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NUST COLLEGE OF

ELECTRICAL AND MECHANICAL ENGINEERING

Microstrip Quad Mode Reconfigurable Power Divider

A PROJECT REPORT

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Submitted by

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YEAR - 2022

DEDICATION

This project is dedicated to our parents, their efforts and all the prayers were with us during the project. It is also dedicated to our teachers and all the technical staff who really helped us for the completion of this project.

CERTIFICATE OF APPROVAL

It is to certify that the project "**Microstrip Quad Mode Reconfigurable Power Divider**" is done by **NC Mubashar Ahmed Khan** and **NC Muhammad Hanif** under the supervision of **Dr. Mojeeb bin Ihsan.**

This project is submitted to **Department of Electrical Engineering**, College of Electrical and Mechanical Engineering (Peshawar Road Rawalpindi), National University of Sciences and Technology, Pakistan in partial fulfilment of requirements for the degree of Bachelors in Electrical engineering.

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DECLARATION

We hereby declare that no portion of the work in this Project Report has been submitted in support of an application for another degree or qualification of this of any other university or other institute of learning. If any act of plagiarism found, we are fully responsible for every disciplinary action taken against us depending upon the seriousness of the proven offence, even the cancellation of our degree.

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We acknowledge the efforts of many people whose names may not appear on the front page, but whose hard work, friendship, cooperation, and understanding have enabled us to complete this report. Here we would like to cite the support and guidance provided by our supervisor Dr. Mojeeb bin Ihsan. His availability and quick responses to our issues helped us successfully to complete this work. The Department of electrical engineering also supported us in completing this project. Moreover, RWR provided us with the facility to fabricate our design on PCB.

ABSTRACT

The evolution in communication systems demands low cost, compact size, reconfigurable or multi-functional microwave circuits that are easy to integrate. In this project a quad mode reconfigurable power divider, based on the design presented by Yahya Antar et. al [1], was designed, fabricated, and tested. Reconfigurability was obtained by converting two ports of a quadrature coupler ports into a single input port with the help of a feeding structure made of parallel coupled microstrip transmission lines. The four modes of operation discussed in this work includes (0:1), (1:0), (1: j) & (j:1), i.e. directing total power into one out of two ports and two-way equal power split with +90 or – 90 degrees phase shifts. All the four modes were designed and simulated using Keysight ADS. Reconfigurability was achieved by employing 4-switches. Out of four switches 2 switches were placed at the end of coupled lines and the remaining two at the center of quadrature coupler. In this project instead of switches through hole via to ground were used to control the mode of operation of the power divider. Out of these four modes, fabrication was done for only two modes of operation (0:1) & (1: j). A very close agreement between the simulated and measured results was achieved. Simulated results of reconfigurable quadrature coupler operating in mode (0,1) were $S_{11} = -22.988$ dB, $S_{21} = -27.263$ dB and $S_{31=} - 0.114$ dB and the measured results for this mode were $S_{11=} - 25.75$ dB, $S_{21} = -23.39$ dB and $S_{31} = -0.948$ dB representing that almost all the power is delivered to port 3. Moreover, the simulated results of circuit operating in mode (1,j) were $S_{11} = -24.522$ dB, $S_{21} = -3.2$ dB and $S_{31} = -2.9$ dB and the phase difference was of -90 degrees while measured results for this mode of operation were $S_{11} = -24.22$ dB, $S_{21} = -3.463$ dB and $S_{31} = -3.903$ dB and the phase difference obtained was -93.7 degrees, showing quadrature mode of operation and almost equal split of power between the port 2 & port 3.

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Chapter 1

1.1 Introduction

Power dividers are of great importance in many microwave systems such as modulators, power amplifiers and antenna array feed systems. Using the simplest power divider the input signal can be spilt into two or more output signals with a certain amplitude and phase. An ideal power divider is also an ideal power combiner, but it is not always true. Power divider can act as power combiner but it depends on the configuration in which it is used. There are different types of power dividers in RF/Microwaves such as Wilkinson Power Divider, Magic T-type Power Divider and 3dB Hybrid Coupler (Quadrature Coupler). Wilkinson Power Divider is a three port network that can divide the power both equally and unequally while the Quadrature Coupler is a four-port network which can equally divide the power with a 90° of phase difference. These power dividers can be designed based on different parameters which are discussed in later sections.

The word “Reconfigurable” means to modify or rearrange a previously defined configuration. RF/Microwave devices can be reconfigured depending on different parameters like for antennas they can be reconfigured on the basis of frequency, polarization and radiation pattern and for power dividers they can be reconfigured on the basis of the operational frequency, (power division ratio) phase and the functionality. Reconfigurability in devices is necessary due to the advancement of communication systems because we can save resources while achieving multiple applications on a single device. Due to the development in new systems, space technology and commercial applications it is a constant need for smaller, multimode, and frequency agile devices. Power dividers can be reconfigured in many different ways wherein two-way power dividers can be cascaded to create higher order of power dividers.

Industrial Wireless applications need high performance miniaturized RF components having easy integration and low cost. Integration of multiple functions in a single component can be effective and a good approach to achieve compact size and operation performance. For example different power dividers were designed by Gang Zhang et. al. [2] to perform multiple operations such as filtering power dividers. They exhibit attractive features with satisfactory operation performance, low cost, easy implementation, and integration, miniaturization as well as flexible design freedom.

There are a lot of practical applications of RF/Microwave devices like in case of frequency reconfigurable antennas they adjust their frequency of operation dynamically so they can be used in such places where communication systems converge hence a number of antennas can be replaced by a single reconfigurable antenna. Power Dividers are widely used in microwave circuits and systems, lots of practical power divider structures have been developed to improve circuit performances such as dual band designs, broad band applications, filter integrations and many more. The requirement of flexible operating frequency applications, tunable microwave components have attracted many researchers' attention. Tunable filters, couplers, and controlled bandwidth power dividers have been developed by several researchers [3]. The power dividers having the characteristics of tunability can be used in frequency agile systems. Moreover reconfigurable power dividers are used in increasing the efficiency of power amplifiers.

Another important area of application is in Radio Detecting and Ranging (Radar). Radar were developed and widely used in many applications such as for air surveillance, weather predictions, and traffic controlling, military applications. Microwave passive components such as compact power divider, coupler and microstrip cavity filter have application in surveillance radar system. As we know the requirement of the compact components is necessary so the three modules used in radar are Power divider, directional coupler and band pass filter.

Chapter 2

2.1 Literature Review

One of the important function of electronics is power splitting and combining. This process is facilitated by many RF and microwave circuits. The advancement in communication system has led to an increase demand for microwave components with low energy loss and compact size. Many successful attempts were done to design a reconfigurable power divider using RF Switches and Varactors with variable ratios as explained in [4] and [5]. In [4] the power divider with variable power division ratio has been designed, the idea was to use the principle of coupled line coupler. The switches were placed at the isolated and coupled ports. Changing the state of the switches open/short is changing the power division ratio. Reconfigurable power dividers have many applications like they are used in Time modulated array (TMA) to improve the efficiency of an array. Reconfigurable Power Divider has application in TMA because the power which is absorbed during off states is transferred to the elements of an array during on state. TMA with reconfigurable Power Divider/Combiner (RPDC) increases the gain by 0.98, 1.27 and 1.65 dB when side lobe level are -20, -25 & -30 dB. TM Technique provides flexibility in designs of array antennas by introducing the time factor. This technique did not get attention due to low speed of switches at RF frequencies. TMA has attracted the interest again with the development in RF switches. Low power efficiency was the big issue in TMA due to power loss in side band radiation. The power loss in the feeding network contributes to low efficiency caused by the absorption of power during off state of switches. TMA has been proposed to improve the efficiency of an array by using the RPDC instead of switches in the feeding network and the power absorbed can be reused during off state. As compared to the conventional TMA, the RPDC design can significantly enhance the gain as well as reduce the SBLs (side band level) and the ratio of power loss in sideband radiation [6].

In Power routing scheme coupled line couplers are used which are controlled by the mode control switches depending on the operating conditions of switches. This can be done by using 2-way Wilkinson Power Divider or coupled line coupler. Input and output matching can be achieved by using the even and odd mode characteristic impedances of coupled line coupler. Reconfigurable Power Divider has also been designed using MEMS on highly resistive silicon substrate with the variable power ratios [7].

Reconfigurable power divider has an application in WLAN smart antenna system. Two quadrature hybrids connected to dual band phase shifters. With this simple and compact architecture any power ratio can be independently produced. WLAN available today are having the high bit rate services such as inn multimedia. There was a severe problem of the quality of communication, conventional techniques used for mitigating the multipath effects were based on the equalization techniques using algorithms and implemented using costly power consuming ASICs or FPGAs. Reconfigurable feeding network provided the solution for resolving such problems. If a simple switch is employed this results in a switched beam antenna. Making use of reconfigurable power dividers a full control in the amplitude distribution is achievable thus allowing a wide range of beam shapes. This device is a key component in the implementation of reconfigurable feeding networks for conformal arrays capable of beam shaping and interference nulling independently [8].

The revolution in telecommunication which has led to the need to integrate many services, such as long-term evolution (LTE), 5G, wireless local area network (WLAN), and Bluetooth, in one receiving and transmitting device. In the same way, all active and passive microwave circuits must be compatible with the integration of services, including the power divider. Wilkinson power divider is of great importance in microwave as it can be used in RF testing instrument, microwave systems & have applications in 5G telecommunication systems due to increasing demand in high speed rates, high efficiency and high mobility required by the wireless applications [9].

For our project we worked on “Microstrip Quad mode Reconfigurable Power Divider” which comprises of three components that are Quadrature 90° Hybrid, Coupled Lines and RF Switches and it can operate in four different modes by using different configurations of switches. Previous work is done on it and it is explained in [1]. The design that is presented in the paper used the SPDT switches but the switching behavior can be implemented by using through-hole vias. The complete procedure of designing the power divider and its fabrication is explained in detail in further sections.

Chapter 3

The software that we used was Advance System Design [10]. It is quite a powerful tool that can simulate circuits at low and high frequency. In this chapter we will get familiar with some ADS functionalities that necessary in order to simulate any circuit design.

- Line-calc
- Layout Design
- Substrate Selection
- Port Modeling
- EM Simulation setup

3.1 Linecalc

Linecalc is a built-in tool in ADS which is used to calculate the length, width and other required parameters for a given type of transmission line. To use it go to “Tools” and select “Linecalc” and the click on “Start Linecalc”. Parameters like design frequency, characteristic impedance, and substrate-related data, such as relative permittivity, substrate thickness, copper thickness, and loss tangent, are taken as input parameters. While the length, width are taken as outputs. After putting all the required parameters, it gives the length and width. Moreover, it offers different units like mils, cm, mm, inch, meter and ft. The Linecalc window in ADS is shown in Figure 3.1 [10].

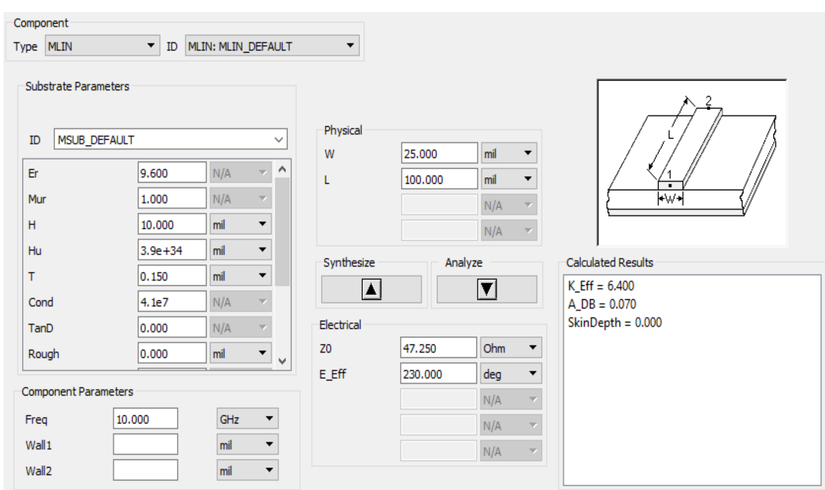


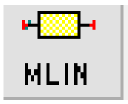
Figure 3.1: Linecalc Layout in ADS

3.2 Layout Design

ADS [10] provides a number of options for circuit designing that we can choose based on our needs. Some of the most commonly used parts are

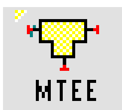
MLIN

MLIN stands for microstrip line and it is used for the drawing of transmission line.



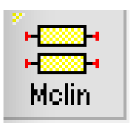
MTEE

It is used to make a T-junction where there is a need for connecting any three lines.



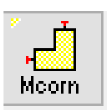
MCLIN

It is a symbol for coupled lines. The output/physical parameters for MCLIN are length, width and separation between the two transmission lines.



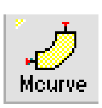
MCORN:

It is used connect the corners of two transmission lines at 90 Degrees.



MCURVE:

It is used to connect one transmission line with another transmission line at some specified angle.



3.3 Substrate Selection

The Substrate selection is one of the initial steps for Layout simulations. To define a substrate open the “Substrate Editor” and go to “add from database” and choose the required substrate from the library. If the required substrate is not in the predefined substrate database then we can define our own substrate by selecting “add dielectric. After the selection of the substrate, add appropriate height of the substrate and the height of the conductor layer. We can also add vias in the substrate. The complete substrate defining window is shown in Figure 3.3.

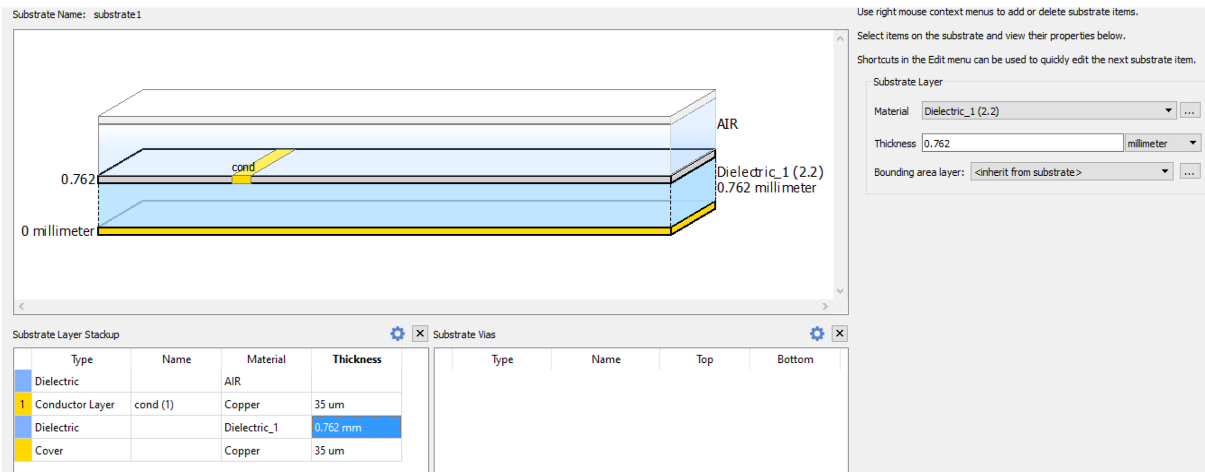


Figure 3.2: Substrate Defining Window in ADS [10]

3.4 Port Modeling

Port modelling is also a crucial step because improper port modelling can lead to inaccurate results. We have multiple options for ports like dot port, rectangular port, circular port and delta-gap port. All of these ports have different functionality so they must be used correctly to meet our goals. In some cases using the default port, which is a dot port, could result in errors because it may not always be necessary to excite the entire transmission line. If we select a rectangular port, it only stimulates a specified area because we can adjust its length and width to meet our needs. Port modeling window is shown below in Figure 3.3 [10].

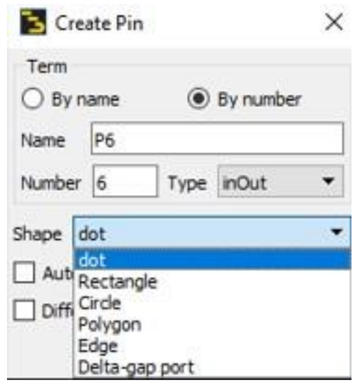


Figure 3.3: Choice of Port Type in ADS

3.5 EM Simulation Setup

To simulate the design we need to set the simulation setup. In order to do that click on "EM" button and an EM simulation window will appear. From there we can choose one of the setup type that is either "EM Simulation/Model" or "EM co-simulation". Then we can check whether or not our substrate and our port definition is correct. Then we can select a frequency range and the number of frequency points in that range on which we want to simulate the design. We also select "Edge Mesh" for better results. A simple EM model layout is below in Figure 3.5 [10].

