1 Laboratory 1

Microwave Measurements

Summary: Introduction to [s]-parameter and spectral measurements with the FieldFox (FFox). Students will measure the s-parameters of an amplifier and characterize its output power capability. Microwave Office (MWO) will be introduced, which will be used to import data and to analyze the results.

1.1 Useful Resources

https://awrcorp.com/download/faq/english/docs/getting_started/gs_datafile.html https://awrcorp.com/download/faq/english/docs/Users_Guide/working_with_graphs.html http://cp.literature.agilent.com/litweb/pdf/N9912-90001.pdf

1.2 Preparation

- Obtain an educational MWO license by going to https://awrcorp.com/register/customer.aspx?univ.
- Use the instructions on the EE150 Moodle site and install the software. Ensure that you specify mils for the units of length during the installation.
- Remember to bring a USB stick for data transfer.

1.3 Required Equipment

Descrition	Model	Quantity	Notes
FFox	N9917A or N9918A	1	-
Calibration Kit	85052D	1	-
10 dB Attenuator	VAT-10+	1	-
Cables	TM26-3131-36	2	-
Amplifier	ZX60-V63	1	http://www.minicircuits.com/pdfs/ZX60-V63+.pdf
Band-pass Filter	VBFZ-5500	1	http://www.minicircuits.com/pdfs/VBFZ-5500+.pdf

Table 1: Required Equipment

1.4 S-parameter Measurements

1.4.1 VNA Calibration

Before the instrument can be used to measure a device it must be calibrated. During calibration the instrument measures a series of precision standards, whose complex reflection coefficients are known. At the end of the calibration the instrument uses the measurements to solve for the 12 error terms associated with 2-port measurement. These errors are then removed from subsequent measurements of the DUT following calibration. For the class we will use open, short, load, thru (OSLT) coaxial calibrations[1].

1. Connect the coaxial cables to port 1 and 2 of the FFox. Torque SMA connectors using the torque wrench[2] to 8 in/lb. Connect 'savors' should be used at the end of the coaxial lines. Port 1 should have a male connector gender and Port 2 a female connector gender.

2. Set FFox to NA mode. **Mode** ⇒ **NA**. Set start and stop frequencies to 0.1 GHz and 18 GHz respectively**Freq/Dist** ⇒ **Start,Stop**. Set the number of points to 1001. **Sweep** ⇒ **Resolution** ⇒ **801.**

3. Set the IF bandwidth to 10 kHz.**BW** ⇒ **IF BW** ⇒ **10 kHz.**

4. Set the power to -30 dBm. **Meas Setup** ⇒ **Power Level** ⇒ **-30 dBm**. *Note that the input power setting is critical for amplifiers. You want to make sure that you set the power level low enough so that its output does not start to compress (or damage the Fieldfox!) and high enough that good measurement accuracy is ensured. For measurements of passives, the input power of the NA should be set as high as possible, as accuracy is the only concern.*

5. Start the Calibration. Select **Cal**.

6. Select **Mechanical Cal Ecal**.

7. On the next screen select **Change Cal Type**. Scroll down and select **Full 2-port**. This specifies that a full 2-port calibration will be performed.

8. The input connectors now need to be specified. This procedure informs that FFox which calibration standards will be used at the two ports, and apply the corresponding corrections

[1]Other calibration types are thru, reflect, line, commonly used for waveguide calibrations

[2]Torquing of connectors ensures that connections are repeatable, typically on the order of -30 dB, while not damaging the connector from excessive torque.

accordingly. Select **Change DUT Connectors**. Scroll through the list and select **3.5 mm**. Ensure that the gender of the connector reads **Male**. If it does not, press **Change Gender** until the correct gender is applied. Select **Next Port 2**.

9. Follow the same process for port 2, but select the gender to be **Female**.

10. At the next window, select **85052D: 3.5 mm Calibration Kit**. Then select **Next Port 2**.

11. Select the same Calkit for port 2, then press **Finish**. The calibration is now ready to start. Press **Start Calibration**.

