ECE320: Fields and Waves

Lab 2 Report: Standing Waves and Waveguides

PRA106

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1 Introduction

This laboratory session was focused on investigating the voltage standing wave (VSW) pattern along a microstrip transmission line, as well as its depedance on the load impedance. Figure 1 shows the diagram of a microstrip line that sits on the PCB substrate at the bottom and free space (or air) above, due to which the voltage wave effectively travels through $\epsilon_{\text{eff}}\epsilon_0$. We measure the fringing electric field using a probe, acting as a monopole antenna, at the top of the strip. Since the measured, vertically oriented, electric field is proportional to the voltage at that position we are able to determine the VSW pattern along the line.

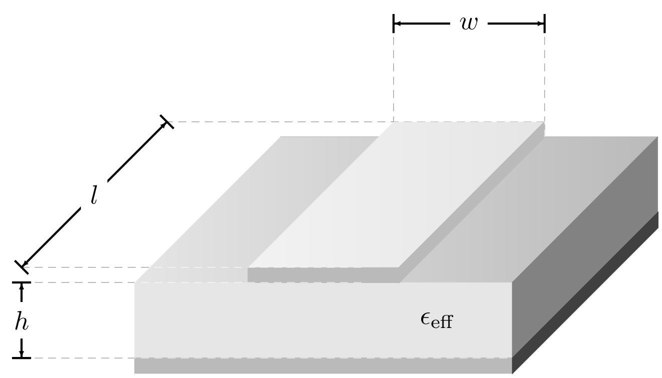


Figure 1: A microstrip transmission line

2 Measurement of Microstrip Line Characteristics

We know that since the wave travels in a compound medium – the PCB substrate and the air – we will have to consider an effective dielectric constant dependant on the geometry as well as the substrate parameters. It has been found that this is best described using a combination of conformal mapping and empiral formulae, which are:

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \left(\frac{\epsilon_r - 1}{2}\right)\left(1 + \frac{10}{s}\right)^{-xy}$$

where $s = \frac{w}{h}$ and

$$x = 0.56\left(\frac{\epsilon_r - 0.9}{\epsilon_r + 3}\right)^{0.05}$$

$$y = 1 + 0.02\ln\left(\frac{s^4 + 3.7\cdot 10^{-4}s^2}{s^4 + 0.43}\right) + 0.05\ln\left(1 + 1.7\cdot 10^{-4}s^3\right)$$

The characteristic impedance of a microstrip line can also be found using empiral formulae, such as:

$$Z_0 = \frac{60}{\sqrt{\epsilon_{\text{eff}}}} \ln\left(\frac{6 + (2\pi - 6)e^{-t}}{s} + \sqrt{1 + \frac{4}{s^2}}\right) \quad \text{where} \quad t = \left(\frac{30.65}{s}\right)^{0.75}$$

We measured the width of the microstrip line and used the above formulae to calculate the theoretical values of the characteristic impedance, effective dielectric constant, the phase velocity of the voltage wave, its wavelength at $f = 1$ GHz, the reflection coefficient at the short circuit load, and the voltage standing wave ratio (VSWR). The results can be found below in table 1.

Parameter	**Value**
w	0.3 cm
Z_0	48.697Ω
ϵ_{eff}	3.347
v_p	$1.639 \cdot 10^8$ m/s
λ	0.163 m
Γ_L	-1
VSWR	∞

Table 1: Theoretically calculated parameters of the microstrip transmission line

Using the vector network analyzer (VNA) in the lab, we sampled the magnitude of the electric field every 5 mm, starting at the location of the first minimum magnitude d_{min}. The experimental SWR pattern can be found in figure 2.