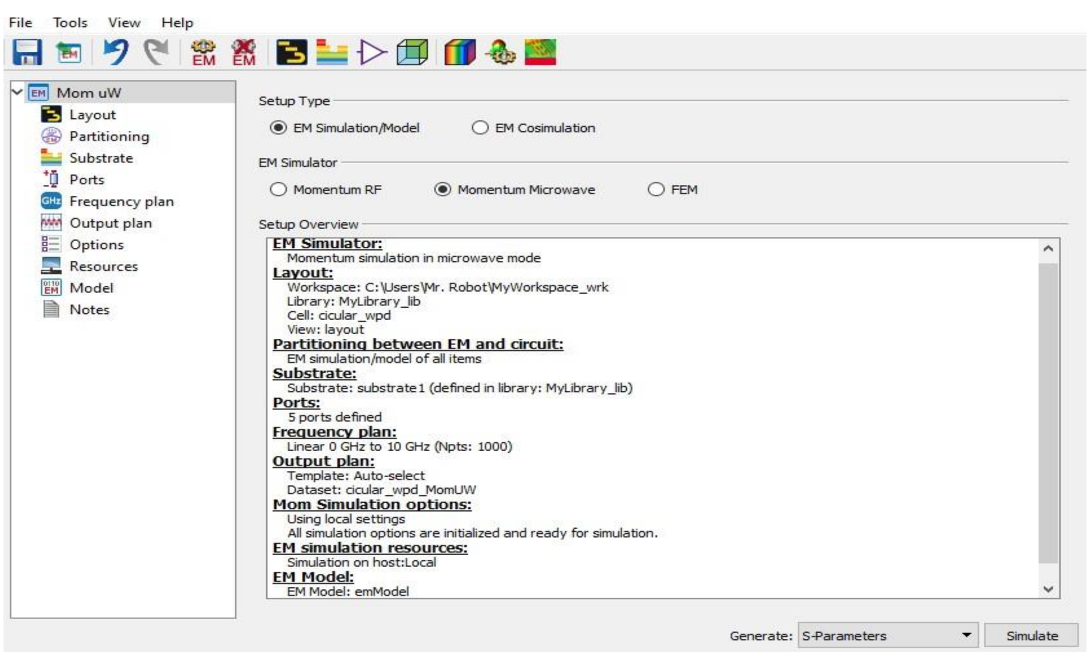


Figure 3.4: EM Simulation Setup Window in ADS

Chapter 4

4.1 Power Dividers

The passive devices like power dividers are used in many applications for power division and they may include lumped or distributed elements. The most basic functionality of a power divider is to divide the input signal into two or more output signals. Power dividers have the ability to divide the power equally and unequally. A power divider when used in reverse, can function as a power combiner. It is ideally lossless. Different types of power dividers are discussed in detail in further sections. A simple representation of a power divider and combiner is shown below in Figure 4.1.

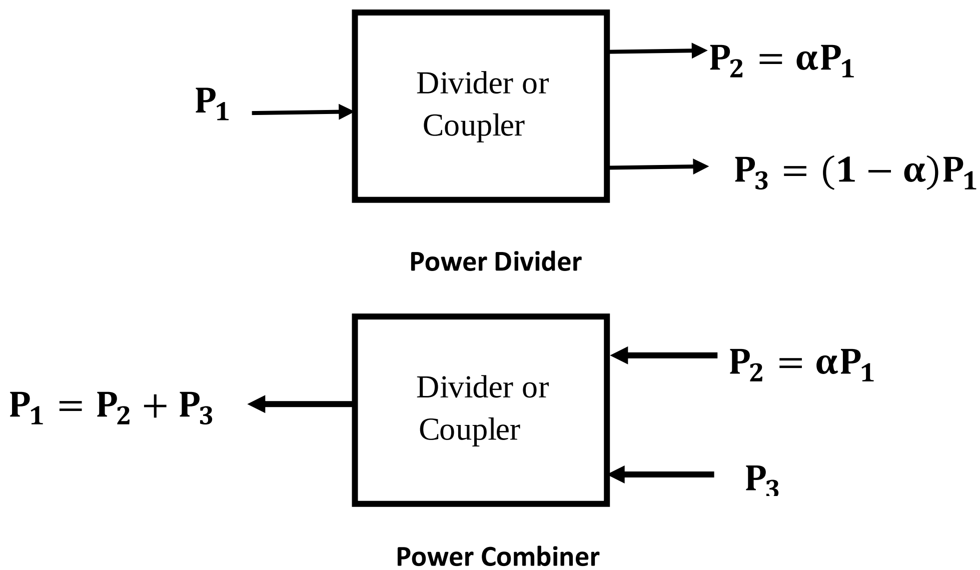


Figure 4.1: Diagram of Power Divider & Combiner

4.2 The Quadrature 90° Hybrid

Quadrature 90° Hybrid is a four port network that can equally divide the power between the output ports with a phase difference of 90°. It is a lossless and reciprocal network. There are four transmission lines that have the length of $\lambda/4$. Two of these transmission lines have the characteristic impedance of $Z_o/\sqrt{2}$ and the other two have the characteristic impedance of Z_o. The Quadrature 90° Hybrid is highly symmetric so any of its ports can be used as an input port. The port adjacent to the input port is called isolated port which is always terminated with an impedance of Z_o. The other two ports are output ports and are called through port and coupled port. A Quadrature 90° Hybrid is shown below in Figure 4.2.

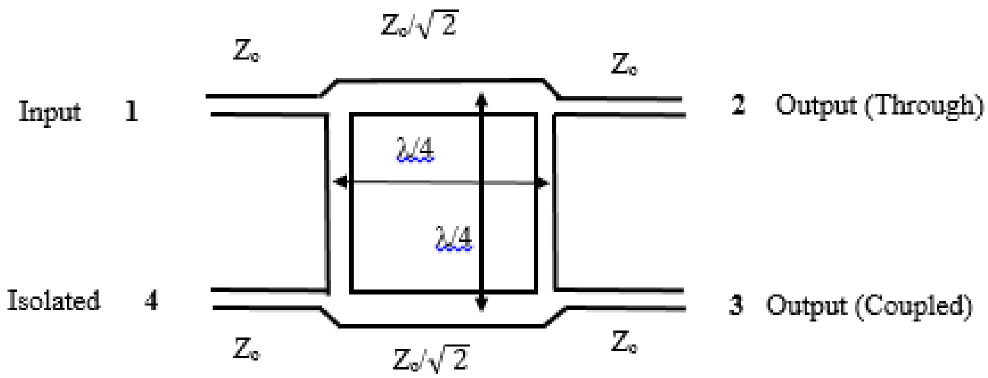


Figure 4.2: Quadrature 90° Hybrid

The scattering matrix of the Quadrature 90° Hybrid is shown below. From the matrix we can see that all ports are matched and the power entering from port one is equally divided between the output ports with a phase difference of 90°. Also no power is coupled to port 4.

$$[S] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix}$$

There are some parameters that must be taken into consideration while working on Quadrature 90° Hybrid and they are as follows:-

- Insertion Loss
- Directivity
- Coupling
- Isolation

Coupling:

The fraction of the input power that is delivered to the output port is called coupling factor. Mathematically it is written as [11],

$$\text{Coupling} = C = 10^* \log \frac{P_1}{P_3} \text{ dB}$$

Directivity:

Directivity is the ability of the coupler to isolate the coupled and uncoupled ports. Mathematically it is written as [11],

$$\text{Directivity} = D = 10^* \log \frac{P_3}{P_4} = 20 \log \frac{\beta}{|S_{14}|} \text{ dB}$$

Isolation:

Isolation is the measure of the input power that is transferred to the isolated port (uncoupled port). Mathematically it is written as:

$$\text{Isolation} = I = 10^* \log \frac{P_1}{P_4} = -20 \log \frac{\beta}{|S_{14}|} \text{ dB}$$

Insertion Loss:

Insertion loss is the fraction of the input power that is delivered to the through port. Mathematically it is written as:-

$$\text{Insertion Loss} = I = 10^* \log \frac{P_1}{P_2} \text{ dB}$$

The relation between I, D & C is shown as I (dB) = D (dB) + C (dB). Directivity (D) and coupling (C) are both expressed in decibels (dBs) [11].

For the design of Quadrature 90° Hybrid the mathematical equations mentioned in [11] were studied. Then the lengths and widths of transmission lines were calculated using those same equations. These equations are mentioned below [11]:-

$$\mathbf{W} = \frac{8he^{A}}{e^{2A}-2} \qquad \textbf{For W} \leq \textbf{2h}$$

$$W = \frac{2h}{\pi}[B - 1 - (\ln 2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\{\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\}] \qquad \textbf{For W} > \textbf{2h}$$

Where **"h"** is the height of substrate & **"w"** is the width of microstripline.

$$A = \frac{Z_o}{60} * \sqrt{\frac{(\varepsilon_r+1)}{2}} + \frac{(\varepsilon_r-1)}{(\varepsilon_r+1)} * \left(0.23 + \frac{0.11}{\varepsilon_r}\right) \;\&\; B = \left(\frac{377*\pi}{2Z_o*\sqrt{\varepsilon_r}}\right)$$

$$\varepsilon_{effective} = \frac{(\varepsilon_r+1)}{2} - \frac{(\varepsilon_r-1)}{2}\left(1 + \frac{12*d}{w}\right)^{-1/2}$$

$$\textbf{And} \qquad L = \lambda/4 = \frac{\lambda_o}{4\sqrt{\varepsilon_{effective}}}$$

We calculated the lengths and widths of the Z_0 = 50ohm T/L and the Z_0 = 35.35 ohm T/L using above mentioned formulas, and we then confirmed these calculations using the ADS Linecalc tool.

$$L_{50} = \left(\frac{\lambda}{4} - \frac{W_{35}}{2}\right) = 14.27\ mm$$

$$L_{35} = \left(\frac{\lambda}{4} - \frac{W_{35}}{2}\right) = 14.94\ mm$$

4.3 Quadrature Coupler Design, Simulation & Results

The Quadrature 90° Hybrid was initially designed on FR4 substrate with the dielectric constant of 4.6 and a loss tangent of 0.001. The height of substrate was 1.6mm and the operating frequency was 2.4GHz. The lengths and widths of the Quadrature Coupler were calculated using the formulas mentioned in section 4.2 and by using linecalc these lengths were confirmed in ADS.

4.3.1 Schematic & Layout Design

The schematic design of quadrature is shown in Figure 4.3.1a. MLIN & MTEE were used in the layout design that was made on ADS and it is shown below in Figure 4.3.1b.

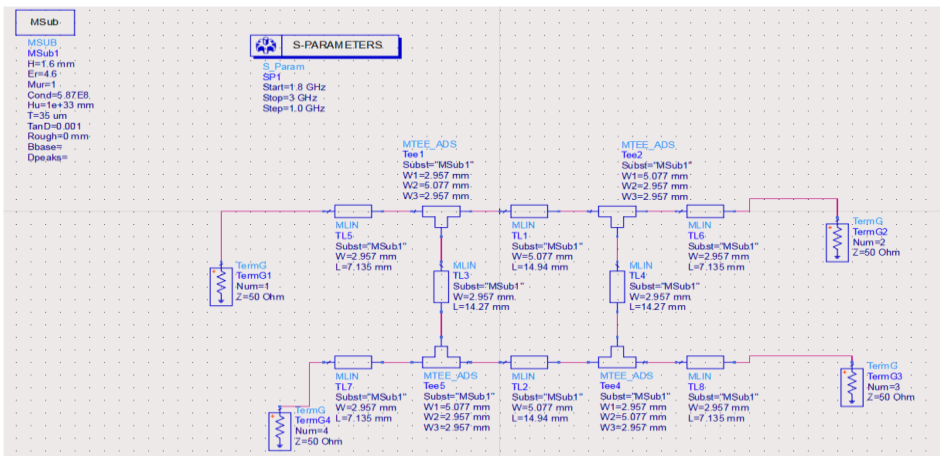


Figure 4.3.1a: Schematic Design of Quadrature Hybrid at 2.4 GHz in ADS

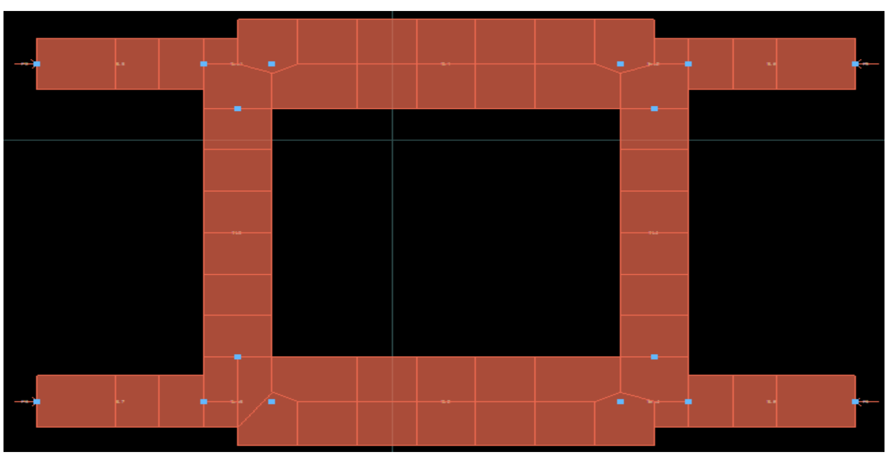


Figure 4.3.1b: Layout Design of Quadrature 90° Hybrid at 2.4 GHz in ADS

4.3.2 Momentum Setup Simulation Results

Figure 4.3.2a shows the visualization of Quadrature 90° Hybrid in ADS. The results for Quadrature 90° Hybrid are shown in Figure 4.3.2b. From the results we observed that all four ports of Quadrature 90° Hybrid are matched with $S_{11} = S_{22} = S_{33} = S_{44}$ = -48dB and the power that is being transmitted from port 1 to port 2 and port 3 is evenly divided with S_{21} = -3 dB and S_{31}= -3.195 dB with a 90° phase difference between them. A high degree of isolation is also observed between port 2 and port 3 with S_{23} = -30 dB and since port 4 is an isolated port the S_{41} = -30 dB which shows that no power is being transmitted to port 4.

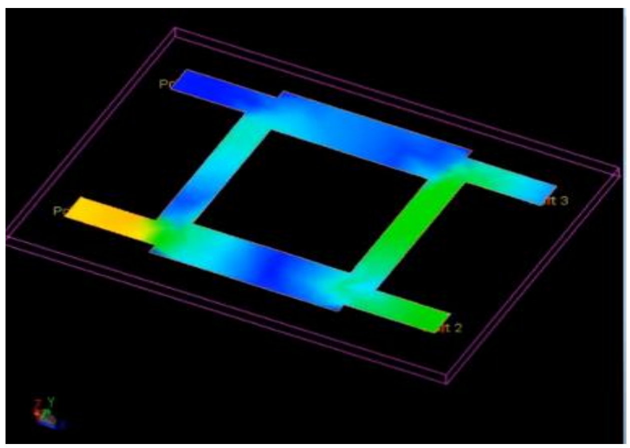


Figure 4.3.2a: Visualization of Quadrature Hybrid at 2.4 GHz in ADS

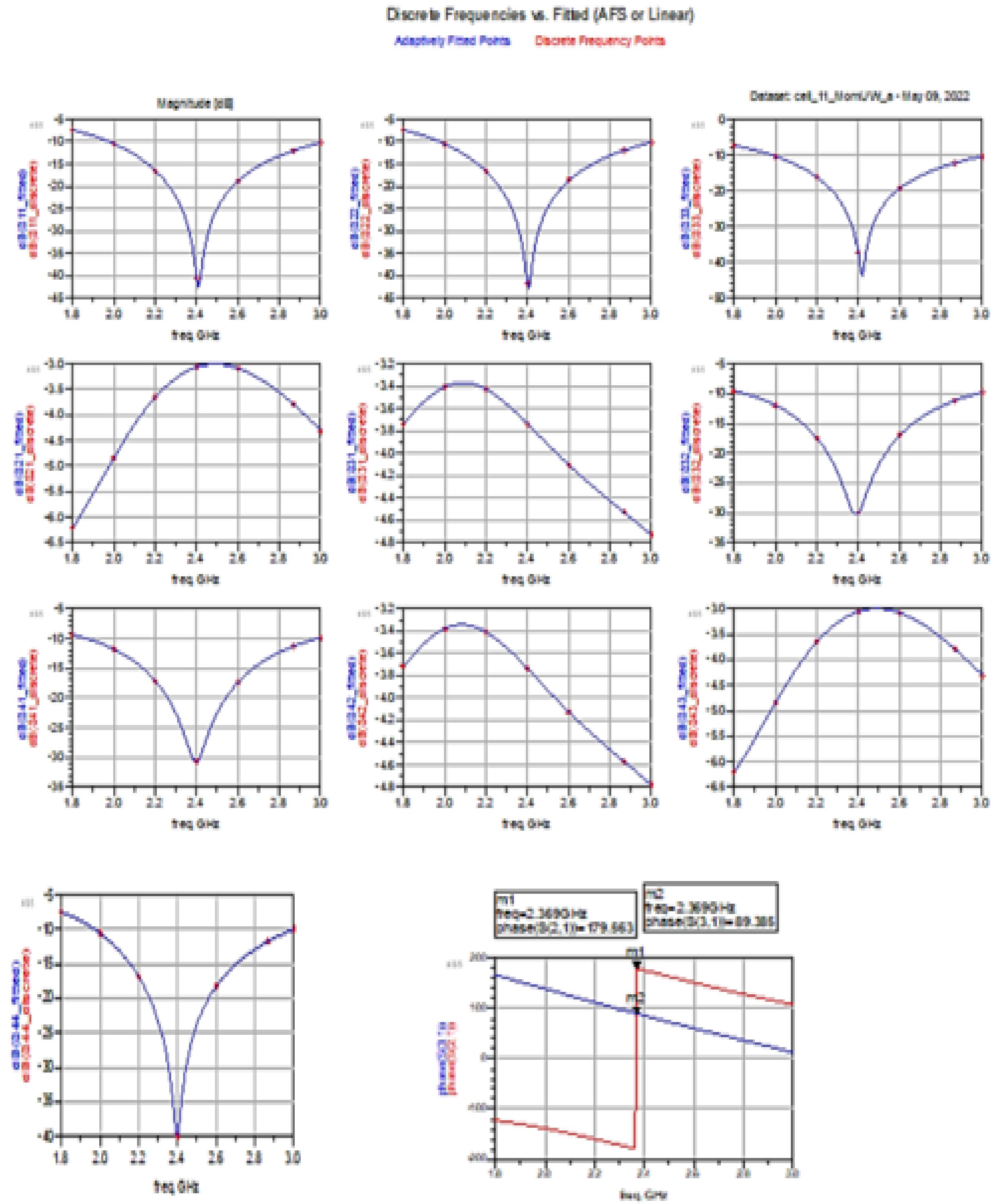


Figure 4.3.2b: S-parameters of Quadrature 90° Hybrid @ 2.4 GHz in ADS

4.4 Wilkinson Power Divider

The Three Port Network has a disadvantage that it cannot be lossless, reciprocal, and matched at all ports at the same time. A network can be designed if any one of these three characteristics is reduced. A Wilkinson power divider is such a network that has the lossless property when the output ports are matched, it means that only the reflected power from the output ports is dissipated. Resistor is used for the purpose of isolation between port 2 & port 3. The WPD (Wilkinson power divider) can be made with any power division ratio, but we will consider the case of equal division (3 dB). Figure 4.4.1 below shows a WPD [11].

