NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

School of Electrical & Electronic Engineering

EE3001 Engineering Electromagnetics

L3001B

Microwave Circuits

Communications Lab (S2-B4c-17)

Dress Code in the Laboratory

- **Work shirt that covers the upper torso and arms.**
- **Lower body clothing that covers the entire leg.**
- **Closed-toe shoes that cover the top of the foot.**

Laboratory Manual

L3001B: Microwave Circuits

[All students are expected to read through this manual before attending this laboratory session. Complete and submit the worksheet after the laboratory session.]

OBJECTIVES

- To become familiar with the main types of modern microwave circuit functional blocks.
- To determine circuit characteristics by applying the basic knowledge of reflection and transmission coefficients*.
- To become familiar with the swept frequency reflectometer measurement method.

*__Recall the basic theory of reflection and transmission of electromagnetic waves in EE3001__.

N.B. During the course of the laboratory session, you gain an understanding of the theoretical concepts given in this manual, and answer questions in brief, in the space provided.

1. SAFETY RULES & CONNECTOR CARE

In this section, you will learn safety procedures to avoid microwave radiation hazard, safe working practice, and the correct care of expensive microwave connectors.

1.1 Radiation Hazards

Radiation is divided into two categories. *Ionising radiation*, which comprises high speed protons, electrons, atomic nuclei and gamma rays, which cause damage to biological molecules, including DNA. Adverse health effects can range from a greater probability of suffering cancer in future to hair loss and bleeding, which is characteristic of radiation sickness. Although the risk reduces as the radiation level is reduced, there is always some risk even at low levels of exposure.

Non-ionising radiation comprises electromagnetic (EM) waves at radio or microwave frequency. The only known mechanism for damage by EM waves is by heating of the biological tissues which are conductive and therefore absorb the wave energy. As the power is increased, the damage, which first appears, is burning of the retina of the eye and damage to sexual organs, causing sterility. At very high power, the effects are worse and may cause burning of flesh to several centimetre depth inside the body. Fortunately these effects only appear above a certain threshold, with few detectable biological effects at low powers (e.g., from cell phones). To date, while there is no definitive increase in the number of cancers in those who work with EM waves, exposure to microwaves is classified as 'possibly carcinogenic'.

1.2 Safety Procedures

When you work with radio-frequency (RF) circuits, always use the following safety rules. Start to use the rules today, even though you will only be using low power in this experiment.

- **Turn off the power before opening a transmission line or circuit housing**
  — you don't want to be hit by 100kW or more of power from an antenna feeder.
- **Never look down a transmission line/waveguide or hold any powered up circuit or transmission line against your body**
  — if you forget to turn off the power, or someone turns it on by mistake, tissue damage can occur. The retina of the eye and genital organs are especially sensitive.

- **When working near live equipment, use a radiation meter to ensure that the signal strength** is below the legal safety limit for the country you are in, or if there is no law, then below 20 mW/cm^2 or less.

- **Do not operate RF power sources into a mismatched load**
  — the power reflected from the load returns to the source where it may cause electrical breakdown, overheating, or at very high power, a fire.

- **Make sure nuts and bolts which join transmission lines together are tightened to an appropriate level**.

1.3 Connector Care

You must handle the RF components/devices carefully and strictly follow the procedure of connecting and disconnecting SMA connectors; otherwise you may damage the expensive and precision modules.

- **To align and join the male and female SMA connectors**
  - Always keep both male and female connectors in a straight line; otherwise you will damage the inner conductors and the threading of the connectors.
  - Use only your fingers to turn the lock nut until gentle pressure cannot advance it further.

- **To separate the male and female connectors:**
  - Use your fingers to turn the lock nut until the connectors are separate.

N.B. When you tighten or loosen the lock nuts never hold up the modules to which SMA connectors are attached and turn.

- **Always keep the modules on the bench and never hold them up;** otherwise you will damage the connectors of the modules.

1.4 Power Supply

- **Never exceed the power supply outputs beyond ±15 V**; otherwise you are likely to damage the voltage controlled oscillator (VCO) module.

Question 1. How does radiation from microwave circuits cause health hazards? What is the safety limit for microwave radiation?

Ans:

Question 2. When connecting and disconnecting high precision SMA connectors what is the technique that you should implement?

