SİVAS UNIVERSITY OF SCIENCE AND TECHNOLOGY
FACULTY OF ENGINEERING AND NATURAL SCIENCES

APPLIED MICROWAVE ENGINEERING

Experiments Manual Report

Supervisor: Prof. Dr. Fatih KABURCUK
Research Assistant: Şekip DALGAÇ
Research Assistant: Kağan Murat PÜRLÜ

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1-MATCHING CIRCUIT DESIGN WITH LUMPED ELEMENTS

1. OBJECTIVES

- Designing a matching circuit with lumped elements over a microstrip line.
- To investigate L-section impedance matching circuits.
- Understanding the Smith Chart usage.
- Usage of admittance and impedance values in the Smith Chart.

2. BRIEF INFORMATION ABOUT THE LUMPED ELEMENT MATCHING CIRCUITS:

1- Effective Dielectric Constant and Microstrip Line Impedance Calculation

In order to calculate the microstrip line impedance, you need to calculate the effective dielectric constant and use it in the impedance calculation.

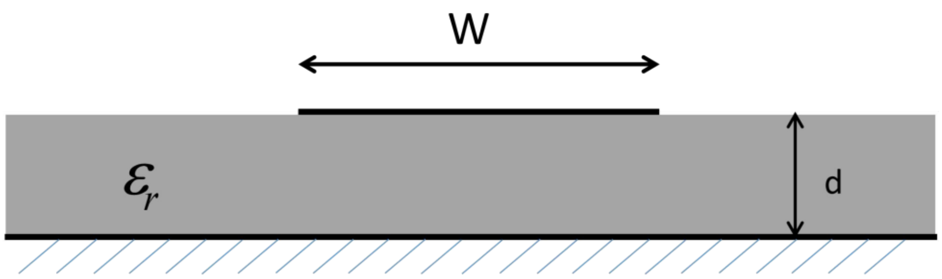


Figure 1 Microstrip Line Representation

The effective dielectric constant of a microstrip line is given by;

$$\epsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12d/W}} \qquad (1)$$

The microstrip impedance is calculated with the formula below;

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_e}} \ln\left(\frac{8d}{W} + \frac{W}{4d}\right) & \text{for } W/d \leq 1 \\ \frac{120\pi}{\sqrt{\epsilon_e}\,[W/d + 1.393 + 0.667 \ln(W/d + 1.444)]} & \text{for } W/d \geq 1 \end{cases} \qquad (2)$$

Calculate the effective dielectric constant and characteristic impedance for 4 mm, 8 mm, 12 mm, 16 mm, 20 mm and 24 mm line widths (W) and 4.5 mm dielectric height (d). It is easier to write a MATLAB or OCTAVE code for this calculation.

Microstip Line Widths (W)	Effective Dielectric Constant (ε_e)	Characteristic Impedance (Z_0)
4 mm		
8 mm		
12 mm		
16 mm		
20 mm		
24 mm		

2- Impedance Matching

Impedance matching or tuning is an important subject of microwave engineering. Impedance matching can be between any two components or between a component and a transmission line. The aim of using a matching circuit is usually to deliver the maximum power. The matching circuits are generally designed for a single frequency but it is generally desired to have the matching over a frequency bandwidth. We will use microstrip stubs to match the source impedance to the load impedance during the experiments. Z_L is the load impedance, Z_0 is the characteristic impedance and Z_S is the source impedance. Zs is nearly equal to Z_0 in the experiments. There are different impedance matching topologies for lumped element and microstrip line stubs. We need to use Smith Chart for impedance matching during the experiments.

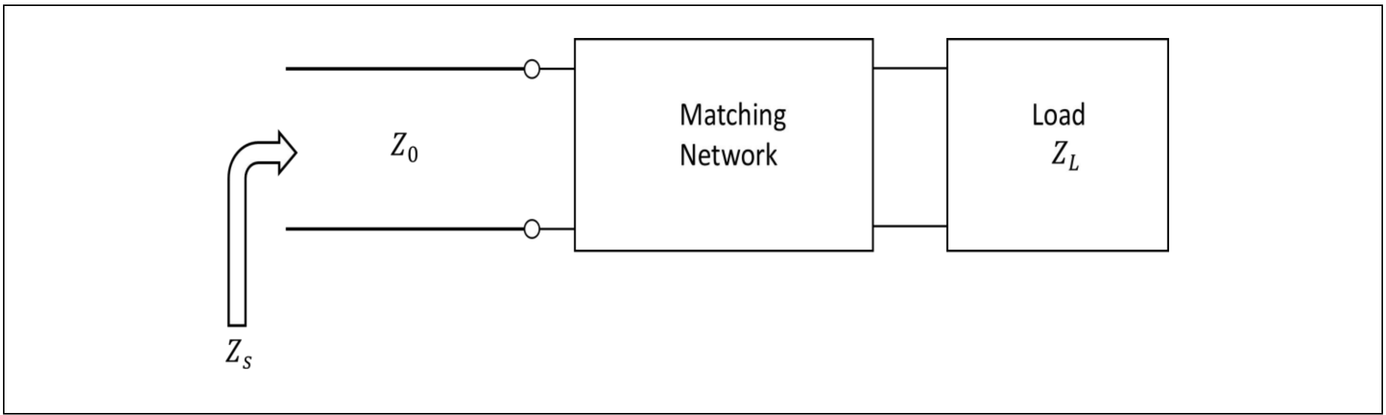


Figure 2 Impedance Matching Network

3- Impedance Matching with Lumped Elements

L-section impedance matching:

Impedance matching with L-section lumped elements is one of the simplest ones. It aims to match the load impedance Z_L with 2 reactive elements. These elements can be inductance or capacitance.

If the normalized load impedance $z_L = Z_L/Z_O$ is inside the 1+jx circle on the Smith Chart, then the circuit in Figure 3 should be used and if it is outside the circle on the Smith Chart, the circuit in Figure 4 should be used. The reactive elements can be inductance or capacitance. Therefore, there are 4 different matching configurations for each circuits in Figure 3 and 4. Below 1 GHz, the circuit elements are very small comparing to the wavelength and the lumped elements are useful. If the circuits are small enough, L-section technique can also be used at higher frequencies.

You can use analytical calculations in Microwave Engineering Book or lossless impedance matching tools practically. The real lumped elements have extra effects and the results won't be the same as in the calculations. You will practice impedance matching during this experiment.

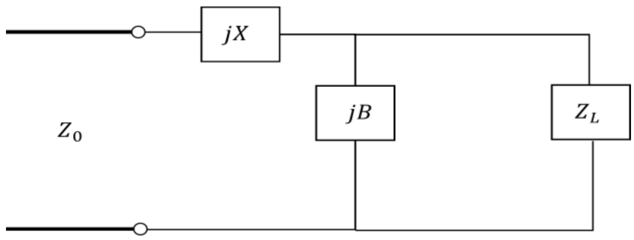


Figure 3 L-section Matching Network for Z_L inside the 1+jx circle

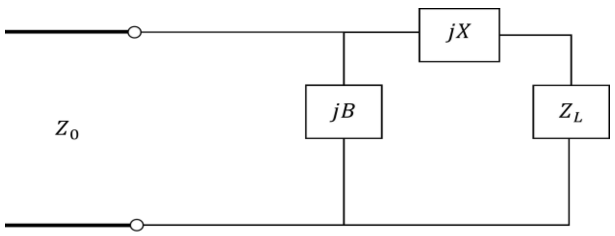


Figure 4 L-section Matching Network for Z_L outside the 1+jx circle

3. EXAMPLE ABOUT DESIGNING A LUMPED ELEMENT MATCHING CIRCUIT WITH ANTEN'IT:

The box in Figure 5 is the matching circuit design with lumped elements experiment box. There are 1.5 mm metal cells, 3 mm metal cells, 1.5 mm beige dielectrics, 3 mm beige dielectrics and lumped element blocks (inductance and capacitance) in the box. We will use them for different impedance matching circuits.

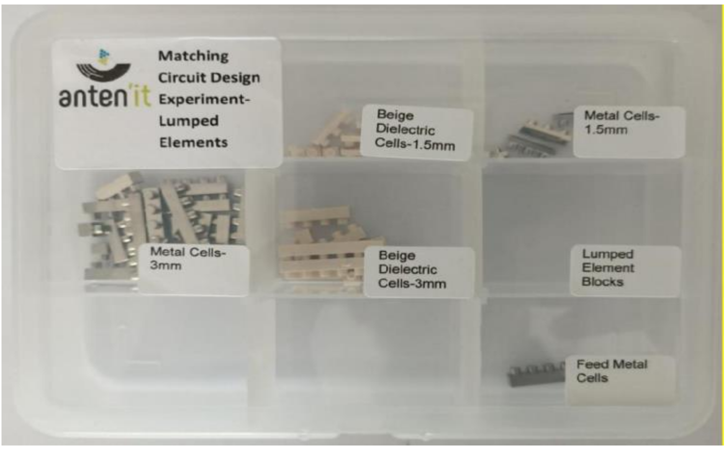


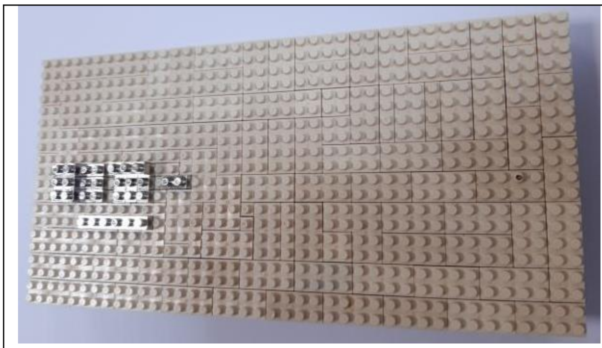
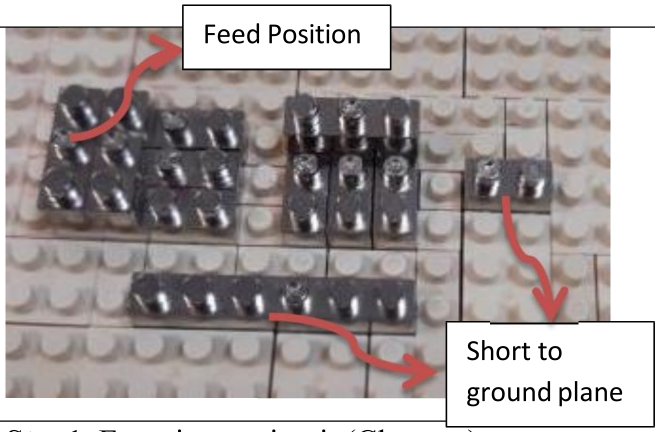
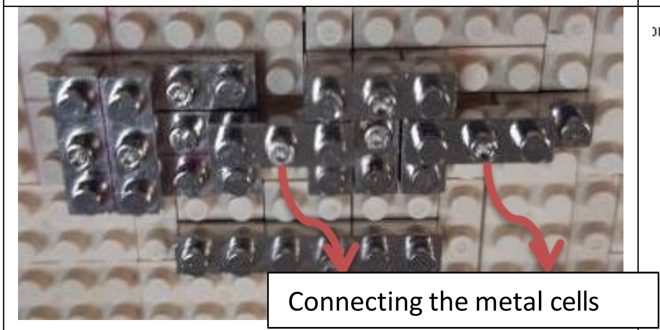
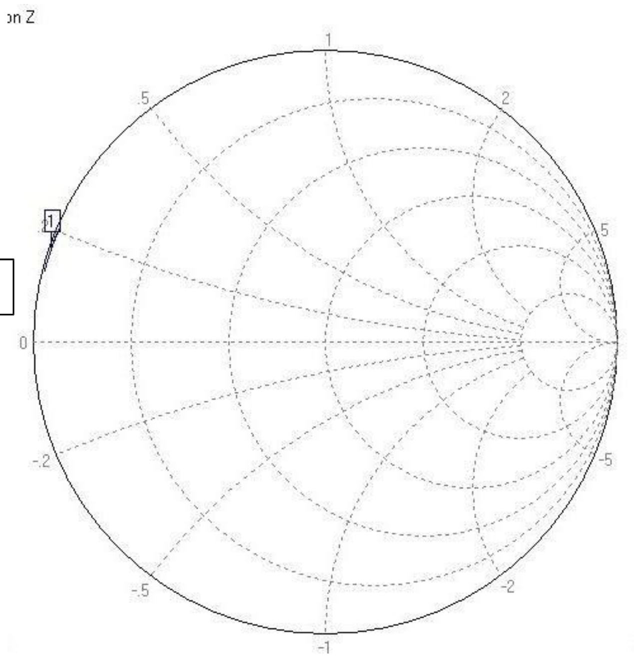
Figure 5 Matching Circuit Design Experiment-Lumped Elements

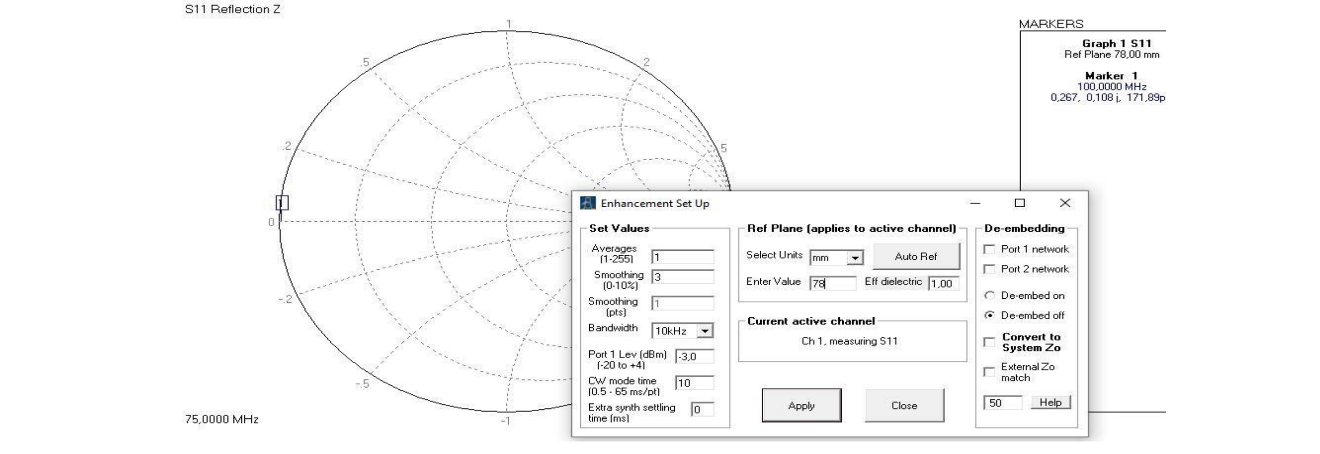
First you need to use the ground plane with the dielectrics over it. It is the ground plane with two connectors in the kit. Then, locate 3 mm metal cells to build a microstrip line. Use 1.5 mm metal cells to have short circuit to the ground plane.

Example Matching Circuit Design:

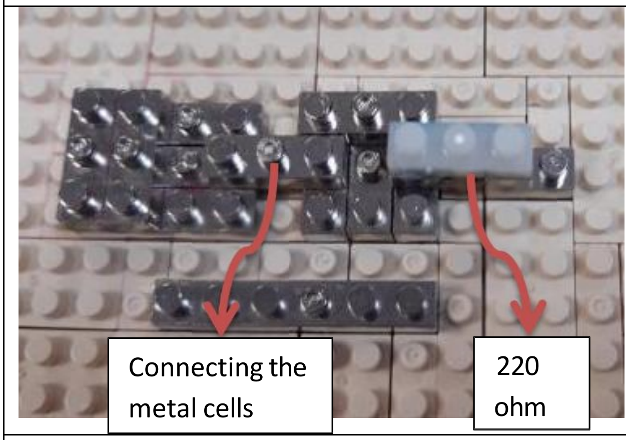
In this example, we will match a 220 ohm load impedance to 50 ohm source impedance. Network analyser port impedance is 50 ohm and we need to match the 220 ohm to the port impedance in order to achieve maximum power transfer.

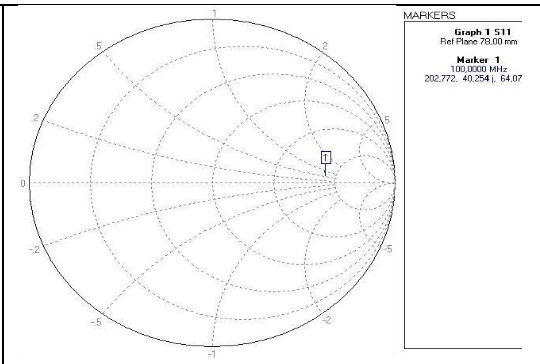
We have the circuit in "Anten'it Matching Circuit Design with Lumped Elements" experiment. Here is the explanation of how to use this circuit. We also have 220 ohm in the experiment box. You can repeat the example to understand how to match the next impedances to 50 ohm.

	
Step1: Experiment circuit	**Step1**: Experiment circuit (Close up)
	
Step2: Locate two 1X3 metal cells to connect the metal cells into each other. We need to change the reference plane to measure the impedance of the lumped resistance correctly.	The impedance before changing the reference plane is seen in the Smith Chart above. You can find the appropriate electrical length to move the marker to short circuit (a value near zero ohm) in Smith Chart.



You can directly add 78 mm to shift the reference plane of the measurement. It is on the short point of the Smith Chart now. If your network analyzer doesn't have this option, skip this step.



