ECS644U Microwave and Millimetrewave Electronics Lab 2

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Contents

1 Aim

The aim of the second lab of ECS644U is to investigate Network Parameters of a microstrip transmission line. Theoretically, Z-Parameters of a two port network are derived; an S-Matrix is analysed to determine the characteristics of its correspondent device; and S-Parameters for a cable-device-cable network are evaluated. Following this theoretical analysis, an AWR simulation is performed to retrieve S-Parameters for the microstrip line used in the lab. During the lab session, infact, S-Parameters of a physical device, equivalent to the AWR model, is analysed with a VNA. The data collected during the lab is then analysed with a MATLAB script, to verify unity and symmetry properties and plot magnitude and phase graphs of its S-Parameters, in order to compare it with the results of the AWR simulation.

2 Method

2.1 Theory: Network Parameters and Measurements

2.1.1 Z-Parameters

A Z-Matrix represents the impedance of a device as it's seen from its ports. Given the definition of impedance for a high frequency circuit

$$Z_{n_\omega} = V_n/I_n = \frac{\int E_{n_t} \cdot dl}{\oint_S H_{n_t} \cdot dl} \tag{1}$$

where both Electric and Magnetic field are dependent upon the position at which they're evaluated, we understand how important the definition of a reference plane is in evaluating these parameters, as it will determine the phase references for voltage and current. This allows us to evaluate transmitted and reflected voltage (and current) at *specific* ports, as shown in the equations below.

$$V_n = V_n^+ + V_n^- \tag{2}$$

$$I_n = I_n^+ + I_n^- \tag{3}$$

These two equations justify why definition 1 of impedance respects the Maxwell Equations governating high frequency networks[1].
With the knowledge of both voltages and currents at the N-ports of a network, determining the Z-Matrix is equivalent to carrying out a classic circuit analysis. Hence an N-port network will be characterised by an NxN matrix, in which the Z_{ij} elements can be evaluated by

$$Z_{ij} = \left.\frac{V_i}{I_j}\right|_{I_k=0 for j\neq i} \tag{4}$$

giving the matricial equation

$$\begin{bmatrix} V_1 \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1n} \\ \vdots & \ddots & \vdots \\ Z_{n1} & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} I_1 \\ \vdots \\ I_n \end{bmatrix} \tag{5}$$

In 4.1.1 observations on what network characteristics we can determine by observing its Z-Matrix will be made.

2.1.2 S-Parameters

Given the high-frequency nature of microwave circuits, where the voltage (or current) at a specific port is the sum of transmitted and reflected quantities (eq. 2), a more useful characterisation of these networks can be provided by the defining how much voltage for *each* of the

[1] Chap 4 M.Pozar Microwave Engineering

N-ports is transmitted and reflected from and towards another N-port. This would lead us to a matricial equation as the one shown below

$$\begin{bmatrix} V_1^- \\ \vdots \\ V_n^- \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \begin{bmatrix} V_1^+ \\ \vdots \\ V_n^+ \end{bmatrix} \tag{6}$$

in which, as we said each S_{ij} element can be defined as

$$S_{ij} = \left. \frac{V_i^-}{V_j^+} \right|_{V_k^+ = 0 for j \neq i}. \tag{7}$$

These values can be evaluated via VNA measurements, or starting from eq. 2. As for 2.1.1 , in depth explanations of the network characteristics that can determined from its S-Matrix will be made in 4.1.2. For the purpose of Methodology it will be sufficient to state that:

1. A network can be considered passive and reciprocal if its S matrix is symmetric $S = S^T$
2. A network can be considered lossless if its S-Matrix is unitary $S^T S^* = 1$. As the S parameters are complex values and $zz^* = Re(z)^2 + Im(z)^2$, this can also be evaluated by squaring all S terms in for each column and checking the sum of all row elements per column adds up to 1:

$$\sum_{i,j=1}^{N} S_{ij}^2 = \begin{cases} 1, & \text{if} i = j \\ 0, & \text{else} \end{cases} \tag{8}$$

Once derived the S-Matrix, it is possible to evaluate both return and insertion loss. The first can be defined as the loss of power in the signal returned/reflected by a discontinuity[2] in the network and can be quantified by

$$RL(dB) = 10log_{10}\frac{P^+}{P^-} = -20log_{10}\Gamma \tag{9}$$

where the minus sign takes into account the definition of Γ.

$$\Gamma = V^-/V^+ \tag{10}$$

The latter, Insertion Loss, is the loss of signal power resulting from the insertion of a device in a transmission line or optical fiber[3] and can be quantified by

$$IL(dB) = 10log_{10}\frac{P^+}{P^-} = -20log_{10}S_{ij}, i \neq j \tag{11}$$

Knowledge of the physical behaviour of high frequency circuits and of their distributed circuit nature, allows us to evaluate Return and Insertion Losses when, connecting loads to ports of our network. An analysis of the approaches to evaluate Return Loss when connecting three different loads is now carried out.

1. Matched Load: a matched load won't figure as a discontinuity in the network, hence the reflection measured at the input port will be equivalent to the reflection coefficient of the network itself. Using this value in 9 will allow to evaluate the Return Loss when loading the network with a matched impedance.

[2] en.wikipedia.org/wiki Return loss
[3] en.wikipedia.org/wiki Insertion loss

2. Short Circuit: when short circuiting a port, because of the physical phenomena in act [4], the voltage difference between the two branches of the mesh has to be 0. This implies, from 2, that reflected and incident voltages cancel each other out $V_n^+ = -V_n^-$, hence $\Gamma = -1$. Applying this to 6 its possible to derive an equation for the reflected voltage V_n^- in terms of $V_n^+, S_{11}, S_{12}, S_{21}, S_{22}$, which leads to a reflection coefficient in the form of $\Gamma(S_{11}, S_{12}, S_{21}, S_{22})$. Using this value in 9 will allow to evaluate the Return Loss when loading the network with a short circuit.