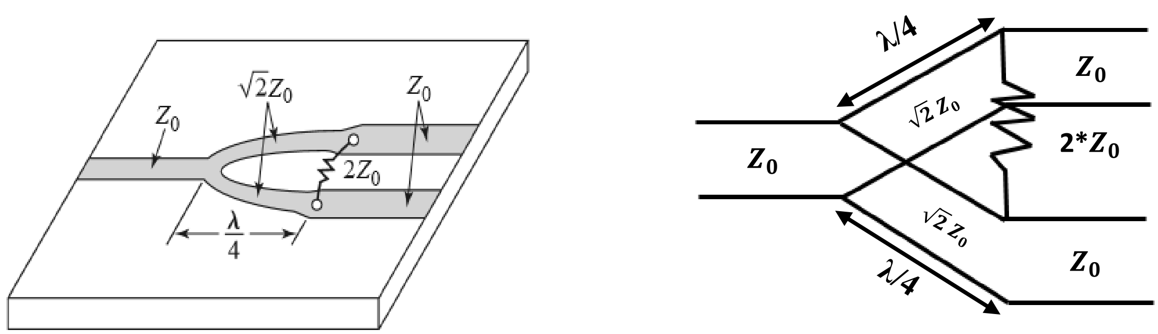


Figure 4.4.1: Wilkinson Power Divider [11]

4.4.1 3dB Wilkinson Power Divider Design, Simulation & Results

WPD was designed using a PTFE-ceramic substrate with a dielectric constant of 10, thickness of 0.635mm and loss tangent (tanδ) of 0.0010. It operates at a frequency of 6GHz. Zo of value 50Ω. Characteristic impedance of the quarter wave T/L is $\sqrt{2}$ ∗Zo=70.7 Ω.

4.4.2 3dB Wilkinson Power Divider Design, Simulation & Results

We had used the ADS Line calculator for the length and width parameters. The components that were used are MLIN, MTEE and MCURVE. As there was the resistor as a lumped element in the circuit so to accommodate that we performed co-simulation. Figures 4.4.2a and 4.4.2b shows the Wilkinson Power Divider schematic and layout, respectively.

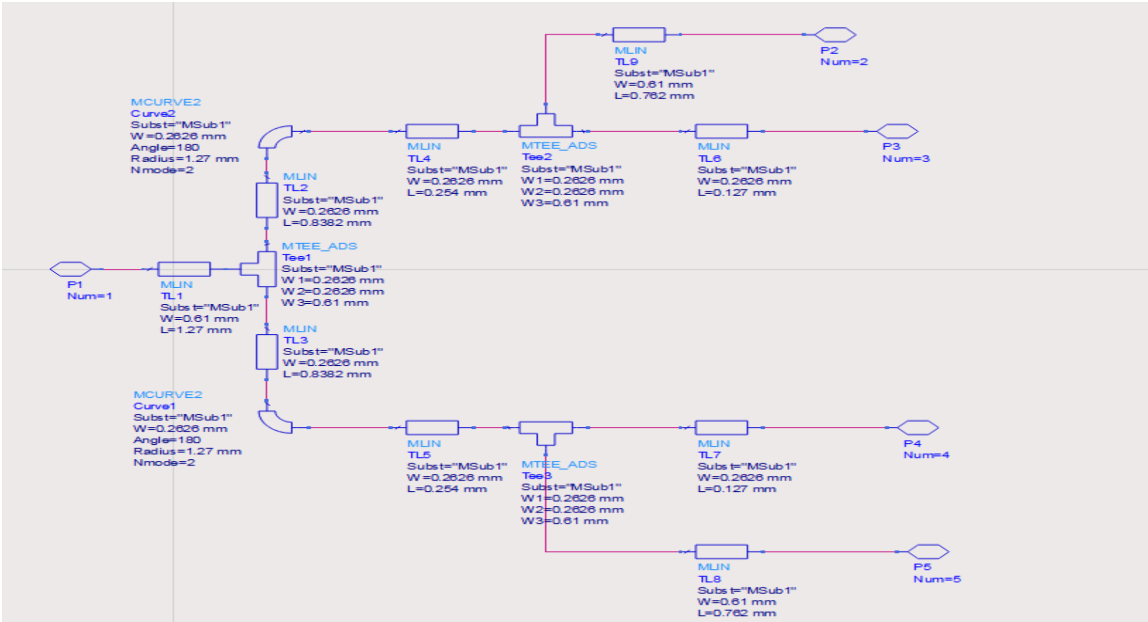


Figure 4.4.2a: Schematic of WPD in ADS [10]

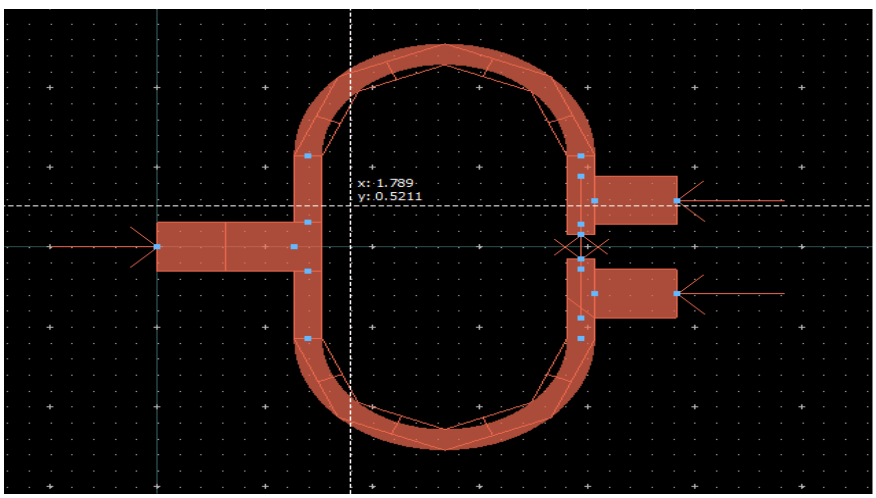


Figure 4.4.2b: Layout of WPD in ADS [10]

To perform co-simulation we need to create a symbol of this layout and use it for co-simulation so it has 5 ports. The 2 ports out of 5 are reserved for connecting the resistor. The results of this layout are shown below in Figure 4.4.2c.

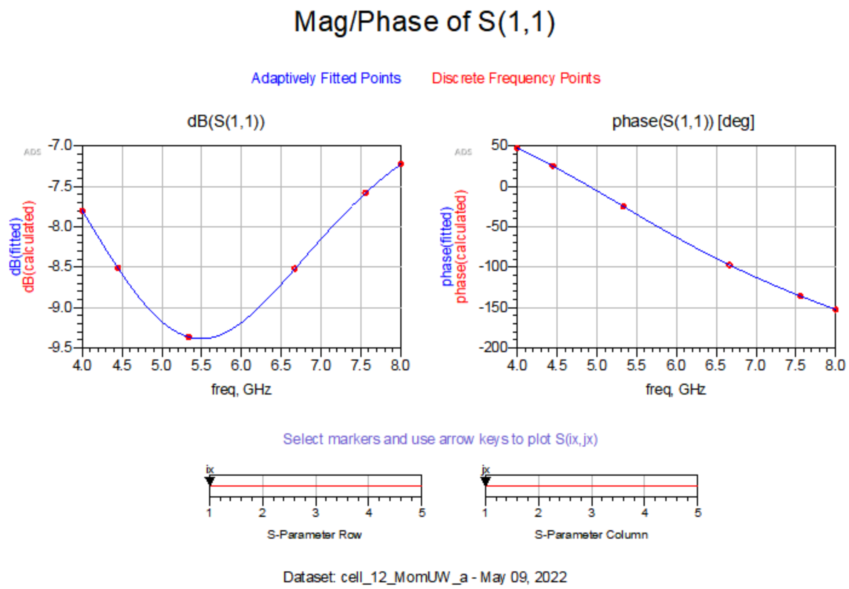


Figure 4.4.2c: Magnitude & Phase Plots in ADS

The Co-Simulation of WPD in ADS [10] is shown below in Figure 4.4.3.

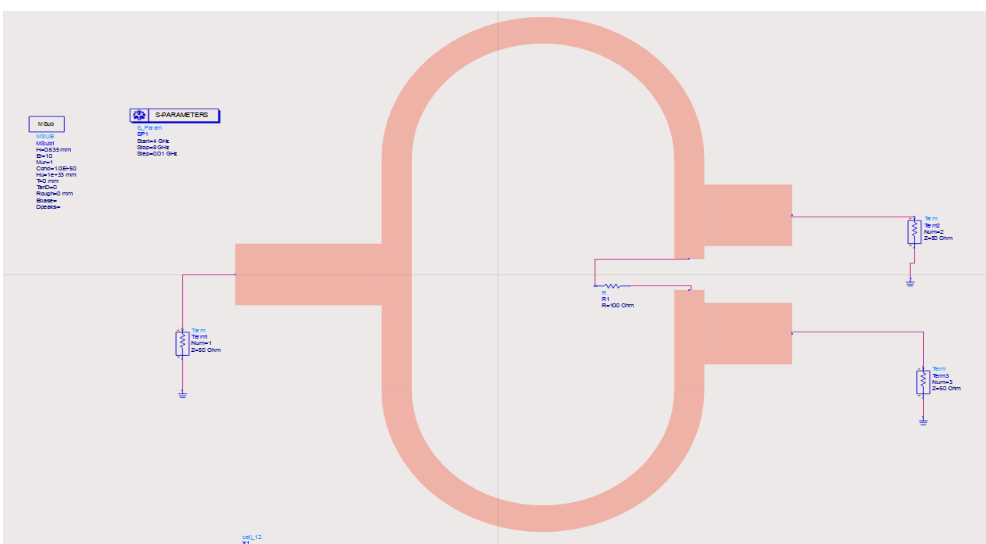


Figure 4.4.3a: Co-Simulation of WPD in ADS

Figure 4.4.3a displays the results of the co-simulated Wilkinson Power Divider.

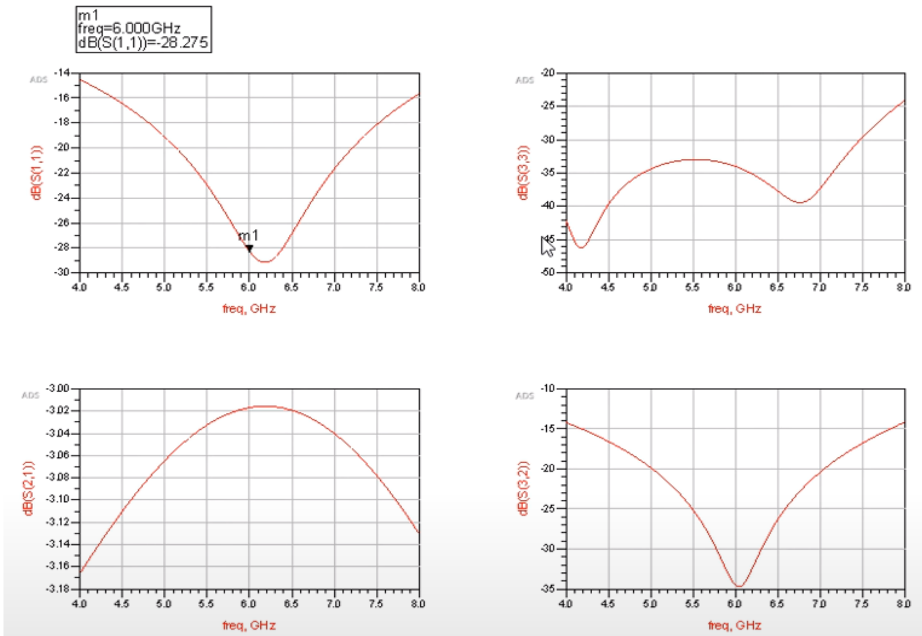


Figure 4.4.3b: S-parameters of Co-simulated WPD in ADS

The visualization of Wilkinson Power Divider can be seen in Figure 4.4.3c.

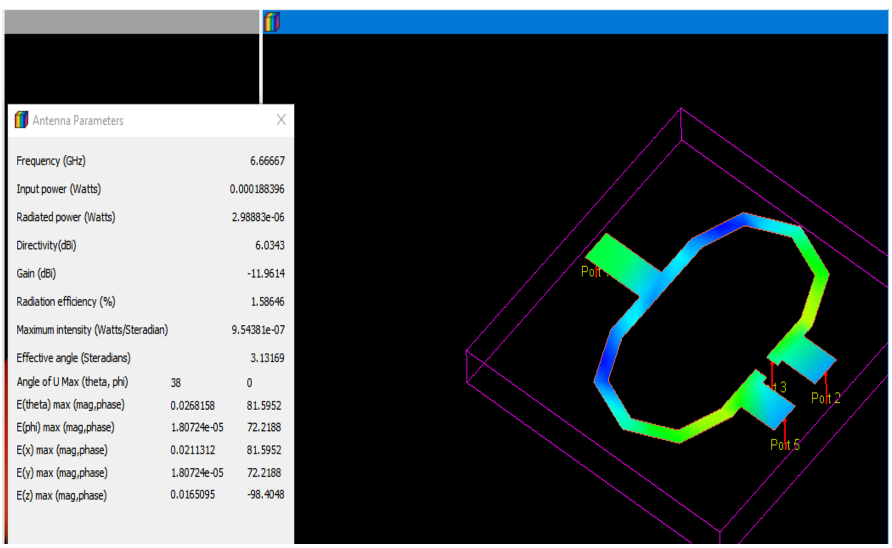


Figure 4.4.3c: WPD visualization in ADS

Comments on Results:-

From S-Parameter plots shown in Figure 4.4.3b we deduced that port is well matched (S_{11} = -28.75 dB), whereas the insertion loss is close to the expected value of 3 dB (S_{21} = -3.02 dB). Unequal power division can also be achieved using the Wilkinson Power Divider.

4.5 Coupled Lines

When two transmission lines are close together such that their power is transferred from one transmission line to the other transmission line then those lines are called Coupled Lines. The topologies of the associated transmission lines determine how various microwave devices, such as directional couplers, filters, phase shifters, and matched networks, are designed. There are three methods for analyzing planar interconnected transmission lines that are Even–odd mode analysis, coupled transmission line equations, and coupled-mode analysis. Moreover there are three different ways in which a line can be coupled. They are shown in Figure 4.5.1a.

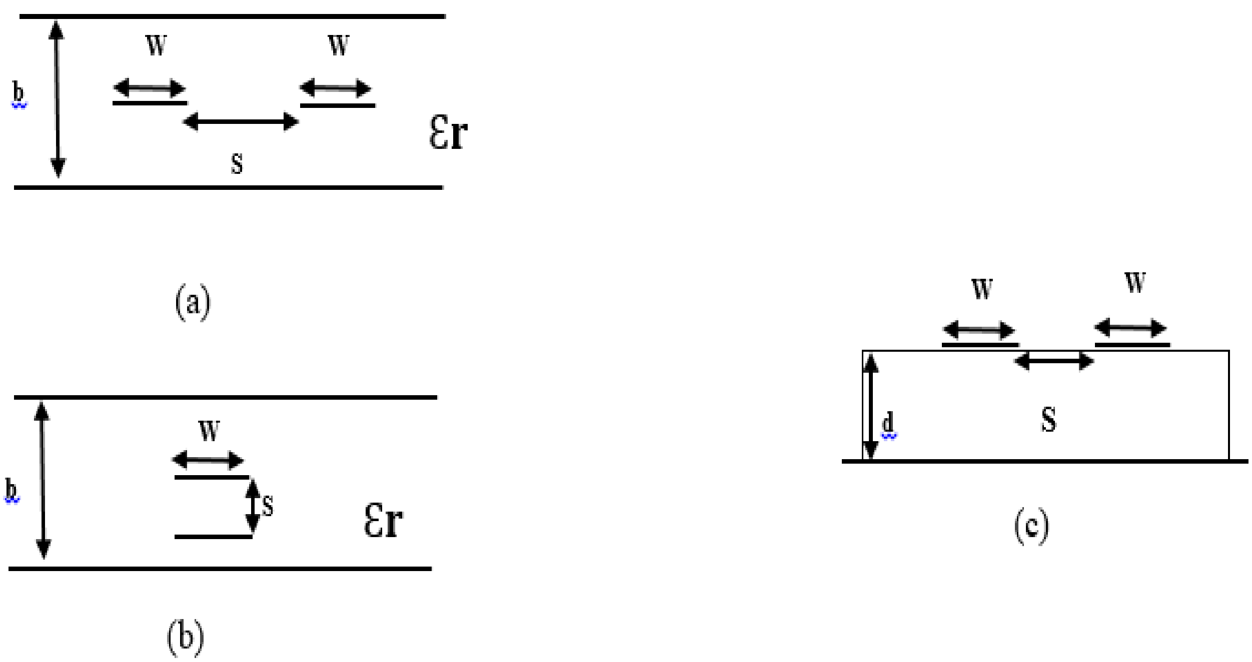


Figure 4.5.1: (a) Edge coupled (b) Broad side coupled (c) Microstrip coupled [10]

We find that these transmission lines are capacitive coupled as shown in the Figure 4.5.1b [12].

