Experiment One
Fundamentals of Electromagnetics Lab
EECE2530/1

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Abstract

The goal of this laboratory experiment is to familiarize oneself with the functions of a vector network analyzer, while, at the same time, applying knowledge of transmission lines and Smith chart analysis. This is done by plugging various components into the vector network analyzer and analyzing their Smith charts and phases.

KEYWORDS: vector network analyzer, transmission line, Smith chart, phase

1 Equipment

Available equipment included:

- E5063A Vector Network Analyzer
- Type N Calibration Kit:
  - Open Circuit
  - Short Circuit
  - Matched Load ($50[\Omega]$)
- Type N to BNC Adapter
- Resistors, capacitors, and inductors

2 Introduction & Objectives

We started off this laboratory experiment by acquainting ourselves with the E5063A Vector Network Analyzer. We first established the correct settings for the network analyzer, after which the machine was tested with various calibration scenarios. Short, open, and matched loads were used to determine whether the network analyzer was well-calibrated. The results of the calibration can be seen in Figures 1-3 below.

Then, assuming the speed of light to be a constant $3 \cdot 10^8 \left[\frac{\mathrm{m}}{\mathrm{s}}\right]$, we determined the length of the transmission line inside of the network analyzer.

Finally, we connected various components, such as capacitors, resistors, and inductors, to determine whether the circuit components had expected behavior at all frequencies, then determining the wavelength in the cable and the dielectric constant.

3 Results & Analysis

First and foremost, the calibration kit yielded the following results:

Figure 1: Shorted Load Smith Chart

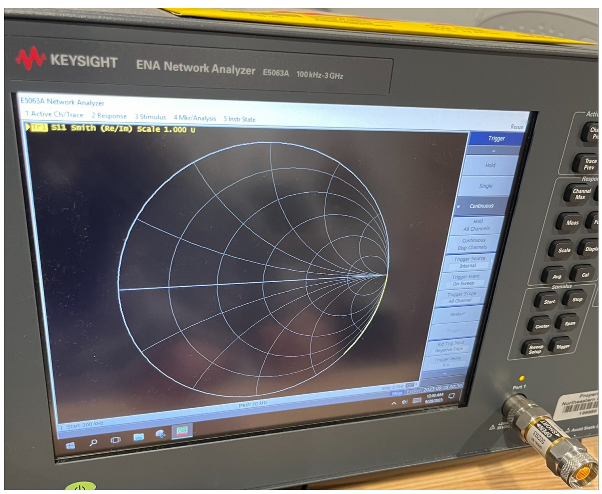

Figure 2: Open Load Smith Chart

Figure 3: Matched Load Smith Chart

Evidently, we see the behavior is exactly as expected; that is, the shorted load appears at the top left of the Smith chart, with slight variation, and the opened load appears at the bottom right, with some variation. The matched load, on the other hand, occurs right at the center of the chart, as it should when the impedance is matched.

We then used this data to estimate the length of the transmission line inside of the network analyzer, Δz, assuming the speed of light in the transmission line as c. As shown in Figure 4 below, the phase shift is roughly 67.87° — we rounded to 70°.[1]

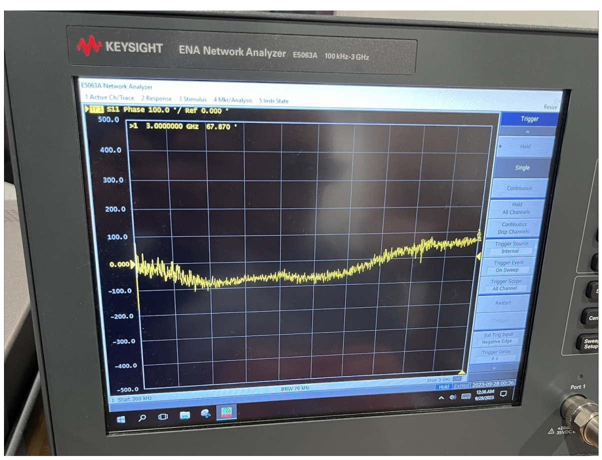

Figure 4: Phase for Matched Load

[1] As a continuous sweep, the phase would jump from roughly 60 to 80 degrees; thus, 70 seemed an appropriate estimate

