ECS644U Microwave and Millimetrewave Electronics Lab 1

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October 18, 2016

Contents

1 Aim

The aim of this first lab of ECS644U is to investigate how a microstrip transmission line can be modelled using the AWR software and how it's characteristic impedence varies as a function of width, length, height and permittivity. Furthermore we were demonstrated how a Vector Network Analyser (VNA) works, the type of network parameters it can measure - with particular attenion to the S parameters- and how to calibrate it prior to its use. Lastly it's required to evaluate telegrapher's equations to relate current and voltage of a transmission line.

2 Method

2.1 Characteristic impedence: TXLINE, Material Paramenters, Physical Characteristics and Electrical Characteristics

The characteristic impedence of a transmission line for a high frequency circuit can be defined as the ratio of the voltage difference and the current flowing between it's two ends.

$$Z_0 = V/I = \frac{\int E \cdot dl}{\oint_S H \cdot dl} \tag{1}$$

Another possible equation, based on the resistance, conductance, impedence and capacitance of the transmission line is:

$$Z_0 = \sqrt{\frac{R + jwL}{G + jwC}} \tag{2}$$

Below are the equations which relate physical and electrical properties of the microstrip to its impedence

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_e}}(ln(\frac{8h}{W} + \frac{W}{4h}) & \text{for } W/h \leq 1 \\ \frac{120\pi}{\epsilon_e[\frac{W}{h}+1.393+0.667ln(\frac{W}{h}+1.44]} & \text{for } W/h > 1 \end{cases} \tag{3}$$

Where ϵ_e is the effective dielectric constant, which can be determined as a function of the effective dielectric constant ϵ_r according to the following equation

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} + \frac{1}{\sqrt{1 + 12\frac{h}{W}}} \tag{4}$$

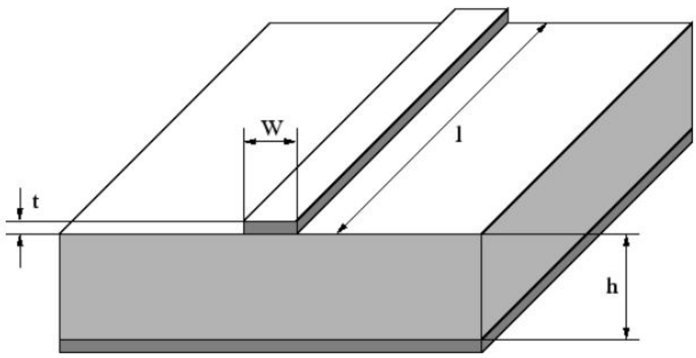


Figure 1: Diagram of a microstrip transmission line.

- The Material Parameters represent:
  Dielectric: type of substrate in use for the fabrication of the microstrip line.
  Dieletric constant: resistance of the material to changes of the electric field.
  Loss Tangent: expresses lossiness of the dielectric material or else, how much power is dissipated per meter of transmission line.
  Conductor: metalic strip above the dielectric where our signal propagates.
  Conductivity: how strongly an electric material opposes the flow of current.

- The Electrical Characteristics represent:
  Impedence: ratio of the voltage phasor to the electric current phasor, a measure of the opposition to time-varying electric current in an electric circuit. Standard microwave and millimetrewave values are both 50Ω and 75Ω. For the purpose of the lab, 50Ω , is selected.
  Frequency: frequency of operation of our system, it's require to evaluate the wavelength of the signal.
  Electrical Length: affects the physical length of the microstrip. In order to evaluate the input impedence of a microstrip transmission line it is required for it to be $\frac{\lambda}{8}$ or, expressing this as a phase shift 45° .

- The physical characteristics represent:
  Physical Length (L): length of the microstrip.
  Width (W): width of the conductor.
  Height (H): height of the dielectric.
  Thickness (T): thickness of the conductor.

Within AWR Design Envioronment the TXLINE Tool enables us to set both the parameters of the material used to fabricate the microstrip and the electrical characteristics it should respect. The tool then evaluates the physical characteristics the microstrip should have to respect the set criteria.

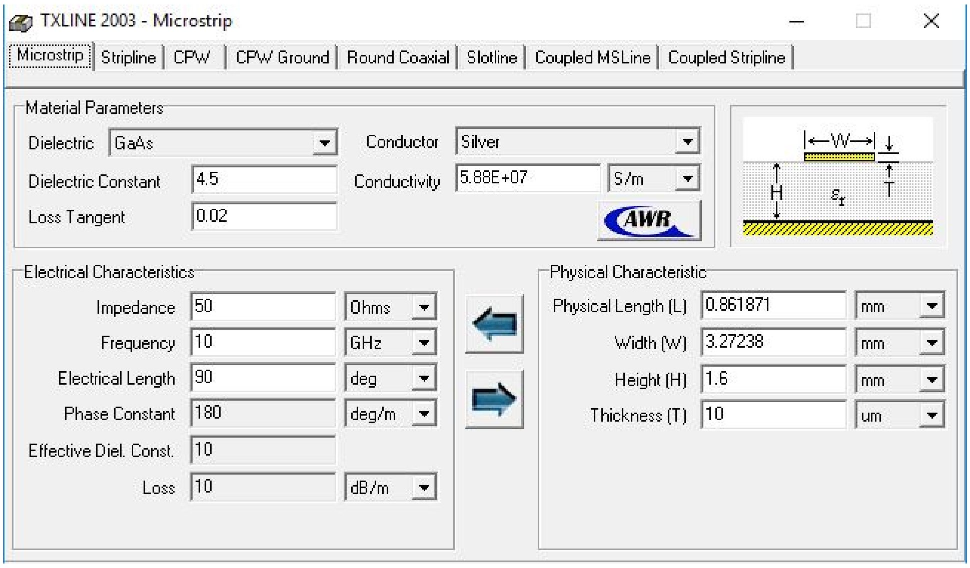


Figure 2: Screenshot of the TXLINE tool.

Prior to setting these values the global units within the AWR Design Environment should be set to metric units (mm).

Completed the calculations with the TXLINE tool, the values that have been achieved are used for the circuit design. For the purpose of the lab it is enough to short circuit one end of a transmission line to ground and short cricuit the other end to a measurement port. This allows us to measure the magnitude of the characteristic impedence. In order to visualise the measurments taken from the port we create Graphs within the AWR Design Environment.
In order to investigate the relationship between the magnitude of the characteristic impedence and one of the various parameters of the microstrip, it's possible to create a sweep variable and link it to the investigated parameter. When defining this type of variable lower and upper limits are provided, along with the step unit size. When using a swept variable it is possible and desired to set the x-axis of the graph to represent the various values the parameter can have.

Below are presented all the circuit schematics designed with AWR to investigate the various parameters of the microstrip line.

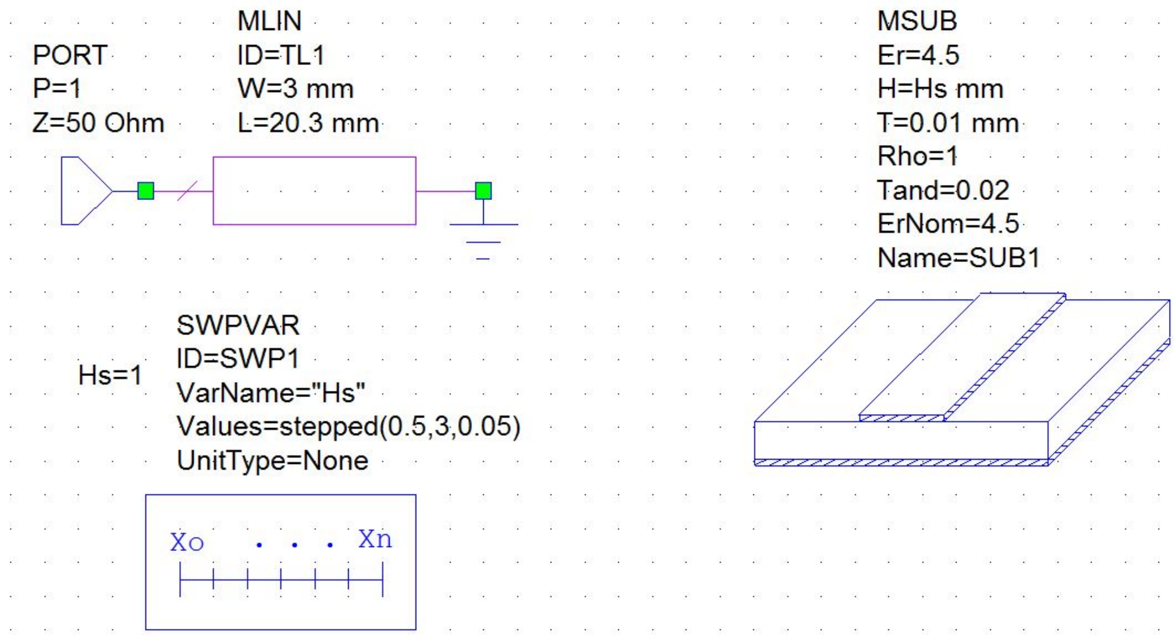


Figure 3: Circuit design to investigate Zo vs H.

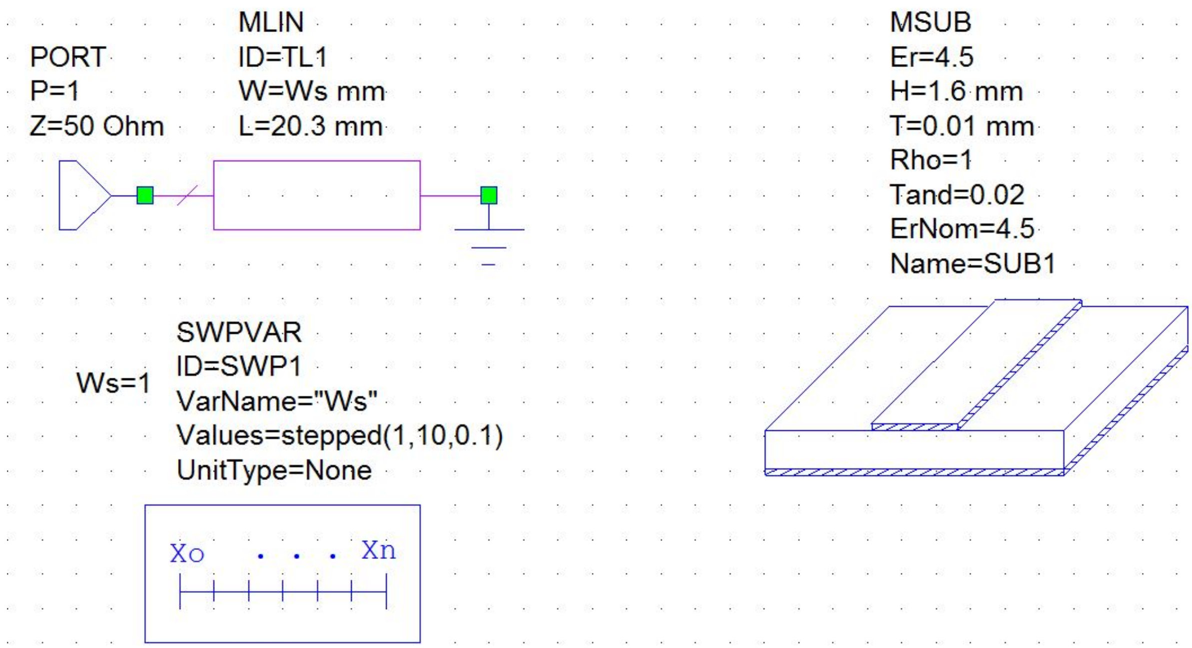


Figure 4: Circuit design to investigate Zo vs W.

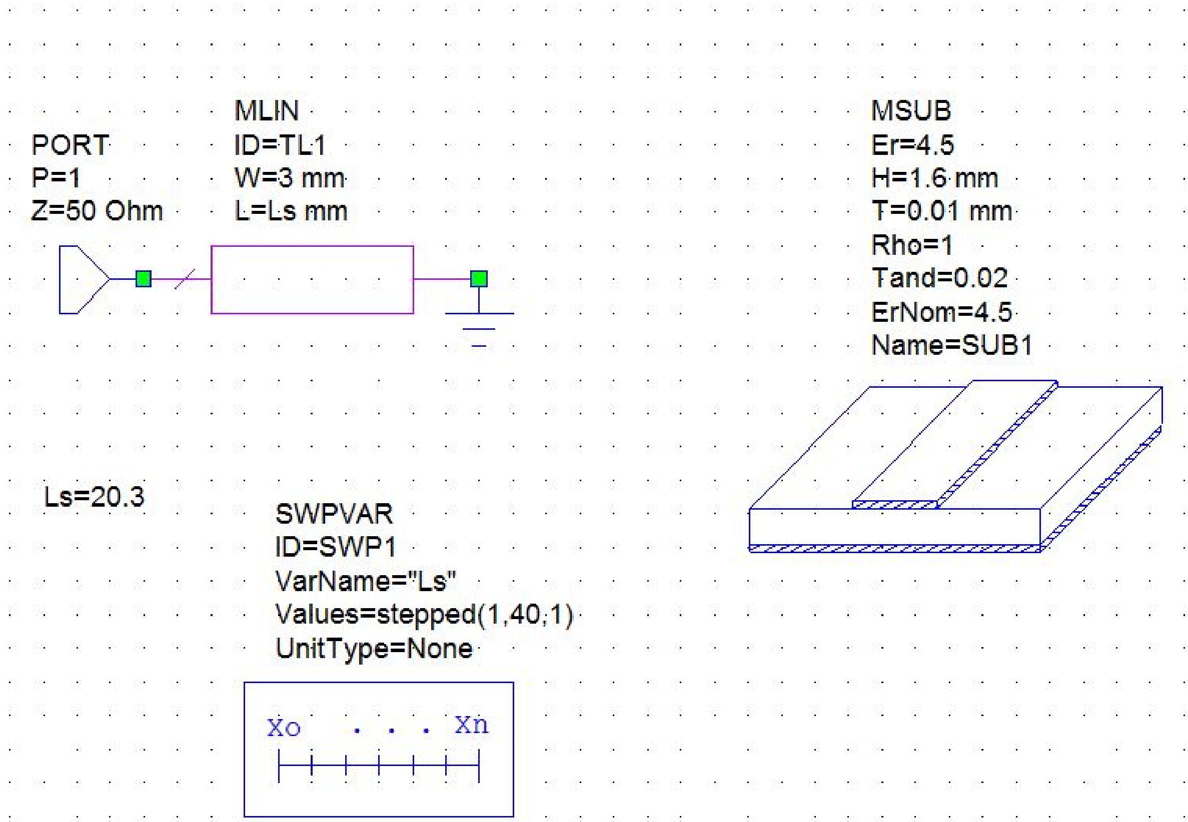


Figure 5: Circuit design to investigate Zo vs L.

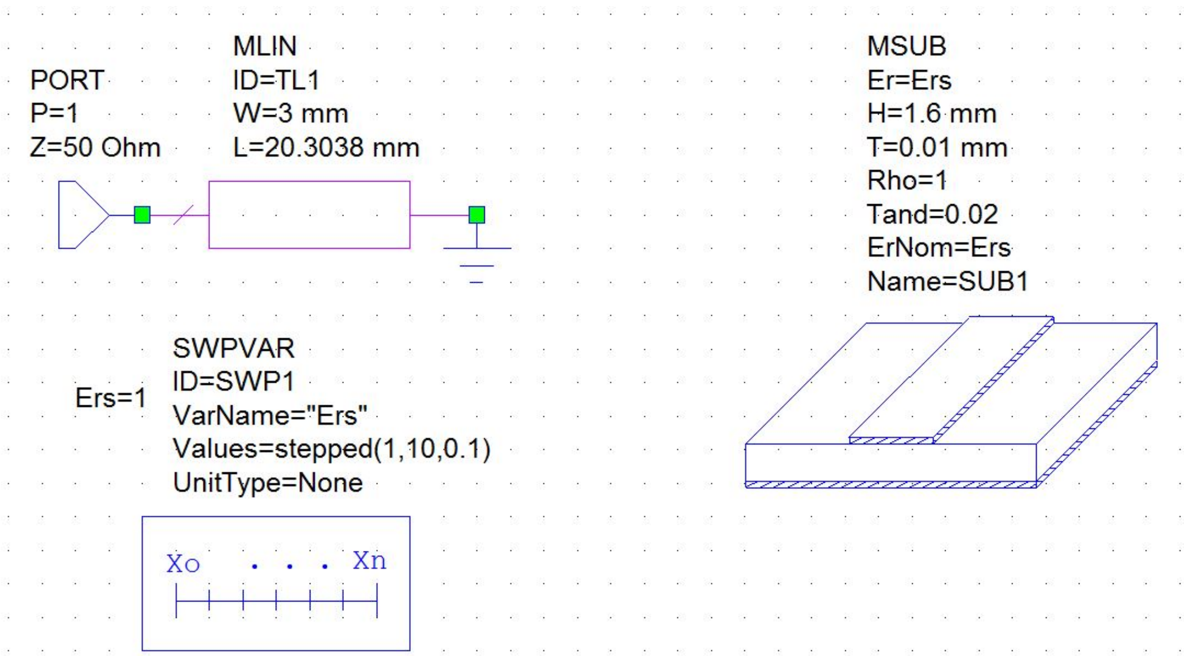


Figure 6: Circuit design to investigate Zo vs Er.

2.2 The Vector Network Analyser

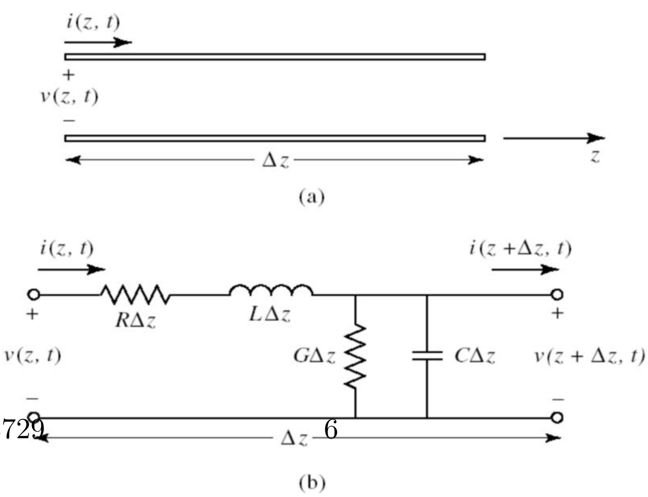
A Vector network Analyser (VNA) is an instrument that evaluates the characteristics of many different network devices by plotting their scattering S-parameters. When starting to use a VNA resetting the machine is the first step, in this way all the settings of the previous user will be erased. Secondly Calibration has to be done. Calibration removes systematic errors, which are caused by imperfections in the device and can be mathematically characterized due to their systematic nature. This is done by sending some energy into the input port and sensing how much energy is either transmitted to the output port and how much is reflected back.
One of the major imperfections when measuring a device, connected to the VNA via (coaxial) wires, is that the length of the wires will interfere with the measurements. Calibration ensures that the measurements are taken from the reference plane (ie the interface between the error network and the tested device).
Calibration is a sequential procedure, carried out with a calibration key. The calibration key allows us to calibrate the input and output port, that will be connected to input and output ports of the tested device, via calibration standards. These are one or two port networks with well-known standard values of which engineers which allow to highlight the systematic errors that are occurring. Despite the multiple existing techniques to calibrate a VNA the demonstrator showed us how to use a TOSM device to complete this requirement. The standards for this technique are shown below:

1. Short circuit: a signle port is connected to the calibration key. The known total reflection will be $\Gamma = -1$
2. Open circuit: a signle port is connected to the calibration key. The known total reflection will be $\Gamma = 1$
3. Matched impedence: a signle port is connected to the calibration key. The known total reflection will be $\Gamma = 0$ and the total transmission will be $T = 1$
4. Through: input and output port are connected together via the calibration key. The expected result is $\Gamma = 0$ and $T = 1$

When calibrating the first three standars have to be applied to the input and the output port individually, before the final standar is applied between the two ports. Once these measurements have occured a calibration file can be generated, saved, and loaded at a different time.