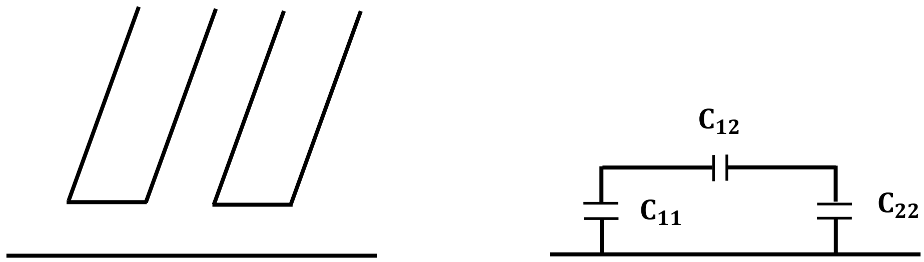


Figure 4.5.1b: Capacitive Equivalent Network and Coupled Transmission Lines [12]

If the two T/L are the same, the plane of symmetry exists, and we can analyze it using the even/odd analysis as shown in Figure 4.5.2a below taken from [12].

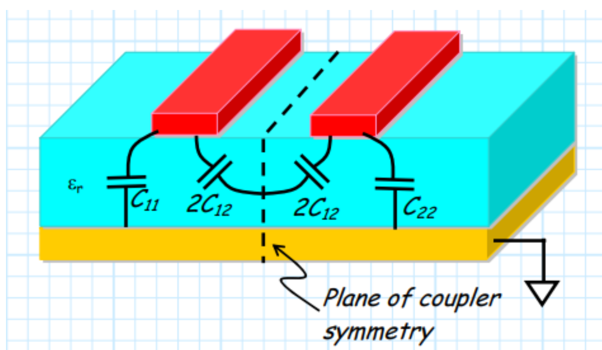


Figure 4.5.2: C_{12} is divided into two parts, each of which has the value 2 C_{12} [12]

Odd Mode

When the two incident waves are of equal magnitude but are 180° out of phase, a virtual ground plane is created at the plane of circuit symmetry and it can be seen in Figure 4.5.3a [12].

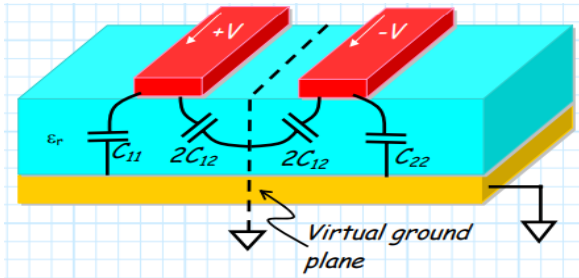


Figure 4.5.3a: Virtual Ground Plane Created [12]

Each transmission line's capacitance per unit length in the odd mode will be

$$C_0 = C_{11}+2C_{12} = C_{22} + 2\,C_{12}$$

Characteristic impedance becomes

$$Z_o{}^{o} = \sqrt{L/C_o}$$

Even Mode

As shown in Figure 4.5.3b virtual open plane is created at the plane of circuit symmetry when the two incident waves are equal in magnitude and phase [12].

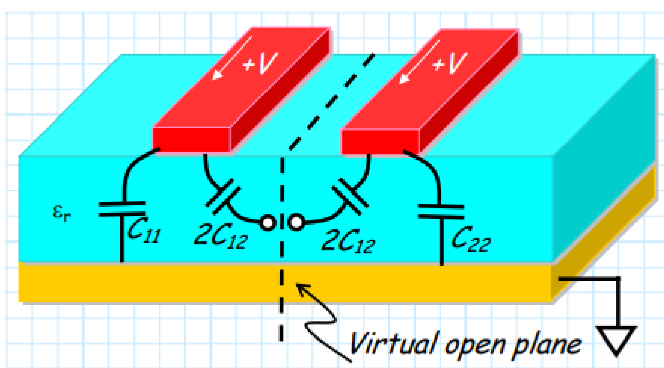


Figure 4.5.3b: Virtual Open Plane Created [12]

As we can see from Figure 4.5.3b [12], the two C_{12} capacitors have been "disconnected" and each transmission line's capacitance per unit length is now in the even mode which is written as $C_e = C_{11} = C_{22}$

The characteristic impedance becomes $Z_o{}^e = \sqrt{L/C_e}$

In order to find the length, width and the separation between the T/L of the coupled lines, the equations mentioned in [11] were followed. MATLAB was used for coupled line calculations and the code can be seen from Figure 4.5.4. It should be noted that initial calculations were done before using this code.

```
clear all, close all;
syms w s
g=cosh((pi*s)/2); % where s= s/h
d=cosh(pi*w+(pi*s)/2); % where w=w/h and s =s/h
e= 1+(2.23)/2;
eqn1=0.8805 == (2/pi)*acosh((2*d-g+1)/(g+1));
eq2=3.14 ==(2/pi)*acosh((2*d-g-1)/(g-1))+ (4/(pi*e)) *acosh(1+(2*w)/s) ;

eqns=[0.8805 == (2/pi)*acosh((2*d-g+1)/(g+1)),3.14 ==(2/pi)*acosh((2*d-g-1)/(g-1))+ (4/(pi*e)) *acosh(1+(2*w)/s)];
S= vpasolve(eqns,[w,s]);
x=S.w
y=S.s
```

```
x =

-0.29824183435129313403083551782559


y =

-0.36918142765296015381779635691076
```

Published with MATLAB® R2021a

Figure 4.5.4: MATLAB Code for Coupled Lines

Chapter 5

Goal:

The main objective of our project is to design a reconfigurable power divider that can operate in four different modes. The research paper that we followed was [1]. Firstly, we designed our reconfigurable power divider and the design specifications that we choose were those mentioned in [1]. After confirming the results of the research paper [1] we proceeded to redesign the power divider to our desired specifications, i.e. at a different operating frequency and on a different substrate. The parameters of our design are as follows: -

- Operating frequency = 1.8GHz
- Substrate: Rogers 4003C with dielectric constant of 3.55 and loss tangent of 0.0022
- Height of substrate = 20 mils

The main three components that our design was comprised of were Quadrature 90° Hybrid, Microstrip Coupled Lines and RF switches (the switches are modeled through vias). We designed our own Quadrature Hybrid and Microstrip Coupled Lines on the above-mentioned parameters. The detailed analysis of the designs is mentioned below.

5.1 Quadrature 90° Hybrid

As discussed earlier in section 4.1 Quadrature 90° Hybrid is a four-port network that can divide the power equally between the coupled and through port with a 90° of phase shift.

The Quadrature 90° Hybrid was designed on Rogers 4003C substrate with the dielectric constant of 3.55 and a loss tangent of 0.0022. The operating frequency was 1.8GHz. The lengths and widths of the Quadrature Coupler can be calculated using the formulas mentioned in section 3.4 but for ease of calculation we can use software like line-calc and TX-line calculator. In our case we used TX-line calculator.

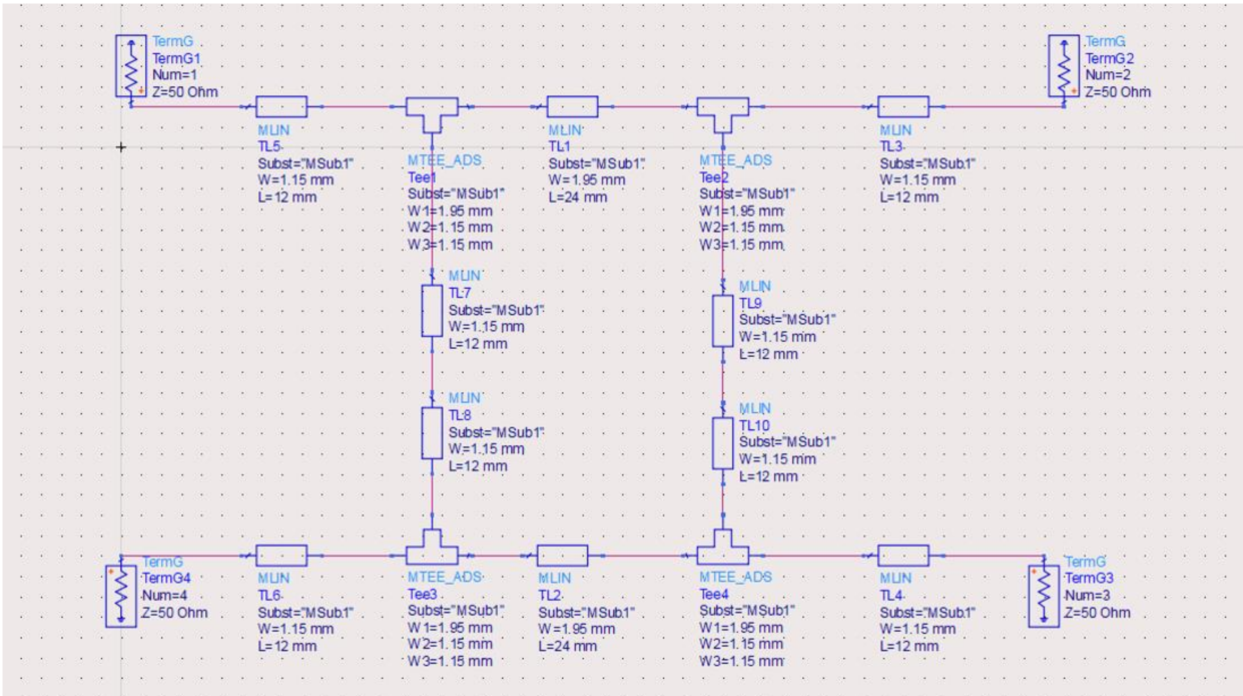


Figure 5.1.1a: Schematic of Quadrature 90° Hybrid in ADS

The circuit was designed and simulated on Keysight ADS [10]. The lengths and widths of all TL-lines in the Quadrature 90° Hybrid are optimized and can be seen in Figure 5.1.1a. It is important to set the widths of the T-junctions appropriately. We can use ADS Help for clarity. The specifications of the substrate and the S-parameters can be seen in Figure 5.1.1b.

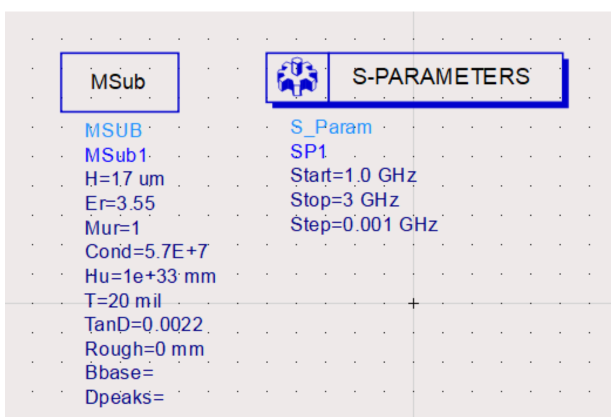


Figure 5.1.1b: Substrate parameters of Quad Mode Reconfigurable Power Divider in ADS

After designing and optimizing the Quadrature 90° Hybrid on schematic we can proceed towards its implementation on Layout.

The first step for Layout simulations is to define the substrate. In order to do that open the Substrate Editor and go to “add from database” and choose the required substrate from the library. If it is not present there, then we can define our own substrate by selecting “add dielectric”. In our case we used a predefined substrate from the library named Rogers_RO4003 with dielectric constant of 3.55 and loss tangent of 0.0022.

After selecting the substrate, we have to include the height of the substrate which in our case was 20 mils. The height of conductor layer is also included. It should be 17 um or 35 um because only these heights are applicable in fabrication. The complete substrate design is shown in Figure 5.1.2a.

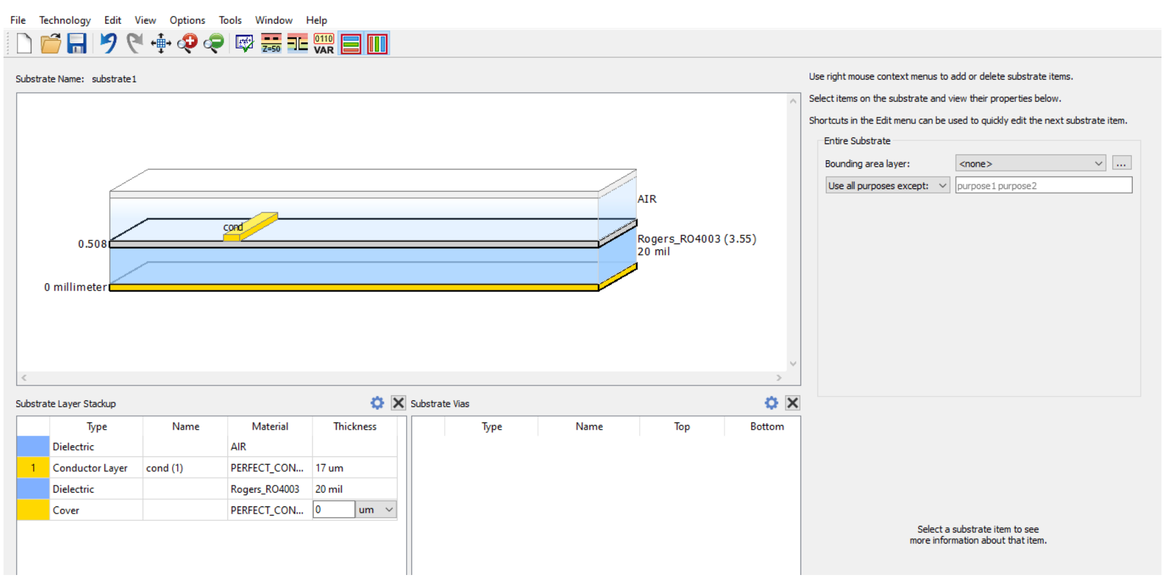


Figure 5.1.2a: Substrate Selection in ADS [10]

After selecting the substrate, we moved towards the design of the Quadrature 90° Hybrid on Layout. Four T-junctions were used and the lengths and widths of all TL-lines are the ones that were used in the optimized schematic design. This can be seen in Figure 5.1.1a. It should be noted that while simulating the design in schematic we used the component "TermG" where there is a port but for layout simulations "PIN/PORT" is used. The layout design can be seen in Figure 5.1.2b.

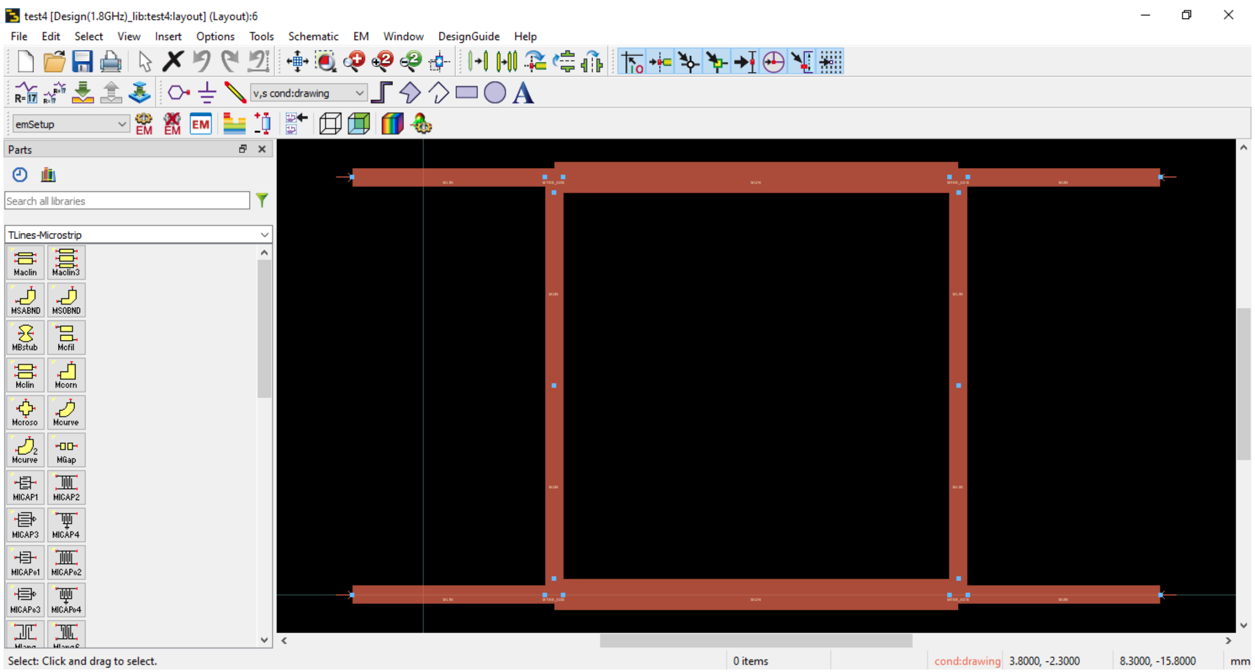


Figure 5.1.2b: Layout of Quad Mode Quadrature Hybrid in ADS

The results for Quadrature 90° Hybrid are shown in Figure 5.1.2c. From the results we observed that all four ports of Quadrature 90° Hybrid are matched with $S_{11} = S_{22} = S_{33} = S_{44} =$ -48dB and the power that is being transmitted from port 1 to port 2 and port 3 is evenly divided with $S_{21} =$ -2.938 dB and $S_{31} =$ -3.195 dB with a 90° phase difference between them. A high degree of isolation is also observed between port 2 and port 3 with $S_{23} =$ -46.678 dB and since port 4 is an isolated port the $S_{41} =$ -46.538 dB which shows that no power is being transmitted to port 4.

