NOVEL CAPATIVELY COUPLED TWO AND THREE WAY POWER DIVIDER

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A project report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor (Hons.) of Electrical and Electronic Engineering

Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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Date : ______15th April 2011_______

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"NOVEL CAPACITIVELY COUPLED TWO AND THREE WAY POWER DIVIDER"** was prepared by **SOO CHOY KIT** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Electronic and Communications Engineering (Hons.) at Universiti Tunku Abdul Rahman.

Approved by,

Signature : ___________________________

Supervisor : Dr. Lim Eng Hock

Date : ______15th April 2011_______

Specially dedicated to

my beloved parents and friends.

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NOVEL CAPATIVELY COUPLED TWO AND THREE WAY POWER DIVIDER

ABSTRACT

Power dividers are fundamental component in microwave communication system. A passive component designed for dividing a single input signal into multiple ones. The output power of the signal will depends on the number of outputs. Ideally, the input power of the signal will be dividing equally in the output. The power divider can designed to operate in multi-band operations but the efficiency of the power divider will be low. In the research, new design and idea presented where the power divider is dividing the input power in the output ports and having the bandpassing characteristic. The power divider designed based on the proposed shape and operate in a single frequency. This research is divided into 3 development stages which are simulation, fabrication and experiment. All the results obtained from simulations and experiments used to optimize the power divider design. A novel two-way and three-way capacitively coupled power dividers designed in this project. Both the power divider had the bandpassing characteristic. Good performances of the proposed power dividers at the specified frequency are obtained.

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LIST OF SYMBOLS / ABBREVIATIONS

λ	wavelength, m
f	frequency, Hz
c	speed of light, m/s
ε_r	dielectric constant
ε_{eff}	effective dielectric constant
h	thickness of substrate, mm
w	width of striplines, mm
Z_o	characteristic impedance, Ω
Z_{in}	input impedance, Ω
S_{11}	reflection loss, dB
S_{21}	insertion loss, dB
θ	electrical length
λg	Guided wavelength, m
θ	electrical length, m
π	pi constant = 3.142
l	physical length, m
β	propagation constant

CHAPTER 1

INTRODUCTION

1.1 Background

Power dividers are fundamental component in microwave communication system. It is a passive component that divide single input signal into multiple ones according to the number of output ports. The output power of the signal will depend on the number of outputs; the higher number of output ports, the lower the output power. Ideally, the input power of the signal is dividing equally among the output. The power divider can designed to operate in multiband operations but the efficiency of the power divider will be very low. Similarly, a power divider can operate as a power combiner. Several signals can combine as one by inverting the input and output but the efficiency is lower for power combiner. A Dual- Band Wilkinson Hybrid power divider is a widely implemented power divider and famous around the world. Many journals and research had done on the Wilkinson Hybrid power divider and optimization of the design had been done. Basically a Wilkinson power divider required resistors to be coupled among the output port and the signal can be divided evenly.

Nowadays, microstrip power divider is widely implemented as it can easily integrated into a system, the size of the power divider is small, efficiency is high due to the accurate fabrication of the microstrip power divider, the operating frequency of the power divider can be optimize and tuned accordingly to the application of the power divider. Noticeably, there have been more than 600 publications on various designed of microstrip filters and power divider in recent 10 years.

A multi-port microstrip power divider is very useful because it is able to operate in one frequency ranges and dividing the input signal into multiple paths. Example of the application of power divider is in the wireless local area network (WLAN) communication system where it has three directional antennas that faced to different direction. The power divider used to divide the signal into three paths and the each of the output is being amplified and connected to the antenna. Therefore, the same signal transmitted through the three antennas.

Moreover, it has the characteristic of high power handling, low insertion loss, high isolation, excellent phase balance and small in size.

1.2 Research Aims and Objectives

The main objective of the project is to propose and study on the capacitively coupled rectangular ring coupled power divider. The power divider should be able to divide the power equally at the output port, a wide operating bandwidth and able to operate in odd and even numbers of output ports.

Journals and articles found in IEEE Xplore database show that there are only a few publication on rectangular ring power divider and usually the input port and output ports are joint together on the same ring and the power divider is hard to achieve -15 dB return loss. So, in this project, the power divider that designed should able to overcome this problem.

