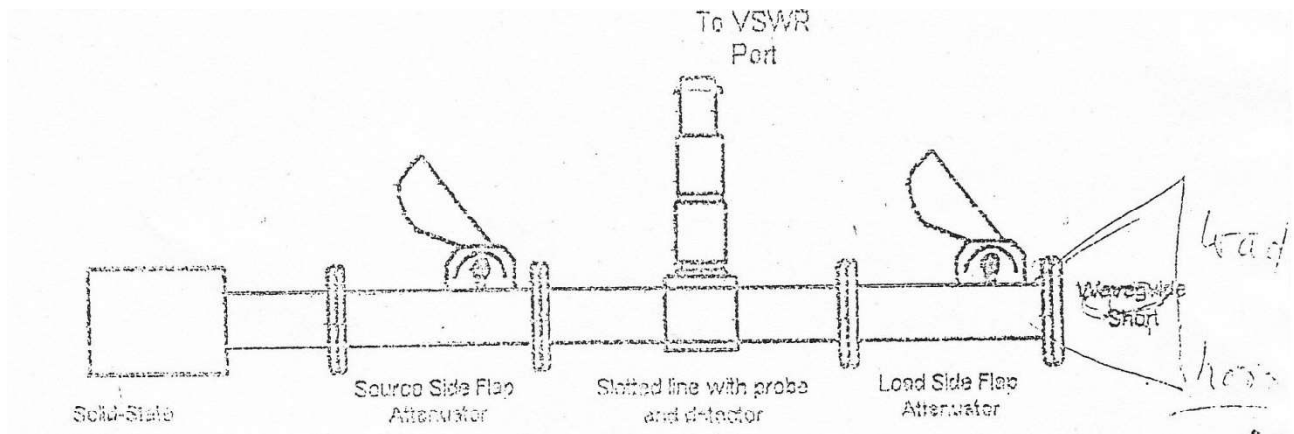


Fig. 2.6 Experimental set up for VSWR measurement

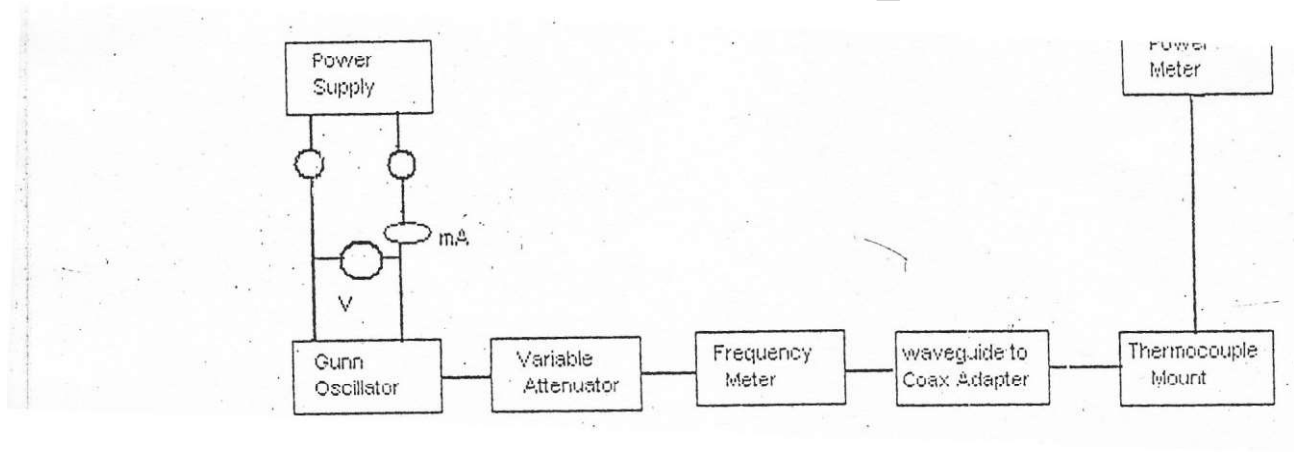


Fig. 2.7 Experimental set up for frequency measurement (set-up2)

Experiment No: **03**Name of the Experiment: **Measurement of unknown Impedance using SMITH chart****a) Objective:**

1. To understand the theoretical background of smith chart.
2. To learn how to use smith chart to measure unknown impedance.

b) Equipment & Waveguide component list:

1. **Gunn and Klystron power supply(see lab sheet of Expt. No.-1)**
2. **Gunn and Klystron oscillator(see lab sheet of Expt. No.-1)**
3. **PIN-diode modulator (see lab sheet of Expt. No.-1)**
4. **Isolator**
The isolator is a two port device with small insertion loss in forward direction and a large in reverse attenuation. It thus allows power flow in one direction only. It can thus absorb reflected power from a mismatched load and isolate the Gunn source.
5. **Variable attenuator((see lab sheet of Expt. No.1)**
6. **Slotted line(see lab sheet of Expt. No.-2)**
7. **Slide screw tuner(see lab sheet of Expt. No.2)**
8. **Matched termination(see lab sheet of Expt. No.-2)**
9. **SWR indicator(see lab sheet of Expt. No.-2)**
10. **Frequency meter (see lab sheet of Expt. No.-2)**

c) Theory:**1. Smith Chart:**

Smith chart is a graphical representation of the impedance transformation property of the length of transmission line. The chart coordinates give the normalized resistance and reactance. The VSWR circles can be constructed with a compass centered on the center point of the chart.

2. Impedance measurement :

For the transmission line of Fig.3.1, ' ρ' ' can be expressed in complex form

$$\rho = |\rho| e^{j\theta}$$

where, $|\rho|$ = ratio of amplitude of incident and reflected signal
 θ = angle of rotation of phase at point of reflection

The angle of rotation of the phase of ' ρ' ' at a distance 'd' from the load is determined by

$$\theta = 2\pi d / \lambda_g$$

The determination of the load impedance can be done in three steps;

- (i) Obtain data on waveguide in similar way as of experiment-2.
- (ii) Determine the magnitude and phase of ' ρ' '
- (iii) Calculate load impedance using *smith chart*.

Fundamentals of impedance measurement

- (i) Draw a VSWR (S) circle on the smith chart, impedance at the voltage minima is 1/S.
- (ii) When a short is placed across the load, the min of the VSWR moves towards the load. Therefore, the impedance at the load is determined by drawing a straight line from a point d/λ_g away from the zero of the outer most circle to the center of the VSWR circle. The intersection of the circle and straight line represents the load impedance.
- (iii) The method described here is based on the fact that the waveguide is lossless, otherwise traces of smith chart will be spiral rather than a circle. In a lossy line, the SWR increases

when the point of observation moves towards the load and decreases towards the generator.

d) Experiment procedure

Impedance measurement

i) Basic measurement

1. Set up the equipment as shown in the Fig.3.1 (for set-up2).
2. Completely unscrew the probe.
3. Turn on the Gunn oscillator
4. Apply 1 KHz mod signal to the PIN diode modulator
5. Measure the max and min values on SWR indicator
6. Measure the frequency of the oscillator.

ii) Impedance measurement [set-up2]

1. Observe the SWR indicator deflection at the 40 dB range. Take the reading.
2. Bring the probe of the slide screw tuner into the device such that the depth of the probe is approx 5 mm.
3. Move the probe along the slotted line until a maximum deflection is observed on the SWR indicator.
4. Adjust the SWR indicator until the meter indicates 1.0.
5. Move the probe along the slotted line until min deflection is observed.

Table 3.1

Probe penetration (mm)	Load SWR S_L	Load min d_L	Short minima d_L (mm) d_{s2} (mm)	$\lambda_g = 2$ ($d_{s1} - d_{s2}$)	$d_L - (d_{s1})/\lambda_g$	Load impedance
Frequency GHz						

Note : ($d_L - d_{s1}$) is positive when we move towards generator and vice versa.

6. Remove the slide screw tuner and the matched termination from the setup. Place a shorting plate to the slotted line.
7. Obtain the distance d_{s1} and d_{s2} which corresponds to two adjacent min VSWRs. The guide wavelength, λ_g is $2 \times (d_{s1} - d_{s2})$. During measurement of min, it may be useful to increase the gain of the SWR indicator to obtain better accuracy.
8. Repeat the procedure for two or more different probe lengths.

(iii) Impedance measurement [set-up1]

1. Use Fig. 2.6 of experiment 2 follow steps 1-7 of VSWR measurement
2. Then use similar steps as discussed in (i-ii) of experiment-3 to calculate impedance of unknown load.

e) Report:

1. Draw respective block diagrams of experimental set-ups and briefly explain the function of each part.
2. Discuss the results
3. Explain (a) Reflection coefficient, (b) Transmission coefficient, (c) Standing wave ratio, (d) Smith Chart & (e) Impedance measuring technique with respect to a microwave signal transmission line.

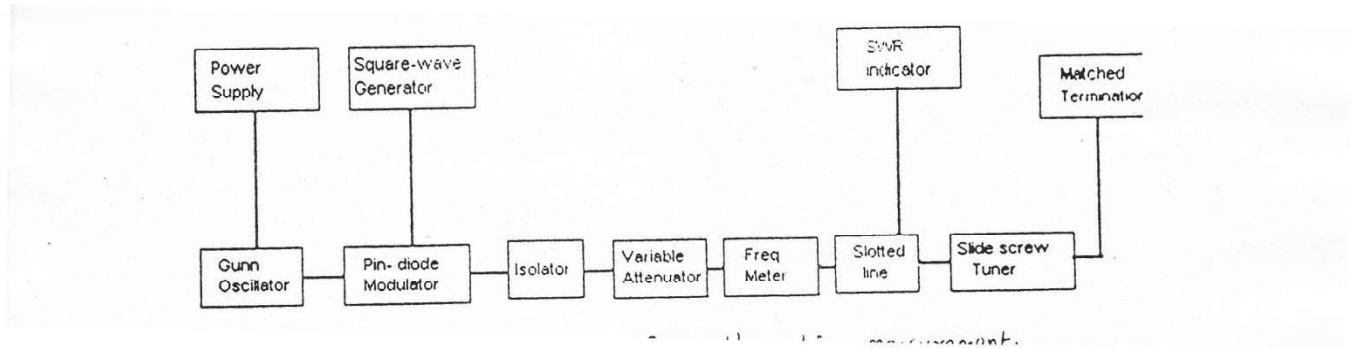


Fig. 3.1 Experimental set-up for impedance measurement

AUST/EEE

Experiment no: **4**
 Name of the Experiment: **Study of Waveguide components**

a) Objective:

1. To learn the basic properties of a directional coupler.
2. To understand the basic principle of hybrid tee.
3. To study isolators and circulators.

b) Equipment List:

1. **Gunn power supply (see lab sheet of Expt. No.1)**
2. **Gunn oscillator(see lab sheet of Expt. No.1)**
3. **PIN-diode modulator (see lab sheet of Expt. No.1)**
4. **Variable attenuator (see lab sheet of Expt. No.1)**
5. **Waveguide**

A six-inch straight section of waveguide used in measurements of wavelength and the phase velocity inside a waveguide.

6. **Crystal Detector (see lab sheet of Expt. No.2)**
7. **SWR indicator (see lab sheet of Expt. No.2)**
8. **Matched termination (see lab sheet of Expt. No.2)**
9. **Isolator (see lab sheet of Expt. No.3)**
10. **Frequency meter (see lab sheet of Expt. No.2)**
11. **Waveguide to Coax adaptor (see lab sheet of Expt. No.1)**
12. **Thermocouple mount (see lab sheet of Expt. No.1)**
13. **Power Meter (see lab sheet of Expt. No.1)**

14. Directional coupler (Fig. 4.1(a)-(c))

It is a sampling device that does not introduce reflections to the main systems. It is a transmission line with one input port but two output ports. The directivity of directional coupler allows energy coupling in one directional only.

It allows directional coupling of energy in the waveguide is basically a microwave signal sampling device. It consists of two waveguides combined together and coupled by holes at the joining section of the two. It is useful to determine SWR by measuring incident and reflected power.

The basic properties of the directional coupler are presented in the Fig.4.1. One end of the directional coupler contains a matched termination.

Mathematically,

$$\text{Coupling coefficient} = 10 \text{ Log } (P_1/P_{3F})$$

$$\text{Directivity} = 10 \text{ Log } (P_{3F}/P_{3R})$$

Return loss measurement :

To measure return loss, the input signal is applied at the PORT2 and the device under test (DUT) is connected to port1 then the return loss signal is picked up at PORT3.

The power at the detector when the coupling coefficient is C (or log C dB)

$$P_3 = P_r / C$$

Since the voltage reflection coefficient of the DUT is given by

$$(P_r/P_1)^{0.5} = \rho$$

P_1 should be known to make use of the expression. If the DUT is replaced by a short all the power is reflected back and therefore P_1 should appear at the PORT3. The actual power at port3 is equal to P_1/C . The ratio of the two signals detected at PORT3 is

$$(P_1/C) \times (C/ P_r) = 1/ \rho^2 = \text{Return Loss}$$

The accuracy of return loss measurement is dependent on directivity of the coupler, which describes how much of i/p power at port2 leaks to port3.

15. Hybrid Tee(Fig. 4.2(a)-(d))

A hybrid-T is basically a microwave version of hybrid coil of the type commonly used in telephone repeater circuits.

When the bridge circuits is properly matched by external impedances, the input signal applied at the port 1 appears at port 2 and port 2, but no signal appears at port 4. In the same

manner when the input signal applied at the port 4, then the signal appears at port 2 and port 3, but no signal appears at port 1. The above input and output relationship can be described in terms of the field distribution inside the hybrid-T. A view of the electric field, with the input applied at port 1 is shown in Fig.4.2(c). It is assumed that all terms of hybrid-T are properly matched. The field is an even symmetry about the mid plane. If the input is applied at the port4 the signal splits equally to port 2 and port 3 but no part of the signal enters port 1. In the Fig.4.2(d), a side view at the junction of the hybrid-T is shown when the input signal is applied at the port4 in TE₁₀ mode. The reason for no coupling to port 1 is due to the reciprocity and symmetry of electric and magnetic field. The signal divides equally to port2 and port3 but the phase is 180 deg out of phase. Arm1 is sometimes referred to as H-arm because it is in the plane of the magnetic field. Arm4 is referred as E-arm for the similar reason. When inputs applied to arm 2 and arm3 at the same time, vector sum and difference of them appeared at arm1 and arm4 respectively.

16. Circulator (Fig.4.3)

The circulator is a three port junction that permits transmission in only CW direction. A wave incident on port1 is coupled to port2 only. . A wave incident on port2 is coupled to port3 etc. Some parameters of isolator and circulator:

- a. **Insertion loss:** The ratio of the power supplied by a source to the input port to the power detected by the detector in the coupling arm (ie output arm with other port terminated to the matched load) is defined as insertion loss or forward loss.
- b. **Isolation:** It is the ratio of power fed in the input arm and the power detected at not coupled port with other port not terminated in the matched load.
- c. **Input VSWR:** The input VSWR of an isolator or circulator is the ratio of the voltage max to the voltage min of the standing wave existing on the line and the others have matched termination.

(c) Experiment procedure:

- **Directional coupler measurement**

(i) Coupling factor measurement

1. Set up the equipment as shown in Fig.4.4(a). Set the variable attenuator at 20 dB. Apply 1000 Hz modulation signal to pin diode modulator and turn on to the Gunn oscillator. Read the SWR indicator. Use this value as reference.
2. Replace the waveguide with the directional coupler (Fig. 4.4(b)). Move the crystal detector to the auxiliary arm of the coupler.

Table 4.1

A1 (dB)	A2 (dB)	A3 (dB)	A1-A2 (dB)	A4 (dB)	(A3-A4) + n*10 (dB)

3. Adjust the variable attenuator until the same reference reading as in (1) is obtained.
4. Fill in the table above with attenuation of the attenuator. The coupling factor of the directional coupler is A1-A2.

(ii) Directivity measurement

1. Set the attenuator to 20 dB.
2. Read the SWR. Use this value as reference. Record the attenuator setting.
3. Change the coupler orientation as shown in Fig.4.4(c).
4. Reduce the attenuation and increase the SWR indicator gain by 10 dB steps until the same value in (2) is obtained. The directivity is (A3-A4) + n x10) dB.

(iii) Return loss measurement

1. Set up the equipment as shown in Fig.4.4(d).
2. Set the probe depth of the slide screw tuner to 5mm.
3. Set the attenuator to 0 dB. A5. Read the SWR indicator. Use this as reference.

4. Change the attenuator to maximum attenuation. Replace the load with a short.
5. Decrease the attenuator until the reference level in (3) is obtained. Record the attenuator position (A6) in case it is necessary to change the range on the SWR indicator, add increase value to the position of the attenuator to get A6.
6. The return loss = $(A6-A5+ n \times 10)$ dB
- 7.

Table 4.2

A5 (dB)	A6 (dB)	$(A5-A6)+ n \times 10$ dB	ρ	SWR

• **Waveguide hybrid- T measurement**

(i) Initial adjustments

1. Set the equipment according to Fig. 4.5(a).
2. Adjust the SWR indicator gain for obtaining any convenient deflection.
3. Apply 9 volt to the Gunn oscillator.
4. Apply modulation voltage to the pin diode modulator.
5. Adjust the offset voltage and the pulse freq of the square wave generator to obtain max deflection on the SWR indicator.

(ii) Measurement of decoupling b/w H-arm and E-arm

1. Set the equipment according to Fig. 4.5(b).
2. Set the attenuator to 20 dB (A1)
3. Select the range on SWR indicator which gives a reasonable deflection on the indicator. Adjust the gain control to a reference reading on the dB scale of the indicator.
4. Remove the detector and connect the variable attenuator to arm1.
5. Connect matched termination and power meters to arm2 and arm3 and connect the detector to arm4. Keep the power meter at off position.
6. Increase the sensitivity of the SWR indicator in 10 dB increment until the same reference level as in (3) is obtained. The attenuation (Az) of the attenuator may be reduced if necessary.
7. Record the result as in table.

Table 4.3

Attenuation of the variable attenuator		Variation of the SWR meter gain (in 10 db steps)	Decoupling $A1-A2 + (n \times 10)$
A1 (dB)	A2 (dB)		

(iii) Measurement of insertion loss of Hybrid-T

1. In the Connect the detector to the attenuator which is set to be 20 dB.
2. Select a range on the SWR indicator which gives a reasonable deflection on the indicator. Adjust the gain control to a reference reading on the dB scale of the indicator.
3. Remove the detector and connect the arm (1) of the hybrid T to the attenuator.
4. Connect the matched termination and the power meters to arm3 and arm4. Also connect the detector to arm2.

5. Decrease the attenuator (A4) until the same reference level as in (2) is obtained. The insertion loss between arm 1 and arm 2 is A3-A4.
6. For insertion loss between arm 1 and arm 3 repeat (4) and (5).
7. For insertion loss between arm 4 and arm 2 repeat (3), (4) and (5)
8. Record the results.

Table 4.4

Signal path arms	A3 (dB)	A4(dB)	Insertion loss (dB)
1-2	20		
1-3	20		
4-2	20		

(iv) Return loss Measurement of H-arm

1. Set up the equipment as in Fig. 4.5 (c).
2. Turn on the oscillator. Do not exceed 9 V. Adjust the square wave output for the max modulation.
3. Set the variable attenuator to 20 dB (A5)
4. Set up the reference point on the SWR indicator.
5. Remove the shorting plate. Connect arm1 to the directional coupler as shown in Fig. 5(d). Connect a matched termination to arm3. Leave arm4 open. (arm4 is the E-plane T. Since the decoupling to arm4 is almost 30-40 dB leaving it open should not affect the accuracy).
6. Increase the gain of the SWR indicator in 10 dB increments. Decrease the attenuation (A6) until the same level as in (4) is obtained. Record the results.
7. Repeat (5) and (6) using E-plane T (arm4) instead of H-plane T (arm1)

• **Circulator and Isolator measurement**

(i) Input VSWR measurement

1. Set up the equipment as shown in Fig. 4.6(a).
2. Connect the isolator or circulator in the direction of flow of energy. The input port is towards the gunn and the output port is connected to matched termination.
3. Energize the microwave source for 10 GHz of frequency.
4. With the help of the slotted line, probe and VSWR meter find out SWR of the isolator or circulator for low and medium SWR measurements.
5. Repeat the procedure for other frequencies.

(ii) Measurement of insertion loss and isolation

1. Remove the isolator and circulator from slotted line. Connect the detector at end of slotted line. The output of the detector mount should be connected to the VSWR meter.
2. Energize the microwave source for maximum output for a particular frequency of operation (eg. 10 GHz). Tune the detector mount for maximum output in the VSWR meter.
3. Set any reference level of a power in VSWR meter with the help of a variable attenuator and gain control knob of the VSWR meter. (P_1)
4. Remove the detector mount from slotted line without disturbing others. Insert isolator/circulator between slotted line and detector mount. Keeping input port to the slotted line and detector mount.
5. Record the reading in the VSWR meter. If necessary change range dB switch to high or lower position and taking 10 dB change for one step change for one step change of switch position (P_2).
6. Compute insertion loss on P_1 - P_2 in dB.

7. For measurement of isolation, the isolator or circulator has to be connected in reverse, the output port to the slotted line and detector to input port with other port terminated by matched termination after setting a reference level without isolator or circulator in the set up as described in insertion loss measurement. Let same P_1 level is set.
8. Record the reading of VSWR meter inserting the isolator or circulator as given in step 7. Let it is P_3 .
9. Do the same for other ports of circulator. Always terminate the unused port of the circulator.
10. Repeat the same for other frequencies.

d) Report:

1. Draw respective block diagrams of experimental set-ups and briefly explain the function of each part.
2. Show results according to experimental procedure and explain the nature of results.
3. Briefly explain the basic principles of directional coupler, Hybrid-T, circulators and insulators.

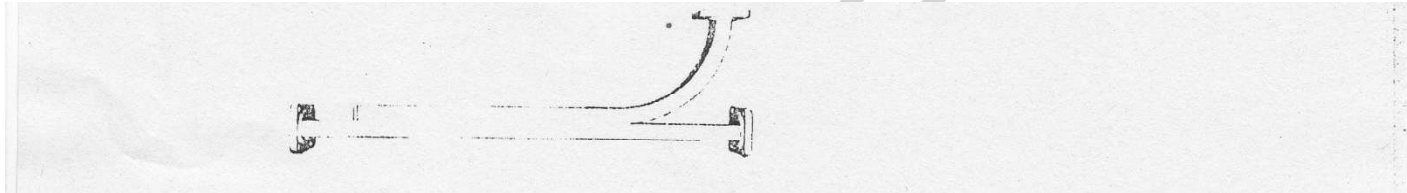


Fig. 4.1 (a) Directional coupler

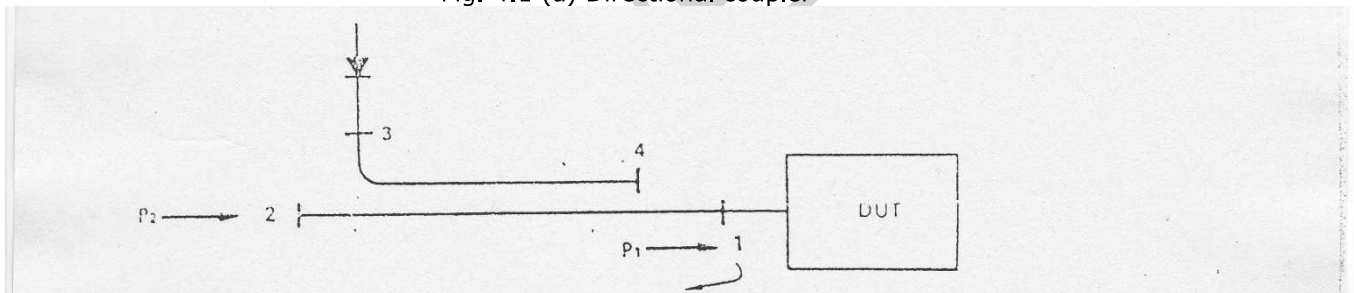


Fig. 4.1 (b) Return Loss measurement

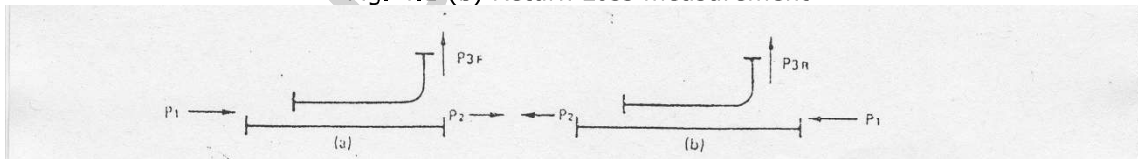


Fig. 4.1 (c) Sampling direction of a directional coupler
a. Incident wave b. reflected wave

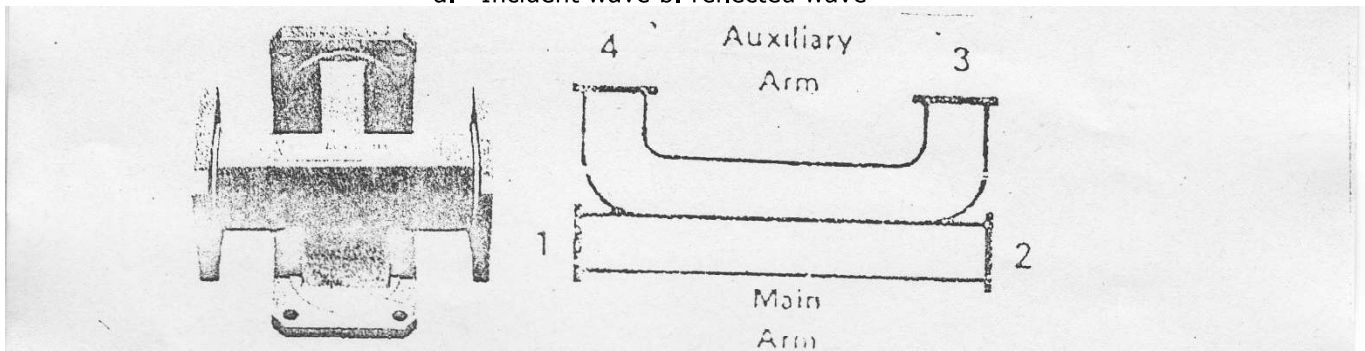


Fig. 4.2 (a)-(b) Hybrid T structure

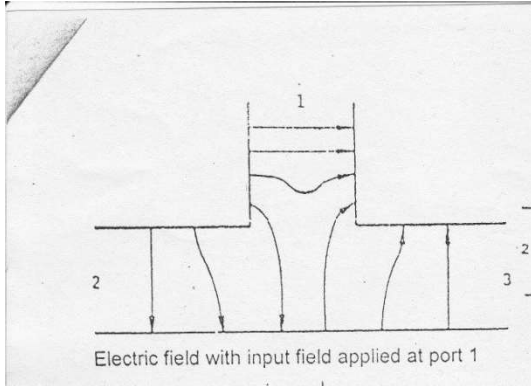


Fig. 4.2 (c)

