



DEPARTMENT OF
ELECTRICAL AND COMPUTER ENGINEERING

ECE332

LAB 3: HIGH FREQUENCY MEASUREMENTS

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Objective

The vector network analyzer (VNA) will be introduced as a measurement tool, and will be used to study the characteristic parameters of transmission line networks, the reflections caused by various load terminations and for characterization of a bandpass filter design.

Concepts Covered

- Vector Network Analyzer calibration
- Standing Wave Ratio
- Reflection coefficient
- Scattering matrix

1 Pre-Lab Assignment

- Review sections 2.6 - 2.10 in Ulaby[1].
- Design a passive bandpass filter with the following parameters: $f_c = 1.6 \text{ MHz} \pm 10 \text{ kHz}$, $Q = 8$. Record your design in your logbook.
- Choose standard (*std*) component values for your filter design. Record these values in your logbook.
- Perform a frequency sweep analysis of your filter design (using *std* values) in LTspice®. Record the simulated values for f_c , Δf , Q , S_{11} and S_{21} in Table 8.

2 Introduction

With the ever increasing role of communications in our daily lives, it has become increasingly important to connect remote sites together to share data and information. One method for providing links between remote sites is to use transmission lines. Some everyday examples include telephone lines, coax lines for cable television, and even electrical lines. In order to provide the best link possible, it is necessary to understand how signals propagate along transmission lines.

In basic electronic circuits, it is assumed that if a voltage is applied at the input of a circuit, the output voltage appears instantaneously at the output of the circuit. For circuits where the line lengths are much smaller than the wavelength of the signal, this assumption is acceptable with only negligible consequences. However, when the length of the wires or transmission lines are an appreciable fraction of the wavelength or longer, the output signal changes phase compared to the input signal, and at impedance discontinuities, reflections can occur.

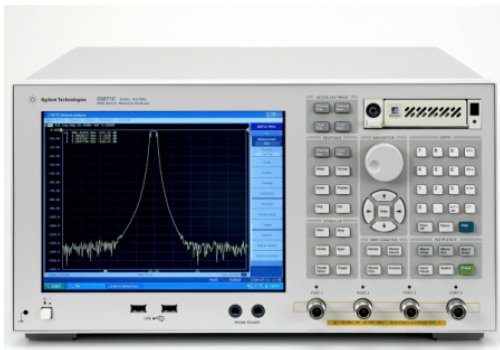
In this lab, you will explore the characteristic parameters of transmission lines and the reflections caused by different load terminations. You will be introduced to a new tool for analyzing transmission line systems (or networks), the vector network analyzer (VNA). In addition, you will use the VNA to characterize a filter network.

2.1 Vector Network Analyzer

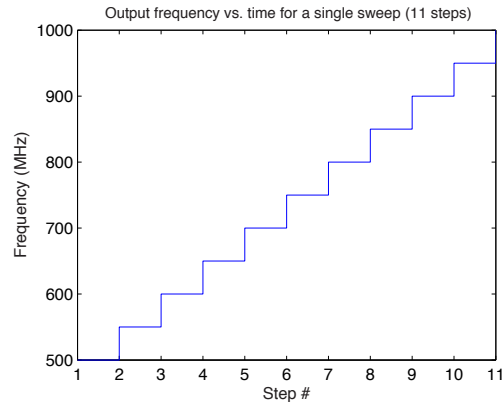
The VNA is used for a variety of device and component characterization tasks in both laboratory and production environments. This highly accurate (with proper calibration) instrument can evaluate both active and passive components. With the addition of time-domain capabilities (generally implemented as add-on software packages), a VNA can also gate out unwanted responses during measurements, leaving only the desired information.

The VNA is a measurement tool for making phase and magnitude measurements. The VNA (Agilent E5071C) you will use is capable of making phasor (magnitude and phase) measurements in the frequency range from 300 kHz - 20 GHz. *The most vulnerable parts of the VNA are the connectors and the calibration kit components. Whenever you are taking*

measurements with the VNA be sure to wear an ESD safety clip and always discharge the conductor (center pin) when connecting cables to the VNA and the Device Under Test (DUT).



(a) Agilent E5071C ENA



(b) Frequency vs. time plot for the output of the network analyzer.

The signal transmitted by the vector network analyzer (VNA) is a stepped frequency signal. This means that if you look at a plot of the frequency output of the VNA versus time, instead of a continuous line (called a ramp), you will see a discrete line (called a discrete ramp) as shown in Figure 1b.

2.2 Scattering Matrix

A practical problem exists when trying to measure voltages and currents at high frequencies because the direct measurement usually involves the magnitude (inferred from the power) and phase of a traveling (or standing) wave in a given direction. Therefore, the equivalent voltages and currents become somewhat of an abstraction when dealing with high frequency networks. A representation more in accord with the direct measurements and the ideas of incident and reflected waves is given by the scattering S parameters, as shown in Figure 1.

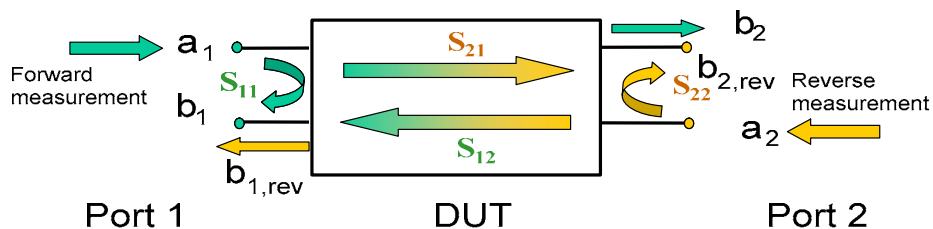


Figure 1: 2-Port S parameter diagram.

From Figure 1, we see that the S parameters relate the incident and reflected voltages from their respective ports. To determine the S parameter for a given port relation we

represent the network in matrix notation and solve for S_{pq} :

$$[\mathbf{V}^-] = [\mathbf{S}] [\mathbf{V}^+] \quad (1)$$

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix} \quad (2)$$

$$S_{pq} = \left. \frac{V_p^-}{V_q^+} \right|_{V_k^+ = 0 \text{ for } k \neq q} \quad (3)$$

Equation (3) shows that S_{pq} is found by driving port q with an incident wave of voltage V_q^+ and measuring the reflected wave V_p^- coming out of port p . The incident waves on all other ports except the q th port are set to zero (i.e. the port is terminated by a matched load). Therefore, S_{pq} is equivalent to the reflection coefficient Γ seen looking into port i when all other ports are terminated in matched loads and S_{pq} is equivalent to the transmission coefficient τ from port q to port p when all other ports are terminated by matched loads. We have limited our discussion to the S parameters for a 2-port network, but it should be noted that (1) - (3) can be extended to include an N -port network.

2.3 Calibration

It is important to understand the factors contributing to measurement errors in order to determine the appropriate steps that should be taken to improve accuracy. Measurement errors are classified into three categories: Drift, Random and Systematic.

Drift Errors

Drift errors are caused by deviations in the performance of the measuring instrument that occur after calibration. Major causes are the thermal expansion of connecting cables and thermal drift of the frequency converter within the measuring instrument. These errors may be reduced by carrying out frequent calibrations as the ambient temperature changes or by maintaining a stable ambient temperature during the course of a measurement.

Random Errors

Random errors occur irregularly in the course of using the instrument. Since random errors are unpredictable, they cannot be completely eliminated by calibration. These errors are further classified into the following subcategories depending on their causes.

Instrument noise errors These errors are caused by electrical fluctuations within components used in the measuring instrument. These errors may be reduced by increasing the power of the signal supplied to the DUT, narrowing the Intermediate Frequency (IF) bandwidth, or enabling sweep averaging.

Switch repeatability errors These errors occur due to the fact that the electrical characteristics of the mechanical Radio Frequency (RF) switch used in the measuring instrument change every time it is switched on. These errors may be reduced by carrying out measurements under conditions in which no switching operation takes place. NOTE: Not all VNAs use mechanical switching, consult your system manual to determine what type of RF switching your instrument uses.

Connector repeatability errors These errors are caused by fluctuations in the electrical characteristics of connectors due to wear. These errors may be reduced by handling connectors with care.

Systematic Errors

Systematic errors are caused by imperfections in the measuring instrument and the test setup (cables, connectors, fixtures, etc.). Assuming that these errors are repeatable (i.e. predictable) and their characteristics do not change over time, it is possible to eliminate them mathematically at the time of measurement by determining the characteristics of these errors through calibration. There are six types of systematic errors, they are as follows:

- Errors caused by signal leaks in the measuring system:
 - Directivity : Directivity errors are caused by the fact that, in a reflection measurement, signals other than the reflection signal from the DUT are received by receiver through the directivity coupler.
 - Isolation (cross-talk) : Isolation errors are caused by signals other than the transmission signal of the DUT leaking to the test receiver of the transmission measurement port.
- Errors caused by reflections in the measuring system:
 - Source match : A source match error is caused when the reflection signal of the DUT reflects at the signal source and enters the DUT again.
 - Load match : A load match error is caused when part, but not all, of the signal transmitted in the DUT reflects at a response port and is measured by the receiver of the response port.
- Errors caused by the frequency response of the receiver within the measuring instrument:
 - Reflection tracking : A reflection tracking error is caused by the difference in frequency response between the test receiver and the reference receiver of a stimulus port.
 - Transmission tracking : A transmission tracking error is caused by the difference in frequency response between the test receiver of a response port and the reference receiver of a stimulus port.

Calibration Method	Standard(s) Used	Corrected Error Factor	Measurement Parameter	Characteristics
No Calibration	None	None	All parameters	Low accuracy. Calibration not required.
1-Port Calibration	Short, Open, Load (SOL)	Directivity, Source Match, Reflection Tracking	S_{11} (Reflection characteristics at 1 port)	Highly accurate 1-port measurements.
Full 2-Port Calibration	Thru, Short, Open, Load (TSOL)	Directivity, Isolation, Source Match, Load Match, Transmission Tracking, Reflection Tracking	$S_{11}, S_{21}, S_{12}, S_{22}$ (All S-parameters at 2 ports)	Highly accurate 2-port measurements.

Table 1: Some different calibration types and their features.

The calibration method used is largely dependent on the type of measurement that you are performing. Fortunately, for all these experiments you will be using the Agilent N4619B auto calibration kit. This type of auto calibration kit is beneficial because it can calibrate the VNA to the end of the SMA cables without the need for the operator to define their own calibration standards. For these experiments you will be performing a 1-Port calibration and a Full 2-Port calibration (see Table 1).

3 Experiments

3.1 Line Parameters of a Lossless Line

Agilent E5071C Vector Network Analyzer	SMA Cable
Short Circuit Termination	Meter Stick
SMA/F-SMA/F Adapter	

Table 2: Experiment 1 Equipment List

Introduction

You have seen in class that the wave propagation properties of transmission lines are governed by several parameters. One of these parameters is the relative dielectric constant ϵ_r . In this experiment, you will use the VNA to compute the line parameters of a lossless line (β (rad/s), C' (F/m), L' (H/m), u_p (m/s) and ϵ_r) by making reflection measurements to determine ϵ_r .

There are many formats used to display the reflections caused by mismatched loads. Some of these formats include magnitude and phase, VSWR and the Smith Chart. In this experiment we will utilize the Smith Chart. The Smith Chart is a powerful tool in microwave engineering, allowing the microwave engineer to represent the complicated equations governing the reflections at load mismatches in a compact graphical format.

Although the cable that you will use for this experiment is a coaxial cable which does have some inherent loss, we will make the assumption for this experiment that $\alpha \approx 0$. We are justified in making this assumption since the loss for this particular cable is < 0.7 dB/ft at 18 GHz. Since the piece of cable you are using is only 3' in length, the loss is ≈ 2.1 dB which is roughly 2%.

The relative permittivity ϵ_r for the transmission line is determined by measuring u_p for the transmission line and comparing it to u_p for free space (in vacuum). Phase velocity can be determined by measuring the time (Δt) that a wave takes to travel down a transmission line of length l and return to the VNA. The value of ϵ_r can then be determined from u_p , using (4) and (7).

$$u_p = \frac{2l}{\Delta t} (m/s). \quad (4)$$

To measure the time delay Δt of the cable, you will use the electrical delay feature of the network analyzer and terminate the patch cord with a load of known reflection coefficient. In this experiment, the transmission line will be terminated in a short. Recall that $\Gamma = -1$ for a short-circuit termination.

When a transmission line is placed between the VNA and a load termination, an electrical delay is added to the load response. The term electrical delay means that the signal has an added phase shift from traversing the transmission line. In particular, if you look at a short

termination, you will see that the response is a set of concentric circles wrapping around the outside edge ($|\Gamma| = 1$ circle) of the Smith Chart (See Figure 2a).

When you add electrical delay, you are actually adding a phase correction to the received signal. The phase correction is given in terms of time. When you have added the correct amount of electrical delay, the response of the short termination will collapse to a point.

In reality, the response will collapse to what is termed a “point-like” response (as shown in Figure 2b). This means that the response is not a true point, but is more spread out. This is due to the finite loss in the cable and connectors.

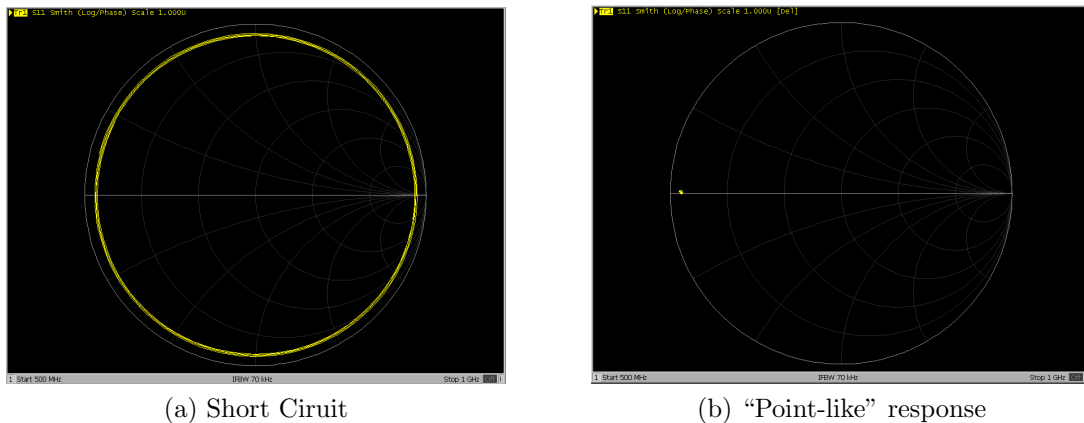
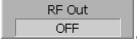


Figure 2: Response on the Smith Chart.

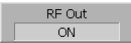
Setup

Before you begin the experiment measure and record the physical length of the SMA cable in Table 5.

- Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .
- Connect one end of the SMA cable to Channel 1 on the VNA.
- Connect the short circuit termination to the end of the SMA cable using the SMA/F to SMA/F adapter.
- Configure the VNA:
 - Set the start frequency to 500 MHz.
 - * Press Start > Type 500 000 000.

- Set the stop frequency to 1 GHz.
 - * Press Start > Type 100 000 000.
- Set the display to Smith Chart format.
 - * Press Format > Smith Chart > Log/Phase.

Procedure

1. Turn RF power on.
 - Press Sweep Setup > Power > RF Out [OFF].
 - You should now see the Power button display .
2. Add electrical delay until the response is point like:
 - (a) Press Scale > Electrical Delay.
 - (b) Rotate the knob on the VNA to the right until the response is “point-like”.
3. Record the added electrical delay in Table 5.
4. Take a screen capture of the “point-like” response of the SMA cable.

Collected Data

- Screen capture of the "point-like" response of the SMA cable.
- Measured values:
 - Physical length of SMA cable.
 - Value of the added electrical delay.
- Using Equation (4), compute u_p for the SMA cable using the experimentally determined electrical delay. Record the value of u_p in Table 5.
- Using $c = 3 \times 10^8$ (m/s) and 7, and the calculated value of u_p , calculate ϵ_r for the SMA cable. Record the value of ϵ_r in Table 5.
- Using the calculated value of ϵ_r , calculate β for this transmission line (assume $\mu = \mu_0$ and $f = 800$ MHz). Record the value of β in Table 5.
- Using $Z_0 = 50\Omega$ and the relationship $\mu\epsilon = L'C'$, calculate L' and C' of the transmission line. Record the values in Table 5.

$$\lambda = u_p/f \tag{5}$$

$$\beta = \omega/u_p = \omega\sqrt{\mu\epsilon} = \omega\sqrt{L'C'} \tag{6}$$

$$\epsilon_r = (c/u_p)^2 \tag{7}$$

$$Z_0 = \sqrt{L'/C'} \tag{8}$$

3.2 Reflection Coefficient

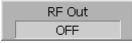

Agilent E5071C Vector Network Analyzer	SMA Cable
Agilent N4691 ECal Module	A-B USB Cable
SMA/F-N/F Adapter	SMA/F-SMA/F Adapter
Horn Antenna	

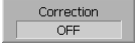
Table 3: Experiment 2 Equipment List

Introduction

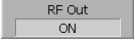
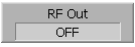
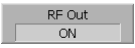
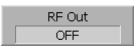
In this experiment, you will familiarize yourself with the VNA calibration procedures by measuring the reflection coefficient of three standard impedances. Then you will use the SWR feature of the VNA to determine the bandwidth that a horn antenna operates over.

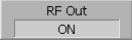
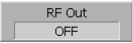
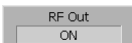
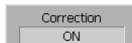
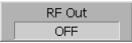
Setup

- Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .
- Connect the SMA cable to Channel 1 on the VNA.
- Configure the VNA:
 - Split the display to show Channel 1 in both views.
 - * Press Display > Num of Traces > 2.
 - * Press Display > Allocate Traces > .
 - Set the start frequency to 300 kHz.
 - * Press Start > Type 300 000.
 - Set the stop frequency to 18 GHz.
 - * Press Start > Type 18 000 000 000.
 - Set Trace 1 display to logarithmic format.
 - * Press Format > Log Mag.
 - Set Trace 2 display to phase format.
 - * Press Trace Next.

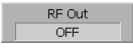
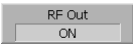
- * Press Format > Phase.
- Set a Marker on Channel 1 at 500 MHz.
- Turn off device calibration:
 - * Press Cal > Correction [ON].
 - * You should now see the Correction button display .

Procedure - Load Impedance Measurements

1. Connect the short circuit termination to the end of the SMA cable using the SMA/F to SMA/F adapter.
2. Turn RF power on.
 - Press Sweep Setup > Power > RF Out [OFF].
 - You should now see the Power button display .
3. Record the magnitude and phase of the short circuit reflection coefficient at 500 MHz in Table 6.
4. Take a screen capture of the short circuit reflection coefficient.
5. Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .
6. Connect the SMA/F to SMA/F Adapter to the end of the SMA cable.
7. Do not connect any termination to the end of the adapter (open circuit load).
8. Turn RF power on.
 - Press Sweep Setup > Power > RF Out [OFF].
 - You should now see the Power button display .
9. Record the magnitude and phase of the open circuit reflection coefficient at 500 MHz in Table 6.
10. Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .

11. Connect the 50 Ω termination to the end of the SMA cable using the SMA/F to SMA/F adapter.
12. Turn RF power on.
 - Press Sweep Setup > Power > RF Out [OFF].
 - You should now see the Power button display .
13. Record the magnitude and phase of the matched load reflection coefficient at 500 MHz in Table 6.
14. Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .
15. Turn on device calibration:
 - Connect the SMA cable to Port A on the ECal module.
 - Connect the ECal module to the VNA via the USB Cable.
 - Wait for the green READY light to turn on.
 - Turn RF power on.
 - Press Sweep Setup > Power > RF Out [OFF].
 - You should now see the Power button display .
 - Press Cal > Correction [OFF].
 - You should now see the Correction button display .
 - Press Cal > ECal > 1-Port Cal > Port 1.
 - You should see [F1] in the upper left hand corner of the trace display menu.
16. Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .
17. Repeat steps 1 - 13 with device calibration enabled.

Procedure - Antenna Bandwidth Measurement

1. Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .
2. Connect the SMA cable to the horn antenna with the SMA-N adapter.
3. Maximize Trace 1.
 - Press Trace Next until Tr1 is highlight in the upper left hand corner of the trace display menu.
 - Press Trace Max.
4. Change Trace 1 format to SWR.
 - Press Format > SWR.
5. Turn measurement conversion off.
 - Press Analysis > Conversion [ON].
6. Turn RF power on.
 - Press Sweep Setup > Power > RF Out [OFF].
 - You should now see the Power button display .
7. Place a marker on Trace 1.
 - Press > Marker.
8. Using the position knob on the front panel of the VNA, move the marker to the frequency where the SWR is a minimum. Record this frequency and the corresponding SWR in Table 7.
9. Using the marker, locate the two frequencies nearest the minimum where the SWR becomes 2.5. Record these two frequencies in in Table 7.

Collected Data

- Screen captures of the uncalibrated and calibrated short circuit load.
- Measured values at 500 MHz:
 - Calibrated and uncalibrated reflection coefficient for the short circuit load.

- Calibrated and uncalibrated reflection coefficient for the open circuit load.
- Calibrated and uncalibrated reflection coefficient for the matched (50Ω) load.
- For each of the loads measured (short, open, matched), calculate the theoretic reflection coefficient. Since the VNA performs a power measurement, the conversion to a linear scale is given by (9). Record these values in your logbook.

$$|\Gamma_{linear}| = 10^{\frac{|\Gamma|}{20}} \quad (9)$$

- Calculate the magnitude of the input impedance at the frequency where the SWR minimum occurred. Record this value in Table 7. For your calculations, assume that Γ is real.

$$SWR = S = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (10)$$

$$|\Gamma| = \frac{S - 1}{S + 1} \quad (11)$$

$$Z_{in} = Z_0 \frac{1 - |\Gamma|}{1 + |\Gamma|} \quad (12)$$

3.3 Filter Characterization

Agilent E5071C Vector Network Analyzer	x2 - SMA Cables
Prototype Bread Board	x2 - SMA/F-Prototype board adapters
\leq x3 - Inductors	Capacitors and Resistors of varying values

Table 4: Experiment 3 Equipment List

Introduction

Often, both the magnitude and phase behavior of a component can be critical to the performance of a system. In this experiment you will validate your bandpass filter design using the VNA to take measurements of common filter characteristics.

Complete characterization of filters is typically achieved with swept-frequency measurements. Shown in Figure 3 are the frequency responses of a bandpass filter. On the left and bottom the transmission response is shown in log magnitude format, and on the right we see the reflection response S_{11} (return loss).

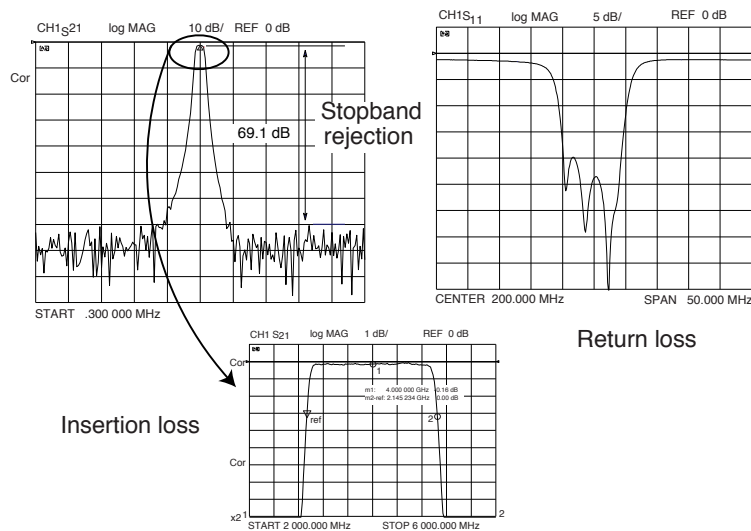
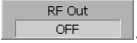

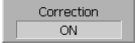



Figure 3: Testing filters with frequency sweeps[2].

The most commonly measured filter characteristics are insertion loss S_{21} and bandwidth, shown on the lower plot with an expanded vertical scale. Another common measured parameter is out-of-band rejection. This is a measure of how well a filter passes signals within its bandwidth while simultaneously rejecting signals well outside that same bandwidth. A

measurement systems' dynamic range generally determines how well it can evaluate this characteristic.

Setup

- Build the bandpass filter you designed in Section 1 using standard component values.
- Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .
- Connect one end of an SMA cable to Channel 1 on the VNA.
- Connect one end of the second SMA cable to Channel 2 on the VNA.
- Turn on device Calibration:
 - Connect Channel 1 SMA cable to Port A on the ECal module.
 - Connect Channel 2 SMA cable to Port B on the ECal module.
 - Connect the ECal module to the VNA via the USB Cable.
 - Wait for the green READY light to turn on.
 - Turn RF power on.
 - * Press Sweep Setup > Power > RF Out [OFF].
 - * You should now see the Power button display .
 - Press Cal > Correction [OFF].
 - You should now see the Correction button display .
 - Press Cal > ECal > 2-Port Cal.
 - You should now see [F2] in the upper left hand corner of the trace display menu.
- Configure the VNA:
 - Split the display to show Channel 1 in four views.
 - * Press Display > Num of Traces > 4.
 - * Press Display > Allocate Traces > .
 - Set the start frequency to 300 kHz.
 - * Press Start > Type 300 000.
 - Set the stop frequency to 5 MHz.

- * Press Start > Type 5 000 000.
- Set trace 1 to logarithmic format.
 - * Press Format > Log Mag.
- Set the measurement type on trace 1 to S_{11} .
 - * Press Meas > S_{11} .
- Set trace 2 to logarithmic format.
 - * Press Trace Next.
 - * Press Format > Log Mag.
- Set the measurement type on trace 2 to S_{21} .
 - * Press Meas > S_{21} .
- Set trace 3 to phase format.
 - * Press Trace Next.
 - * Press Format > Phase.
- Set the measurement type on trace 3 to S_{11} .
 - * Press Meas > S_{11} .
- Set trace 4 to phase format.
 - * Press Trace Next.
 - * Press Format > Phase.
- Set the measurement type on trace 4 to S_{21} .
 - * Press Meas > S_{21} .
- Set a Marker on at 1.6 MHz.
 - * Press Start > Type 160 000 000.
- When you are finished your display should look like Figure 4.

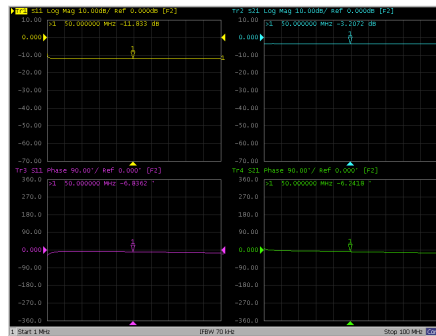
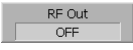
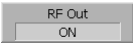

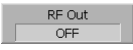


Figure 4: VNA 2-port S-parameter calibration.

Procedure

1. Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .
2. Connect the Channel 1 SMA cable to the INPUT port of your filter circuit.
3. Connect the Channel 2 SMA cable to the OUTPUT port of your filter circuit.
4. Turn RF power on.
 - Press Sweep Setup > Power > RF Out [OFF].
 - You should now see the Power button display .
5. Configure the VNA to display bandpass filter parameters.
 - Press Marker Search > Max.
 - You should now see Marker 1 at the bandpass center frequency.
 - Press Bandwidth.
 - You should now see the bandpass filter parameters in the northwest corner of the plot and the Bandwidth button display .
6. Record the the values for the center frequency (cent), maximum S_{21} , minimal S_{11} , and bandwidth (BW) in Table 8.
7. Determine the in-band and out-of-band rejection of you bandpass filter. Record these values in your logbook.
8. Take a screen capture of the 2-port S parameters of your filter, see Figure 5.
9. Turn RF power off.
 - Press Sweep Setup > Power > RF Out [ON].
 - You should now see the Power button display .

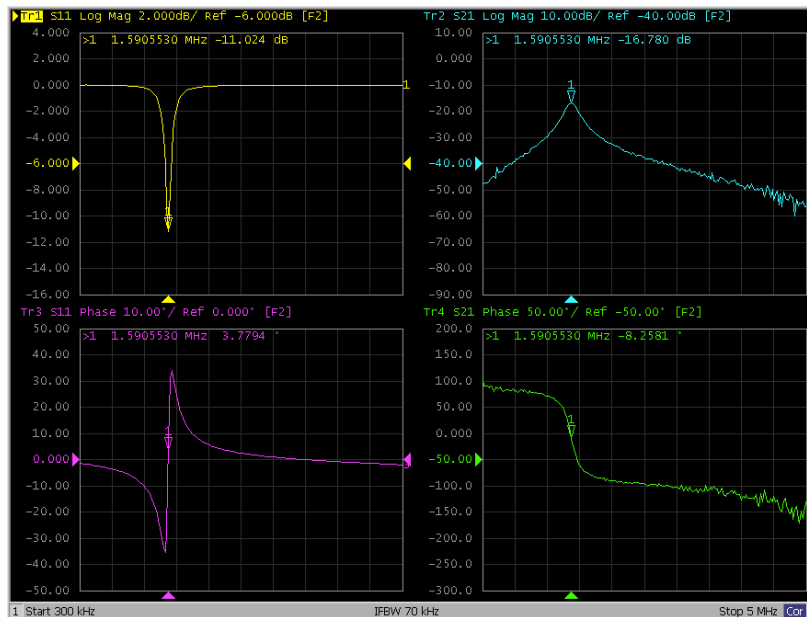


Figure 5: VNA bandpass filter S-parameter measurement.

