

## Part I

# Network Analyzer and Network Analysis

## 1 Objectives

Upon completion of the lab experiment , the student will become familiar with the following topics:

1. Get acquainted with the major elements of the Network Analyzer.
2. Using the Network Analyzer to characterize two port passive elements, such as filters, coaxial cable etc.
3. Understand the meaning of S parameter measurement using a Network Analyzer.
4. Get familiar with the various *Reflection* and *Transmission* parameters such as return loss, reflection coefficient, time delay, and group delay.
5. Understand the basic properties of passive networks, such as lossless, reciprocal etc.
6. Understand the concept of various calibration of the Network Analyzer.

## 2 Prelab Exercise

1. Define the following parameters: return loss, lossless network, unitary matrix, delay, phase delay, group delay.
2. An electromagnetic wave  $s(t) = 2\pi 10^9 t$  pass through 10m coaxial cable, the velocity of the electromagnetic wave is  $2/3c$ ,
  - (a) Find the dielectric constant of the coaxial cable.
  - (b) Calculate the time delay of the cable.

(c) Calculate the phase delay of the cable..

3. Two set of measurement were taken, at frequencies  $f_1$  and  $f_2$ , can you decide if either is dispersive?

Frequency	$ H(f) $ (dB)	$\angle H(f)$ (deg)	Frequency	$ H(f) $ (dB)	$\angle H(f)$ (deg)
$f_1$	0	10	$f_2$	0	10
$2f_1$	0	40	$2f_2$	0	40
$3f_1$	0	70	$3f_2$	0	100
$4f_1$	0	100	$4f_2$	0	190

1. The measurement results of 4 ports network, directional coupler is given by the scattering matrix,

$$[S] = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}j & 0 \\ \frac{1}{\sqrt{2}} & 0 & 0 & \frac{1}{\sqrt{2}}j \\ \frac{1}{\sqrt{2}}j & 0 & 0 & \frac{1}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}}j & \frac{1}{\sqrt{2}} & 0 \end{pmatrix}$$

determine whether the network is matched, reciprocal, and lossless?

## 2.1 References

- [1] D.M. Pozar, "Microwave engineering", 3rd edition, 2005 John-Wiley&Sons.

# 3 Background Theory

## 3.1 Transmission Line Summary

Transmission line theory apply, when the dimension of the line is in the same order of magnitude as the wavelength transmitted through. In this case if the load impedance  $Z_L \neq Z_0$ , part of the incident wave is reflected back to

the source. The amount of reflection is defined by the quantity  $\Gamma$

$$\Gamma = \frac{V_{REFLECT}}{V_{INCID}} = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (1)$$

$$-1 < \Gamma < 1 \quad \rho = |\Gamma|$$

$$0 < \rho < 1$$

$$Z_0 = 50\Omega \quad (2)$$

$$Z_L = 25\Omega \quad (3)$$

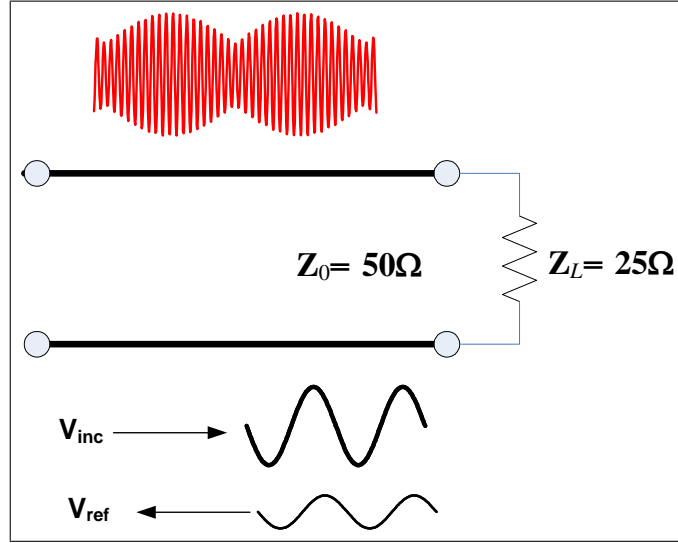


Fig. 1 Transmission line, having characteristic impedance of  $50\Omega$ , terminated with  $25\Omega$

In our application we need to deal with wide dynamic value of reflection coefficient, therefore we define a new logarithmic name of reflection coefficient, which is called Return loss, and defined by

$$Return Loss (dB) \equiv 20 \log \rho \quad (4)$$

Reflection coefficient  $\Gamma$  has complex value, while  $Z_L$  or  $Z_0$  have complex value. Another important reflection quantity is Standing Wave Ratio (SWR), which related to reflection coefficient magnitude by

$$SWR = \frac{1 + \rho}{1 - \rho} \quad (5)$$

$$1 < SWR < \infty$$

### 3.2 Propagation Constant

Propagation constant is a complex quantity, which describe the effect of the transmission line, on the propagate wave. The linear effects describe by the real part, the attenuation  $\alpha$  (*neper/meter*), and imaginary part  $\beta$  (*radian/meter*), phase constant, or wave number and defined by

$$\begin{aligned}\gamma &= \alpha + j\beta \\ \beta &= \frac{2\pi}{\lambda}\end{aligned}\tag{6}$$