3. 25 Ω Load: when loading a port with an impedence smaller than the characteristic one, differently to open and short circuit loads, the standing wave resulting from the reflection of some voltage, is not characterised by peaks and nulls, but by maxima and minima[5] : this imposes $V_n^- \neq V_n^+$.
   Combining 1 with 10 , rearranging the equations and taking into account that $I_L = \frac{V^+}{Z_0} + \frac{V^-}{Z_0}$, it is possible to prove that

   $$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{12}$$

   Using this value in 9 will allow to evaluate the Return Loss when loading the network with an impedance different to the characteristic one.

As seen in 6 the S parameters depend fully upon the amplitude of incident and reflected waves. Hence, exactly as for the Z-Parameters, we need a reference plane, of which the evaluated S-Parameters will be fully dependent upon. At a distance z from its evaluation point, the amplitude of a high frequency voltage could be defined as

$$V' = Ve^{j\theta} \tag{13}$$

where θ corresponds to the electrical length of the z shift of the reference plane

$$\theta = \frac{2\pi}{\lambda} z = \frac{2\pi f}{c} z \tag{14}$$

Hence, if the S-Parameters of a whole network was to be evaluated at a distance z_n, we would have

$$\begin{bmatrix} e^{j\theta_1} & & 0 \\ & \ddots & \\ 0 & & e^{j\theta_n} \end{bmatrix} \begin{bmatrix} V_1'^- \\ \vdots \\ V_n'^- \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \begin{bmatrix} e^{-j\theta_1} & & 0 \\ & \ddots & \\ 0 & & e^{-j\theta_n} \end{bmatrix} \begin{bmatrix} V_1'^+ \\ \vdots \\ V_n'^+ \end{bmatrix} \tag{15}$$

which is effectively equivalent to

$$\begin{bmatrix} V_1'^- \\ \vdots \\ V_n'^- \end{bmatrix} = \begin{bmatrix} e^{-j\theta_1} & & 0 \\ & \ddots & \\ 0 & & e^{-j\theta_n} \end{bmatrix} \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \begin{bmatrix} e^{-j\theta_1} & & 0 \\ & \ddots & \\ 0 & & e^{-j\theta_n} \end{bmatrix} \begin{bmatrix} V_1'^+ \\ \vdots \\ V_n'^+ \end{bmatrix} \tag{16}$$

Hence the new S-Matrix can be determined as

$$\begin{bmatrix} S_{11}' & \cdots & S_{1n}' \\ \vdots & \ddots & \vdots \\ S_{n1}' & \cdots & S_{nn}' \end{bmatrix} = \begin{bmatrix} e^{-j\theta_1} & & 0 \\ & \ddots & \\ 0 & & e^{-j\theta_n} \end{bmatrix} \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \begin{bmatrix} e^{-j\theta_1} & & 0 \\ & \ddots & \\ 0 & & e^{-j\theta_n} \end{bmatrix} \tag{17}$$

[4] 2.5.2.1.3 Conquer RF

[5] Conquer RF 2.8.5

2.2 Simulations: Microstrip Transmission Lines

In order to simulate the measurement of S-Parameters (Magnitude and phase) of the microstrip line adopted in lab, its dimensions and physical, material and electrical parameters are required. These were provided by the lab demonstrator and are listed below:

- Nominal Dielectric constant: 4.5 mm
- Effective Dielectric constant: 4.5 mm
- Height of dielectric: 41.6 mm
- Dielectric Loss Tangent: 0.02
- Bulk resistivity of conductor metal: 1
- Width of conductor: 3 mm
- Length of conductor: 50 mm

To correctly set unit measures in AWR, prior to inserting MSUB and MLIN elements (shortcut CTRL+L), global units should be set to *mm* from 'Project Options'. Furthermore, from the Frequencies tab in the 'Project Options' view, the correct frequency range should be set, in order to simulate the circuit with the same frequencies the microstrip had been swept with by the VNA in the lab. To do so, after having opened one of the multiple files saved from the VNA, having subtracted from the end frequency the starting one, and having divided the difference by the number of measurements taken, *start*, *stop* and *step* frequencies can be inserted. Below formal calculations to evaluate step frequency and a view of the 'Project Options' window.

$$f_{step} = \frac{f_{end} - f_{start}}{N_{samples}} \tag{18}$$

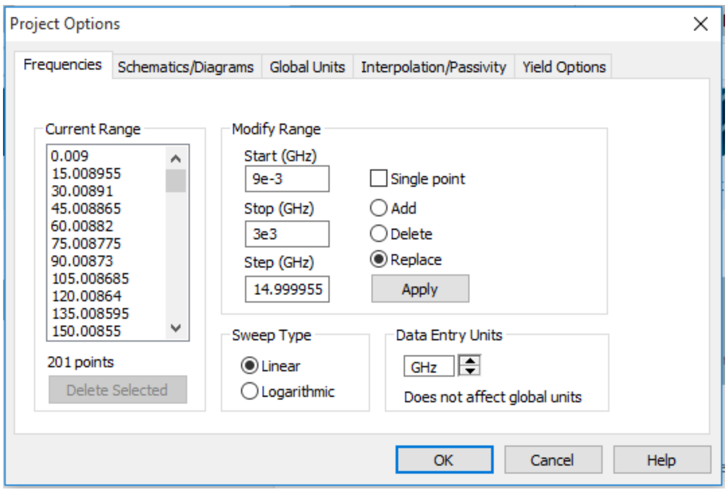

Figure 1: *Project Options ¿ Frequencies* view in AWR.

Having set all the parameters, connected our microstrip (MLIN) to two ports, which represent the VNA ports, we can then simulate our circuit. Below an image of the full schematic.

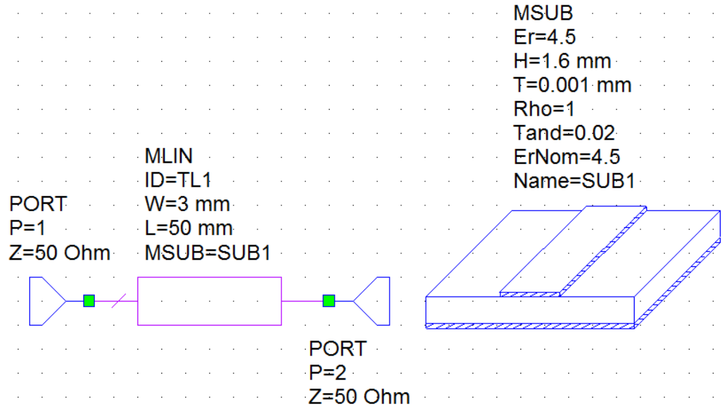

Figure 2: Circuit schematic of the AWR simulation.

Given this is a 2-port network, it will be characterised by 4 S-Parameters. In order to visualise phase and magnitude for each of these, we will have to create 8 graphs, add a new measurement for each of these graphs. Within *Graph¿Options* it's possible to label axis and the graph, whereas from *Measurement¿Properties* it's possible to set what type of measurement we wish to perform, what port we are stimulating and at what port we are measuring the received (transmitted/reflected) power.

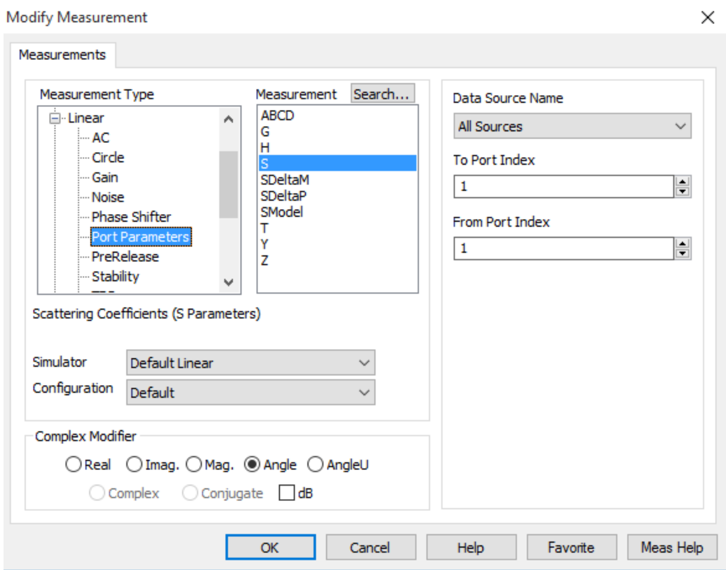

Figure 3: *Graphs ¿ Mesurement ¿ Properties* view in AWR.

To respond the great dynamic range of these values and to show data in multiplicative factors, logarithmic scale is used to plot the magnitude for various S-Parameters. This can be set from the Measurement Properties window as well. Given phase doesn't have such a dynamic range, the classic, linear scale will be adopted.

2.3 Measurements: Microstrip Transmission Line

A VNA sweeps frequencies through the connected network and returns graphs of its S-Parameters when set to do so. This can be acheived by pressing *MES* in the trace section of the control buttons and selecting the S_{ij}value of interest. Pressing on *Format*, it is then possible to select whether to trace Magnitude or Phase. It has to be noted that before carrying out any sort of measurements *Trigger* should be held, in order to have consistent measurements between phase and magnitude. In order to externally save the measured data for each S-Parameter, an external USB is instered in the VNA and the data is saved on it in form of a .csv file.
A MATLAB analysis is then carried out, in order to plot the measured data, comapre it with the simulated graphs and verify unity and symmetry properties (2.1.2). Within the MATLAB code 6, a function is written to correctly read the files into *frequency* and *value* vectors. Unity and symmetry properties are then verified for each frequency value. A vector *unit* stores a 0 if for a given frequency the unity property is not valid, a 1 if it is. Similarily, a vector *sym* stores a 0 if for a set frequency $S_{12} = S_{21}$.

3 Results

3.1 Theory: Network Parameters and Measurements

3.1.1 Z-Parameters

Applying eq. 5 to the circuit provided in the Lab Sheet, it is possible to directly derive its Z-Parameters. Below working out is shown.

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_a + Z_c & Z_c \\ Z_c & Z_b + Z_c \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{19}$$

3.1.2 S-Parameters

Given the following S-Matrix

$$\begin{bmatrix} 0.6 & 0.8e^{j\frac{\pi}{4}} \\ 0.8e^{j\frac{\pi}{4}} & 0.6 \end{bmatrix} \tag{20}$$

and testing for the symmetry and unity properties 2.1.2, it is possible to evaluate that:

- Symmetry:

$$S_{12} = S_{21} \tag{21}$$

  The S-Matrix is symmetrical, hence the network is passive and reciprocal

- Unity:

$${S_{11}}^2 + {S_{21}}^2 = {S_{12}}^2 + {S_{22}}^2 = 0.6^2 + 0.8^2 = 1 \tag{22}$$

  The S-Matrix respects the Unity Property, hence the network is lossless.

- Return Loss

  The following points will present the maths required to evaluate Return Loss when connecting different loads to the network. The theory behind it is presented in 2.1.2.
  Matched load

$$\Gamma = S_{11} \longmapsto RL = -20log0.6 = 4.44dB \tag{23}$$

  Short circuit

$$\Gamma = \frac{V^-}{V^+} = -1 \tag{24}$$

$$V_1^- = S_{11}V_1^+ + S_{12}V_2^+ = S_{11}V_1^+ - S_{12}V_2^- \tag{25}$$

$$V_2^- = S_{21}V_1^+ + S_{22}V_2^+ = S_{21}V_1^+ - S_{22}V_2^- \tag{26}$$

$$V_2^- = \frac{S_{21}V_1^+}{1 + S_{22}} \tag{27}$$

$$V_1^- = S_{11}V_1^+ - \frac{S_{12}S_{21}V_1^+}{1 + S_{22}} \tag{28}$$

$$\Gamma = \frac{V_1^-}{V_1^+} = S_{11} - \frac{S_{12}S_{21}}{1 + S_{22}} = 0.2 \longmapsto RL = -20log0.2 = 13.98dB \tag{29}$$

<u>25 Ω load</u>

$$\Gamma = \frac{Z_l - Z_0}{Z_l + Z_0} = -\frac{1}{3} \longmapsto RL = -20log-\frac{1}{3} = -0.48dB \tag{30}$$

3.1.3 Cable-Device-Cable

As for the Return Loss, this section, refers to equations explained in 16

$$= \frac{2\pi}{\lambda} \longmapsto \theta = \frac{2\pi}{\lambda}d = \frac{2\pi f}{c}d = \frac{2\pi 10^1 0}{3 10^8}10^{-2} = \frac{2\pi}{3} \tag{31}$$

$$\begin{bmatrix} S'_{11} & S'_{12} \\ S'_{21} & S'_{22} \end{bmatrix} = \begin{bmatrix} e^{-j\theta_1} & 0 \\ 0 & e^{-j\theta_n} \end{bmatrix} \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} e^{-j\theta_1} & 0 \\ 0 & e^{-j\theta_2} \end{bmatrix} \tag{32}$$

$$\begin{bmatrix} S'_{11} & S'_{12} \\ S'_{21} & S'_{22} \end{bmatrix} = \begin{bmatrix} e^{-j\frac{2\pi}{3}} & 0 \\ 0 & e^{-j\frac{2\pi}{3}} \end{bmatrix} \begin{bmatrix} 0.6 & 0.8e^{j\frac{\pi}{4}} \\ 0.8e^{j\frac{\pi}{4}} & 0.6 \end{bmatrix} \begin{bmatrix} e^{-j\frac{2}{3}} & 0 \\ 0 & e^{-j\frac{2}{3}} \end{bmatrix} \tag{33}$$

$$\begin{bmatrix} S'_{11} & S'_{12} \\ S'_{21} & S'_{22} \end{bmatrix} = \begin{bmatrix} 0.6e^{-j\frac{4\pi}{3}} & 0.8e^{j\frac{\pi}{4}} \\ 0.8e^{j\frac{\pi}{4}} & 0.6e^{-j\frac{4\pi}{3}} \end{bmatrix} \tag{34}$$

3.2 Simulation: Microstrip Transmission Lines

Below presented the graphs obtained in the AWR simulation.

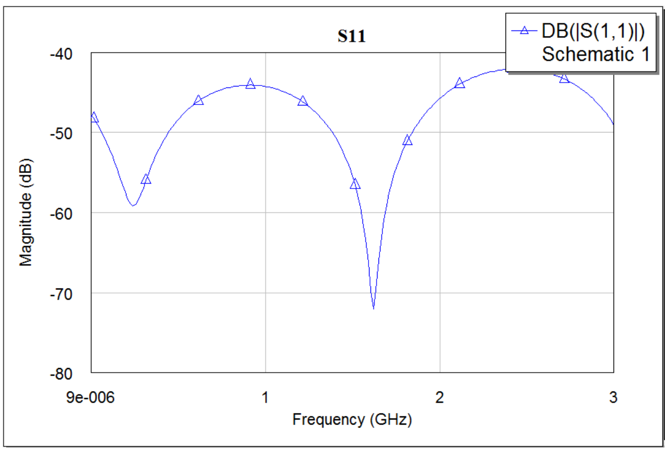

Figure 4: S_{11} Magnitude (dB) v Frequency.

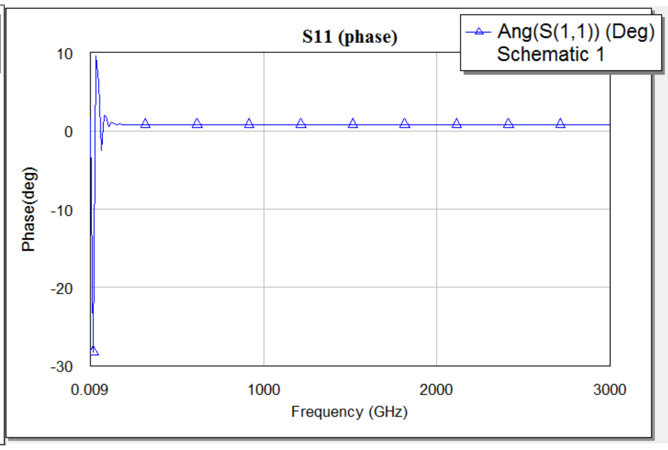

Figure 5: S_{11} Phase v Frequency.

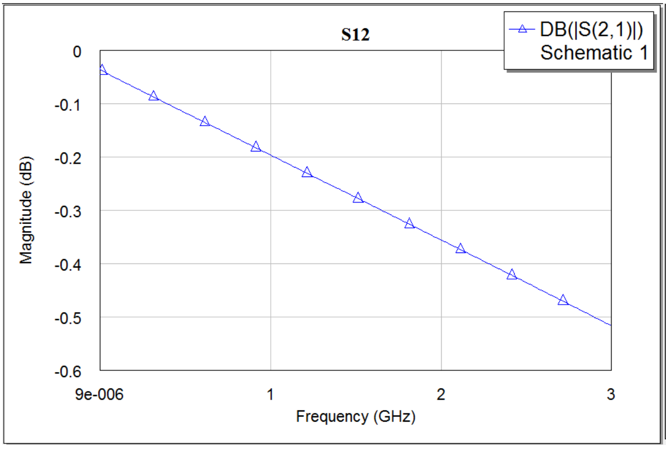

Figure 6: S_{12} Magnitude (dB) v Frequency.

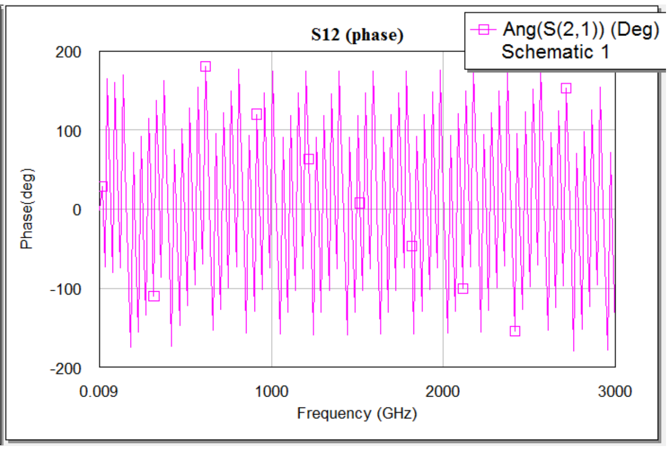

Figure 7: S_{12} Phase v Frequency.

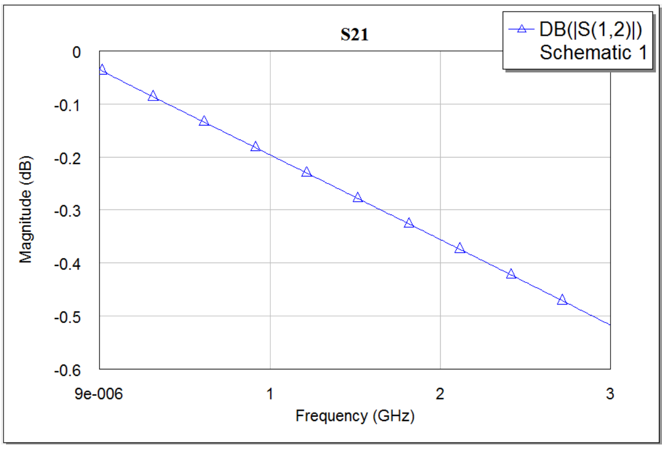

Figure 8: S_{21} Magnitude (dB) v Frequency.

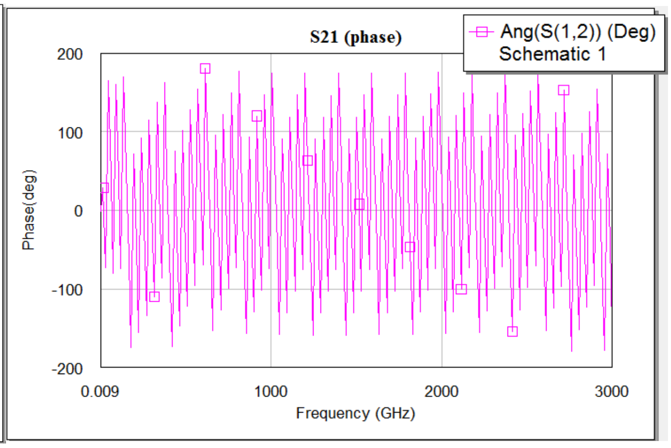

Figure 9: S_{21} Phase v Frequency.

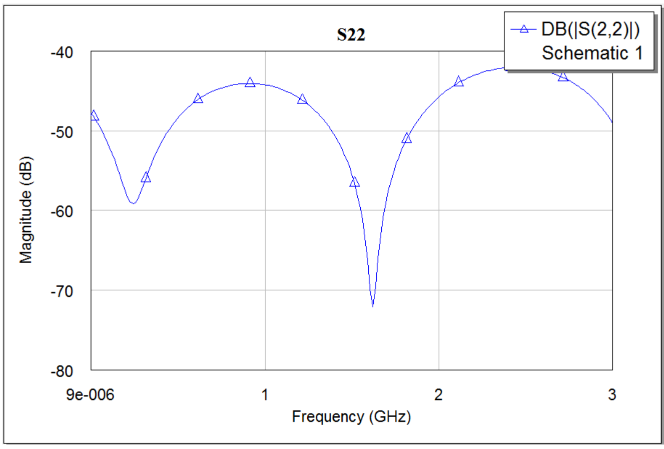

Figure 10: S_{22} Magnitude (dB) v Frequency.

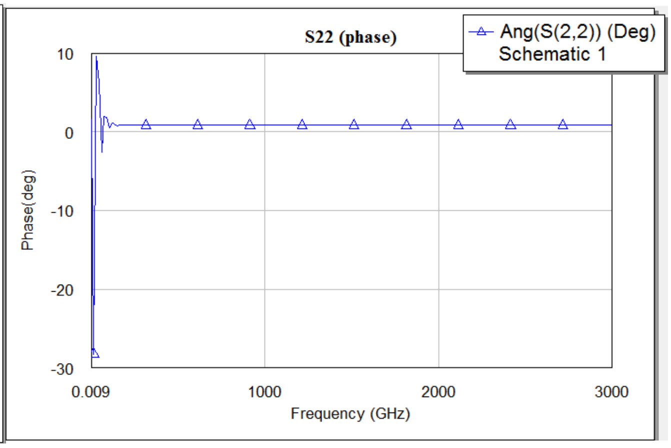

Figure 11: S_{22} Phase v Frequency.

3.3 Measurements: Microstrip Transmission Lines

Below presented the graphs obtained processing the data measured by the VNA with MATLAB.

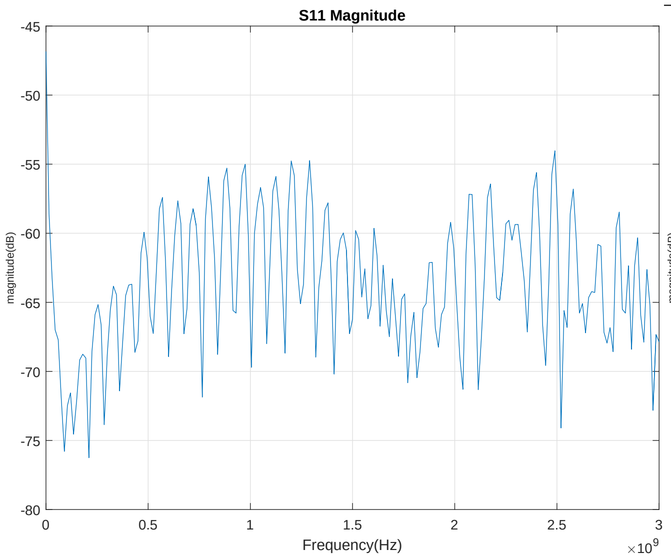

Figure 12: S_{11} Magnitude (dB) v Frequency.