The first part of project is to design a two-way capacitively coupled microstrip power divider that able to divide input power equally among the 2 output ports. The designed power divider must be operating efficiently at 3 GHz. The bandwidth of the power divider should maintain in 1 GHz. The second part in project aims to optimize the 2-way rectangular ring microstrip power divider to a 3-way power divider. It should have equal power division and same bandwidth.

1.3 Project Motivation

The motivation of the project is to design a capacitively coupled power divider that has good performance and easy to implement, which can be justified from the operational bandwidth, impedance matching, insertion loss, coupling factor, and isolation. A good power divider should have wide operational bandwidth, low insertion loss and high isolation between input and output. The designed power divider is been hoped that able to be published in the international journals. This is due to the capacitively coupled power divider is a very new idea in power divider design. There is no much journal or article on the web nowadays and this design can be optimized and modified easily for different operating frequency.

Moreover, many power dividers such as the Wilkinson power divider are very complicated in design, complex structure and hard to fabricate. This motivates the author to design a new type of microstrip power divider that is simpler in design and good in performance.

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CHAPTER 2

LITERATURE REVIEW

2.1 About Microstrip Power Divider

Power divider is a passive device that used in the radio frequency and microwave communication. With the significant growth with computer technology and simulation software, microstrip designed power dividers are widely use and designed to operate in various applications. The performance of the microstrip power divider can measure with the suitable equipment and the optimization process can carry out easily.

The function of power divider is to divide the power into several paths. The most basic power divider is the T-junctions power divider. This kind of power divider often suffers poor isolation between the output ports, where phase difference among output ports is large. Next, is the Wilkinson power divider where it consist of 2 parallel uncoupled transmission line, then input is couple to both the line in parallel and output is terminated with twice the system impedance bridge between them. The Wilkinson Power Divider had the benefit of low VSWR at all ports and high isolation between output ports. However, the Wilkinson Power Divider requires resistor coupled at the output ports. Then, there is also the Hybrid ring coupler where it is a directional coupler. The directional coupler is similar to power divider and it is only operate in single direction.

All these type of power dividers and directional coupler can be built on the microstrip. The computer aided design method used during designing the structure of the power divider and simulations done in computer to have the result of the designed power divider. Furthermore the optimization of the design will be carried out to obtain the best possible results. Then, only the design will be fabricated on the microstrip.

The general configuration of microstrip power divider is as shown in Figure 2.1. It consists of a top layer of metal, substrate, and ground. These three structures must exist in every microstrip power divider, otherwise it is unable to operate and function. It is also possible to have power divider with 2 layers of substrates. Each microstrip power divider designs have their own characteristics and advantages. The design of the microstrip power divider can be selected according to the designers' requirements and knowledge.

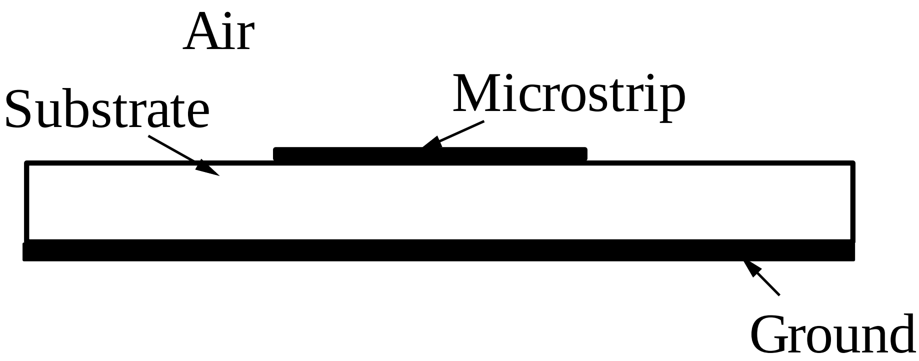


Figure 2.1: General configuration of the microstrip power divider

2.1.1 Microstrip Lines

Microstrip line is type of transmission line which fabricated using the printed circuit board technology and used in the microwave frequency signal. The microstrip technology is invented by ITT laboratories.

Figure 2.2 shows the microstrip line cross section that consist the microstrip line, substrate and ground. The microstrip line and the ground plane is a conductive metal layer and separated by a dielectric layer of thickness, h as below. In Figure 2.2, W stands for width, t stands for thickness and h stands for height. ε_R is the relative permittivity of the substrate.