### 3.3 Network Analyzer

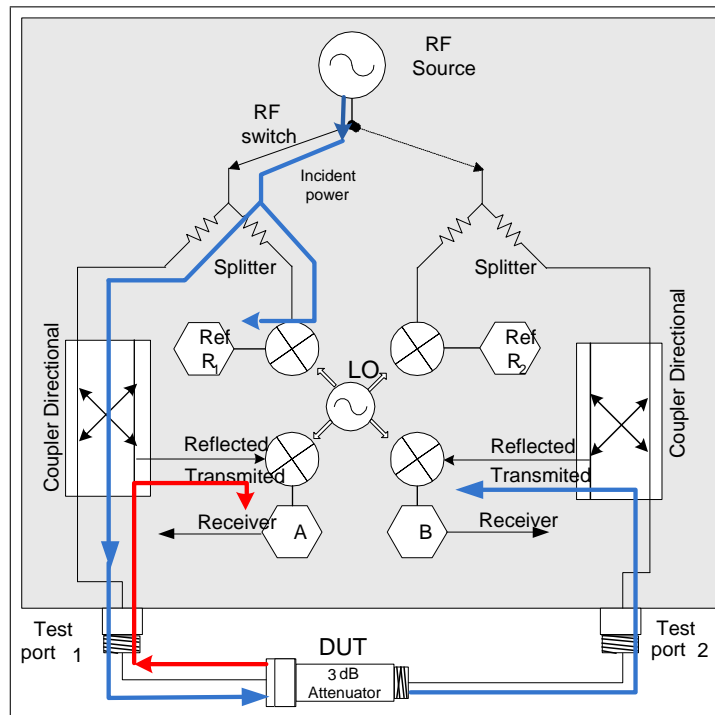


Fig. 2 Major elements of Network Analyzer

### 3.4 Signal Source

The signal source supplies the stimulus for our stimulus-response test system. We can either sweep the frequency of the source or sweep its power

level. Modern source are synthesized sources, providing excellent frequency resolution and stability.

### 3.4.1 Signal Separation Devices- Splitter and Directional Coupler.

The next major area is the signal separation block. The hardware used for this function is generally called the “test set”. There are two functions that our

signal-separation hardware must provide. The first is to measure a portion of the incident signal to provide a reference for ratioing. This can be done with splitters or directional couplers. Splitters are usually resistive. They are non-directional devices and can be very broadband. The trade-off is that they usually have 6 dB or more of loss in each arm. Directional couplers have very low insertion loss (through the main arm) and good isolation and directivity.

The second function of the signal splitting hardware is to separate the incident (forward) and reflected (reverse) traveling waves at the input of our DUT.

### 3.4.2 Receiver

The receiver provides the means of converting and detecting the RF or microwave signals to a lower IF. The tuned receivers provide a narrowband-pass Intermediate-Frequency (*IF*) filter to reject spurious signals and minimized the noise floor of the receiver. The vector measurement systems have the high dynamic range, and immunity to harmonic and spurious responses, they can measure phase relationships of input signals and provide the ability to make complex calibrations that lead to more accurate measurements.

## 4 Input Impedance $Z_{in}$ and Characteristic Impedance $Z_0$

According to the transmission line theory input impedance of a lossless transmission line terminated by load  $Z_L$ , expressed by

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l} \quad (7)$$

where  $Z_0$  is characteristic impedance and  $l$  is the line length.

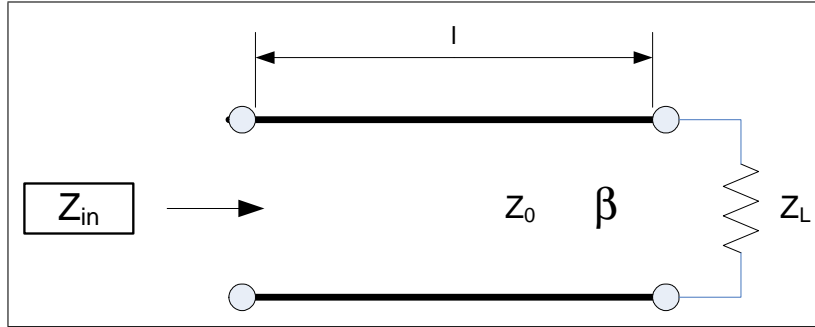


Fig-3 Input impedance of transmission line with arbitrary load  $Z_L$ .

If  $Z_L = 0$  or  $Z_L = \infty$  equation [7] reduce to

$$Z_{in(sc)} = jZ_0 \tan \beta l \quad (8)$$

$$Z_{in(oc)} = \frac{Z_0}{j} \cot \beta l$$

using equation [8] we may rewrite

$$Z_0 = \sqrt{Z_{in(sc)} Z_{in(oc)}} \quad (9)$$

The idea of equation [9] is a useful way to measure characteristic impedance, of DUT, by measuring  $Z_{in(sc)}$  and  $Z_{in(oc)}$  of the DUT.

## 5 The Definition of S-Parameter

Scatter Parameters, also called S-parameters. Like the H,Y,Z or ABCD parameter, they describe the performance of linear n-ports device completely. They relate to the traveling waves that are scattered or reflected when a network is inserted into a transmission line of a certain characteristic impedance  $Z_L$ .