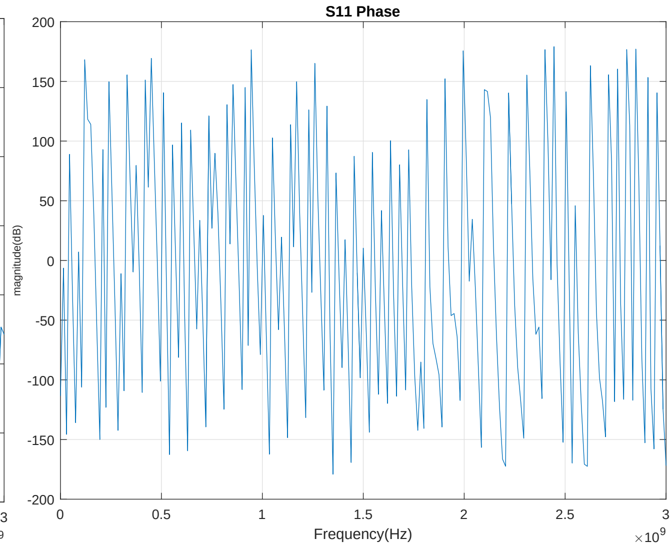

Figure 13: S_{11} Phase v Frequency.

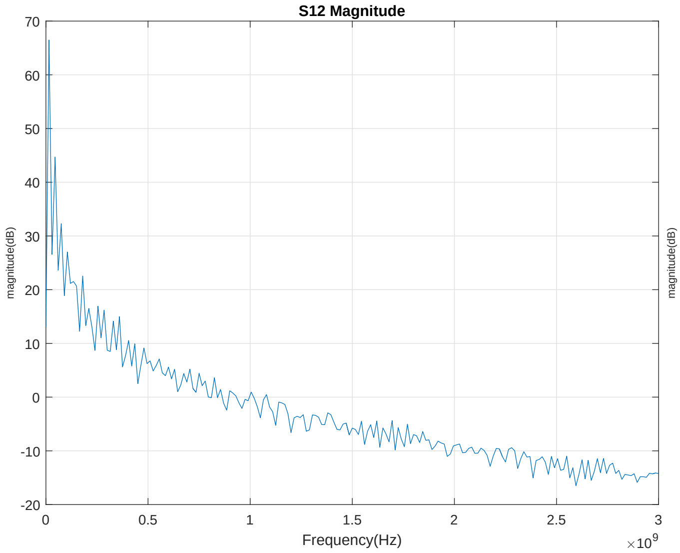

Figure 14: S_{12} Magnitude (dB) v Frequency.

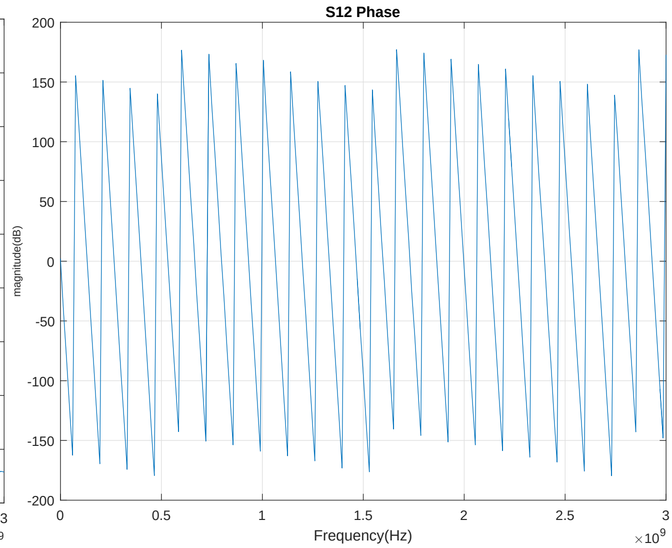

Figure 15: S_{12} Phase v Frequency.

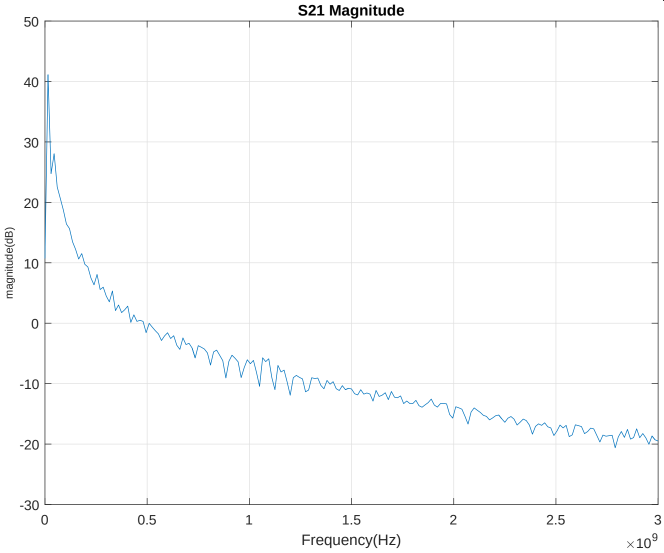

Figure 16: S_{12} Magnitude (dB) v Frequency.

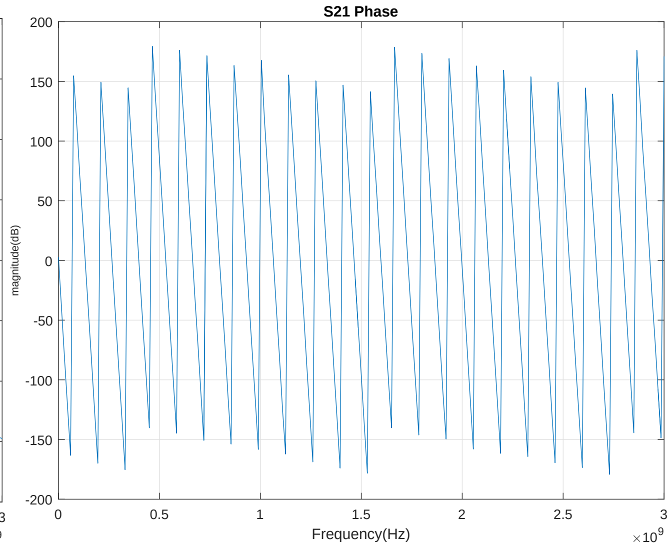

Figure 17: S_{21} Phase v Frequency.