Ans:

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2. INTRODUCTION TO MODERN MICROWAVE CIRCUITS

2.1 Microstrip Transmission Line

For high power radio transmitter applications, vacuum tubes and metallic waveguides are still the only technology available. However, since the invention of the microstrip line in the 1960's, low and medium power applications have increasingly used a variety of planar transmission line technologies, leading today to the use of transmission lines on-chip in the monolithic microwave integrated circuit (MMIC). In this experiment, the coaxial and microstrip transmission lines are used. The coaxial line is used for the interconnection of the circuit functional blocks and the microstrip line is used for the working part of the components.

The two-wire transmission line (Figure 1) comprises two signal conductors. The potential difference between the conductors is in the form of a wave, which travels along the two wires. A corresponding signal current flows in each of the two conductors, as shown in Fig. 1.

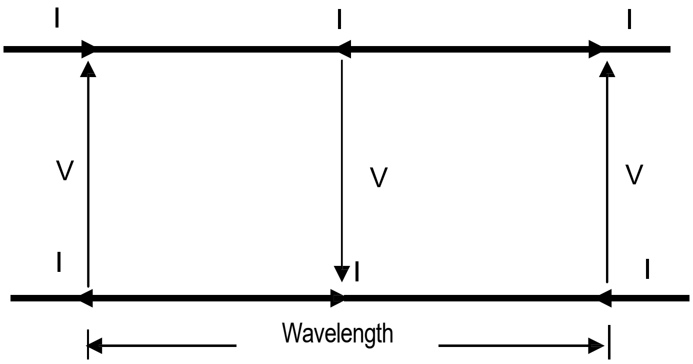


Figure 1. Two-wire transmission line

Any transmission line, which comprises two conductors insulated from each other, can be represented by this model, for example, a coaxial transmission line which has an inner and an outer conductor. The terminal pair of the two conductors is called a *port,* in microwave circuit nomenclature.

The microstrip line (Figure 2) can also be modelled to a good accuracy by the two-wire transmission line. It is commonly found on printed circuit boards, and comprises a dielectric sheet with two conductors, namely a metal (usually copper) strip on the top surface, and a ground plane on the bottom surface.

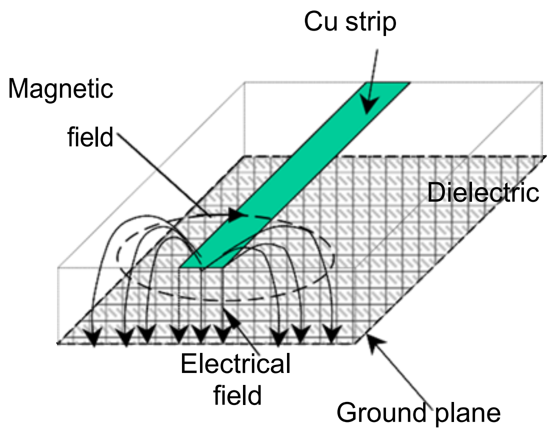


Figure 2. Microstrip transmission line structure and em fields

At low frequencies, a low-cost fiber-glass dielectric (e.g. FR4) works well, but at higher frequencies, one of several available special materials, designed to have low loss, must be used. As shown in Figure 1, when a wave of current flows in the top strip, an equal and opposite current wave flows in the ground plane.

2.2 Microstrip Circuit Components

In this experiment, you will be using various circuit components which are fabricated using microstrip technology. Each circuit component has one or more input and output ports as shown in Figure 3.

