

Lab 3: Calibration and De-Embedding

In this lab you are going to simulate the behavior of a vector network analyzer (VNA), an instrument used to measure reflection coefficients. We haven't talked about a vector network analyzers in class yet (though we will), but you should still be able to gain an appreciation of the practical difficulties involved in measuring reflection coefficients.

After this lab, you will be able to:

1. Interpret Smith Charts for common loads and parasitic effect that you will see in labs.
2. Simulate the reflection coefficient of a load using S-Parameter simulation and plot Smith Charts. (Optionally using RF packages like Scikit-RF and PyPlot.)
3. Describe and implement a calibration procedure for unknown fixturing attached to a load.

Practical Questions

1. Figures 1 and 2 depict design files for boards in the lab that are referred to as the "50 ohm through" board and the "40 ohm through" board. The [KiCAD files for test boards](#) can be found at the embedded link (to the RF webpage). These boards were built in the OshPark two-layer PCB fabrication process. I've included screenshots of the layouts in Figures 4 and 5.
 - a. These boards, like many, are specified in units of mils. What's a mil?
 - b. What type of transmission lines are implemented on these boards?
 - c. Find a formula describing the characteristic of that type of transmission line and verify that the dimensions of these boards are labeled honestly.

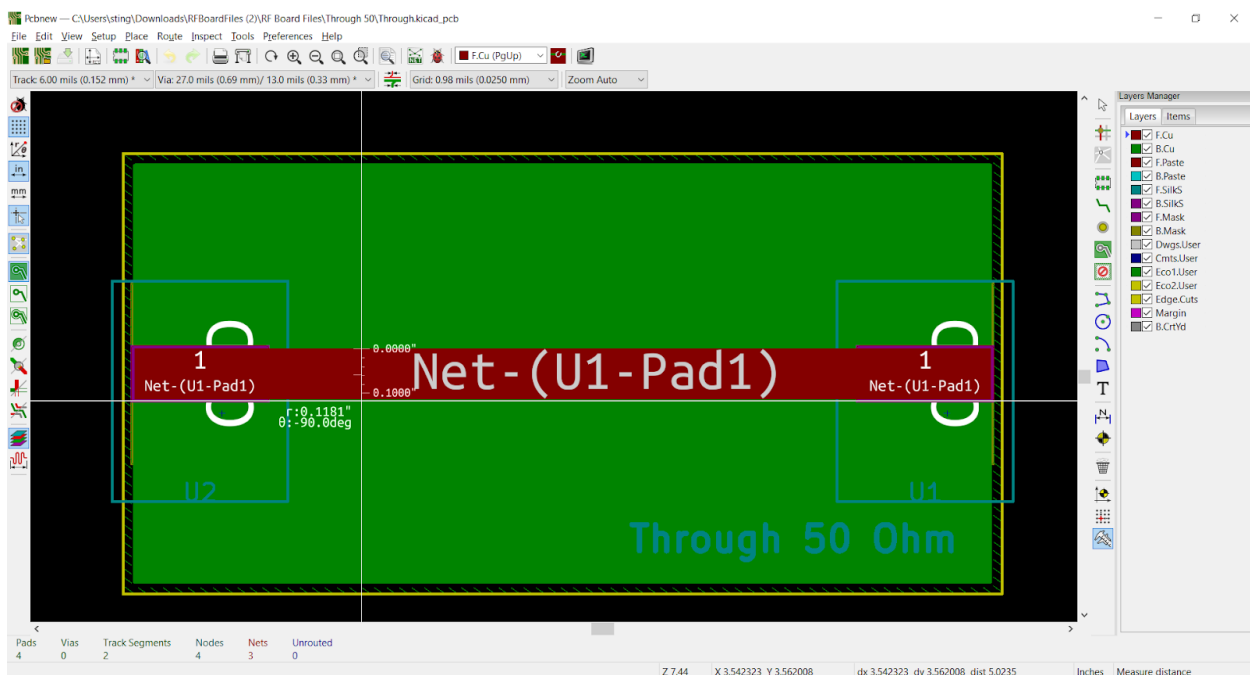


Figure 1: 50 ohm through

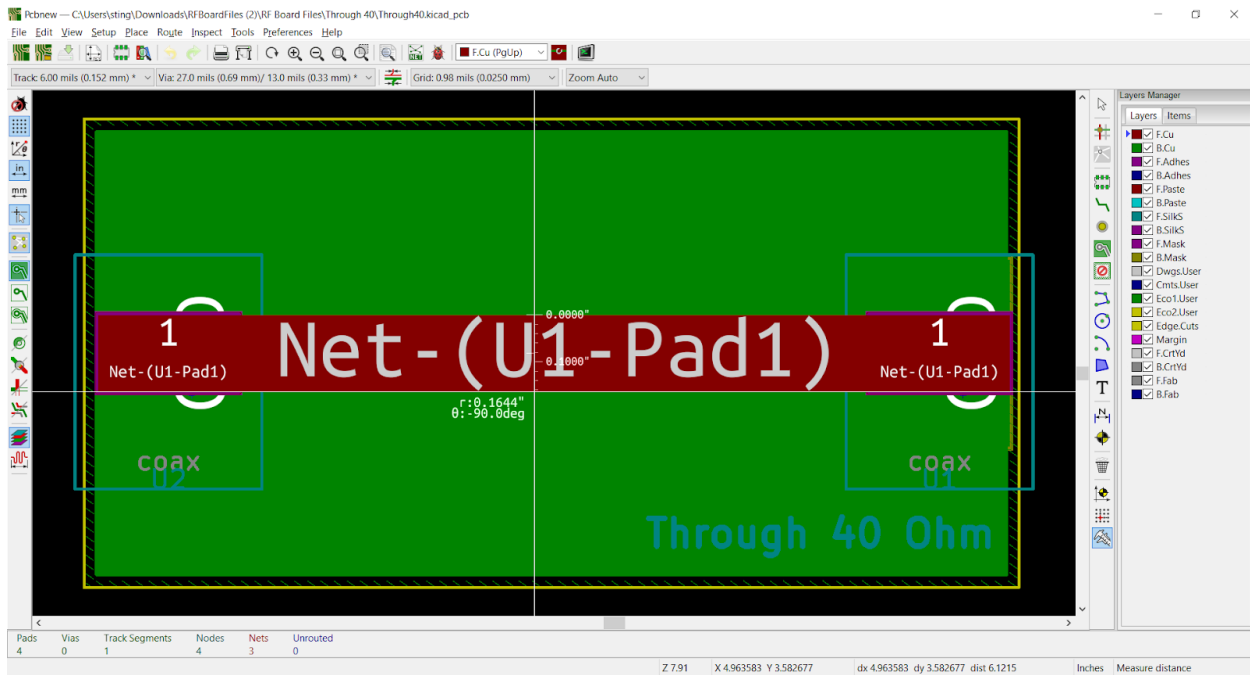


Figure 2: 40 ohm through

2. What is an SMA landing pattern and how can it affect the design of RF printed circuit boards?