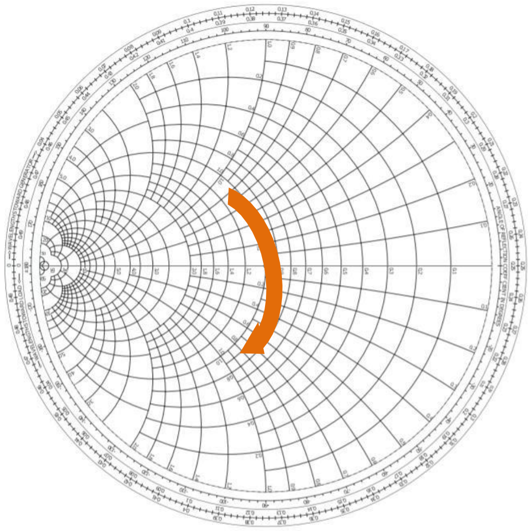
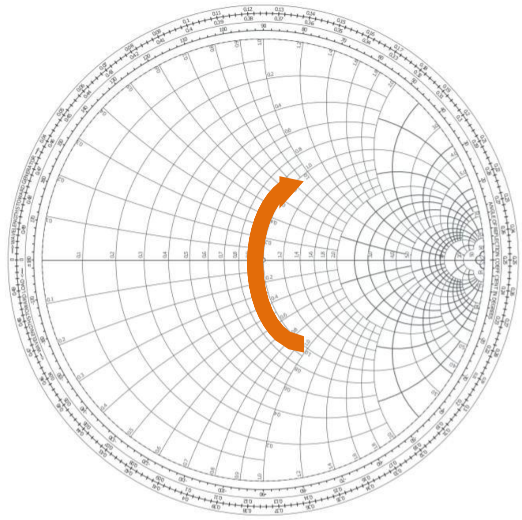
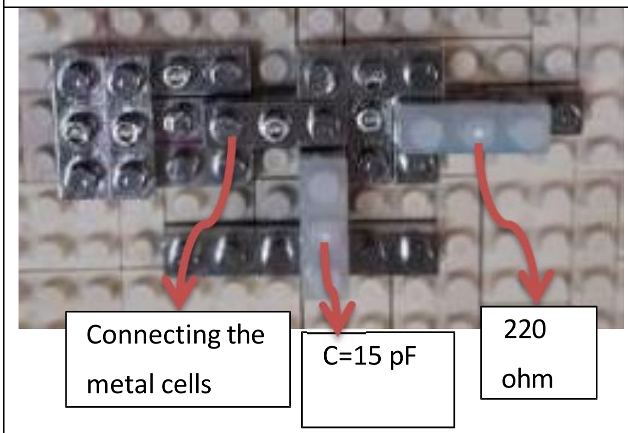


Step3: Connect the metal cell and 220 ohms.

Measure the impedance @ 100 MHz as approximately 202+40 j ohm.

There are two ways to go to 50-ohm impedance circle. One is with a shunt capacitance and the other one is with a shunt inductance. We go on with a shunt capacitance. Shunt components move on the admittance circles. Admittance circles are shown in the next figure.

Series components move on the impedance circles.

<table>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Admittance circles (Shunt components change the impedance by moving on the admittance circles.)</td>
<td>Impedance circles (Series components change the impedance by moving on the impedance circles.)</td>
</tr>
<tr>
<td>
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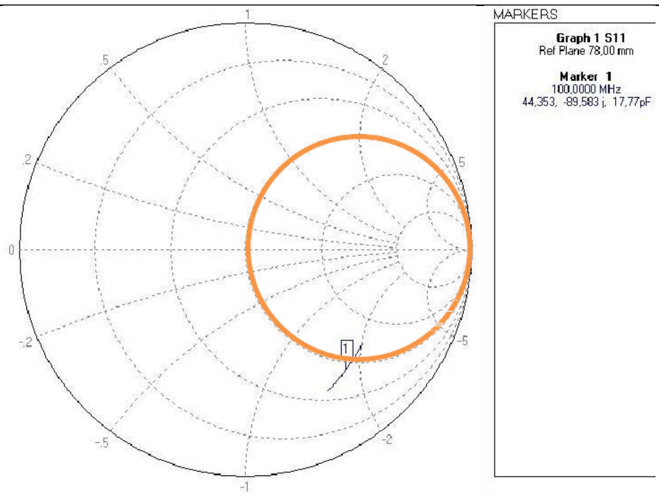
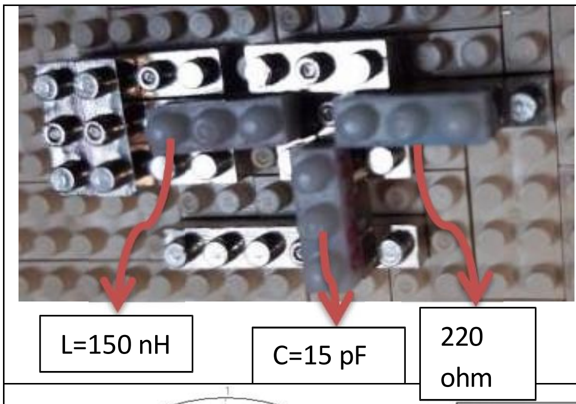
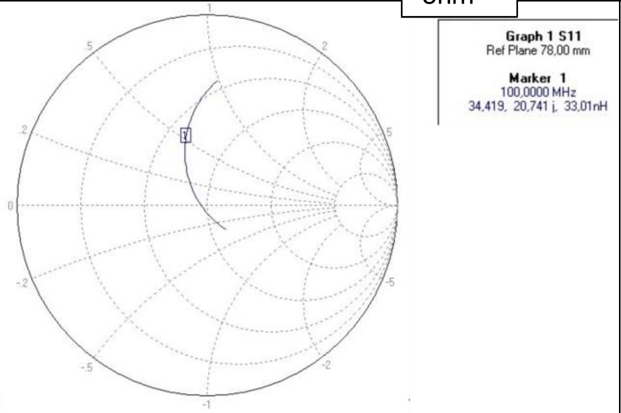
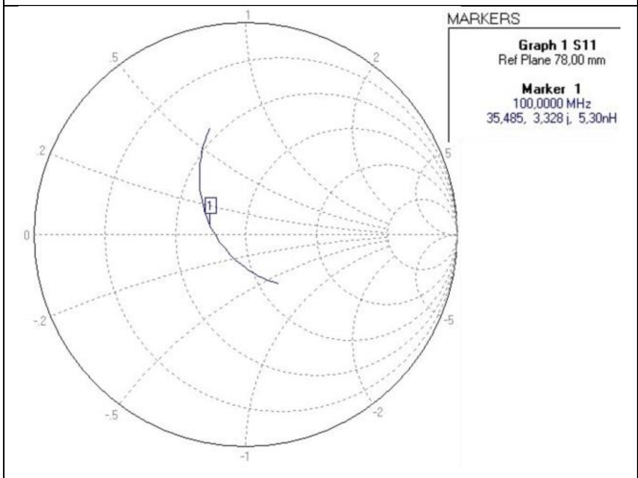
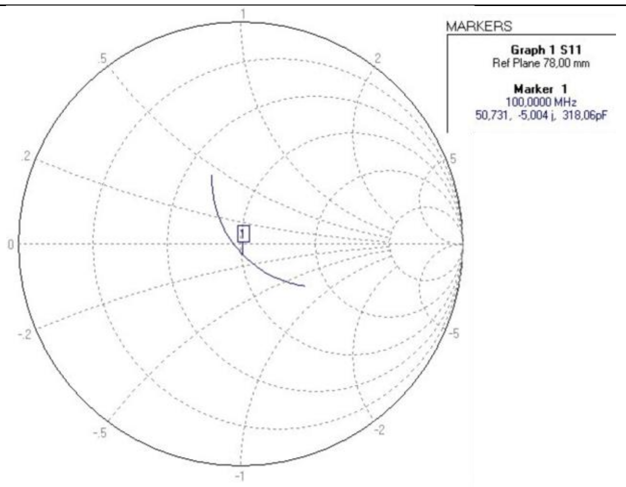
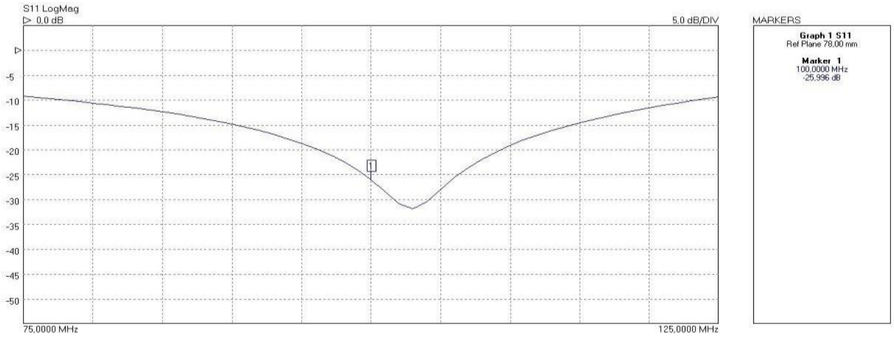
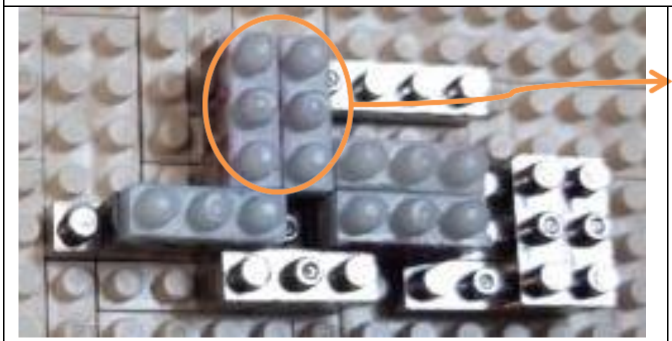
<td>
</td>
</tr>
<tr>
<td>Step4: Calculate the capacitance or try different capacitances and find the appropriate value. C=15 pF moves the marker close to 50-ohm impedance circle.</td>
<td>The impedance is 44-89j ohm at 100 MHz (The values may change a bit due to the tolerances when you apply the same process). Now we need an inductance to compensate the imaginary part. (The orange circle is the 1+jx circle)</td>
</tr>
</table>

	**Step5**: L=140 nH is calculated. Since there are 120 and 150 nH values in Anten'it SMD components, we choose to use 150 nH.
	The measured results show that the impedance is 34+20j ohms at 100 MHz. It is closer to 50 ohms but a better impedance can be achieved. First, we change the series inductance to 120 nH instead of 150 nH.
	
35+3 j ohm is achieved with 120 nH inductance. Now we will try to change the capacitance value 12 pF.	The impedance is measured as 50-5j ohm which is very close to 50 ohm. 12 pF shunt capacitance and 120 nH series inductance reached to 50-5j ohm.

<table>
<tr><td colspan="2">
</td></tr>
<tr><td colspan="2">S11 at 100 MHz is -25.9 dB. The same procedure can be applied by adding a shunt inductance and series capacitance. These are both L-section matching circuits.</td></tr>
<tr><td></td><td>Parallel components</td></tr>
<tr><td>Capacitance and inductance values are discrite such as 100 nH, 120 nH, 150 nH etc. If you need some values in between, you can connect the components parallel as shown in the figure above.</td><td></td></tr>
</table>

<u>The calculation of height:</u>

There are two kinds of beige dielectrics; one with 1.5 mm height (beige dielectric cells-1.5mm) and the other one with 3 mm height (beige dielectric cells-3mm). 1.5mm cells are connected to the ground plane and 3 mm cells are mounted over the 1.5 mm cells.

The dielectrics and metal cells are already mounted to build a microstrip line for this experiment. You will use the cells in the box to build the stubs.

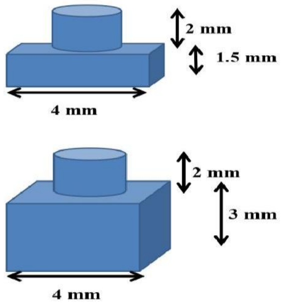


Figure 6 Anten'it 1.5 mm and 3 mm cell dimensions

Removing the cells:

Removing the cells is one of the most important parts to learn. The misusage can damage the cells. Brick remover holds two of the cylinders at the same time. You just need to push to the high end of the remover as in Figure 7.

The removing tool for this experiment is a plastic brick remover. In order to get the best efficiency, we need to start dismounting the cells from outside. First, remove the smallest metal cells which are on the outside. Second, remove the cells which are on the outside but larger. To remove the cells, always hold the cylinders in the center as in Figure 7.

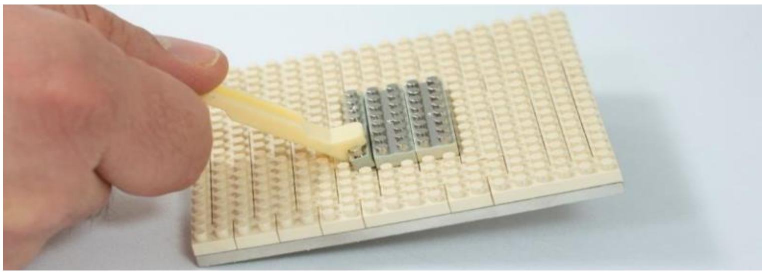


Figure 7 Brick Remover Usage

SSMA to SMA adaptors are used for calibration.

<u>The list of SMD Component Values in the kit:</u>

SMD Capacitances	**SMD Inductances**	**SMD Resistances**
10 pF	15 nH	27 ohm
12 pF	22 nH	33 ohm
15 pF	33 nH	
22 pF	39 nH	
33 pF	47 nH	
39 pF	56 nH	
47 pF	68 nH	
56 pF	100 nH	
68 pF	120 nH	
100 pF	150 nH	
	220 nH	
	330 nH	

4. PRELIMINARY WORK:

1. Read and understand the example in Section 3 before starting the experiment. Use Smith Chart tools to understand it if you can't do it in the laboratory.
2. What does the reflection coefficient mean? What is the relationship between the reflection coefficients and transmission coefficients in a microstrip line with 2 ports?
3. What is the relationship between the Smith Chart and decibel format S-parameter values?
4. What percentage of the input power is reflected when S_{11} is -10 dB?
5. Explain what values the Smith Chart represent and the usage of it.
6. Explain why we use lumped elements instead of regular larger elements.

5. EXPERIMENTAL PROCEDURE:

1. Connect the cables to the Network Analyser and connect the SSMA-Female to SMA-Male adapters to the SSMA-male side of the cables as shown in Figure 8. Calibrate the Network Analyzer for 1 port measurement between 100 MHz and 1000 MHz.

Figure 8 Cable to SSMA-SMA Adaptor Connection

2. Connect the microstrip line board to the VNA. Check if the total dielectric height is 4.5 mm except the cylinders of the bricks. There must be the beige dielectric bricks with 1.5 mm over the ground plane and 3 mm beige dielectrics over the 1,5 mm beige dielectrics. Check if both ground planes are connected to each other as in the figure below.

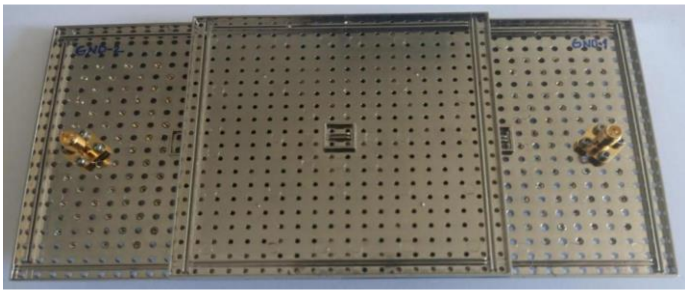


Figure 9 Ground plane connection

Two ground planes are connector into each other with another ground plane at the bottom of them. There are 1,5 mm beige dielectrics layer over the ground planes. There is a second layer with 3 mm dielectric cells over the 1,5 mm dielectric cells. The third layer is the 3 mm metal cells which builds the microstrip line over the dielectrics.
1,5 mm metal cells are used to have short circuit to the ground planes. 3 mm metal cells are connected over the 1,5 mm metal cells.

3. Locate the feed metal cells over the connector inner conductors. The red or blue point needs to be over the inner conductor.

Figure 10 Red or blue feed point

4. Use a multi-meter or voltmeter in order to check if the inner conductor of the connector is connected to the feed cell. Turn the multi-meter to "short" buzzer option. With one probe touch to the inner conductor of the SSMA connector from the bottom of the ground plane and with the other probe touch to the feed cell. If the buzzer is ringing, they are connected to each other and we can start the experiment.

Figure 11 Buzzer

5. Go to the impedance matching example in section 3 and go over this example with the kit.

6. Match the impedance for 220 ohms again by using a shunt inductance and series capacitance. This is different from the example. In the example, we used a shunt capacitance and a series inductance. Iterate your design as in the example to have the best impedance matching. Write down the shunt capacitance and series inductance values, S11 [dB] and the impedance you reached. Try to match the S11 [dB] below -15 dB.

Shunt Inductance	Series Capacitance	S11 [dB]	Impedance

7. Use 27 ohm lumped element block as the load impedance instead of 220 ohm. The configuration of the L-section needs to change. You need admittance circles to reach to 50

ohm. Select one of the L-section configurations. You can calculate the inductance and capacitance values or directly iterate if you know how to reach to 50 ohm. Use the table below for each point you iterate. Use 100 MHz frequency as in the example. Try to match S11 [dB] below -15 dB.

* You can start the iteration by changing the capacitance and inductance values to one value up or down from the lumped elements in the experiment box. Iteration means repetition of a mathematical or computational procedure applied to the result of a previous application, typically as a means of obtaining successively closer approximations to the solution of a problem. You need to watch the Smith Chart each time you change the lumped element values and understand if you are closer to your target impedance.

Calculation results if you have:			

Shunt Capacitance	Series Inductance	S11 [dB]	Impedance
Shunt Inductance	Series Capacitance	S11 [dB]	Impedance

“”

6. RESULTS:

- State the objective of the experiment and give a short summary of the procedure.
- Did you use any tool or calculated the component values? If yes, did you match the impedance with the same values?
- What are the reasons of the difference between theoretical and practical values?
- Is there any other matching configuration such as L-section in this experiment?
- Discuss the results of your experiment.

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2-MATCHING CIRCUIT DESIGN WITH QUARTER WAVE TRANSFORMER AND STUBS

1. OBJECTIVES

- Designing a microstrip line using Anten’it microwave kit.
- To investigate return loss.
- Designing a matching circuit via quarter wave transformers.
- Designing a matching circuit via microstrip stubs.