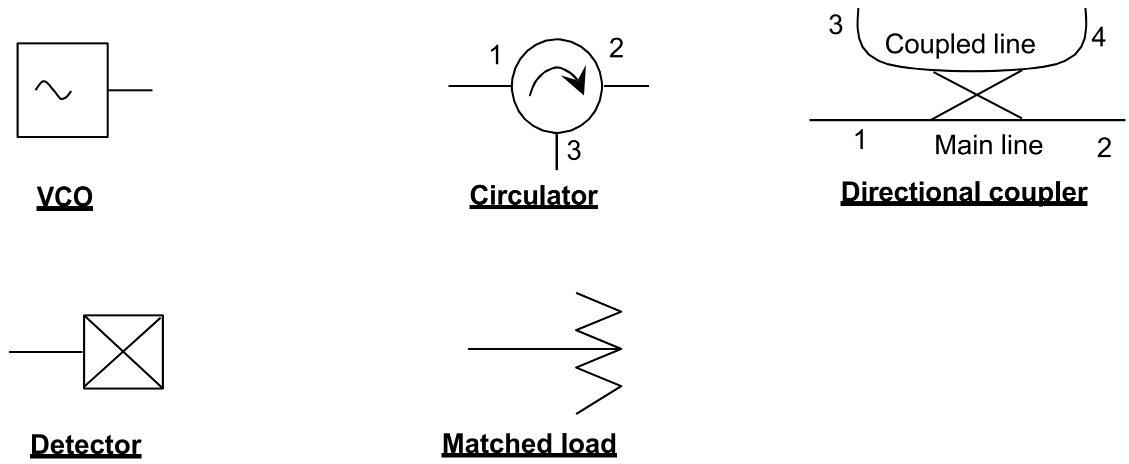


Figure 3. Circuit symbols of microwave components

Voltage Controlled Oscillator (VCO)

The VCO uses a microwave-transistor circuit to produce a sine wave output at a frequency which can be varied by means of a dc tuning voltage input. The output power is about 5mW. Internal amplitude modulation by a square wave can be selected by a switch on the housing of the VCO. In this experiment, the tuning voltage is a triangular waveform which causes the VCO output frequency to sweep across a band of frequencies. **Remember to operate the VCO only into a matched load**.

Circulator (CIRC)

The circulator uses a ferrite disc which is placed in a static magnetic field to make the transmission coefficient between adjacent ports in the direction of the arrow high, and the transmission coefficient against the direction of the arrow low. It is used in series with a signal source to divert any power reflected from the load safely away from the source into a matched load. This prevents overheating of the source and also prevents the frequency of the source being “pulled” by the effect of the mismatch.

Directional Coupler (DC)

Directional coupler allows a certain portion (sample) of the microwave power to transmit through coupled ports. The directional coupler comprises two parallel transmission lines. The proximity of the lines allows coupling between them through the magnetic field such that the wave travelling on the main line induces a proportionate wave on the coupled line. A fraction of the forward wave on the main line appears at one port of the coupled line and a fraction of the reverse wave on the main line appears at the other port of the coupled line. The directional coupler can thus be used to separate the forward and reverse waves without the need for complicated standing wave measurements.

The properties of a directional coupler may be summarized as follows.

With *matched terminations* on all the output ports:

(1) a portion of the wave travelling from port 1 to port 2 is coupled to port 3 (coupled port), but not to port 4 (isolated port);

(2) similarly due to the symmetry, a portion of the wave traveling from port 2 to port 1 is coupled to port 4, but not port 3;

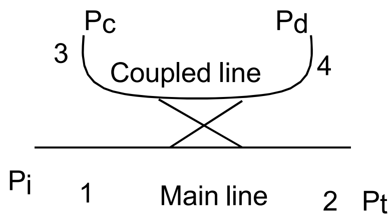
(3) the performance of a directional coupler is usually described in terms of its *insertion loss*, *coupling*, *directivity* and *isolation*, which are defined in the following manner:

Insertion loss (dB) = $10 \log_{10} (P_i/P_t)$

Coupling (dB) = $10 \log_{10} (P_i/P_c)$

Directivity (dB) = $10 \log_{10} (P_c/P_d)$

Isolation (dB) = $10 \log_{10} (P_i/P_d)$



where P_i is the incident power at the input port (1), P_t is the transmitted power to the through port (2), P_c is the coupled power at port (3), and P_d is the power out of the isolated port (4).

Detector

The detector uses a microwave diode rectifier and a low-pass filter, usually comprising the diode's parasitic capacitance, to convert wave power to a DC output voltage. Detectors having dc output voltage directly proportional to the input RF power are called *square law detector* since the output voltage is proportional to the input voltage squared. In practice, such a relationship applies only for a certain range of input power. The detector is used as the measuring sensor for wave power. Students must use the *Crystal Detector Calibration chart* to find the input power vs output voltage characteristics of the detector.

Attenuator

The attenuator reduces the signal amplitude, i.e. has a magnitude of transmission coefficient less than one, whilst remaining matched at input and output ports.

Matched Load (ML)

The matched load terminates a transmission line with a zero reflection coefficient.

Question 3. Identify the modules provided in the microwave trainer kit MST532 and write appropriate letters beside the symbols in Figure 3.

Ans:

3. MEASUREMENT TECHNIQUE

The detector is used as the sensor to measure the incident wave power incident on it. This gives information about the wave amplitude only, not its phase. In this experiment we will be concerned with the magnitude of reflection and transmission coefficients only, i.e. we will be measuring power reflection coefficient and power transmission coefficient.