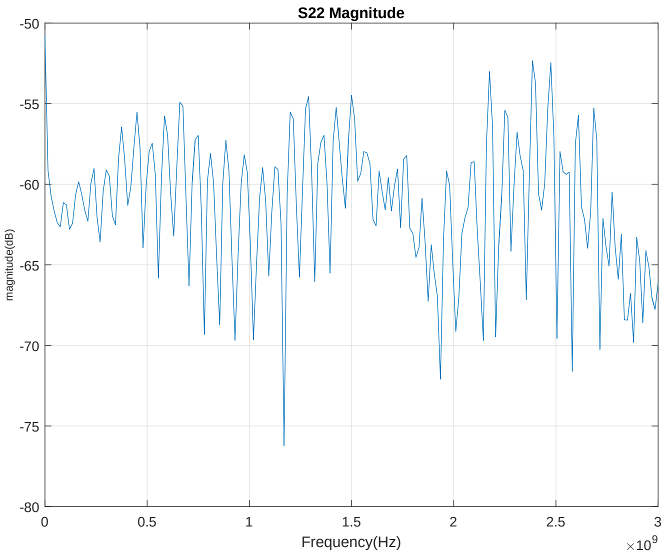

Figure 18: S_{22} Magnitude (dB) v Frequency.

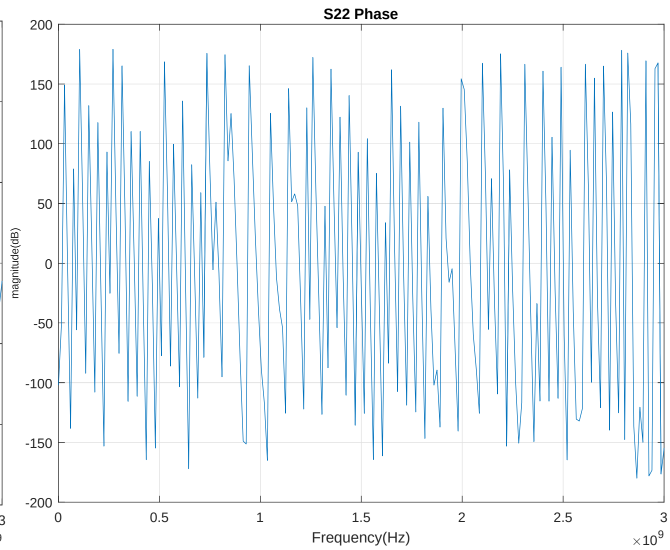

Figure 19: S_{22} Phase v Frequency.

Both unity and symetry test fail *for all frequencies*,hence the MATLAB script 2.3 fills both *unit* and *sym* vectors of zeros, indicating the tests failed.

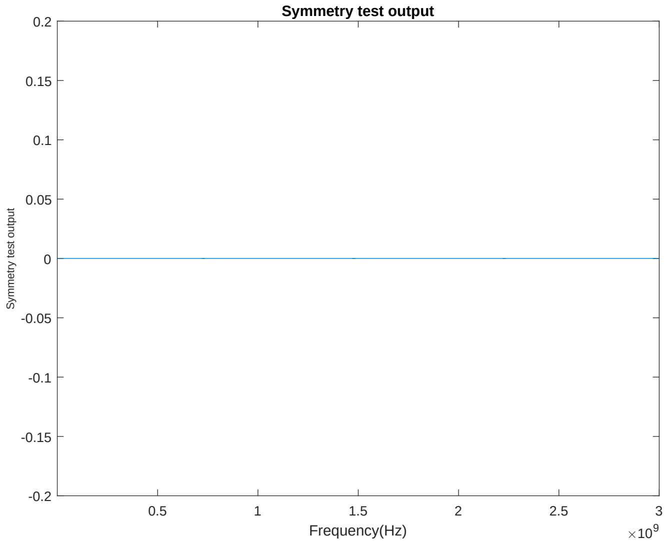

Figure 20: S_{22} Magnitude (dB) v Frequency.

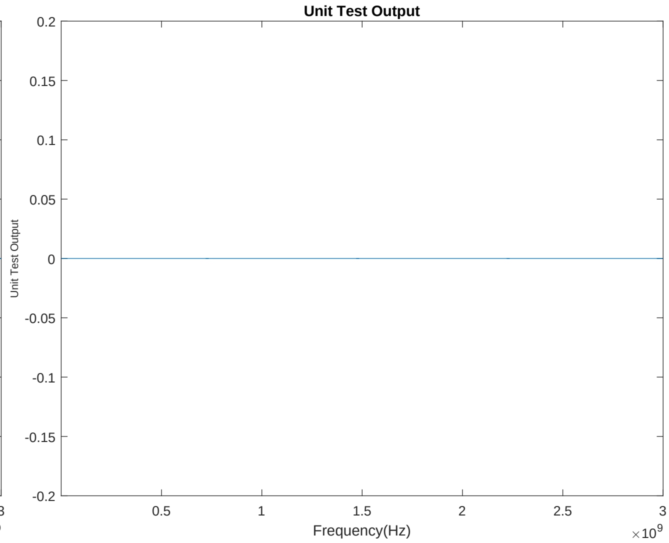

Figure 21: S_{22} Phase v Frequency.

4 Discussion

4.1 Theory: Network Parameters and Measurements

Mathematical proofs of the statements presented in the following paragraphs are omitted, although present in Chapter 4, Microwave Engineering, M. Pozar.

4.1.1 Z-Parameters

If a Z-Matrix is symmetrical, the described network is passive and reciprocal: no matter in what direction the netwrok is crossed, the effects of it on a voltage or on a current will be equivalent. If a Z-Matrix is purely imaginary, hence not affecting the amplitude or neither voltage nor current, the network is said to be lossless.

4.1.2 S-Parameters

If an S-Matrix is symmetrical, the described network is passive and reciprocal: the effects of transmitted and reflected voltage will not vary depending upon the direction of stimulation of the netwrok. They will vary according to the route taken to cross the network (from N-port to N-port). If an S-Matrix is unitary, the network is said to be lossless, as no component will dissipate power.

4.1.3 Return Loss

- Matched Load: RL is a positive value, hence, the network can be viewed as a passive device, because the reflection coefficient is less than unity.
- Short Circuit: RL is a positive value, hence, the network can be viewed as a passive device, because the reflection coefficient is less than unity.
- 25 Ω Load: RL is a negative value and no active devices are present in the network: the gain of the network is negative.