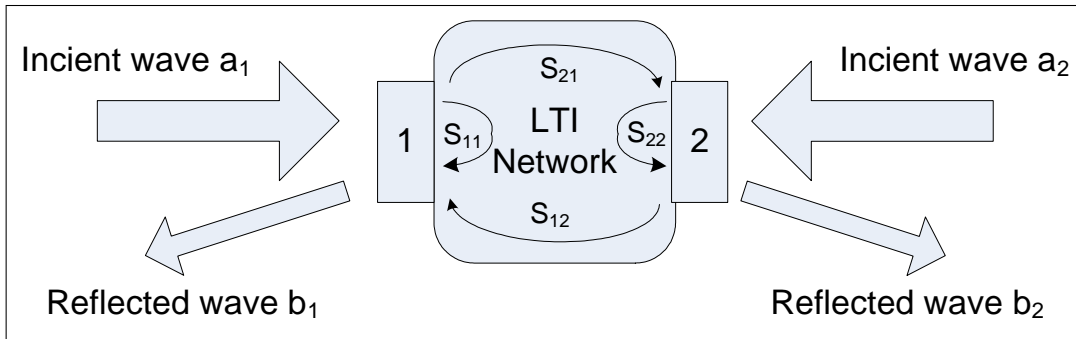


Fig. 4 S parameter flow graph

S-parameters are important in microwave design because they are easier to measure and to work with at high frequencies than other kinds of two port parameters. However, it must be kept in mind that -like all other two port parameters, S-parameters apply to LTI network, I.e. they represent the linear behavior of the two ports.

S-parameters are defined as:

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned} \quad (10)$$

- $a_i$  -Effective value (rms) of the incident wave traveling towards the  $i$ -th two port gate.
- $b_i$  -Effective value (rms) of the wave reflected back from the  $i$ -th two port gate.

The signal flow graph gives the situation for the S-parameter interpretation in voltages:

Looking at the S parameter coefficients individually, we have

$$\begin{aligned} S_{11} &= \Gamma_1 = \frac{b_1}{a_1} = \frac{V_{\text{reflected at port 1}}}{V_{\text{forward port 1}}} \Big|_{a_2=0} \\ S_{12} &= \frac{b_1}{a_2} = \frac{V_{\text{out of port 1}}}{V_{\text{forward port 2}}} \Big|_{a_1=0} \\ S_{21} &= \frac{b_2}{a_1} = \frac{V_{\text{out of port 2}}}{V_{\text{forward port 1}}} \Big|_{a_2=0} \\ S_{22} &= \Gamma_2 = \frac{b_2}{a_2} = \frac{V_{\text{out of port 2}}}{V_{\text{forward port 2}}} \Big|_{a_1=0} \end{aligned} \quad (11)$$

$S_{11}$  and  $S_{21}$  are determined by measuring the magnitude and phase of the incident, reflected and transmitted signals when the output is terminated in a perfect  $Z_0$  load. This condition guarantees that  $a_2$  is zero.  $S_{11}$  is equivalent to the input complex reflection coefficient or impedance of the DUT, and  $S_{21}$  is the forward complex transmission coefficient.

Likewise, by placing the source at port 2 and terminating port 1 in a perfect load (making a  $a_1$  zero),  $S_{22}$  and  $S_{12}$  measurements can be made.  $S_{22}$  is equivalent to the output complex reflection coefficient or output impedance of the DUT, and  $S_{12}$  is the reverse complex transmission coefficient.

## 5.1 Properties of Network

- **Matched network**  $S_{11} = S_{22} = 0$
- **A reciprocal network** -S-parameter matrix is symmetric about its diagonal or equal to its transpose,  $S_{ij} = S_{ji}$
- **Lossless network** the power incident on the network must be equal to the power reflected, or  $\sum_{i=1}^n |a_i|^2 = \sum_{i=1}^n |b_i|^2$ , or in mathematics, a unitary matrix is an  $n$  by  $n$  complex matrix  $U$  satisfying the condition  $U^+U = UU^+ = I_n$ .

## 5.2 Nondispersive (Distortionless) Transmission

In communication systems, a nondispersive channel, or low distortion is often desired. This implies that the channel output  $y(t)$  is just proportional to a time delayed version of the input  $x(t)$

$$y(t) = Ax(t - T_d) \quad (12)$$

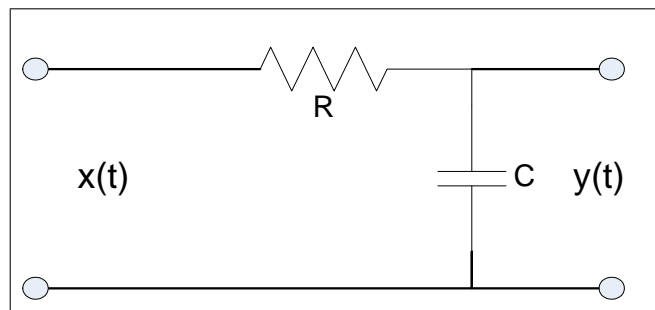


Fig-5 An arbitrary network

where  $A$  is the gain (which may be less than unity) and  $T_d$  is the delay.