This experiment uses the **insertion** or **calibration** method of measuring various circuit components. In this method, a measurement is first taken using a device, whose transmission or reflection coefficient is accurately known. For example, for transmission, the absence of any inserted device between the power source and the detector gives a transmission coefficient of +1. For reflection, it is very easy to make a short circuit whose voltage reflection coefficient is almost exactly −1, i.e., a power reflection coefficient of +1. This first measurement is called a calibration measurement.

A second measurement is then made with the unknown device inserted in the circuit. The ratio of the two results, can be shown to be the ratio of the unknown to the known transmission or reflection coefficient. This statement will be justified by the theory that is given in detail for each part of the experimental procedure below.

During the experiment, you can analyze qualitatively or quantitatively what is happening in the circuit. A good way to start is to think where the wave from the source goes. Where is the wave transmitted to? Where is it reflected from? Where does it go after that?

4. EXPERIMENTS

4.1 Set Up to Generate Microwave Swept Frequency signal

1. Before connecting anything, set the output voltage of both DC supply outputs to 15V. Set the output of the function generator to a ±10V triangle wave. *Combining 15V DC output with the ±10V triangle wave produces a varying DC output from +5V to +25V. This varying output voltage is the tuning voltage of the VCO. The tuning voltage produces a swept frequency signal.*

2. Important: switch off the power supplies whilst connecting up.

3. Connect up the circuit. Refer to Figure 4 for the DC connections. Note that the input to the **WHITE** socket of the VCO is a +5V to +25V variable tuning voltage. This is obtained using the function generator in series with a 15V DC supply.

N.B. #1 power supply must remain floating from ground in order not to short circuit the function generator output. It should not be grounded. Use the oscilloscope to confirm that your connections are correct.

4. You may connect the ground (black) terminal of the oscilloscope X input to the (chassis) ground of power supply # 1 instead of keeping it floating. It is a good practice not to keep a probe of testing equipment unconnected.

5. Confirm that your connections are correct before switching on the power.

For all parts of the experiment, ensure proper care in the use of the equipment keeping the set up as shown in Figure 4.

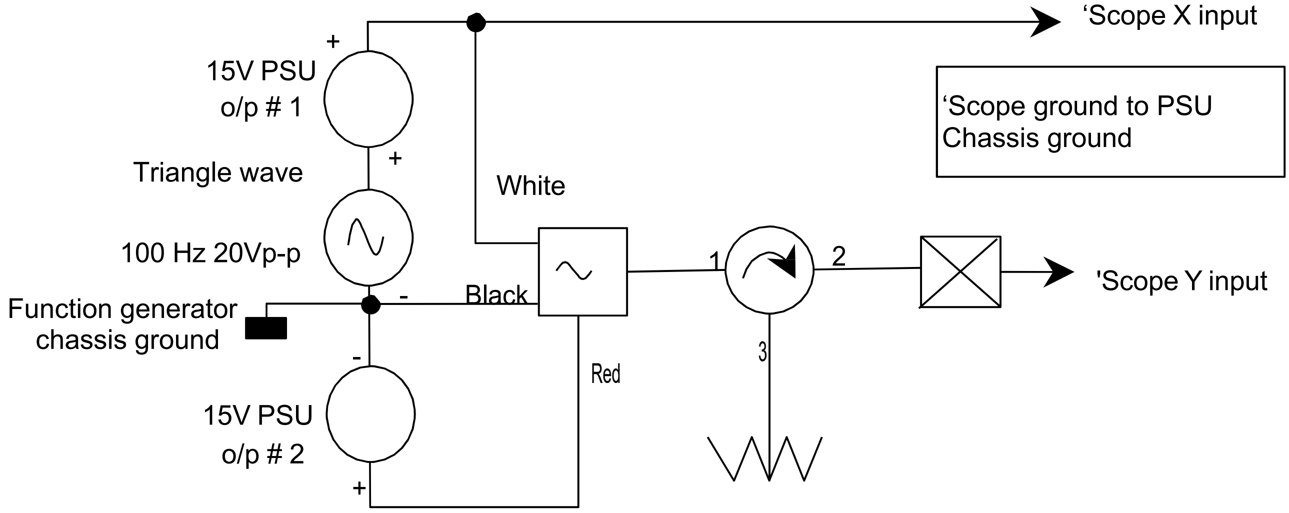


Figure 4. VCO and detector connections

N.B. A reference chart is available on the lab bench to help you expedite the connection stage.

