Xidian University & Heriot-Watt University

PCB Dielectric Constant Measurement

(B39HF | B31HD)

High Frequency Circuit Design

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PCB Dielectric Constant Measurement

1. Introduction

During the process of laboratory2, the first objective is to the dielectric constant of a printed circuit board (PCB), and the next goal is to become familiar with micro transmission lines. Finally, the last goal is to become familiar with the vector Network Analyzer (VNA).

2. Theory

(1) Microstrip lines

The two determining factors of transmission line performance are the geometric structure of the transmission line and the material properties of the transmission line, among which the material properties include many factors such as dielectric constant and permeability. The phase speed of most transmission lines (TEM lines) meets the following formula:

$$\mu_p = \frac{1}{\sqrt{L'C'}} = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}}$$

Formula (1) applies to a uniform transmission line medium (that is, the transmission line medium consists of a solid material). It is usually μ_r= 1. The transmission lines used in this experiment are called microstrip lines. The heat conductor of the transmission line separates the transmission line from the ground plane below and is located at the top of the board. The microstrip transmission line is shown in figure 1.

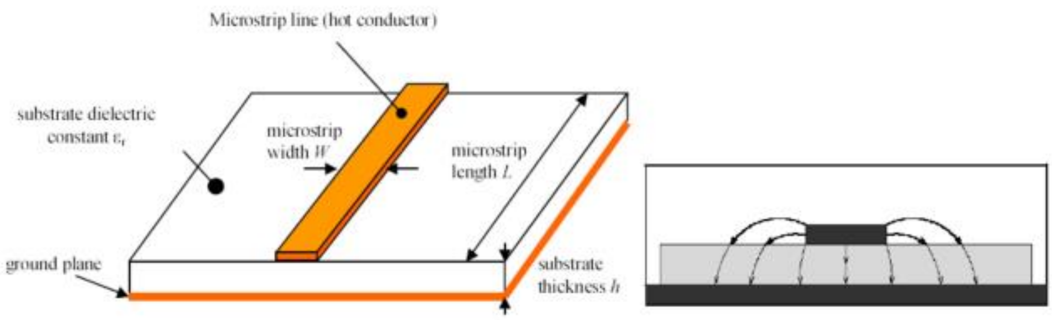


Figure 1. *A microstrip line and its cross-sectional electric field distribution.*

The way some of the field lines of the microstrip extend into the air before descending to the board or substrate can cause the dielectric material of the transmission line to be uneven. However, if we define the effective dielectric constant, we can still use equation (1). The effective dielectric constant will be the dielectric constant of some hypothetical material that completely encloses the microstrip conductor. Since the actual electric field lines are either in air (εr air = 1) or in the dielectric of the substrate (ε_r), it is reasonable to assume that the effective permittivity is $1 < \varepsilon_{eff} < \varepsilon_r$, where ε_r is the actual permittivity of the substrate. By using ε_{eff} instead of ε_r, the phase velocity, guided wavelength λ_g, and characteristic impedance calculated by equation (1) are the same as those of the actual microstrip transmission line. A rigorous mathematical analysis of the microstrip line can lead to the following useful formula

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{\ln\left(\frac{\pi}{2}\right) + \left(\frac{1}{\varepsilon_r}\ln\left(\frac{4}{\pi}\right)\right)}{\ln\left(\frac{8h}{W}\right)}\right)$$

(2) Measuring the effective dielectric constant

In this experiment, a sliding reactive power shunt element will be used to determine ε_{eff}. Using (2) to determine the dielectric constant ε_r of the substrate. The role of the reactive element is to deliberately produce a large reflection coefficient Γ. The reaction shunt element that will be used is just a large piece of aluminum that will stay on top of the microstrip line and come into contact with the microstrip line. The circuit model is shown in Figure 2.

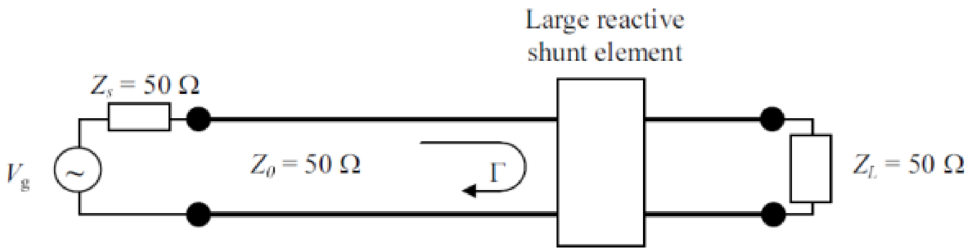


Figure 2. *Circuit model of metal block on a microstrip line.*

Now, remain the block rest at the initial position on the line (the dashed lines in Figure3).

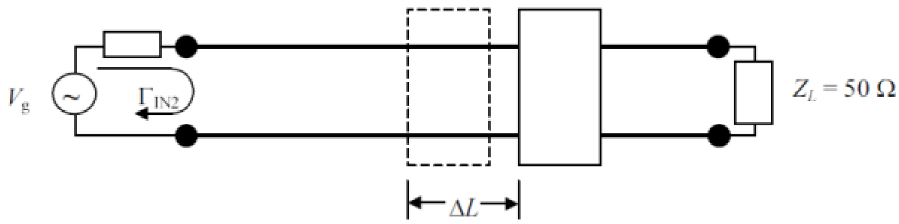


Figure 3. *Reflection coefficient measured at the generator when the block is moved down the line by ΔL.*

The reflection coefficient measured at the generator is Γ_{IN}. If ΔL moves the block away from the generator, the new reflection coefficient will be

$$\Gamma_{IN} = \Gamma_{IN} e^{-j2\beta\Delta L}$$

The added phase delay of $2\beta\Delta L$ is twice the electrical length $\beta\Delta L$.

Now we give the equation $\beta = \frac{2\pi}{\lambda_g}$, when $\Delta L = \frac{\lambda_g}{2}$, the measured reflection coefficient's phase will have changed by exactly 2π radians.
Equation (4) shows the formula of TEM waves:

$$\lambda_g = \frac{u_p}{f} = \frac{c}{f\sqrt{\varepsilon_{eff}}}$$

(Assuming $\mu_r = 1$)

3. Procedure

In the experiment, we use a modern measure device to observe the reflection coefficient.
First, we set the frequency range for the VNA from 500MHz to 3GHz and complete the calibration.

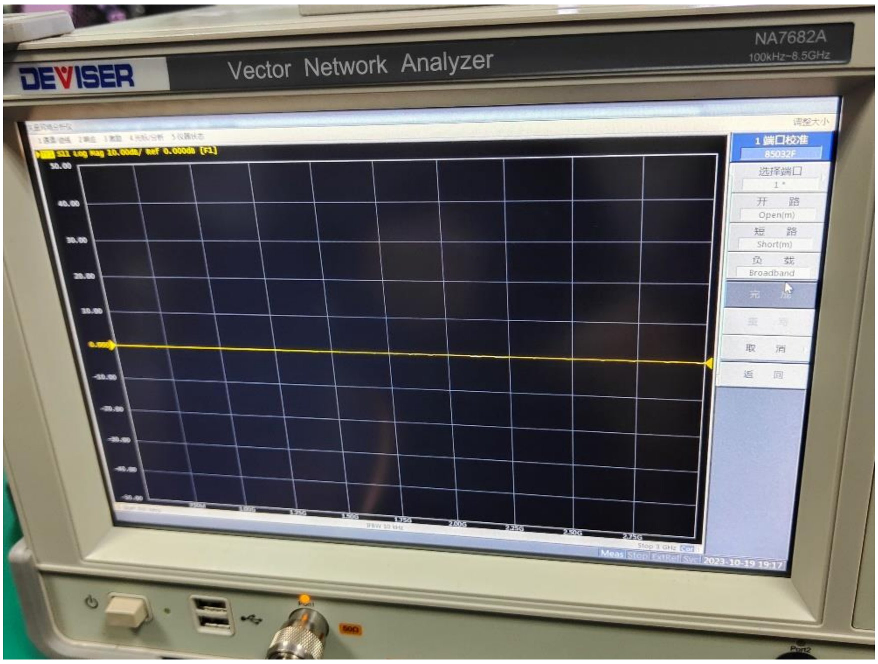


Figure 4: Modern measure device

Measure and record the height of the substrate is 1.60mm and the width of the microstrip transmission line is 3.12mm.

Then connect the microstrip line and 50-Ohm in the two sides of the coaxial cable. Put the aluminum block on the transmission line and move it longitudinally down the line, observing the effect on the phase.

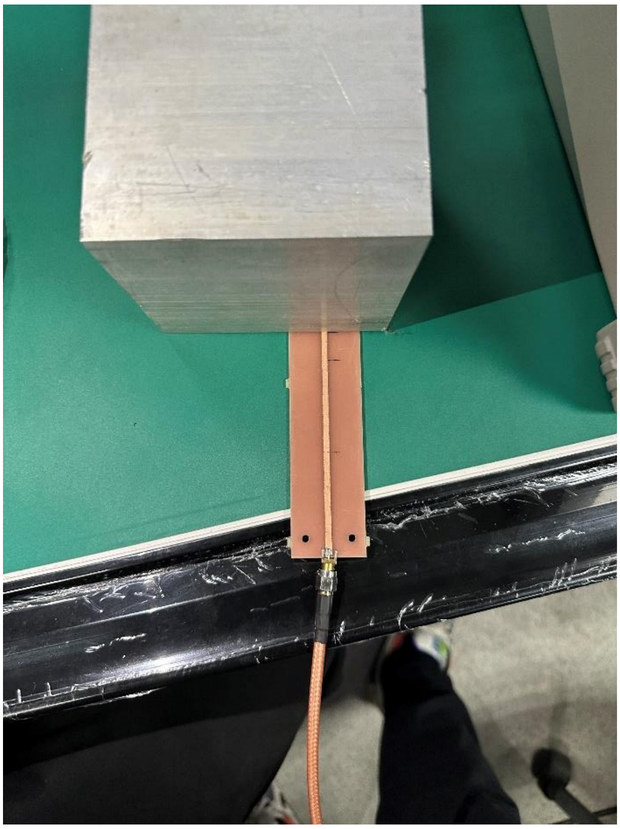


Figure 5: Record the starting and ending positions of the aluminum block

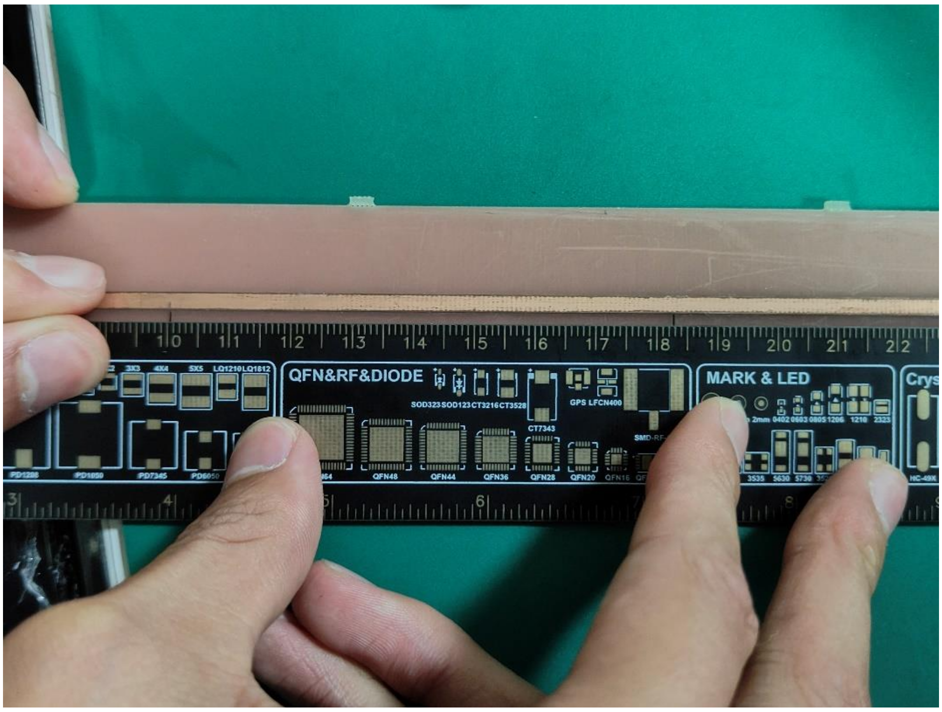
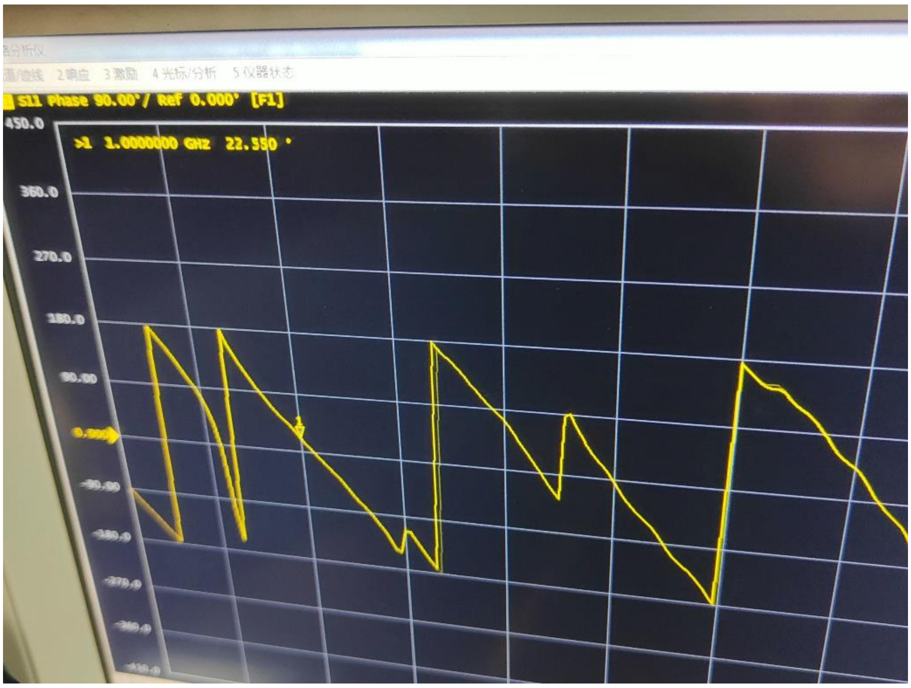


Figure 6: Measure the distance of the mark

4. Analysis and Discussion

When the measured reflection coefficient's phase changes by 360°, record the change in position. We choose 3 different frequencies 1GHz, 1.5GHz, 2GHz from range 500MHz to 3GHz.



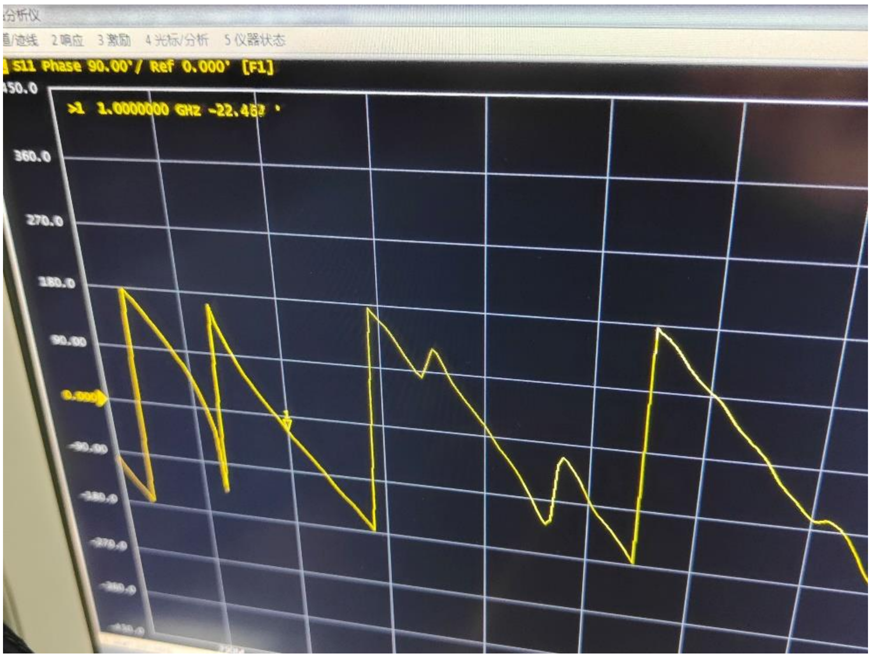


Figure 7: Graph of phase moving 360°in frequency 1GHz

Now we use the equation (4), we can get the equation(5):

$$\varepsilon_{eff} = \left(\frac{c}{\lambda_g f}\right)$$

$$\lambda_g = 2\Delta L$$

*Answer Questions

Question 7: Complete a table showing the calculated Eeff and Er. Is the dielectric constant of the substrate constant over the frequency range?
Using equation(2), We will calculate the data as shown in the following table 1:

Frequency f (Hz)	ΔL(cm)	λ_g (cm)	ε_{eff}	ε_r
$1*10^9$	8.3	16	3.516	4.71027
$1.5*10^9$	5.5	11	3.306	4.39404
$2*10^9$	4.1	8.2	3.346	4.45426

Table 1: ε_{eff}, ε_r in three different frequencies

See appendix for specific calculation process.
From the theory we can know that effective dielectric constant is in the range of 1 <ε_{eff} < ε_r. In 750MHz, 1.5GHz, 2.5GHz we have chosen, all the data fits that equation.
So it is correct.
The dielectric constant of the substrate constant is not over the frequency range. The dielectric constant of substrate remains unchanged, but some deviation will occur.
In our group's view, the main reasons for this deviation are as follows:
(1) There are errors in the measurement process. Due to the inaccuracy of the measuring tools we used and the gap in the line of sight, the calculation results were incorrect.
(2) Oxidation between the aluminum block and the microstrip results in deviations in impedance and dielectric constant.
(3) Due to environmental reasons, the dielectric constant is affected to a certain extent, which leads to errors in the results.

Question 8: The sliding reactive load method is a suitable method to find the dielectric constant of microstrip lines. Describe some factors that can limit the accuracy of this procedure.1111
(1) When the aluminum block is placed on the transmission line and moved vertically in a straight line, the aluminum block will be moved horizontally due to artificial factors, which will affect the load reactance, thus affecting the accuracy of this program.
(2) Our observed data may be biased from the actual data. Therefore, the data recorded in the end are not real data, resulting in large errors in subsequent calculations.
(3) External factors may also affect the accuracy of this procedure due to laboratory temperature instability.
(4) Aluminum blocks, aging of transmission lines and long disuse will affect the accuracy of this procedure.

Question 9: Given that you are assuming in this lab that the transmission line is 50 Ohm, using your measured thickness for the width and dielectric

thickness compare your results with Keysight ADS Line calc. Are there any differences in the results? What about at the different frequency values? Provide a brief explanation.

In Lab Activity 7, We figured out what the λ_g and ε_{eff} are. In order to verify the accuracy of the experimental results, we use ADS Line calc to simulate microstrip lines.

We set the value of Er in Substrate Parameters Block to be equal to the value of ε_r, and the Freq is the frequency we chose (1GHz, 1.5GHz and 2GHz). As well as the Z_0=50Ω in matched circuit. Because the phase difference in the experiment is a wavelength, ε_{eff}in degree is 360°. Using "Synthesize" to get the physical based on measured thickness. The results in different frequency are shown in the figure below.

Figure 7.8.9 show the simulation results of λ_g in 1GHz, 1.5GHz, 2GHz respectively.