3. Why are the SMA connectors on this designed to mount on the sides of the board rather than vertically?
4. What is a mating plane in an SMA connector? (Or any connector.)
5. What is a slotted line, and how does it relate to a vector network analyzer? What does the “vector” in vector network analyzer refer to?
6. What is the difference between a wrapped phase plot and an unwrapped phase plot?
7. What is the measurement plane when you are taking a radio frequency measurement?
8. What does DUT stand for?
9. Is it easier to build high quality short circuits or open circuits at very high frequencies?

Theory Questions

These questions center on using a vector network analyzer (VNA) to take a measurement of the reflection coefficient of a device under test. We need a few facts about VNAs to approach these questions. First, some vocabulary: the cables and connectors used to connect a VNA to a device under test are referred to as fixturing. Second, what does a VNA do? For now, it's OK to think of the function of a vector network analyzer as generating sinusoids of different frequencies while measuring magnitude and phase of reflected sinusoids (not the sum of sinusoids that forms the standing wave pattern). This means your VNA will produce two points of data at each measurement: $|V_{\text{reflected}}(f, S)|$ and $\angle V_{\text{reflected}}(f, S)$ where f is the driving frequency, S is the length of the fixturing cable, $| \cdot |$ is the magnitude operator and $\angle \cdot$ is the phase operator.

For these questions, note that SMA cables have a velocity factor of 0.8 and a characteristic impedance of 50 ohms. Note also that vector network analyzers all have 50 ohms of source impedance on each port.