<u>4.2 Calibration of Microwave Swept Frequency signal and Detector Output Power</u>

Look at the X (Channel 1) and Y (Channel 2) signals separately on the oscilloscope. Setting for the channels should be DC. Use your oscilloscope in the X-Y mode. Adjust the settings so that you can read off the VCO tuning voltage from the X axis. From this voltage, the microwave frequency can then be read from the *VCO calibration chart*. Record the tuning voltage vs microwave frequency for every 5V step from +5V to +25V.

<u>Attention</u>: All the following experiment is conducted at the five discrete frequency points in correspondence with the tuning voltages of +5, +10, +15, +20, +25V**!**

Your oscilloscope Y axis voltage may be assumed to be proportional to the VCO output power (see the description of the detector in section 3.2.4). Note that the detector output has negative-polarity, due to the sense of connection of its rectifier diode. You need to use the *Crystal Detector Calibration Chart* to convert detector output DC voltage readings from the oscilloscope to microwave power readings.

<u>4.3 Experiment with Directional Coupler</u>

Transmission Measurement

Connect up the calibration set up for transmission measurement (Figure 4). Measure the detector output voltage as a function of microwave frequency in GHz. Convert the detector output voltage to power.

Insert the directional coupler with attached matched loads as in Figure 5. The matched loads prevent the result being affected by waves reflected back from the unused ports. Obtain a second set of readings of the detector output voltage. Convert the detector output voltage to power.

From these two sets of readings, obtain a table of values of T_p, the *power transmission coefficient*, of the directional coupler from port 1 to port 2 as follows.

In the circuit of Figure 4, the detector output is:

P_{in1} = (source o/p power) × (circulator attenuation) × (detector sensitivity)

In the circuit of Figure 5, the detector output is:

P_{out2} = (source o/p power) × (circulator attenuation) × T_p × (detector sensitivity)

$\therefore T_p = P_{out2}/P_{in1}$ (convert the reading into dB using $10\log_{10}T_p$)

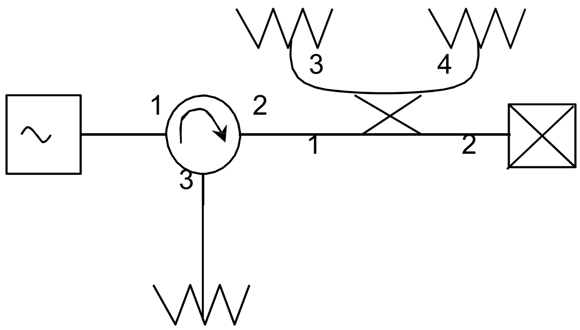


Figure 5. Insertion measurement of directional coupler from port 1 to port 2

Question 4. Given your value of T_p, describe where the wave energy in the directional coupler circuit is going besides port 2?

Ans:

Interchange the detector and the matched load as shown in the left-hand diagram of Figure 6. This enables you to find the power transmission coefficient of the directional coupler from port 1 to port 3. Do this at all the frequency points corresponding to the five discrete tuning voltages.

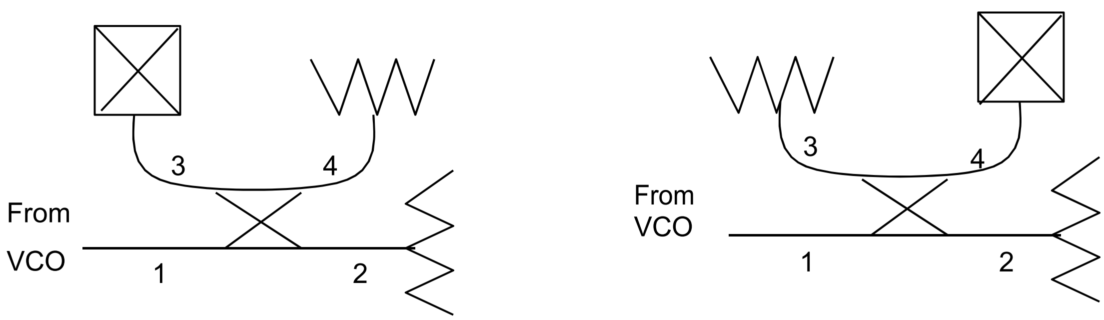


Figure 6. Directional coupler used to measure power

Use the right-hand diagram of Figure 6 to find the power transmission coefficient of the directional coupler from port 1 to port 4, at all five frequency points.