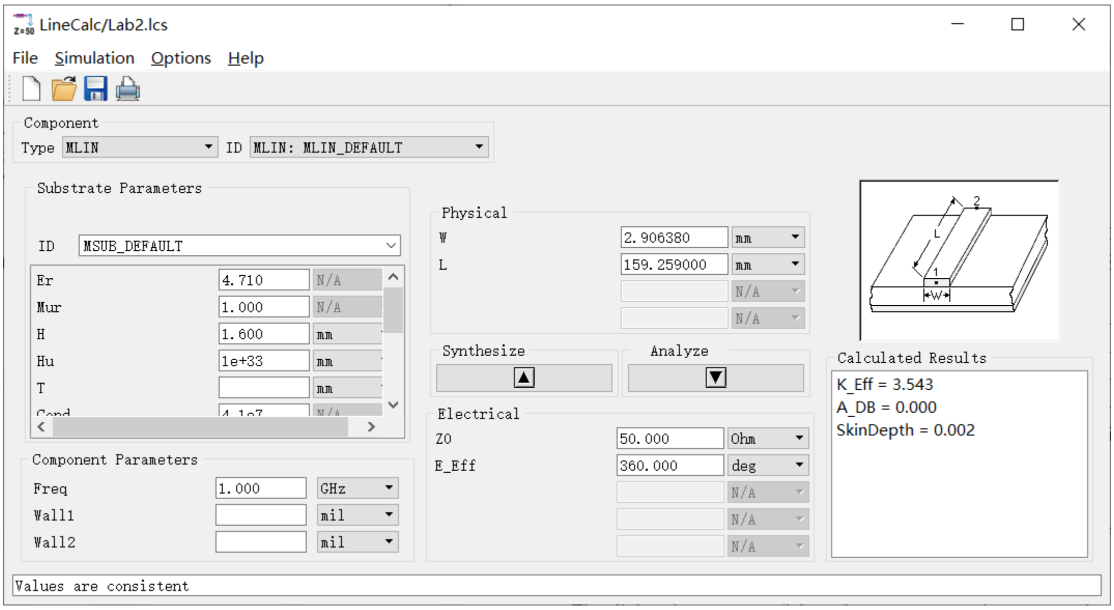


Figure 8. The simulation results of λ_g in 1GHz

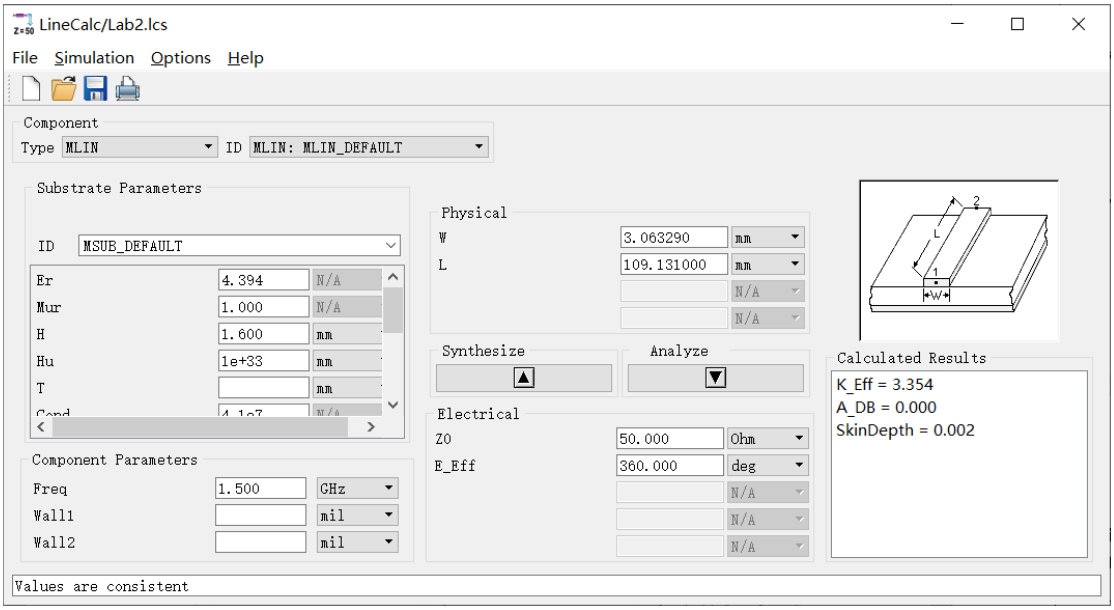


Figure 9. The simulation results of λ_g in 1.5GHz

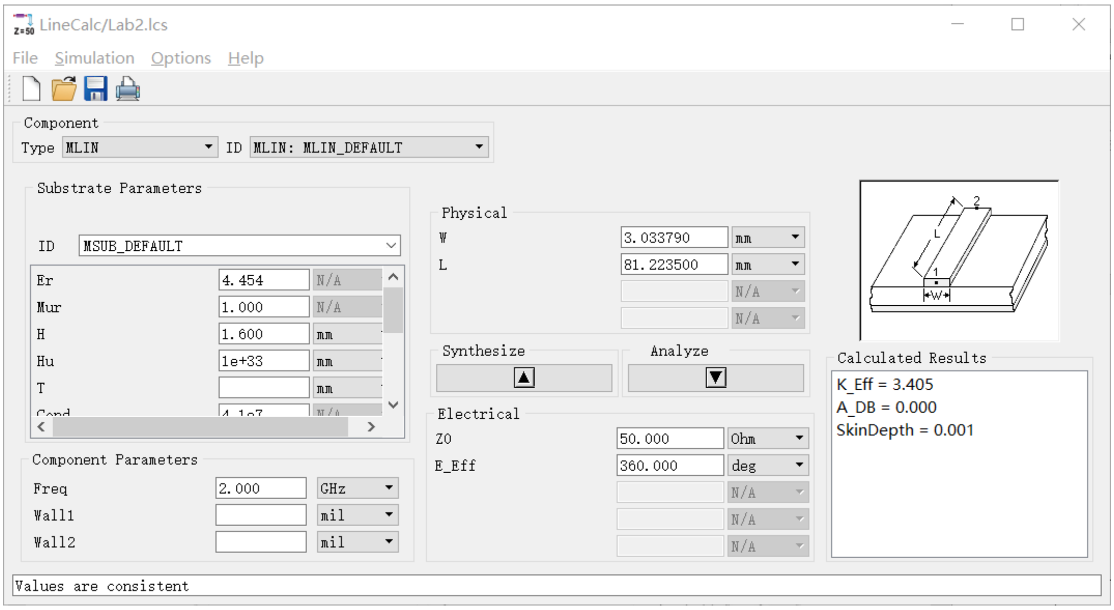


Figure 10. The simulation results of λ_g in 2GHz

Frequency	Measured guided wavelength(cm)	Theoretical guided wavelength(cm)
1GHz	16	15.9259
1.5GHz	11	10.9131
2GHz	8.2	8.12235

Table 2 : Theoretical and measured values

The error analysis:

1GHz:(16-15.9259)/16=0.463125%

1.5GHz:(11-10.9131)/11=0.17%

2GHz:(8.2-8.12235)/8.2=0.94695121%

The difference between the measured and calculated values is small and within the margin of error.

5. Conclusion

Through experiments, we learned the theory of microstrip line, understood the relative dielectric constant, observed the reflection coefficient by using vector network analyzer (VNA), and analyzed the error by comparing the measurement and calculation data, and discussed the results.

6. Reference:

B39HF B31HD Laboratory 2 - Dielectric Constant of Microstrip - v2

(1)Appendix:

Alternate forms

$$3.516 = \frac{0.354205\left(1.86319\,x^2 + 1.20159\,x - 0.241564\right)}{x}$$

$$3.516 = \frac{0.5\left(x^2 + 1.17113\,x - 0.171127\right)}{x} + 0.159953\,(x-1)$$

$$3.516 = \frac{x+1}{2} + 0.354205\,(x-1)\left(\frac{\log(4)-\log(\pi)}{x} + \log(\pi) - \log(2)\right)$$

Alternate form assuming x is positive

$x = 4.71027$ (for $x \neq 0$)

Alternate forms

$$3.306 = \frac{0.354205\left(1.86319\,x^2 + 1.20159\,x - 0.241564\right)}{x}$$

$$3.306 = \frac{0.5\left(x^2 + 1.17113\,x - 0.171127\right)}{x} + 0.159953\,(x-1)$$

$$3.306 = \frac{x+1}{2} + 0.354205\,(x-1)\left(\frac{\log(4)-\log(\pi)}{x} + \log(\pi) - \log(2)\right)$$

Alternate form assuming x is positive

$x = 4.39404$ (for $x \neq 0$)

Alternate forms

$$3.346 = \frac{0.354205\left(1.86319\,x^2 + 1.20159\,x - 0.241564\right)}{x}$$

$$3.346 = \frac{0.5\left(x^2 + 1.17113\,x - 0.171127\right)}{x} + 0.159953\,(x-1)$$

$$3.346 = \frac{x+1}{2} + 0.354205\,(x-1)\left(\frac{\log(4)-\log(\pi)}{x} + \log(\pi) - \log(2)\right)$$

Alternate form assuming x is positive

$x = 4.45426$ (for $x \neq 0$)