1. A 10cm long SMA cable is terminated in a short circuit and driven by a VNA. The VNA is set to measure the frequency range from 800MHz to 1.2GHz.
 - a. Draw a Smith Chart indicating the locus of reflection coefficients the VNA will perceive when it compares the magnitude and phase of reflected waves to the incident wave.
 - b. Draw a plot of (wrapped) reflection coefficient phase vs. frequency for this combination of fixturing and load.
 - c. Draw a plot of the magnitude of the reflection coefficient vs. frequency for this combination of fixturing and load.
 - d. Repeat parts a-c assuming the cable is 1m long instead of 10cm.
2. In problem 1, you should have observed a rapidly changing value in your phase vs. frequency plot. That change in phase is a property of the cable you use, not of your load (which is presumably what you're trying to measure). Can you perform some mathematical operation on your data so that your measured magnitude and phase only reflect the properties of the load? i.e.: What mathematical transformation would you apply to $|V_{\text{reflected}}(f, -S)|$ and $\angle V_{\text{reflected}}(f, -S)$ to find $|V_{\text{reflected}}(f, 0)|$ and $\angle V_{\text{reflected}}(f, 0)$?
3. If you were using a VNA to drive an unfamiliar cable, how could you calculate the length of the cable in wavelengths by measuring the reflections from a short termination? Can you compute the phase shift (wave number * S) of a signal with frequency ω using you calculated length? Hint: Recall that VNAs can operate at many different frequencies, and you can take advantage of that in your measurement.
4. Design an L-match from a 100 Ohm load to a 50 Ohm characteristic impedance at 1GHz using a shunt capacitor. What is the bandwidth of this matching network?
5. Use a series-to-parallel transformation to find the quality factor of the network in Figure 3 at frequency ω .

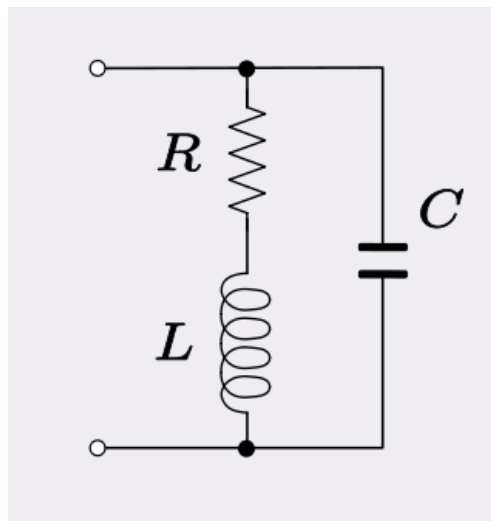


Figure 3

Lab Instructions

These steps are going to simulate the use of a VNA to measure reflection coefficient. This simulation won't include every parasitic of a VNA, more on that soon, but will require you to "de-embed" your DUT by correcting your data for the fixturing that you are using (which is idealized in simulation). You can do

this with either AC simulations or S parameter simulations. If you use S-parameters, then think of the parameter S11 as the reflection coefficient for now. This writeup will describe your simulation results in terms of S11, though you may be looking at the ratio of voltages in an AC simulation instead.

1. Simulate the circuit in Figure 4 to represent a VNA driving a 1m long SMA cable driving a short circuit. Vary the drive frequency from 800MHz to 1.2GHz. This figure includes an unfamiliar transformer network, which is called a directional coupler. It is used to extract the reflected wave from the sum of the waves. More on directional couplers and transformers at these links: <http://k6jca.blogspot.com/2015/01/notes-on-directional-couplers-for-hf.html> <https://www.analog.com/en/technical-articles/ltspice-basic-steps-for-simulating-transformers.html>
 - a. Plot $\langle S_{11}(f) \rangle$, $|S_{11}(f)|$ and a Smith Chart of $S_{11}(f)$. ItSpice won't plot a Smith Chart for you, so you'll need to export your data and use an external program capable of making polar plots. Overlay Smith Chart reactance and resistance curves on any plot you make. (I find that scikit-rf, a Python package, simplifies this process a great deal. Your mileage may vary. <http://scikit-rf.org/> for more information.)
 - b. Use information from this simulation to calculate correction factors for this cable that you will use to remove cabling effects from your S11 data. Pretend that you don't know the length of your transmission line when performing this calculation.
 - c. Apply this correction to the data from this simulation and verify that your short circuit is in the right place on the Smith Chart.