In Figure 6, there will be two waves travelling along the transmission line, between the VCO and the load on port 2: the **FORWARD** wave in the direction from the VCO to the load, and the **REVERSE** wave reflected back from any unmatched load.

Question 5. Which setup in Figure 6 should be used to measure the power in the **FORWARD** wave?
Ans:

Question 6. Record the average values (averaged over all the five frequency points) of *insertion loss*, *coupling*, *directivity* and *isolation* (in dB) of the coupler with reference to port 1.

Ans:

4.4 Experiment with Unknown Loads

Reflection Measurement

In this section, the directional coupler will be used to measure the wave reflected from the device under test. A short circuit (S/C) will be used as a device with known reflection coefficient for **calibration**. The calibration circuit is shown in Figure 7. Choose the connection of the matched load and detector from Figure 6, so as to measure the power of the **REVERSE** wave reflected from the short circuit, as a function of frequency.

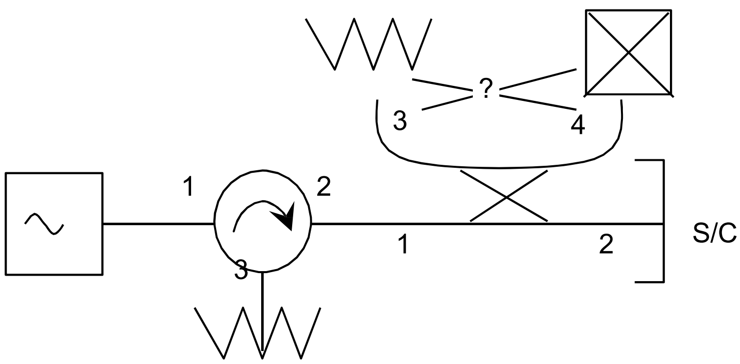


Figure 7. Calibration measurements with short circuit (S/C).

Take the power readings with the short circuit. Obtain a set of readings of the detector output voltage. Convert the detector output voltage to power. These power readings will be the calibration data of this experiment.

The measurement circuit for the next part is shown in Figure 8. The device under test is an unknown one-port circuit connected internally to port A of device ZT. Unused ports of ZT may be left open. Obtain a second set of readings of the detector output voltage. Convert the detector output voltage to power.

From these two sets of readings, obtain the value of Γ_p, the *power reflection coefficient* of ZT, as follows. In the circuit of Figure 7, the detector output is:

P_{inA} = (source o/p power) X (attenuation from source to s/c) X {s/c power reflection coefficient (value = 1)} X (coupling from main to coupled line of coupler) X (detector sensitivity)

In the circuit of Figure 8, the detector output, which is reflected from the unmatched (also unknown here) load, is:

P_{refleA} = (source o/p power) x (attenuation from source to detector) $\times$ Γp X (coupling from main to coupled line of coupler) X (detector sensitivity)

$\therefore \quad \Gamma p = P_{refleA}/P_{inA}$.

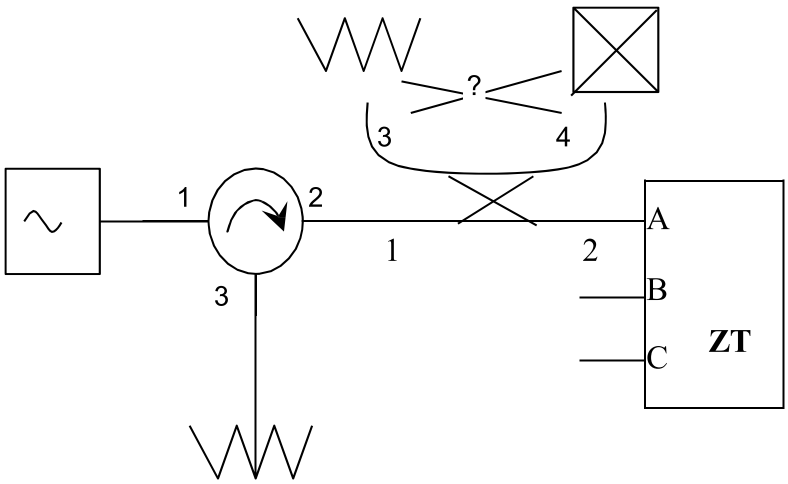


Figure 8. Reflection measurement of device ZT

<u>Question 7.</u> Given that the device ZT comprises a resistor with a pure resistance of $ZT=RT$ and the characteristic impedance of the microstrip line is $Z_0=50\Omega$, what is the value of the resistor at port A?