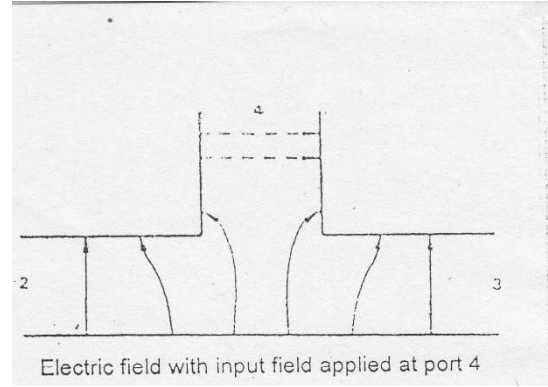


Fig. 4.2 (d)

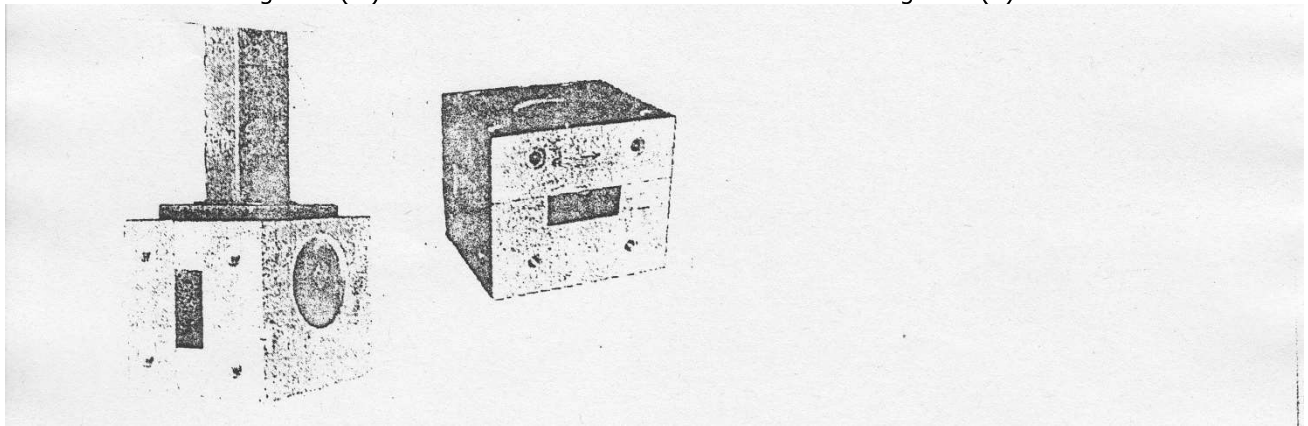


Fig. 4.3 Circulator and isolator

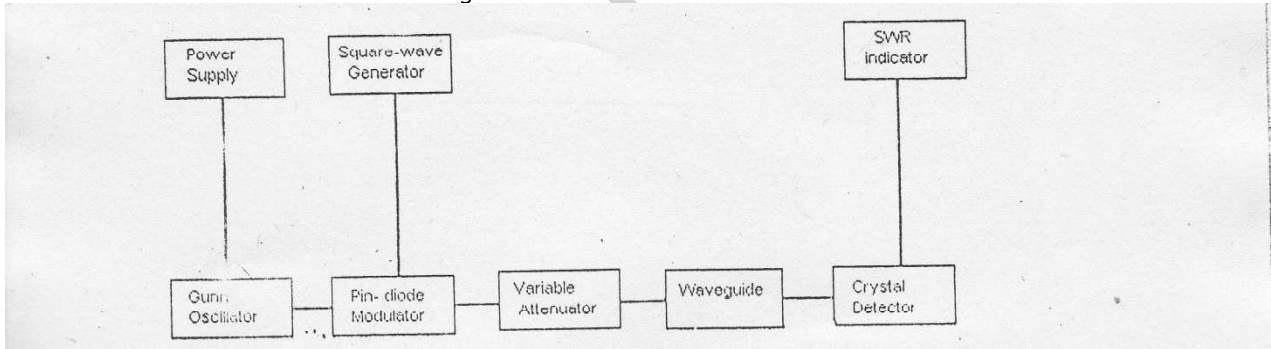


Fig. 4.4 (a) Coupling factor measurement

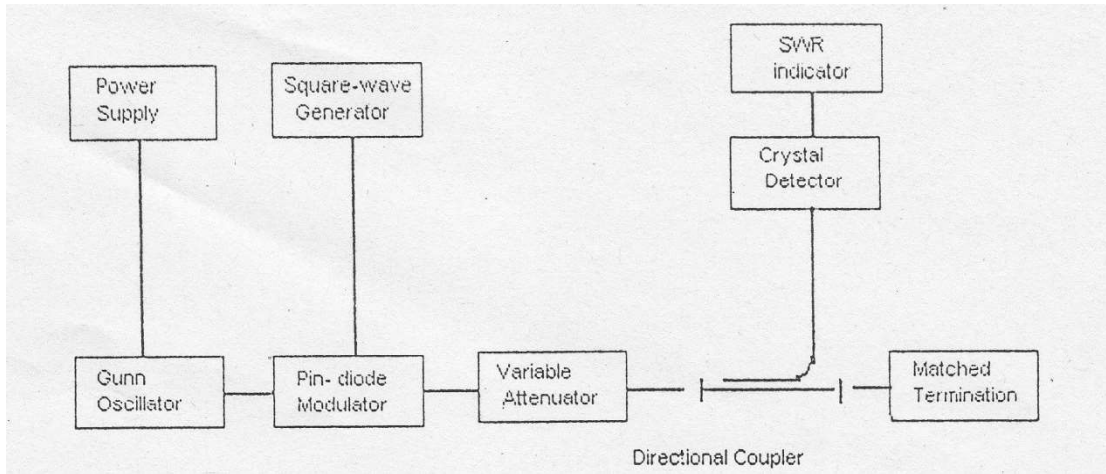


Fig. 4.4 (b) Coupling factor measurement

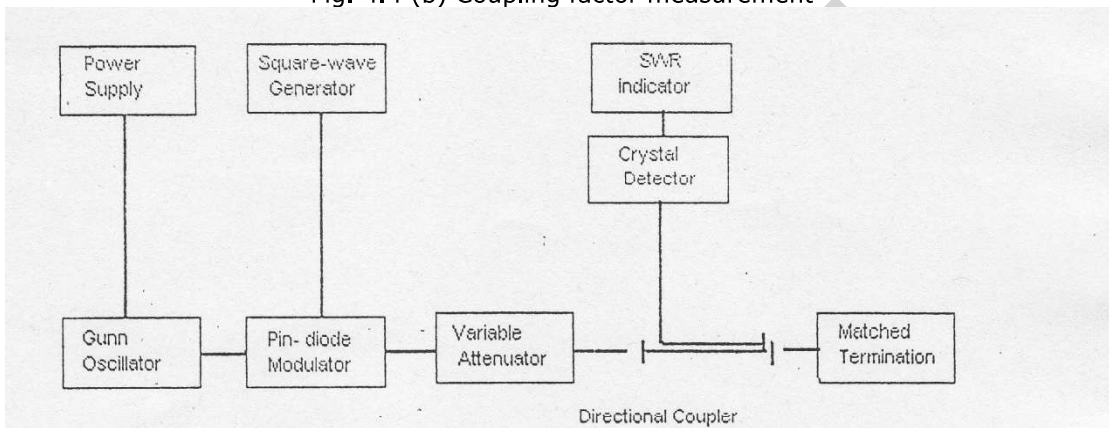


Fig. 4.4 (c) Directivity measurement

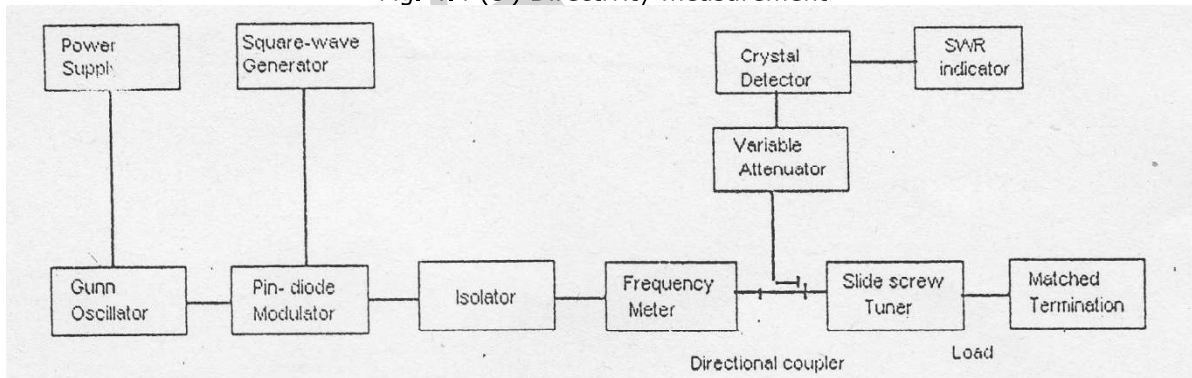


Fig. 4.4(d) Return loss measurement

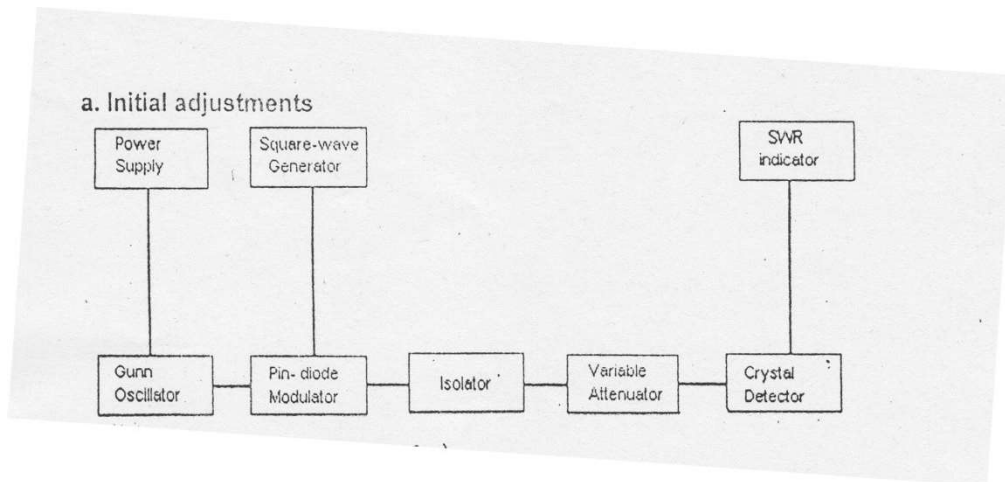


Fig. 4.5(a)

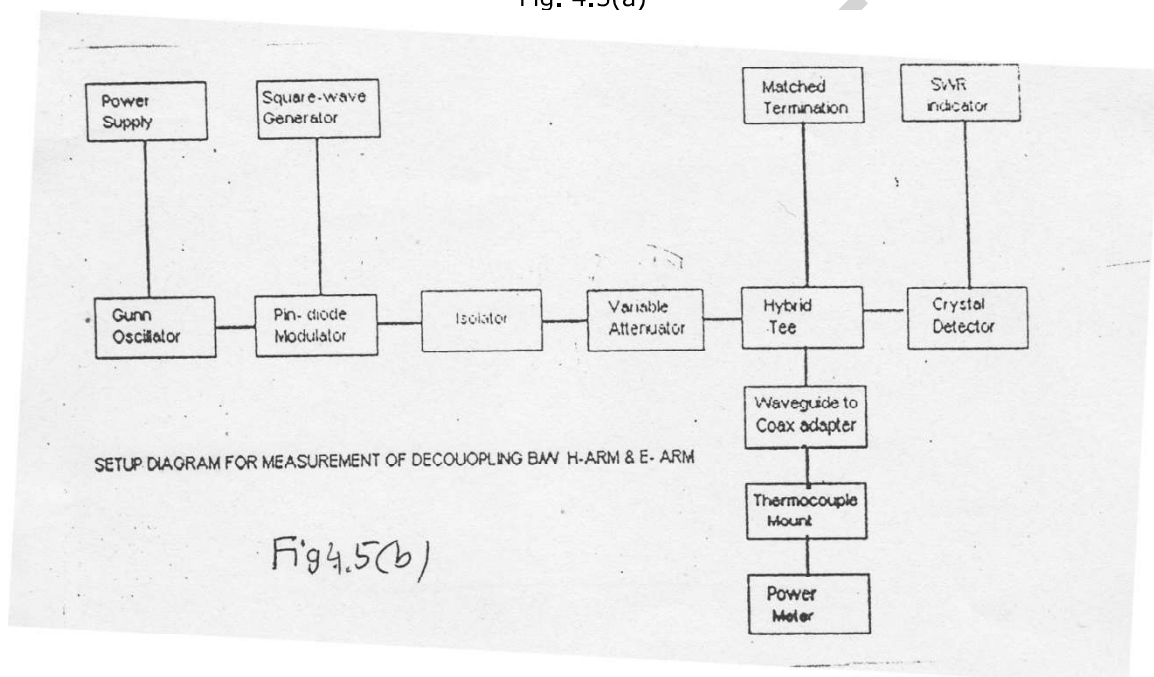


Fig. 4.5 (b)

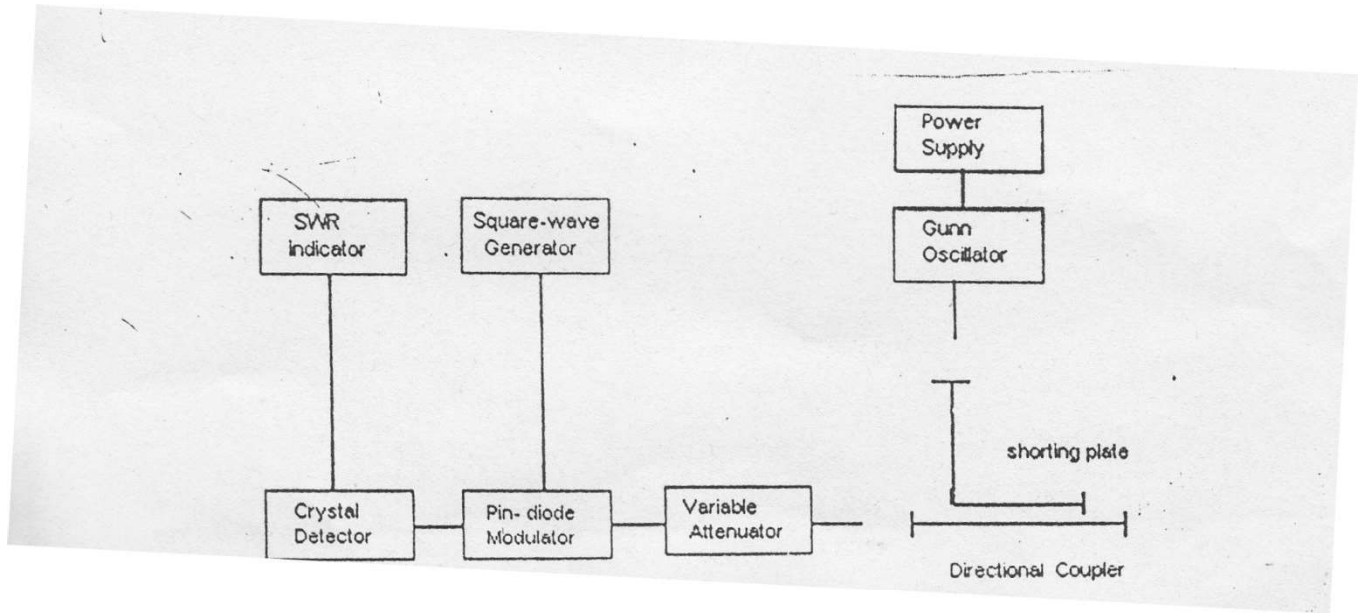
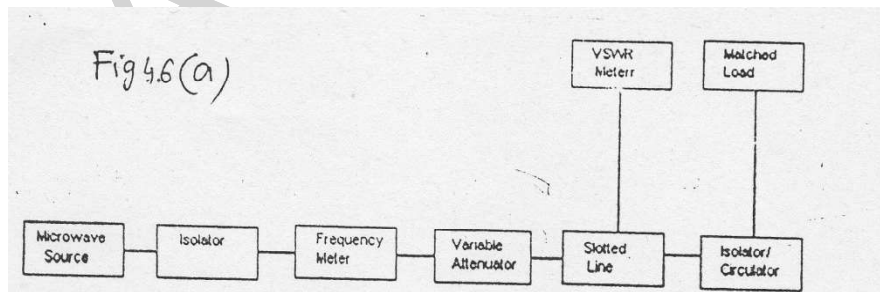
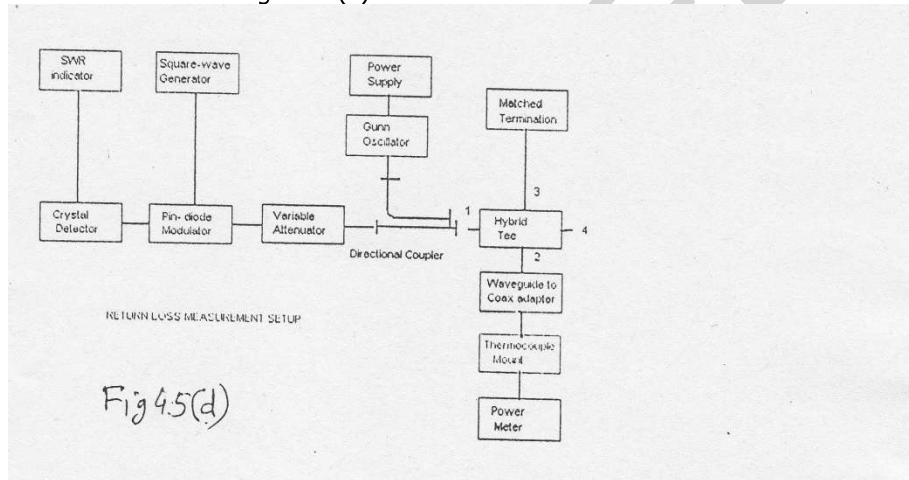


Fig. 4.5 (c) Retrun loss measurement



Experiment no: **5**
 Name of the Experiment: **Attenuation Measurements**

a) Objective:

To learn the attenuation measurement techniques of the microwave components.

b) Equipment List:

1. **Gunn power supply (see lab sheet of Expt. No.-1)**
2. **Gunn oscillator(see lab sheet of Expt. No.-1)**
3. **PIN-diode modulator (see lab sheet of Expt. No.-1)**
4. **Variable attenuator (see lab sheet of Expt. No.-1)**
5. **Crystal Detector(see lab sheet of Expt. No.-2)**
6. **SWR indicator (see lab sheet of Expt. No.2)**
7. **Matched termination (see lab sheet of Expt. No.-2)**
8. **Isolator (see lab sheet of Expt. No.-2)**
9. **Slotted line(see lab sheet of Expt. No.-2)**
10. **Shorting plate**

When measuring the wavelength inside the waveguide a shorting plate is used to create a short (zero impedance) at the open end of a waveguide.

(c) Theory

• **Attenuation**

Generally, attenuation means reduction or decrease of power.

Mathematically,

Attenuation (A) = $10 \log (P_1/P_2)$; where P_1 = input power, P_2 = output power

Another term 'insertion loss' is similar in mathematical form, but it has a different meaning. Attenuation is deliberately introduced but insertion loss occurs due to non-ideal physical component of the system.

• **Attenuation measurement techniques**

In microwave waveguides, two different measurements method are popular

i) Power ratio method

This method is simply to take the power readings with the power detector operates at different power level in each case (causing errors due to nonlinearity of the device). Therefore the measurements results needed to be compensated. For example, when the output power of the detector is maintained at less than 1 mW level, about 0.3 dB compensation is necessary for up to 20 dB attenuation. Assume that the error due to impedance mismatch is insignificant.

ii) RF substitution method

The error associated with the detector in the above method is eliminated in the RF substitution method by (i) first measuring the o/p power with the DUT, (ii) then replacing the DUT with calibrated variable attenuator. By properly adjusting the variable attenuator to the same power level as before attenuation of DUT then, is simply the amount of attenuation of the variable attenuator. Assume that the error due to impedance mismatch is insignificant. Sometimes the SWR introduces a small amount of errors.

• **Practical attenuators**

There are two types of attenuators used in a waveguide system- fixed type and variable type. The former one is used only if a fixed amount of attenuation is

to be provided. There are various types of variable attenuators available.

i) Movable vane attenuator (Fig.5.1)

The vane is tapered at both ends and is placed in the middle of the waveguide where it gives a maximum attenuation. The vane may be moved laterally from the center of waveguide to the edges, where attenuation is considerably reduced because the electric field intensity there is much lower for the dominant load. To reduce reflections from the mounting rods, they are made perpendicular to the electric field. These are also placed $\lambda/2$ apart so that reflections (if any) from one get cancelled with that from other. Attenuation capacity is in excess of 80 dB.

ii) Flap attenuator (Fig.5.2)

Here a resistive element is fixed on a hinged arm, allowing it to descend into the center of the waveguide, which has a long slot in the top wall of the waveguide. The advantage of the technique is the support of the resistive card is very simple and no part of the support extends into the waveguide. The depth of insertion of the flap governs the attenuation. This type of attenuator is used in waveguide system where a little radiation from the slot is not considered of much significance. Attenuation capacity is in excess of 80 dB.

iii) Rotary attenuator (Fig.5.3)

The basic component of this instrument consists of two rectangular-to-circular waveguide tapered transitions, together with an intermediate section of circular waveguide that is free to rotate. A very thin tapered resistive card is placed at the output end of each transition section and the oriented parallel to the broad walls of the rectangular waveguide. A similar resistive card is located in the intermediate circular guide section.

(d) Experiment procedure:

(i) Preliminary adjustment

1. Set up the equipment as shown in the Fig.5.4.
2. Turn the power supply on
3. Apply 1 KHz modulation to the PIN diode
4. Adjust the pulse repetition rate for the maximum deflection on the SWR indicator.

(ii) Measurement using power ratio method

1. Set the variable attenuator to 20 dB (Fig.5.5).
2. Set the SWR indicator gain to either 30 dB or 40 dB range and adjust the indicator for 0 dB.
3. Using a directional coupler add a matched termination to the set up as shown in Fig.
4. Obtain the reading of the SWR indicator. Calculate the actual coupling of the directional coupler.
5. Repeat the same for 15 and 10 dB respectively.
6. Repeat the same using fixed attenuators.

(iii) Measurement using RF substitution method

1. Connect the crystal detector to the PIN modulator.
2. Set the variable attenuator to 20 dB. Adjust the SWR indicator range switch and gain control so that the indicator can indicate 0 dB.
3. Insert the directional coupler and connect the crystal detector to the auxiliary arm of the directional coupler. Without altering the SWR indicator setting, adjust the variable attenuator setting until the SWR indication is same as before. Record the attenuator setting. This is actual value of attenuation of directional coupler in this case.
4. Repeat the same using fixed attenuator as a DUT.

(iv) Measurement of low values of attenuation

1. Set the equipment as shown in Fig 5.6. Set the variable attenuator to 20 dB.

2. Measure the input SWR of the device under test (a directional coupler in this case).
3. Determine the attenuation using the following expression.

$$A = 10 \log_{10} \left(\frac{SWR+1}{SWR-1} \right)$$

e) Report:

1. Draw respective block diagrams of experimental set-ups and briefly explain the function of each part.
2. Show results according to experimental procedure and explain the nature of results.
3. Briefly explain the basic principles of attenuators and their classifications.

AUST/EEE

Experiment no: **6**

Name of the Experiment: **Inverse square law of Electromagnetic Wave Propagation.**

a) Objective:

1. To understand the function of antenna as a radiating structure.
2. To be familiarized with antenna transmitter, receiver and stepper motor controller
3. To be familiarized with various antenna types.
4. To study the variation of field strength of radiated wave with distance from transmitting antenna (verification of inverse square law).
5. To understand the Friis radiation formula.

b) Equipment list:

1. Antenna Transmitter

It delivers necessary electrical signal to the antenna so that it can be transmitted in the form of electromagnetic wave. Fig. 6.1(a) & (b) shows the front panel layout of AMITEC & FALCON antenna transmitter respectively. The following controls are similar for both the cases-

- **LCD** (is used to display the frequency of the signal generated. The range is 86-860 MHz. The frequency displayed on Power ON is the frequency stored in the memory before power was switched off. For AMITEC, various step size for scrolling the frequency upward/downward are available from 50, 100, 250, 500 KHz, 1, 10, 100 MHz. For ATS, the resolution is 100 KHz with accuracy better than 10 KHz.)
- **UP/DOWN** (increases/decreases generated frequency by selected steps),
- **MIC** (connects the condenser microphone to frequency modulate the voice signal in the carrier signal displayed).
- **FM/CW** (This toggle switch is used to select the modulation; CW is used for taking antenna measurements as the level remains stable; FM is used to frequency modulate voice etc. for communication).
- **EXT** (This BNC input is used to connect any external signal to frequency modulate the generated carrier).
- **RF OUT** (this is where the transmitted signal is present; for AMITEC & ATS, output impedance are 50 & 75 ohms respectively; the transmitting antenna can be connected to it with BNC lead provided).
- **HIGH LOW** (the toggle switch is used to adjust the output level of the transmitted signal; high level is 110 db μ V & low level is 70db μ V). In case of AMITEC, it is a pin diode attenuator.

AMITEC only

- **ENTER** for AMITEC (Purpose is to store a particular frequency in the current location of memory and also to select & store a particular step size and initiate serial dump. Frequency and level both are stored at any desired memory location on pressing this button. This display will blink to indicate that frequency has been changed.
- **MENU** (is used to select the operation modes like frequency step size from 50 KHz to 100 MHz. Also to change from Manual to auto mode).
- **ESCAPE** (is used to cancel any command and revert to default position)
- **FM deviation** (is used to vary the frequency deviation of the FM signal. Rotating CW will increase the deviation and vice versa)

FALCON only

- **Memory UP & DOWN** (is used to increment/decrement memory locations. There are 63 locations. On pressing the switch, the location number will be displayed in place of frequency for few secs after which the display revert back to frequency for that location.). Pressing it long will start the scroll mode & locations will start rolling,
- **STORE** (is used to memorize a particular frequency to a specific location. This will blink to indicate that frequency has been stored)
- **STEP** (is used to to select the frequency step size from default of 1 MHz to 100 KHz).

2. Antenna Receiver

Electromagnetic wave received from antenna is converted to electrical signal. Fig. 6.2(a) & 6.2 (b) shows the front panel layout of AMITEC & FALCON antenna receivers respectively. The following controls are similar for both the cases-

- **LCD** (is used to display the frequency of the signal received. The range is 86-860 MHz. The rest is similar to the transmitter LCD)
- **UP/ DOWN** (increases/ decreases received frequency by selected steps)
- **RF IN** (this is where the received signal from antenna is present for measurement. For AMITEC & ATS, input impedance are 50 & 75 ohms respectively; the receiving antenna can be connected to it with BNC lead provided).
- **HIGH LOW** (the toggle switch is used to adjust the input level of the received signal; in low level the sensitivity is 40 db down).

AMITEC only

- **ENTER** for AMITEC (purpose is same as transmitter)
- **MENU** (purpose is same as transmitter).
- **ESCAPE** (purpose is same as transmitter)
- **FM demodulation** (it gives demodulated output at CRO)
- **RS 232** (used to dump serial data with the help of RS232 cable into PC. If MENU key is pressed a number of times till serial mode dump appears. If it is No press up key and it will toggle to Yes. Now press Enter key and LCD will display uploading. It will actually upload whatever data has been stored in instrument to PC. Before uploading data into PC, open the software GUI and select the comport where RS232 lead from instrument is to be connected to PC. Suppose lead has been connected to COM1 to PC. Select Com1 from software GUI, then dump data from instrument.)
- **Down converter** (It is a 39 MHz output which can be connected to any spectrum analyzer for viewing FM modulation and received RF level of receiver. When received signal decreases, it also decreases.)
- **RSSI** (stands for received signal strength indicator. It is a DC output corresponding to received RF level. It can be viewed on CRO in DC coupled mode or a multimeter)
- **Stepper in** (A stepper in cable with a switch is connected at the end of cable can be connected at this input. Put receiver in auto mode using menu and press the switch at different angular positions by rotating the antenna to be plotted in step size of 5 degree etc.. It will advance the memory location and store the received signal at different angular position.)

FALCON only

- **Memory UP & DOWN** (purpose is same as transmitter.)
- **STORE** (purpose is same as transmitter)
- **PC2** (this earphone socket is used to connect lead to the 'line in' of computer. An internally generated 1 KHz signal whose level varies in proportion to the received signal strength is sent to the sound card of computer. The software in computer then plots the pattern of the antenna)
- **STEP** (purpose is same as transmitter).

3. Stepper motor controller

Fig. 6.3(a) & 6.3 (b) shows the front panel layout of AMITEC & FALCON stepper motor controller respectively. The following controls are similar for both the cases-

- **Motor on** (LED lights up to indicate that stepper motor is running)
- **Beep** (This buzzer is used to indicate that the motor has reached its desired/specified position and readings can be taken)
- **UP** (increases angular position of motor tripod by selected steps, pressing it longer starts the scroll mode and position will start to roll slowly and then faster. There is delay of few sec after which the motor starts to rotate).
- **DOWN** (decreases angular position of motor tripod by selected steps & rest is same as UP).
- **Auto** (is used to initiate the auto rotation mode. All other switches are disabled in auto mode. Pressing again will switch off the auto mode)
- **Motor control output** (This 9 pin socket is used to connect the poles of the stepper motor to the controller).
- **LCD** (to display the angular position of the motor tripod along with memory locations step size etc. Display is 0 degree on power reset)

AMITEC only

- **POS** (this LED is used to indicate that the motor has reached its specified location and readings can be taken)
- **MENU** (used to select the operation modes like angular step size from 1,5,10, 45 degree. Also to change from Manual to auto mode).)
- **ESCAPE** (purpose is same as transmitter)
- **Enter** (is used to store a particular angular position in the current location of memory and also to select and store a particular step size)
- **Pulse** (this phone socket is used to connect lead to the PULSE input of receiver. A 10 ms pulse is generated internally and supplied to the receiver every time the motor reaches its specified location. This triggers the receiver to take reading of RF signal level)
- **Trigger out** (it's a BNC o/p which is used to connect additional stepper motor controller. Instead of pressing pulse key everytime a manual reading is to be recorded, a stepper motor controller will send pulse everytime stepper motor rotates by 1 or 5 degree and with receiver and stepper motor controller in auto mode the pulse from motor controller will advance and log readings in memory locations.)

FALCON only

- **Memory UP & DOWN** (is used to increment memory locations. There are 99 locations. On pressing the switch, the location number will be displayed in place of angular position for few secs after which the display revert back to frequency for that location.)
- **STORE** (purpose is same as transmitter)
- **PC1** (this earphone socket is used to connect lead to the 'line in' of computer. A 10 ms pulse is generated internally & send everytime the motor reaches its specified location. This triggers the software to take reading of received signal level.
- **STEP** (purpose is same as transmitter).

4. Antenna Tripod**5. Yagi-Uda and Yagi antenna**

These are passive antenna arrays with a single driven element and other elements driven parasitically. The elements are strung out along the direction of propagation. The phase of the currents in each passive elements are such that when the phase delay is added for the wave to get from element to the next, the individual element currents all add contribution to the radiated field which are in phase with each other at the front of the antenna (Fig, 6.4).

c) Introduction:**1. Function of an antenna**

Antennas are basically radiating structure which radiates electromagnetic energy into free space (Fig. 6.5). It is a transducer that converts electrical energy into radiating energy and vice versa. It transfers electric signal (it receives from its feeder circuit) into electromagnetic energy at its output. The power for such radiation is supplied by a feeder which is often a length of transmission line or a waveguide having well defined characteristics impedance. The process of electromagnetic wave propagation through an antenna is effected by an impedance transformation between space and source. The transmission line/ waveguide act as an antenna when its ends are flared or tapered in such a way that fields of the propagating EM wave expand in an ordinary manner thereby reduce the mismatch between guide/line and source. Antennas are actually tank circuit which resonates at a particular frequency (the radiating signal frequency).

2. Basic antenna types:

There are various types of antennas used for various purposes- dipole type, wire type, slot type, aperture type, parabolic type etc.(Fig.6.6)

- Dipole type** : A straight conductor broken at some point so that most electromagnetic wave propagate into space & not remained confined within the system. There are different types of dipole antenna such as halfwave dipole, infinitesimal dipole, folded dipole etc. (Fig. 6).
- Wire type** : Simplest form of all radiators (Fig.) Here wire need to be straight.

- iii) **Slot type** : Used in the frequency range 200 MHz to 10 GHz. (Fig.6.6) Series of half wave slots are used in rectangular waveguide to form a leaky RF field across a narrow slot in a conducting plane.
- iv) **Loop antenna** : It's a magnetic dipole type antenna (dimension \ll wavelength). Here a coil loop usually carry rf current. The loop need not be circular. There can be more than one turn.
- v) **Aperture type**: Radiation emanate from a open area in a conducting surface. It works on the basis of Huygens principle such that any wavefront is a source of secondary wavefront. (eg. Waveguide horn). Most ground based satellite receiver dish have a smooth horn feed of narrow gain at focus of dish (0.5-1 m). There are different types such as flared H-plane , flared E-plane (Fig.6). If impedance is correct, all energy toward waveguide will radiate.
- vi) **Parabolic type** : Radiation from a short dipole/slot/horn directed towards a large conducting surface which reflects energy. If primary radiation is at infinity, geometric optics predicts parallel beam will emerge from such a reflector (Fig.6.6).
- vii) **Helix antenna**: Used to generate circular polarization (Fig.6.6).
- viii) **Lens antenna**: Convert a spherical wave into a plane wave.
- ix) **Microstrip antenna**: Recently very popular and can easily be fabricated. It consists of an area (almost any shape) of conductor which is excited on the surface of substrate dielectric having back plane so there is more energy stored in reactive rf region.
- x) **Dielectric rod antenna**: It is a dielectric extension to the waveguide.
Moreover
 - **Isotropic antenna** : It's a kind of antenna which radiates equally in all direction. It is a reference radiator with which other antennas are compared. If the power supplied to this radiator is P watts, then the energy density at a distance R meter is $P/(4\pi R^2)$
eg. Yagi, quad, log periodic, helix.
 - **Omnidirectional antenna**: This kind of antenna has rotational invariance around vertical axis (radiates uniformly in azimuthal plane)
eg: Whip, monopole, vertical dipole.
 - **Directional antenna** – This kind of antenna has the rotational variance around vertical axis.
 - **Antenna array** : These are formed from multiples of the other kind of antennas. Active arrays have individual element individually driven by its own feed, whereas passive arrays have a primary radiator passing near field energy to parasitic elements. eg. Yagi, Broad side, End fire, Log periodic etc.
 - **Non-Array antenna** : Eg dipole, wire, loop, aperture, slot, helix, discone, parabolic etc.

3. **Inverse square law: (Fig.6.7)**

Let the total power radiated from a point source (eg. Antenna) is P. At large distance from the source (compared to the size of source), this power is uniformly distributed over larger and larger spherical surfaces as the distance from the source increases. Since the surface area of the sphere of radius 'R' is 'A=4 π r²' then radiation intensity (which can be measured in dB) at distance 'R' is

$$I = (P/A) = (P/4\pi R^2)$$

4. **Friis radiation formula**

For the microwave radio link shown in Fig.6.7, where

P_t, P_r = transmitted & received power

G_t, G_r = transmit & receive antenna gain

R= distance between transmitter & receiver

then

$$P_r = P_t (G_t G_r \lambda^2) / (4\pi R)^2$$

It is known as Friis power transmission equation.

5. **Near field region/ Far-field region**

Near field region: In this case, the polar radiation pattern depends on the distance from the antenna and there is reactive power flow in and out of the region. Energy emerging here has an oscillatory longitudinal component and is transferred to and from the near field region.

Far field region: In this case, the polar radiation pattern is completely independent of distance from the antenna.

Rayleigh distance: The transition from near to far field happens at Rayleigh distance (far field distance) which is equal to $2d^2/\lambda$.

d) Experiment procedure:

1. Keep both tripods at a minimal distance of 0.5 m from each other, center to center using measuring tape (Fig. 6.8)
2. The minimal distance ensures that testing antennas are in the far field region.
3. Transmitted RF signal from Yagi (4el) antennas is intercepted by Yagi (3el) and sent to receiver. Measure the level in db μ V.
4. Note down the level reading at 0.5 m distance.
5. Take the reading at 0.7 m distance. Ensure that no scattering objects are in the vicinity of the antenna, which could reradiate and distort the field pattern and consequently the reading. Avoid any movement of persons while taking the readings.
6. Take further readings at 1m, 1.4m, 2m, 2.8 m, 4m, 5.6m, 8 m, 11.3 m..
7. Readings can be distorted if the Yagi captures signal from its behind due to wall or from the ceiling etc.

e) Report:

1. Plot db reading vs. distance.
2. Relate the results with theory.

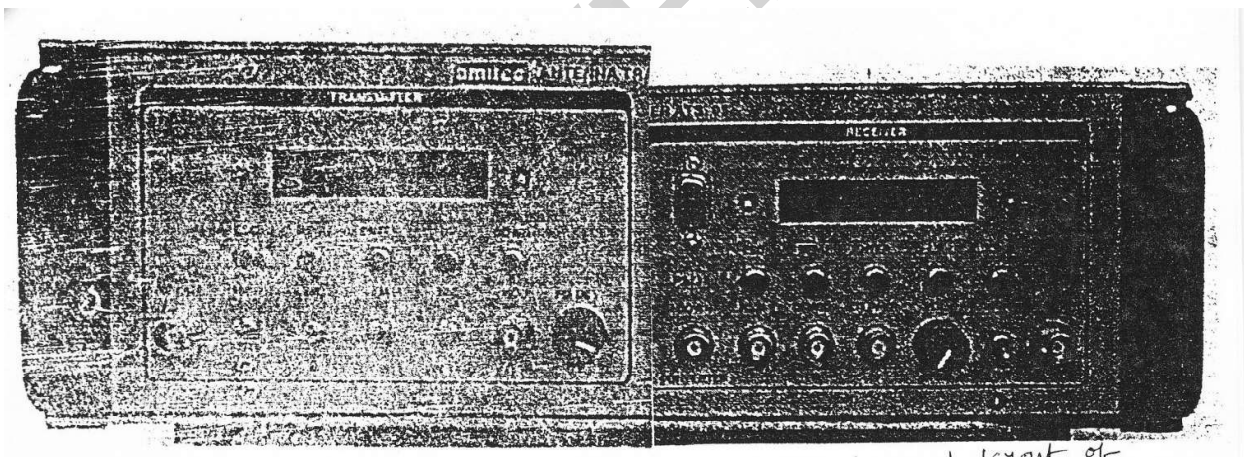


Fig. 6.1 (a) Front panel layout of transmitter (AMITEC)

Fig. 6.2 (a) Front panel layout of receiver (AMITEC)

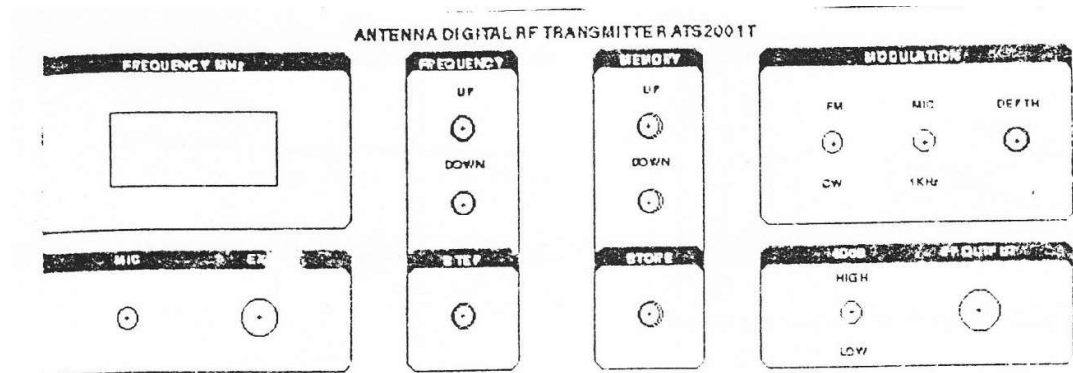


Fig. 6.1 (b) Front panel layout of transmitter (FALCON)

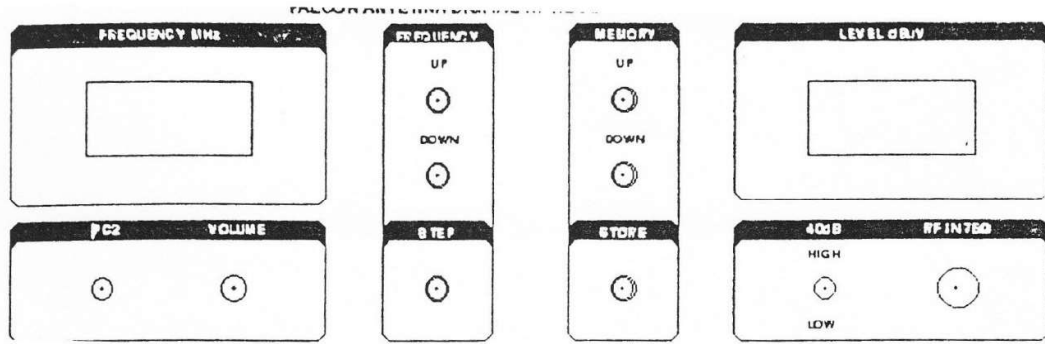


Fig. 6.2 (b) Front panel layout of receiver (FALCON)

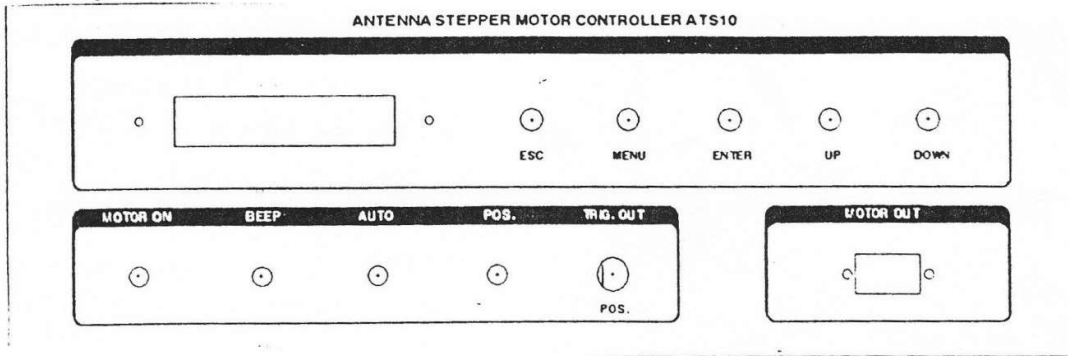


Fig. 6.3 (a) Front panel layout of stepper motor controller (AMITEC)

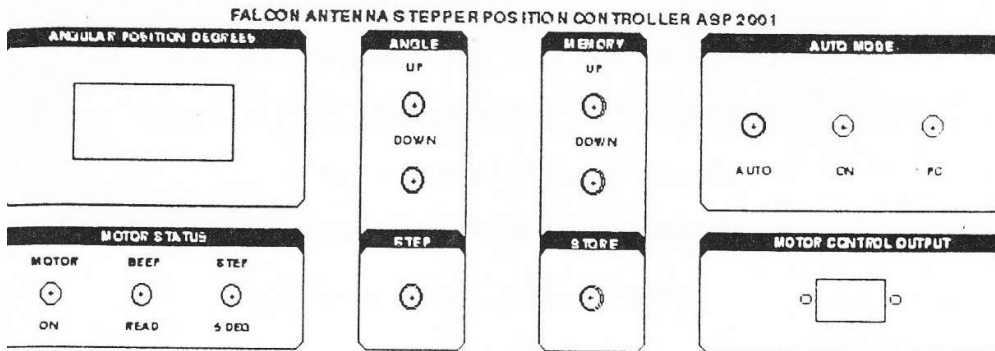


Fig. 6.3 (b) Front panel layout of stepper motor controller (FALCON)

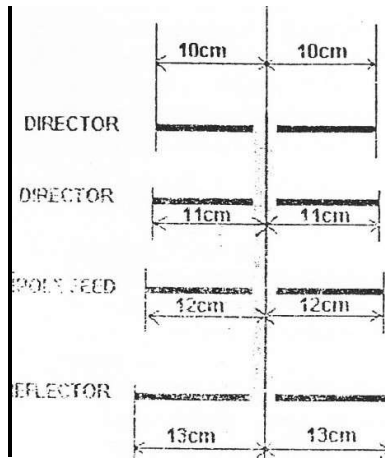


Fig. 6.4 (a) Yagi (4el) antenna

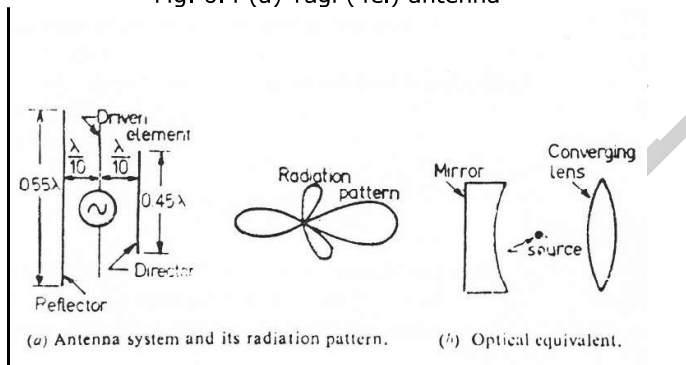


Fig. 6.4 (b) Yagi-uda antenna

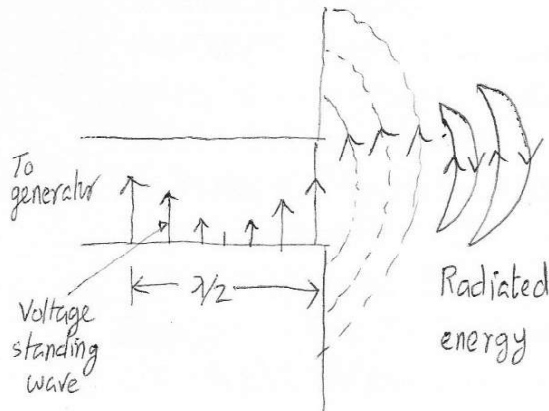


Fig. 6.5 Building up of energy radiation from antenna

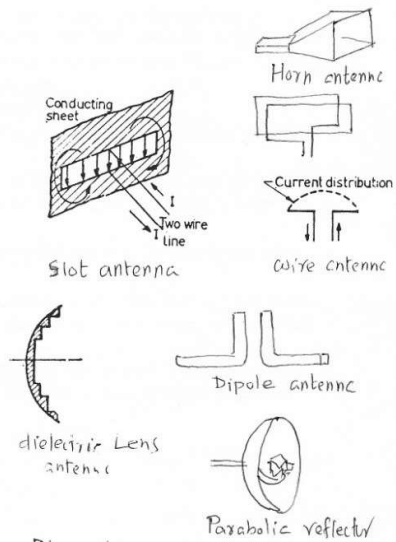


Fig. 6.6 Various types of antenna

Experiment No: 7

Name of the Experiment: **Study of the Characteristics Features of Various Antennas.****a) Objective:**

1. To understand the concept of radiation pattern of an antenna.
2. To understand the concept of azimuthal plane, elevation plane, boresight direction, beamwidth etc.
3. To be familiarized with the radiation pattern of omni-directional, directional, dipole and folded-dipole type antenna.
4. To confirm reciprocity theorem of antenna..
5. To differentiate between resonant and non-resonant antennas, calculate resonance frequency, VSWR and impedance of antenna..

b) Equipment list:

1. **Antenna Transmitter (already discussed in the lab sheet of Expt. 6)**
2. **Antenna Receiver (already discussed in the lab sheet of Expt. 6)**
3. **Stepper motor controller (already discussed in the lab sheet of Expt. 6)**
4. **Antenna Tripod (already discussed in the lab sheet of Expt. 6)**
5. **Yagi antenna (already discussed in the lab sheet of Expt. 6)**
6. **Directional & omnidirectional antenna (already discussed in the lab sheet of Expt. 6)**
7. **Dipole antenna**

It is the most common radiating structure which consists of a straight conductor broken at some point where it is excited by a voltage derived from transmission line etc. Dipole antennas that are much smaller than the wavelength of the signal are called Herizian, short or infinitesimal dipoles. They have very low radiation resistance and a high reactance. Dipole antennas which have half the wavelength of the signals are called half-wave dipole (Fig.7.1) A half wave dipole is cut to length according to formula l (in feet) = $468/f$ (in MHz) or l (in meter) = $142.65/f$ (in MHz) .

8. Folded dipole antenna : It is an halfwave dipole antenna where an additional parallel wire links the two ends of the halfwave dipole. It presents a driving point impedance of about 300 ohms (4 times of dipole) (Fig.7.2) Here addition of an extra rod raises the impedance because current in the extra rod mirrors the current in the driven rod, both currents being in the same direction. Since it can be considered as two parallel wire transmission line shorted at top and bottom ends where the folds are), the folded dipole presents an open circuit to any differential mode current which might be included in the transmission line considered as a parallel rod line. The current which radiates is twice the current delivered by feeder to the real radiation impedance. Therefore, the same total radiated power halving the feed current must quadruple the radiation resistance.

9. Polarizer connector

10. Resonant antenna : It corresponds to a transmission line that is exact number of half wavelengths long and is open at both ends. A low impedance source can easily be coupled to it at its low impedance point without causing any disturbance to the standing wave pattern.

11. Non-resonant antenna : It's a kind of non-resonant transmission line in which standing wave are suppressed by correct termination so that no power is reflected and only forward wave exist.

12. Retrun loss bridge (FALCON)

It has three terminals –antenna, RX ,TX . Here, RLB is matched to 75 ohms of receiver and transmitter and its reference impedance. It compares the antenna impedance to 75 ohms. If the antenna is 75 ohm then bridge is balanced and there is no output at the receiver end.

13. Directional Coupler (AMITECH)

The directional coupler is matched to 50 ohms input impedance of receiver & 50 ohms output impedance of transmitter. It compares the antenna impedance to its internal reference impedance of 50 ohm (which is port 4). If the antenna is 50 ohm, then the bridge is balanced and there is no power at receiver end. The more antenna impedance differs from 50 ohms, the more will be output of receiver. Maximum receiver output will be

at antenna impedance shorted or open circuited. For VHF and UHF, the null will be 35 dB and 15 dB respectively.

c) Theory:

1. Antenna radiation pattern

The relative field strength/ radiation intensity/ power density/ average pointing vector in various direction or the general dependence of directivity on elevation and azimuthal plane is called the radiation pattern. (Fig,7.3). Radiation pattern of omni directional and directional antennas are shown in Fig.7.4. For the later case, the pattern consists of a major lobe in boresight direction and smaller lobes in other direction.

2. Some definitions related to antenna radiation pattern:

(i) **Boresight direction:** The direction along which the radiation is most highly concentrated.

Azimuthal plane : From the radiation point of antenna, if we look around horizontally then we get the azimuthal plane. Angle varies between 0 to +360°.

Elevation plane : From the radiation point of antenna, if we look up and down with respect to local horizon, then we get the elevation plane. Angle varies between -90° to +90°.

(ii) **Beamwidth** [angular separation between two half power points on the power density radiation pattern]

Bandwidth [The frequency range over which satisfactory operation is possible or the frequency separation between two 3 dB points in q-curve.]

Front to back ratio [Difference between the field strength etc. (in dB) in the boresight and in its 180° opposite direction]

(iii) **Antenna Gain :** It measures the directive character of a given antenna. It is defined by the ratio of maximum radiation intensity from subject antenna and the radiation intensity from lossless perfect isotropic source / antenna having the same total accepted input power. If the direction is not specified, the value for gain is taken to mean the maximum value in any direction for the particular antenna.

Mathematically,

$$\text{Gain, } G = (4\pi A) / \lambda_0^2$$

Where, A = capture area (intercept or absorption x- section of received antenna)

In case of horn antenna both at transmit and receive end,

$$G = (4\pi r / \lambda_0) \sqrt{P_{rec} / P_{tr}}$$

If two identical horn antennas are not available,

$$G = (13325.71 / \theta_{az} \theta_{el})$$

Where, θ_{az} and θ_{el} are azimuthal and elevation beamwidth respectively.

Directivity : ratio of radiation intensity in any direction by a particular antenna to that by an isotropic antenna. Assume both antenna radiates same amount of power. In another angle, directivity is also defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all the directions. This averaged intensity is equal to the total power of the antenna divided by 4π . If the direction is not specified, the directivity refers to the direction of maximum radiation intensity.

$$D = (41000 / \theta_{az} \theta_{el})$$

Where, θ_{az} and θ_{el} are azimuthal and elevation beamwidth in degrees respectively.

Efficiency : The ratio of gain and directivity.

(iv) **Radiation resistance** [The resistive impedance presented by an antenna to the transmission line / free space impedance is called radiation resistance. Energy transferred to antenna & environment by resistive power flow heats up surrounding. Mathematically,

$$\text{Radiation resistance} = (\text{power radiated by antenna} / (\text{current at feed point})^2)$$

3. Reciprocity theorem (Fig. 7.5)

Consider two separate sources, $\mathbf{J}_1, \mathbf{M}_1$ and $\mathbf{J}_2, \mathbf{M}_2$ which generates fields $\mathbf{E}_1, \mathbf{H}_1$ and $\mathbf{E}_2, \mathbf{H}_2$ respectively in the volume V enclosed by the closed surface S. The equation corresponding to reciprocity theorem is given in the following table for two separate cases-

When S encloses no charges	When S bounds a perfect conductor
$\int (\mathbf{E}_1 \times \mathbf{H}_2) \cdot d\mathbf{s} = \int (\mathbf{E}_2 \times \mathbf{H}_1) \cdot d\mathbf{s}$	$\int (\mathbf{E}_1 \cdot \mathbf{J}_2 - \mathbf{H}_1 \cdot \mathbf{M}_2) dv = \int (\mathbf{E}_2 \cdot \mathbf{J}_1 - \mathbf{H}_2 \cdot \mathbf{M}_1) dv$

The theorem states that the system response E_1 & E_2 is not changed when the source and observation points are interchanged.

For antenna, it means that the transmitting and receiving radiation patterns of an antenna are equal.

The physical reason is that the only difference between outgoing and incoming waves lies in the arrow of time. Since the electromagnetic equations are invariant except for the signs of magnetic field and current, under time reversal, there can be the difference between transmit and receive mode in the physical current and field distribution.

4. **Antenna resonance:**

The tendency of a system to absorb more energy when the frequency of its oscillations matches the system natural frequency of vibration is called resonance. Electrical resonance occurs in an electrical system when the impedance between the input and output of the circuit is at minimum (or when the transfer function is minimum). Resonance of a circuit involving capacitors and inductors occurs when the collapsing magnetic field of the inductor generates an electric current in its windings that charges the capacitor and discharging the capacitor provides an electric current that builds the magnetic field in the inductor and the process is repeated continuously. In some cases the inductive reactance and capacitive reactance of the circuit are of equal magnitude causing electrical energy to oscillate between the magnetic field of inductor and electrical field of capacitor. If L & C are inductive and capacitance respectively, then $\omega L = 1/\omega C$ and $\omega = 1/\sqrt{LC}$

$$RL = -20 \log(\rho)$$

$$VSWR = (1 + \rho)/(1 - \rho) = Z_0/R_i \text{ or } R_i/Z_0 \text{ which is high}$$

d) **Experiment procedure:**

* **Omni directional antenna (Fig.7.6)**

1. Connect a polarization connector to the tripod and a dipole antenna to the polarization connector. Dipole antenna should rest in vertical position.
2. Set transmitting frequency at 600 MHz, attenuator low/high for FALCON/ AMITECH
3. Connect the monopole antenna to the stepper tripod and set the frequency of receiver To 600 MHz and attenuator upward for maximum sensitivity.
4. Set the distance between antennas to be around 1 m (a distance between 1-1.5 m ensures multipath reflection is minimized, otherwise reading will vary, variation higher than 6 dB is not good. Keep the antennas in same horizontal plane & remove any stray object in the LOS)
5. Using stepper tripod, rotate the vertical monopole antenna around its axis & take readings.

* **Directional antenna**

Follow the same procedure as before but, (i) connect dipole antenna directly to transmitter tripod and (ii) connect Yagi antenna in place of monopole antenna in the receiver tripod, (iii) reading should be taken for both azimuthal & elevation plane.

* **Dipole antenna**

Follow the same procedure as before but, connect another dipole antenna in place of yagi antenna.

* **Folded dipole antenna**

Follow the same procedure as before. But, connect a folded dipole antenna in place of dipole antenna at the receiver.

* **Antenna resonance test**

AMITECH approach	FALCON approach
<p>1. Set up the directional coupler for forward power measurement as Fig. 7.7</p> <p>2. Connect the TX at input port of directional coupler (RF IN, port 1), RX at coupled port (SAMPLE, port 3), antenna at output port (RF OUT, port 3). Take forward power reading.</p> <p>3. Connect the antenna at input port of directional coupler (RF IN, port 1), RX at coupled port (SAMPLE, port 3), TX at output port (RF OUT, port 2). Take reverse power reading. Difference between the two reading is the return loss.</p> <p>4. Follow step 3-6 of the FALCON approach.</p>	<p>1. Connect the return loss bridge to the transmitter tripod through the TX RF connector.</p> <p>2. Connect the dipole antenna to the RLB at the connector, connect the receiver to the RLB at ANT connector..</p> <p>3. For frequencies set from 500 to 750 MHz, record receiver readings, there will be distinct decrease in level due to bridge null where antenna resonates. Locate that frequency.</p> <p>4. Change antenna dimensions and locate the new null frequencies.</p> <p>5. Repeat the same for folded dipole antenna.</p> <p>6. From the return loss table, calculate antenna impedance, VSWR.</p>

* **Antenna reciprocity test**

1. Connect Yagi to receiver stepper and dipole antenna to transmitter tripod, keep antennas in horizontal plane at 1 meter distance and both are set at frequency 600 MHz.
2. Rotate the Yagi around its axis and take readings.
3. Interchange Yagi and dipole antenna, rotate dipole antenna & take readings

e) Report:

1. Plot radiation pattern of different antennas studied during the experiment.
2. Calculate beamwidth, front to back ratio, side lobe level, directivity and gain of antennas studied.
2. Relate the results with theory.
3. Present other results studied during the experiment, relate them with theory.

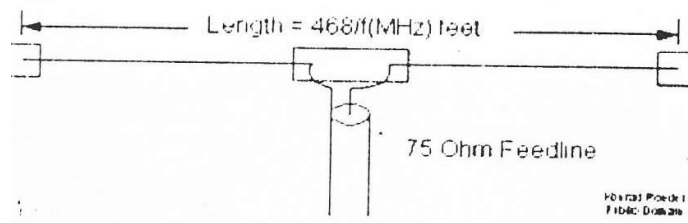


Fig. 7.1 Simple half wave dipole antenna

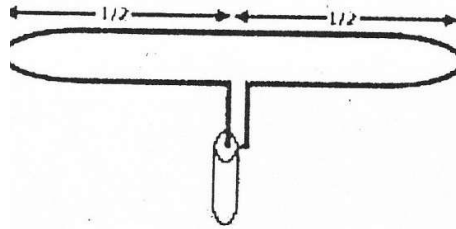


Fig. 7.2 Folded dipole antenna antenna

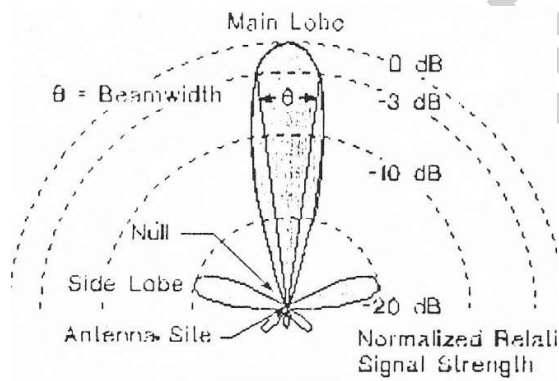


Fig. 7.3 Radiation pattern of an antenna

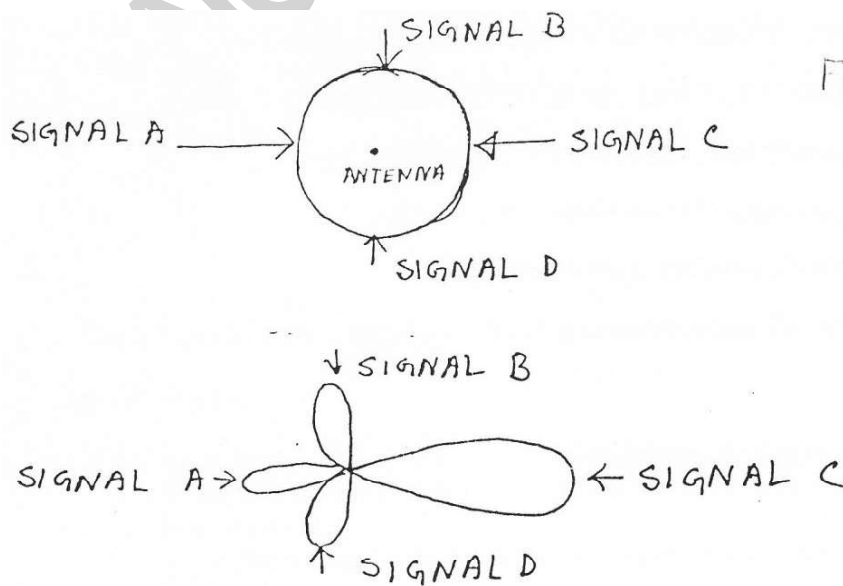
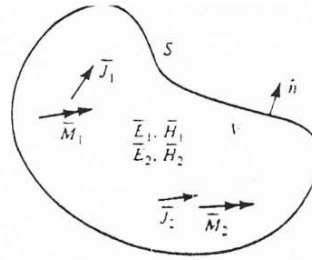


Fig. 7.4 Radiation pattern of omni directional and directional antenna



Geometry for the Lorentz reciprocity theorem.

Fig. 7.5 Reciprocity theorem

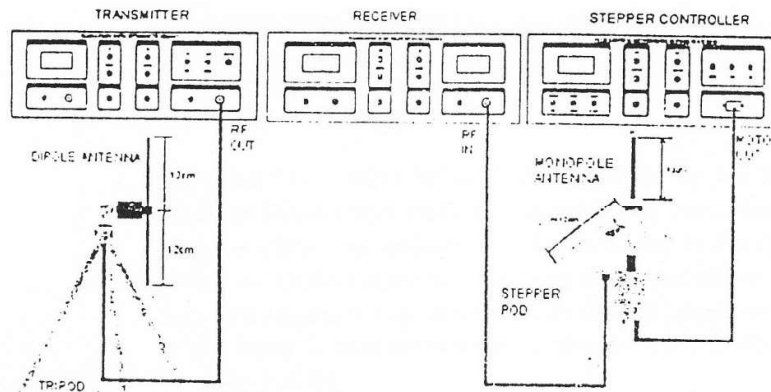


Fig. 7.6 Set-up for measurement of Radiation pattern of omni directional antenna

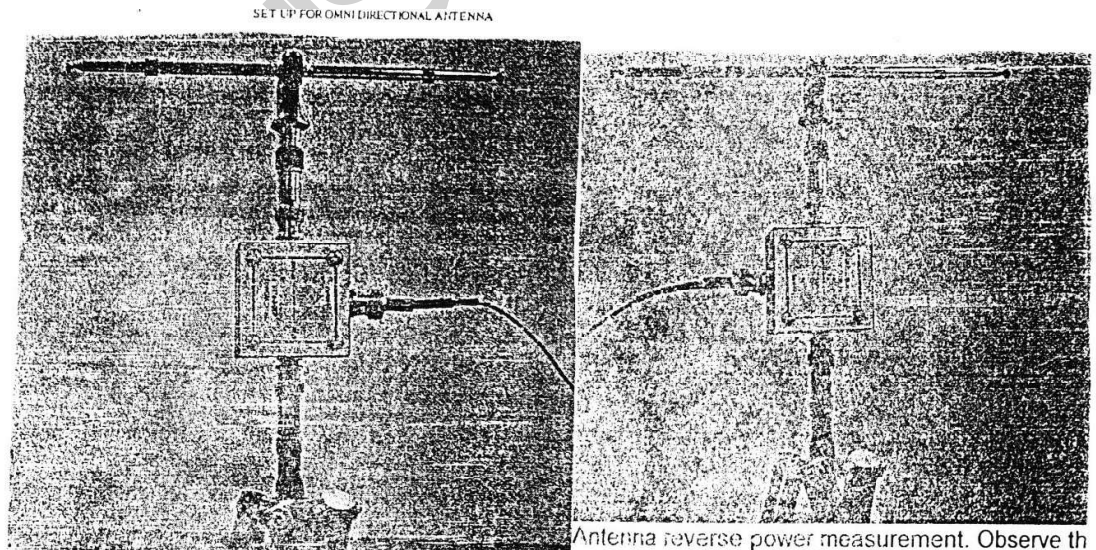


Fig. 7.7 Antenna forward and reverse power measurement

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Experiment No.: **08**

Name of the Experiment: **Introduction to software based study of Antenna training system**

a) Objective:

1. To be familiarized with the use of polar plot software to understand the operating characteristics of antenna.
2. To compare characteristics of various antennas under different condition.

b) Equipment & Software used:

1. Antenna transmitter, tripod and receiver stepper tripod with connecting cables, measuring tape, polarization connector.
2. Different types of antennas such as Yagi (4el and 3el), dipole, monopole etc.
3. Polar plot software.
4. Personal computer.

c) Introduction:

Polar plot software:

- The primary purpose of Antenna Plot software is to better understand the operating characteristics of acquired data of Antenna System.
- The program plots Relative Power in dB and Relative Field strength polar diagrams, and gives an indication of the gain in dBi of the measured antenna in the range from maximum to minimum of 40 dB.
- To collect the values, a 9 Pin RS-232 Connector is used to connect the Spectrum Analyzer/Antenna receiver to PC for data analysis and mass storage, using Suitable Software.

- **Principles of Operation**

Plotting a polar diagram involves measuring and recording received signal strength at known intervals of angular positions of antenna.

To do this a constant level RF signal source (from either transmitter or signal generator or a noise generator) and receiver is required. The RS 232 output of the receiver is connected to the comport in a computer.

To measure the transmitting station's polar diagram the receiving station's antenna remains stationary and the transmitting station's antenna rotates & vice versa.

There are two methods of Data acquisition : 1) Uploading 2)Real time plot

➤ **Uploading**

The stepper motor controller provides a 10 ms pulse on reaching a particular position which is available at pulse out of SCU (stepper Controller unit).This pulse out is then connected to Trigger Stepper BNC of Rx. The Rx(receiver) stores the dBuV reading when an externally provided trigger pulse is received. Hence when the stepper controller is operated in auto mode with step size of 1 degree and start position of 0 degrees it will

give 359 pulses to the Rx for taking 359 readings before coming to a halt. For each pulse received from SCU, the Rx stores the instantaneous dBuV reading of Rx which then can be uploaded to PC from Rx menu – Uploading. The receiver can accept trigger pulses from transmitter also and advance the frequency in selected step sizes. The receiver will store the instantaneous dBuV reading on receiving the trigger pulse. This mode will help plot return loss, antenna bandwidth plots etc.

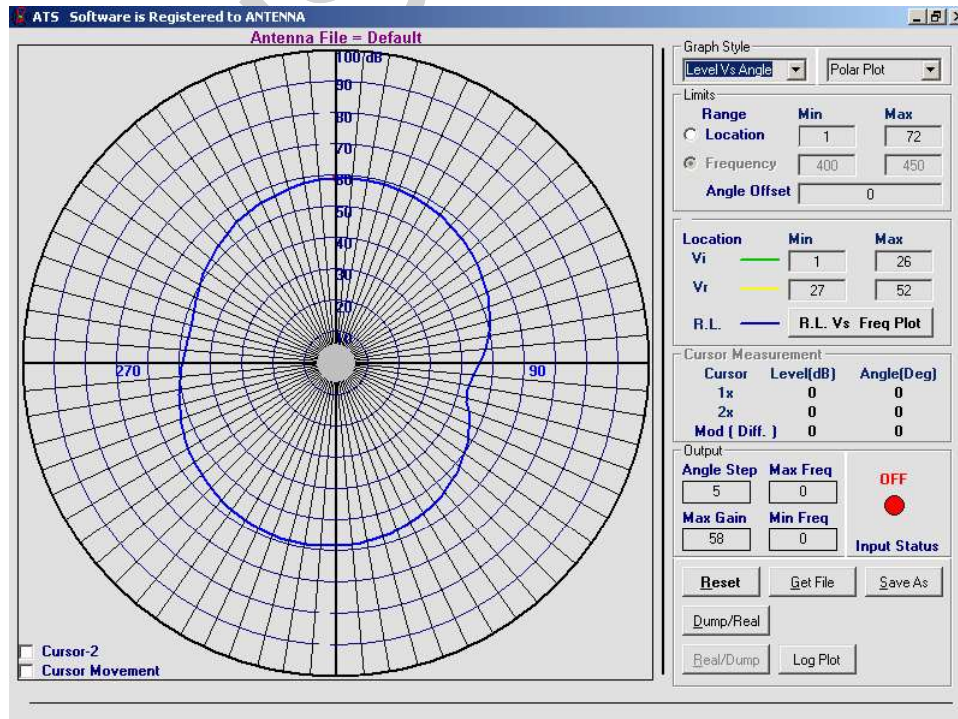
➤ Real time Plot

For real time plot simply connect the receiver to the comport of the PC. Open the software user interface and press the realtime button. Now the antenna will be plotted while it is being rotated.

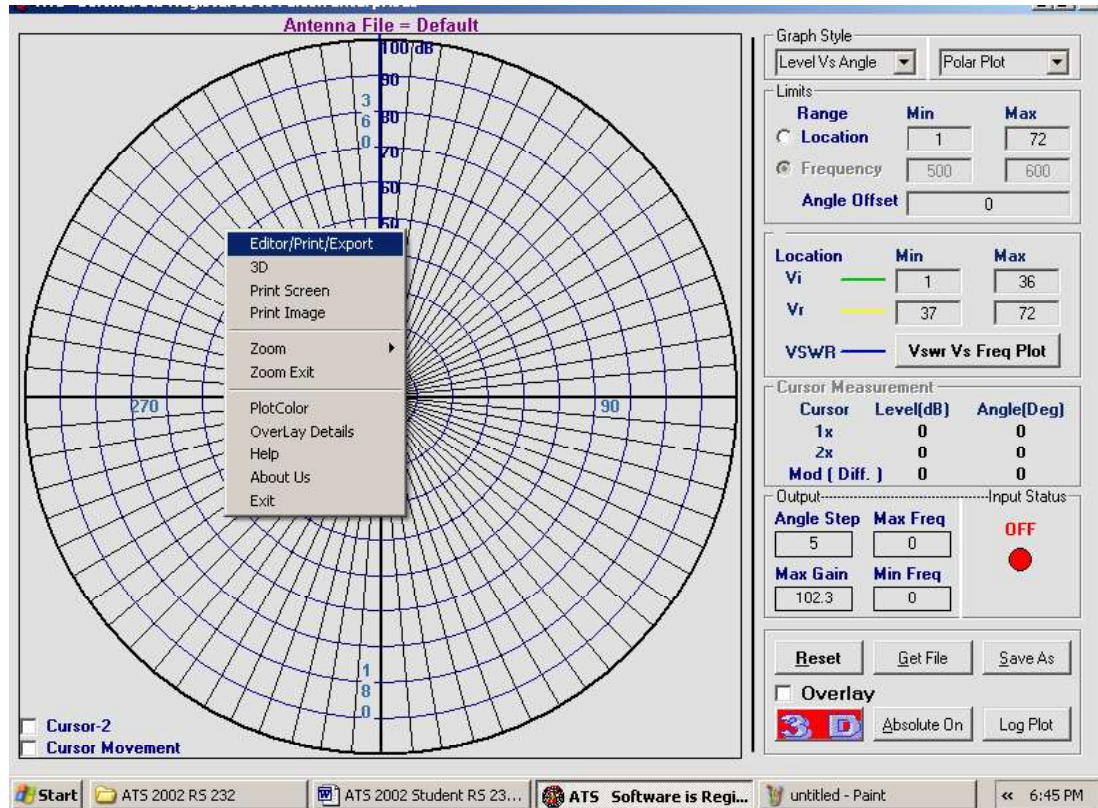
d) Experimental procedure:

1. Collecting Data

- * Set up antenna, Tx, Rx and SCU etc as given in the experimental manual.
- * Without altering any of the settings, the antenna to be measured should then be turned to one end of the rotator travel at 0 degrees.
- * Physically rotate the antenna tripods so that the antenna point towards each other.
- * This will ensure a maximum signal being received by the receiver.
- * Press auto mode on Stepper controller unit to rotate the stepper by 1 or 5 degree steps. This will automatically send a trigger pulse to Rx.
- * Rx will then start storing readings in it's memory. After storing dBuV readings on 359 locations, the readings can be uploaded to PC after selecting Uploading option from receiver menu. The receiver will upload all 1000 locations to the computer.



* For plotting the relevant readings select locations from the software control panel say 1 to 73 locations. Please note down the memory locations manually when a particular antenna is being tested. As with 1000 locations and say 72 locations being used for testing a particular antenna plot- in all more than 12 antennas could be tested and stored in receiver.



2. Software Operation Procedure

a) Copying the Plot To An Image Processing Program

Polar Plot window can be copied to the Windows clipboard by using the appropriate key combination for your operating system - usually Print Screen or ALT+Print Screen. The clipboard contents can then be pasted into a graphics editing program such as Paint

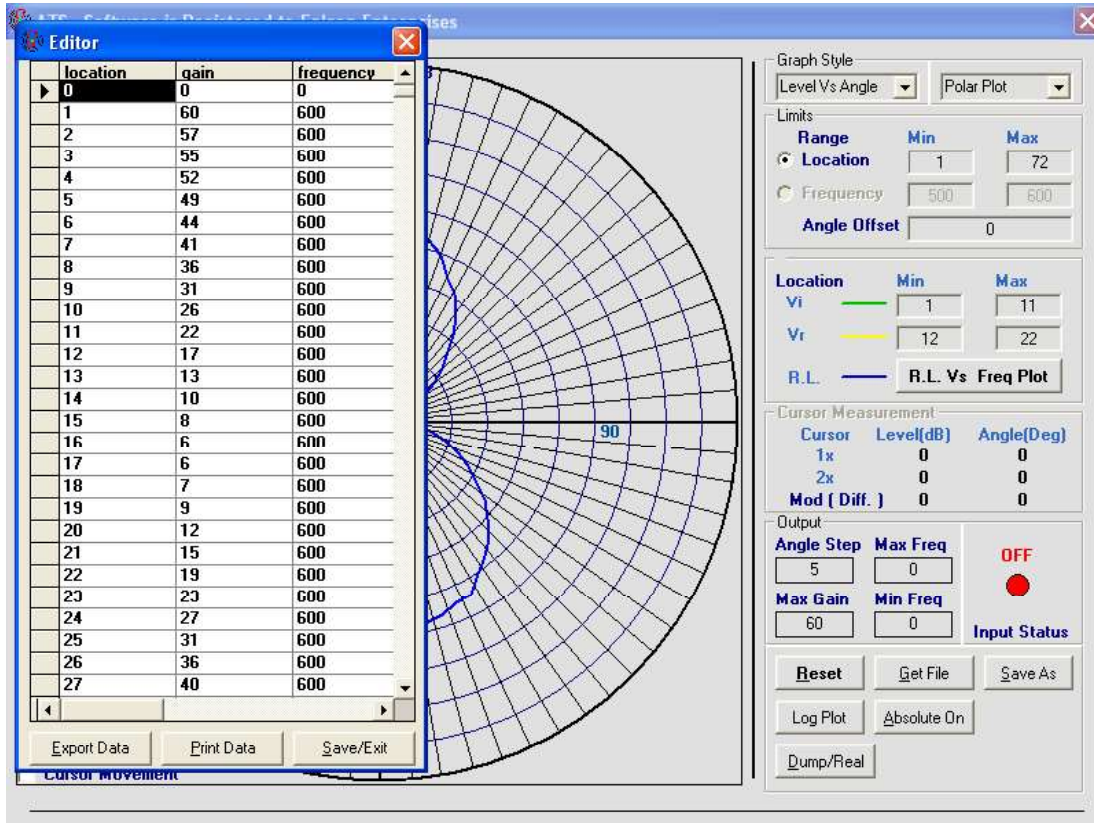
b) Saving A Plot click the 'Save As' button.

c) Re-loading A Previously Saved Plot click the 'Get File...' button.

d) Overlaying One Plot on Another Click on the 'Overlay...' button. The displayed rotation of any plot can be reversed by clicking on the 'Reverse' button and then re-saving.

e) Detailed overview of different options

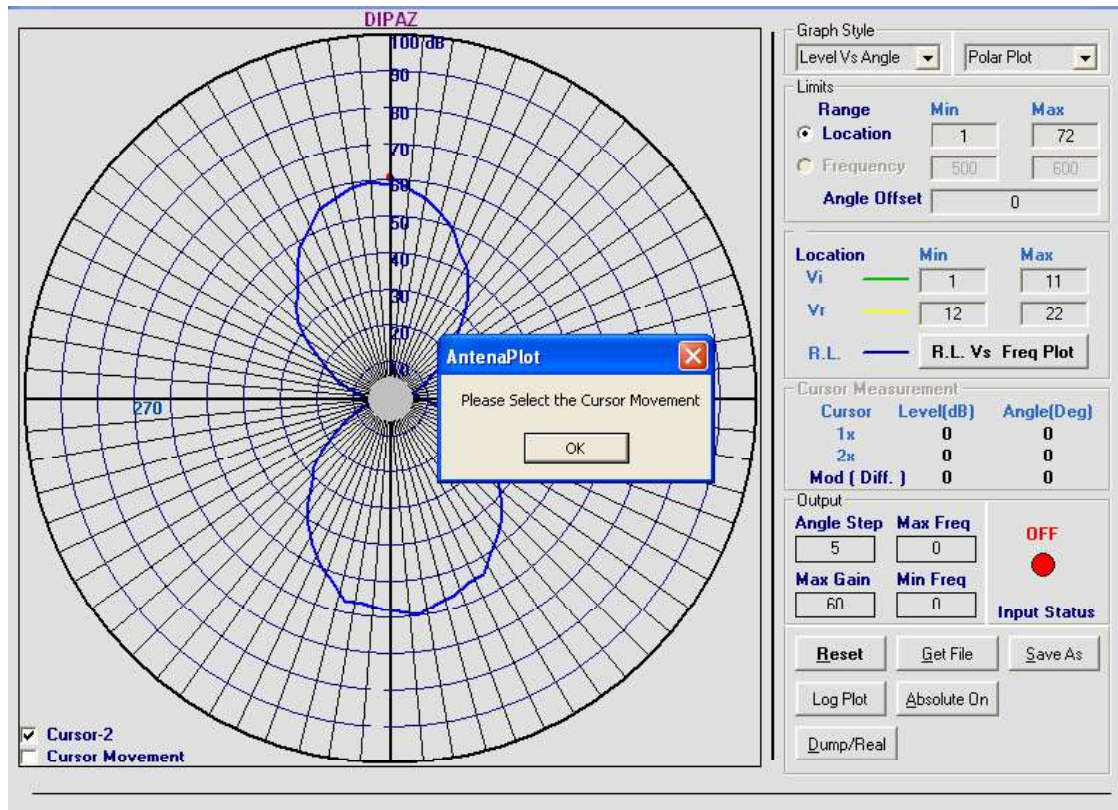
Starting from Top under Heading **Graph Style** Select either 1. **Level Vs Angle** or 2. **Level Vs. Freq.** Select **Level Vs. Angle** option for plotting antenna gain readings with respect to angle. As antenna is rotated with the help of stepper motor controller, antenna gain readings are stored at particular rotated angles in receiver. This data containing frequency, RF level(gain) and location is dumped into PC. The angle by which antenna is rotated can be found out from location in **location gain frequency** Table under **Editor** Heading. **location gain frequency** Table can be obtained by right clicking the graph and clicking the option.