2.3 Telegrapher's equations

The telegrapher's equations in the circuit below are derived by:



1. Applying Kirchoff's Voltage Law by setting the sum of all voltages present within the mesh to zero, to get

$$v(z,t) - R\Delta z i(z,t) - L\Delta z \frac{\delta i(z,t)}{\delta t} - v(z+\Delta z,t) = 0 \tag{5}$$

2. Dividing by Δz and taking the limit as $\Delta z \to 0$, to get:

$$\frac{v(z,t)}{\Delta z} - Ri(z,t) - L\frac{\delta i(z,t)}{\delta t} - \frac{v(z+\Delta z,t)}{\Delta z} = 0 \tag{6}$$

$$\frac{v(z,t) - v(z+\Delta z,t)}{\Delta z} - Ri(z,t) - L\frac{\delta i(z,t)}{\delta t} = 0 \tag{7}$$

$$\frac{\delta v(z,t)}{\delta z} = -Ri(z,t) - L\frac{\delta i(z,t)}{\delta t} \tag{8}$$

   (a) Converting this result from the current time domain to the frequency domain by applying $\frac{\delta i}{\delta z} = jwi$ which results in

$$\frac{dV(z)}{dz} = -(R + jwL)I(z) \tag{9}$$

3. Applying Kirchoff's Current Law by setting the sum of all currents adding up in the common node to zero, to get

$$i(z,t) - G\Delta z v(z+\Delta z,t) - C\Delta z\frac{\delta v(z+\Delta z,t)}{\delta t} - i(z+\Delta z,t) = 0 \tag{10}$$

4. Dividing and taking the limit of Δz , as per step 2 , to get

$$\frac{i(z,t) - G\Delta z v(z+\Delta z,t) - C\Delta z\frac{\delta v(z+\Delta z,t)}{\delta t} - i(z+\Delta z,t)}{\Delta z} = 0 \tag{11}$$

$$\frac{i(z,t) - i(z+\Delta z,t)}{\Delta z} - Gv(z+\Delta z,t) - C\frac{\delta v(z+\Delta z,t)}{\delta t} = 0 \tag{12}$$

$$\frac{\delta i(z,t)}{\delta z} = -Gv(z,t) - C\frac{\delta v(z,t)}{\delta t} \tag{13}$$

   Again converting the result from time to frequency domain, as per 2a, results in

$$\frac{dI(z)}{dz} = -(G + jwC)V(z) \tag{14}$$

   Equations 9 and 14 are the coupled differential equations, whereas the equivalent time domain functions (8 , 13) are defined as Telegrapher's equations.

5. The Telegrapher's Equations can be uncoupled by derivating 14 with respect to z, then substituing9 into it.

$$\frac{d^2v(z)}{dz} = (R + jwL)\frac{dI(z)}{dz} \tag{15}$$

$$\frac{d^2v(z)}{dz} = (R + jwL)(G + jwC)v(z) \tag{16}$$

It is possible to derive the complex propagation constant, as we can easily reconduct 16 to an equation of the form of