Ans:

Hint: The voltage reflection coefficient is: $\Gamma = \dfrac{RT-Z_0}{RT+Z_0}$ and $\Gamma p = \Gamma^2$.

Continue to discover the unknown loads at ports B and C.

<u>Question 8.</u> What are the average values of impedances at ports B and C?

Ans:

4.5 Experiment with Filter

Simultaneous measurements of reflection and transmission coefficients

Use the circuits of Figure 9 to measure the power reflection coefficient and power transmission coefficient of the unknown device LPF.

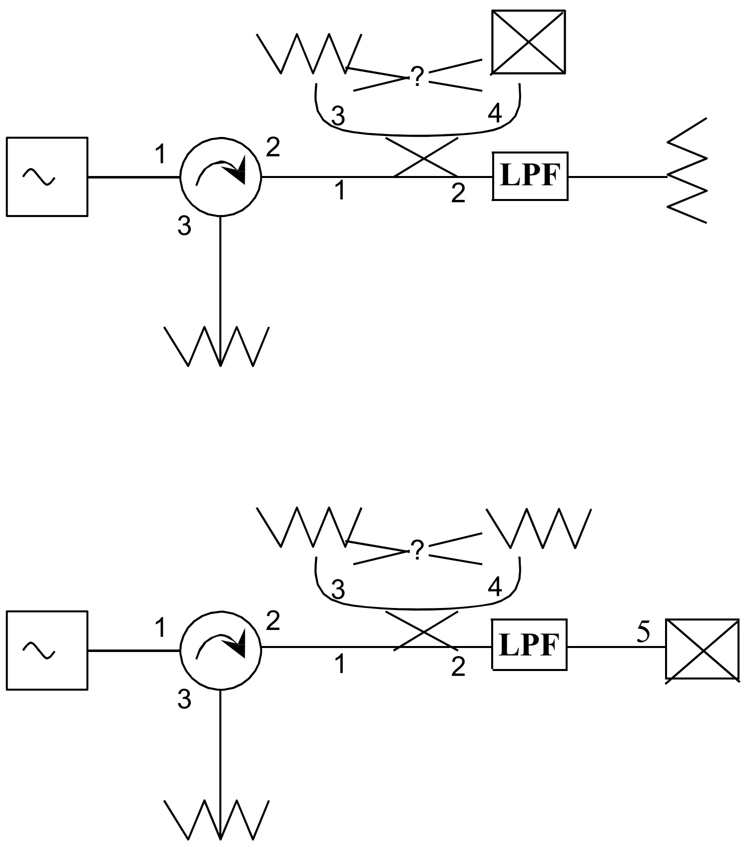


Figure 9. Measurement of reflection and transmission coefficients

Question 9. Identify the circuit function of the device LPF.

Ans:

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Question 10. At what frequency does its power transmission coefficient fall by 3 dB wrt to the maximum value?
Ans:

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Worksheet (L3001B Microwave Circuits)

Student's Name:______________________________Group No.:__________Subgroup No.________(A/B)