2. BRIEF INFORMATION ABOUT THE MICROSTRIP LINE AND IMPEDANCE MATCHING CIRCUITS:

Effective Dielectric Constant and Microstrip Line Impedance Calculation

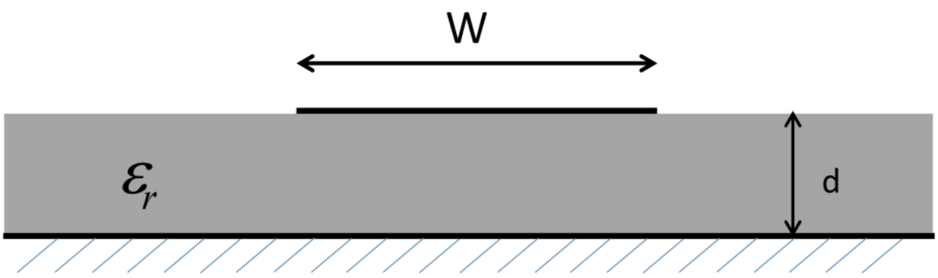

Figure 1 Microstrip Line Representation

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$$\epsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12d/W}} \qquad (1)$$

The microstrip impedance is calculated with the formula below;

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_e}} \ln\left(\frac{8d}{W} + \frac{W}{4d}\right) & \text{for } W/d \leq 1 \\ \frac{120\pi}{\sqrt{\epsilon_e}\,[W/d + 1.393 + 0.667 \ln(W/d + 1.444)]} & \text{for } W/d \geq 1 \end{cases} \qquad (2)$$

Calculate the effective dielectric constant and characteristic impedance for 4 mm, 8 mm, 12 mm, 16 mm, 20 mm and 24 mm line widths (W) and 4.5 mm dielectric height (d). ϵ_r of the substrate is 2,6. It is easier to write a MATLAB or OCTAVE code for this calculation.

“”

Microstip Line Widths (W)	Effective Dielectric Constant (ε_e)	Characteristic Impedance (Z_0)
4 mm		
8 mm		
12 mm		
16 mm		
20 mm		
24 mm		

Quarter-Wave Transformer

Quarter-wave transformer is a basic and practical way for impedance matching. If you know R_L load resistance and Z_0 characteristic impedance, quarter wave transformer has only two variables; one of them is the the length of the quarter wavelength and the other one is the Z_1 (the characteristic impedance of the quarter wavelength) resistance. Z1 needs to be calculated.

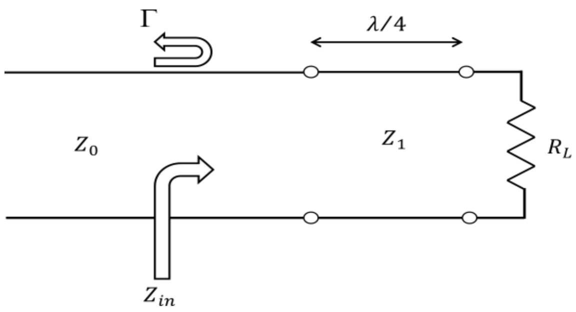


Figure 2 Quarter Wave Transformer

$$Z_{in} = Z_0 \left[\frac{R_L + JZ_1 \tan \gamma l}{Z_1 + JR_L \tan \gamma l}\right] \quad (3)$$

$$\gamma l = \frac{2\pi}{\lambda}\frac{\lambda}{4} \quad (4)$$

The equation becomes;

$$Z_{in} = Z_1{}^2/R_L \quad (5)$$

As a result;

$$Z_1 = \sqrt{Z_0 R_L} \quad (6)$$

“”

Impedance Matching

Impedance matching or tuning is an important subject of microwave engineering. Impedance matching can be between any two components or between a component and a transmission line. The aim of using a matching circuit is usually to deliver the maximum power. The matching circuits are generally designed for a single frequency but it is generally desired to have the matching over a frequency bandwidth. We will use microstrip stubs to match the source impedance to the load impedance during the experiments. Z_L is the load impedance, Z_0 is the characteristic impedance and Z_S is the source impedance. Zs is nearly equal to Z_0 in the experiments. There are different impedance matching topologies for lumped element and microstrip line stubs. We need to use Smith Chart for impedance matching during the experiments.

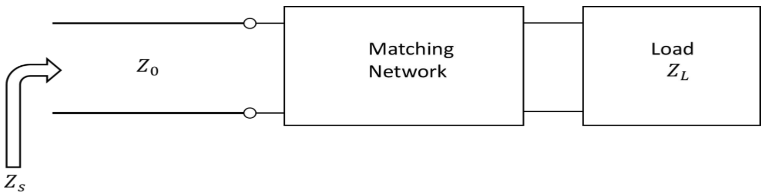


Figure 3 Impedance Matching Network

Single Stub Tuning

An alternative technique for impedance matching is to use open-circuited (open stub) or short-circuited (short stub) length of transmission line connected in series or in parallel with the transmission line at a distance from the load impedance. Since the stubs are a part of the transmission

line, it is easy to produce them. We will use shunt stubs during the microstrip line stub matching experiments. For a single stub matching, there are only 2 variables; one of them is the distance of the stub from the load impedance and the other one is the reactance or susceptance value corresponding to the stub dimensions. A shunt stub circuit which will be used during the experiments is shown in Figure 4 below:

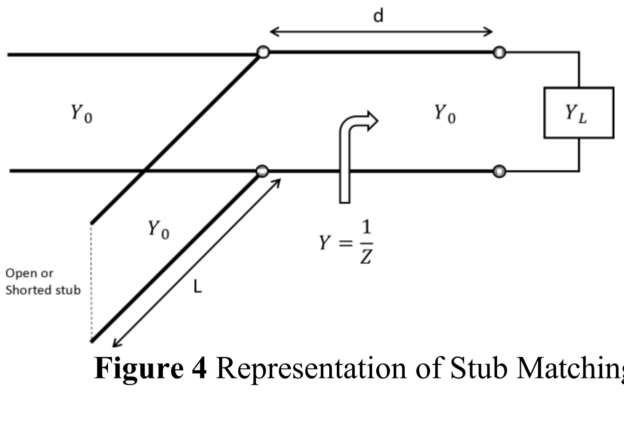


Figure 4 Representation of Stub Matching

“d” represents the distance from the load admittance and “Y” is the admittance of the stub. The stub can be short circuited or an open circuited. The length of the stub is shown as “L” and the stub impedance depending on the stub width in the experiments is represented as “Y0”. By changing the stub dimensions, any reactance or susceptance value can be achieved. The difference of using a short stub or an open stub for the same reactance or susceptance value corresponds to a quarter wavelength.

Bandwidth:

The impedance bandwidth of a matching circuit is a frequency range between the highest and lowest frequency where return loss is below a certain value. For most of the applications, 10 dB return loss is a rule of thumb. Most microstrip passive components have typical bandwidth characteristics, and the frequency bandwidth changes with the center frequency. Therefore, the percentage bandwidth is used as a typical parameter. The percentage bandwidth is a ratio of the frequency range divided by the center frequency as in Equation 7.

$$B = \frac{f_h - f_l}{f_c} \quad (7)$$

: The highest frequency intersecting -10 dB S_{11}[dB] f_L:
The lowest frequency intersecting -10 dB S_{11}[dB] f_C:
Center frequency

3. EXPLANATION ABOUT DESIGNING A MICROSTRIP LINE WITH ANTEN’IT:

The box in Figure 5 is the microstrip impedance matching kit. There are 1.5 mm metal cells, 3 mm metal cells, 1.5 mm beige dielectrics, 3 mm beige dielectrics in the box. We will use the pieces for different impedance matching circuits.

Figure 5 Microstrip Impedance Matching Box

There are two kinds of beige dielectrics; one with 1.5 mm height (beige dielectric cells-1.5mm) and the other one with 3 mm height (beige dielectric cells-3mm). 1.5mm cells are connected to the ground plane and 3 mm cells are mounted over the 1.5 mm cells.

The dielectrics and metal cells are already mounted to build a microstrip line for this experiment. You will use the cells in the box to build the stubs.

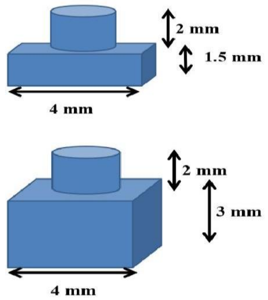


Figure 6 Anten'it 1.5 mm and 3 mm cell dimensions

Removing the cells:

Removing the cells is one of the most important parts to learn. The misusage can damage the cells. Brick remover holds two of the cylinders at the same time. You just need to push to the high end of the remover as in Figure 7.

The removing tool for this experiment is a plastic brick remover. In order to get the best efficiency, we need to start dismounting the cells from outside. First, remove the smallest metal cells which are on the outside. Second, remove the cells which are on the outside but larger. To remove the cells, always hold the cylinders in the center as in Figure 7.

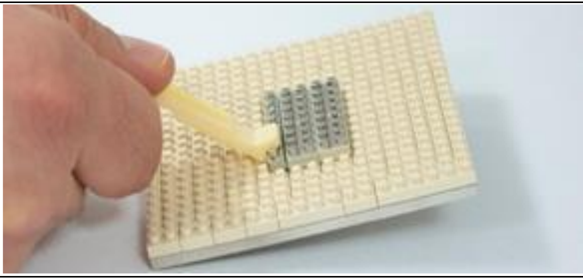


Figure 7 Brick Remover Usage

SSMA to SMA adaptors are used for calibration.

4. PRELIMINARY WORK:

1. **1.** Read open stub matching and short stub matching sections and solve the exercises in Microwave Engineering Book. You have a calculation during the experiment in the 15th step. Calculate before the experiment and fill the boxes in 15th step. Watch videos and exercise by using the Smith Chart. The formulas and the explanation are not given in the experiment sheet for this experiment.
2. **2.** How does a quarter wave transformer work ?
3. **3.** What is the difference between an open stub and a short stub ?
4. **4.** How do you use impedance and admittance circles in Smith Chart ?

5. EXPERIMENTAL PROCEDURE:

1. Connect the cables to the Network Analyser and connect the SSMA-Female to SMA-Male adapters to the SSMA-male side of the cables as shown in Figure 8. Calibrate the Network Analyzer for 1-port measurement between 100 MHz and 2.500 MHz.

Figure 8 Cable to SSMA-SMA Adaptor Connection

2. Connect the microstrip line board to the VNA. Check if the total dielectric height is 4.5 mm except the cylinders of the bricks. There must be the beige dielectric bricks with 1.5 mm over the ground plane and 3 mm beige dielectrics over the 1.5 mm beige dielectrics. Check if both ground planes are connected to each other as in Figure 10.

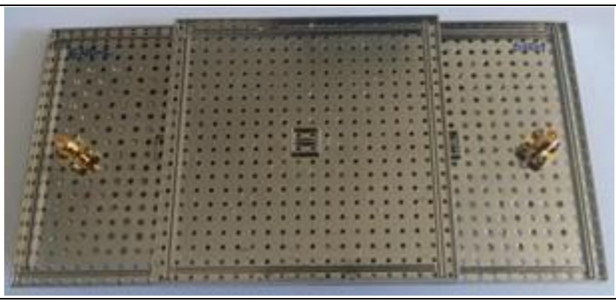


Figure 9 Ground plane connection

Two ground planes are connector into each other with another ground plane at the bottom of them. There are 1.5 mm beige dielectrics layer over the ground planes. There is a second layer with 3 mm dielectric cells over the 1.5 mm dielectric cells. The third layer is the 3 mm metal cells which builds the microstrip line over the dielectrics.
1.5 mm metal cells are used to have short circuit to the ground planes. 3 mm metal cells are connected over the 1.5 mm metal cells.

3. Locate the feed metal cells over the connector inner conductors. The red point needs to be over the inner conductor.

Figure 10 Red feed point

4. Use a multi-meter or voltmeter in order to check if the inner conductor of the connector is connected to the feed cell. Turn the multi-meter to “short” buzzer option. With one probe touch to the inner conductor of the SSMA connector from the bottom of the ground plane and with the other probe touch to the feed metal cell. If the buzzer is ringing, they are connected to each other and we can start the experiment.

Figure 11 Buzzer

“”

5. The microstrip line width is 12 mm for this experiment which is close to 50 ohm. Use the configuration in the figure below to start the quarter wave transformer experiment. Locate the 100 ohm lumped resistor block between the single metal cell and the short metal cells. The impedance of the 100 ohm side of the circuit is nearly 100 ohm and 12 mm microstrip line is nearly 50 ohm. You need the match both sides.

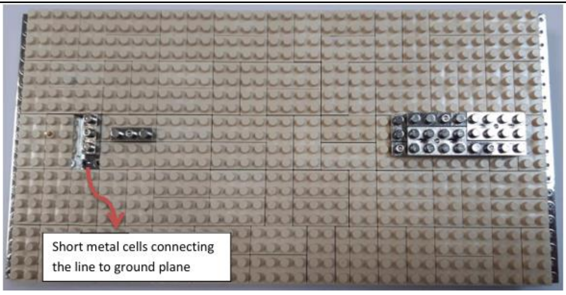


Figure 12 The configuration at the beginning of the experiment (You need to use a 1X3 metal cell with 1.5 mm height over the ground plane and two 1X3 metal cells with 3 mm height as shorting pins. The other metals have 3 mm height and they are over beige dielectrics.)

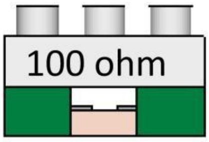


Figure 13 Lumped Element 100 ohm

6. Calculate quarter wavelength over 2.6 dielectric constant material at 1 GHz. Use the formula (6) and calculate Z1 to find the ideal transformer impedance to match 100 ohm to 50 ohm.

Quarter wavelength	Z1 impedance

7. Build the transformer by locating the 3mm metal cells over the dielectrics. If the calculated values can’t be built with the cells (Since the metal and dielectric cells have 4 mm resolution), use the nearest dimensions.

8. Connect the cables to the microstrip line. Display S-parameters dB scale on the network analyzer screen.

“”

9. Measure 1-port S-parameters for the microstrip line. Write down the S-parameter values for 1 GHz.

S11 [dB]

10. Change the display to Smith Chart for S11. Write down the impedance value for 1 GHz.

S11 impedance

11. If the transformer did not match at least -10 dB S11, iterate your design by changing the length and the width of the transformer. Write down the best impedance and S11 [dB] you measured.

S11 impedance	S11 [dB]

12. Add or remove metal cells to change the configuration into the figure below.

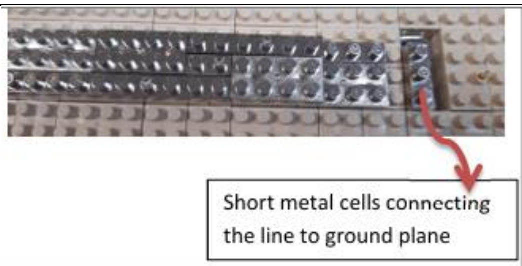
	
	Use metal cells with 1.5 mm height over the ground plane and locate 2 rows of 3 mm height metal cells over 1.5 mm metal cells.

Figure 14 Configuration for the second experiment

“”

13. Change the frequency range into 975 to 1025 MHz or only 1000 MHz if possible. If your network analyzer can't narrow down the frequency range, use a marker at 1000 MHz.

14. We will design a single stub to match our 50 ohm source to 220 ohm load. We start with an ***open stub***. There are two parameters to be calculated as explained in section 1. You need to exercise the calculation before the experiment. Use Smith Chart and find the load to stub matching distance (d) and the stub length (L) values for a single open stub matching. There must be two values for each. Use effective dielectric constant as "2" for this calculation.

d (load to stub matching distance)	L (stub length)

* There is a more practical way to find "d" and "L" with a Smith Chart Tool. If the lecturer lets you use one of these tools, he/she will share a link from the answers key of this experiment.

15. You get two "d" and "L" with the calculation. Use shorter stub length (L) and build the stub. d is the distance from the last cell to the center of the stub as explain in the example figure below:

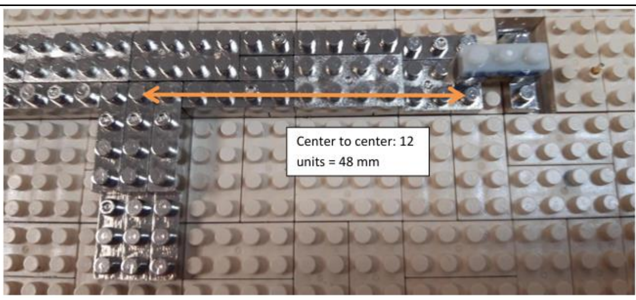


Figure 14 Load to stub matching distance (d) example

“”

16. Use closest dimensions to your calculation. Build the open stub and measure the impedance in Smith Chart. Use Log scale and see S11 in dB. Write down the values.

S11 [dB] @ 1 GHz	Impedance @1 GHz	Impedance Bandwidth (%)

17. If you couldn’t reach below -10 dB S11, iterate your design by changing “L” and “d”.

18. Disconnect the open stub. We will match the circuit again with a ***short stub***. There are still two parameters to be calculated. You need to exercise the calculation before the experiment. Use Smith Chart and find the load to stub matching distance (d) and the stub length (l) values for a single short stub matching. There must be two values for each. Use effective dielectric constant as “2” for the calculation.

d (load to stub matching distance)	L (stub length)

19. You get two stub lengths with the calculation. Use shorter stub length (L) and build the short stub. You can see an example of shorting the stub to the ground plane in the figure below:

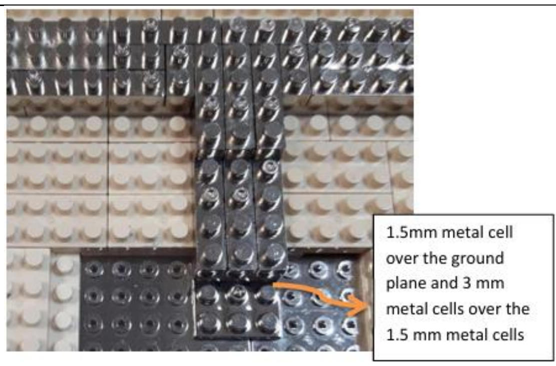


Figure 14 Short stub example

“”

20. Use closest dimensions to your calculation. Build the short stub and measure the impedance in Smith Chart. Use Log scale and see S11 in dB. Write down the values.

S11 [dB] @ 1 GHz	Impedance @1 GHz	Impedance Bandwidth (%)

21. If you couldn’t reach below -10 dB S11, iterate your design by changing “L” and “d”.

22. Compare the impedance bandwidth of open and short stub matching circuits.

23. Disconnect all metal pieces over the dielectrics and lumped element blocks. Locate them into the experiment box to make it ready for other students.

6. RESULTS:

- State the objective of the experiment and give a short summary of the procedure.
- What are the differences of the measured and theoretical quarter-wave transformers ?
- What are the differences of the open stub experiments and the theoretical calculations ?
- What are the differences of the short stub experiments and the theoretical calculations ?
- Compare the theory and experimental results.
- Discuss the results of your experimen

3-MICROSTRIP POWER DIVIDERS DESIGN EXPERIMENT

1. OBJECTIVES

- Designing a T-junction Power Divider
- Turning the T-junction Power Divider into a Wilkinson Power Divider
- Designing a Resistive Power Divider
- To investigate the S-parameters of the power dividers
- To compare the theoretical and measured results.