$$\frac{d^2v(z)}{dz} - k^2v(z) = 0 \tag{17}$$

Doing so we derive

$$k = \sqrt{(R + jwL)(G + jwC)}$$

6. The same result is acheived by derivating 9 and substituing 14 into it.

3 Results

3.1 Characteristic impedence

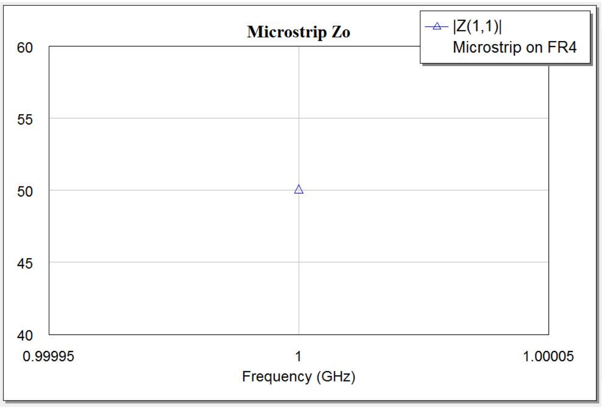


Figure 8: Characteristic impedence of circuit scehmatic 1 .

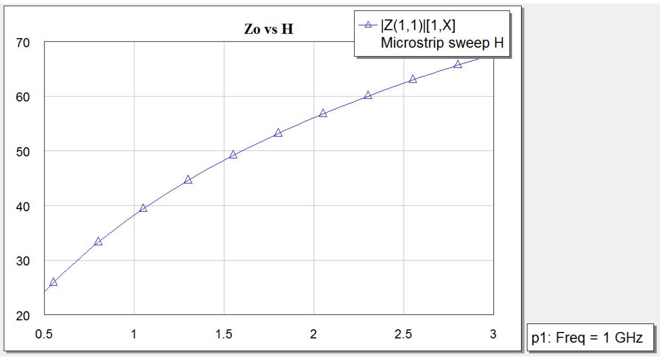


Figure 9: Characteristic impedence of circuit scehmatic 3 .

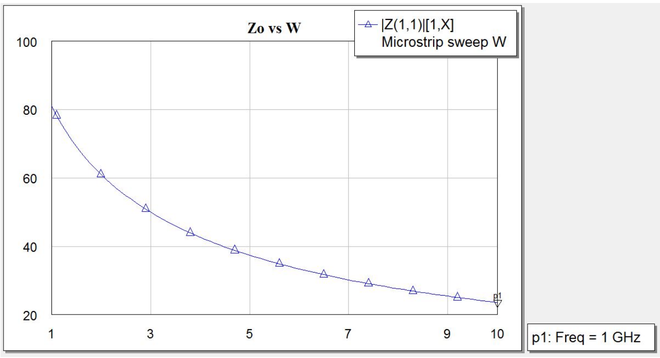


Figure 10: Characteristic impedence of circuit scehmatic 4 .

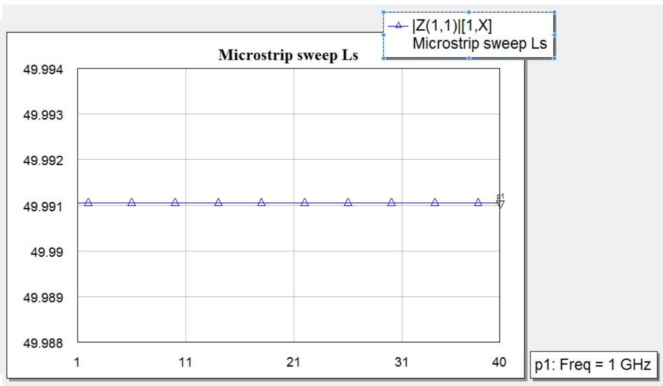


Figure 11: Characteristic impedence of circuit scehmatic 5 .