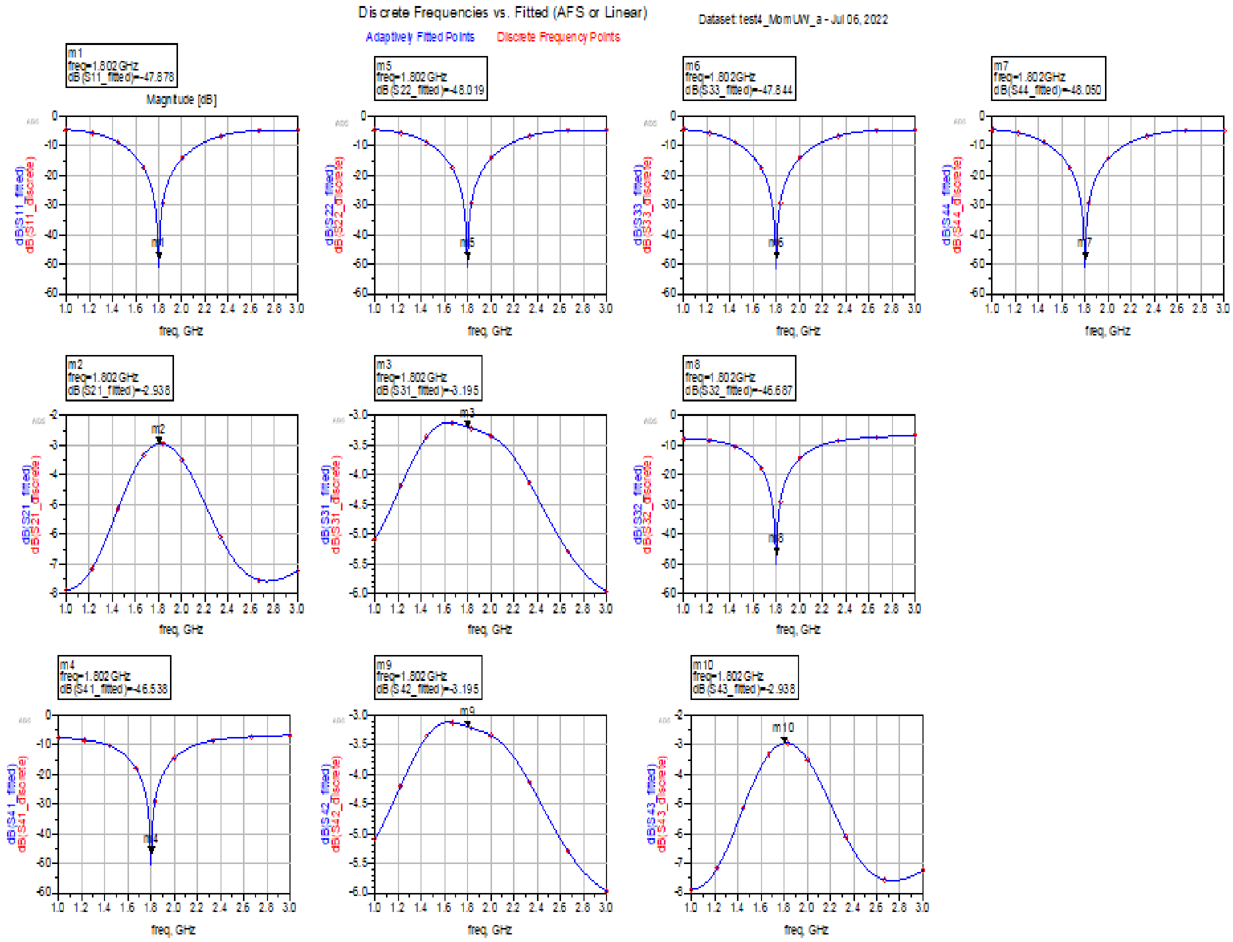


Figure 5.1.2c: S-parameters of Quadrature 90° Hybrid @ 1.8GHz in ADS

5.2 Design of Coupled Lines

As discussed previously in section 4.5, when two unshielded transmission lines are in close proximity then the power from one line can be coupled to the other due to the interactions of the electromagnetic fields. These lines are called Coupled Transmission Lines.

The coupled lines were also designed on Rogers 4003C substrate with dielectric constant of 3.55 and a loss tangent of 0.0022 with a height of 20 mils and the height of conductor was 17um. Initially for the design of coupled lines the procedure followed in [4] was used and later on the line-calc was used for their calculations. The design specifications for the coupled lines that we used are as follows:-

- Z $_{even}$ = 110 Ohm
- Z $_{odd}$ = 20 Ohm
- Coupling Coefficient = -3.19

The theoretical analysis for the width of coupled lines, the separation between them and their lengths was also done and the procedure that we followed was the same as mentioned in section 3.6. Figure 5.2.1 shows the coupled line calculations that were done on line-calc.

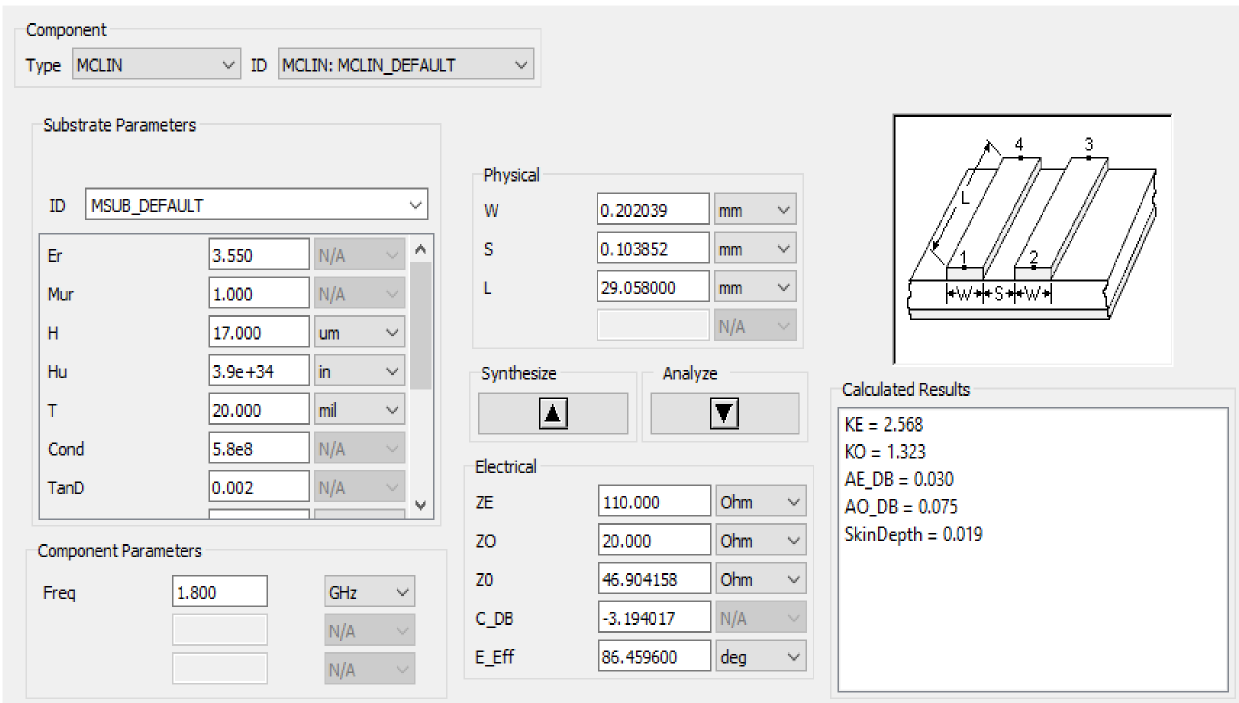


Figure 5.2.1: Parameters of Coupled Lines in ADS

The physical parameters for our coupled lines that we got using line-calc are as follows: -

- Width of coupled lines = 0.2mm
- Separation between the coupled lines = 0.1mm
- Length of coupled lines = 29mm

After determining the parameters of Coupled Lines, they were designed on ADS layout and their results were simulated. The coupled line at the top and bottom are labeled as coupled line 2 and coupled line 1 respectively. The complete design and the simulation results are shown in Figure 5.2.2a and Figure 5.2.2b respectively.

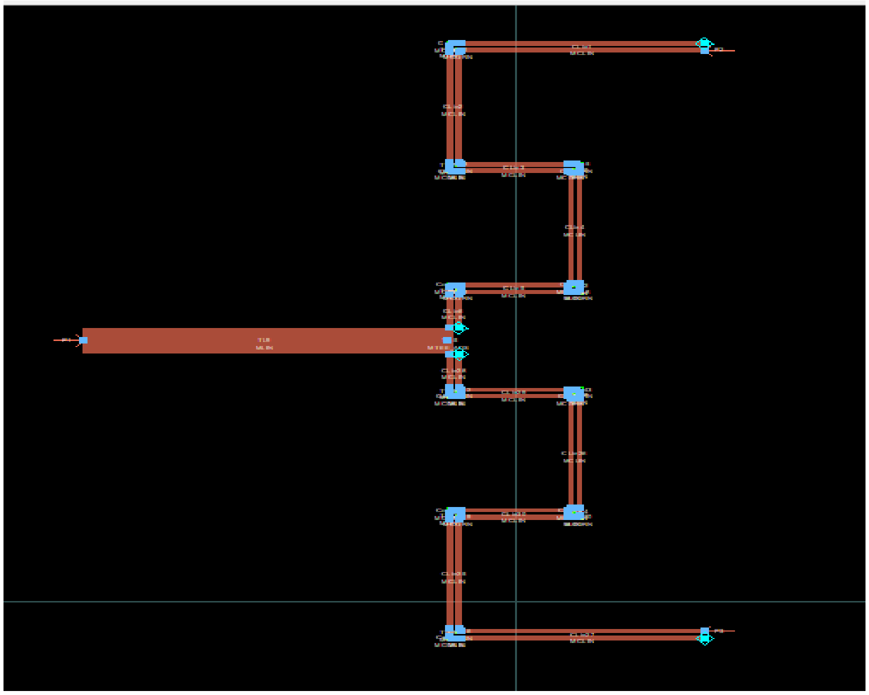


Figure 5.2.2a: Layout of Coupled Lines Converting the Two inputs of Quad Mode Quadrature Hybrid into single input [10]

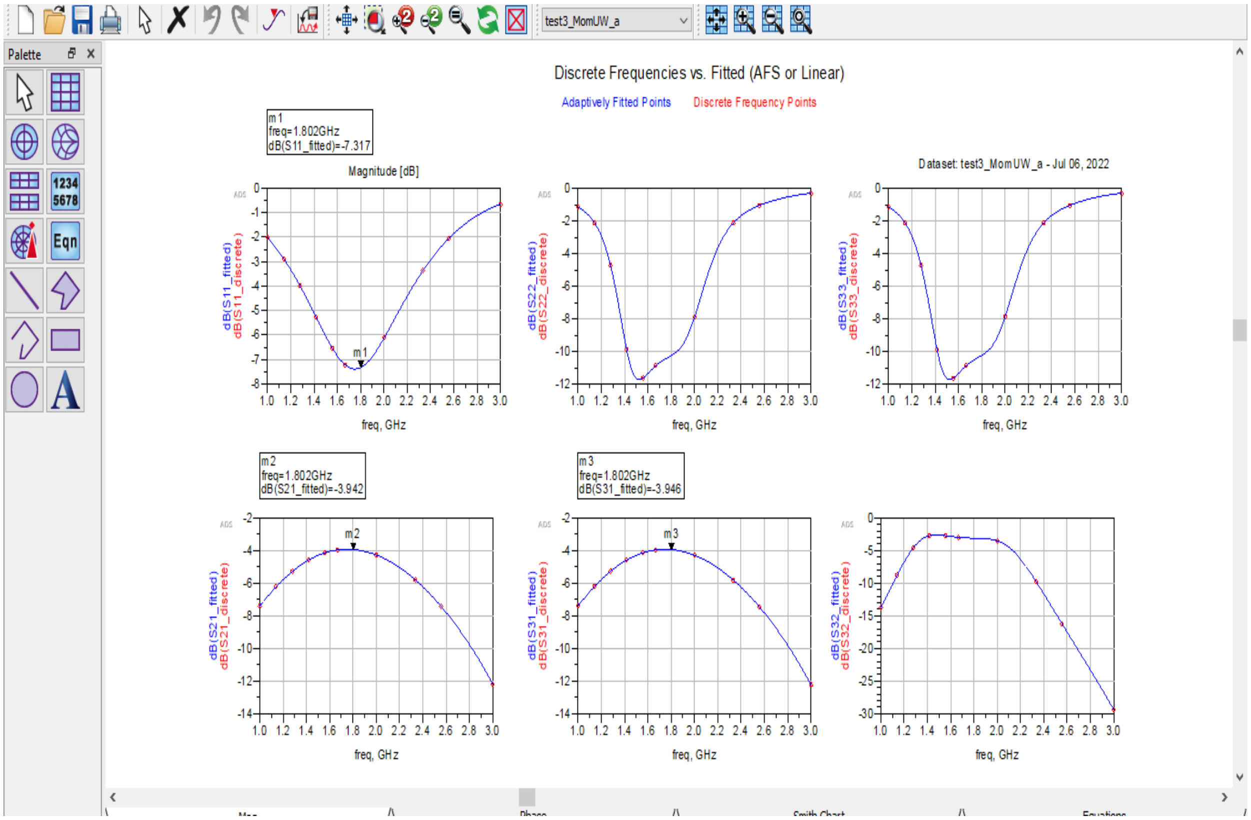


Figure 5.2.2b: S-Parameters of Coupled Lines in ADS

5.3 Microstrip Quad Mode Reconfigurable Power Divider

As always, the first step in the layout design is defining the substrate. See section 5.1 on how to define a substrate in ADS. The parameters that we kept for our substrate are the same as those that were mentioned in section 5.1. Additionally, a conductor via was added while defining the substrate. To add the conductor via in the substrate right click on the dielectric portion of the substrate and select “Map Conductor Via”. The complete substrate specifications can be seen in Figure 5.3.1.

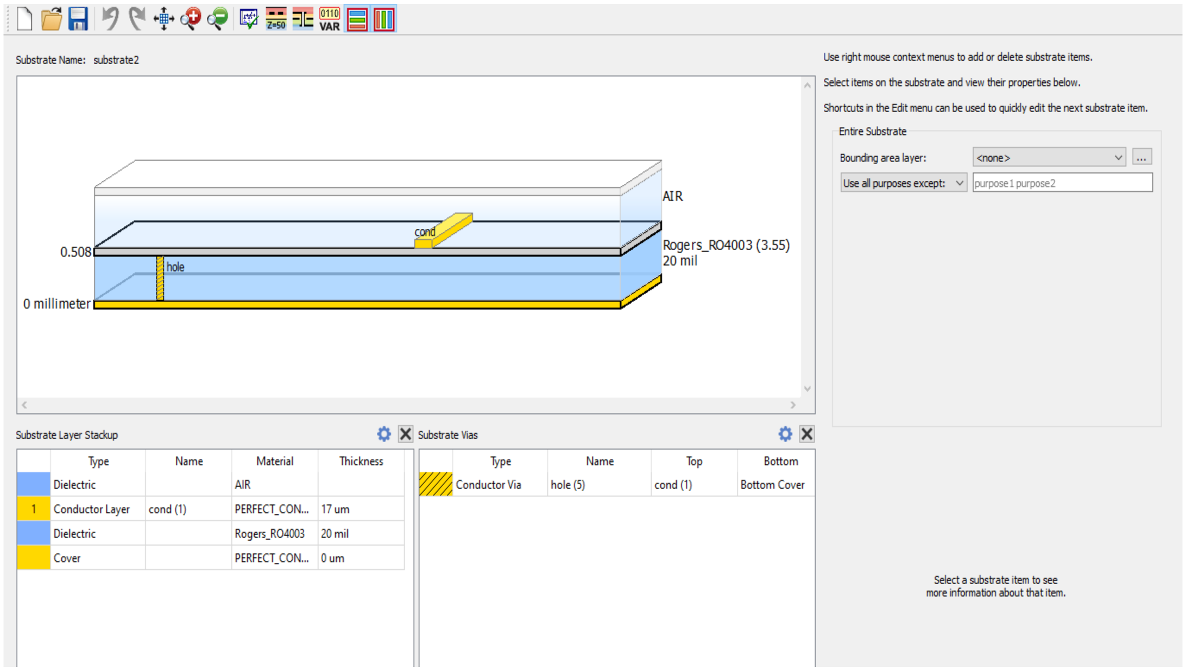


Figure 5.3.1: Substrate of Reconfigurable Power Divider in ADS

Since the design of Quadrature 90° Hybrid and the Coupled Line is complete and their results are verified, now we moved towards the next step that is the complete design of Microstrip Quad Mode Reconfigurable Power Divider.