2. BRIEF INFORMATION ABOUT THE MICROSTRIP POWER DIVIDERS:

Effective Dielectric Constant and Microstrip Line Impedance Calculation

In order to calculate the microstrip line impedance, you need to calculate the effective dielectric constant and use it in the impedance calculation.

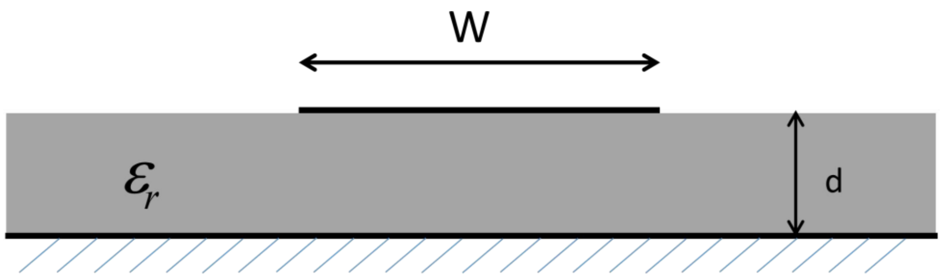


Figure 1 Microstrip Line Representation

The effective dielectric constant of a microstrip line is given by;

$$\epsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12d/W}} \qquad (1)$$

The microstrip impedance is calculated with the formula below;

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_e}} \ln\left(\frac{8d}{W} + \frac{W}{4d}\right) & \text{for } W/d \leq 1 \\ \frac{120\pi}{\sqrt{\epsilon_e}\ [W/d + 1.393 + 0.667 \ln(W/d + 1.444)]} & \text{for } W/d \geq 1 \end{cases} \qquad (2)$$

Calculate the effective dielectric constant and characteristic impedance for 4 mm, 8 mm, 12 mm, 16 mm, 20 mm and 24 mm line widths (W) and 4.5 mm dielectric height (d). ϵ_r of the substrate is 2,6. It is easier to write a MATLAB or OCTAVE code for this calculation.

Microstip Line Widths (W)	Effective Dielectric Constant (ε_e)	Characteristic Impedance (Z_0)
4 mm		
8 mm		
12 mm		
16 mm		
20 mm		
24 mm		

Power Dividers

Power dividers or combiners have at least three ports. The power in the input port of the power divider is divided into two or more output ports. Ideally the power sum of output ports needs to be the same as the input power. The same passive component is also used as a power combiner. If you change the output ports into input ports and the input port into an output port, then component is turned into a power combiner. Therefore, power divider, power splitter and power combiner represents the same component if it is passive.

If the power divider is a three port component, the input power is divided into two output powers. For an equal power divider, the output power is -3 dB lower than the input port. If it is a 5 port equal power component, where there is one input and four output ports, then each output port has -6 dB lower than the input power. Depending on the needs, a power divider can also be designed as an unequal power divider, where the power at one output port is higher than another output port. We will design a two-port equal power T-junction power divider, then turn it into a Wilkinson power divider. Then, we will design a resistive power divider to compare the results of a Wilkinson power divider.

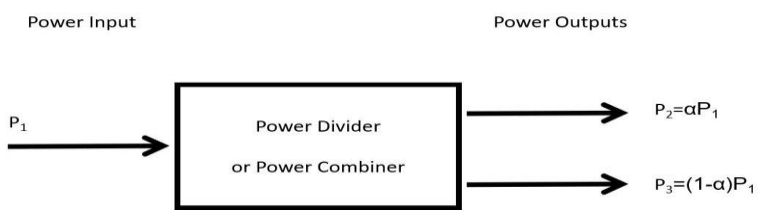


Figure 2 Representation of a two-port power divider

T-Junction (Three Port) Power Divider

A T-junction power divider has one input and two output ports. Although it is physically impossible, the S-parameter matrix of the lossless T-junction power divider, which has no anisotropic materials, is reciprocal. Reciprocal means that the scattering matrix is symmetric ($S_{ij}= S_{ji}$). If we assume that all ports are perfectly matched, S-parameter matrix becomes;

$$\begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix} \quad (1)$$

Since the network is lossless, the input power is exactly the same as the sum of output powers. Then the equations below apply.

$$|S_{12}|^2 + |S_{13}|^2 \quad (2)$$

$$|S_{12}|^2 + |S_{23}|^2 \quad (3)$$

$$|S_{13}|^2 + |S_{23}|^2 \quad (4)$$

$$S^*{}_{13}S_{23} \quad (5)$$

$$S^*{}_{23}S_{12} \quad (6)$$

$$S^*{}_{12}S_{13} \quad (7)$$

If the transmission lines are lossless, the transmission line impedance becomes real and the power equation for a T-junction becomes:

$$\frac{1}{0} = \frac{1}{1} + \frac{1}{2} \quad (8)$$

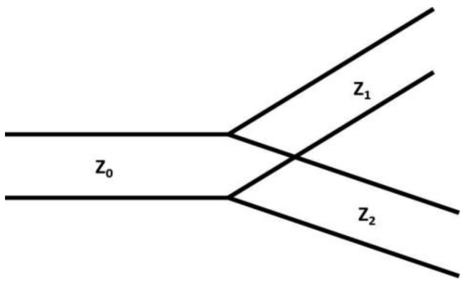


Figure 3 Representation of transmission line model of a lossless T-junction

Wilkinson Power Divider

T-junction power divider is a basic element but it has two important problems:

- It is not matched at all ports (reflection coefficients) so some ports reflect a part of the power.
- There is an isolation problem between two output ports.

Therefore, a more useful Wilkinson power divider solves these two problems. Wilkinson power divider can be in equal or unequal power forms. Here an equal power divider is sketched below:

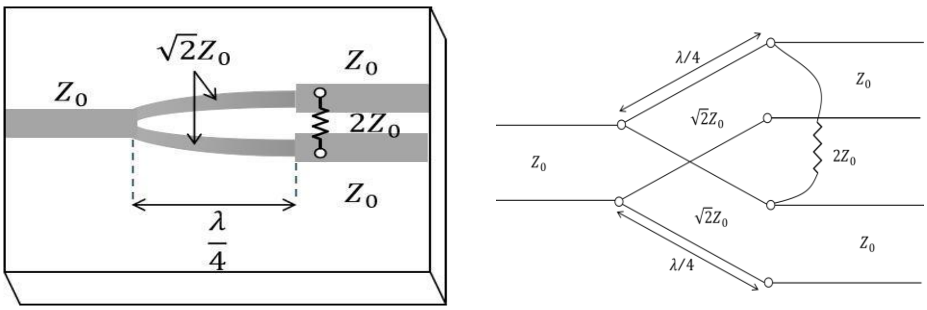


Figure 4 Representation of an Equal Power Three-port Wilkinson Power Divider

Figure 4 shows that both three ports have the same characteristic impedance (Z_0), two arms with $\sqrt{2}Z_0$ impedance have quarter wavelength dimensions and there is an isolation resistor with $2Z_0$ impedance.

A Resistive Power Divider

By using resistors in a resistive power divider, all ports can be matched but the isolation between the two output ports can't be achieved. An equal resistive power divider is represented in the figure below. This ideal power divider output insertion loss needs to be -6 dB instead of -3 dB. The half of the input power is lost and the other half is divided into two.

In Wilkinson power divider, there were dimensions depending on the wavelength, therefore Wilkinson power divider frequency bandwidth is limited but resistive power divider has no dependency on the wavelength. That is why a resistive power divider is theoretically frequency independent. It is not an efficient power divider but useful for some wide bandwidth applications where 3 dB extra loss is not important.

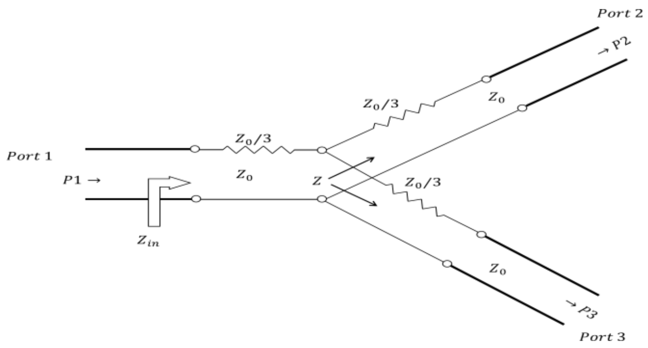


Figure 5 Representation of an Equal Power Three-port Resistive Power Divider

Bandwidth:

The impedance bandwidth of the power divider is a frequency range between the highest and lowest frequency where return loss is below a certain value. For most of the applications, 10 dB return loss is a rule of thumb. Power divider types have typical bandwidth characteristics, but the frequency bandwidth changes with the center frequency. Therefore, the percentage bandwidth is used as a parameter to compare. The percentage bandwidth is a ratio of the frequency range divided by the center frequency as in Equation 1.

$B = \frac{f_h - f_l}{f_c}$	(7)

The highest frequency intersecting -10 dB S_{11}[dB] f_h:
The lowest frequency intersecting -10 dB S_{11}[dB] f_l:
Center frequency f_c

3. EXPLANATION ABOUT DESIGNING A POWER DIVIDER WITH ANTEN'IT:

The box in Figure 6 is the microstrip power divider experiment box. There are 1.5 mm beige dielectrics, 3 mm beige dielectrics, 3 mm metal cells and lumped element (resistor) blocks within the box. We will use them to design 3 different power dividers during the experiment.

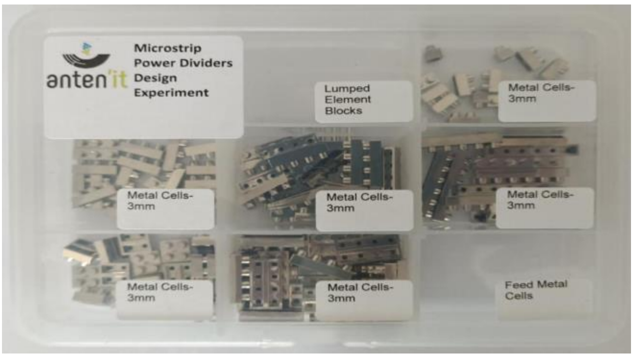


Figure 6 Microstrip Power Dividers Design Experiment Box

First you need to connect the two 80 X 80 mm ground planes into each other. Second, locate the 1.5 mm beige dielectrics over the two ground planes. Third, locate the 3 mm dielectric cells over 1.5 mm dielectric cells. Then, locate 3 mm metal cells to build a microstrip line. Use resistive lumped element blocks for isolation and in the resistive power divider.

The calculation of height:

There are two kinds of beige dielectrics; one with 1.5 mm height (beige dielectric cells-1.5mm) and the other one with 3 mm height (beige dielectric cells-3mm). 1.5mm cells are connected to the ground plane and 3 mm cells are mounted over the 1.5 mm cells.

The dielectrics and metal cells are already mounted to build a microstrip line for this experiment. You will use the cells in the box to build the stubs.

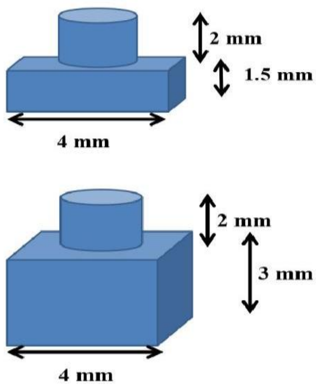


Figure 7 Anten'it 1.5 mm and 3 mm cell dimensions

Removing the cells:

Removing the cells is one of the most important parts to learn. The misusage can damage the cells. Brick remover holds two of the cylinders at the same time. You just need to push to the high end of the remover as in Figure 8.

The removing tool for this experiment is a plastic brick remover. In order to get the best efficiency, we need to start dismounting the cells from outside. First, remove the smallest metal cells which are on the outside. Second, remove the cells which are on the outside but larger. To remove the cells, always hold the cylinders in the center as in Figure 8.

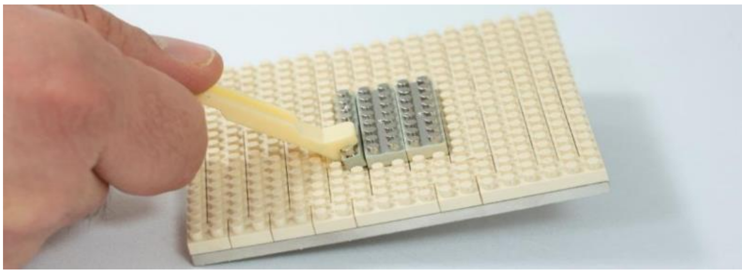


Figure 8 Brick Remover Usage

The list of SMD Component Values in the kit:

SMD Resistances
5,6 ohm
10 ohm
18 ohm
27 ohm
33 ohm
100 ohm

4. PRELIMINARY WORK:

1. What is the difference between a T-junction power divider and a Wilkinson power divider ?
2. What is the difference between a resistive power divider and a Wilkinson power divider ?
3. How can you calculate the loss of a power divider ?
4. What are the expected differences between an ideal and a real power divider ?

5. EXPERIMENTAL PROCEDURE:

1. Connect the cables to the Network Analyser and connect the SSMA-Female to SMA-Male adapters to the SSMA-male side of the cables as shown in Figure 9. Calibrate the Network Analyzer for 2 port measurement between 30 MHz and 2.500 MHz.

Figure 9 Cable to SSMA-SMA Adaptor Connection

2. Connect the microstrip line board to the VNA. Check if the total dielectric height is 4.5 mm except the cylinders of the bricks. There must be the beige dielectric bricks with 1.5 mm over the ground plane and 3 mm beige dielectrics over the 1.5 mm beige dielectrics. Check if both ground planes are connected to each other as in the figure below.

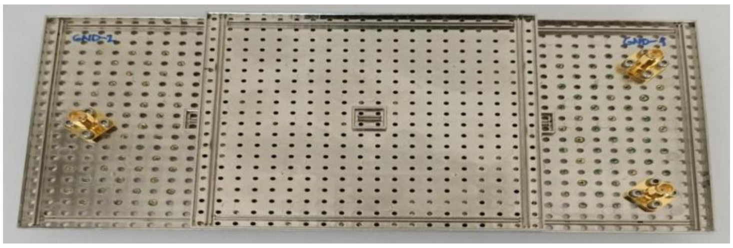


Figure 10 The ground plane connection

Two ground planes are connector into each other with another ground plane at the bottom of them. There are 1.5 mm beige dielectrics layer over the ground planes. There is a second layer with 3 mm dielectric cells over the 1.5 mm dielectric cells. The third layer is the 3 mm metal cells which builds the microstrip line over the dielectrics.

1.5 mm metal cells are used to have short circuit to the ground planes. 3 mm metal cells are connected over the 1.5 mm metal cells.

3. Locate the feed metal cells over the connector inner conductors. The red point needs to be over the inner conductor.

Figure 11 Red feed point

4. Use a multi-meter or voltmeter in order to check if the inner conductor of the connector is connected to the feed cell. Turn the multi-meter to "short" buzzer option. With one probe touch to the inner conductor of the SSMA connector from the bottom of the ground plane and with the other probe touch to the feed cell. If the buzzer is ringing, they are connected to each other and we can start the experiment.

Figure 12 Buzzer

5. Use the impedance calculations for different microstrip line widths given in section 2. The T-section power divider is shown in the figure below:

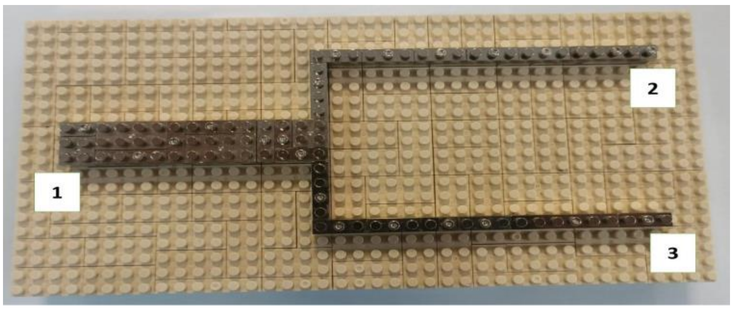


Figure 13 T-section power divider and port numbers

6. Connect the cables to Port 1 and Port 2. Port 1 is the input port, port 2 and 3 are the output ports.

   Display S-parameters dB scale on the network analyzer screen, write down the measurement results for S11, S12 and S22 at 750 MHz.

   As a second step, disconnect the cable from port 2 and connect it to port 3. Now, your cables are connected to port 1 and port 3 of the power divider. Write down the S33 and S13 [dB].

   As a third step, disconnect the cable from port 1 and connect it to port 2. Now, your cables are connected to port 2 and port 3. Write down S23 [dB].

S11 [dB]	S22 [dB]	S33 [dB]	S12 [dB]	S13 [dB]	S23 [dB]

   Compare S12 and S13. Is that an equal or unequal power divider ?

   The isolation between the output ports is S23. Reflection coefficients are S11, S22 and S33. Are they below -10 dB at 750 MHz ?

7. Now, you will design a Wilkinson power divider. Calculate the quarter wavelength dimensions over beige dielectrics with 2.6 dielectric constant. The height of the dielectrics is 4.5 mm. Use the effective dielectric permittivity for the calculated width to find our the quarter wavelength dimension.

   Calculate the microstrip line width in order to have $\sqrt{2}\,Z_0$ impedance. Turn the T-section power divider into a Wilkinson equal power divider. Use a lumped resistor in order to isolate port 2 and port 3. The target frequency is 750 MHz.

$\sqrt{2}Z_0$ impedance	Quarter wavelength over 2.6 dielectric constant beige dielectrics.	$2Z_0$ isolation impedance

8. Build the Wilkinson power divider at the target frequency. The connection of the lumped element block between the metal cells is shown in the photo below.