The calculation performed began with the formula

$$e^{-j\theta} = e^{-2j\beta\Delta z}$$

$$\theta = 2\beta\Delta z$$

$$\Delta z = \frac{\theta}{2\beta}$$

In terms of radians, we found θ as:

$$\frac{70 \cdot 2\pi}{360} = 1.2217[\text{rad}]$$

We know $\beta = 2\pi/\lambda$, and $\lambda = c/f$. Substituting gives us:

$$\Delta z = \frac{\theta c}{4\pi f}$$

Using the values we have, we get:

$$\Delta z = \frac{(70)(3 \cdot 10^8)}{4\pi(3 \cdot 10^9)} = 9.97 \cdot 10^{-3}[\text{m}] \approx 1[\text{cm}]$$

We now connect the BNC adapter. With an open-circuit BNC, we obtain the Smith chart shown in Figure 5:

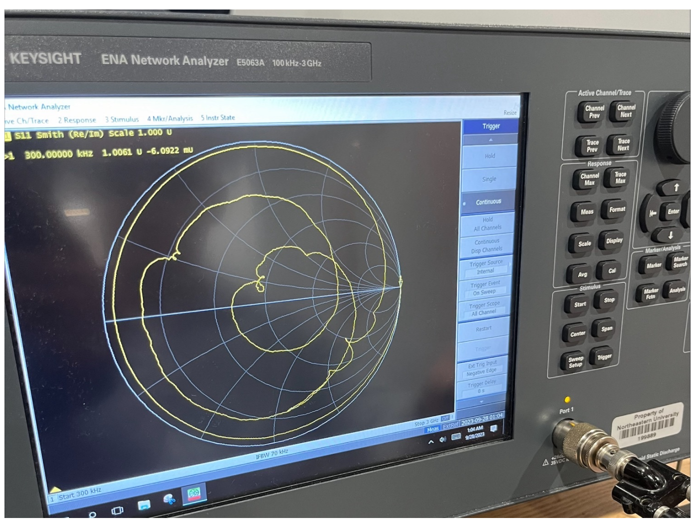

Figure 5: Open Load with BNC Adapted

We can see that the output immediately becomes more lossy than the open circuit calibration connector. This can be explained by the fact that the BNC adapter adds length to the transmission line. In doing so, more of the same wavelengths can fit, which means the wave travels farther. Thus, more of the current and voltage is lost.

We know plug in various components with the BNC, as described in Figures 6-8:

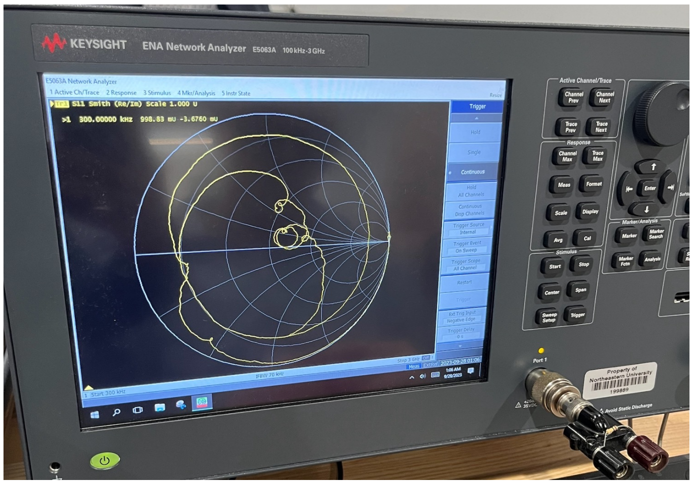

Figure 6: BNC with Resistor

The resistor more or less looks as it should; that is, it starts with no impeding component; however, as the frequency increases, significant loss occurs.