In order to join the Quadrature 90° Hybrid with the Coupled line structure, the port extension of port 1 and port 4 of Quadrature 90° Hybrid was removed and the coupled line structure was attached there. It should be noted that the main characteristics of the Quadrature 90° Hybrid will not change by removing the port extensions.

Afterwards the implementation of the switches was done and as discussed previously, the switches were modeled as through-hole vias. So in the place of each switch's ON state a through-hole via was placed. Since we had four different operations, accordingly four designs were made having same circuit design but different via placement. The complete design and the placement of switches is shown in Figure 5.3.2

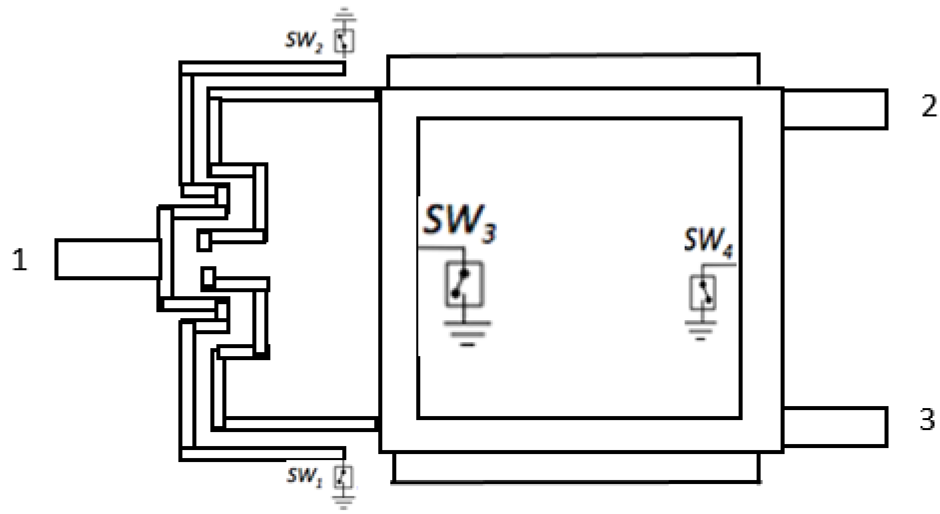


Figure 5.3.2: Schematic Showing Switch Positions of Reconfigurable Power Divider

From Figure 5.3.2 it should be noted that the input is from port 1 and the output is taken from port 2 and port 3. The four modes of operation are labeled as (m: n) where m and n are outputs at port 2 and port 3 respectively. The four operating modes are totally directing the power into one of the two output ports or 3dB equal power division between the two output ports with a +90° or -90° phase difference. The modes are interchanged by different configuration of the switches and the switches configuration for each mode is given in Table I. It should be remembered that for our design the ON state of switch is modeled by a through-hole via.

Table I: Modes & States of Switches

Mode(m: n)	SW_1	SW_2	SW_3	SW_4
(1 : 0)	ON	OFF	ON	ON
(0 : 1)	OFF	ON	ON	ON
(1 : j)	ON	OFF	OFF	OFF
(j : 1)	OFF	ON	OFF	OFF

The Layout design of the reconfigured power divider is shown in Figure 5.3.3. It should be noted that there are no vias implemented on it yet. From Figure 5.3.2, it can be seen that there are two switches that are placed on the coupled lines and the other two switches are on Quadrature 90° Hybrid. So whenever the state of a switch is ON only then a through-hole via is placed on the circuit design. All four modes were simulated and their results were observed. They are discussed in detail below.

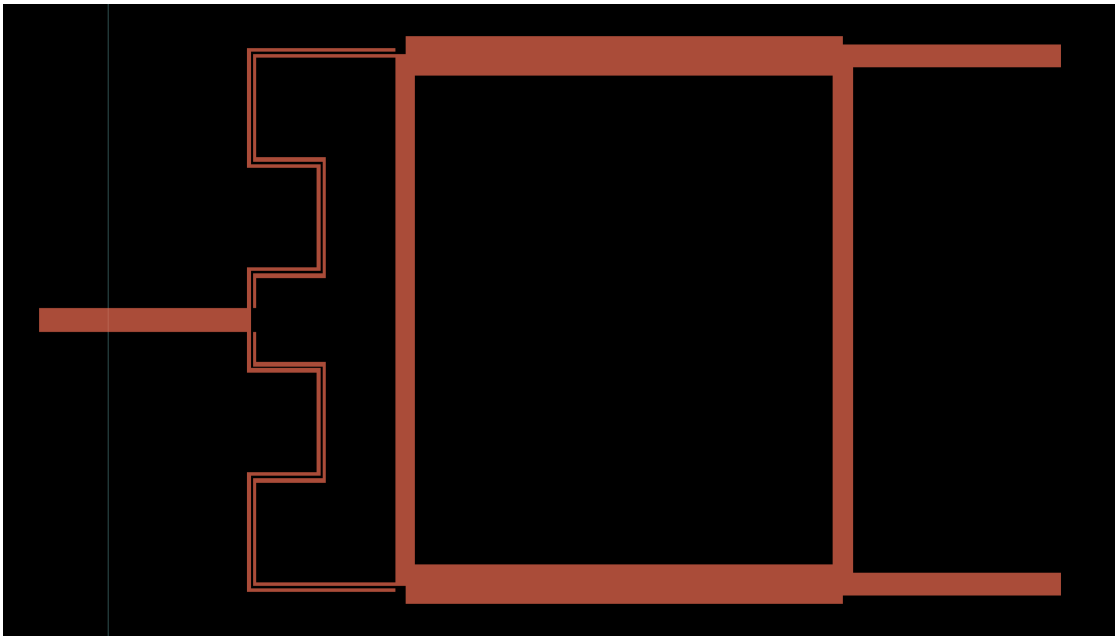


Figure 5.3.3: Quad Mode Reconfigurable Power Divider in ADS

5.3.1 Mode (0: 1)

When the circuit is operating in mode (0: 1) all the output power is transferred into port 3 while port 2 is completely isolated. To operate the circuit in this mode, switch 1 is turned OFF while all other switches are turned ON. To implement the switches ON state, we placed the through-hole vias in the place of switch 2, switch 3 and switch 4, as shown below in Figure 5.3.4a.

For Quadrature 90° Hybrid the through-hole vias are placed in the center of the λ/4 lines, with characteristic impedance of $Z_{o,}$ which then behave as short circuited λ/8 stubs. Then the input impedance for the Quadrature 90° Hybrid becomes Z_o which means it is matched.

For Coupled Lines the through-hole via is placed at the end of their output port of coupled line. Since switch 2 is turned ON the input impedance for coupled line 2 theoretically becomes infinity hence all the power is transferred to coupled line 1 as it is behaving as a normal transmission line.

Figure 5.3.4a shows the power divider operating in Mode (0: 1).

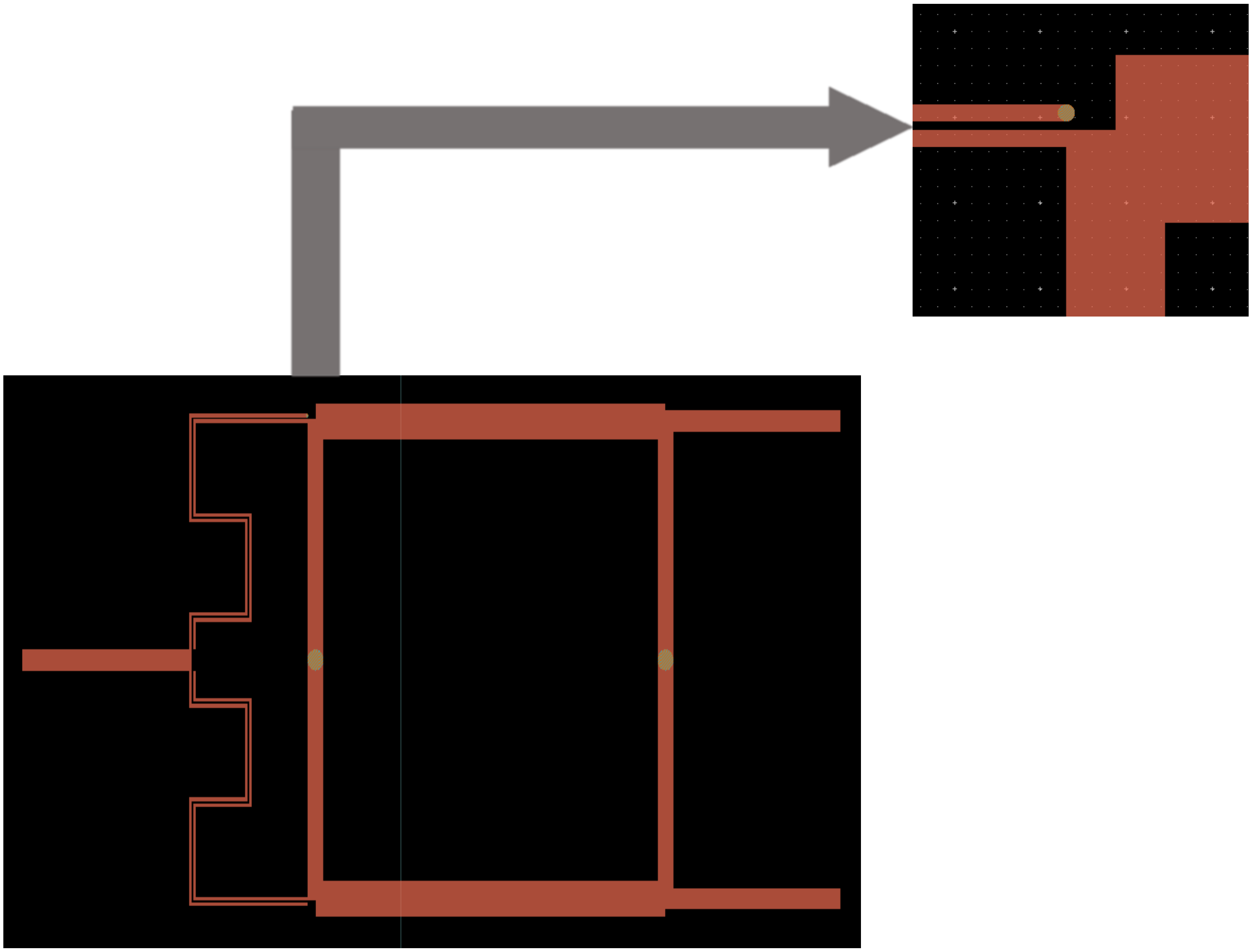


Figure 5.3.4a: Reconfigurable quadrature coupler operating in Mode (0: 1)

Simulation results for mode (0: 1) are shown in Figure 5.3.4b. The S-parameters that we got for this mode of operation were S_{11} = -22.988 dB, S_{31} = -0.144 dB and S_{21} = -27.263 dB. From these results we observe that almost all the power from port 1 is transferred to port 3 while no power is transmitted to port 2.

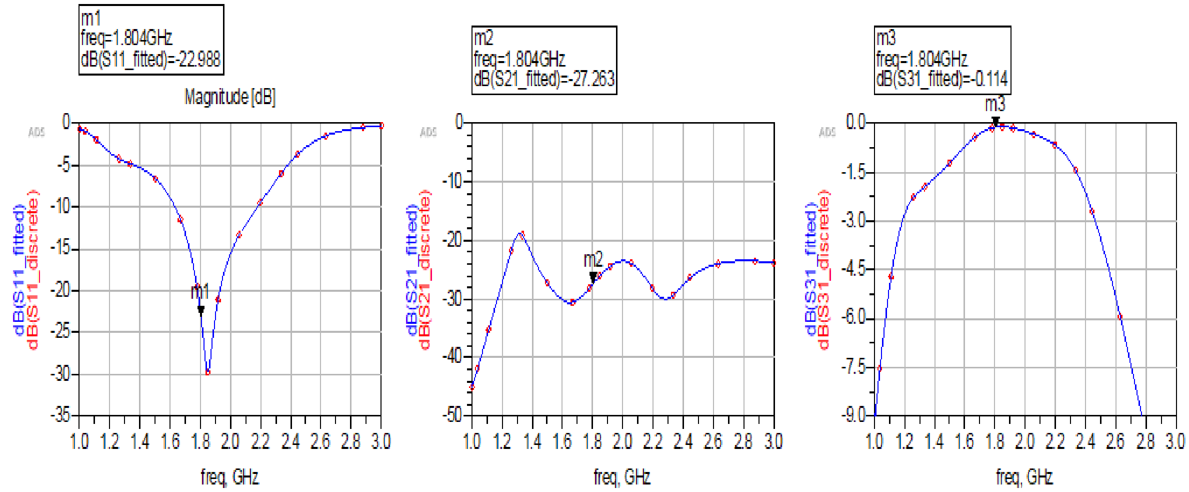


Figure 5.3.4b: Simulation Results of reconfigurable quadrature coupler operating in Mode (0: 1)

5.3.2 Mode (1: 0)

When the circuit is operating in mode (1: 0) all the output power is transferred to port 2 while port 3 is completely isolated. To operate the circuit in this mode, switch 2 is turned OFF while all other switches are turned ON. As discussed previously, to implement the ON state of switches, we placed the through-hole vias in the place of switch 1, switch 3 and switch 4.

For Quadrature 90° Hybrid the through-hole vias are placed in the center of the $\lambda/4$ lines, with characteristic impedance of Z_o, which then behave as short circuited $\lambda/8$ stubs. Then the input impedance for the Quadrature 90° Hybrid becomes Z_o which means it is matched.

For Coupled Lines the through-hole via is placed at the end of their output port of coupled line. Since switch 1 is turned ON the input impedance for coupled line 1 theoretically becomes infinity hence all the power is transferred to coupled line 2 as it is behaving as a normal transmission line.

Figure 5.3.5a shows the power divider operating in mode (1: 0).

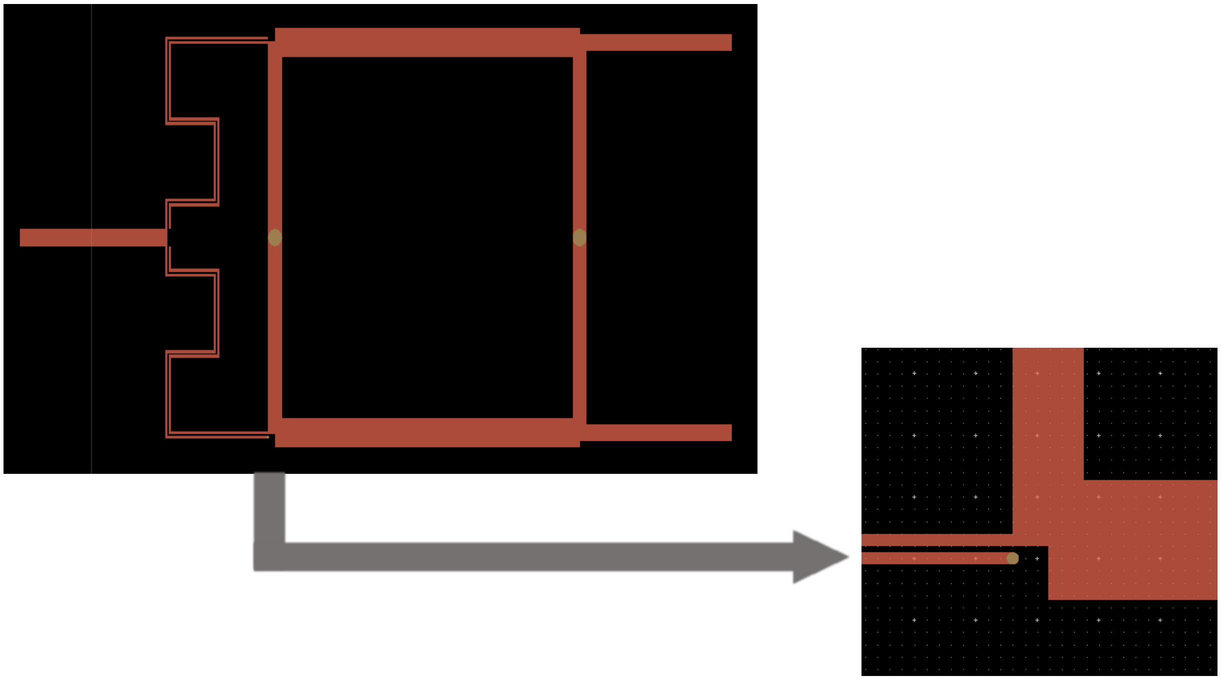


Figure 5.3.5a: Reconfigurable quadrature coupler operating in Mode (1: 0)

The simulation results are shown in Figure 5.3.5b. The S-parameters that we got for mode (1: 0) were S_{11} = -22.944dB, S_{21} = -0.144dB and S_{31} = -27.276dB. From these results we observe that all the power from port 1 is transferred to port 2 while no power is transmitted to port 3.