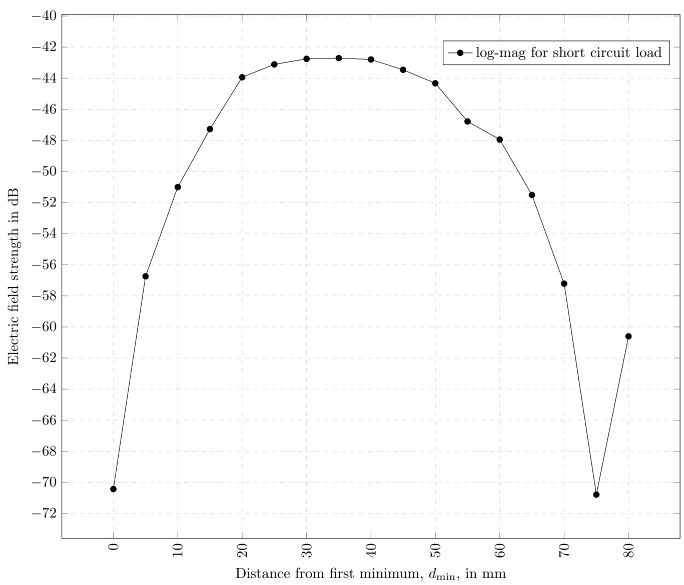


Figure 2: VSW pattern for a shorted load on the microstrip line

Using the data in figure 2, we know that

$$||\tilde{V}_{\text{max}}|| = k \cdot ||\tilde{E}_{\text{max}}|| = k \cdot 10^{-\frac{42.707}{20}} = k \cdot 0.00732$$

Similarly,

$$||\tilde{V}_{\text{min}}|| = k \cdot 10^{-\frac{70.430}{20}} = k \cdot 0.00030$$

Thus,

$$\text{VSWR} := \frac{||\tilde{V}_{\text{max}}||}{||\tilde{V}_{\text{max}}||} = 24.330$$

Although here the VSWR is large, it is still very small compared to the theoretical value of ∞. But to show that our measurements are still accurate, we can show that the corresponding value of reflection coefficient at the load, $||\Gamma_L|| = \frac{\text{VSWR}-1}{\text{VSWR}+1} = 0.921 \approx 1$ is close to the theoretical value of 1. We also measured that two consecutive voltage minimums were ≈ 8 cm apart, thus giving us the wavelength of the voltage wave $\frac{\lambda}{2} = 8 \text{ cm} \implies \lambda = 16 \text{ cm} \approx 16.3$ cm, since the wavelength observed in the SWR pattern is half of the wave's wavelength. Using the above result for wavelength and the chosen frequency of 1 GHz, we get $v_p = 1.6 \cdot 10^8 \text{ m/s} = \frac{c}{\sqrt{\epsilon_{\text{eff}}}} \implies \epsilon_{\text{eff}} = 3.511 \approx 3.347$. Thus, our measurements do closely match the theoretical results for all the parameters.

3 Using Standing Wave Patterns for Load Calculations

Using data from figure 3 and performing similar calculations as above we get

$$||\tilde{V}_{\max}|| = k \cdot 10^{-\frac{46.294}{20}} = k \cdot 0.00484 \quad \text{and} \quad ||\tilde{V}_{\min}|| = k \cdot 10^{-\frac{53.823}{20}} = k \cdot 0.00203$$
$$\therefore \text{VSWR} = 2.379 \quad \text{and} \quad ||\Gamma_L|| = 0.408$$

Here we note that $\Gamma_L = ||\Gamma_L||e^{j\phi_\Gamma}$. To get phase of the reflection coefficient, ϕ_Γ, we recorded the distance of the first minimum from the load towards the generator, $d_{\min} = 6.9$ cm, and used previous measurement of $\lambda = 16$ cm. Thus,

$$\phi_\Gamma = \pi + \frac{4\pi d_{\min}}{\lambda} = 8.561 \text{ radians}$$

We can get the load impedance using our measurements by

$$\Gamma_L = 0.408e^{j8.561} = \frac{Z_L - Z_0}{Z_L + Z_0} \implies Z_L = 24.568 + j18.2892 \quad [\Omega]$$