### 5.2.1 Delay and Phase Delay

For a non-dispersive DUT, e.g. a coaxial cable, phase  $\theta(f)$  is a linear function of frequency:

$$\theta(f) = -360^\circ f T_d \quad (13)$$

where  $T_d$  is the delay time of the cable which is the time that the electromagnetic wave pass through the cable. Phase delay is directly related to its mechanical length  $l$  via the permittivity  $\epsilon_r$  of the dielectric material within the cable, therefore the time delay is defined by

$$T_d = \frac{l\sqrt{\epsilon_r}}{c} \quad (14)$$

The corresponding requirement in the frequency domain is obtained by taking the Fourier transform of both sides of Eq. (12).

$$Y(f) = AX(f) \exp(-j2\pi f T_d) \quad (15)$$

Thus, for distortionless transmission, we require that the transfer function of the channel be given by

$$H(f) = \frac{Y(f)}{X(f)} = A \exp(-j2\pi f T_d) \quad (16)$$

which implies that, distortionless network, must be satisfied two requirements:

1. The amplitude response versus frequency must be flat. That is

$$H(f) = \text{constant} = A \quad (17)$$

2. The phase response is a linear function of frequency. That is

$$\theta(f) = \angle H(f) = -2\pi f T_d \quad (18)$$

When the first condition is satisfied, there is no **amplitude distortion**. When the second condition is satisfied, there is no **phase distortion**. For non dispersive transmission, both conditions must be satisfied.

By Eq.(14), it is required that  $T_d(f) = \text{constant}$  for non dispersive transmission. If  $T_d(f)$  is not constant, there is phase distortion. The linearity of phase versus frequency is characterized by **group delay** which defined as

$$\tau(f) \triangleq - \frac{1}{360} \frac{d\theta(f)}{df} \quad (19)$$

That is the negative of the rate of change of phase ( which measure in degree) with frequency. The quantity  $\tau$  has the dimension of time, but the question is; what time does it represent? Many textbooks follow the definition of group delay with a discussion of an ideal element that delays a signal by time  $T_d$ .

# Part II

## Experiment Procedure

### 6 Required Equipment

1. RF Network Analyzer E5062A
2. Type N calibration kit Agilent - 85032E
3. Band Pass Filter Mini - Circuit BBP - 10.7 MHz
4. Terminator 50Ω NTRM - 50
5. Keysight ADS simulation software

#### 6.1 Simulating a Network Analyzer Measurement.

In this part of the experiment we simulate the reflection and transmission measurement of a 10.7MHz BPF.

1. Simulate a reflection and transmission measurement ( $S_{11}$  and  $S_{21}$ ), of a 10.7 MHz BPF, using ADS software. The definition of the filter parameter is given in Fig. 10.

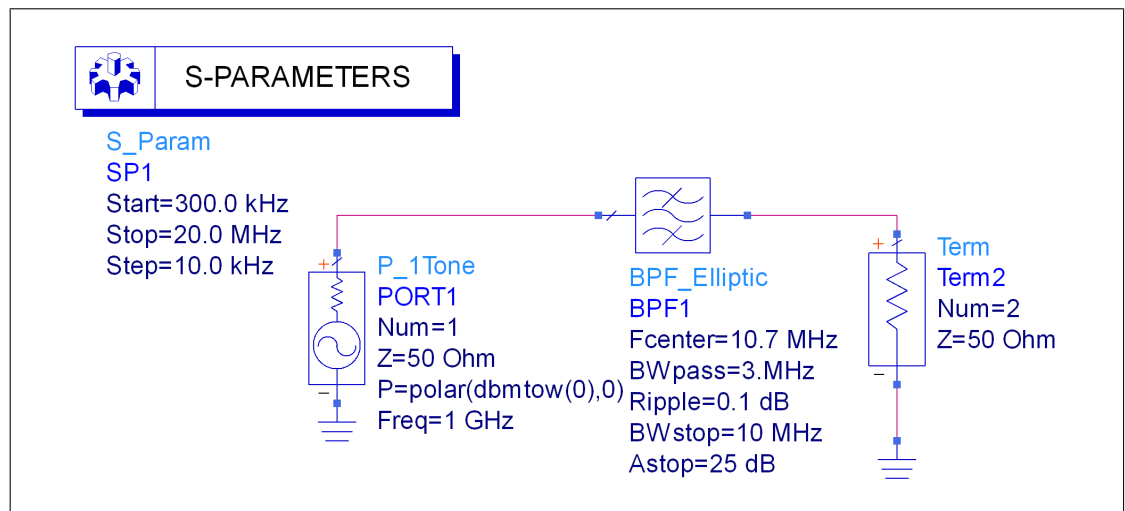


Fig. 9 simulation of reflection and transmission of 10.7MHz BPF

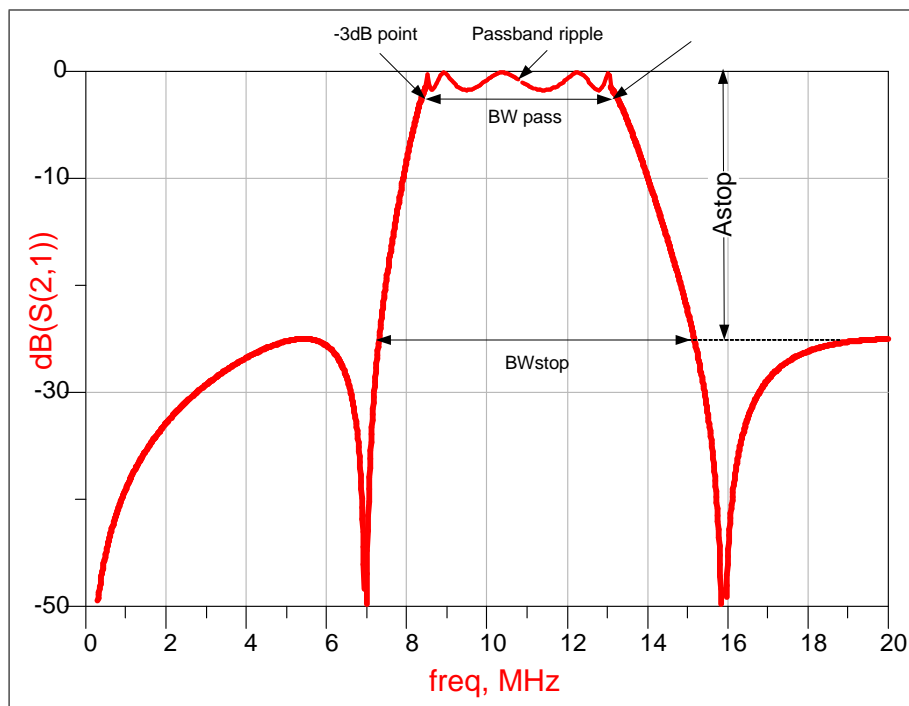


Fig.-10 Definition of an Elliptic BPF

2. Draw a graph of  $S_{11}$  (magnitude),  $S_{11}$  (dB),  $S_{21}$  and and Fill Table-1 according to simulation results.

BPF Electrical Transmission Results				
Passband $IL$		Stopband		
Center Freq.	BW(-3dB)	$IL > 20dB@Freq.$	$IL@7.5$ MHz	$IL@15$ MHz
Selectivity $\left(\frac{20dB \text{ bandwidth}}{3dB \text{ bandwidth}}\right)$				
Reflection				
max $ \Gamma $ 9 to 12MHz,		max RL 9 to 12MHz	$ \Gamma  @7.5$	RL@15MHz
Table-1				

## 7 Getting Started With Network Analyzer

### 7.1 Front Panel View Refer to Fig.-6:

1. **Standby Switch**

Allows the switch between power-on (I) and standby mode (Ö) on the E5061A/E5062A.

2. **LCD Screen**

Displays measurement traces, instrument setting conditions, and menu bars.

3. **ACTIVE CH/TRACE Block**

A group of keys used for selecting the active channel and an active trace.

4. **RESPONSE Block**

A group of keys used for the selection of a measurement parameters/data formats, displaying, calibration, etc.

5. **STIMULUS Block**

A group of keys used for specifying the setup for signal sources, trigger, etc.

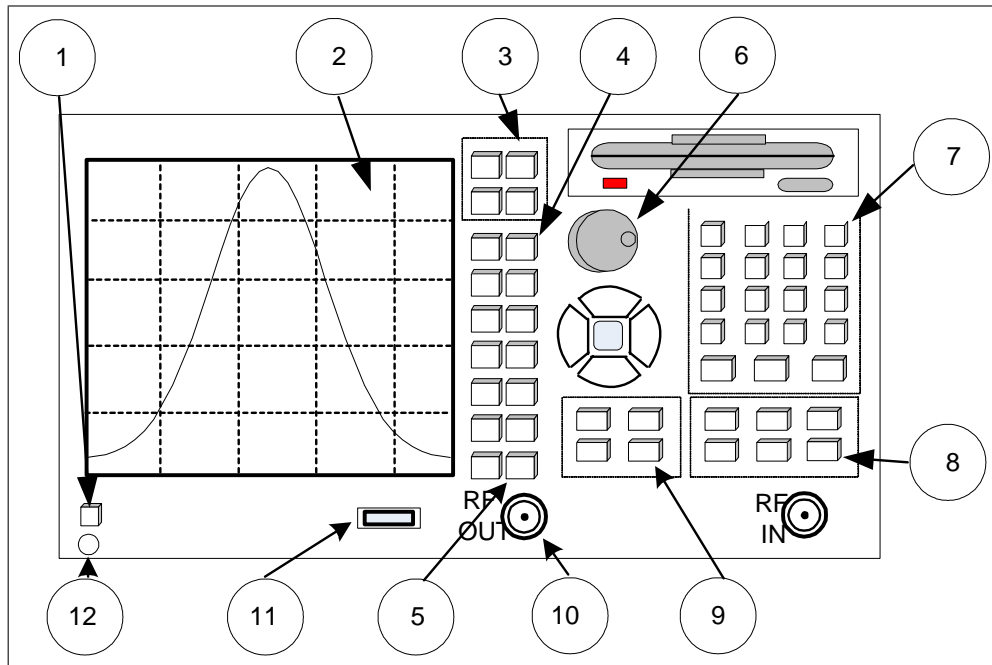


Fig-6 Front panel tour

**6. NAVIGATION Block**

A group of keys used for the movement/selection of the focus in menu bars/soft-key menu bar/dialog boxes and for manipulating markers.

**7. ENTRY Block**

A group of keys used for entering numeric data on the E5061A/E5062A settings.

**8. INSTR STATE Block**

A group of keys used for specifying the setup for controlling and managing the E5061A/E5062A such as executing printing measurement results, and presetting (initializing) the E5061A/E5062A.

**9. MKR/ANALYSIS Block**

A group of keys used for analyzing measurement results through markers, the limit test function, etc.

**10. Test Port**

While the signal is being output from a test port, the yellow LED above the test port lights up. The connector type adopted is the  $50\Omega$  -based N-type (female) connector.

#### 11. Front USB Port

Used to connect a printer, or an ECal module compatible with the USB (Universal Serial Bus). Using a USB port allows the accessories to be connected after the E5061A/E5062A has been powered on.

#### 12. Ground Terminal

Connected to the chassis of the E5061A/E5062A. You can connect a banana type plug to this terminal

## 8 Reflection Measurement

### 8.1 Preparation to Reflection Measurements, Reflection Calibration

When you require best possible accuracy, or you need to add an adaptor or cable between the DUT and the test port, it is strongly recommended to perform a proper calibration.

1. Press **Preset** and **OK** .
2. Press **CAL** key and then choose **Calibrate, 1- Port Cal**
3. Connect an **open** to the reflection port and press **Open(f)** (see figure 7).
4. Connect a **short** to the reflection port and press **Short(f)**.
5. Connect a **load** to the reflection port and press **Load** and in the end press **Done**.
6. You use 3 standards, (open short and  $50\Omega$  load), could you determine  $Z_0$  using two standards? Prove your answer using proper equation.
7. Disconnect the load ( $50\Omega$  termination) and return all the standards devices carefully to their box.

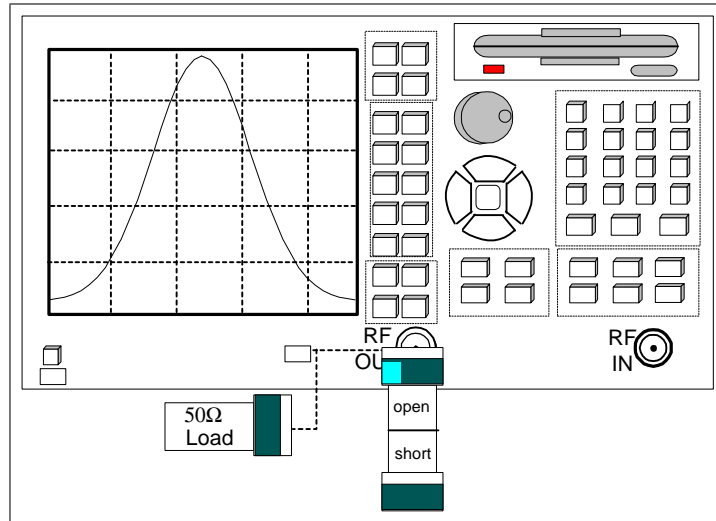


Fig. 7 Calibration for Reflection measurement

## 8.2 Preparation to Reflection Measurement, Setting Signal Source

S. parameters is a ratioing measurement. If your device is sensitive to the incident power, you can increase or decrease the incident power.

1. Connect a 10.7MHz BPF to the Network Analyzer as shown in Figure 8.
2. Press the **Preset** key situated at INSTR STATE Block.
3. Press the **Measr** key situated at Response Block, and choose  $S_{11}$  from the soft menu, and press **Enter**.
4. Press the **Scale** key, and choose **Autoscale** from the soft menu.
5. At the **STIMULUS Block** press: **Start** key and insert **5 MHz** by pressing 5 M/ $\mu$ , press **Stop** key and insert **20 MHz**.



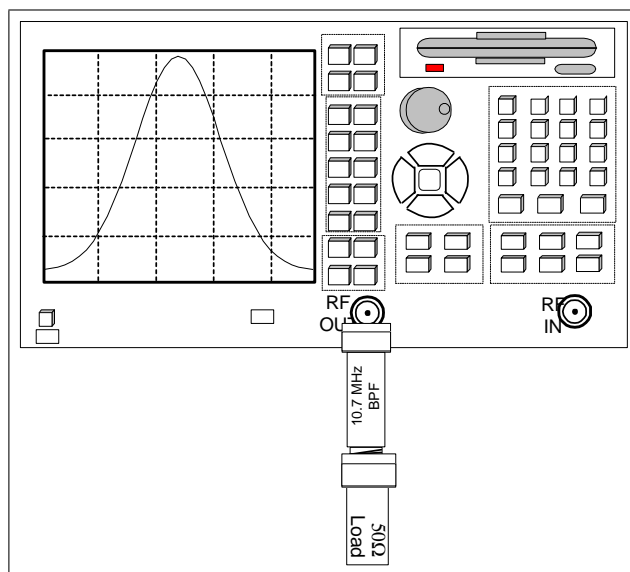


Fig. 8 Basic reflection measurement

6. By default the power level of the Network Analyzer is 0 dBm (1mw). If necessary you can change the power by pressing **Sweep Setup** keys and then choose **Power** option and set power level to **3dBm**, by pressing **3** × **1** keys.

## 9 Reflection Measurement of a BPF

Under Reflection measurement you can measure: reflection coefficient magnitude and phase, return loss , SWR, and impedance of a DUT.

1. Press the **Preset** key situated at INSTR STATE Block.
2. Press the **Measr** key situated at Response Block, and choose  $S_{11}$  from the soft menu, and press **Enter**.
3. Press the **Scale** key, and choose **Autoscale** from the soft menu.
4. Press **Freq**, then **Start** 1 MHz and **Stop** 25 MHz, **Scale**, **Autoscale**, return loss ( $S_{11}$ , reflection coefficient  $|\Gamma|$  in dB) as a function of frequency is displayed). **Save the data of  $S_{11}$  and  $S_{22}$  on magnetic media, Excell and image format.**

5. Press **Format, Lin Mag**, to get the absolute value of reflection coefficient as a function of frequency is displayed ( $\rho = |\Gamma|$ ).Set marker 1 to 10.7MHz, and marker 2 to 25MHz. Explain what happen to the incident power at that frequencies? **Save the data on magnetic media.**
6. Press **Format Polar**, to get polar plot of the reflection coefficient, could you explain where  $\rho, \angle \theta$  and frequency is displayed?.**Save the data on magnetic media.**
7. Fill Table-2.

Freq(MHz).	RL(data)	RL(meas.)	$ \Gamma $ (meas.)	$P_{inc} (mw)$	$P_{ref} =  \Gamma ^2 P_{inc}$
Stop band	x	x	x	x	x
5.3	-0.2			1	
15	-0.4			1	
10.7 (center)	-17.6			1	

Table-2

## 9.1 Standing Wave Ratio and Impedance

1. Press **Format**, and **SWR**. The SWR as a function of frequency is displayed.**Save the data on magnetic media.**
2. Press **Format** and **Smith Chart** for getting a display of the real and imaginary values of the impedance as function of frequency. Set the start frequency to 7 MHz and stop frequency 20 MHz, verify that the impedance of the filter is about  $50\Omega$  in the pass Band (8.5 to 12.5MHz).**Save the data on magnetic media.**
3. Fill Table-3

Stop band<7.5MHz	
SWR(Data )	SWR(measured)
16	
Pass band(9.5 to 11.5MHz)	
SWR(Data )	SWR(measured)
< 1.7	

Table-3

## 10 Make a Transmission Measurement of a BPF

In this part of the experiment you measure insertion loss (attenuation,  $S_{21}$ ) of a BPF as a function of frequency using Transmission measurement.

### 10.1 Preparation to transmission Measurement- Response Calibration

In this part of the experiment we eliminate the errors due to frequency response of the external cable connected between port-1 and port-2 of the Network Analyzer.

1. Connect a coax cable to the network between **RF out** port and **RF in** port (see Fig. 10 dashed line).
2. Set the frequencies range, 300kHz to 1GHz.
3. Press **Preset**, **Ok** and **Measurement, S21**.
4. Press **CAL**, **calibrate**, **Response(Thru)**, **Thru**, **Done**.

### 10.2 Transmission Measurement of an Elliptic BPF.

In this part you measure the insertion loss of the BPF, at the pass band and at the stop band.

1. Disconnect the coaxial cable and connect the BPF to the reflection port of the Network Analyzer, as indicated in Figure 10.
2. Set the frequency range to start frequency 5MHz stop frequency 20MHz, transmission coefficient measurement in dB is displayed ( $S_{21}$ ) .
3. Press **Scale**, **Autoscale**. and **Save the data of  $S_{21}$  and  $S_{12}$  on your media, Excell, and image format**.
4. Press **Marker Search**, **Max** verify that the center frequency of the filter is about 10.7 MHz and fill Table-4.

5. Set the marker to 9.5 MHz and 11.5 MHz by pressing **Marker 9.5 MHz** , and then **11.5 MHz**, verify that the insertion loss is less than 1.5 dB.

Pass Band measurements			
Center Freq. (10.7MHz)	Passband(IL<1.5dB)	Typ. bandwidth(-3dB)	Bandwidth(-20dB)
	(9.5 to 11.5MHz)	(8.9 – 12.7MHz)	(7.8 – 14.4)
Selectivity( $\frac{20dB}{3dB}$ ) (1.7)	IL@9.5 MHz	IL@11.5 MHz	IL@Center Freq
	(-1dB)	(-1dB)	
Stop Band			
IL@7.5 MHz	IL@15 MHz	IL@0.6 MHz	Freq.@-20dB
(30dB)	(30dB)	(60dB)	(7.6&14.4)
Table-4			

6. Measure the phase of the filter in the pass band (9.5-11.5 MHz), **explain if the phase is linear in the passband?**

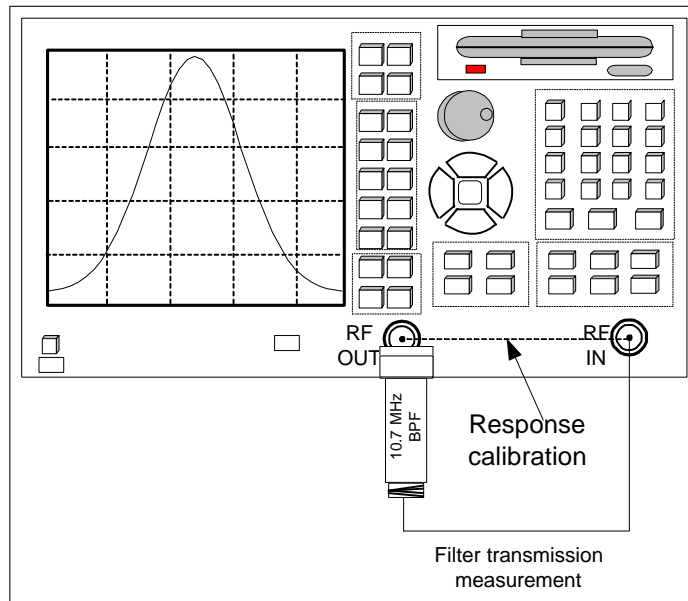


Fig. 10 Response calibration and transmission measurement of a BPF.

## 11 Delay and Phase Delay

In this part of the experiment you simulate and measure the delay (group delay), and phase delay of a coaxial cable.

### 11.1 Group Delay, and Phase Simulation

1. Simulate a 5m coaxial cable as indicated in Fig. 11
2. Allow group delay simulation by double click on **S PARAMETER**, then click on **parameters**, and select **Group delay**.

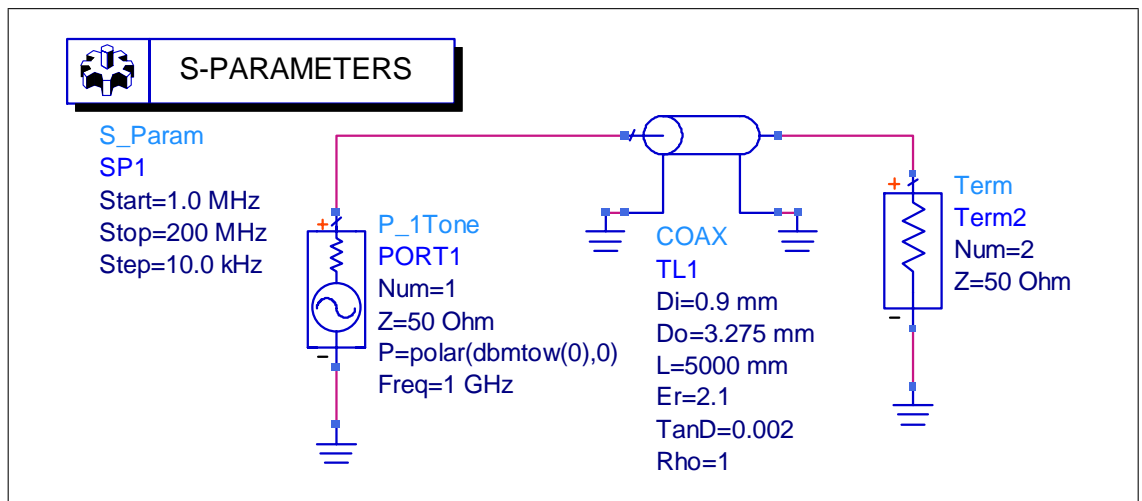


Fig-11 Group delay and phase delay simulation

3. Plot a graph of delay  $S_{21}$  (group delay) as a function of frequency, according to the graph **explain if the cable is dispersive element?**
4. Calculate, phase constant  $\beta$ , and phase delay at 100MHz. Plot a graph of  $S_{21}$  phase and find the phase delay at 100 MHz, you can verify your result by changing the graph expression to plot `_vs(unwrap(phase(S(2,1))), freq)`.
5. Replace the coaxial cable with elliptic band pass filter as indicated in Fig. 12 and simulate the group delay of the filter.

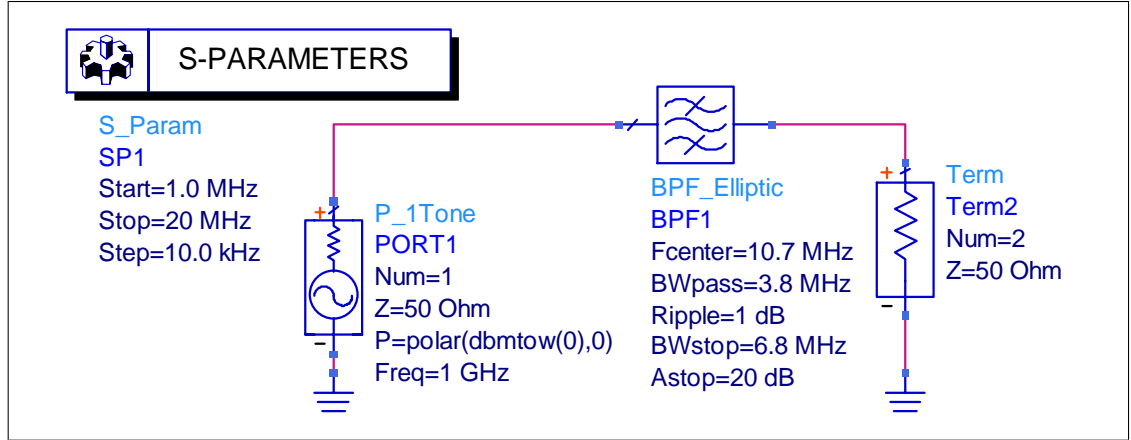


FIG. 12 group delay of elliptic BPF

- Plot a graph of  $S_{21}$  group delay and  $S_{21}$  phase, according to the graphs, explain if the filter can be used for baseband digital communication (linear phase versus frequency is important).

## 11.2 Group Delay and Phase Delay Measurement

- Connect a 5m long, coaxial cable to the Network Analyzer as indicated in Fig. 10 dashed line.
- Calculate the group delay** (time delay), assume  $\epsilon_r = 2.29$ .
- Calculate the phase shift of the cable**, at 100MHz.
- Under transmission measurement, frequency range 300kHz to 1GHz, measure the group delay of the cable (under **Format, Group Delay**). according to your measurement explain if the cable is dispersive element? Compare your measurement to the calculation.
- Measure the phase shift of the cable, and compare to the calculation.
- Replace the cable with BPF and measure the group delay of the filter, and compare to the simulation result.

## 12 Final Report

Using your data and mathematics software, or spreadsheet answer the following Questions.

1. Attached the graphs that you save, and answer the question of the text Lab.
2. Draw a graph of return loss ( $S_{11}$  in dB) based on measurement as a function of frequency of the Elliptic filter. Calculate the worst SWR of the cable. in the passband (9.5 to 11.5 MHz).
3. Use the data of the filter to fill the following S parameters matrices, determine

$$\begin{aligned} [S] @ C.F &= \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \\ [S] @ 8.5 MHz &= \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \end{aligned}$$

- (a) If the filter is matched, reciprocal, and lossless at center frequency.
- (b) If the filter is matched, reciprocal, and lossless at 8.5MHz.