In this table location specifies the angle for eg., 1st location means 5 degree in case 5 degree step size is selected from stepper motor controller unit whereas 72nd location means 360 degree rotated angular position. Similarly 2nd location means 2 degree in case 1 degree step is chosen and 20 degree in case 10 degree step size is selected.

After selecting **Level Vs. Angle** option you can view the graph in polar form (circular graph) or Cartesian form (rectangular graph) after selecting 1. **Polar Plot** or 2. **Cartesian (XY)** option under **Graph Style** menu just right to **Level Vs. Angle** option.

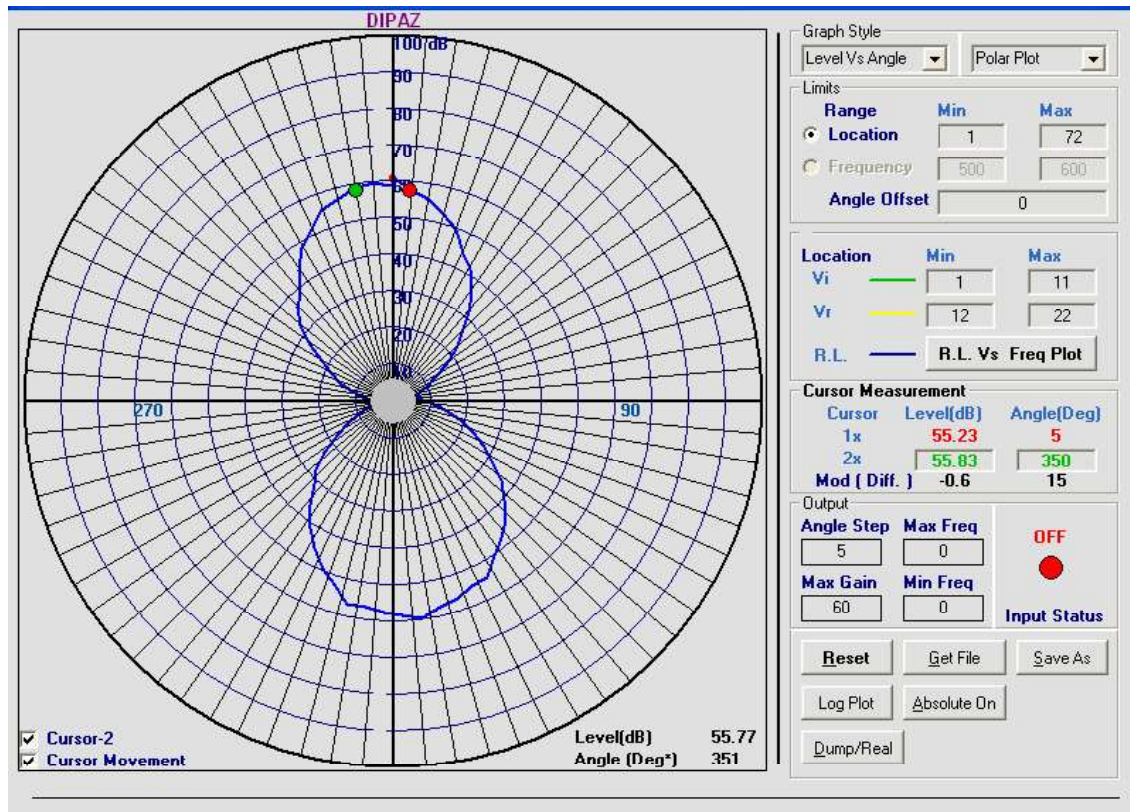
Now, select **Locations Min 1** and **Max 72** under **Limit Range** menu in case 5 degree step size is chosen for motor rotation. The **Frequency Min** and **Max** option below **Location** is disabled and shall be enabled only when **Level Vs. Freq** option is selected from **Graph Style** menu. **Angle Offset** option under **Limits** menu is used to rotate the antenna plot under polar plot graph by angles ranging from 1 to 360 degrees or more. Below **Limit** menu is **Location Min** and **Max Vi, Vr** and **R.L.** option which is used for plotting Incident voltage Vs. frequency, Reflected Voltage Vs. frequency and finally Return Loss Vs. Frequency plot using directional coupler or return loss Bridge. This option is used while plotting **Level Vs. Freq.**



Below

this option is **Cursor Measurement** menu which normally remains disabled. This can be enabled by selecting **Cursor movement** and **Cursor 2** option on extreme left at the bottom of graph. If you select **cursor -2** first a display telling **Antenna Plot Please Select the cursor movement. OK** comes. Click **OK** and select cursor movement first. After selecting cursor movement and cursor -2 , Level (dB) say 100 and Angle (deg*) say 226 appears below graph opposite to cursor movement options. This option displays the instantaneous level and angle of moving cursor as the cursor is scrolled over the graph.

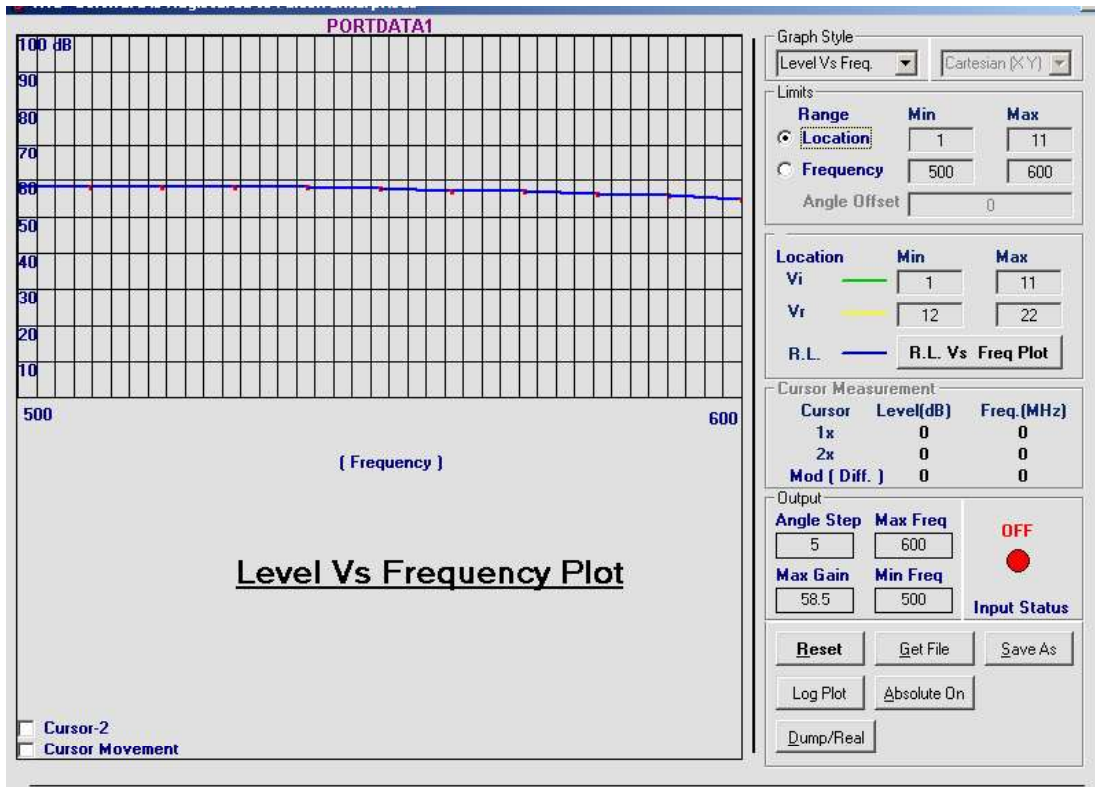
Now, suppose the moving cursor is clicked at one point on graph, a red dot appears on graph and it's corresponding level and angle is displayed in red under **Cursor Measurement** menu, right to the graph as **1x Level (dB)** say 55.23(in red) and **Angle(deg)** 5 (in red). Now, click the moving cursor once again on graph, this time a green dot appears on graph and it's corresponding level and angle is displayed in green under **Cursor Measurement** menu, right to the graph as **2x Level (dB)** say 55.83(in green) and **Angle (deg)** 350 (in green). And the difference between two level readings and two angle reading is displayed below 2x menu as **Mod (Diff.)** Level (dB) -0.6 and Angle (deg) 15.



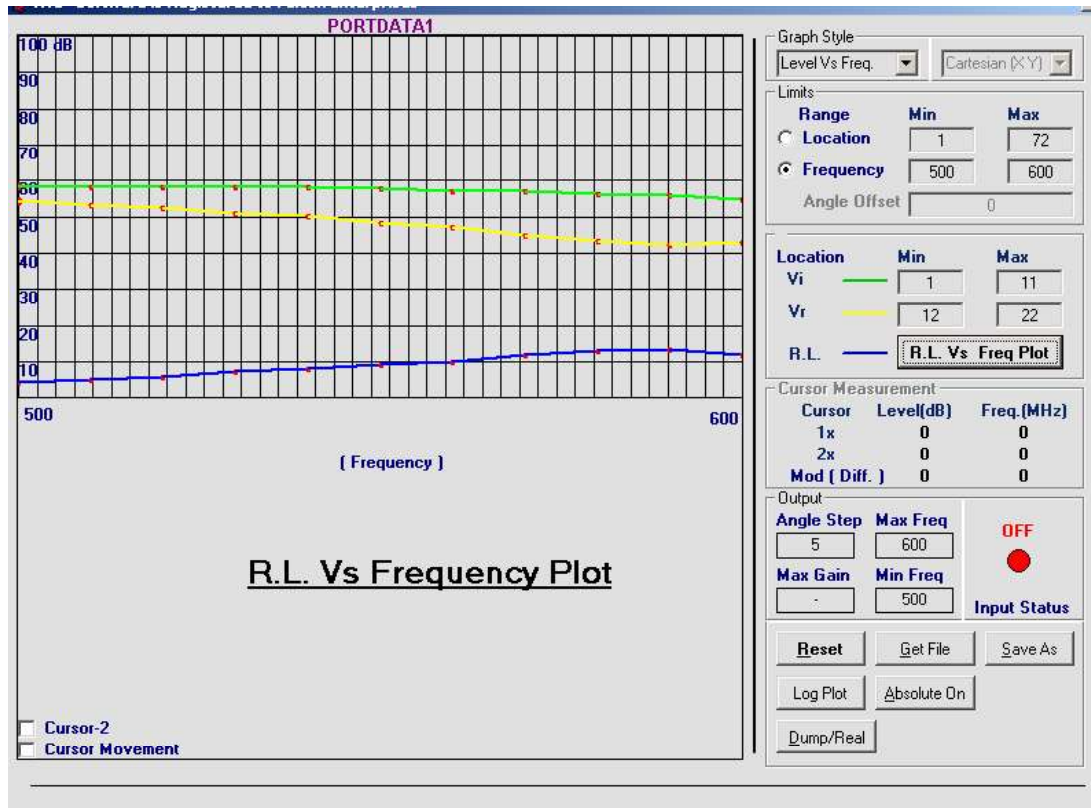
Under **Output** menu **Angle step** option automatically displays the angular step size in accordance with the **Location Min** and **Max** under **Limit** range menu. Suppose, Min 1 and Max 72 is fed, then **Angle step** displays 5 i.e., $360/72$. If max is 71, then **Angle step** displays 5.0704225 i.e., $360/71$. Below angle step option is **Max. gain** option under **Output** menu which displays the maximum gain reading under 1 to 72 locations in case min location is 1 and max location is 72.

Min Freq and **Max Freq** shows minimum and maximum freq under location 1 to 72. In case, **Level Vs. Angle** graph Style is selected which is plot of an antenna at a particular frequency at different angular positions, the **Min Freq** and **Max Freq** display is 0 as only single frequency exists from 1 to 72 locations.

The **Get file** option. Clicking it will open a window where the stored files can be opened or called. All the files previously stored contains **.mdb** filename extension and henceforth can be opened. Select the file by clicking on the file with extension **.mdb** and click **Open** or simply double click the file name. The selected file is displayed on graph. The name of file is displayed on the top of the graph. Color of plot can be selected by clicking **Plot color**. Clicking it will open a Color window where any **.Clicking VSWR Calculator** will open **Calculator** window. Entering Return Loss value and clicking **VSWR/Reflection Co.eff** button will display corresponding Reflection coefficient and VSWR.



When **Graph Style, Level Vs. Freq.** is chosen **Cartesian (XY)** get displayed right to it and gets disabled. This type of plot is useful for antenna bandwidth plotting using Log Periodic as reference antenna. Suppose a yagi is to be plotted against LP from 500 MHz to 600MHz in 10 MHz interval, then select location of 500MHz as **Location Min 1** and 600MHz as **Location Max 11** then, Enter **Frequency Min** as 500 and **Frequency Max** as 600. Click **location** and graph gets plotted. **Angle Offset** will get disabled during **Level Vs. freq** selection.



Similarly,

Return loss or VSWR of any antenna can be plotted using RLB or Directional Coupler. Say, an antenna is theoretically tuned or designed at say, 550 MHz Now, Suppose you want to plot VSWR or return Loss from 500 MHz to 600MHz. First using directional coupler take readings of incident voltage from 500 to 600 MHz say from **Location Min 1 to Max 11**. Now, take Reflected voltage readings from 500 to 600 MHz say from **Locations Min 12 to Max 22**. Now, click **R.L. Vs. Freq Plot** and three plots shall be displayed simultaneously – Vi , Vr and R.L. (Return Loss) Vs. Freq with Vi plot in green, Vr in yellow and R.L. in Blue colour. Cursors can be used to read any particular reading.

d) Experimental procedure

1. Set up the antenna, Tx, Rx and SCU etc according to any experiment done before.
2. Connect RS232 to the computer com port socket.
3. Start polar plot and select comport.
4. Physically rotate the antenna tripods so that the antenna point towards each other.
5. Press auto mode on scu to rotate the stepper by 1 or 5 degree steps. This will automatically send a trigger pulse to RX.
6. RX will start storing readings in its memory. After stroing dBV readings on 359 locations, the readings can be uploaded to PC after selecting uploading option from menu. The receiver will upload all 1000 locations to the computer. For plotting the relevant readings selct locations form software control panel (73 locations)

e) Report:

1. Plot radiation pattern of different antennas studied during the experiment.
2. Calculate beamwidth, front to back ratio, side lobe level, directivity and gain of antennas studied.
2. Relate the results with theory.
3. Present other results studied during the experiment, relate them with theory.

AUST/EEE

Experiment No.: **09**

Name of the Experiment: **Introduction to Antenna Array System.**

a) Objective:

1. To understand the importance, features and classification of antenna array system.
2. To plot the radiation pattern of End fire and Broadside antenna arrays.
3. To measure beam width, front to back ratio, directivity and gain of End fire and Broadside antenna arrays.
4. To study antenna resonance and measure VSWR, impedance of antenna.

b) Equipment list:

1. **Antenna Transmitter (already discussed in the lab sheet of Expt. 6)**
2. **Antenna Receiver (already discussed in the lab sheet of Expt. 6)**
3. **Stepper motor controller (already discussed in the lab sheet of Expt. 6)**
4. **Antenna Tripod (already discussed in the lab sheet of Expt. 6)**
5. **Polarizer connector (already discussed in the lab sheet of Expt. 7)**
6. **Return loss bridge (already discussed in the lab sheet of Expt. 7)**
7. **Broadside/ End fire antenna (to be discussed in the 'theory' part of this lab sheet)**

c) Theory:

1. Antenna array

An antenna array is a system of antenna elements designed to produce a certain desired antenna pattern, directivity, gain etc. The array is spatially extended collection of similar radiators or elements all having the same radiation pattern oriented in the same direction in 3D space. Antenna elements are all spaced in a certain geometric manner (eg. Straight line) and they are driven with source whose amplitudes and phases are suitably designed to obtain the desired effect. This can also be termed as 'antenna synthesis.'

The simplest effect of antenna array is the increase in antenna gain. Assume, two element antenna array fed in phase with each other and spaced by $\lambda/2$ apart (In figure, $d = \lambda/2$, $\theta = 0^\circ$). Considering the radiation in a particular direction (normal to plane containing the dipole), the contribution from each element arrives in phase with the other. The field strength will be double that for one element. So, radiation power density is four times that for one element. However the two elements together are fed with twice the power of a single element. The increase in gain is by a factor 4/2.

The polar radiation pattern of a single element is called, 'element pattern.' Yagi-uda antenna is an array of dipoles with different amplitude and phases of the dipole current.

The 'array pattern' is the polar radiation pattern which would result if the elements are replaced by isotropic radiator having the same amplitude and phase of excitation of the actual elements and spaced at points on a grid corresponding to the far field phase centers of the elements.

If the all element radiation pattern are identical and all aligned in the same direction in azimuthal or elevation plane, then total array antenna pattern is got by multiplying array pattern by element pattern.

2. Linear array (Fig. 9.1)

A linear array consists of a system of radiating elements which are arranged along a straight line and the elements are spaced equally. A linear array is said to be uniform if its elements are fed with currents which are equal in magnitude but have a uniform progressive phase shift.

3. End fire array (Fig.9.2)

It is kind of linear array (i) which is polarized in the direction of its elements, (ii) whose maximum radiation occurs along the length of array. End fire array with its element end pointing upwards is vertically polarized. The amplitudes of the feed of all the elements are the same but phases are progressively delayed. The amount of phase delay equal to the phase

delay in a plane wave travelling in the same direction. The progressive phase delay equals the electrical spacing 'kd' of the elements. End fire is a directional antenna with higher gain compared to dipole antenna. The Examples are long wire antenna, rhombic antenna etc.

4. Broad side array(Fig.9.3)

It is kind of linear array whose maximum radiation occurs along the direction perpendicular to array elements. Examples are short wire antenna, yagi antenna etc.

5. Schelkunoff's Theory of linear arrays (Fig.9.4)

Theorem-1 (Every linear array with commensurable separations between the elements can be represented by a polynomial (*array polynomial*) and every polynomial can be interpreted as a linear array)

Theorem-2 (There exist a linear array with a space factor equal to the product of the two linear arrays)

Theorem-3 (The space factor of a linear array of N apparent elements is the product of (N-1) virtual couplets with their null points at the zeroes of f(z))

Here,

Array polynomial/ Space factor, $S(\theta) = \sum a_n \exp j(n\psi + \alpha_n)$

$\psi = kd \cos \theta + \alpha$,

a_n are proportional to amplitude of current

α_n progressive phase shift from left to right

right

replacing $a_n \exp j \alpha_n$ by A_n and $\exp j\psi$ by 'Z'

Array polynomial,
Array factor,

$f(z) = \sum A_n Z^n$
 $P(\theta) = |S(\theta)|^2$

d) Experiment procedure:

*** Radiation Pattern**

1. Connect the Dipole antenna to the tripod and set the frequency to 600 MHz. Keep the antenna in vertical position using polarizer connector.
2. Now connect the end fire antenna to the stepper tripod and set the receiver to 600 MHz.
3. Set the distance between antennas to be around 1 m
4. Take the level reading of the receiver (level greater than 70 dB should be avoided)
5. Using stepper tripod, rotate the endfire antenna around its axis & take readings. Take both manual and auto reading.
6. Without disturbing the set up, rotate the endfire antenna at receiver from vertical to horizontal plane using a polarizer connector. Rotate the antenna and take readings.
7. Follow step 2-6 by replacing end fire antenna by broadside antenna.

*** Study of antenna resonance**

AMITECH approach	FALCON approach
1. Set up the directional coupler for forward power measurement as Fig. 2. Connect the TX at input port of directional coupler (RF IN, port 1), RX at coupled port (SAMPLE, port 3), antenna at output port (RF OUT, port 3). Take forward power reading. 3. Connect the antenna at input port of	1. Connect the return loss bridge to the transmitter tripod through the TX RF connector. 2. Connect the endfire to the RLB at the ANT connector, connect the receiver to the RLB at RX connector. 3. For frequencies set from 500 to 750 MHz, record receiver readings, there will be distinct

<p>directional coupler (RF IN, port 1), RX at coupled port (SAMPLE, port 3), TX at output port (RF OUT, port 2). Take reverse power reading. Difference between the two reading is the return loss.</p> <p>4. Follow step 3-6 of the FALCON approach.</p>	<p>decrease in level due to bridge null where antenna resonates. Locate that frequency.</p> <p>4. Change antenna dimensions and locate the new null frequencies.</p> <p>5. Repeat the same for broad side antenna.</p> <p>6. From the return loss table, calculate antenna impedance, VSWR.</p>
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e) Report:

1. Plot radiation pattern of different antennas studied during the experiment.
2. Calculate beamwidth, front to back ratio, side lobe level, directivity and gain of antennas studied.
2. Relate the results with theory.
3. Present other results studied during the experiment, relate them with theory.

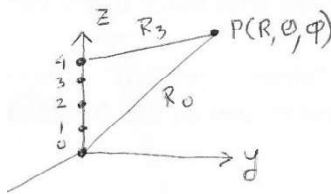


Fig. 9.1 Linear array

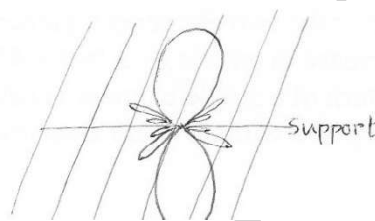


Fig. 9.2 Rad. Pat for broadside array

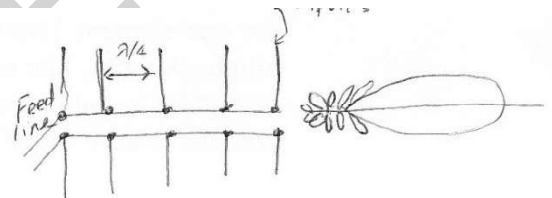


Fig. 9.3 Rad. Pat for end fire array

Experiment no: **10**

Name of the Experiment: **Introduction to Special types of Antenna.**

a) Objective:

1. To understand the features and working principle of various types of antennas.
2. To plot the radiation pattern of various types of antennas.
3. To study antenna resonance of various types of antennas.

b) Equipment list:

1. **Antenna Transmitter (already discussed in the lab sheet of Expt. 6)**
2. **Antenna Receiver (already discussed in the lab sheet of Expt. 6)**
3. **Stepper motor controller (already discussed in the lab sheet of Expt. 6)**
4. **Antenna Tripod (already discussed in the lab sheet of Expt. 6)**
5. **Polarizer connector (already discussed in the lab sheet of Expt. 7)**
6. **Return loss bridge (already discussed in the lab sheet of Expt. 7)**
7. **Square Loop/Biconical/Crossed dipole/Discone/Vee/Slot/ Helix antenna (to be discussed in the Theory' part of this lab sheet)**

c) Introduction:

1. Square loop/ Quad antenna (Fig.10.1)

The loop antenna can be thought of a coil carrying a rf current. The loop may have one or more turns according to the frequency employed. Normally, loop dimensions are small compared to the wavelength and the current in wire of the loop is everywhere same in magnitude and phase. The loop is thus surrounded by a magnetic field everywhere perpendicular to the loop. The polarization of these antenna is a function of its feed point and the direction of elements. When the quad is supplied with a feed pointing downward is horizontally polarized and when it is feed laterally then polarization is vertical. Quad is directional antenna with higher gain than that of dipole antenna.

The total length of square loop antenna is nearly equal to one wavelength. For quad, the distance between elements is less than quarter wavelength. Both are narrow band antennas with impedance 50 ohm.

The property of loop antenna is used for directional finding purpose. Quad antenna is used by amateur for radio communication.

2. Biconical antenna (Fig.10.2)

These antennas are polarized in the direction of its elements. Elements pointing upward means vertical polarization of these antennas. It is a directional antenna with slightly higher gain as compared to a dipole antenna. Elements are fed in anti-phase. It is basically a broadband antenna. The length of antenna elements is an indication of its lowest frequency of operation. Impedance is higher (about 150 ohm). The VSWR is constant over a broad range of frequencies. The phantom biconical antenna closely simulates the conical surfaces.

It is used in EMI/EMC measurement due its broadband nature.

3. Crossed dipole antenna (Fig.10.3)

It is a circularly polarized antenna. It has one pair of element pointing upwards is vertically polarized and other pair of elements pointing horizontal is horizontally polarized. The two are spaced at a distance of quarter of wavelength, giving a 90 degree phase difference in feed. The combined effect is to rotate the wave front as in circular polarization. The direction of circular polarization is same on both side of the axis.

The LHCP and RHCP crossed dipole antennas will show a polarization discrimination of around 10 dB when communicated against each other. A dipole antenna cannot distinguish between LHCP and RHCP antennas.

4. Discone antenna (Fig.10.4)

It is basically a broadband omni-directional antenna with low gain. It is a combination of a disk and a cone in close proximity. It is a ground plane antenna evolved from a typical dipole and having a very similar radiation pattern. The length of the antenna elements is an indicator of its lower most frequency of operation ($D=\lambda/4$). It offers a similar impedance as compared to a dipole of around 75 ohms. The VSWR is nearly constant over a broad range of frequencies. A phantom discone antenna closely simulates the conical surface. It is a UHF antenna used at airports where communication has to be made with an aircraft from any direction.

5. Vee antenna (Fig.10.5)

It is polarized in the direction of its elements. The Vee is a directional antenna with a slightly higher gain compared to a dipole antenna. Vee is basically a long wire type antenna to which rhombus antenna also belongs. It is half of a rhombus type antenna. The length of the antenna elements is an indicator of its lower most frequency of operation. It is designed for 600 KHz when the fully extended element length is around 1.2λ . It offers an impedance of around 150 ohms. The VSWR is nearly constant over a broad range of frequencies. Varying the induced angle of Vee will change the polar plot considerably. It is used by military for low frequency communication.

6. Slot antenna (Fig.10.6)

Whenever a RF field exists across a narrow slot in a conducting plane, radiation is bound to take place. The energy for the field excitation is fed to the slot with the help of a two wire transmission line. The electric field across the slot is maximum at the center and reduces towards the edge. When the slot is halfwavelength long, the electric field distribution is sinusoidal. It behaves similarly to a dipole antenna. It is horizontally polarized and tuned at 800 MHz (in case of our FALCON supplied antenna). Boresight direction is perpendicular to the surface of antenna. Impedance is similar to that of a dipole. It is useful for aircraft due to its low profile.

7. Helix antenna (Fig. 10.7)

It is an omni-directional broadband antenna and its gain is comparable to a dipole antenna. Its advantage is its space saving capability at VHF band for walkie-talkie handsets. The springy antenna resonates at 800 MHz.

If the circumference, pitch and length of the helix are small compared to the wavelength, so that current is approximately uniform in magnitude and phase in all parts of helix, the *normal mode* of radiation is excited, that is the radiation is maximum in the plane normal to the helix axis. So, the normal mode helix antenna is vertically polarized in the direction of its axis. If the dimension of the helix are such that the circumference is of one turn is approximately one wavelength, the antenna radiates in the *Axial mode*. The axial mode helix antenna is circularly polarized in end-fire direction along its axis. The direction of circular polarization is same on both sides of the axis if it is fed without the ground plane. The ground plane increases the directivity in the end-fire direction. Its design frequency is around 800 MHz. It is highly directional antenna. The antenna is inherently broadband over its design frequency. The two LHCP and RHCP helices provided will show a polarization discrimination of over 10 dB when compared to each other. If we pair RHCP helix and RHCP crossed dipole or similar LHCPs against each other, then it will result in more signal strength. Rotating a dipole from horizontal to vertical using polarization adaptor in front of a helix will not show much variation in signal strength indicating it is circularly polarized.

d) Experiment procedure:*** Radiation Pattern**

1. Connect the Dipole antenna to the tripod and set the frequency to 600 MHz. Keep the antenna in horizontal plane. For Helix/ Slot/ Crossed dipole antenna, the frequency should be set at 800 MHz.
2. Now connect the antenna (to be studied) to the stepper tripod and set the receiver to 600 MHz (in case of helix/slot/ crossed dipole antenna, then frequency should be set at 800 MHz). For Biconical/Discone/Vee antenna- connect elements at an angle of

- around 30° to form two cones). For Vee antenna, keep the elements in horizontal plane with elements fully elongated. For Helix antenna, the element total length 24 cm.
3. Set the distance between antennas to be around 1 m (for Helix 3m, for Vee 2m)
 4. Take the level reading of the receiver (level greater than 70 dB should be avoided)
 5. Using stepper tripod, rotate the antenna (to be studied) around its axis & take readings (auto/manual)
 6. Without disturbing the set up, rotate the square loop/quad antenna at receiver from horizontal to vertical plane using a polarizer connector. Also turn the dipole antenna other end vertical. Rotate the antenna and take readings.

*** Study of antenna resonance**

AMITECH approach	FALCON approach
<ol style="list-style-type: none"> 1. Set up the directional coupler for forward power measurement as Fig. 2. Connect the TX at input port of directional coupler (RF IN, port 1), RX at coupled port (SAMPLE, port 3), antenna at output port (RF OUT, port 3). Take forward power reading. 3. Connect the antenna at input port of directional coupler (RF IN, port 1), RX at coupled port (SAMPLE, port 3), TX at output port (RF OUT, port 2). Take reverse power reading. Difference between the two reading is the return loss. 4. Follow step 3-5 of the FALCON approach. 	<ol style="list-style-type: none"> 1. Connect the return loss bridge to the transmitter tripod through the TX RF connector. 2. Connect the antenna to the RLB at the antenna connector, connect the receiver to the RLB at Rx connector. 3. For frequencies set from 500 to 850 MHz, record receiver readings, there will be distinct decrease in level due to bridge null where antenna resonates. Locate that frequency. 4. Change antenna dimensions and locate the new null frequencies. 5. From the return loss table, calculate antenna impedance, VSWR.

e) Report:

1. Plot radiation pattern of different antennas studied during the experiment.
2. Calculate beamwidth, front to back ratio, side lobe level, directivity and gain of antennas studied.
2. Relate the results with theory.
3. Present other results studied during the experiment, relate them with theory.

(

Experiment No: 11
Name of the Experiment: Introduction and calibration of Vector Network Analyzer

(a)Objective:

- 1) Necessity of transmission line theory in Microwave and millimeter wave devices
- 2) Challenges of Measurement in microwave frequency.
- 3) Introduction to Scattering Parameter and its usefulness
- 4) Introduction to Vector Network Analyzer
- 5) Understanding Error Model of a 2-port Network.
- 6) Calibration method and SOLT calibration

(b)Theory

2.1 Lumped element model and Distributed element model (Transmission line Model):

The lumped element model simplifies electrical network by considering the electrical network as combination of resistors, capacitors, and inductors, etc. joined by perfectly conducting wires. The model also assumes the energy transfer from source to load is instant.

Practically energy transfer is not instant, but EM field propagate in the circuit at propagation velocity ($v_p = \frac{c}{\sqrt{\epsilon_r}}$). The wavelength, λ , is defined as a function of the propagation speed (V_p or c) and the sine wave generator frequency (f_0) in Equation

$$\lambda = \frac{v_p}{f_0}$$

When the frequency (f_0) is low, the wavelength is large, and the length of the cable is negligible compared to the size of the wavelength. As a result, the measured voltage and current are independent of the location on the cable. As the energy transfer in the network is instant the voltage in point 'a' and point 'b' is the same (there is no voltage drop or phase change). This situation is illustrated in Fig 1(a), and the circuit is referred to as being a lumped element circuit or lumped.

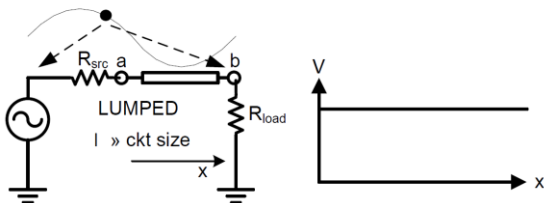


Fig 1(a): Circuit response at low frequency

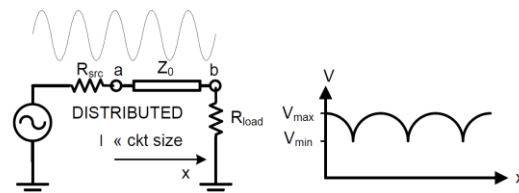


Fig 1(b): Circuit response at high frequency

When the frequency (f_0) of the source increases, the wavelength is reduced. Thus, as frequency increases, the wavelength eventually becomes similar in size or even smaller than the length of the cable. In a scenario where the wavelength of the signal is similar or smaller in size to the length of the cable, the measured voltage and current will depend on the position, as shown in Fig 1(b) Thus, measuring the voltage with a voltage probe is invalid because the result will be dependent on the probe's position. In this scenario, the circuit must be treated as a distributed element circuit rather than as a lumped circuit.

Analysis of a distributed circuit is more complex and involves the use of transmission line theory. In transmission line theory, electrical power traveling along the line can be considered as a voltage (E-field) and current (H-field) traveling and relation is imposed by the electrical properties of the line. the cable itself will behave such that it is characterized by an inherent impedance that does not change as long as the properties of the line or cable do not change. This impedance is called the characteristic impedance (Z).

As the electrical power hits the termination (R_{load}), the voltage to current relationship is now imposed by the impedance of the load. Under the condition where the load impedance is equal to the characteristic impedance, the power is fully absorbed. If the load impedance is different from the characteristic impedance, the ratio of voltage and current will change at the point where the transmission medium occurs. As a result, the load will not absorb all the power, resulting in a portion of the power

traveling back towards the source. They are known as incident and reflected wave. The ratio of them is known as reflection coefficient:

$$\Gamma(\omega_0) = \frac{V^+(\omega_0)}{V^-(\omega_0)} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

At each point along transmission line, there are two waves traveling. They are a) forward wave moving towards load b) reflected wave moving generator/signal source keeping a variable phase relationship between them. So, there are some points where both waves are in phase & in some they are in antiphase. Corresponding voltages in those points will be Vmax and Vmin respectively. Ratio of Vmax & Vmin is called VSWR

2.2 Scattering parameter/ S- parameter:

The S-parameters describe the magnitude and phase relationship between incident and reflected waves. S-parameters have long been the chosen method for this because they are relatively easy to derive at high frequencies. S-parameters have many advantages over H, Y or Z-parameters. They relate to familiar measurements such as gain, loss, and reflection coefficient. They are defined in terms of voltage traveling waves, which are relatively easy to measure. S-parameters don't require connection of undesirable loads to the device under test. The measured S-parameters of multiple devices can be cascaded to predict overall system performance. If desired, H, Y, or Z-parameters can be derived from S-parameters. And very important for RF design, S-parameters are easily imported and used for circuit simulations in electronic-design automation (EDA) tools. S-parameters are the shared language between simulation and measurement.

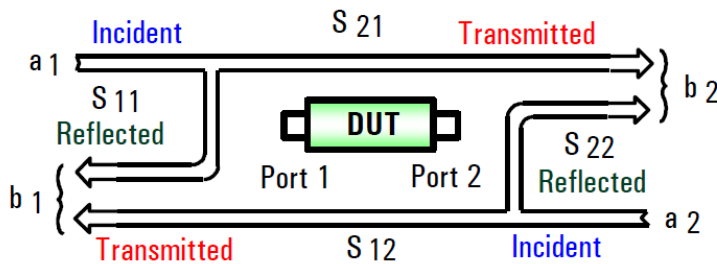


Fig 2: Signal Path in an ideal two port network

For a two-port network shown in Fig. 2 \$a_1\$ and \$a_2\$ are the incident wave in port 1 and port 2, \$b_1\$ and \$b_2\$ are reflected/ transmitted wave in port 1 and port 2 respectively. Because the system is linear mathematically it can be written as:

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

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

when the characteristic impedance (\$Z_0\$) is equal to 50 Ohms, and if a 50 Ohm termination is present at port 2 (in fig 3 \$a_2\$ is reduced to zero) resulting in equations for \$S_{11}\$ and \$S_{21}\$. This principle can be applied in the reverse direction as well. By setting \$a_1\$ to zero, equations for \$S_{22}\$ and \$S_{12}\$ can be obtained.

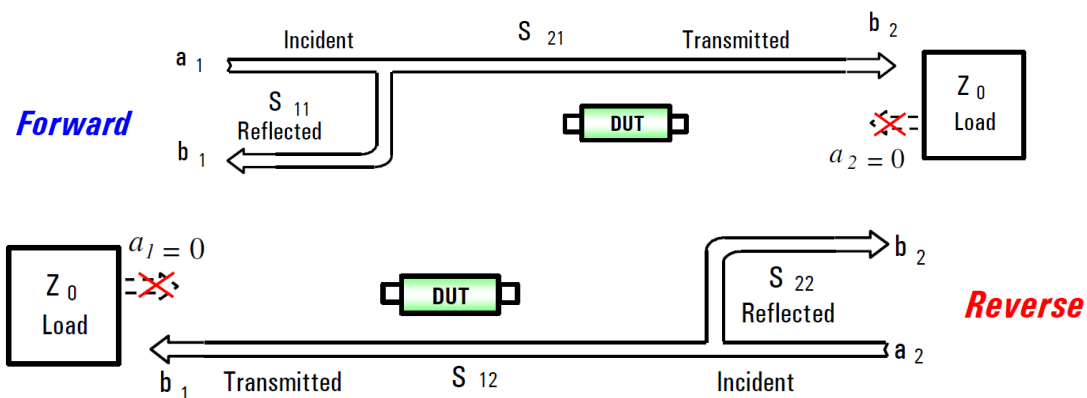


Fig 3: Definition of S parameter from forward and reverse transmission

Defining incident wave as $a_1 = V_1^+$ and $a_2 = V_2^+$ and reflected/transmitted waves as $b_1 = V_1^-$ and $b_2 = V_2^-$

So for forward transmission the s parameters are

$$S_{11} = \frac{\text{Wave reflected from port 1}}{\text{Wave Incident at port 1}} = \frac{V_1^-}{V_1^+} = \frac{b_1}{a_1} \Big|_{a_2=0}$$

$$S_{21} = \frac{\text{Wave transmitted to port 2}}{\text{Wave Incident at port 1}} = \frac{V_2^-}{V_1^+} = \frac{b_2}{a_1} \Big|_{a_2=0}$$

And for reverse transmission the s parameters

$$S_{22} = \frac{\text{Wave reflected from port 2}}{\text{Incident wave at port 2}} = \frac{V_2^-}{V_2^+} = \frac{b_2}{a_2} \Big|_{a_1=0}$$

$$S_{12} = \frac{\text{reflected wave from port 2}}{\text{Incident wave at port 2}} = \frac{V_1^-}{V_2^+} = \frac{b_1}{a_2} \Big|_{a_1=0}$$

An N-port device has N^2 S-parameters. So, a two-port device has four S-parameters. The numbering convention for S-parameters is that the first number following the “S” is the port where the signal emerges, and the second number is the port where the signal is applied. So, S_{21} is a measure of the signal coming out port 2 relative to the RF stimulus entering port 1. When the numbers are the same (e.g., S_{11}), it indicates a reflection measurement, as the input and output ports are the same. The incident terms (a_1 , a_2) and output terms (b_1 , b_2) represent voltage traveling waves. So for 1 port network the scattering matrix is $[S_{11}]$ similarly for 2 port network the matrix is $\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$ and so on.

2.3 Vector Network Analyzer:

Network Analyzer is an instrument used to measure impedance. At lower frequencies impedance can be measured with a sine wave generator, a volt meter, a current meter. The ratio of voltage and current will give out the impedance of the network. At higher frequency, the voltage and current vary with position due to the standing wave produced by the interaction of transmitted and reflected wave (explained in the previous section). Thus, impedance measurement at higher frequencies is done with measurement of incident and reflected waves. In fact, the VNA is able to measure the amplitude and phase differences between incident and reflected waves, using one of the waves as a reference.

The primary use of a VNA is to determine the S-parameters of numerous passive components, including cables, filters, switches, diplexers, duplexers, triplexers, couplers, bridges, transformers, power splitters, combiners, circulators, isolators, attenuators, antennas, and many more. In addition, VNAs can also characterize active devices such as transistors and amplifiers using S-parameters, as long as they are operating in their linear mode of operation.

2.4 Architecture of a 2-port Vector Network Analyzer:

The fundamental principle of a vector network analyzer is to measure the amplitude and phase of both incident and reflected waves at the various ports of the DUT. The general design of a VNA is to stimulate an RF network at a given port with a stepped or swept continuous wave (CW) signal and to measure the travelling waves, not only at the stimulus port but at all the ports of the network terminated with specific load impedances, typically 50 Ohms or 75 Ohms. A typical but simplified VNA architecture is illustrated in Fig 4.

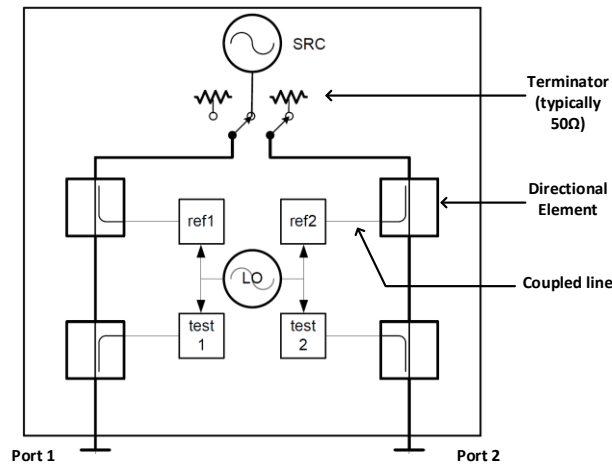


Fig 4: Simplified VNA block diagram

A typical VNA have one or more signal source (SRC) with controllable frequency. The test port contains some signal separation hardware (e.g. directional coupler) to split out the incident and reflected travelling waves. The test set can contain switches to route the signal source to the different test ports and terminates other ports with specific load impedances. The ‘ref’ port typically measure the incident wave from the coupled line and the test port measure the reflected signal.

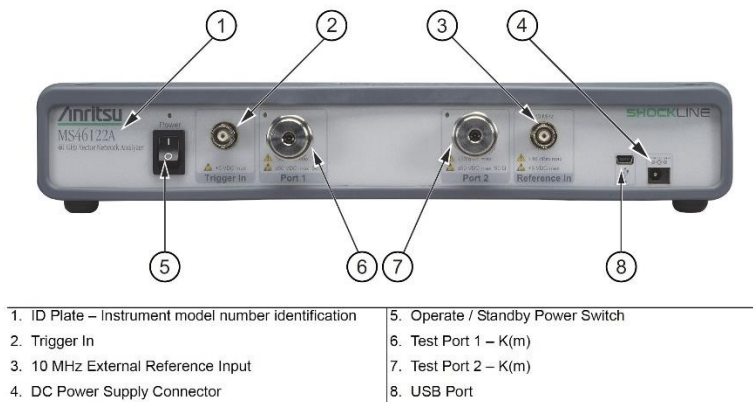


Fig 5: Anritsu MS43122A-20 Vector Network Analyzer

2.5 VNA Errors and Calibration:

In the VNA measurement there are three types of errors: random, systematic and drift. Random errors vary with time and are thus unpredictable and cannot be removed by calibration. Typical random errors include those caused by instrument noise, and the repeatability of switches, cables, and connectors. In contrast, systematic errors occur in a reproducible manner. They are caused by imperfections in the VNA, can be characterized, and thus can be removed mathematically through calibration. Drift occurs after a calibration has been performed because of changes in VNA performance arising from variations in ambient temperature.

A VNA is only as useful as the accuracy with which it makes measurements, and this requires the instrument to be calibrated. The calibration process employs a technique called *vector error correction*. Vector-error correction is the process of characterizing systematic error terms by measuring known calibration standards, and then removing the effects of these errors from subsequent measurements mathematically. The process of removing these errors requires the errors and measured quantities to be measured vectorially (Magnitude and Phase).

Each network analyzer can be separated into an error network (or linear error model) and an ideal network analyzer. The parameters of the error network are considered ‘error terms’ and can be directly interpreted as raw system data. Correcting

system errors is the primary goal of calibration, and any remaining errors are expressed by the effective system data and depend on the accuracy of the error terms and the repeatability of the measurement process.

The calibration process determines the *error terms*, requires a test system consisting of a VNA, cables and a calibration standard. These calibration standards are one-port and two-port networks that have known characteristics. It is impossible to manufacture a calibration standard that has ideal properties, so the deviations of the standards are sent to the VNA as 'characteristic data'. This data is provided as data files to the VNA software. After calibration, the analyzer mathematically computes the error terms using the values it measured during the calibration process along with the characteristic data of the standards. It is then possible to correct the raw measured values in later measurements and calculate systematic error free S-parameters for the device under test.

2.6 Error Model:

Fig 6 show simplified error model of the *Error network*. There are three class of systematic error in an Error network. Signal leakage, Signal reflection and Frequency response. The errors relating to signal leakage are directivity and crosstalk. Errors related to signal reflections are source and load match. The errors related to frequency response of the receivers are reflection and transmission tracking. The full two-port error model includes all six of these terms for the forward direction and the same six (with different data) in the reverse direction, for a total of twelve error terms. This is why two-port calibration (3 receiver VNA architecture) is referred as twelve term error correction.

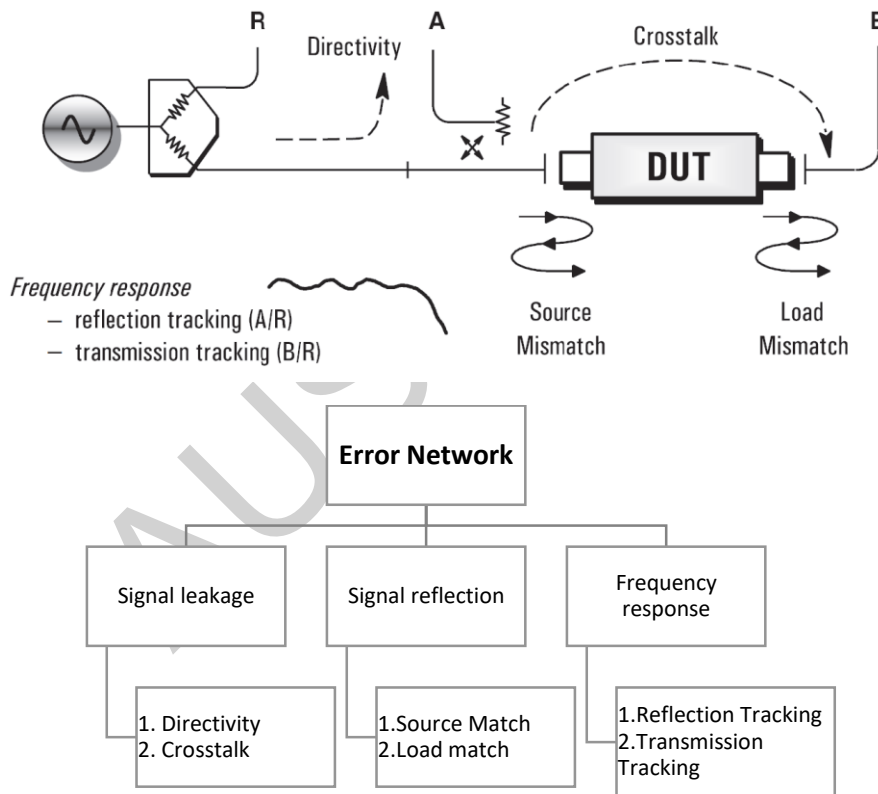


Fig 6: Classic Two-Port 12 term Error Model of VNA

The interface between the error network and the device under test is called the reference plane. When using coaxial calibration standards, the reference plane is the mating plane of the outer conductor, an example of which is shown in Fig 7.

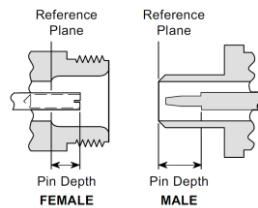


Fig 7: Location of the reference plane in a Type-N connector

2.7 Calibration standard and SOLT Calibration:

There are many different types of VNA calibration methods like SOLT, SSLT, SSST, LRL, ALRM and so on. For our purpose, we will use the most common calibration technique called SOLT (Short, Open Load, Through). SOLT calibration technique use four standards (short, open, load and through) to acquire all 12 term which is required for full two port calibration (see appendix for detail). The characteristics data of the SOLT standard can be seen in figure 8 with the actual cal kit and the data sheet of the kit.

The screenshot shows the 'Standard Info (SOLT)' window in ShockLine software. It includes fields for Cal Kit Label (TOSLKF50A) and Serial Number (XXXXXX). The 'Broadband Load' section shows a circuit diagram with parameters: R (50 Ω), Z0 (50 Ω), I0 (0 mm), L0 (0 e-12), and C0 (0 e-15). Below this, it lists parameters for Short (SN XXXXXXX) and Open (SN XXXXXXX) standards, including L0-L3 and C0-C3 coefficients and their respective offset lengths (5.01 mm).

TOSLKF50A-20 Calibration Kit Specifications

Through (Thru)	Spec	Open	Spec	Short	Spec	Load	Spec
Length	16.07 mm	Length	5.01 mm	Length	5.01 mm	DC Resistance	50 Ω ± 0.25 Ω
Return Loss (DC to 10 GHz)	≥ 34 dB	C0 (1E-15) F	5.000	L0 (1E-12) H	8.000	Return Loss (DC to 10 GHz)	≥ 42 dB
Return Loss (10 to 20 GHz)	≥ 32 dB	C1 (1E-27) F/Hz	0.000	L1 (1E-24) H/Hz	-995.000	Return Loss (10 to 20 GHz)	≥ 36 dB
Insertion Loss (DC to 20 GHz)	≤ 0.025 × √(f/GHz) dB	C2 (1E-36) F/Hz ²	1.500	L2 (1E-33) H/Hz ²	33.000	Max Power	0.5 W
		C3 (1E-45) F/Hz ³	0.100	L3 (1E-42) H/Hz ³	-0.290		
		Phase (DC to 10 GHz)	≤ ± 1.5°	Phase (DC to 10 GHz)	≤ ± 1.5°		
		Phase (10 to 20 GHz)	≤ ± 3.0°	Phase (10 to 20 GHz)	≤ ± 2.5°		

Fig 8: Calibration kit, characteristic data in ShockLine Software and data sheet of TOSLKF50A-20 coaxial calibration kit from Anritsu

Short: A coaxial short (Fig 9) can be constructed that has near ideal characteristics, with a total reflection of magnitude 1. The reflection coefficient of the short is dependent only on its length offset, which represents the length between the reference plane and the short. The loss occurring over this length can generally be ignored. Modeling the short in a VNA requires that only its electrical length be entered into the instrument, but in some cases the model can be extended using the polynomial coefficients L₀ to L₃ to account for parasitic inductance.

$$L = L_0 + L_1f + L_2f^2 + L_3f^3$$



Fig 9: Internal construction and equivalent circuit diagram of the short standard

Open: A coaxial open standard (Fig 10) is constructed using a closed design to avoid effects caused by entry of stray electromagnetic energy. At the open end of the inner conductor, a frequency-dependent fringing capacitance is formed. Even if an open standard could physically be constructed with a length of 0, fringing capacitances would result in a negative imaginary part for S11 at higher frequencies.

$$C = C_0 + C_1f + C_2f^2 + C_3f^3$$

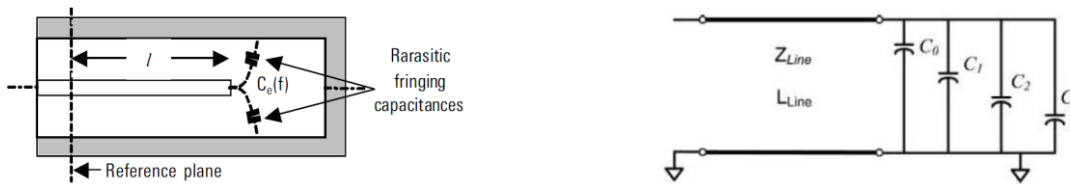


Fig 10: Internal construction and equivalent circuit diagram of the open standard

Match/ Load: A match is a precision broadband impedance that has a value corresponding to the system impedance (50 Ohm in this case). An implementation in which the inner conductor terminates into a resistively-coated substrate is shown in Fig 11.

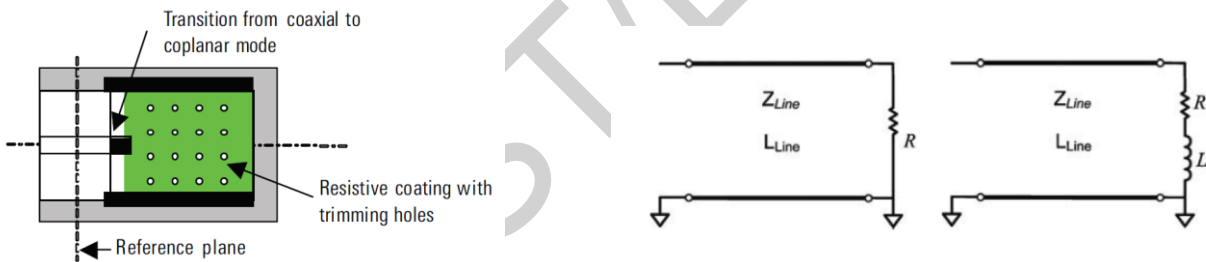


Fig 11: Internal construction and equivalent circuit diagram of the load standard

Through: A through (Fig 12) is a two-port standard that allows direct connection of two test ports with low loss. The characteristic quantities of a through are insertion loss and electrical insertion length. The through is assumed to be ideally matched. If connectors of the same type but of a different gender are used, the two test ports can be directly connected to produce a through connection. This special case of a through has an electrical insertion length of 0 mm. Through standard is modeled as a transmission line length with some frequency dependent loss. A root-f frequency dependence of that loss is assumed. If 0 is entered for f₀ (the reference frequency), the loss is assumed to be constant with frequency.

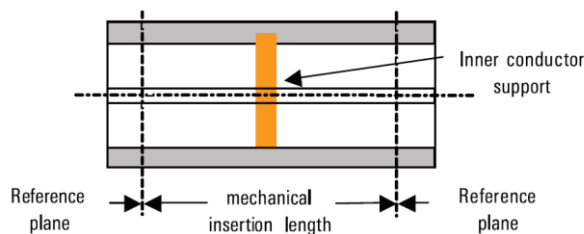


Fig 12: Thru standard

(c) Experimental Procedure:

1. Connect both the wire to Test Port 1 and Test port 2 (see Fig 5).
2. Turn on the power supply.
3. Click to open “ShockLine” software. ShockLine is a software made by Anritsu which can be used as the interface of the MS46122A-20 Vector Network Analyzer.

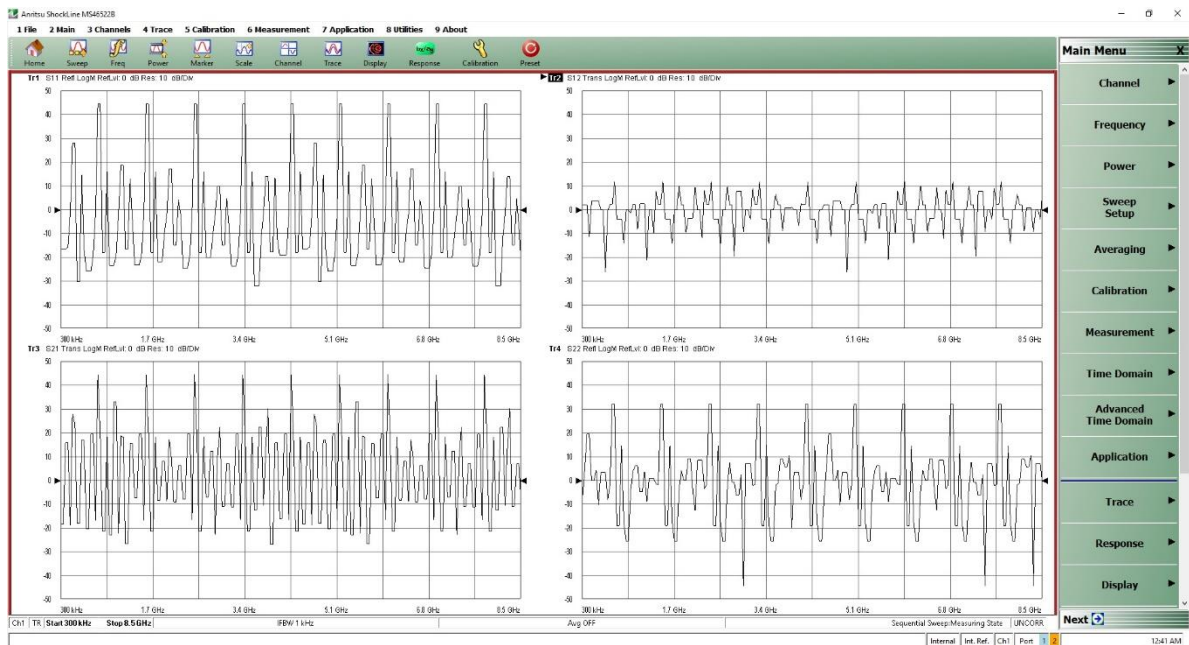


Fig 13: Anritsu ShockLine software interface

4. The default interface should look like Fig 13.
5. Click ‘Preset’. This will change all the setting of the VNA to its default setting. In the status bar (bottom of the screen) the Start Stop frequency of the VNA, frequency, IF bandwidth, Measurement status can be seen at a glance. As the VNA is in default status the calibration is void. (can be seen as “UNCORR” in the status bar)
6. To change the start and stop frequency of the sweep, click frequency on the right side of the screen or Click ‘Main>Frequency’ from the main menu.

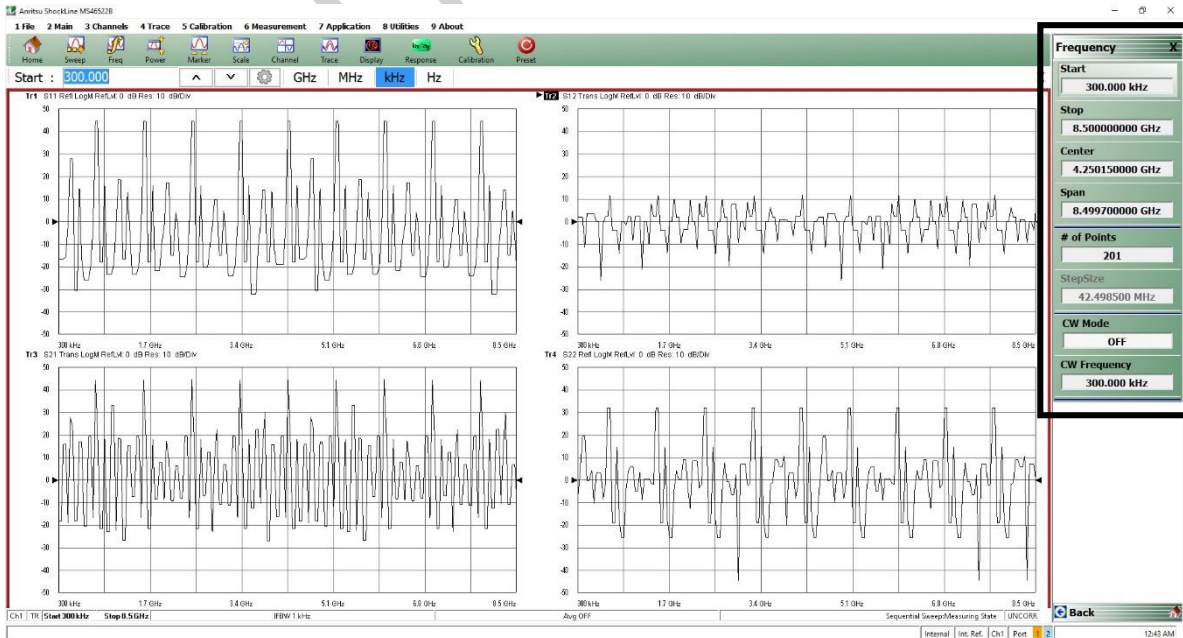


Fig 14: Start and Stop frequency selection

7. Enter the Start and Stop frequency in the dialog box (Fig 14), also enter the ‘number of points’. By increasing the number of points the resolution of the measurement can be increased but it will also slow down the sweeping speed.
8. To start calibration, click ‘calibrate’ from the main menu. In the calibration menu click Calibrate>Manual Cal> 2 Port Cal (Fig 15). In ‘Two Port Cal’ menu port 1, port 2 is calibrated one at a time using the Open, Short, Load standard. Then Thru calibration is done.

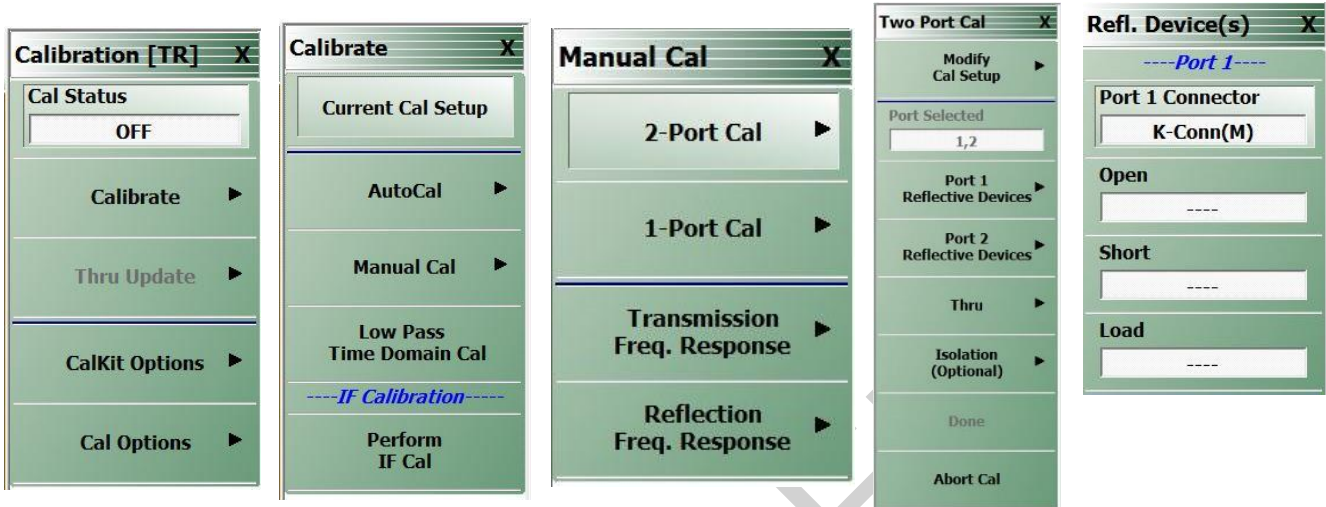


Fig 15: Calibration Sub menu

9. To calibrate port 1, click ‘Port 1 Reflective Devices’.
10. In the Refl. Device(s) sub-menu click ‘port 1 Connector’
11. Set all the parameter according to the Fig 16. Select “TOSLKF50A” as the Cal kit for test port 1 and test port 2. Click Ok.

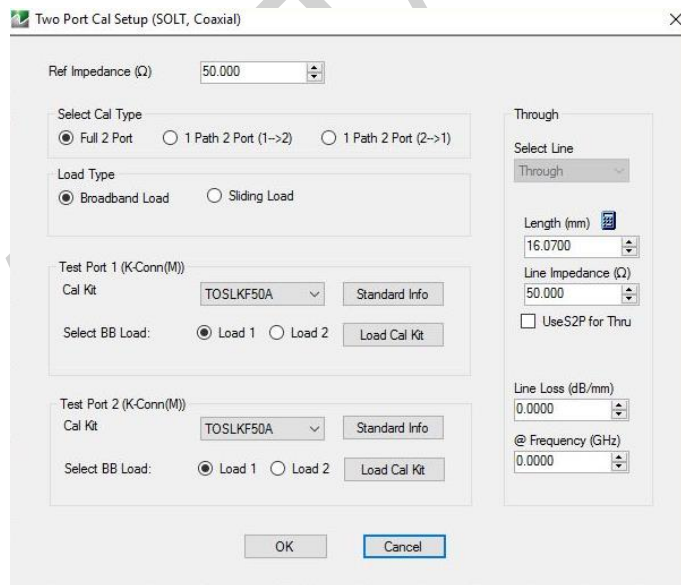


Fig 16: Calibration process

12. Now connect the Open standard at the end of the cable and click ‘open’ in the ‘refl. Device(s)’ menu. After the calibration, there will a small check mark on the side of open menu.
13. Then disconnect the open standard and connect the short standard. Click ‘short’. After the calibration, there will a small check mark on the side of Short menu.
14. Then disconnect the short standard and connect the Load standard. Click ‘Load’. After the calibration, there will a small check mark on the side of Load menu.
15. If all three standards are calibrated successfully the menu will look like Fig 17.
16. Now for port 2 calibration, repeat steps 12-14 for port 2.

17. For thru calibration connect thru standard in-between port 1 and in port 2. Click thru in ‘two port cal’ Menu. After the calibration, there will be a check mark on side of the thru menu.
18. If all is done right after the Thru calibration there will be a dialog box saying “Please click “done” button to complete the calibration”. Click ok.
19. Click Done in the ‘Two port cal’ Menu (fig 17)

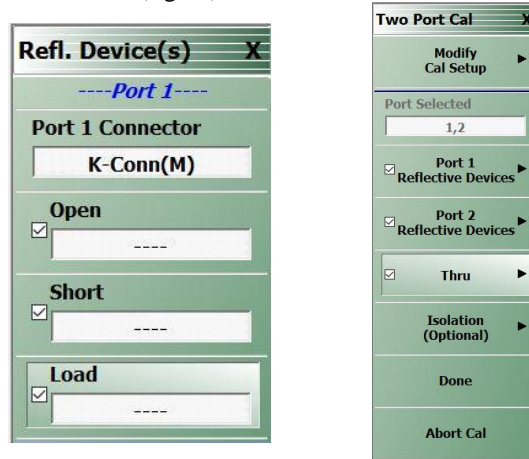


Fig 17: Menu after complete two port calibration

20. If the calibration is done the Status bar will show “CORR” as the Measuring State.

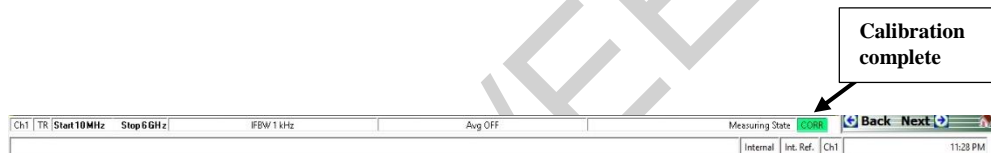


Fig 18: Software interface after Calibration

21. Verify all the calibration during or after the calibration by connecting the short, open and load to port 1 and 2 ,view the impedance in smith chart format and compare with fig 19.

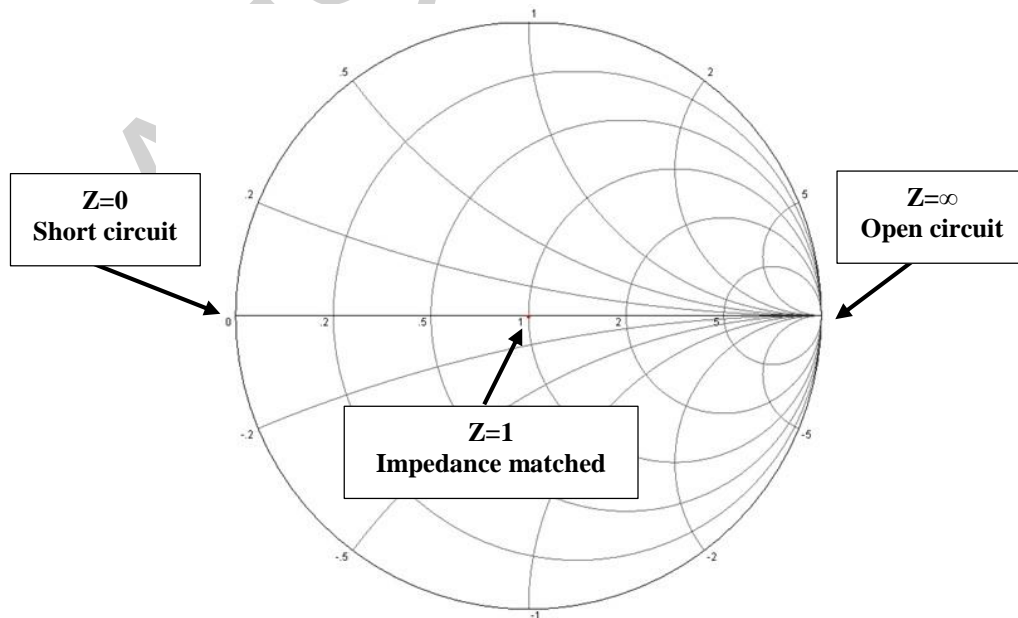


Fig 19: Ideal Position for Open, Load and short circuit in Smith Chart

22. To view the measurement in smith chart format, connect load/short/open in port 1 or 2 then click Display>Trace Format> Smith (R+jX) >Impedance.

(d)Report:

1. What type of connector does the VNA and cable use? Why?
2. Why it is absolutely essential to calibrate a VNA before using it for measurement?

(e)Appendix:

Detail 12 term Error Model

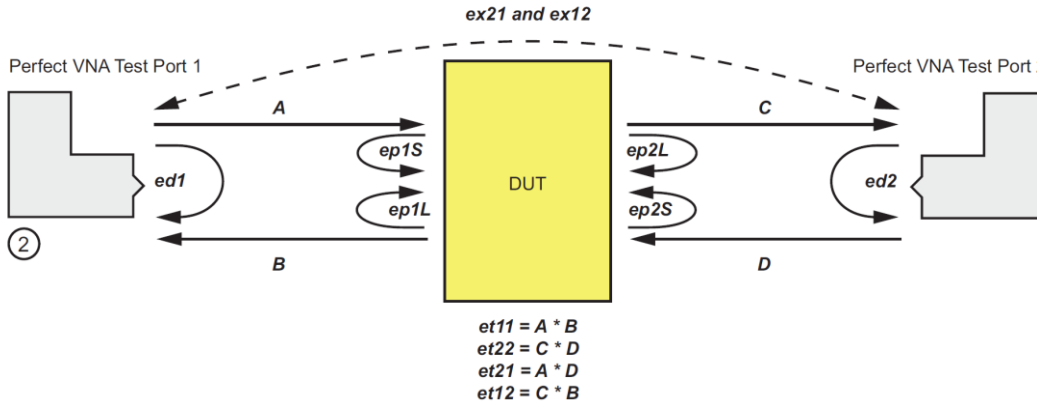


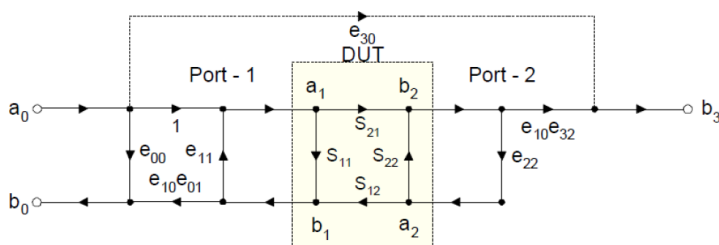
Fig 20: Simplified 12 Term error model diagram

- Directivity (ed1 and ed2) describes the finite directivity of the bridges or directional couplers in the system. Partially includes some internal mismatch mechanisms that contribute to effective directivity.
- Source match (ep1S and ep2S) describes the return loss of a driving port.
- Load match (ep1L and ep2L) describes the return loss of a terminating port.
- Reflection tracking (et11 and et22) describes the frequency response of a reflect measurement including loss behaviors due to the couplers, transmission lines, converters, and other components.
- Transmission tracking (et12 and et21) is the same as above but for the transmission paths. The tracking terms are not entirely independent and this fact is used in some of the calibration algorithms.
- Isolation (ex12 and ex21) takes into account certain types of internal (non-DUT dependent) leakages that may be present in hardware. It is largely present for legacy reasons and is rarely used in practice since this type of leakage is typically very small in modern VNAs.