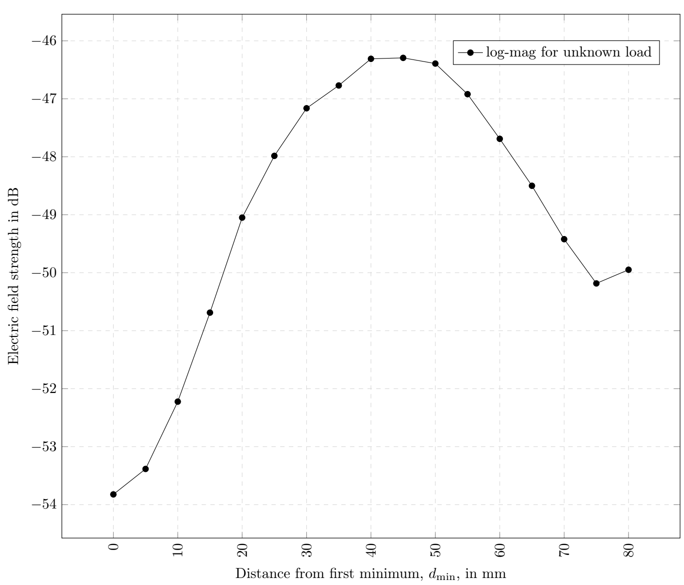


Figure 3: VSW pattern for the unknown load on the microstrip line

This impedance was also measured directly using the VNA on a Smith chart, shown in figure 4. The direct measurement yielded $Z_{\text{L,VNA}} = 29.974 + j4.581$, which has magnitude $||Z_{\text{L,VNA}}|| = 30.322$ which is very close to the magnitude of our derived impedance $||Z_L|| = 30.628$. Since the expression for load impedance, Z_L, is dependant on both ϕ_Γ and $||\Gamma||$, slight errors in measurement make a large difference to the final result due to error multiplication. Our measurements have still given us a good estimate of the actual impedance, and this is also shown on the Smith chart in figure 5.

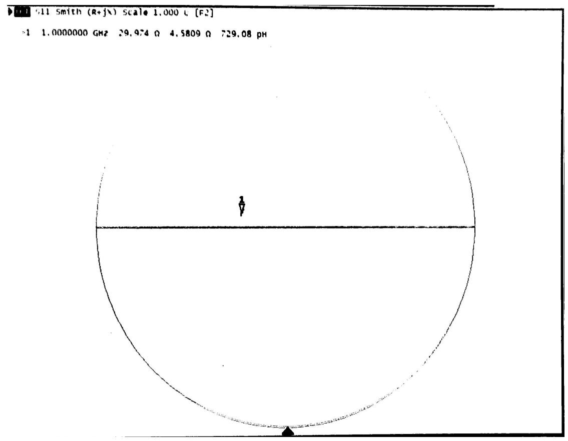


Figure 4: Impedance of the unkown load measured by the VNA

We suspect that the error mainly originates from the adapter as well as the load connector since there was a difference in geometry and material (and hence impedance); the conector and adapater were coaxial instead of a microstrip structure. Furthermore, there could also be error in accurately measuring the added length of the connector.

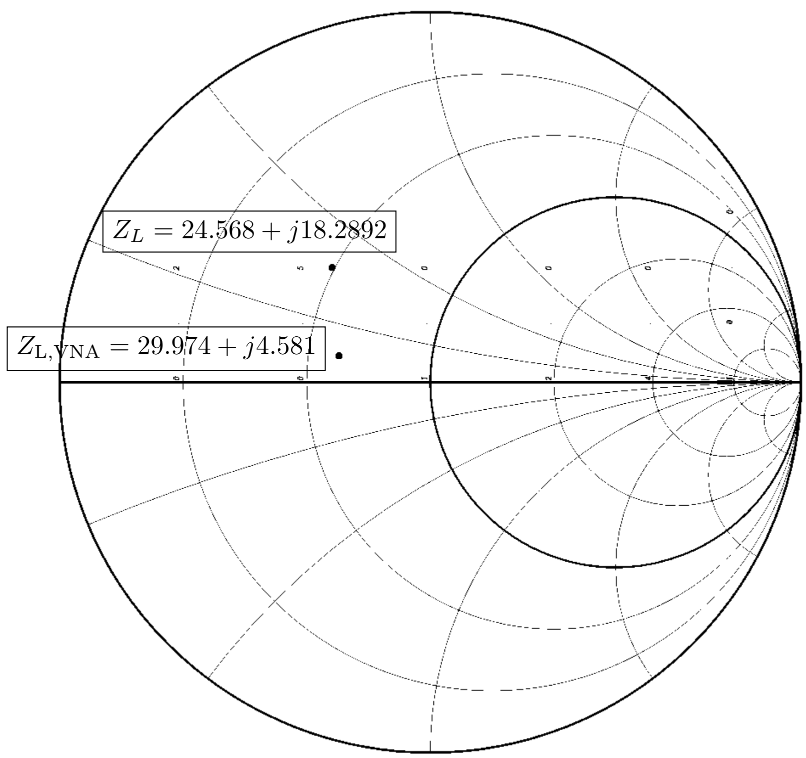
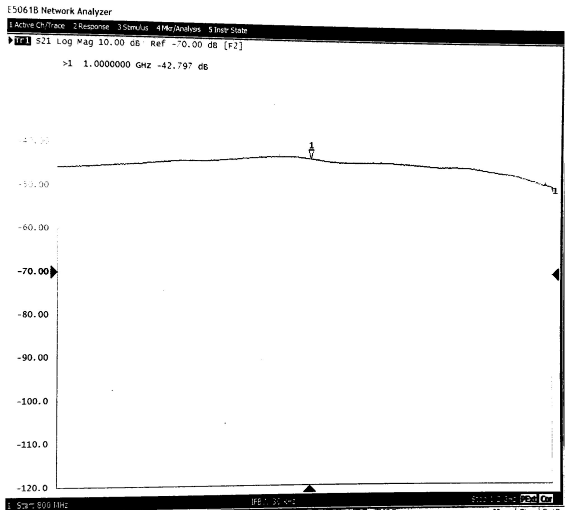