12. Using the 85052D Calkit, connect the various standards (open,short, and load) to the ends of the test port cables, following the prompts from the FFox. ***Note that when connecting the standards, make sure to turn the connecting nut, do not spin the body of the calibration standard. Spinning the body of the calibration standard wears it contacts, leading to premature failure.***

13. Set the display to Smith Chart, S11.**Measure** ⇒ **S11, Format** ⇒ **Smith**. The Smith Chart will be discussed in Lecture 2. For now, we want to grasp the concept of reference plane extension. The calibration reference plane is defined at the interface of the NA cables following calibration. It can be extended, moved forward into the DUT, by adding phase to the measurement, a reference plane extension. For now, all that is needed to be known about the Smith Chart is that it plots impedance as a function of frequency[3]. A short (0 Ω to ground) is located at the 9 o'clock position of the chart, an open (∞ to ground) at the 3 o'clock position, and a load (50 Ω) at the center of the chart. Adding electrical phase moves the response in a counter clockwise direction about the chart. For an open or short, this moves the response around the outer perimeter of the chart. For the load, it simply rotates about its center.

14. Hook up the calibration short standard to port 1. Note that the response is not at the 9 o'clock position as expected. This is because the actual shorted plane of the standard is located several mm inside of it. We will determine what this distance is. Hint: it is close to an integer number of mm. First save the data, insert your clean USB drive. Then select **Save/Recall** ⇒ **Device**⇒ **USB, File Type** ⇒ **Data** ⇒ **S2P**, then select **Save**. Enter the file name of your choice and select **Done**.

[3] In fact many additional quantities can be determined from the Smith Chart, these will be discussed in the second lecture

15. Now select **Meas Setup** ⇒ **Port Extensions,** ⇒ **Port Extensions** ⇒ **On.**

16. Now determine the time taken for input wave to travel 1 mm down port 1, at the speed of light. Enter this value as the port extension selecting the appropriate time units. Keep incrementing the number of sec delay (corresponding to integer value of mm) until the response as viewed on the Smith Chart is close to being centered at the 9 o'clock position. Adjust the value by several psec to get it perfectly centered. Note done the value and save the data to file using the method previously described.

17. Now turn the port extensions off **Meas Setup** ⇒ **Port Extensions,** ⇒ **Port Extensions** ⇒ **Off.**

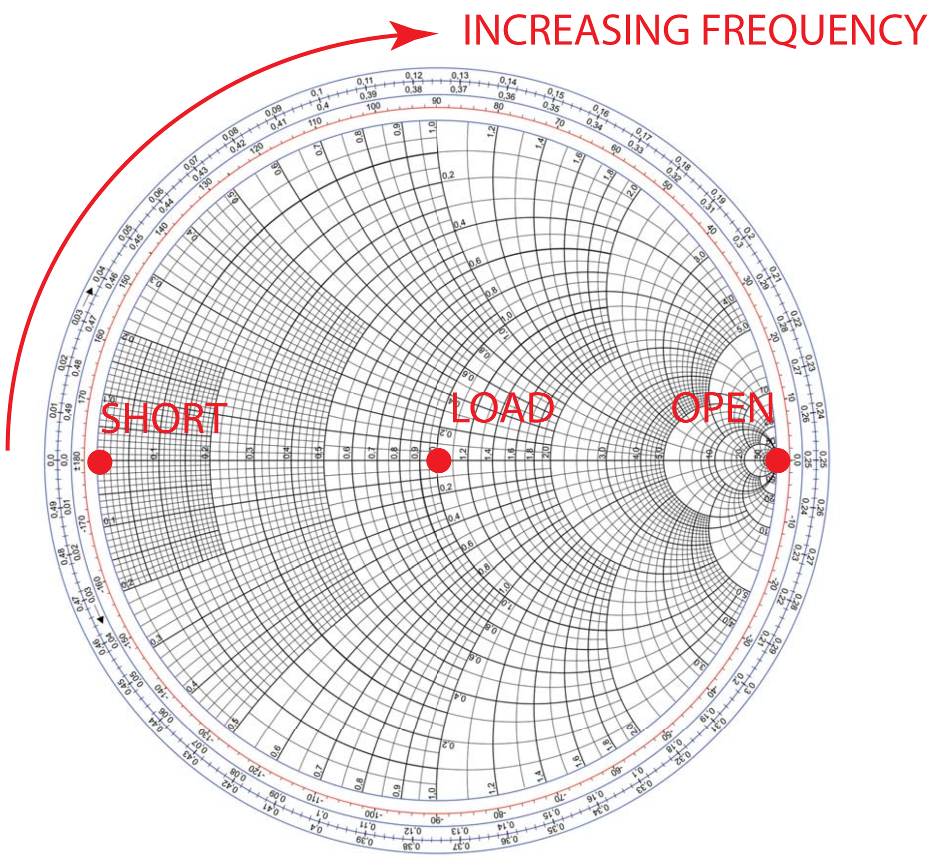

Figure 1: The Smith Chart

1.4.2 VNA Measurements

The S-parameters of an amplifier and filter will be measured, individually and cascaded, with the VNA. MWO will be later used to compare the results.