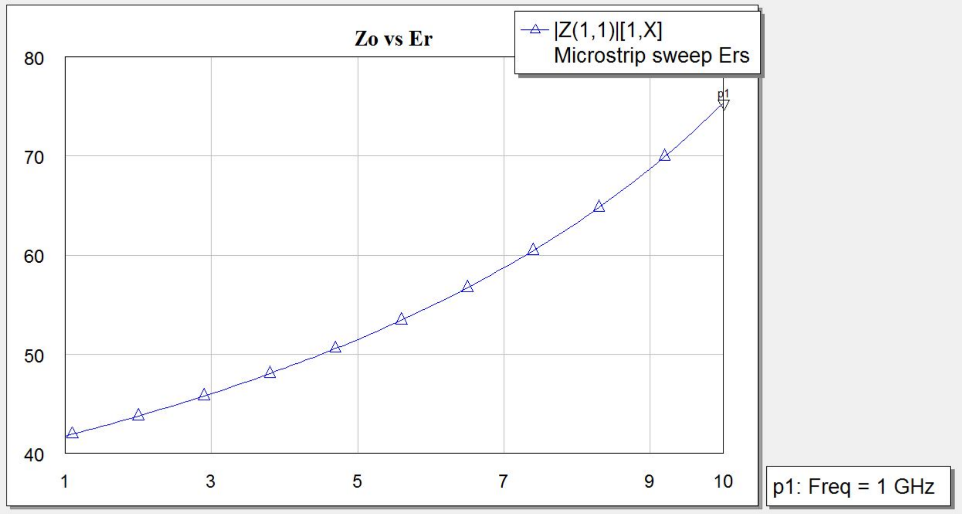


Figure 12: Characteristic impedence of circuit scehmatic 6 .

4 Discussion

4.1 Characteristic impedence

This discussion will refer to equations 1 and 3 which relate the characteristic impedence to both physical and electrical properties in the microstrip. It should be stated that these equations are approximations and don't take into account the thickness of the metal involved in the fabrication. This would increase capacitance of the lines, hence affect also the permittivity.

When varying the:

- Height: figure 9 shows the characteristic impedence increases with the height of the microstrip. This is intuitively a correct result given that the distance over which the voltage is evaluated, corresponds exactly to the varying parameter. Furthermore we can see Zo is directly proportional to H in the stated equations.
- Width: figure 10 shows the characteristic impedence Zo decreases as the width increases. This is intuitively a correct result given the radius considered to evaluated the closed surface integral of the magnetic field corresponds to half the width of the microstrip. Furthermore we can see Zo is inversely proportional to W in the stated equations.
- Length: figure 11 shows the characteristic impedence Zo doesn't vary with the length of the microstrip. This is intuitively a correct result given this term doesn't affect the propagation of neither magnetic nor electric field. Furthermore we can see there is no direct nor indirect relatoinship between L and Zo.
- Permittivity: figure 12 shows the characteristic impedence Zo increases as the permittivity increases. This result is wrong. Permittivity can be thought as the resistance encountered in forming an electric field in a medium, hence it intuitively is clear how, increasing this resistance should decrease the characteristic impedence of the microstrip. Furthermore, as the equations show, permittivity and characteristic impedence are inversely propoertional.

4.2 The Virtual Network Analyser

Once calibration is completed measurements of the S-Parameter of some devices are made. The S-Parameter values make up a matrix with the network's individual input/outpu port reflection coefficient and reverse/forward votlage gain. These enable us to characterize the device. For a two port network the S-Parameter matrix is shown below

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

To measure S_{11} we are sending power out of Port 1 and measuring the power reflected back into Port 1. If $S_{11} = 0$ we are in the ideal case of no reflection or 0dB loss in power. To measure S_{21} we are sending power out of Port 2 and measuring the power reflected back into Port 2. If $S_{21} = 1$ we are in the ideal case of full transmission or 0dB loss in power.

4.3 Telegrapher's equation

The propagation constant derived using Telegrapher's equations is a complex number. The propagation constant of an electromagnetic wave is a measure of the change undergone by the amplitude of the wave as it propagates in a given direction. The quantity being measured can be the voltage or current in a circuit or a field vector such as electric field or magnetic flux density. The propagation constant will provoke a delay in the transmitted signal.This justifies why it's a complex number, the imaginary part will provoke a phase shift in our signal, which represents its delay.

5 Conclusions

The main skills acquired in the lab are:

- Use of AWR Design Environment software to simulate microwave and millimetrewave circuit schematics.
- Calibration of a Vector Network Analyser
- Physical meaning of S-parameters
- Mathematica derivation andphysical meaning of propagation constant via the use of Telegrapher's equations.

All results seem to be coherent, made exception of the graph 12 .