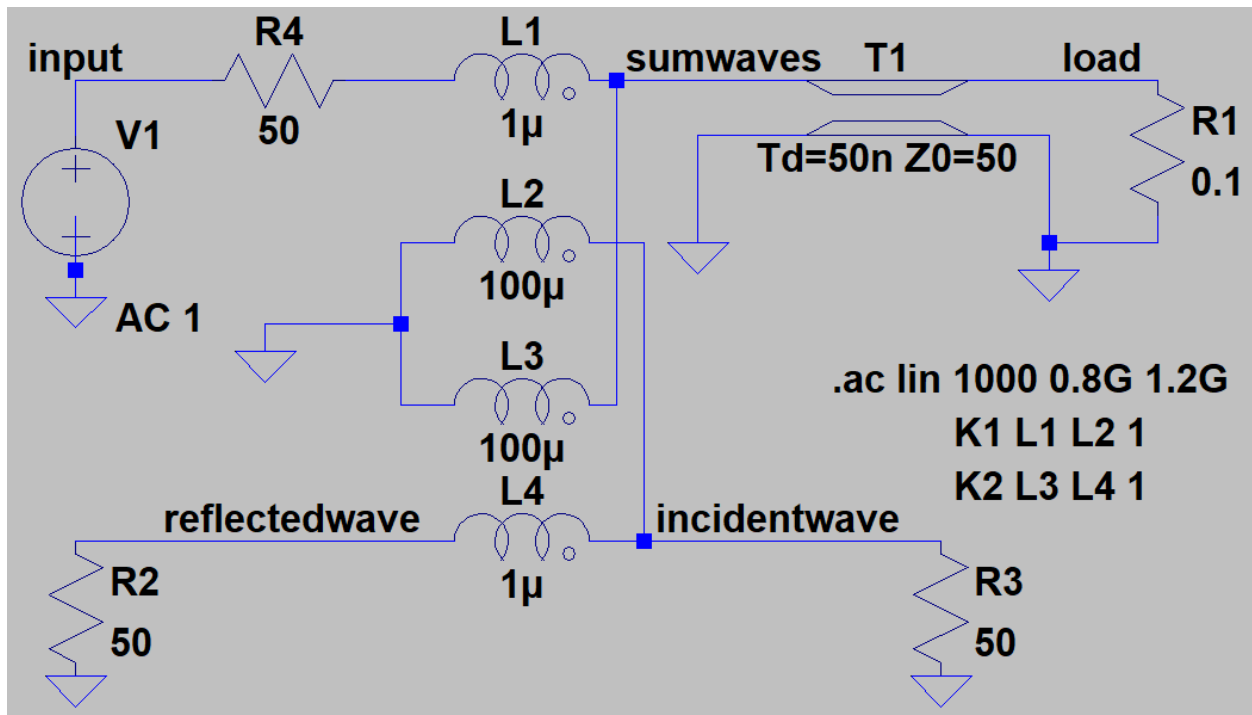


Figure 4: Simulated one-port vector network analyzer with directional coupler.

2. Simulate a VNA driving through the same cable into the following loads and make plots of $\angle S_{11}(w)$, $|S_{11}(w)|$ and Smith Charts of $S_{11}(w)$ for each of them. Vary the drive frequency from 100MHz to 10GHz.
 - a. A 100 ohm resistor
 - b. A 100 ohm resistor with a 1.6pF capacitor in shunt
 - c. A 100 ohm resistor with a 1.6pf capacitor in shut and a 8nH resistor in series.
 - d. A resistor soldered in shunt between the transmission line and a shorting pad on the "Filter" board in the package of KiCAD files linked above. This resistor can be effectively modeled by Figure 3, where the resistor represents a resistance of your choice, the capacitor represents parasitic capacitance between the metal of the shunt pad and ground, and the inductor represents the series inductance of a via in the (look up an approximation for inductance in a via).
3. For lab instructions 2a-c, compare the results of these simulations against the L-match you designed in theory problem 4.
4. For lab instruction 2d, compare the resonant frequency in your simulation against your answer to theory problem 5.

Required data in lab notebook: $\angle S_{11}(f)$, $|S_{11}(f)|$ and Smith Charts for $S_{11}(f)$ for each termination. Include both the calibrated and uncalibrated data for the short, but otherwise only include the calibrated data. Calculations for de-embedding your DUT. Calculations comparing bandwidth and center frequency of your matching network to simulation results. Calculations comparing the resonant frequency of the structure in Figure 3 against simulation. (You may need to copy some of the answers of your theory questions into the lab notebook to make these final two data requests make sense.)