1. Hook up the Mini-Circuits (MC) amplifier, port 1 to the input and port 2 to the output. Torque the connectors.

2. Turn on the DC supply. Set the over voltage protection (OVP) to 5.5 V and the over current protection (OCP) to 100 mA. Set the nominal voltage to 5 V and disable its output (output off).

3. Hook the DC supply to the amplifier, check the connections, and turn the amplifier bias on. **Note down the final bias voltage and current**.

4. Allow the VNA to sweep several times. The response should closely match that in the datasheet. Use the FFox data markers for comparison. **Save the data to file**.

5. Take a photo of your setup.

6. Disable the DC supplies output. Remove the port 2 connector and place the MC band-pass filter at its output. The orientation of the filter does not matter, but it must be consistent with the next set of measurements and your analysis later. Replace the port 2 FFox cable.

7. Enable the power supply, record the voltage and current, and save the data from the FFox to file.

8. Disable the power supply and remove the amplifier from the test setup. Replace the port 1 connector onto the input of the filter.

9. Save the data to file.

10. Take a photo of your setup.

1.5 Spectrum Analyzer Power Measurements

The spectrum analyzer feature of the FFox will be used to measure the P1dB point of the amplifier (output power at 1 dB gain compression).

1. The 1 dB compression point and saturated output power of the amplifier will now be measured.
2. Set the FFox mode to Spectrum Analyzer. **Mode** ⇒ **SA**.
3. Set the start and stop frequencies to 1 and 18 GHz respectively. **Freq/Dist** ⇒ **Start/Stop**
4. Set the number of sweep points to 801. **Sweep** ⇒ **Points** ⇒ **801**.
5. Set the resolution bandwidth (RBW) to 3 MHz. **BW** ⇒ **Res BW** ⇒ **Man** ⇒ **3 MHz**. Set the video bandwidth (VBW) to 100 kHz.**BW** ⇒ **Res VBW** ⇒ **Man** ⇒ **100 kHz**.
6. Attach a 10 dB attenuator to the output of the MC amplifier, but do not connect it to the FFox. This protects the input of the FFox from damage, but will have to be removed from your measurements later.
7. Set the frequency of the Hittie or National Instruments Signal Generator (GEN) to 5.9 GHz.
8. Set the input power to -20 dBm.
9. Attach the output cable on the GEN to the port 2 cable of the FFox[4]. Torque all connections.
10. Turn on the GEN. Place a marker on the observed output tone at 5.9 GHz. **Marker** ⇒ **Peak.** Record the output power (it will not be exactly -20 dBm, due to instrument error and cable losses).
11. Increase the input power on the GEN by 1 dBm. Record the power.
12. Continue increasing the input power and record the power in 1 dBm steps until the reading at 0 dBm has been taken.
13. Turn the power of the GEN back down to -20 dBm and turn its output off.
14. Hook the GEN cable to the input of the amplifier. Hook the output of the amplifier to the input of the FFox.
15. Connect the DC power supply to the amplifier and enable its output. Note down the final bias voltage and current.

[4]Note, the SA input is port 2, port 1 is inactive in SA mode

16. Turn on the GEN. Place a marker on the observed output tone at 5.9 GHz. **Record the output power.**.
17. Save the data to file. In SA mode select**Save/Recall** ⇒ **File Type** ⇒ **Data (CSV)**.
18. Increase the GEN power 1 dBm. **Record the output power**.
19. Continue increasing the input power in 1 dBm steps to 0 dBm, recording the output power at each GEN setting.
20. At 0 dBm, also save the data to file. You will have to spectral plots saved, one at -20 and one at 0 dBm input power.
21. Take a photo of your test setup.
22. Turn the GEN power back down to -20 dBm and disable its output.
23. Disable the power supplies output.
24. Remove all items from the setup.