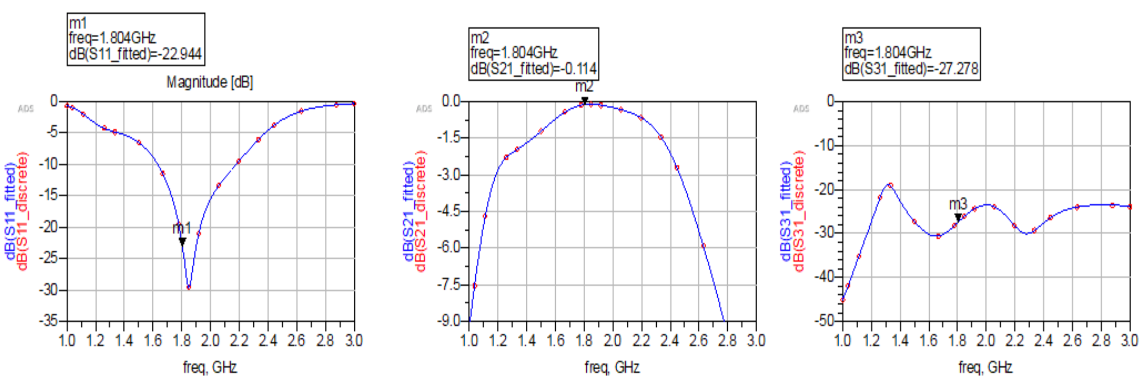


Figure 5.3.5b: Simulation Results of Reconfigurable Quadrature Coupler operating in Mode (1: 0)

5.3.3 Mode (1: j)

When the circuit is operating in mode (1: j), the input power is transferred to both of the output ports with equal power division moreover a phase difference of -90° is also observed and to operate the circuit in this mode, the only switch that is turned ON is switch 1 while the other three switches (switch 2, switch 3 and switch 4) are turned OFF hence in our circuit design we placed only one through-hole via and that is on coupled line 1.

Since there is no via placed on the Quadrature 90° Hybrid, there will be no change in its behavior and the through-hole via that is placed on the coupled line 1 will behave in exactly the same way as explained previously in section 5.3.2. Figure 5.3.6a shows the power divider operating in mode (1: j).

Simulation results for mode (1: j) are shown in Figure 5.3.6b. The S-parameters for mode (1: j) that we got were S_{11} = -24.522dB, S_{21} = -3.234dB and S_{31} = -2.967dB. From these results we observe that all the power from port 1 is almost equally divided between port 2 and port 3. From Figure 5.3.6c, we can also see the phase difference between the two output ports and that is -90.448°. It should be noted that while calculating the phase difference, the phase of S_{21} is kept first in the formula.

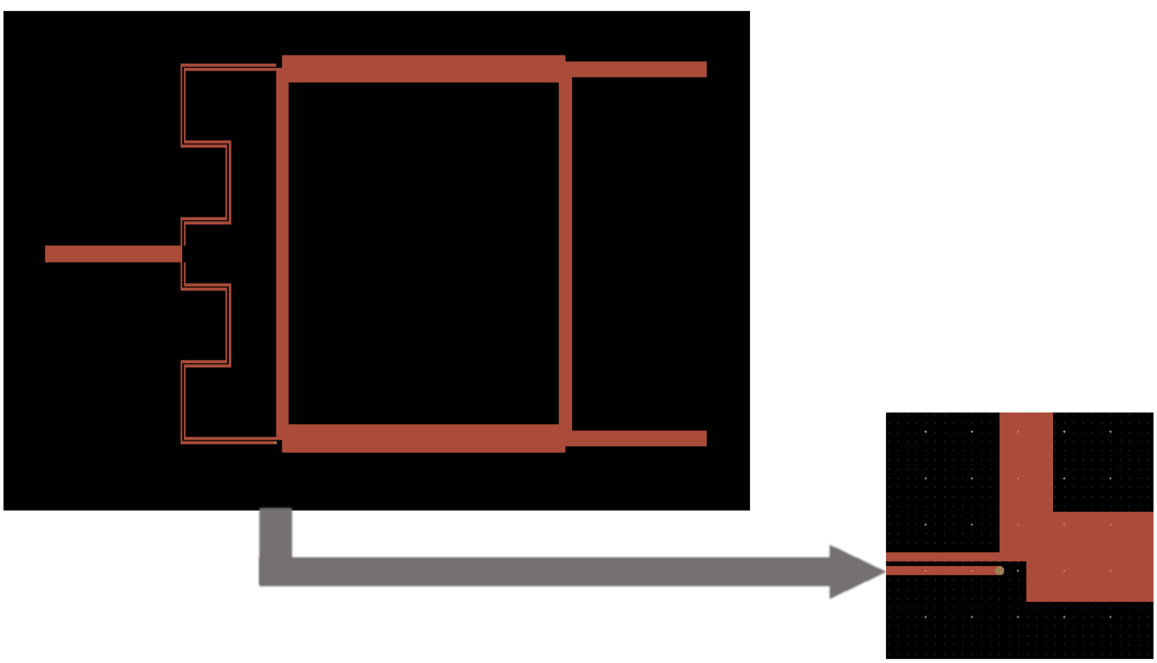


Figure 5.3.6a: Reconfigurable Quadrature Coupler Operating in Mode (1: j)

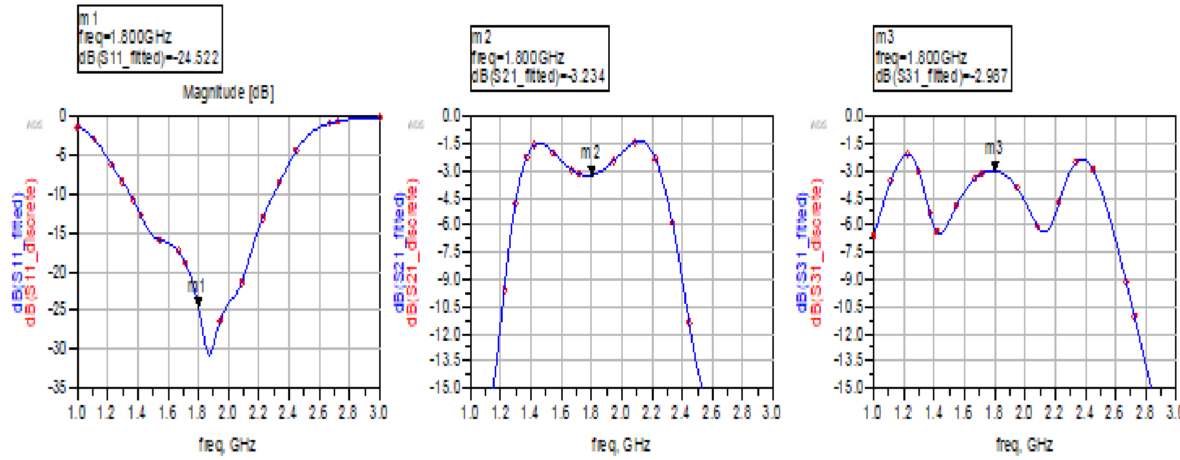


Figure 5.3.6b: Simulation Results of reconfigurable quadrature coupler operating Mode (1: j)

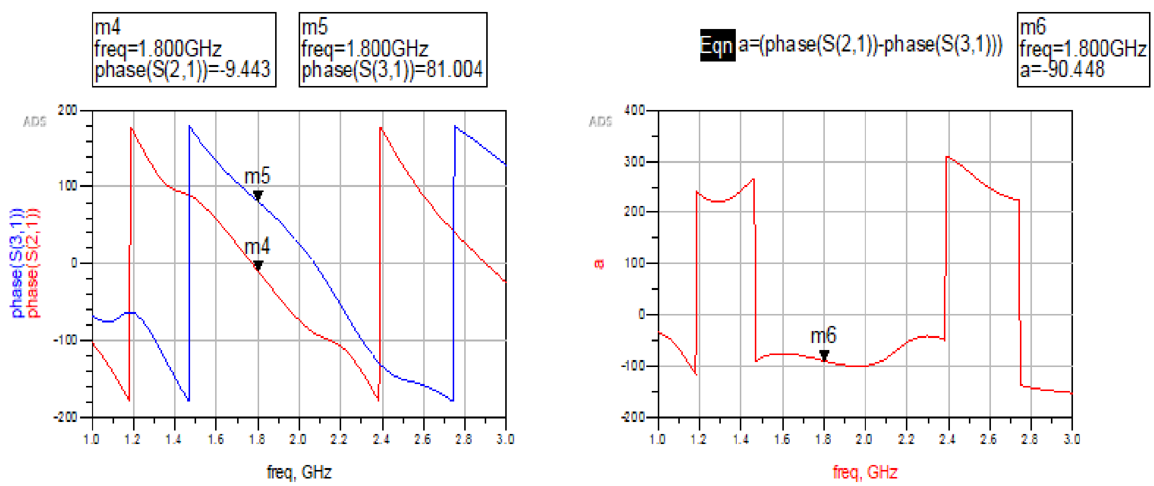


Figure 5.3.6c: Phase difference of reconfigurable quadrature coupler operating Mode (1: j)

5.3.4 Mode (j: 1)

When the circuit is operating in mode (j: 1), the input power is transferred to both of the output ports with equal power division moreover the phase difference between port 2 and port 3 will be +90°. To operate the circuit in this mode, the only switch that is turned ON is switch 2 while the other three switches (switch 1, switch 3 and switch 4) are turned OFF hence in our circuit design we placed only one through-hole via and that is on coupled line 2.

Since there is no via placed on the Quadrature 90° Hybrid, there will be no change in its behavior and the through-hole via that is placed on the coupled line 2 will behave in exactly the same way as explained previously in section 5.3.1. Figure 5.3.7a shows the power divider operating in mode (j: 1).

Simulation results are shown in Figure 5.3.7b. The S-parameters for mode (j: 1) that we got were S_{11} = -24.550dB, S_{21} = -2.989dB and S_{31} = -3.232dB. From these results we observe that all the power from port 1 is almost equally divided between port 2 and port 3.

From Figure 5.3.7c, we can also see the phase difference between the two output ports that is +90.442°. It should be noted that while calculating the phase difference, the phase of S_{21} is kept first in the formula.

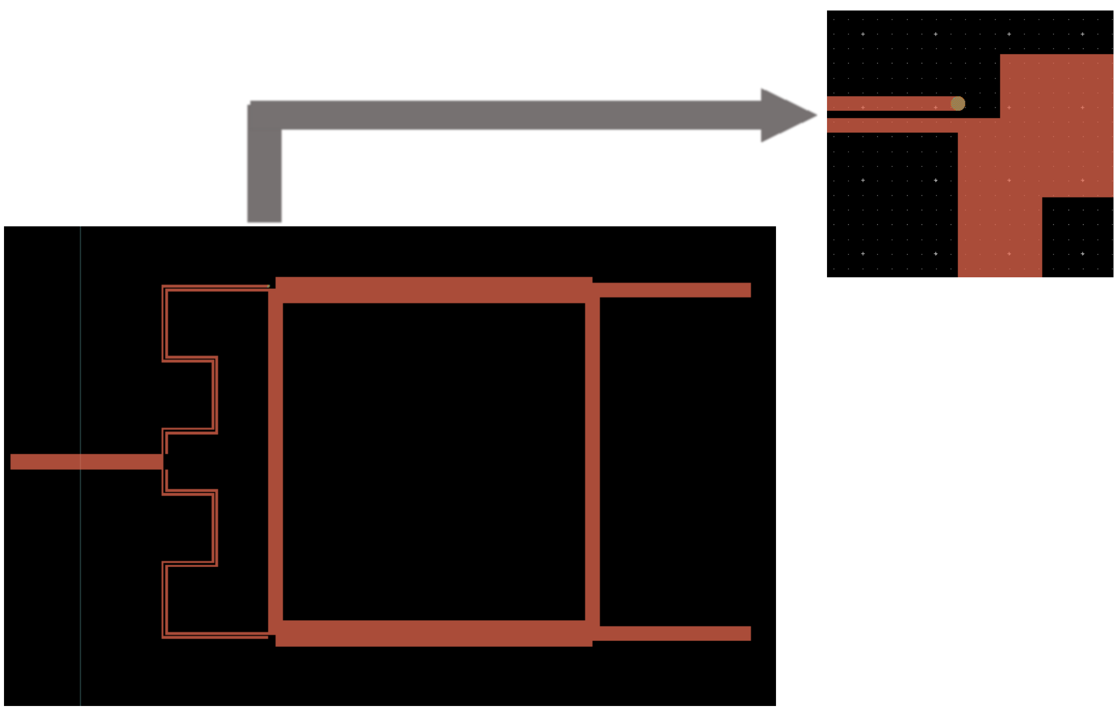


Figure 5.3.7a: Layout of reconfigurable quadrature coupler operating in Mode (j: 1)

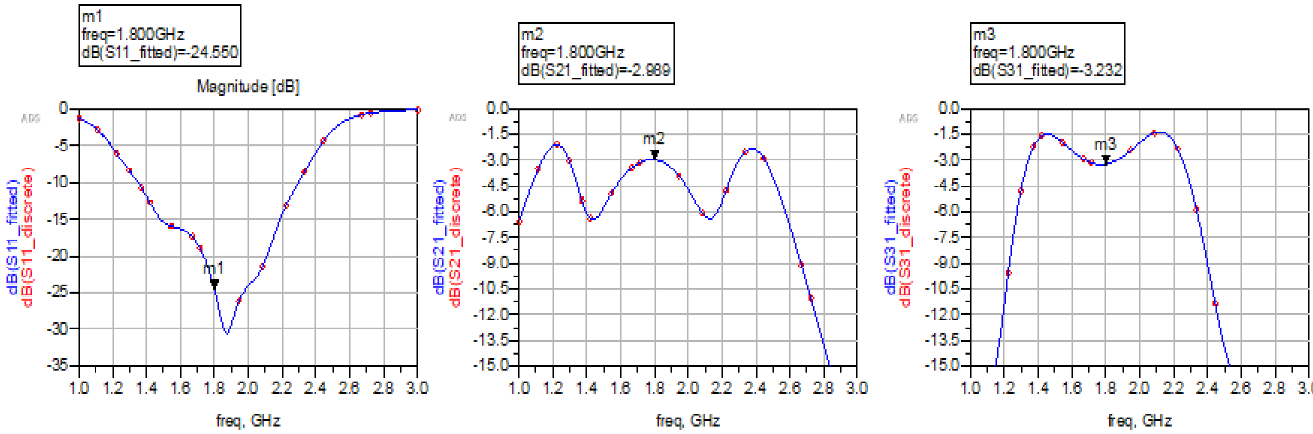


Figure 5.3.7b: Simulation Results of reconfigurable quadrature coupler operating Mode (j: 1)

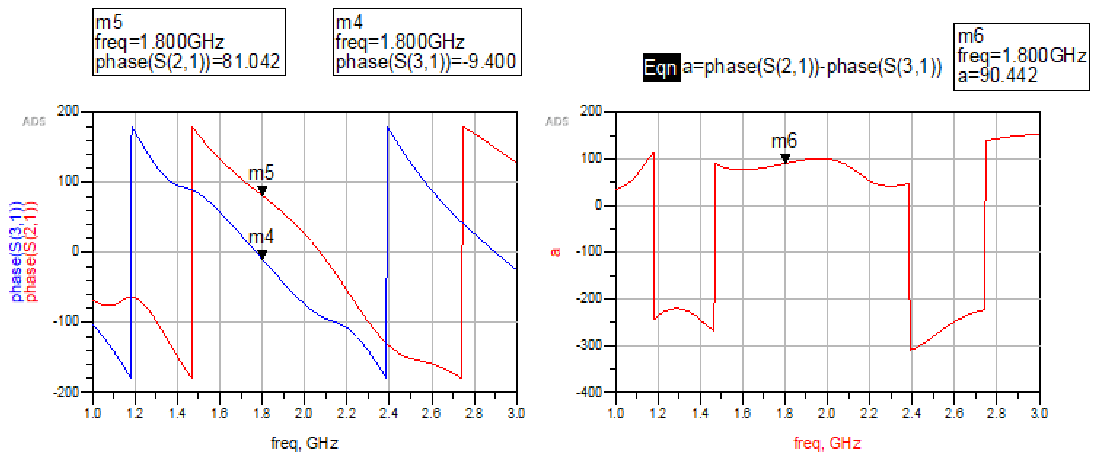


Figure 5.3.7c: Phase difference of reconfigurable quadrature coupler operating for Mode (j: 1)

5.4 Fabrication

After the completion of the circuit design, we now move towards its fabrication and the first step for fabricating any circuit is to make its Gerber Files. Since we made a different design for each mode of operation, we proceeded to fabricate two circuit designs. The modes of circuit that were fabricated are mode (0: 1) and mode (1: j). The complete process for fabrication is discussed below.