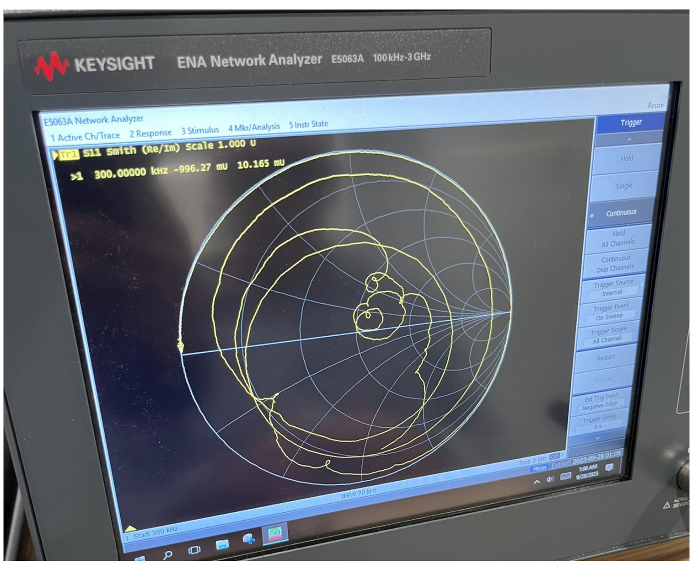

Figure 7: BNC with Capacitor

At lower frequencies, the capacitor appears as it should — it is following an impedance proportional to $-\frac{j}{\omega C}$. As the frequency increases, however, a loss occurs, as indicated by the spiral. This can be explained by the fact that capacitors begin as open circuits, but, at high frequencies, capacitors act as short circuits.

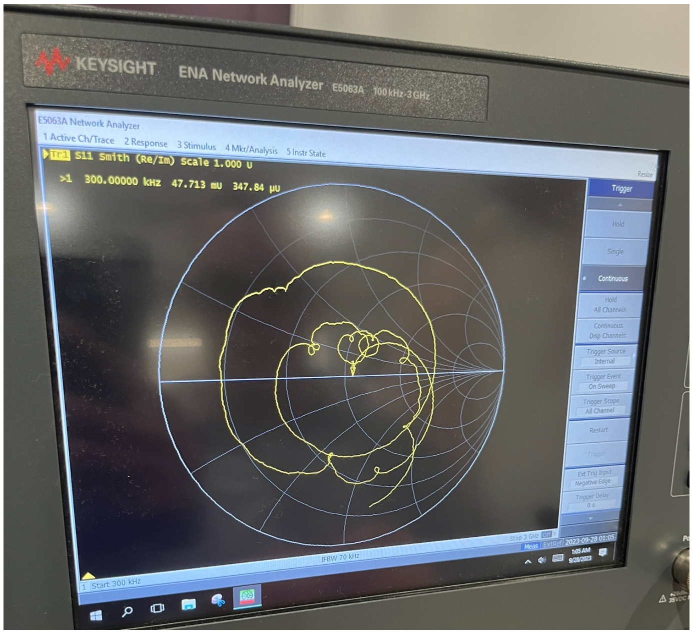

Figure 8: BNC with Inductor

In the picture above, the inductor doesn't behave exactly as expected; this is most likely because it was not coiled tight enough. We do see, however, a tendency for lossiness as the frequency increases.

After this, we plug in a short and long wire, as shown in Figures 9 and 10:

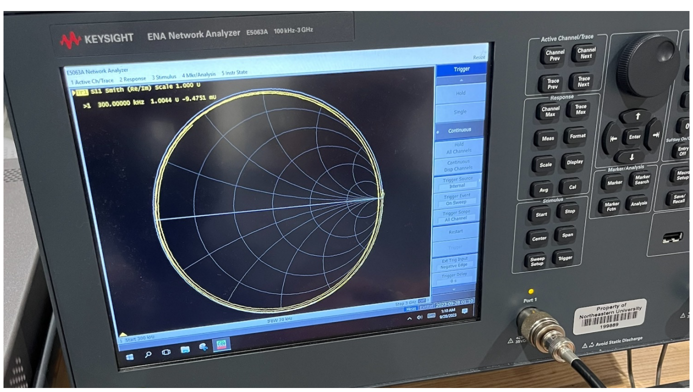

Figure 9: The Short Wire

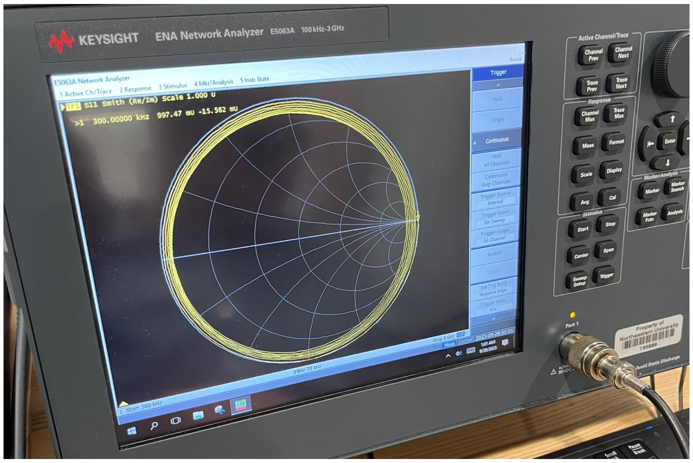

Figure 10: The Long Wire

We see that, with the longer cable, the Smith chart has more “rings” or loops. Logically, this makes sense. We know that a single “loop” is one phase/360 degrees. As a wire gets longer, it will fit more phases/wavelengths in it, and, thus, display more loops in a Smith chart. Both wires show increasing losses, as the circles spiral into the center. The length of the cable was measured as approximately 23.5[cm]. We can then calculate the dielectric constant:

$$\varepsilon_r = \left(\frac{\lambda_o \theta_m}{4\pi \Delta z}\right)^2$$

Using the values we obtained for the longer wire, we get:

$$\varepsilon_r = \left(\frac{(.1)(7.5\text{ cycles})}{4\pi(.235+.01)}\right)^2$$

$$\varepsilon_r = \left(\frac{(.1)(47.124[\text{rad}])}{4\pi(.245)}\right)^2 = 2.34$$

Now analyzing the amplitude, phase, and Smith outputs for a matched load, we find the outputs shown in Figures 11-13:

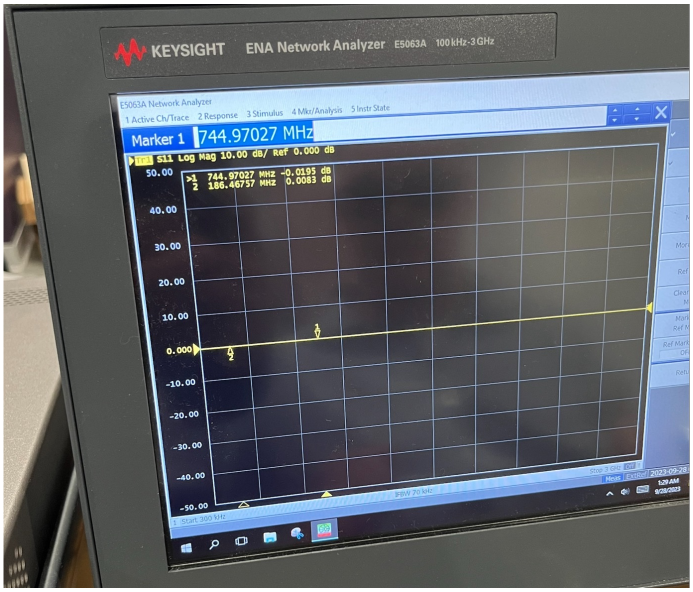

Figure 11: The Amplitude Display with Log Magnitude

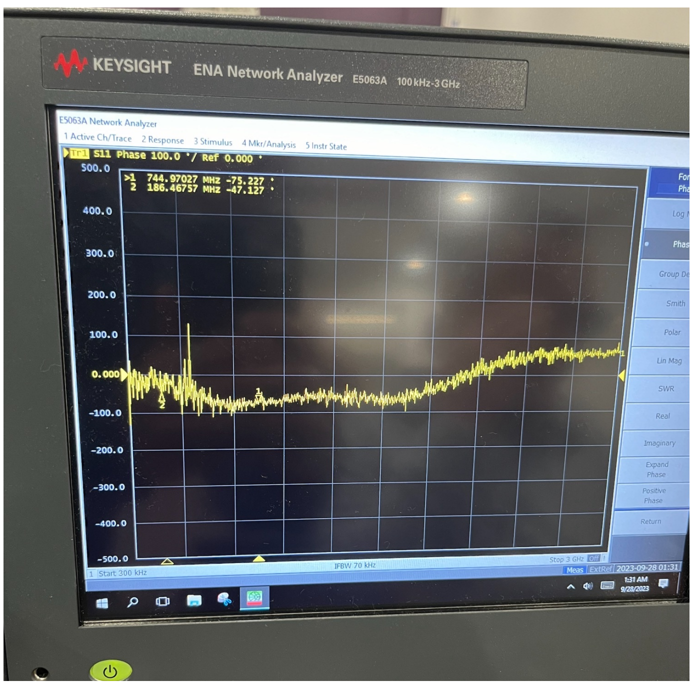

Figure 12: The Phase Display

Figure 13: The Smith Chart Display

Overall, the most graphically concise (that is, most information in simplest format) chart seems to the Smith chart. Though it depends on exact purpose (like, sometimes, the phase display can more easily show the phase angle), the Smith chart seems the best tool.

4 Conclusion

4.1 Questions

a. How does the Smith chart frequency dependence of the matched load compare with the frequency dependence of any other component load that you tried? Can you get 50[Ω] load at any frequency? Can you get a 50[Ω] load at more than one frequency at the same time?

   Unlike all of the other tested components, the matched load is independent of the frequency; that is, no matter what the value of the frequency was, the load was displayed at the same point on the Smith chart. This indicates that it is possible to obtain a 50[Ω] (matched) load at any frequency (or, at least, in the wide range we tested). Furthermore, as indicated by the matched load, it is possible to have a load at more than one frequency at the same time.

b. Is the impedance of the components what you expect at low frequencies (0.3 MHz)? What happens when the frequency increases toward 3 GHz?

   With the exception of the inductor (most likely due to poor coiling), all of the devices behaved as expected at low frequencies. The resistors both stayed at roughly the same impedance value to begin with, but then, due to the lossy line, the impedance was slightly shifted. The capacitor, beginning as an open circuit as expected, began to increase in lossiness, and act more like a short circuit. It was expected that the inductor would begin as a short circuit and then, at high frequency, spiral inwards; however, the inductor never began as a short circuit. Overall, however, it is apt to say that, generally, at low frequencies, the components acted as expected, but increased in lossiness as we approached 3 GHz.

c. Explain in your own words how the network analyzer can display the impedance of the device under test (DUT) by measuring the amplitude and phase of the reflection from the DUT of a known transmitted signal.

   A vector network analyzer utilizes the input signal and reflected signal to determine impedance characteristics. It measures the amplitude and phase of the original signal and then compares it to the reflected wave. In doing so, the vector network analyzer is able to display the information in its impedance form.

d. Explain how you can analyze your data to find the "electrical length" of the cable? How can you compare the electrical length with the physical length of the cable to get a value for the effective dielectric constant of the cable? Assuming that all the materials are non-magnetic, the effective dielectric constant in a coaxial cable is just the ε of the insulating material. Compare the value you get for ε_r to handbook values for insulating materials such as Teflon. Does your measurement make sense? If the insulating material were slightly lossy, what difference would that make? How might you estimate the imaginary part of ε_r from your measurements?

   We determined the "electrical length" of the cable by essentially measuring the amount of wavelengths present in the transmission line at a given frequency, in tandem with the phase angle. We then applied this to the formula:

$$e^{-j\theta} = e^{-2j\beta\Delta z}$$

   After doing this, we used a different wire, which essentially extended the transmission line to determine the dielectric constant. The physical length of the wire was measured and compared to its electrical length in the following formula:

$$\varepsilon_r = \left(\frac{\lambda_o\theta_m}{4\pi\Delta z}\right)^2$$

   The formula leverages a ratio of the "electrical length" to the physical length to obtain a dielectric constant. Our obtained value was 2.34, which is comparable to that of teflon: 2.1. Our result varied by approximately 11.34%, which makes sense. A lossy material would mean a less accurate measurement of the dielectric value. The imaginary part of ε_r can be estimated by way of the loss factor of the material.

4.2 Summary

Overall, we learned about the use and operation of vector network analyzers, as well as how to calculate the electrical length of the cable, and then the dielectric constant from the electrical and physical length. By obtaining a phase angle of 70°, we initially determined that the length of the internal transmission line was approximately 1[cm]. Then, we used this value, in tandem with an external wire, to determine the dielectric constant, or electrical permittivity, of the coaxial insulator. Using a formula we derived for the dielectric constant, we obtained a value of 2.34. As instructed, we compared this value to teflon, which has a dielectric constant of 2.1. Since the two values are quite comparable, we were able to confirm our measurements as fairly accurate. This allowed us to verify what we learned about Smith charts, VNA operation, and various transmission line formulas.