2 Port SOLT Calibration [3]:

Calibration procedure consists in measuring 7 different reference standards (2 Opens, 2 Shorts, 2 matches and a Thru) with known reflection and/or transmission values from a TOSM calibration kit. In this paper reference standards are considered to have ideal values as follows

$$\Gamma_{OPEN} = 1, \Gamma_{SHORT} = -1, \Gamma_{MATCH} = 0, S_{THRU} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$



- e00 : Directivity (F)
- e11 : Port-1 Source Match (F)
- e10e01 : Reflection Tracking (F)
- e10e32 : Transmission Tracking (F)
- e30 : Leakage (Crosstalk)(F)
- e22 : Port-2 Load Match (F)

Fig. 21: Forward 12-term error model flow chart

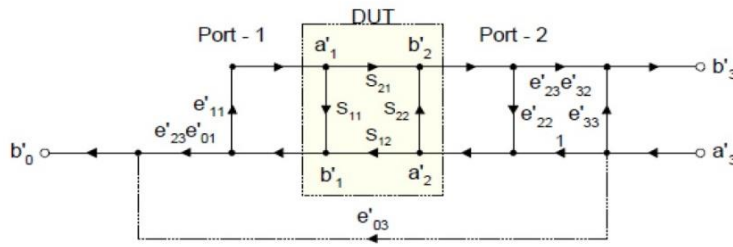


Fig 22: Reverse 12-term error model flow chart

Solving measured S-parameters from figures 20 and 21

$$S_{11M} = \frac{b_0}{a_0} = e_{00} + \frac{e_{10}e_{01} \cdot (S_{11} - e_{22}\Delta_S)}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S} \quad \dots(1)$$

$$S_{21M} = \frac{b_3}{a_0} = e_{30} + \frac{e_{10}e_{32} \cdot S_{21}}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S} \quad \dots(2)$$

$$S_{22M} = \frac{b'_3}{a'_3} = e'_{33} + \frac{e'_{23}e'_{32} \cdot (S_{22} - e'_{11}\Delta_S)}{1 - e'_{11}S_{11} - e'_{22}S_{22} + e'_{11}e'_{22}\Delta_S} \quad \dots(3)$$

$$S_{12M} = \frac{b'_0}{a'_3} = e'_{03} + \frac{e'_{23}e'_{01} \cdot S_{12}}{1 - e'_{11}S_{11} - e'_{22}S_{22} + e'_{11}e'_{22}\Delta_S} \quad \dots(4)$$

where

S_{xxM}: Measured, i.e. uncorrected, S-parameters

S_{xx}: Corrected S-parameters

$$\Delta_S = S_{11}S_{22} - S_{12}S_{21}$$

Port 1 Calibration: By performing Open, short and Match calibration to Port 1 the following forward error terms are calculated from eq. (1)

$$e_{00} = S_{11M}(match_1)$$

$$e_{11} = \frac{S_{11M}(open_1) + S_{11M}(short_1) - 2 \cdot e_{00}}{S_{11M}(open_1) - S_{11M}(short_1)}$$

$$e_{10}e_{01} = \frac{-2 \cdot [S_{11M}(open_1) - e_{00}] \cdot [S_{11M}(short_1) - e_{00}]}{S_{11M}(open_1) - S_{11M}(short_1) - 1 - e'_{11}S_{11} - e'_{22}S_{22} + e'_{11}e'_{22}\Delta_S}$$

$$S_{12M} = \frac{b'_0}{a'_3} = e'_{03} + \frac{e'_{23}e'_{01} \cdot S_{12}}{1 - e'_{11}S_{11} - e'_{22}S_{22} + e'_{11}e'_{22}\Delta_S}$$

Port 2 Calibration: By performing Open, short and Match calibration to Port 2 the following reverse error terms are calculated from eq. (3)

$$e'_{33} = S_{22M}(match_2)$$

$$e'_{11} = \frac{S_{22M}(open_2) + S_{22M}(short_2) - 2 \cdot e'_{33}}{S_{22M}(open_2) - S_{22M}(short_2)}$$

$$e'_{23}e'_{32} = \frac{-2 \cdot [S_{22M}(open_2) - e'_{33}] \cdot [S_{22M}(short_2) - e'_{33}]}{S_{22M}(open_2) - S_{22M}(short_2) - 1 - e'_{11}S_{11} - e'_{22}S_{22} + e'_{11}e'_{22}\Delta_S}$$

Isolation Ports Calibration: Conning Load to port 1 and port 2 is optionally made only when very low transmission parameters must be measured. In most cases this error term is neglected.

$$e_{30} = S_{21M}(\text{match}_{1,2})$$

$$e'_{03} = S_{12M}(\text{match}_{1,2})$$

Calibration between Ports: By Connecting thru standard in-between port 1 and port 2 and Transmission Tracking error terms are calculated from (1), (2), (3) and (4) as follows

$$e_{22} = \frac{S_{11M}(\text{Thru}) - e_{00}}{S_{11M}(\text{Thru}) \cdot e_{11} - \Delta e}$$

$$e_{10}e_{32} = [S_{21M}(\text{Thru}) - e_{30}] \cdot (1 - e_{11}e_{22})$$

$$e'_{11} = \frac{S_{22M}(\text{Thru}) - e'_{33}}{S_{22M}(\text{Thru}) - \Delta e'}$$

$$e'_{23}e'_{32} = [S_{12M}(\text{Thru}) - e'_{03}] \cdot (1 - e'_{33}e'_{11})$$

where

$$\Delta e = e_{00} \cdot e_{11} - e_{01}e_{10}$$

$$\Delta e' = e'_{33} \cdot e'_{22} - e'_{23}e'_{32}$$

Calibration	Reference	Error to be corrected	Description
Port 1	Open	e_{11}	Source Match (F)
	Short	$e_{10}e_{01}$	Reflection Tracking (F)
	Match	e_{00}	Directivity (F)
Port 2	Open	e'_{11}	Source Match (R)
	Short	$e'_{23}e'_{32}$	Reflection Tracking (R)
	Match	e'_{33}	Directivity (R)
Isolation of ports	Match ₁	e_{30}	Crosstalk (F)
	Match ₂	e'_{03}	Crosstalk (R)
Calibration between Ports	Thru	e_{22}	Load Match (F)
		e'_{11}	Load Match (R)
		$e_{10}e_{32}$	Transmission Tracking (F)
		$e'_{23}e'_{01}$	Transmission Tracking (R)

Table: Summary of the 2-port calibration process

Solving equations (1) to (4), corrected S-parameters of the DUT can be expressed as follows

$$S_{11} = \frac{A_{11} \cdot (1 + A_{22} \cdot e'_{22}) - e_{22} \cdot A_{21} \cdot A_{12}}{D}$$

$$S_{21} = \frac{A_{21} \cdot [1 + A_{22} \cdot (e'_{22} - e_{22})]}{D}$$

$$S_{22} = \frac{A_{22} \cdot (1 + A_{11} \cdot e_{11}) - e'_{11} \cdot A_{21} \cdot A_{12}}{D}$$

$$S_{12} = \frac{A_{12} \cdot [1 + A_{11} \cdot (e_{11} - e'_{11})]}{D}$$

where

$$N_{11} = \frac{S_{11M} - e_{00}}{e_{10}e_{01}}$$

$$N_{12} = \frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}$$

$$N_{21} = \frac{S_{21M} - e_{30}}{e_{10}e_{32}}$$

$$N_{22} = \frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}$$

$$D = (1 + A_{11} \cdot e_{11}) \cdot (1 + A_{22} \cdot e'_{22}) - A_{21} \cdot A_{12} \cdot e_{22} \cdot e'_{11}$$

(f) Reference:

1. Introduction to Network Analyzer Measurements Fundamentals and Background-National Instrument
2. Vector Network Analyzer (VNA) Calibration: The Basics, Michael Hiebel- Rohde & Schwarz
3. D. C. DeGroot, K. L. Reed and J. A. Jargon, "Equivalent Circuit Models for Coaxial OSLT Standards," 54th ARFTG Conference Digest, Atlanta, GA, USA, 1999, pp. 1-13. doi: 10.1109/ARFTG.1999.327370
4. Network Analyzer Basics- Agilent
5. Understanding the Fundamental Principles of Vector Network Analysis-Keysight
6. Understanding VNA Calibration- Anritsu
7. Specifying Calibration Standards and Kits for Keysight Vector Network Analyzers-Application Note
8. Network Analyzer Error Models and Calibration Methods, Doug Rytting

(g) Acknowledgement:

- Lab manual prepared by: Md. Aminur Rahman
- Reviewed by: Dr. A.K.M. Ehtesanul Islam

Experiment no: 12
Name of the Experiment: Study on Transmission line matching circuit using vector network analyzer

a) Objective:

1. To understand the theory of impedance matching.
2. To understand the design of impedance matching networks by using analytical method (transmission line theory)
3. To understand the design of impedance matching networks by using graphical method (Smith Chart)

b) Equipments:

1. Vector network analyzer
2. ETEK MSA-2003-01 Module

c) Theory:

Impedance matching is very important with radio and microwave transmission lines. Otherwise, standing waves lead to increased losses and corresponding transmitter malfunction. A line terminated in its characteristic impedance has a standing-wave ratio of unity and transmits a given power without reflection. Also, transmission efficiency is optimum where there is no reflected power.

Matching a transmission line has a special meaning, one differing from that used in circuit theory to indicate equal impedance seen looking both directions from a given terminal pair for maximum power transfer. In circuit theory, maximum power transfer requires the load impedance to be equal to the complex conjugate of the generator. This condition is sometimes referred to as a conjugate matching. In transmission line problems matching means simply terminating the line in its characteristic impedance.

Impedance matching or tuning is important for the following reasons:

1. Maximum power is delivered when the load is matched to the line (assuming the generator is matched), and power loss in the feed line is minimized.
2. Impedance matching sensitive receiver components (antenna, low-noise amplifier, etc.) may improve the signal-to-noise ratio of the system.
3. Impedance matching in a power distribution network (such as an antenna array feed network) may reduce amplitude and phase errors.

Three methods for Impedance matching are:

1. Matching with Lumped Elements (L Networks)
2. Stub Tuning
3. The Quarter-Wave Transformer

The equation of reflection coefficient, load impedance and characteristic impedance are written as

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (1.1)$$

$$\text{Return Loss} = -20 \log |r| \text{ dB} \quad (1.2)$$

The input impedance of a transmission line terminated in a load is given as [For lossy case, $\gamma=\alpha+j\beta$; γ =propagation constant, α =attenuation constant, β =phase constant. For lossless case $\alpha=0$]

$$\begin{aligned}
 Z_{in} &= \frac{V}{I} \Big|_{z=-l} = \frac{V_0^+ e^{-\beta z} + V_0^- e^{-\beta z}}{V_0^+ e^{-\beta z} - V_0^- e^{-\beta z}} \Big|_{z=-l} \\
 &= Z_0 \frac{V_0^+ (e^{j\beta l} + \Gamma e^{-j\beta l})}{V_0^+ (e^{j\beta l} - \Gamma e^{-j\beta l})} = \frac{Z_L + Z_0 j \tan(\beta l)}{Z_0 + Z_L j \tan(\beta l)}
 \end{aligned}
 \tag{1.3}$$

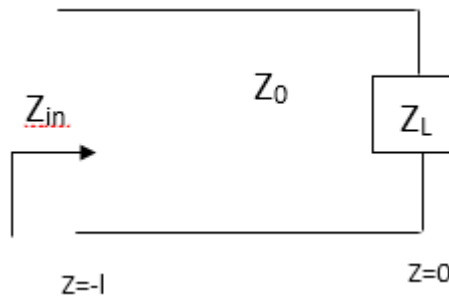


Fig 10-1: input impedance of a transmission line terminated in a load

where Z_0 =The characteristic impedance of transmission line

Z_L =The load impedance

l = the distance to load (Length of transmission line between source and load)

β = the wave number ($2\pi/\lambda$)

Let us consider several special cases from equation (1.3), and discuss about the characteristic of impedance in table1-1.

Table1-1

Sl No	Conditions	Mathematical Relation	Remarks
1.	$l = \lambda / 4$. (Quarter wave transformer)	$Z_{in} = Z_0 \frac{Z_L + Z_0 j \tan[(2\pi/\lambda).(\lambda/4)]}{Z_0 + Z_L j \tan[(2\pi/\lambda).(\lambda/4)]}$ $\Rightarrow Z_0^2 = Z_{in} Z_L$	We can find out a characteristic: if the input impedance Z_{in} and load impedance Z_L are given, we can design a $\lambda / 4$ transmission line with characteristic $\sqrt{Z_{in} Z_L}$ to match Z_{in} and Z_L . Thus the $\lambda / 4$ transmission line is also called as $\lambda / 4$ impedance transformer.
2.	$Z_L = 0$ and $l = \lambda / 4$ (Short circuit condition)	$Z_{in} = jZ_0 \tan(\pi / 2) = \infty$	The $\lambda/4$ short-circuited terminated transmission line can be seen as an open circuit. Therefore, we can use a $\lambda/4$ short-circuited terminated transmission line to substitute the RFC. In implementation, the higher the characteristic impedance of

			transmission line is, the better the result we can obtain.
3.	$Z_L = \infty$ and $l = \lambda/4$ (Open circuit condition)	$Z_{in} = Z_0 \frac{Z_L + Z_0 j \tan[(\pi/2)]}{Z_0 + Z_L j \tan[(\pi/2)]} \Big _{Z_L = \infty}$ $= Z_0 \frac{1}{j \tan(\pi/2)} = 0$	The $\lambda/4$ open-circuited terminated transmission line can be considered as a short circuit. That is, we can use a $\lambda/4$ open-circuited terminated transmission line to substitute the band stop filter
4.	$Z_L = 0$ where $\frac{(n-1)\lambda}{4} \leq l \leq \frac{(2n-1)\lambda}{4}$ $n=1, 2, \dots$	$Z_{in} = -jZ_0 \tan(\beta l)$	A short-circuited terminated transmission line can be seen as an inductive device. Thus, we can use it to substitute a parallel inductive device. Moreover, the trace will move in counter clock-wise on the Smith-Chart
5.	$Z_L = \infty$ where $\frac{(2n-1)\lambda}{4} \leq l \leq \frac{n\lambda}{2}$ $n=1, 2, \dots$	$Z_{in} = -jZ_0 \cot(\beta l)$	An open-circuited terminated transmission line can be seen as a capacitance device. Thus, we can use it to substitute a parallel capacitance device. Moreover, the trace will move in clock-wise on the Smith-Chart.
6.	$Z_L = \infty$ and $l = \lambda/8$	$Z_{in} = -jZ_0$	A $\lambda/8$ open-circuited terminated transmission line can be determined as a capacitance device. Therefore, we can use it to substitute a parallel capacitance device. Moreover, the value of the capacitance is determined by the characteristic impedance of transmission line
7.	$Z_L = \infty$ and $l = 3\lambda/8$	$Z_{in} = jZ_0$	A $3\lambda/8$ open-circuited terminated transmission line can be considered as an inductive device. That is, we can use it to substitute a parallel inductive device, Moreover, the value of the inductance is determined by the characteristic impedance of transmission line.

Stub Matching: This is a method of impedance matching where a small section of short/open circuited transmission line is connected in shunt with main transmission line. The distance l_s or l_o (position of stub) from the load and length l'_s or l'_o (length of stub) are so chosen that reflected

wave produced by shunting impedance of stub is equal and opposite to reflected wave already existing on the line.

Equation related to Single stub match:

For an open-circuited stub $l_o = \frac{\lambda}{2\pi} \tan^{-1}\left(\frac{B_s}{Y_o}\right) = \frac{-1}{2\pi} \tan^{-1}\left(\frac{B}{Y_o}\right)$ (1.4)

For a short-circuited stub $l_s = \frac{-\lambda}{2\pi} \tan^{-1}\left(\frac{Y_o}{B_s}\right) = \frac{1}{2\pi} \tan^{-1}\left(\frac{Y_o}{B}\right)$ (1.5)

Here, B_s = Stub Susceptance
 B = Susceptance
 Y = Admittance

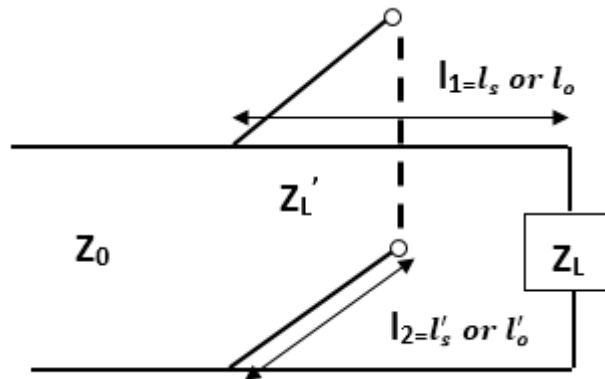


Fig 10-2: Single-stub tuning circuits

d) Procedure:

Case 1: Measurement of $\lambda/4$ impedance transformer matching network

1. Refer to the circuit diagram of $\lambda/4$ impedance transformer in Fig 10-3 or Figure MSA 1-1 of ETEK MSA-2003-01 module.
2. Let the load impedance $Z_L = 150 \Omega$ to be matched to $Z_{in} = 50 \Omega$. Calculate Z_0, λ .
3. Next from the Marker function of the Network Analyzer, mark the frequencies at 2350 MHz, 2400 MHz and 2450 MHz, respectively. Then measure the input return loss (S_{11}) in Smith Chart and S-parameter plot. Finally, record the measured results in graph of table 10-2 and table 10-3 respectively.

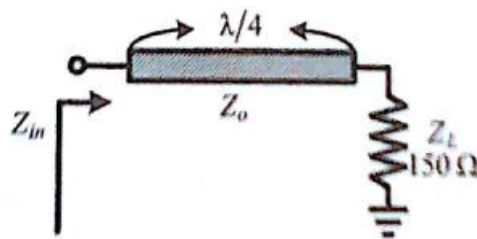


Fig 10-3: $\lambda/4$ impedance-transformer

Case 2: Measurement of single and balanced short stubs matching network

1. Refer to the circuit diagram of single-port short stub in Fig 10-4 or Figure MSA1-2 of ETEK MSA-2003-01 module.
2. Let the load impedance $Z_L = 150 \Omega$ to be matched to $Z_{in} = 50 \Omega$. Calculate l_s and l'_s (distance and stub length).
3. Next, from the Marker function of the Network Analyzer, mark the frequencies at 2350 MHz, 2400 MHz and 2450 MHz, respectively. Then measure the input return loss (S_{11}) in Smith Chart and S-parameter plot. Finally, record the measured results in graph of table 10-2 and table 10-3 respectively.

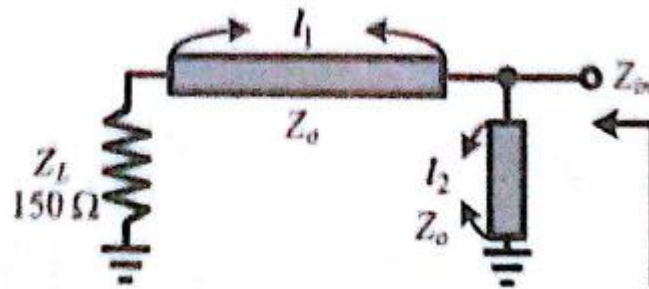


Fig 10-4: Diagram of matching network for single-port short stub.

Case 3: Measurement of single, balanced and radio open stubs matching network

1. Refer to the circuit diagram of single-port short stub in Fig 10-5 or Figure MSA1-2 of ETEK MSA-2003-01 module.
4. Let the load impedance $Z_L = 150 \Omega$ to be matched to $Z_{in} = 50 \Omega$. Calculate l_o and l'_o (distance and stub length).
2. Next, from the Marker function of the Network Analyzer, mark the frequencies at 2350 MHz, 2400 MHz and 2450 MHz, respectively. Then measure the input return loss (S_{11}) in Smith Chart and S-parameter plot. Finally, record the measured results in graph of table 10-2 and table 10-3 2 respectively.

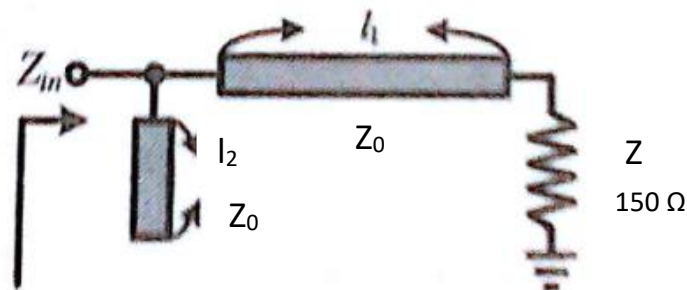


Fig 10-5: Diagram of matching network for single-port open stub

Case 4: Measurement of $\lambda/8$ and $3\lambda/8$ open stabs matching network

1. Refer to the circuit diagram of $\lambda/8$ open stub in Fig 10-6 or Figure MSA-7 of ETEK MSA-2003-01 module.
2. Let the load impedance $Z_L = 150 \Omega$ to be matched to $Z_{in} = 50 \Omega$. Calculate Z_0, λ .
3. Next, from the Marker function of the Network Analyzer, mark the frequencies at 2350 MHz, 2400 MHz and 2450 MHz, respectively. Then measure the input return loss (S_{11}) in Smith Chart and S-parameter plot. Finally, record the measured results in graph of table 10-2 and table 10-3 2 respectively.

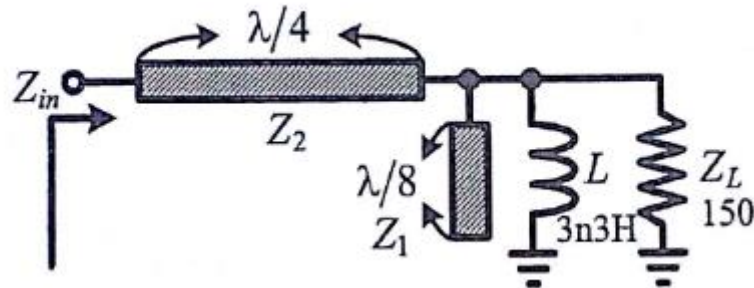


Fig 10-6: Circuit diagram of single-port open-circuited matching network at $\lambda/8$

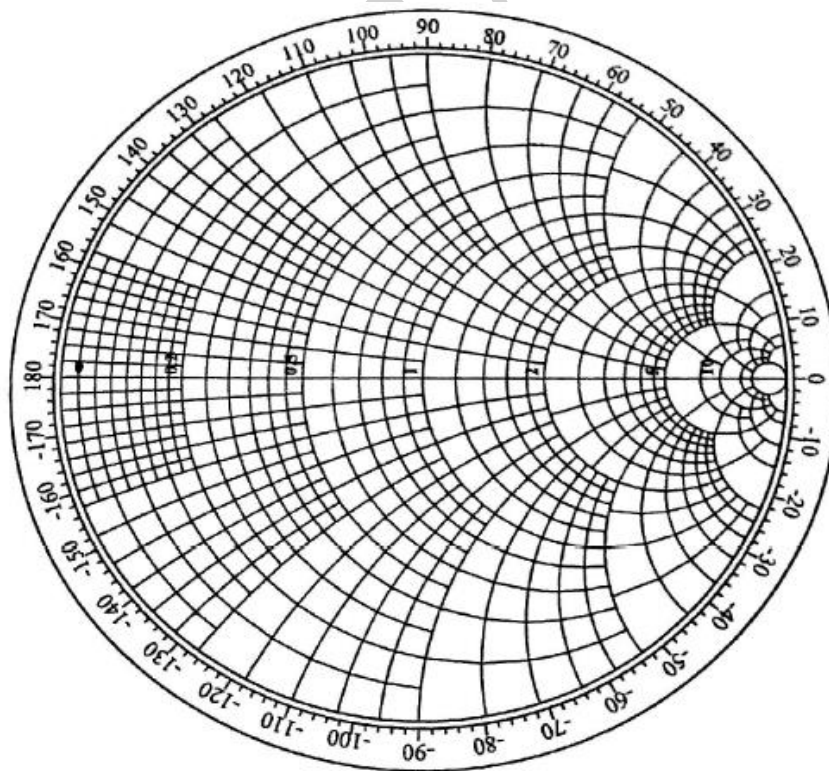


Table 10-2: Measured results of input return loss for different cases (Smith Chart format).

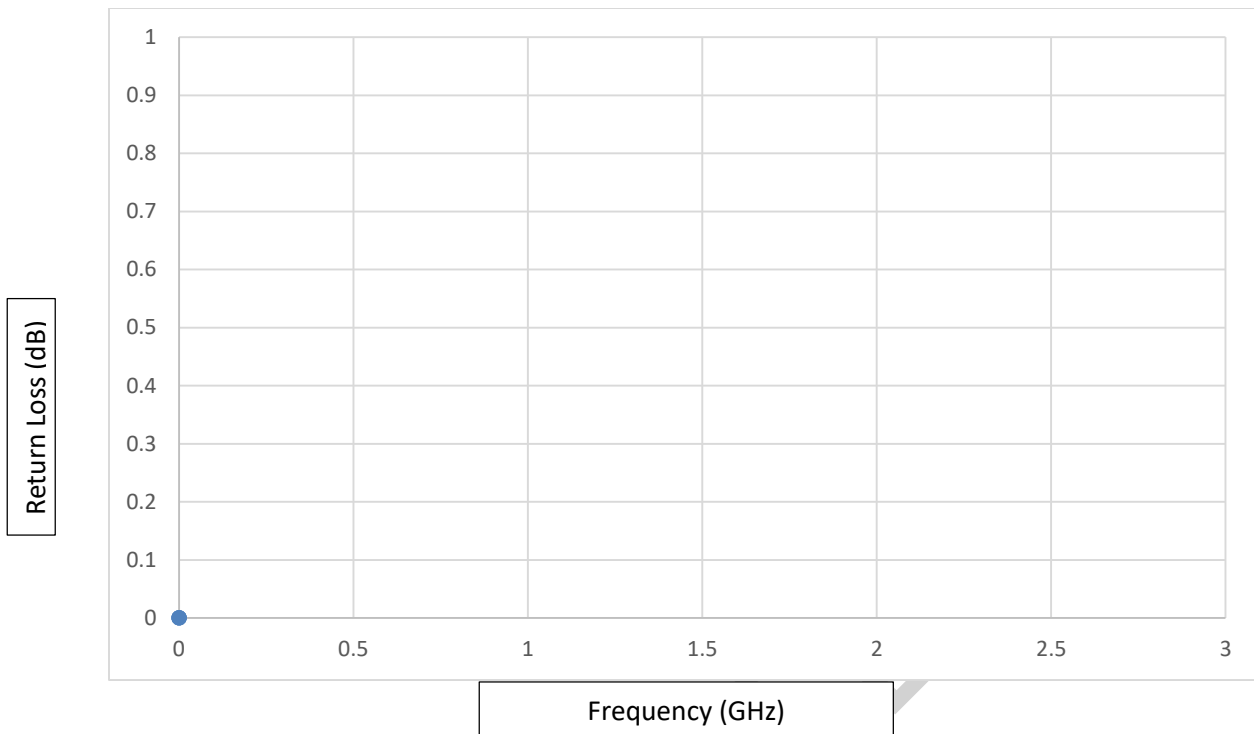


Table 10-3: Measured results of input return loss for different cases (Log Mag format)

e) Report:

1. Discuss and explain different results obtained in the experiment
2. Comment on the effect of varying frequencies in smith chart with marker function of VNA.

(f) Reference:

- 1) Lab manual (Microwave Active Circuit Design of ETEK Technology Co LTD.)
- 2) Electronics communication- S. Gupta
- 3) Microwave Engineering – D. Pozar
- 4) Microwave Devices and Circuits -SAMUEL Y. LIAO

(g) Acknowledgement:

- Lab manual prepared by: Md. Rasheduzzaman Al-Amin
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Experiment no	Reference
1.	1. Lab manual 2. Electronics communication- S. Gupta
2.	1. Lab manual 2. Electronics communication- S. Gupta
3.	1. Lab manual 2. Electronics communication- S. Gupta
4.	1. Lab manual 2. Electronics communication- S. Gupta
5.	1. Lab manual 2. Electronics communication- S. Gupta
6.	1. Corresponding Lab manual (FALCON & AMITECH) 2. Electronics communication- S. Gupta 3. Microwave Engineering- D.M. Pozar
7.	1. Lab manual 2. Electronics communication- S. Gupta 3. Basic Microwave technology and lab manual – Sisodia et. Al 4. Microwave Engineering – D. Pozar
8.	1. Lab manual 2. Electronics communication- S. Gupta

	<ol style="list-style-type: none">3. Basic Microwave technology and lab manual – Sisodia et. Al4. Microwave Engineering – D. Pozar
9.	<ol style="list-style-type: none">1. Lab manual2. Electronics communication- S. Gupta3. Basic Microwave technology and lab manual – Sisodia et. Al4. Microwave Engineering – D. Pozar
10.	<ol style="list-style-type: none">1. Lab manual2. Electronics communication- S. Gupta

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