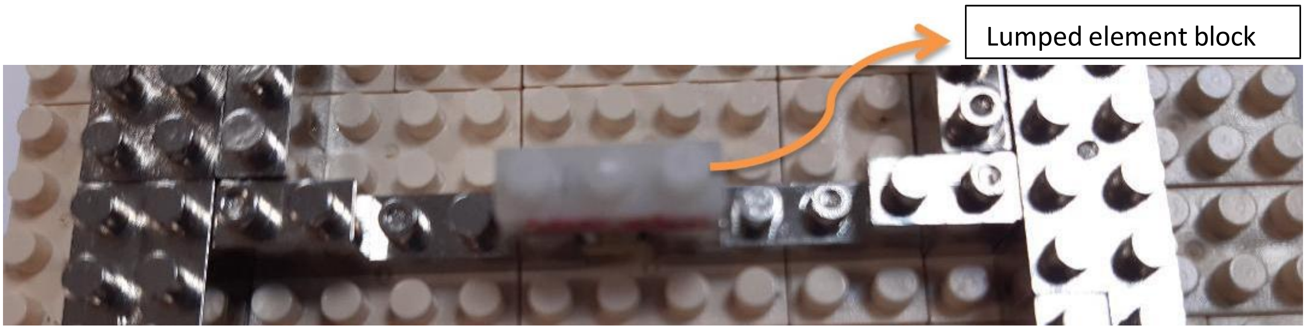


Figure 14 Wilkinson power divider isolation resistance block connection

9. Measure S-parameters S11, S22, S33, S12, S13 and S23 at 750 MHz for your design as you measured for the T-junction power divider. Check if the S-parameters are as expected.

S11 [dB]	S22 [dB]	S33 [dB]	S12 [dB]	S13 [dB]	S23 [dB]

10. S12 and S13 needs to be -3 dB ideally. Check the maximum frequency that the power divider works with 1 dB extra insertion loss from -3 dB theoretical values and S11, S22 and S33 are below -10 dB up to this frequency.

Maximum frequency

11. Disconnect the lumped element block and turn the transmission lines into 50 ohm line in order to get a resistive power divider as in Figure below.

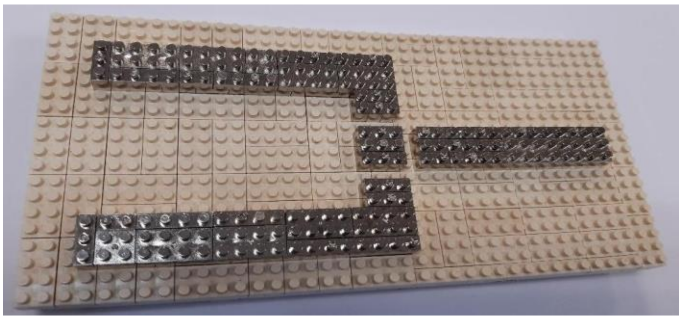


Figure 15 Resistive Power Divider without the resistances.

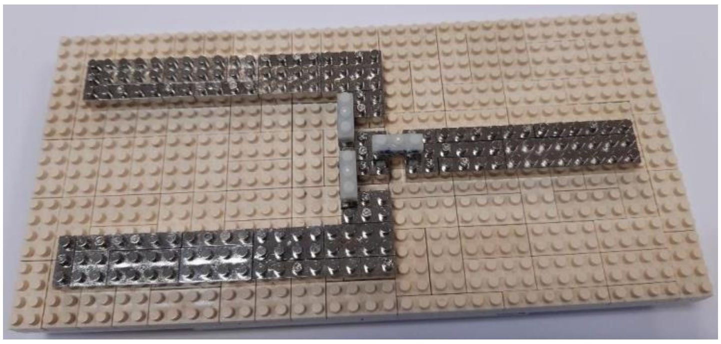


Figure 15 Resistive Power Divider with the resistances

12. Calculate the ideal resistance values. Locate the lumped element resistive blocks with the closest values to the circuit.

Ideal resistive values

13. Measure S-parameters S11, S22, S33, S12, S13 and S23 at 750 MHz. Check if the S-parameters are as expected.

S11 [dB]	S22 [dB]	S33 [dB]	S12 [dB]	S13 [dB]	S23 [dB]

14. Compare the theoretical and measured S12 and S13 values. Check the maximum frequency that the power divider works with 2 dB extra insertion loss from the theoretical values. Check if S11, S22 and S33 are below -10 dB up to this frequency.

Maximum frequency

15. Use different resistance values in order to get an unequal power divider and check the S-parameters. You are free to design an unequal power divider. Choose the resistances from the ones in the experiment box. Write down the resitance values and measured S-parameters below.

Resistance values

S11 [dB]	S22 [dB]	S33 [dB]	S12 [dB]	S13 [dB]	S23 [dB]

16. Disconnect lumped element blocks and turn the configuration into figure 13 (T-junction). Locate them into the experiment box to make it ready for other students.

6. RESULTS:

- State the objective of the experiment and give a short summary of the procedure.
- What is the difference of T-section, Wilkinson and resistive power dividers ?
- What do you gain by using a Wilkinson power divider instead of a resistive power divider ?
- What is the difference in S12 and S13 values for the Wilkinson and resistive power dividers ? Are they the same for Wilkinson and resistive power divider ?
- Compare the theory and experimental results.
- Discuss the results of your experiment.

4-MICROSTRIP BANDPASS and BANDSTOP FILTER DESIGN EXPERIMENT

1. OBJECTIVES

- Designing bandstop filter via stubs
- Designing a bandpass filter via stubs
- Measuring S-parameters of Bandpass and Bandstop Filters
- Comparing the Results of Different Bandstop Filter Types

2. BRIEF INFORMATION ABOUT MICROSTRIP BANDPASS AND BANDSTOP FILTERS:

1- **Effective Dielectric Constant and Microstrip Line Impedance Calculation**

In order to calculate the microstrip line impedance, you need to calculate the effective dielectric constant and use it in the impedance calculation.

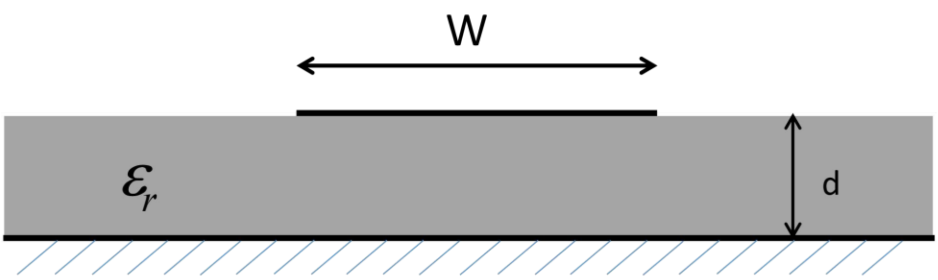


Figure 1 Microstrip Line Representation

The effective dielectric constant of a microstrip line is given by;

$$\epsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12d/W}} \qquad (1)$$

The microstrip impedance is calculated with the formula below;

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_e}} \ln\left(\frac{8d}{W} + \frac{W}{4d}\right) & \text{for } W/d \leq 1 \\ \frac{120\pi}{\sqrt{\epsilon_e}\ [W/d + 1.393 + 0.667 \ln(W/d + 1.444)]} & \text{for } W/d \geq 1 \end{cases} \qquad (2)$$

Calculate the effective dielectric constant and characteristic impedance for 4 mm, 8 mm, 12 mm and 16 mm line widths (W) and 4.5 mm dielectric height (d). The dielectric constant of the substrate is 2.6. It is more practical to write a MATLAB or OCTAVE code for this calculation.

Microstrip Line Widths (W)	Effective Dielectric Constant (ε_e)	Characteristic Impedance (Z_0)
4 mm		
8 mm		
12 mm		
16 mm		
20 mm		
24 mm		
28 mm		
32 mm		

2- Bandpass Filter

Ideal bandpass filter passes only the passband frequencies with zero insertion loss and does not pass the other frequency components. w_1 and w_2 represent the edges of the bandpass filter.

$$\Delta = \frac{w_2 - w_1}{w_0} \quad (3)$$

$$w_0 = \sqrt{w_2 w_1} \quad (4)$$

Δ represents the fractional bandwidth of the filter and w_0 represents the center frequency which is the arithmetic mean of w_1 and w_2.

The number of stubs are equal to the filter degree. Different filter types have different characteristics and different filter coefficients (g_n).

This type of filter has shunt short stubs with different impedances. The impedances are shown between Z_{01} to Z_{0N}. The spacing between the stubs and the stubs lengths are quarter wavelength and shown as θ in the figure.

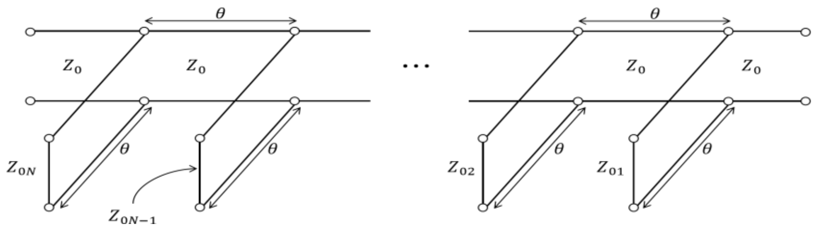


Figure 2 The representation of a bandpass filter

The maximally flat low-pass filter element values are shown in the table below. The same element values are valid for bandpass filters.

We will use two types of filters in the experiments. One of them is the Maximally Flat and the other one is the equal-ripple. The coefficients of both filters are the same as in the low-pass filter. That is why we use the same coefficients for low-pass, high-pass, bandpass and bandstop filters.

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}
1	2.0000	1.0000									
2	1.4142	1.4142	1.0000								
3	1.0000	2.0000	1.0000	1.0000							
4	0.7654	1.8478	1.8478	0.7654	1.0000						
5	0.6180	1.6180	2.0000	1.6180	0.6180	1.0000					
6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176	1.0000				
7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450	1.0000			
8	0.3902	1.1111	1.6629	1.9615	1.9615	1.6629	1.1111	0.3902	1.0000		
9	0.3473	1.0000	1.5321	1.8794	2.0000	1.8794	1.5321	1.0000	0.3473	0.3129	
10	0.3129	0.9080	1.4142	1.7820	1.9754	1.9754	1.7820	1.4142	0.9080	0.3129	0.3129

Figure 3 Element Values for Maximally Flat Low-Pass Filter (g_0=1, w_c=1, N=1 to 10)

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}
1	0.6986	1.0000									
2	1.4029	0.7071	1.9841								
3	1.5963	1.0967	1.5963	1.0000							
4	1.6703	1.1926	2.3661	0.8419	1.9841						
5	1.7058	1.2296	2.5408	1.2296	1.7058	1.0000					
6	1.7254	1.2479	2.6064	1.3137	2.4758	0.8696	1.9841				
7	1.7372	1.2583	2.6381	1.3444	2.6381	1.2583	1.7372	1.0000			
8	1.7451	1.2647	2.6564	1.3590	2.6964	1.3389	2.5093	0.8796	1.9841		
9	1.7504	1.2690	2.6678	1.3673	2.7239	1.3673	2.6678	1.2690	1.7504	1.0000	
10	1.7543	1.2721	2.6754	1.3725	2.7392	1.3806	2.7231	1.3485	2.5239	0.8842	1.9841

Figure 4 Element Values for Equal-Ripple Flat Low-Pass Filter (g_0=1, w_c=1, N=1 to 10, 0.5 dB ripple)

The characteristic impedance of a bandpass filter is shown in the equation below:

$$Z_{0n} = \underline{0}\,\underline{\Delta}\ 4 \tag{5}$$

This equation is essential for designing a bandpass filter. In the realization, you can't have exactly the calculated component (stub length, width and the spacing between the stubs) values. Use the closest component values to get an approximate result.

3- Bandstop Filter:

This type of filter has shunt open stubs with different impedances. The impedances are shown between Z_{01} to Z_{0N}. The spacing between the stubs and the stubs lengths are quarter wavelength and shown as θ in the figure.

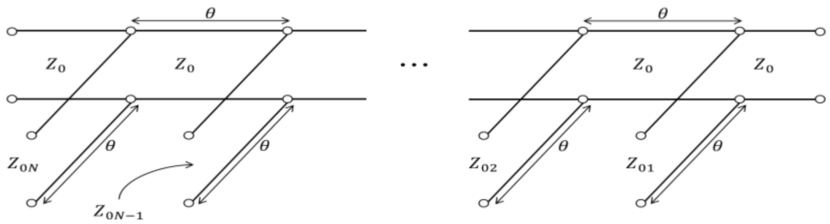


Figure 5 The representation of a bandstop filter

Bandstop filters ideally filter the target frequency range and pass the other frequencies without any loss. This type of filter is built with open stubs. The impedance is calculated with the following equation:

$$Z_{0n} = \frac{4_0}{\Delta} \qquad (6)$$

The same element values are shown with the low-pass filters as in the Figures 3 and 4. In the realization, you can’t have exactly the calculated component values. Use the closest component values to get an approximate result.

3. EXPLANATION ABOUT USING ANTEN’IT PIECES FOR THE EXPERIMENT:

Figure 6 Microstrip Bandpass and Bandstop Filter Design Experiment Box

The box in Figure 6 is the microstrip bandpass and bandstop filter design experiment. There are metal and beige dielectric cells to build a 50-ohm microtrip line. There are two metal cell heights, one with 1.5 mm height (metal cells-1.5mm) and the other one is with 3 mm (metal cells-3mm). 1.5 mm height metal cells are used to mount over the ground plane. They can not be mounted over the dielectrics or any other metal cell. The metal cells with 3 mm height (metal cells-3mm) can be mounted over the dielectrics and other metal cells. Therefore, metal cells-1.5 mm will be used for shorting the stubs and metal cells-3 mm will be used for building the stubs.

There are two kinds of beige dielectrics; one with 1.5 mm height (beige dielectric cells-1.5mm) and the other one with 3 mm height (beige dielectric cells-3mm). 1.5mm cells are connected to the ground plane and 3 mm cells are mounted over the 1.5 mm cells.

The dielectrics and metal cells are already mounted to build a microstrip line for this experiment. You will use the cells in the box to build the stubs.

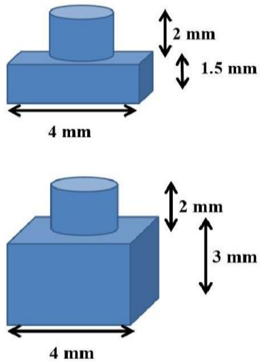


Figure 7 Anten'it 1.5 mm and 3 mm cell dimensions

Removing the cells:

Removing the cells is one of the most important parts to learn. The misusage can damage the cells. Brick remover holds two of the cylinders at the same time. You just need to push to the high end of the remover as in Figure 8.

The removing tool for this experiment is a plastic remover. In order to get the best efficiency, we need to start dismounting the cells from outside. First, remove the smallest metal cells which are on the outside. Second, remove the cells which are on the outside but larger. To remove the cells, always hold the cylinders in the center as in Figure 8.

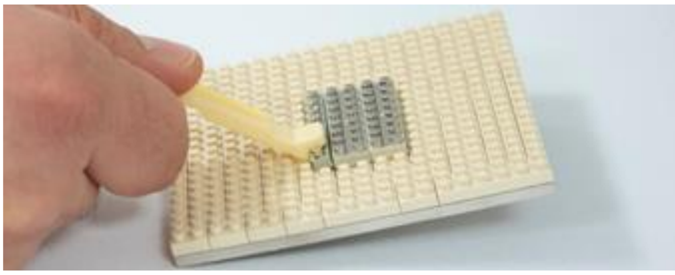


Figure 8 Brick Remover Usage

SSMA to SMA adaptors are used for calibration.

You can see an example bandpass filter built with the bricks. This filter works between 2815-3505 MHz with 1 dB insertion loss. The microstrip line for this filter is only 4 mm since the dielectric height is 1.5 mm. It is a 3rd order filter with 3 short stubs.

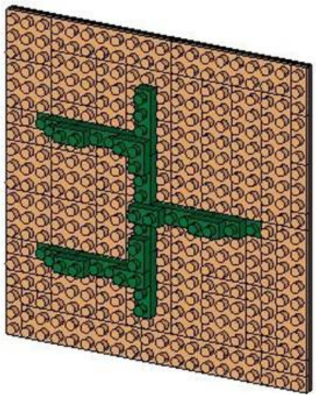


Figure 9 An Example 3rd order Bandpass Filter

4. PRELIMINARY WORK:

1. What are the ideal reflection and insertion coefficients for a band pass filter?
2. Explain the differences between maximally flat, 0.5 dB equal-ripple filters. What are the expected amplitude characteristics ?
3. What kind of change in S-parameters is expected by increasing the filter degree ?

5. EXPERIMENTAL PROCEDURE:

1. Connect the cables to the Network Analyser and connect the SSMA-Female to SMA-Male adapters to the SSMA-male side of the cables as shown in Figure 10. Calibrate the Network Analyzer for 2 port measurements between 200 MHz and 2500 MHz.

Figure 10 Cable to SSMA-SMA Adaptor Connection

2. Connect the microstrip line board to the VNA. Check if the total dielectric height is 4.5 mm except the cylinders of the bricks. There must be the beige dielectric bricks with 1.5 mm over the ground plane and 3 mm beige dielectrics over the 1.5 mm beige dielectrics. Check if both ground planes are connected to each other as in Figure 11.

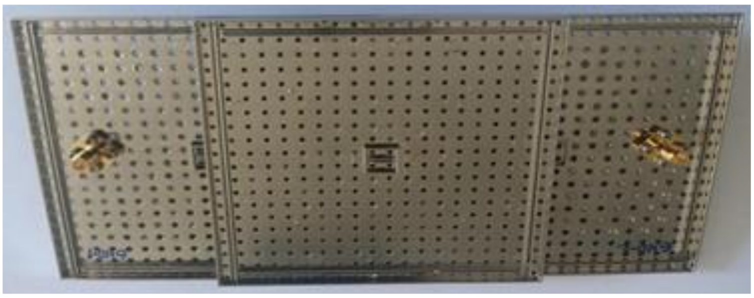


Figure 11 The ground plane connection

Figure 12 The microstrip line

3. We will build a **bandpass filter**. Calculate the stub impedances for N=3 (filter degree), w1 and w2 are 700 and 2250 MHz. Calculate the impedances of the stubs by using the formulas given in the first section. The length of each stub is quarter wavelength and the distance between the center of each stub is quarter wavelength for this filter. Use 0.5 dB equal-ripple low-pass filter element values.

Stub1 impedance	Stub2 impedance	Stub3 impedance
Nearest stub1 width	Nearest stub2 width	Nearest stub3 width

4. Build the bandpass filter and measure the S-parameters. Write down the measured edges (-10 dB for S11 and -3 dB for S21) of the filter. The insertion loss at the best pass band may be higher than usual since the structure is very large.

S11	S12

5. Change the topology to design a **bandstop filter**. Calculate the stub impedances for N=3 (filter degree), w1 and w2 are 925 and 1700 MHz. Calculate the impedances of the stubs. The length of each stub is quarter wavelength and the distance between the center of each stub is quarter wavelength. Use 0.5 dB ripple element coefficients and calculate the stub impedances.

Stub1 impedance	Stub2 impedance	Stub3 impedance
Nearest stub1 width	Nearest stub2 width	Nearest stub3 width

6. **6.** Build the bandstop filter and measure the S-parameters. Write down the measured (-10 dB for S11 and -3 dB for S21) edges of the filter.

S11	S12

7. Change the topology to design a **bandstop filter**. Calculate the stub impedances for N=3 (filter degree), w1 and w2 are 925 and 1700 MHz. Calculate the impedances of the stubs. The length of each stub is quarter wavelength and the distance between the center of each stub is quarter wavelength. Use maximally flat element values.

Stub1 impedance	Stub2 impedance	Stub3 impedance
Nearest stub1 width	Nearest stub2 width	Nearest stub3 width

8. Build the bandstop filter and measure the S-parameters. Write down the measured edges (-10 dB for S11 and -3 dB for S21) of the filter.

S11	S12

9. Iterate this design to get closer to target frequencies. Think about what you can do to change the frequency range. If there is not enough space, you can also extend the stubs by thickening the end part (last rows) of the stubs.

10. If you reach better results, write down the measured edges (-10 dB for S11 and -3 dB for S21) of the filter.

S11	S12

11. Disconnect all the pieces except the dielectrics and the ground planes and put them into the experiment boxes to make them ready for other students.

6. RESULTS:

- State the objective of the experiment and give a short summary of the procedure.
- What are the differences of two different filter types ? Which measured parameters are different ?
- Why do we use different coefficients for the same type of filter ?
- Why are there differences between the calculated and measured parameters ?
- Compare the theory and experimental results.
- Discuss the results of your experiment.

5-MICROSTRIP STEPPED-IMPEDANCE LOW PASS FILTER DESIGN EXPERIMENT

1. OBJECTIVES

- Designing a Microstrip Stepped-Impedance Low Pass Filter.
- Designing a Maximally Flat Low Pass Filter
- Designing an Equal-Ripple Low Pass Filter
- Measuring S-parameters of Low Pass Filters
- Comparing the Results of Different Low Pass Filter Types

2. BRIEF INFORMATION ABOUT LOW PASS FILTERS:

1- Effective Dielectric Constant and Microstrip Line Impedance Calculation

In order to calculate the microstrip line impedance, you need to calculate the effective dielectric constant and use it in the impedance calculation.

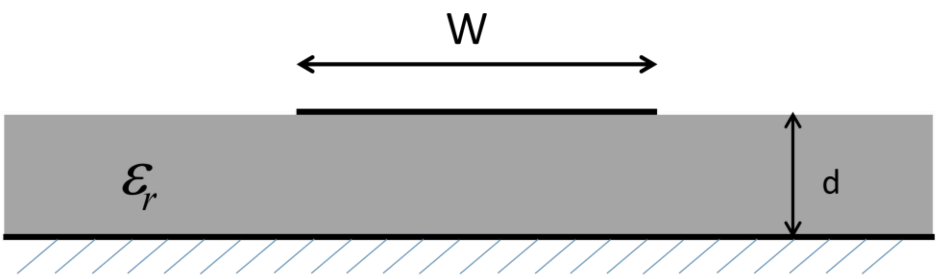


Figure 1 Microstrip Line Representation

The effective dielectric constant of a microstrip line is given by;

$$\epsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12d/W}} \quad (1)$$

The microstrip impedance is calculated with the formula below;

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_e}} \ln\left(\frac{8d}{W} + \frac{W}{4d}\right) & \text{for } W/d \leq 1 \\ \frac{120\pi}{\sqrt{\epsilon_e}\ [W/d + 1.393 + 0.667 \ln(W/d + 1.444)]} & \text{for } W/d \geq 1 \end{cases} \quad (2)$$

Calculate the effective dielectric constant and characteristic impedance for the widths below and 4.5 mm dielectric height (d). ϵ_r of the substrate is 2,6. It is easier to write a MATLAB or OCTAVE code for this calculation.

Microstrip Line Widths (W)	Effective Dielectric Constant (ε_e)	Characteristic Impedance (Z_0)
4 mm		
8 mm		
12 mm		
16 mm		
20 mm		
24 mm		
28 mm		
32 mm		
36 mm		
40 mm		
44 mm		
48 mm		
52 mm		
56 mm		
60 mm		
68 mm		
76 mm		

Low Pass Filter

Ideal low pass filter do not pass the high frequency components and passes the low frequencies. Ideally, the insertion loss is zero at low frequencies and infinite at high frequencies. The cut-off frequency components are determined with some analytical calculations. The number of alternating sections are equal to the filter degree. A low pass filter can be built in different ways. It is easy to implement a stepped-impedance low pass filter. This type of filter doesn't have a sharp cut-off.

Different filter types has different characteristics.

* Minimum insertion loss: Binomial response
* Sharp Cut-off: Chebyshev response

Each L and C component has a corresponding stub length and they are turned into series stubs in this filter. The stub length ($\beta l < \lambda/4$) needs to be short in order to do this transformation. The impedances and the lengths of each series stub needs to be calculated in order to design a stepped-impedance low pass filter.

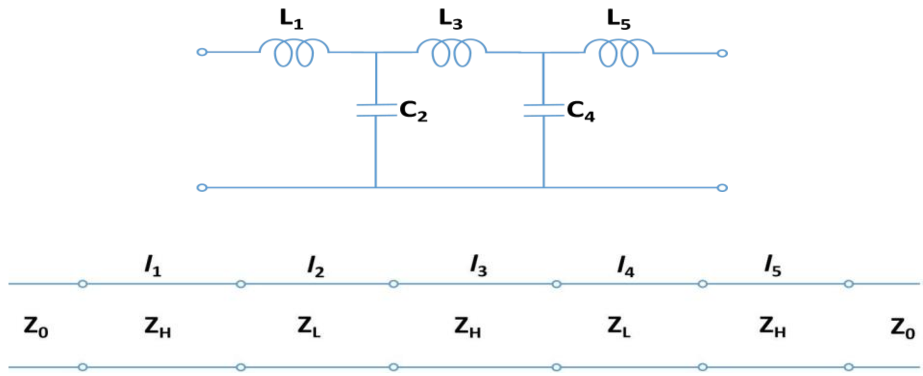


Figure 2 L and C circuit to series stub transformation

Figure 3 Low Pass Stepped-Impedance Filter Representation

In Figure 1, LC circuit is given. This is a circuit of a low-pass filter. We designed a low pass filter with lumped elements in the previous experiments. LC circuit is then transformed into a microstrip line. For each L and C component, we will calculate an electrical length and an impedance. We will turn these values into physical microstrip line and build the filter in Figure 2. We will need to know electrical length calculation over 2.6 beige dielectrics and the microstrip line width & impedance relationship.

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}
1	2.0000	1.0000									
2	1.4142	1.4142	1.0000								
3	1.0000	2.0000	1.0000	1.0000							
4	0.7654	1.8478	1.8478	0.7654	1.0000						
5	0.6180	1.6180	2.0000	1.6180	0.6180	1.0000					
6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176	1.0000				
7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450	1.0000			
8	0.3902	1.1111	1.6629	1.9615	1.9615	1.6629	1.1111	0.3902	1.0000		
9	0.3473	1.0000	1.5321	1.8794	2.0000	1.8794	1.5321	1.0000	0.3473	0.3129	
10	0.3129	0.9080	1.4142	1.7820	1.9754	1.9754	1.7820	1.4142	0.9080	0.3129	0.3129

Figure 4 Element Values for Maximally Flat Low-Pass Filter (g_0=1, w_c=1, N=1 to 10)

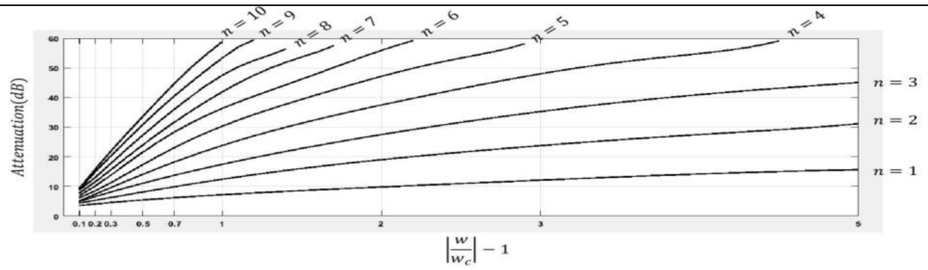


Figure 5 Attenuation versus normalized frequency maximally Flat Filters (g_0=1, N=1 to 10)

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}
1	0.6986	1.0000									
2	1.4029	0.7071	1.9841								
3	1.5963	1.0967	1.5963	1.0000							
4	1.6703	1.1926	2.3661	0.8419	1.9841						
5	1.7058	1.2296	2.5408	1.2296	1.7058	1.0000					
6	1.7254	1.2479	2.6064	1.3137	2.4758	0.8696	1.9841				
7	1.7372	1.2583	2.6381	1.3444	2.6381	1.2583	1.7372	1.0000			
8	1.7451	1.2647	2.6564	1.3590	2.6964	1.3389	2.5093	0.8796	1.9841		
9	1.7504	1.2690	2.6678	1.3673	2.7239	1.3673	2.6678	1.2690	1.7504	1.0000	
10	1.7543	1.2721	2.6754	1.3725	2.7392	1.3806	2.7231	1.3485	2.5239	0.8842	1.9841

Figure 6 Element Values for Equal-Ripple Flat Low-Pass Filter (g_0=1, w_c=1, N=1 to 10, 0.5 dB ripple)

Low-Pass Filter Design Algorithm:

1. Calculate the normalized frequency with the formula below:

$$| \quad | - 1 = |^{(q\,0\ \ g\,0\,0)} \frac{\quad | - 1}{-0} \qquad (1)$$

2. Depending on the filtering requirements, the filter type is selected. In this experiment, we will design maximally flat and 0.5 dB equal-ripple low pass filters. You need to find out the filter degree (N) with the Figure 5 for the maximally flat filter.

3. Use Maximally flat low pass filter element values.

4. If the circuit has an odd degree, the circuit starts with L and stops with another L for a Tee type of low-pass filter circuit.

5. You need to consider the high (Z_H) and low (Z_L) impedances that will be used in this filter. These values are not calculated. The designer selects them. Z_H/Z_L needs to be as large as possible.

6. In this experiment, you can use the impedance levels that you calculated in section 1. You already calculated the stub widths in that section. You can have look at the dimensions that you calculated in section 1 and select the proper values.

7. Calculate the lengths with the formulas below:

$\beta l = \frac{LR_0}{R_0}$ for capacitor	2)

$\beta l = \frac{CZ_l}{Z_h}$ for inductor	(3)

L and C are the normalized element values (g_n) in Figure 4 for maximally flat filter and Figure 6 for Equal-Ripple Flat Low-Pass Filter. R_0 is the filter impedance.

8. In order to find the physical lengths, you need to multiply the βl with $\beta=2\pi/\lambda g$. The dielectric constant of the microstrip line is 2.6 for the beige dielectrics.

9. In the realization, you can't have exactly the calculated length values. Use the closest lengths that can be build with the bricks.

10. Build the filter and measure.

Bandwidth:

The impedance bandwidth of the antenna is a frequency range between the highest and lowest frequency where return loss is below a certain value. For most of the applications, 10 dB return loss is a rule of thumb. Elementary antennas have typical bandwidth characteristics, but the frequency bandwidth changes with the center frequency. Therefore, the percentage bandwidth is used as an antenna parameter. The percentage bandwidth is a ratio of the frequency range divided by the center frequency as in Equation 1.

$$B = \frac{f_h - f_l}{f_c} \qquad (4)$$

f_H: The highest frequency intersecting -10 dB S_{11}[dB]
f_L: The lowest frequency intersecting -10 dB S_{11}[dB]
f_C: Center frequency

3. EXPLANATION ABOUT DESIGNING A MICROSTRIP STEPPED IMPEDANCE LOW PASS FILTER WITH ANTEN'IT:

The box in Figure 7 is the microstrip stepped impedance low-pass filter experiment box. There are metal and beige dielectric cells to build a 50-ohm microtrip lines in the box. We will design 3 different low-pass filters. There will be two maximally flat filters with different degrees and one 0.5 dB equal-ripple filter in this experiment.

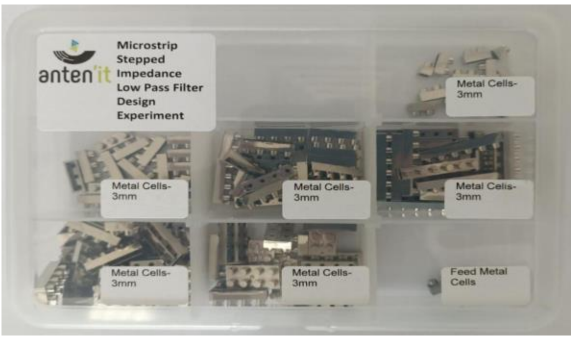


Figure 7 Stepped impedance low pass filter design experiment box

The calculation of height:

There are two kinds of beige dielectrics; one with 1.5 mm height (beige dielectric cells-1.5mm) and the other one with 3 mm height (beige dielectric cells-3mm). 1.5mm cells are connected to the ground plane and 3 mm cells are mounted over the 1.5 mm cells.

The dielectrics and metal cells are already mounted to build a microstrip line for this experiment. You will use the cells in the box to build the stubs.

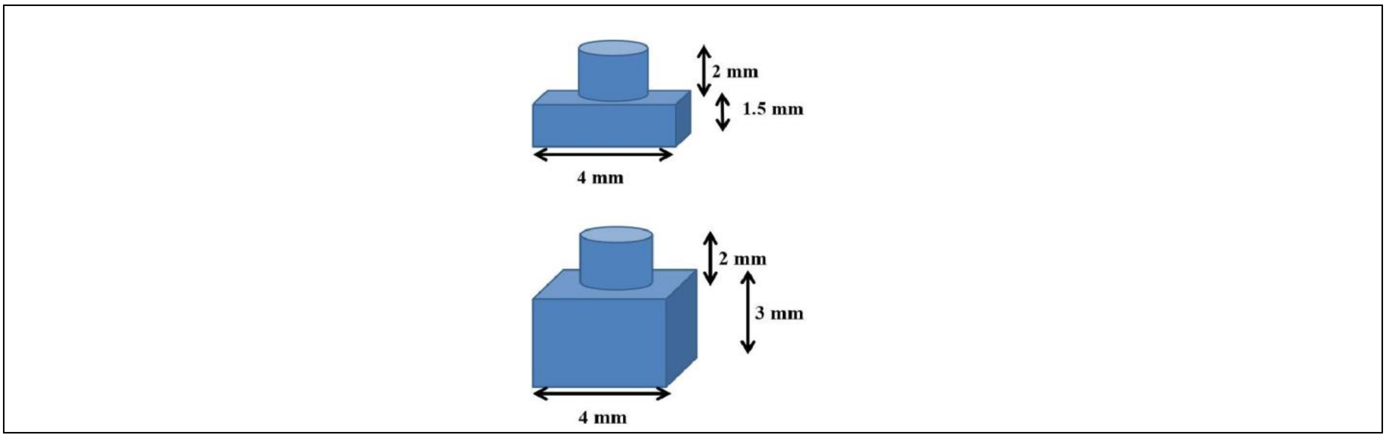


Figure 8 Anten'it 1.5 mm and 3 mm cell dimensions

Removing the cells:

Removing the cells is one of the most important parts to learn. The misusage can damage the cells. Brick remover holds two of the cylinders at the same time. You just need to push to the high end of the remover as in Figure 9.

The removing tool for this experiment is a plastic brick remover. In order to get the best efficiency, we need to start dismounting the cells from outside. First, remove the smallest metal cells which are on the outside. Second, remove the cells which are on the outside but larger. To remove the cells, always hold the cylinders in the center as in Figure 9.

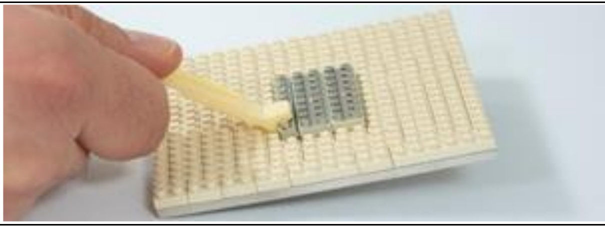


Figure 9 Brick Remover Usage

4. PRELIMINARY WORK:

1. What are the ideal reflection and insertion coefficients for a low pass filter?
2. Explain the differences between maximally flat and 0.5 dB equal-ripple filters. What are the expected amplitude characteristics ?
3. What kind of change in S-parameters is expected by increasing the filter degree ?

5. EXPERIMENTAL PROCEDURE:

1. Connect the cables to the Network Analyser and connect the SSMA-Female to SMA-Male adapters to the SSMA-male side of the cables as shown in Figure 10. Calibrate the Network Analyzer for 2 port measurement between 100 MHz and 2000 MHz.

Figure 10 Cable to SSMA-SMA Adaptor Connection

2. Connect the microstrip line board to the VNA. Check if the total dielectric height is 4.5 mm except the cylinders of the bricks. There must be the beige dielectric bricks with 1.5 mm over the ground plane and 3 mm beige dielectrics over the 1.5 mm beige dielectrics. Check if both ground planes are connected to each other as in the figure below.

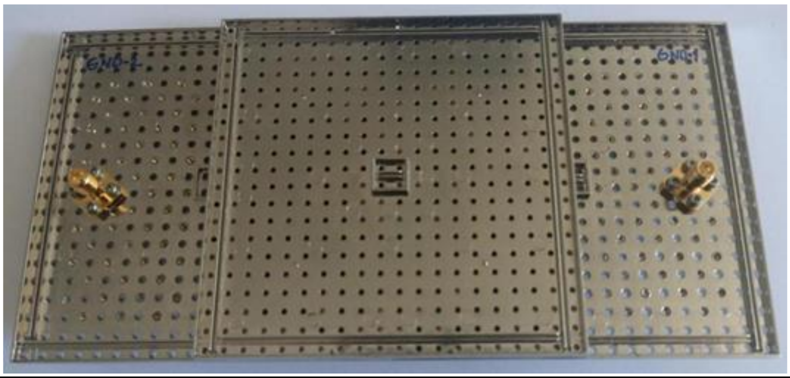


Figure 11 Ground plane connection

Two ground planes are connector into each other with another ground plane at the bottom of them. There are 1.5 mm beige dielectrics layer over the ground planes. There is a second layer with 3 mm dielectric cells over the 1.5 mm dielectric cells. The third layer is the 3 mm metal cells which builds the microstrip line over the dielectrics.

3. Locate the feed metal cells over the connector inner conductors. The red point needs to be over the inner conductor.

Figure10 Red feed point

4. Use a multi-meter or voltmeter in order to check if the inner conductor of the connector is connected to the feed cell. Turn the multi-meter to “short” buzzer option. With one probe touch to the inner conductor of the SSMA connector from the bottom of the ground plane and with the other probe touch to the feed cell. If the buzzer is ringing, they are connected to each other and we can start the experiment.

Figure 12 Buzzer

5. The initial scene of the 2 port circuit is as below. The experiment will start at this point.

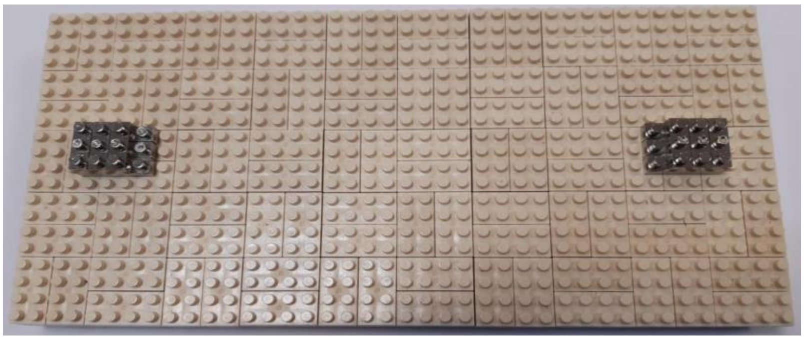


Figure 13 2-port circuit photo

6. Design a stepped-impedance low-pass filter having a maximally flat response and a cutoff frequency of 1 GHz. It is desired to have more than 15 dB insertion loss at 2 GHz. The filter impedance is 50 ohm. The highest impedance is 96 ohm and the lowest impedance is 13.25 ohm. The subsrate height is 4.5 mm and the dielectric constant is 2.6 with 0.002 tangent loss. The microstrip line widths and corresponding impedances are calculated in the first section.

7. Calculate |w/wc|-1 and use Figure 5 to find our the filter degree.

Maximally Flat Low Pass Filter Degree

8. Use Maximally flat low pass filter element values. Use the filter starts with a series inductance, calculate the lengths of each section. Write down the width and length of microstrip line sections

Width:	
Lengths:	

9. Build the filter with the microstrip line sections. Measure S-parameters. Save the graphic with print screen or save graphic option of the network analyser. If there is memory option of the network analyser, store the measurements to memory to compare the results with the next filters.

Insertion loss in the passband frequencies	Measured cut off frequency	Measured insertion loss at 2 GHz

* The measured cut-off frequency may be different than the target one. It is possible to iterate the filter dimensions and reach to target cut-off frequency. We won't iterate in this experiment and we will compare the results of different filter degrees and filter types.

10. Design a stepped-impedance low-pass filter having a maximally flat response and a cutoff frequency of 1 GHz. It is desired to have more than 33 dB insertion loss at 2 GHz. The other parameters are the same.

11. Calculate |w/wc|-1 and use Figure 5 to find out the filter degree.

Maximally Flat Low Pass Filter Degree

12. Use Maximally flat low pass filter element values. Use the filter starts with a series indcutance, calculate the lengths of each section. Write down the width and length of microstrip line sections

Width:	
Lengths:	

13. Build the filter with the microstrip line sections. Measure S-parameters. Save the graphic with print screen or save graphic option of the network analyser. If there is memory option of the network analyser, store the measurements to memory to compare the results with the next filters.

Insertion loss in the passband frequencies	Measured cut off frequency	Measured insertion loss at 2 GHz

14. Compare the measurement results of S12 in two filters with different degrees. Write down the differences between two filters.

15. Design a 0.5 dB maximally ripple level low pass filter with the same degree of the **first** filter degree and for the same target frequency characteristics.

16. Use 0.5 dB equiripple low pass filter element values. Use the filter starts with a series inductance, calculate the lengths of each section. Write down the width and length of microstrip line sections.

Width:	
Lengths:	

17. Build the filter with the microstrip line sections. Measure S-parameters. Save the graphic with print screen or save graphic option of the network analyser.

Insertion loss in the passband frequencies	Measured cut off frequency	Measured insertion loss at 2 GHz

18. Compare the measurement results of S12 in two different kinds of filters (experiment 1 and 3). Write down the differences between two filters.

19. Disconnect the metal cells and make them ready for other students.

6. RESULTS:

- State the objective of the experiment and give a short summary of the procedure.
- What changes with the filter degree ?
- What are the differences of maximally flat and equal-ripple 0.5 dB filter types ? Which measured parameters are different ?
- Why are there differences between the calculated and measured parameters ? Did you measure the calculated cut-off frequency.
- Compare the theory and experimental results.
- Discuss the results of your experiment.

6-MICROSTRIP 180^{O} HYBRID COUPLER DESIGN EXPERIMENT

1. OBJECTIVES

- Designing a Microstrip 180^{O} Hybrid Coupler
- Phase Measurement of S-parameters for a 4-port passive component
- To investigate the S-parameters of the 180^{O} Hybrid Coupler
- To compare the theoretical and measured results.

2. BRIEF INFORMATION ABOUT THE MICROSTRIP 180^{O} HYBRID COUPLER:

1- Effective Dielectric Constant and Microstrip Line Impedance Calculation

In order to calculate the microstrip line impedance, you need to calculate the effective dielectric constant and use it in the impedance calculation.

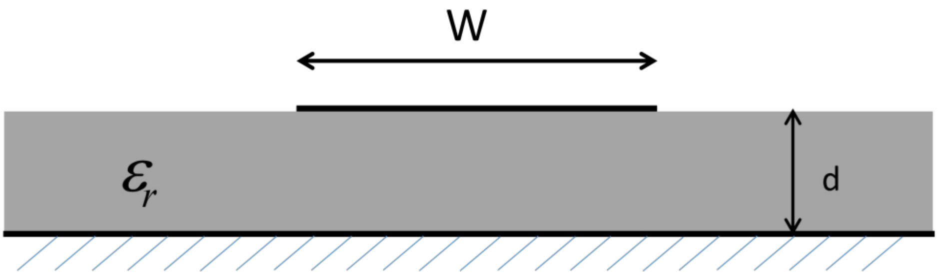


Figure 1 Microstrip Line Representation

The effective dielectric constant of a microstrip line is given by;

$$\epsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12d/W}} \quad (1)$$

The microstrip impedance is calculated with the formula below;

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_e}} \ln\left(\frac{8d}{W} + \frac{W}{4d}\right) & \text{for } W/d \leq 1 \\ \frac{120\pi}{\sqrt{\epsilon_e}\,[W/d + 1.393 + 0.667\ln(W/d + 1.444)]} & \text{for } W/d \geq 1 \end{cases} \quad (2)$$

Calculate the effective dielectric constant and characteristic impedance for 4 mm, 8 mm, 12 mm, 16 mm, 20 mm and 24 mm line widths (W) and 4.5 mm dielectric height (d). ϵ_r of the substrate is 2,6. It is easier to write a MATLAB or OCTAVE code for this calculation.

Microstip Line Widths (W)	Effective Dielectric Constant (ε_e)	Characteristic Impedance (Z_0)
4 mm		
8 mm		
12 mm		
16 mm		
20 mm		

Hybrid Coupler Explanation

180^O Hybrid coupler is a 4-port passive component where there are 2 input and 2 output ports. The output ports are sum and difference (delta) ports. Sum port sums the signal from two inputs with zero degree phase and the difference port sums the signal from two inputs with 180 degree phase difference. The structure of a rat race coupler is skecthed in Figure 1 below. There are also other forms of this component such as magic tee applied in waveguides.

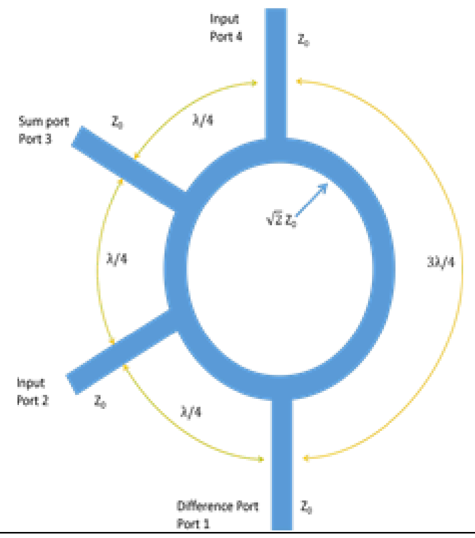


Figure 2 Representation of a rat race coupler

Port 1 is the difference port and port 3 is the sum port in the figure. Port 2 and 4 are the input ports. The electrical length (quarter wavelength) between Port 4 and Port 3 is equal to the electrical length between Port 2 and Port 3. Therefore the sum port combines the signals coming from Port 2 and Port 4.

The electrical length between Port 1 and Port 2 is quarter wavelength where the electrical length between port 1 and port 4 is three quarter wavelength. The difference between these two electrical lengths is half wavelength which corresponds to 180 degree phase difference. For example if the signal coming from port 2 and port 4 are the same, then the difference port will ideally have zero ($Ae^{j0} + Ae^{j180} = A\text{-}A = 0$) signal at the center frequency. Therefore the difference port which is also called as "delta" subtracts the signal at port 2 from port 4.

If we look at the circuit from the sum port, the difference port is isolated and the hybrid coupler is turned into a power combiner. If we look at the circuit from the difference port, then the sum port is isolated and the input signals are combined with 180 degree out of phase.

This is a passive and symmetrical component where the scatttering matrix is also symmetrical as below:

$$[\,] = \frac{-j}{\sqrt{2}}\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{bmatrix} \qquad (1)$$

In the figure, the circular part has $\sqrt{2}\,Z_0$ impedance and the lines going out of the circle has Z_0 impedance.

Since the dimensions of this component are dependent on the wavelength, the bandwidth of this component narrow.

3. EXAMPLE 180 DEGREE HYBRID COUPLER DESIGNED WITH ANTEN'IT KITS:

We start with an example to understand how it is possible to build a 180 degree hybrid coupler with Anten'it cells.

This example hybrid coupler uses different principles than the one in this experiment such as changing the dielectrics of the line. This example is a bit different than conventional hybrid coupler design. In the example, the metal cells of the coupler have 4 mm width and they are all over an air dielectrics layer with 1.5 mm height. This theoretically corresponds to 75 ohm which is close to

$\sqrt{2}\ Z_0$. 4 mm width over 1.5 mm beige dielectrics with 2.6 dielectric constant corresponds to 51.5 ohm. There are beige dielectrics below the feed ports and the other part of the circuit has air as a dielectric which provides the impedance that we need to design a hybrid coupler.

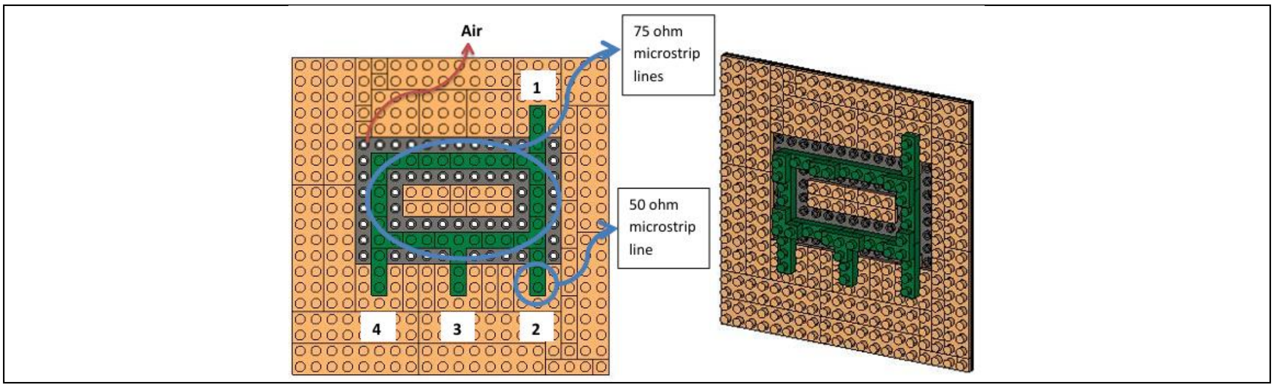


Figure 3 Hybrid Coupler Perspective View

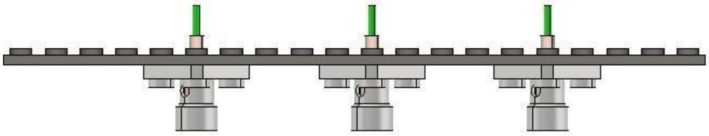
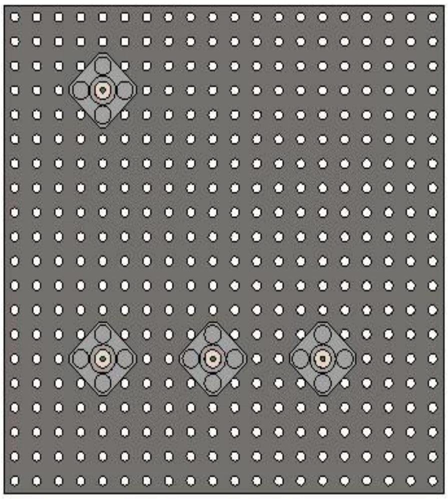
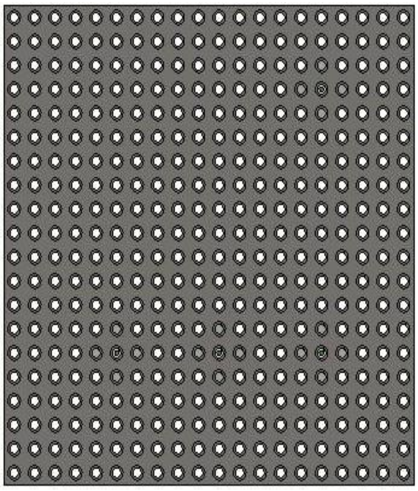


Figure 4 Ground Plane Side View

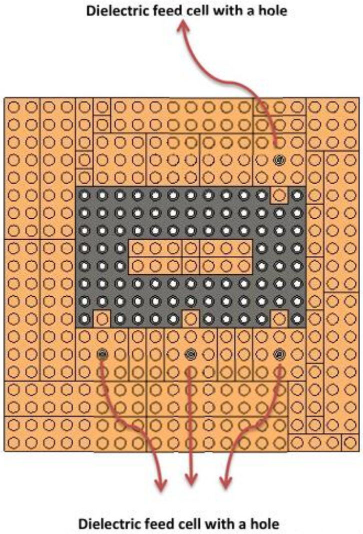
These figures show the first layer over the ground plane and the layers above that. Beige dielectrics with 1.5 mm height, metal cells with 3 mm height are used in this coupler.



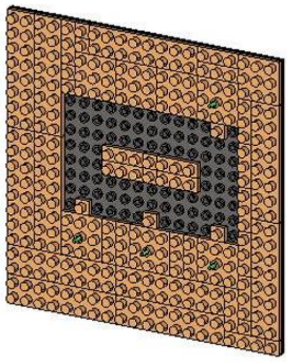
Ground Plane Bottom View



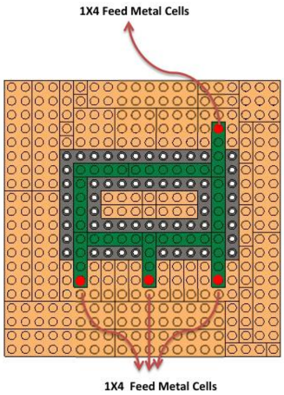
Ground Plane Top View



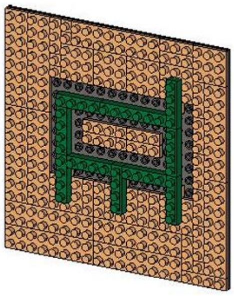
Layer-1 Dielectrics: Front View - Beige Dielectrics with 1.5 mm height



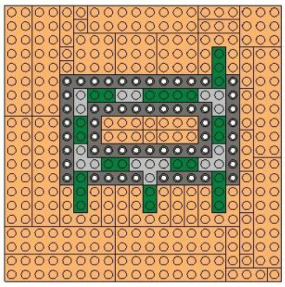
Layer-1 Dielectrics: Perspective View - Air is shown as free space

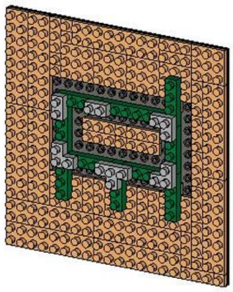


Layer-2 Metal Cells (Green colour): Front View



Layer-2 Metal Cells: Perspective View

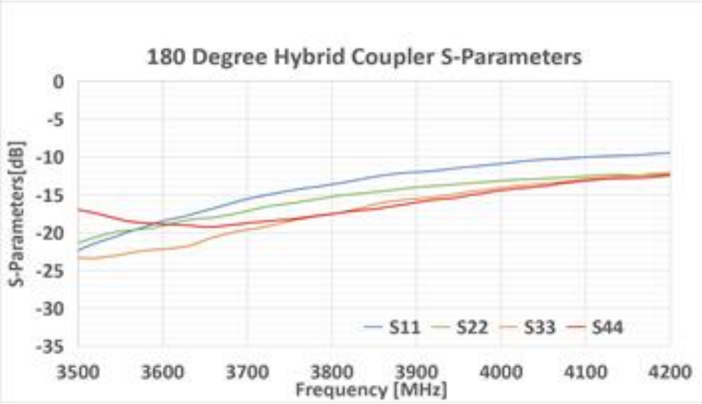




Layer-3 Metal Cells : There is one more metal layer (grey colour) to connect the bricks into each other. They are same dielectrics but shown in different colours.