Collected Data

- Screen captures of S_{11} and S_{21} .
- Measured values:
 - Center frequency f_c of the filter.
 - Bandwidth Δf of the filter.
 - Insertion loss (S_{21}) of the filter .
 - Return loss (S_{11}) of the filter.
- Calculate the quality factor Q of your filter using (13). Record the value of Q in Table 8.
- Calculate the input impedance Z_{in} of your filter using Equation (14). Record this value in your logbook.

$$Q = f_c / \Delta f \quad (13)$$

$$\Gamma_g = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \quad (14)$$

SMA Cable length	(m)
Added Electrical Delay	(ns)
u_p	(m/s)
ϵ_r	
β	(rad/m)
L'	(H/m)
C'	(F/m)

Table 5: Experiment 3.1 - Transmission line characteristic parameters

Load	$ \Gamma $ (dB)	$\angle\Gamma$ ($^\circ$)	$ \Gamma $ (dB)	$\angle\Gamma$ ($^\circ$)
	Uncal.		Cal.	
Short				
Open				
50Ω (matched)				

Table 6: Experiment 3.2 - Reflection coefficient for known load impedances.

Frequency of SWR Minimum	MHz
Minimum SWR value	
(lower) Frequency of SWR = 2.5	MHz
(higher) Frequency of SWR = 2.5	MHz
Z_{in}	Ω

Table 7: Experiment 3.2 - Antenna bandwidth.

	f_c (MHz)	Δf (kHz)	Q	S_{11} (dB)	S_{11} ($^\circ$)	S_{21} (dB)	S_{21} ($^\circ$)
Simulated							
Measured							

Table 8: Experiment 3.3 - Bandpass filter characterization.

Lab Report Questions

Experiment 1

Items to Turn in

- Table 5 (5 pts)
- Screen capture of the "point-like" response of the SMA cable. (5 pts)

Questions

1. No measurements were made to compute R' and G' . Explain why? (5 pts)
2. What is the difference between a lossless line and a dispersionless (distortionless) line? Would this technique for measuring the line parameters work for a dispersionless line? Explain why or why not. (5 pts)
3. When performing the electrical delay measurements, why did we choose the short to terminate the cables instead of the matched load? (5 pts)
4. When computing u_p using the electrical delay technique, why did we have to use twice the length of the cable? (5 pts)

Experiment 2

Items to Turn in

- Table 6 (5 pts)
- Table 7 (5 pts)
- VNA Screen captures of the uncalibrated and calibrated short circuit load. (5 pts)

Questions

1. Compare the printouts of the short termination before and after calibration. What was the effect of the calibration? There are three types of errors: drift, systematic and random. In your own words, explain how calibration affects each of these types of errors. (5 pts)
2. Compare each of the loads measured (short, open, matched) to the theoretic reflection coefficient value. Explain any discrepancies, if they exist. (5 pts)
3. What range of frequencies does the antenna that you measured operate over (i.e. what band was it designed for)? (5 pts)

4. Is the antenna that you measured good for broad-band communication systems (20 MHz - 2 GHz)? Explain why or why not. (Hint: recall the connection between the reflection coefficient and the SWR) (5 pts)

Experiment 3

Items to Turn in

- Table 8 (10 pts)
- LTspice® schematic of your filter design. (10 pts)
- Simulation plots of the filters insertion and return loss. (5 pts)
- VNA Screen capture of the filters insertion and return loss. (5 pts)

Questions

1. Explain why it was necessary to perform a Full 2-port calibration in order to measure the frequency response of your filter. (5 pts)
2. Using what you know about the meaning of S_{11} and S_{21} , describe in your own words the meaning of S_{12} and S_{22} . (5 pts)
3. What are the in-band and out-of-band rejection of your filter design? Is it possible to make these calculations using SPICE? Explain why or why not. (5 pts)
4. Compare the measured to the simulated values in Table 8. Does your filter meet the design constraints? Explain possible discrepancies if they exist. (10 pts)

References

- [1] F. Ulaby, E. Michielssen, and U. Ravaioli, *Fundamentals of Applied Electromagnetics*, 6th ed. Prentice Hall, 2010.
- [2] Agilent, “Network analyzer measurements: Filter and amplifier examples,” *Agilent AN 1287-4*, 2006.
- [3] D. Pozar, *Microwave Engineering*, 3rd ed. Wiley, 2005.