5.4.1 Gerber Files

For Gerber files we first have to create a new layout cell and paste all the designs that we want to fabricate in that cell. We can also create multiple layout cells and paste each circuit design in it individually. For our Gerber files creation we pasted both the circuit designs on the same layout cell. Afterwards we removed all the ports and merged the circuit. To “Merge” any circuit select that whole circuit and go to “Edit” menu and from there go to “Merge” and select “Union”.

Then after pasting the circuit in the new layout cell we drew a “Resi” box around our circuit. Resi is used to give a substrate border for the circuit. In order to do that go to the drawing box and click on “v, s resi: drawing”. After placing the Resi box click on edit and select explode. This will create a borderline required for the substrate.

Afterwards we selected the preferred layers that were necessary for fabrication. For our design the preferred layers were conductor layer, hole layer and Resi layer. To do that go to the layout preferences and select the concerned layers.

Then also made some vias/holes inside the substrate border (Resi layer) for mounting purposes. These vias were for the m2 screws so that the fabricated circuit could be fitted to the aluminum plate. We made sure that these mounting holes were sufficiently away from the circuit, so they do not have any effect on the results.

Then we exported the files. In order to export the file go to “File” menu and select “Export”. Then select “Gerber/drill” from the menu. After selecting the desired location for the Gerber files, select the checkbox “view file after export”. Figure 5.4.1a and Figure 5.4.1b shows the process of creating the Gerber files.

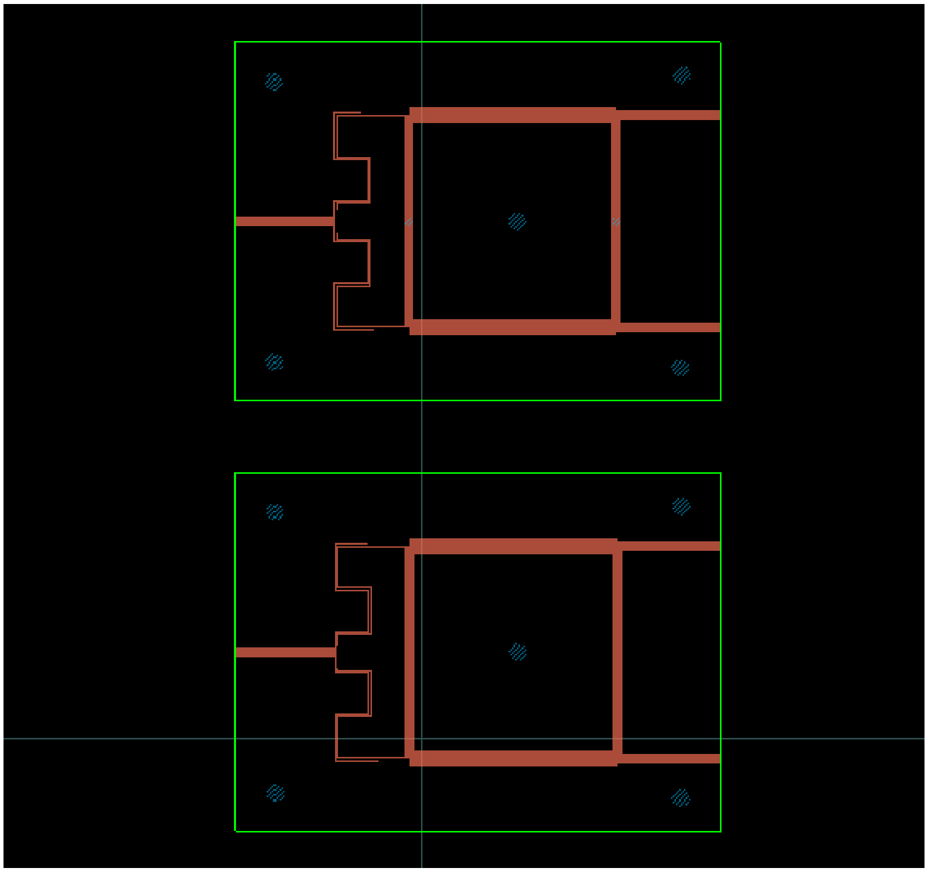


Figure 5.4.1a: Gerber File generation in ADS

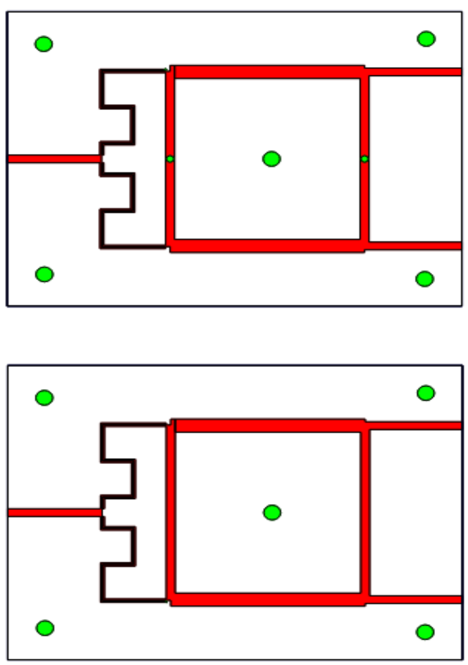


Figure 5.4.1b: Gerber Files of Designed Circuit in ADS

5.4.2 Fabricated Circuits

As discussed earlier in the start of section 5.4, two circuits were fabricated. One of the circuit was operating in Mode (0, 1) while the other circuit was operating in Mode (1, j). The switches configuration of these two modes are given below in Table II.

Table II: Switches States of Fabricated Circuits

Mode(m: n)	SW_1	SW_2	SW_3	SW_4
(0 : 1)	OFF	ON	ON	ON
(1 : j)	ON	OFF	OFF	OFF

The Gerber Files were sent to RWR Private Limited for fabrication. The fabricated circuit was fitted on the aluminum plate and then SMA connectors were attached to it. Both fabricated circuits are shown in Figure 5.4.2a and Figure 5.4.2b.

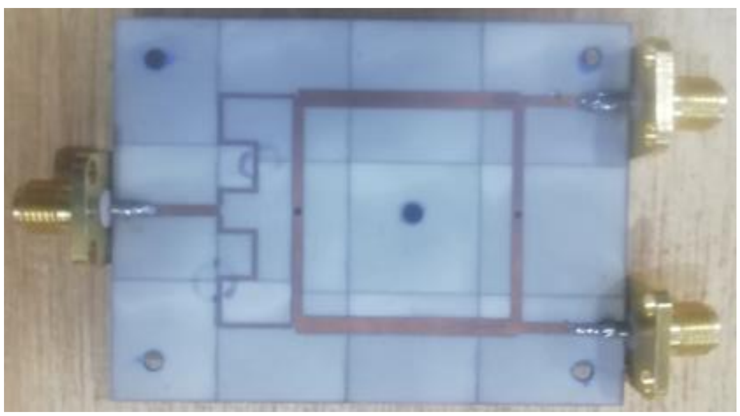


Figure 5.4.2a: Fabricated Reconfigurable Quadrature Coupler operating in Mode (0, 1)

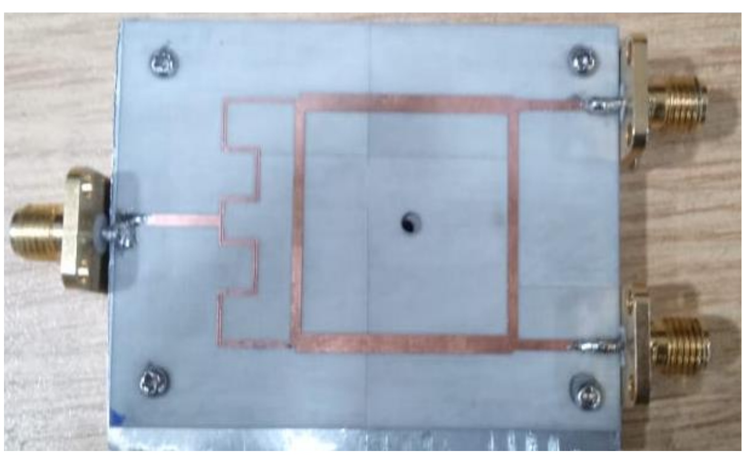


Figure 5.4.2b: Fabricated Reconfigurable Quadrature Coupler operating in Mode (1, j)

It should be noted from Figure 5.4.2b that the SMA connector of port 1 is not properly aligned with the circuit so we attached an extra copper section there by using copper tape. Then that section was soldered. There will be some losses due to this section and results would not be ideal for this mode.

5.5 Measured Results

In order to measure the results of fabricated circuits, we used Agilent E8363b Vector Network Analyzer (VNA). Since our operating frequency was 1.8GHz the VNA was calibrated at the frequency range of 1.5GHz to 2GHz with the help of an electronic calibration module. S_{11} was measured at three different frequency points which were 1.72GHz, 1.8GHz and 1.88GHz while S_{21} and S_{31} were measured at only one point which is 1.8GHz.

After calibrating the VNA, now we connect one port of VNA at port 1 on the circuit while the other port of the VNA was connected at port 2 of the circuit. From this configuration we got S_{11} and S_{21}. While port 3 was matched with 50ohms impedance. Then the VNA ports were connected to port 1 and port 3 of the fabricated circuit. While port 2 was matched with 50ohms impedance. From this configuration we got S_{11} and S_{31}. The measured results for both modes of operation are discussed and shown below.

5.5.1 Measured Results of Mode (1, j)

As discussed in section 5.3.3, in this mode input power from port 1 is equally divided between the two output ports port 2 and port 3 with a phase difference of -90°. The measured results are shown in Figure 5.5.1.

The S-parameters for mode (1: j) that we got were S_{11} = -24.22dB, S_{21} = -3.463dB and S_{31} = -3.903dB. From these results we observe that though there are some losses in power transmission, especially from port 1 to port 3, but to some extent almost all the power from port 1 is equally divided between port 2 and port 3. The measured S-parameters are shown in Figure 5.5.1a and Figure 5.5.1b.

From Figure 5.5.1c and Figure 5.5.1d, we can see the phases of S_{21} and S_{31}

respectively. The phases were measured at three different frequency points which were 1.75GHz, 1.8GHz and 1.85GHz. The average phase difference at all three points is -93.74°. It should be noted that while calculating the phase difference, the phase of S_{21} is kept first in the formula.

Figure 5.5.1a: Measured S-Parameters of Mode (1, j) Showing S_{31}= -3.903 dB

Figure 5.5.1b: Measured result of Mode (1, j) Showing S_{21}= -3.463 dB

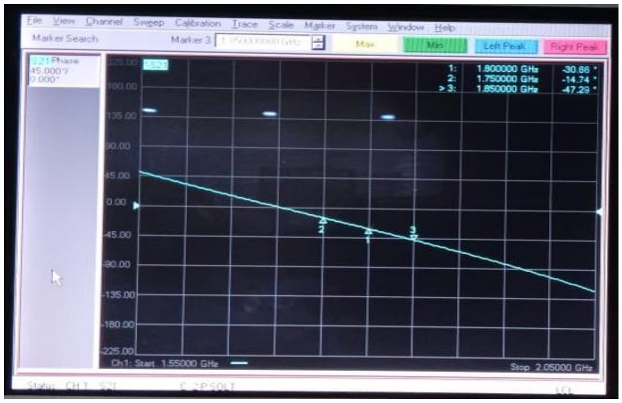


Figure 5.5.1c: Measured result of Phase of S_{21} of Mode (1, j)

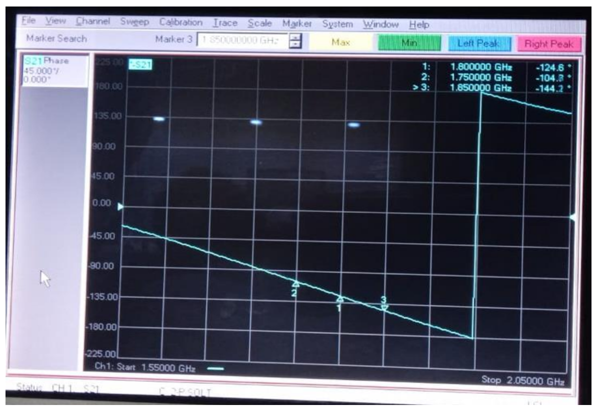
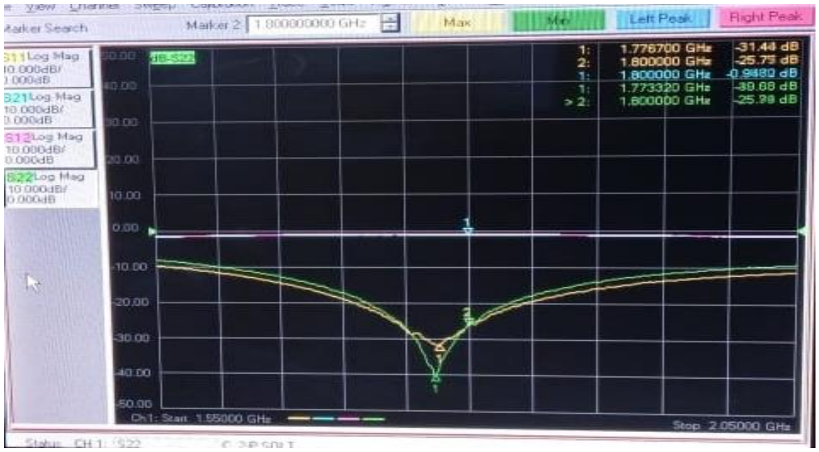


Figure 5.5.1d: Measured result of Phase of S_{31} Mode (1, j)

5.5.2 Measured Results of Mode (0, 1)

As discussed in section 5.3.1, in this mode input power from port 1 is completely transmitted to port 3 while there is no power transferred to port 2. The measured results are shown in Figure 5.5.2.

The S-parameters for mode (0: 1) that we got were S_{11} = -25.75dB, S_{21} = -23.39dB and S_{31} = -0.9480 dB. From these results we observe that port 2 is completely isolated all the power from port 1 is transmitted to port 3. Measured S_{21} and S_{31} are shown in Figure 5.5.2a and Figure 5.5.2b respectively.



(a)

(b)

Figure 5.5.2: Measured Results of Mode (0, 1). (a) S-parameter Measurement of S_{31} (b) S-parameters Measurement of S_{21}

5.6 Comparison of Simulated and Measured Results

The comparison of simulated and measured results is given in Table III. We can see that for Mode (0, 1) the measured and simulated results are very close to each other. There is no power that is transferred to port 2 while all the power from port 1 is being transmitted to port 3. For Mode (1, j) we can see the measured and simulated are again very similar with almost equal power division between the two output ports and a phase difference of 90° for simulated results and 93° for measured results presented in table III.

Table III: Comparison of Simulated and Measured Results of Reconfigurable Quadrature Hybrid

	Mode (0, 1)			Mode (1, j)			
S-parameters	S_{11}(dB)	S_{21}(dB)	S_{31}(dB)	S_{11}(dB)	S_{21}(dB)	S_{31}(dB)	Phase Difference
Simulated	-22.988	-27.263	-0.114	-24.522	-3.2	-2.9	-90°
Measured	-25.75	-23.39	-0.948	-24.22	-3.463	-3.903	-93°

Chapter 6

6.1 Conclusion and Future Work

A reconfigurable power divider, based on the circuit reported by Yahya Antar et. al., was designed and fabricated on Rogers 4003C substrate with a height of 20mils at an operating frequency of 1.8GHz. The power divider can operate in four different modes. The four operating modes are totally directing the power into one of the two output ports and 3dB equal power division between the two output ports with a +90° or -90° phase difference. The modes are enabled by different configuration of the switches. A total of four switches are used which are modeled as through-hole vias. Two switches are placed on the coupled lines and two other switches are placed on Quadrature 90° Hybrid. For circuits reported here through hole vias were used instead of switches. So, when the state of a switch is ON, then a through-hole via to ground is placed on the circuit. Four designs for the four circuit modes, each with an appropriate switch configuration, were simulated and two of these designs were fabricated. A very close relation between the measured and fabricated results was achieved. Simulated results of reconfigurable quadrature coupler operating in mode (0,1) show $S_{11} = -22.988$ dB, $S_{21} = -27.263$ dB and $S_{31=} -0.114$ dB and measured results for this mode were $S_{11=} - 25.75$ dB, $S_{21} = -23.39$ dB and $S_{31} = -0.948$ dB showing that almost all the power is delivered to port 3. For circuit operating in mode (1,j) the simulated results were $S_{11} = -24.522$ dB, $S_{21} = -3.2$ dB and $S_{31} = -2.9$ dB and the phase difference was -90 degrees while measured results for this mode of operation were $S_{11} = -24.22$ dB, $S_{21} = -3.463$ dB and $S_{31} = -3.903$ dB and the phase difference obtained was -93 degrees showing the almost equal split of power between the port 2 & port 3 and quadrature mode of operation.

As part of future work, insertion loss can be improved for all modes of operations, as it can be seen from the measured results that the insertion loss was not ideal. After improving these results, we work on its practical use. It can be used to increase the efficiency of Power Amplifiers so in future we can work on Active devices. Then we can integrate this Microstrip Quad-Mode Reconfigurable Power Divider with the Power Amplifier to improve its efficiency.

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