Layer-3 Metal Cells : Perspective View

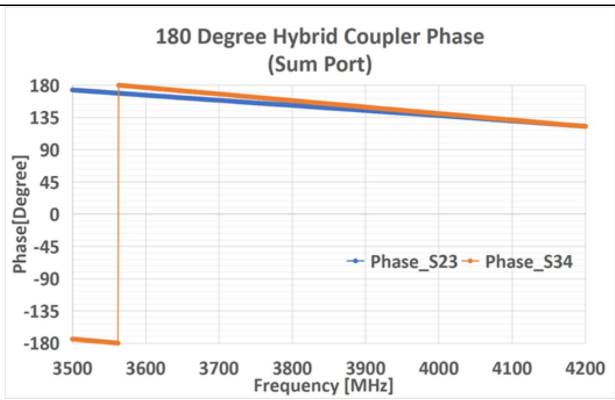
This hybrid coupler is built and measured. The results are given in the graphics below. The first graphic shows the reflection coefficients at each 4 ports. They are all below -10 dB between 3500 MHz and 4100 MHz.

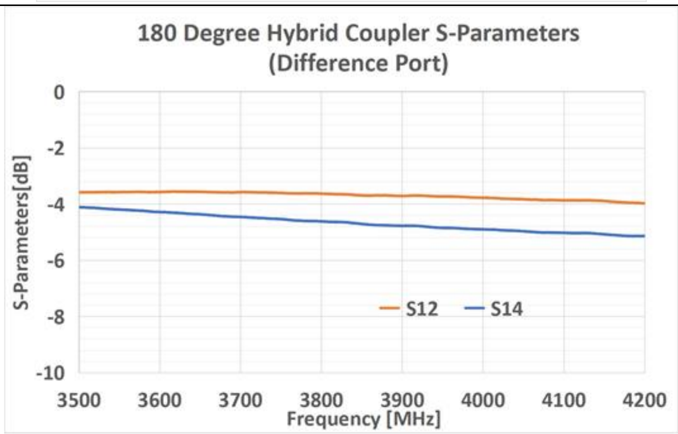


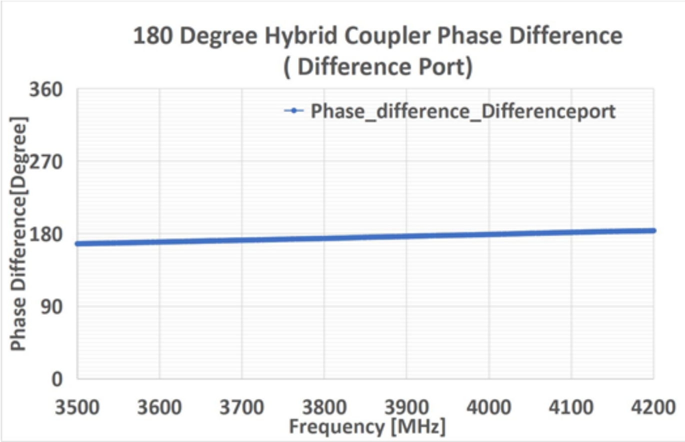
S23 and S43 are two S parameters for the sum port. Ideally, they need to be the same. In practice they are similar to each other. The phase different of these two ports needs to be zero theoretically. In practice, the phase difference needs to be in a range. Here in this example, the phase difference changes between -12 degree and 1 degree.

S14 and S12 are two S parameters for the difference port. In theory, the amplitude of these signals need to be the same where the phases need to have 180 degree difference.

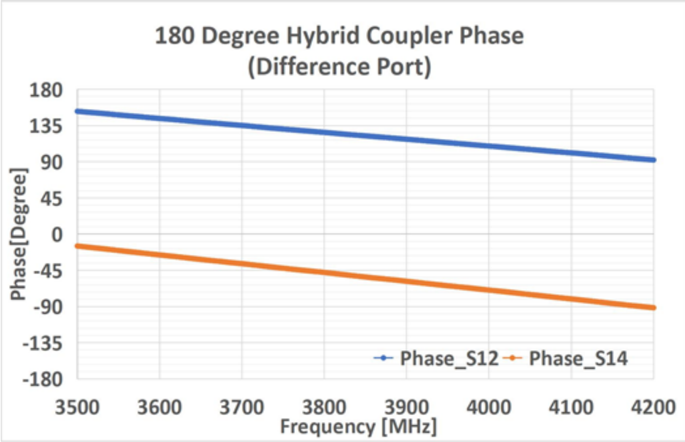
S13 is the isolation between the sum and the difference ports.



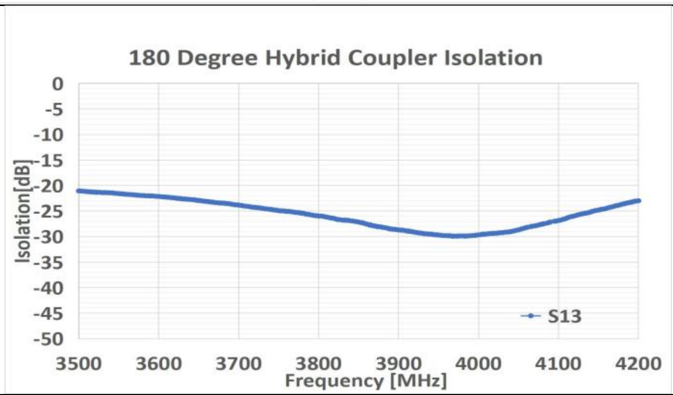




180 Degree Hybrid Coupler Phase Difference
(Difference Port)
Phase_difference_Differenceport
Phase Difference[Degree]
360
270
180
90
0
3500
3600
3700
3800
3900
4000
4100
4200
Frequency [MHz]



180 Degree Hybrid Coupler Phase
(Difference Port)
Phase[Degree]
180
135
90
45
0
-45
-90
-135
-180
Phase_S12
Phase_S14
3500
3600
3700
3800
3900
4000
4100
4200
Frequency [MHz]



180 Degree Hybrid Coupler Isolation
Isolation[dB]
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
S13
3500
3600
3700
3800
3900
4000
4100
4200
Frequency [MHz]

This example was only to check how it is possible to build a hybrid coupler easily with Anten'it kits. You can check the dimensions of the example hybrid coupler and compare if the results are as expected.

We will use only beige dielectrics in our experiment. There is no air or any other dielectric layer. Therefore, our experiment is not as complex as the example.

4. EXPLANATION ABOUT DESIGNING A 180 DEGREE HYBRID COUPLER WITH ANTEN'IT:

The box in Figure 5 is the 180 degree hybrid coupler experiment box. There are metal cells with 3 mm height and feed cells in the box.

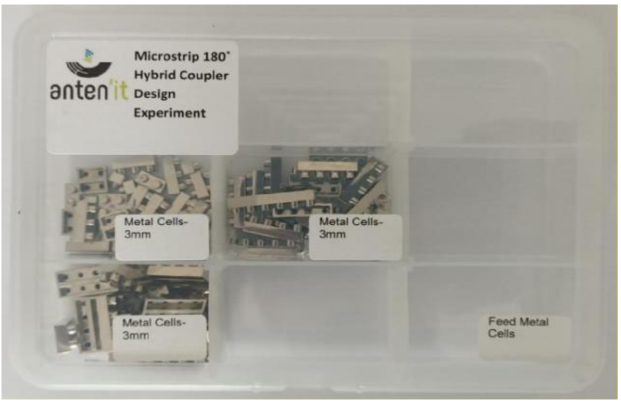


Figure 5 180-degree Hybrid Coupler Design Experiment Box

The calculation of height:

There are two kinds of beige dielectrics; one with 1.5 mm height (beige dielectric cells-1.5mm) and the other one with 3 mm height (beige dielectric cells-3mm). 1.5mm cells are connected to the ground plane and 3 mm cells are mounted over the 1.5 mm cells.

The dielectrics and metal cells are already mounted to build a microstrip line for this experiment.

You will use the cells in the box to build the stubs.

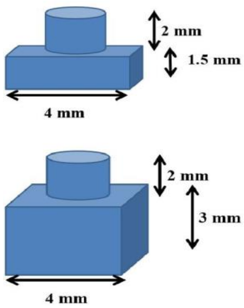


Figure 6 Anten'it 1.5 mm and 3 mm cell dimension

Removing the cells:

Removing the cells is one of the most important parts to learn. The misusage can damage the cells. Brick remover holds two of the cylinders at the same time. You just need to push to the high end of the remover as in Figure 7.

The removing tool for this experiment is a plastic brick remover. In order to get the best efficiency, we need to start dismounting the cells from outside. First, remove the smallest metal cells which are on the outside. Second, remove the cells which are on the outside but larger. To remove the cells, always hold the cylinders in the center as in Figure 7.

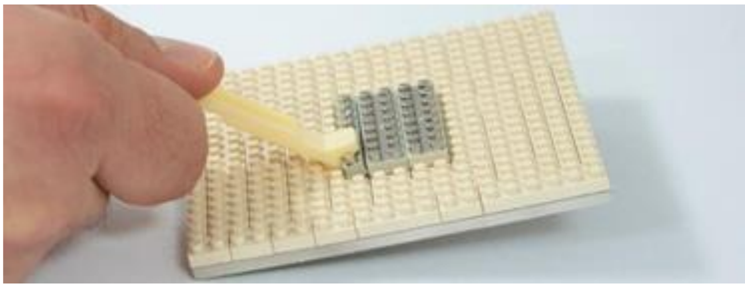


Figure 7 Brick Remover Usage

5. PRELIMINARY WORK:

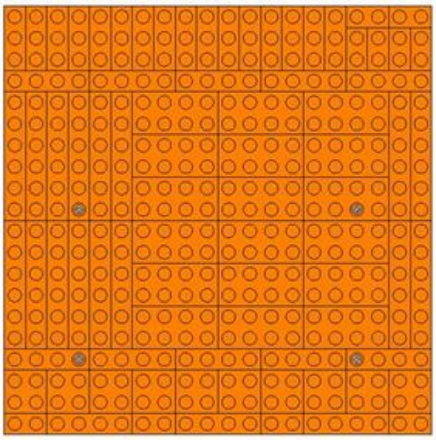
1. How many ports are there in a hybrid coupler ? What are they used for ?
2. What is the difference between a power divider and a hybrid coupler ?
3. Why do we need 180 degree phase difference between two ports ? Which applications use it ?

6. EXPERIMENTAL PROCEDURE:

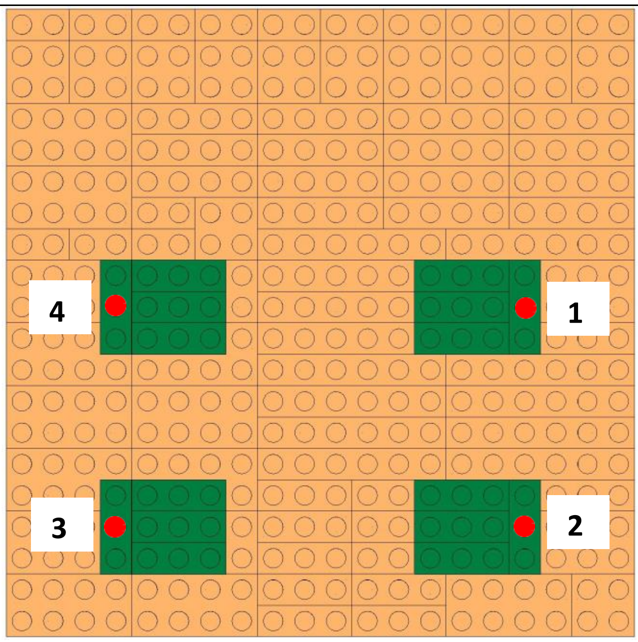
1. Connect the cables to the Network Analyser and connect the SSMA-Female to SMA-Male adapters to the SSMA-male side of the cables as shown in Figure 8. Calibrate the Network Analyzer for 2 port measurement between 500 MHz and 4.000 MHz.

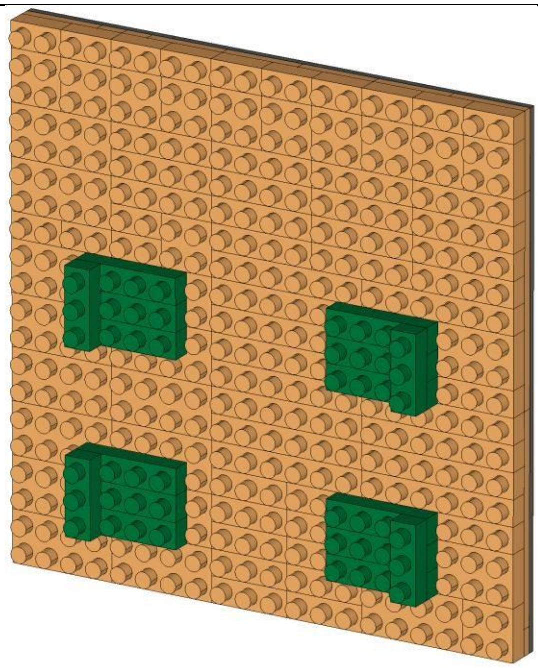
Figure 8 Cable to SSMA-SMA Adaptor Connection

2. Connect the microstrip line board to the VNA. Check if the total dielectric height is 4.5 mm except the cylinders of the bricks. There must be the beige dielectric bricks with 1.5 mm over the ground plane and 3 mm beige dielectrics over the 1.5 mm beige dielectrics. The configuration is shown below.



The feed points are shown





First metal layer	Perpective view
There are two metal layers to make the metals to touch each other. You can see two layer in the perspective view. This is the layer at the bottom. The red circles show the feed points. The feed metal cells are special, so don't dismount them or don't change their location.	(There are two dielectric layers. The bottom layer is beige dielectrics with 1.5 mm and the top layer is beige dielectrics with 3 mm.)

Figure 9 The configuration that the experiment starts

The experiment needs to start with this configuration. You will use the impedance calculations you made in the first section of this document.

3. Locate the feed metal cells over the connector inner conductors. The red point needs to be over the inner conductor. Check if the connector is connected to the feed metal cells via a Multimeter.

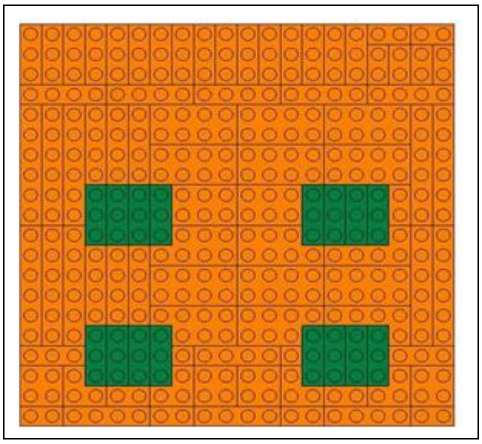
Figure 10 Red feed point

4. Use a multi-meter or voltmeter in order to check if the inner conductor of the connector is connected to the feed cell. Turn the multi-meter to "short" buzzer option. With one probe touch to the inner conductor of the SSMA connector from the bottom of the ground plane and with the other probe touch to the feed cell. If the buzzer is ringing, they are connected to each other and we can start the experiment.

Figure 11 Buzzer

5. Calculate the dimensions you need for this experiment at 2360 MHz. Calculate the length of the microstrip lines between the ports and use the appropriate microstrip line width for $\sqrt{2}Z_0$ and Z_0 impedances. Draw the ideal 180 degree hybrid coupler (rat-race coupler) below.

6. Draw the same hybrid coupler over the dielectrics below. Start labeling each port with port numbers and find out which ports can be input ports and which can be sum and difference (delta ports). Then, proceed with drawing the microstrip lines that $\sqrt{2}\,Z_0$ impedance between include the ports.



7. Build the same structure with the bricks. This is the initial point of your design. You need to measure the phase difference between (input-1 and difference port) and (input-2 and difference port) to understand if the phase difference between these two ports are 180 degrees as ideally. Then, if the phase difference is close to zero, measure the amplitude. The real components may have some tolerances as in the example given in section 1. Measure all S-parameters in the table and write down the values at 2360 MHz below:

S11 [dB] (Difference Port)	
S22 [dB] (Input Port 2)	

S33 [dB] (Sum Port)	
S44 [dB] (Input Port 4)	
S12 [dB] (Input Port 2 to Difference Port)	
S12 Phase [Degree] (Input Port 2 to Difference Port)	
S12 phase [Degree(Input port to difference port)]	
S14 [dB] (Input Port 4 to Difference Port)	
S14 Phase [Degree] (Input Port 4 to Difference Port)	
S13 [dB] (Isolation between Sum and Difference Ports)	

8. Check if the results you have are close to ideal (Phase degrees in ± 10 degrees and the amplitude levels in ± 3 dB difference than ideal levels). If all values are not in this range, start iterating the dimensions and write down the new levels at each iteration. Look if you diverge or converge to the ideal levels at each dimension change. Iterate the next level by using this information. Check which values are dependent on the frequency in theory and which are not. Iterate the dimensions changing with the frequency.

9. Continue the iteration until you reach to target parameters.

	Iteration-1	Iteration-2	Iteration-3	Iteration-4	Iteration-5	Iteration-6
S11 [dB] (Difference Port)						
S22 [dB] (Input Port 2)						
S33 [dB] (Sum Port)						

S44 [dB] (Input Port 4)						
S12 [dB] (Input Port 2 to Difference Port)						
S12 Phase [Degree] (Input Port 2 to Difference Port)						
S14 [dB] (Input Port 4 to Difference Port)						
S14 Phase [Degree] (Input Port 4 to Difference Port)						
S13 [dB] (Isolation between Sum and Difference Ports)						

10. Check if this component is reciprocal. Find out which other port number can be selected as a sum port and which other can correspond to difference port in that situation. Find out all port numbers and measure the coupler for new port configuration. Compare the measured results in the previous step and consider if this component is reciprocal.

S44 [dB] (Difference Port)	
S33 [dB] (Input Port 3)	
S22 [dB] (Sum Port)	
S11 [dB] (Input Port 1)	
S43 [dB] (Input Port 3 to Difference Port)	
S43 Phase [Degree] (Input Port 3 to Difference Port)	
S41 [dB] (Input Port 3 to Difference Port)	
S41 Phase [Degree] (Input Port 1 to Difference Port)	

S42 [dB] (Isolation between Sum and Difference Ports)	

7. RESULTS:

- State the objective of the experiment and give a short summary of the procedure.
- What are the differences between the measured and theoretical 180-degree hybrid coupler ?
- What is reciprocity? How can you determine that a component is reciprocal?
- Compare the theory and experimental results.
- Discuss the results of your experiment.