4.1.4 Cable-device-cable

Given the results presented, it's possible to see how each cable individually adds a delay of $\frac{2\pi}{3}$ to the voltage.

4.2 Simulations and Measurements comparison: Microstrip Transmission Line

4.2.1 Magnitude

Simulation: As visible from the graphs presented in the simualtion results section: reflection is at its minimum around 1.65GHz and at its maximum around 2.5GHz, transmission instead decreases as the frequencies increase.
Measurements: As visible from the graphs presented in the measurements results section: the measured data follows a trend visible in the simulated data. The data is much nosier, due to the unidealised conditions of the lab and, for some of the measurements, to the fact that *Trigger* wasn't operated whilst taking the measurements. This generated .csv files which had to be acquired in the MATLAB program in different ways, according to whether *Trigger* had been selected on the VNA or not, as the format was different. In order to remove precision error from the measured data, the MATLAB script rounds the data to three decimal positions of precision.

4.2.2 Phase

Observing the x-axis of the presented diagrams for the AWR simulation results, along with figure 3, a distraction error is visible: upper and lower limits of the operating frequency don't correspond to those utilised by the VNA. A comparison between the two data sets becomes difficult. Unfrotunately licensing restrictions on the AWR software don't allow me to repeat the measurements for the phase of S-Parameters from home.

5 Conclusions

The main skills acquired in this lab are

- Evaluation and understandment of Z and S-Matrix
- Measurement of S-Parameters via VNA
- Processing of data with MATLAB and comparison with AWR simulation data

6 MATLAB code

Below presented the MATLAB code with which measurement data is processed. A function 6 is used to import the data contained in the .csv files.

```
function [f,val] = readData(datafile,bool,magphase)
fid = fopen(datafile,'r'); %open filename for read returning a scalar file i
if (bool == 1)
    data = textscan(fid,'%f %f %f','HeaderLines',3,'Delimiter',';');
    f = data{1};
    if(magphase == 'mag')
```

```
            val = data{2};
            val = round(val*1000)/1000;
        else
            val = data{3};
            val = round(val*1000)/1000;
        end

else
    data = textscan(fid, '%f %f','HeaderLines',3,'Delimiter',';');
    f = data {1};
    val = data{2};
    val = round(val*1000)/1000;
end
fclose(fid); %closes file
```

This script is then used to plot results.

```
[f,val] = readData('S11.csv',1,'mag');
s11_m = val;
[f,val] = readData('S11P.csv',1,'pha');
s11_p = val;

[f,val] = readData('S12M.csv',0);
s12_m = val;
[f,val] = readData('S12P.csv',0);
s12_p = val;

[f,val] = readData('S21M.csv',1,'mag');
s21_m = val;
[f,val] = readData('S21P.csv',1,'pha');
s21_p = val;

[f,val] = readData('S22M.csv',0);
s22_m = val;
[f,val] = readData('S22P.csv',0);
s22_p = val;
n = (size(s11_m))
unit = zeros (n);
for i = 1 : n
    mag1 = s11_m(i)*s11_m(i);
    mag2 = s21_m(i)*s21_m(i);
    if ((mag1+mag2) == 1)
        mag1 = s12_m(i)*s21_m(i);
        mag2 = s22_m(i)*s22_m(i);
        if ((mag1+mag2) == 1)
            unit(i) = 1;
        end
    end
end

```

```
%Unit Test
figure;
plot(f,unit);
axis([f(1) f(end) -0.2 0.2]);
ylabel('Unit Test Output','FontSize',8);
xlabel('Frequency(Hz)');
title(['Unit Test Output']);
print(gcf,'-depsc2','unit.eps');


sym = zeros (n);
for i = 1 : n
    if((s12_m(i)==s21_m(i))&&(s12_p==s21_p))
        sym(i) = 1;
    end
end
%Symmetry test
figure;
plot(f,sym);
axis([f(1) f(end) -0.2 0.2]);
ylabel('Symmetry test output','FontSize',8);
xlabel('Frequency(Hz)');
title(['Symmetry test output']);
print(gcf,'-depsc2','sym.eps');

% %S11 Mag
 figure;
 plot(f,(-20*log(s11_m)));
 grid on;
 ylabel('magnitude(dB)','FontSize',8);
 xlabel('Frequency(Hz)');
 title(['S11 Magnitude']);
 print(gcf,'-depsc2','s11_m.eps');
 %S11 PHASE
 figure;
 plot(f,s11_p);
 grid on;
 ylabel('magnitude(dB)','FontSize',8);
 xlabel('Frequency(Hz)');
 title(['S11 Phase']);
 print(gcf,'-depsc2','s11_p.eps');
 %S12 MAG
 figure;
 plot(f,(-20*log(s12_m)));
 grid on;
 ylabel('magnitude(dB)','FontSize',8);
 xlabel('Frequency(Hz)');
 title(['S12 Magnitude']);
 print(gcf,'-depsc2','s12_m.eps');
```

```
%S12 PHASE
figure;
plot(f,s12_p);
grid on;
ylabel('magnitude(dB)','FontSize',8);
xlabel('Frequency(Hz)');
title(['S12 Phase']);
print(gcf,'-depsc2','s12_p.eps');
% %S21 MAG
figure;
plot(f,(-20*log(s21_m)));
grid on;
ylabel('magnitude(dB)','FontSize',8);
xlabel('Frequency(Hz)');
title(['S21 Magnitude']);
print(gcf,'-depsc2','s21_m.eps');
%S21 PHASE
figure;
plot(f,s21_p);
grid on;
ylabel('magnitude(dB)','FontSize',8);
xlabel('Frequency(Hz)');
title(['S21 Phase']);
print(gcf,'-depsc2','s21_p.eps');
%S22 MAG
figure;
plot(f,(-20*log(s22_m)));
grid on;
ylabel('magnitude(dB)','FontSize',8);
xlabel('Frequency(Hz)');
title(['S22 Magnitude']);
print(gcf,'-depsc2','s22_m.eps');
%S22 PHASE
figure;
plot(f,s22_p);
grid on;
ylabel('magnitude(dB)','FontSize',8);
xlabel('Frequency(Hz)');
title(['S22 Phase']);
print(gcf,'-depsc2','s22_p.eps');
```