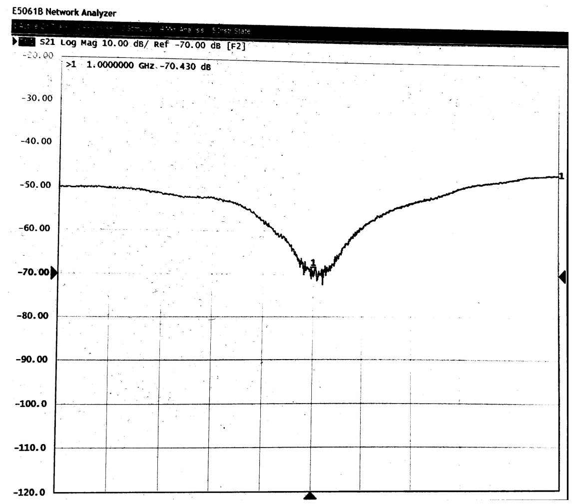
Figure 5: Comparison of indirectly and directly measured imepedance on the Smith chart

4 Appendix

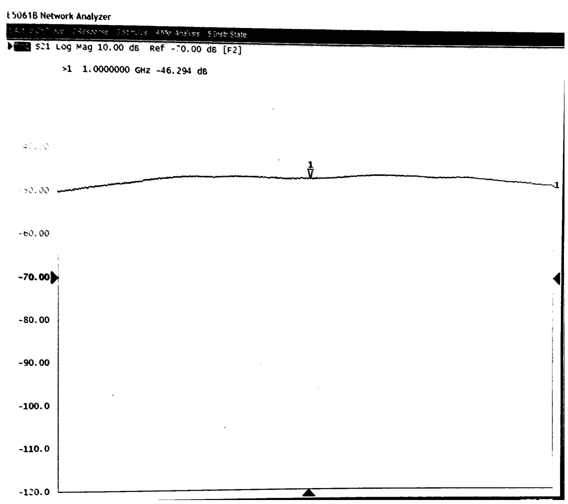
Some key measurements from the log-mag plots on the VNA are shown in figure 6.



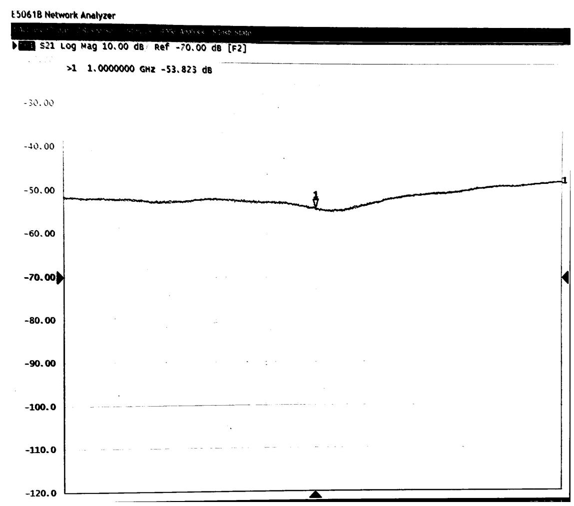
(a) Short circuit load maximum



(b) Short circuit load minimum



(c) Unknown load maximum



(d) Unknown load minimum

Figure 6: Snapshots for measurement of maximum and minimum values of VSW pattern on the VNA

5 Notes

All images taken during the lab were post-processed in a batch using a custom script that bit-wise inverts the pixels and binarizes the resulting image based on a custom threshold. No adjustments or modifications were made to the readings, for which the measurements on the VNA are also shown alongside the waveforms. All scripts and related work can be found at `github.com/pranshumalik14/ece320-labs`.