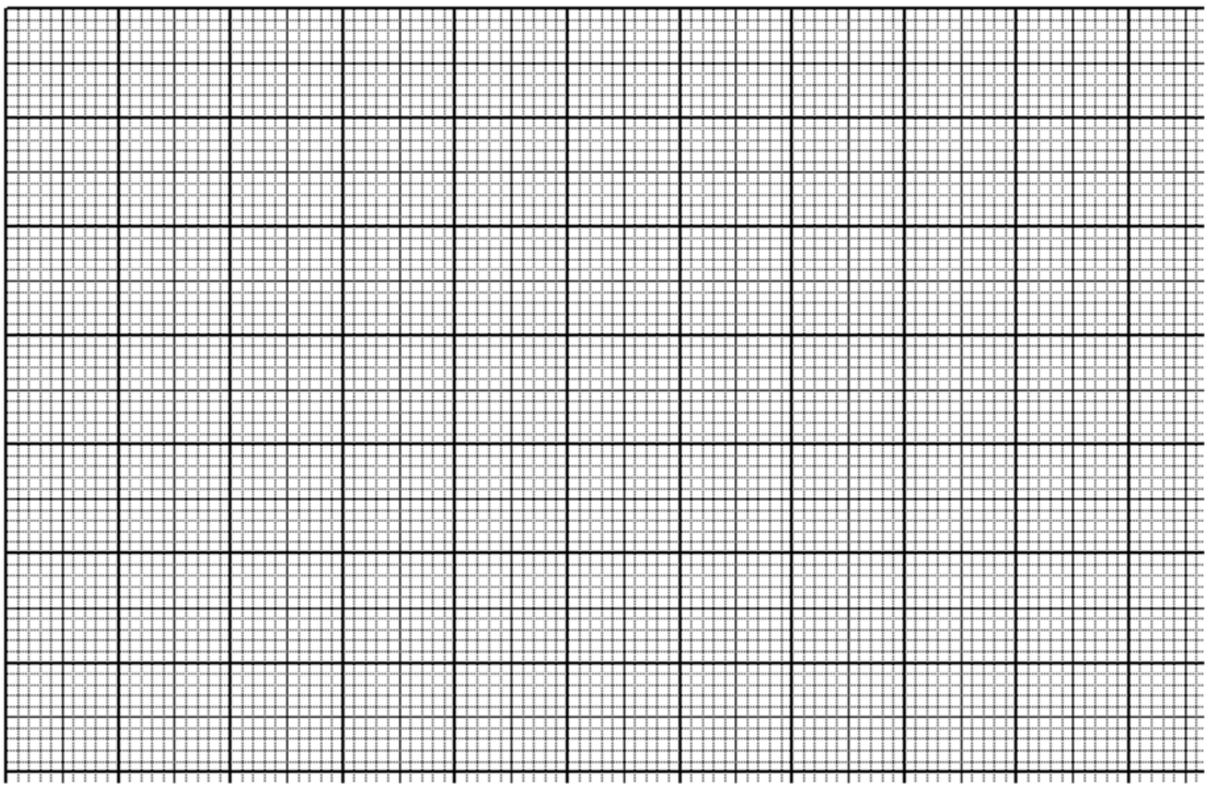
Measurement Data:

Tuning Voltage (V)		5	10	15	20	25
Experiment 4.2:Calibration of Microwave Swept Frequencies and Detector Output Power						
Frequency (GHz)						
P1	Detector Voltage					
	Power					
Experiment 4.3: Directional Coupler						
P2	Detector Voltage					
	Power					
P3	Detector Voltage					
	Power					
P4	Detector Voltage					
	Power					
Experiment 4.4: Unknown Loads						
P4SC (short-circuit)	Detector Voltage					
	Power					
P4A	Detector Voltage					
	Power					
P4B (optional)	Detector Voltage					
	Power					
P4C (optional)	Detector Voltage					
	Power					
Experiment 4.5: Low Pass Filter						
P4LPF	Detector Voltage					
	Power					
P5LPF	Detector Voltage					
	Power					

Parameter Calculations:

Tuning Voltage (V)	5	10	15	20	25	**Average**
Experiment 4.3: Directional Coupler						
Insertion Loss (dB)						
Coupling (dB)						
Directivity (dB)						
Isolation (dB)						
Experiment 4.4 Unknown Load A						
Γp						
RT (in ohms)						
Experiment 4.5: Low Pass Filter						
Γp						**NA**
Tp						**NA**
10 $\log_{10}(Tp)$ in dB						**NA**

Frequency Response of the Low Pass Filter (LPF)



Frequency (GHz)

Your answers to questions in manual

Question 1. How does radiation from microwave circuits cause health hazards? What is the safety limit for microwave radiation?

Ans:

Question 2. When connecting and disconnecting high precision SMA connectors what is the technique that you should implement?

Ans:

Question 3. Identify the modules provided in the microwave trainer kit MST532 and write appropriate letters beside the symbols in Figure 3. (You may use a rough sketch if needed.)

Ans:

Question 4. Given your value of T_p, describe where the wave energy in the directional coupler circuit is going besides port 2?

Ans:

Question 5. Which setup in Figure 6 should be used to measure the power in the **FORWARD** wave?
Ans:

Question 6. Record the average values (averaged over all the five frequency points) of *insertion loss*, *coupling*, *directivity* and *isolation* (in dB) of the coupler with reference to port 1.

Ans:

Question 7. Given that the device ZT comprises a resistor with a pure resistance of *ZT*=*RT* and the characteristic impedance of the microstrip line is Z_0=50Ω, what is the value of the resistor at port A?

Ans:

Question 8. What are the average values of impedances at ports B and C?

Ans:

Question 9. Identify the circuit function of the device LPF.

Ans:

Question 10. At what frequency does its power transmission coefficient fall by 3 dB wrt to the maximum value?

Ans: