

Lab 3: Vector Network Analyzer and L Matching Networks

In this lab you are going to calibrate and use a vector network analyzer (VNA), an instrument used to measure reflection coefficients. (You'll also simulate its behavior, a particularly instructive exercise.) We haven't talked about a vector network analyzers in class yet, but you should still be able to gain an appreciation of the practical difficulties involved in measuring reflection coefficients. We will use the VNA to characterize a circuit that you will solder onto a printed circuit board: an L matching network.

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. Calibrate a VNA an
4. Design an L matching network
5. Solder surface mount passive and connector components
6. Characterize components using a VNA.

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 impedance of that type of transmission line and verify that the dimensions of these boards are labeled honestly.
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. What is fixturing when you're making a measurement with a VNA?
10. Is it easier to build high quality short circuits or open circuits at very high frequencies?

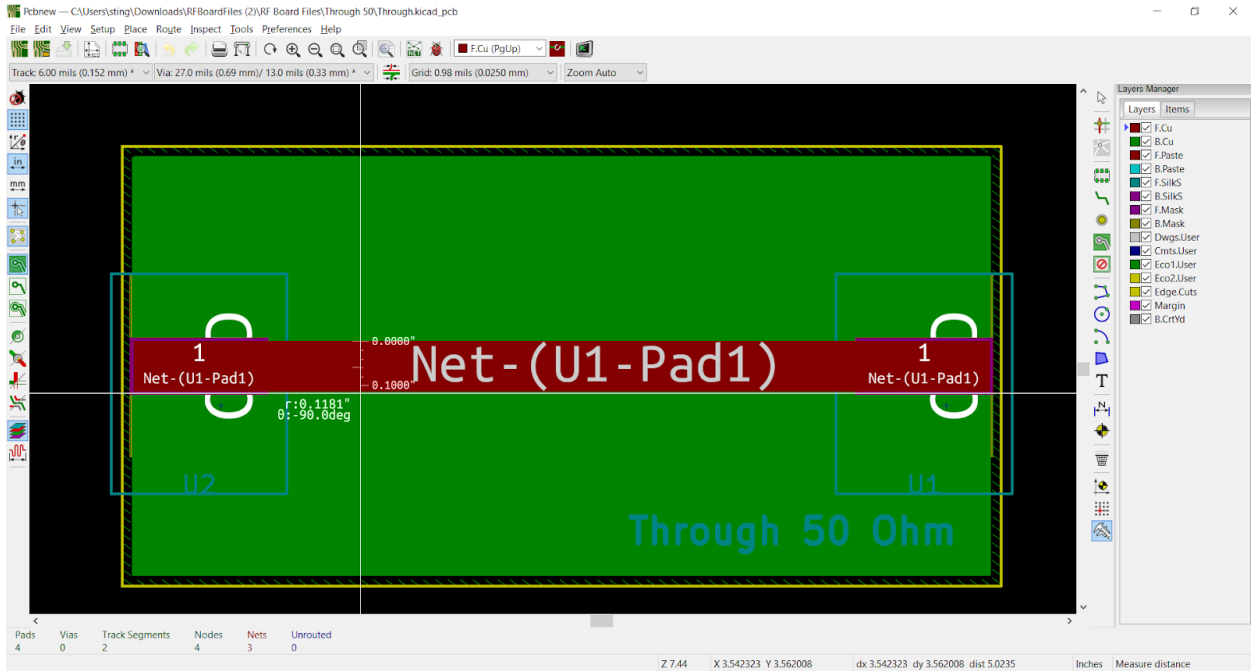


Figure 1: 50 ohm through

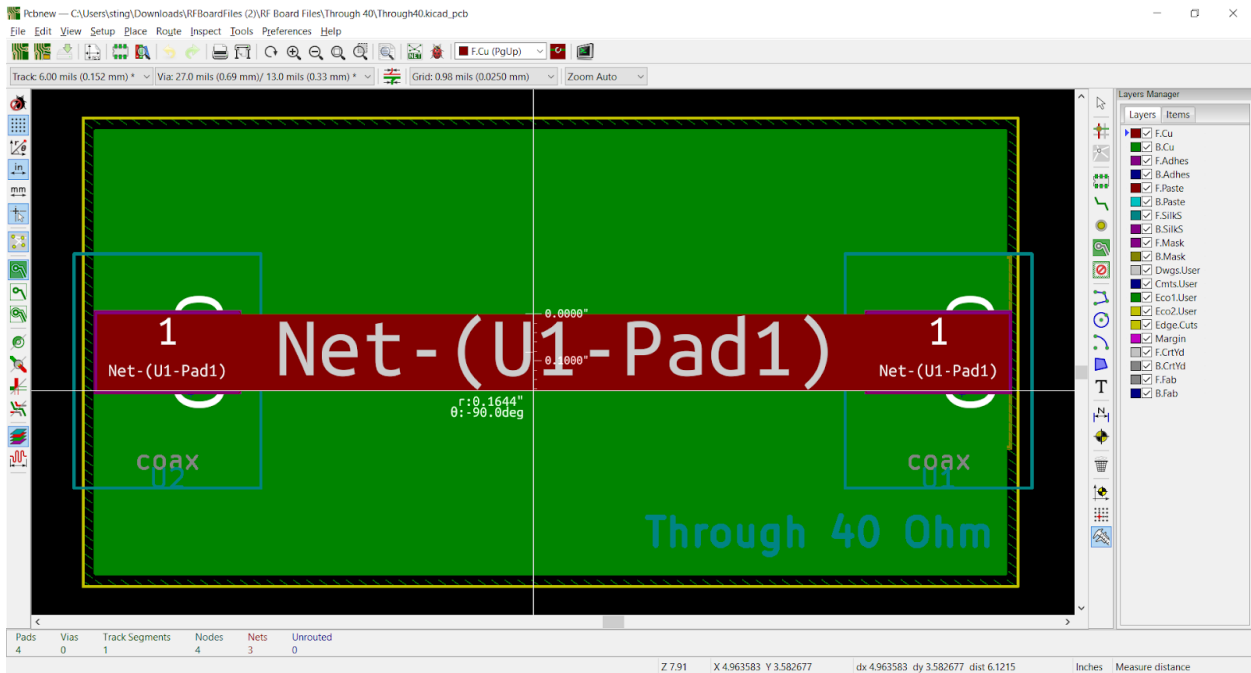


Figure 2: 40 ohm through

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. For now, it's OK to think of the 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 point f : $|V_{\text{reflected}}(f,-S)|$ and $\angle V_{\text{reflected}}(f,-S)$, where f is the driving frequency (swept during operation), S is the length of the attached cable, $|*|$ is the magnitude operator and $\angle*$ is the phase operator. These mathematical expressions presume that we define $x=0$ at the load and $x=-S$ at the source. These reflections can be compared with the forward wave, which is a known quantity because we transmit $V_{\text{forward}}(f,-S)$ onto the line.

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 1m long SMA cable is terminated in a short circuit and driven by a VNA. The VNA is set to measure the frequency range from 70MHz to 130MHz.
 - 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 reflection coefficient phase vs. frequency for this combination of cable and load. Please provide a wrapped phase plot (see practical question 6).
 - c. Draw a plot of the magnitude of the reflection coefficient vs. frequency for this combination of cable and load.
 - d. Repeat parts a-c assuming the following conditions: 1m cable with open termination, 1m cable with 50 Ohm termination, 10m cable with short termination.
2. When you calibrate a VNA (more on how we do that later), you multiply your reflected wave by a complex number that cancels out the effect of the cable. The most prominent effect of the cable is that it adds a lot of phase to our measurements, which you can see by reflecting on the propagation equation: $V(x,t) = V(0,t) \cdot \exp(-\alpha \cdot x) \cdot \exp(-j \cdot k \cdot x)$. We can capture the effect of calibration in our analysis and simulation by multiplying our uncalibrated results by $\exp(+j \cdot k \cdot x)$ to cancel out the phase from the cables. In this question, we're going to practice doing that using a simulation of a VNA.
 - a. Figure 3 (below) is a starting point for simulating a VNA. The schematic uses ideal mutual inductance (the K statements) to represent the behavior of a directional coupler, a circuit element that separates forward and reverse waves. (We'll talk about these more in a few weeks.) The node labels indicate the wave voltages that will be observed on that node, so the reflectedwaveover20 node will display the reflected wave voltage scaled by a factor of 20. Build and simulate Figure 3.
 - b. Modify figure 3 to express each of the situations in theory question 1. Make sure simulations and analysis match.
 - c. Plot $\angle \Gamma(f)$, $|\Gamma(f)|$ and a Smith Chart of $\Gamma(f)$ for each of your schematics. 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. Be sure to overlay Smith Chart reactance and resistance curves on any plot you make.
 - i. 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.

- ii. Alternatively, you can convert an LtSpice AC simulation output file to a Touchstone s1p file, which can be read by Matlab. Be sure to use the in the real, imaginary output format for your AC simulation file, not the magnitude, phase format. Then (1) save the AC simulation output with a filename that ends in “.s1p”, (2) replace the first line with “# Hz S RI R 50”, and (3) replace all commas with spaces. Note that S11 and Γ are synonyms (for this lab).
(here is the s1p spec, FYI: https://ibis.org/connector/touchstone_spec11.pdf)
 - d. Multiply your exported, uncalibrated data by a correction factor that removes the phase of the cables and then replot magnitude, phase and Smith Charts for your newly calibrated Γ . Compare your points to analysis.
3. Design an L-match from a 50 Ohm transmission line to a 270 Ohm load at 100MHz using a series capacitor. What is the bandwidth of this matching network?
 4. Use a series-to-parallel transformation to find the quality factor of the network in Figure 4 at frequency ω_0 , the natural frequency of the resonant network.

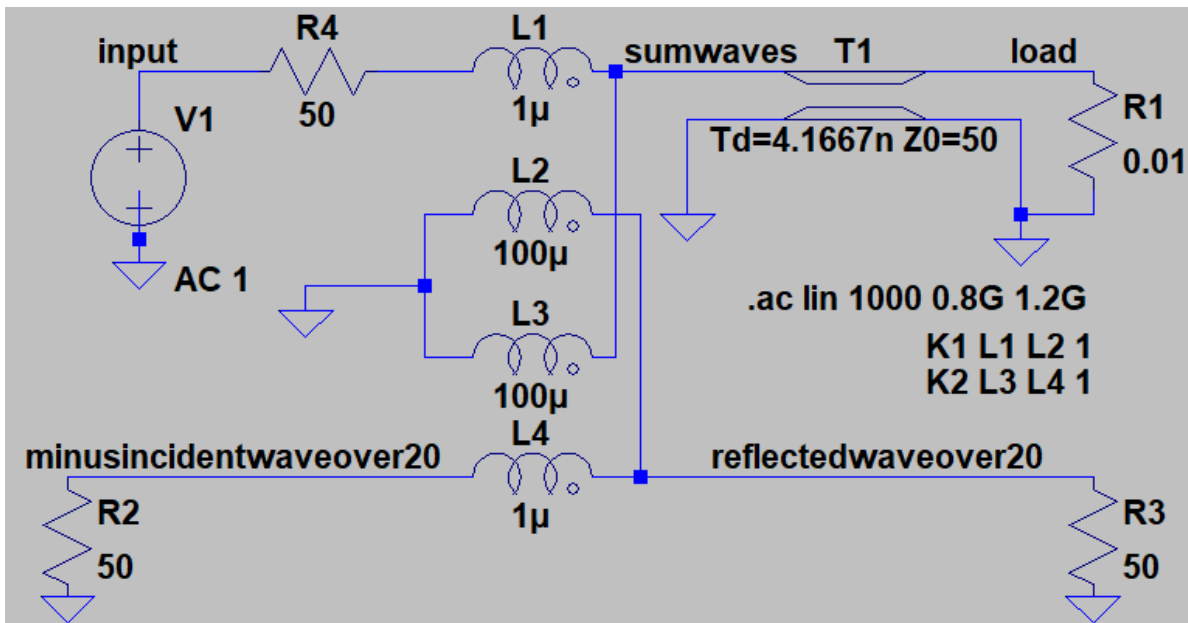


Figure 3: Simulated one-port vector network analyzer with directional coupler.

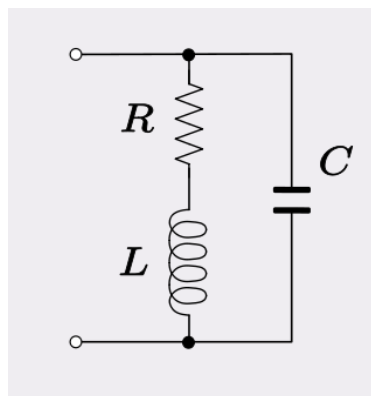


Figure 4

Lab Instructions

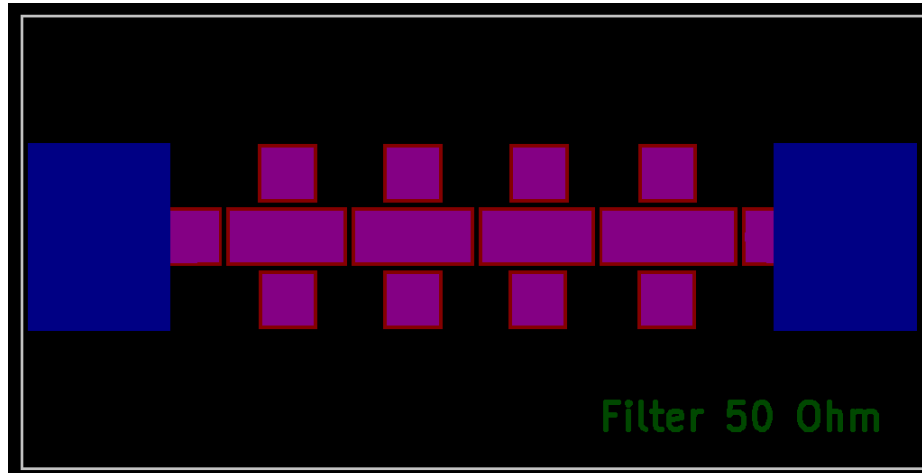
These lab instructions will walk you through the basics of VNA operation, VNA calibration and surface mount construction of radio frequency modules. We will use the Siglent SVA1000X VNA that sits on the bench in the North of the RF lab. This is technically not a full vector network analyzer, it's a spectrum analyzer with a tracking generator, but it is sufficient for this lab. Watch the videos and consult the manuals below to learn some details of operation:

- <https://www.youtube.com/watch?v=AfKowzuxVtI&list=PLmTIWEcPkWvi8XD-j4zHAEUyIsEBEzTe1&index=5>
- <https://siglentna.com/spectrum-analyzers/sva1000x-spectrum-vector-analyzer/>
- https://siglentna.com/wp-content/uploads/2020/07/UserManual_UG0703P_E02A.pdf

Note that we only use the TG port of the VNA during this lab. We will not use the RF input port. Also note that S_{11} is a synonym for reflection coefficient in this lab.

1. Observe operation of a VNA before calibration.
 - a. Connect a SMA cable to the TG port of the VNA. Terminate the cable with a short. (Don't use the calibration standard for this because it is fragile, there are plenty of other SMA shorts lying around the lab.)
 - b. Set your frequency to span to be 70MHz to 130MHz and then configure the instrument in VNA mode. (Side note: we're not messing with your tracking power level because it could be basically anything for this lab without jeopardizing your results, but I advise staying between -20dBm and 0dBm.)
 - c. Manipulate the display to plot S_{11} magnitude, S_{11} phase and a S_{11} Smith Chart, and record these data for your lab notebook. Screenshots may be OK for your lab notebook here if you make judicious use of markers. However, if you export a screenshot, always also export raw data in case you need to do analysis later. Cell phone photos of data are never OK for a lab manual.
 - d. Use your analysis from theory question 1 to justify your observations. Also create a simulation that represents this scenario and compare it to your measurements and analysis.
 - e. Repeat step c for the following two terminations: an open and a 50 Ohm load. Compare your results to appropriate analysis and simulation.
2. Calibrate the VNA and observe how your measurements change.
 - a. Follow the calibration process demonstrated in the video linked above.
 - b. For each of our three terminations (open, short, 50 Ohm load), measure S_{11} magnitude, S_{11} phase and an S_{11} Smith Chart. Compare these results to your observations in lab instruction 1 and theory question 2. What has changed? Does it match theory?
 - c. Change your frequency span to 90MHz to 110MHz, and see if your results still look calibrated. Calibrations are specific to the frequency range, so you need to recalibrate when you change your span. This exercise is to warn you about that!
 - d. Set your span back to 70MHz to 130MHz and recalibrate.

3. Get used to soldering onto our boards
 - a. Watch this video for a refresher on the basics of soldering:
<https://www.youtube.com/watch?v=oqV2xU1fee8>
 - b. Watch this video for a visual reference on how to solder 0805 components, the kind we use in our lab, to a printed circuit board:
<https://www.youtube.com/watch?v=PU7wLcuqc-l>
 - c. Find the filter boards in our lab. They look like this:



- d. Solder a side launch SMA connector to one side of your filter board. Pay very close attention to your ground connections on the back side (they need to be rock solid) and don't over-solder your signal connection on the front side.
 - e. Starting from your connector, solder two series 0 Ohm resistors and a shunt 270 Ohm resistor.
 - f. Measure the (calibrated) S11 magnitude, phase and Smith Chart of this combination of zero Ohm series plus 270 Ohm load, and compare to analysis and simulation.
4. Build the L match that you designed in Theory question 3.
 - a. **DON'T START WITH A FRESH BOARD!** This section asks that you start by manipulating board you've already populated in section 3.
 - b. Instead, add the component of your L match that is closest to your load to your board. If the component that's closest to your load is a series component, replace one of the zero Ohm resistors with this component. If it's shunt, you can just solder it next to your load.
 - c. Look at (and record) the S11 Smith Chart for the combination of this first component and your load. You can account for errors in your manufacturing by looking at the 100MHz point on this Smith Chart. If it isn't where you designed it to be, you can just compute the appropriate inductance to make the best of your situation, and use that instead of your original design. Designing matching networks component by component, looking at the Smith Chart between each soldering job, is an important trick for achieving good results in bespoke, hand-manufacturing of RF boards.
 - d. Solder in your second component, then look at the S11 Smith Chart for your completed L match.
 - e. Finally, when the network is complete, extract the Q value of the network from your results. Compare it to theory.

5. Optional Extra Credit: Design a T match from a 200 Ohm load, simulate it, assemble it and measure it.
6. Optional Extra Credit: Parasitic components are very important in RF design, and small parasitics in your board may be affecting your matching network designs. For extra credit, you can use zero Ohm resistors to extract your parasitic pad capacitance and parasitic via inductance as follows.
 - a. Solder a zero Ohm resistor in series from the SMA connector to a pad, then solder a large capacitor in shunt from the pad to ground. It's important to pick a capacitor with modest ESL, but it needs to be large enough to swamp out other sources of parasitic capacitance. Observe resonance in S11, then back out what inductance causes it. That inductance is most likely a byproduct of your via.
 - b. Remove the shunt capacitor and replace the series zero Ohm with a series inductor. Observe resonance again. The inductance causing the resonance is your series inductor plus your via inductor. The capacitance causing the resonance comes from the parasitic capacitance of the pad.

Required data in lab notebook:

Simulated and measured $\langle \Gamma(f), |\Gamma(f)|$ and Smith Charts for $\Gamma(f)$ for each of the following, along with appropriate analytical comparisons

- Your three uncalibrated measurements (one for each termination) in instruction 1. For all future VNA measurements, only provide calibrated results. However, the uncalibrated results are interesting in this specific part of this lab.
- Your three post-calibration measurements in instruction 2. You may omit the measurement when you change to 90MHz to 110MHz.
- The measurement of your zero Ohm resistors + 100 Ohm termination at the start of your soldering practice.
- The measurement you took after each step of assembling your L match. Make sure to include a marker on your Smith Chart showing where 100MHz is.

Also, be sure to include photographs of your filter board as you construct it.

Finally, provide measurements showing the Q of your matching network, and show that the Q matches your designed Q value. If you provide screenshots (instead of post-processing your data), then be sure to include markers at the points you measured to calculate Q.