1.6 Report Guidelines

- Although labs are done in teams, lab reports must be individually prepared and submitted.
- Reports must be typed and submitted as a .pdf.
- Report should include
  1. A brief introduction describing the lab and its purpose.
  2. A section for each of the measurements, describing what was measured, the conditions (bias), and the results of your measurement/analysis.
  3. A summary providing what was learned, including areas of for further improvement.
- Photos of tests setups for each phase of the laboratory must be included.
- DC bias values (voltage and current) should be included in the title of all graphs where measured data is presented.
- Any differences between simulated and measured values should be thoroughly explained.

1.7 Data Analysis and Report, 100 points

Reports are due by noon October 3rd, emailed to drussell@caltech.edu and to dwinker@caltech.edu

- Open up the Lab1 MWO template from the Moodle site.
- Using the first useful resource link at the beginning of this report, import your .s2p measurements into the MWO file. Your spectral measurements will be handled differently.
- The template already contains the reference .s2p files for the amplifier and filter, downloaded from the Mini-circuits site.
- Go to the Graphs tab of the Project tab in MWO and locate the graph 'Amplifier'. Add your measurements of the amplifier alone to this graph. Ensure Mag/dB is selected for each of the four S-parameters added. Add the measured bias value of the amplifier to the title.
- Change the colors and line types of the traces to make the differences been the MC sourced S-parameters and your measured values clearly visible. One suggestion is to use solid lines for your measurements and dashed lines of the same color for the MC values. The second awr resource at the beginning of this report describes how to modify graph lines,types, etc.
- Include this plot in your report.
- Do the same for the graph 'Filter', importing and formatting your measurements and include it in your report.
- Open up schematic 'AmplifierAndFilterIdeal'. Two ports have been added, you will add the individual S-parameter files from MC as blocks in between the 2-ports and wire them up.
- Go to the 'Elements' tab. Scroll down to 'Subcircuits' in 'Circuit Elements'. Find the data file for MC amplifier measurement and add it to your schematic. Similarly find the MC filter data and add it to the schematic. Wire port 1 to port 1 of the amplifier and port 2 to port 2 of the filter. Wire port 2 of the amplifier to port 1 of the filter.
- Simulate the file and add the S-parameter measurements to the graph 'AmplifierAndFilter'.
- Now add your measurements of the amplifier and filter combination to the same graph. Again note down the measured bias values in title.

- Format the traces as before for clarity
- Include the graph in your report, along with explanations of any differences between measured values and those obtained from MC. Hint: What items were needed to attach the individual elements to the calibrated NA ports?

- Import the measurements of the short calibration standard following NA calibration.
- Go to the schematic 'ReferencePlane'.
- Using the same procedure as with the amplifier and filter, add the measurement file as a block to your schematic, for the measurement of the short alone, without reference plane extension.
- Go to the Element tab, Find Transmission Lines, Physical, and select TLINP to be added to your schematic. Wire port 1 to TLINP, and its output to port 1 of your measurement file. Ground port two of the measurement block.
- Now you need to emulate the effect of reference plane extension in MWO. You will do this by finding the value of parameter L of TLINP which allows the simulated result to concentrate at the 9 o'clock position on the Smith Chart. L will be negative. Why?
- In Graph 'Reference Plane' add your mesurement of the short following calibration, that with the reference plane extension, and the simulated measurement.
- Calculate the value of L in mils (1/1000 inch) from the reference plane value you determined experimentally. Enter this value into parameter L in the schematic and adjust its value until the response is centered at the 9 o'clock position, if necessary.
- Include the graph in your report.

- Plot out the measured input vs output power. Include bias parameters in the title (along with what was measured).
- From your measurements, what is the output power at 1 dB gain compression? Does this agree with the value in the MC datasheet? **Remember to remove the effect of the 10 dB attenuator you added to your test setup.**

- Import the data from spectral measurements at -20 and 0 dBm into Excel or Matlab.
- Bonus (10 pts). Script, using Matlab or Python, a routine that imports and plots the data contained in this section. Include with your report.
- Plot the two data files in the same graph.
- What is the value, in dBc, or dB below the primary tone, of the second harmonic? How much non-linearity, in %, does this represent?
- Remember to include a photo of your test setup.