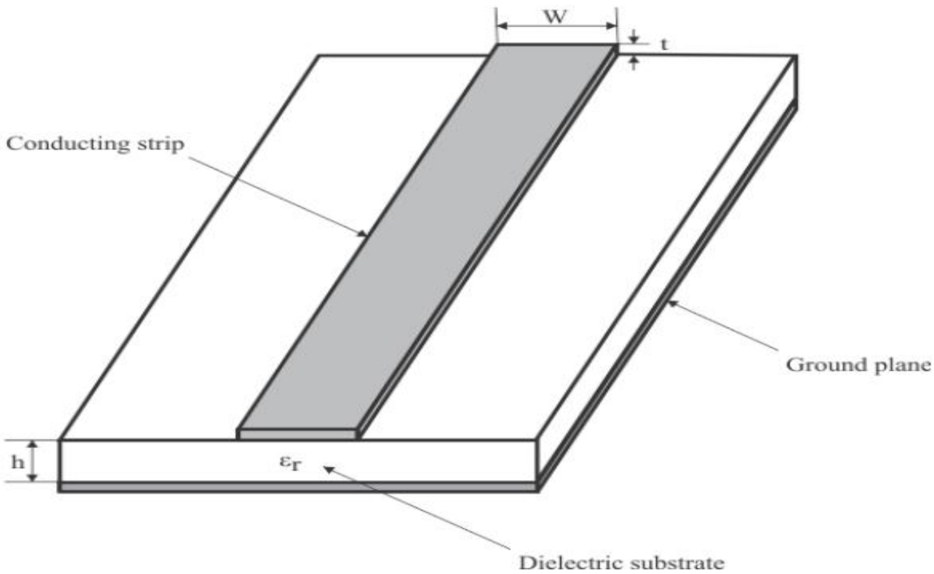


Figure 2.2: Microstrip line cross section

When using the microstrip line, there are some important considerations to choose the appropriate material for the microstrip substrate. These important factors are the size of the design, the surface wave effects, the dielectric loss, power handling and the higher order modes.

Microstrip is chosen in the project due to the several factors. The first factor is the size of the final product will be small compare to others such as the waveguide technology. Nowadays, compact is important in equipment, the compact power divider is an added advantage where it can easily integrated or fitted into any equipment. Furthermore, by fabricating the design on a microstrip can enable designer to integrate several designs or function into one circuit board. This can greatly reduce the size of equipment.

Besides microstrip line, traditional waveguide can be used to convey microwave-frequency signals. However, it is not used in this project because waveguide power divider is hard to build, bulky in size and limited application. When using the waveguide power divider, the system had to be coupled to the waveguide and the design of the waveguide will be much larger than the microstrip line power divider. Moreover, the cost to build a waveguide power divider is also much higher than the microstrip power divider.

In fact, there are several disadvantages when using the microstrip designed power divider. The first disadvantage of the microstrip design is the power handling capability. Compared to waveguide technology, the microstrip can only handle less power but this will not affect in our designed because the dielectric breakdown voltage is so much higher than the voltage that the power divider going to operate. Moreover, due to the microstrip is not enclosed and therefore it may suffer from cross-talk and unintentional radiation. This problem can be overcome by carefully designed of the power divider to minimized the effect of cross-talk and unintentional radiation.

Eventually due to the advantages of microstrip, the power divider is designed on the microstrip technology and it is benefit from the compact size, lower cost, more feasibility and easy to build. Moreover, there are many microstrips available in the market for the design to choose for the appropriate one according to their design and application. With good substrate quality, a good microstrip power divider can be realised.

2.1.2 Substrate

In the project, the designs are fabricated on the Rogers Duroid Laminates. The model of substrate chosen is the RT/Duroid 5870.

- Dielectric constant of 2.33.
- Suitable in the microwave application up to 40GHz.
- Excellent electrical and mechanical properties.
- Low moisture absorption.
- Uniform electrical properties over frequency.
- Ease for fabrication and stability in use.
- Excellent chemical resistance.

The RT/Duroid 5870 is made of PTFE composites reinforced with glass microfibers. The PTFE (polytetrafluoroethylene) is a synthetic fluoropolymer of tetrafluoroethylene. It has the characteristic of high corrosion resistance, excellent dielectric properties, and high melting temperature. The Duroid 5870 also has very low dielectric loss and made it suitable for power divider application where power loss can be minimized.

Moreover, the material is easily cut, sheared and shaped into the shape wanted. The Duroid 5870 is also resistant to the solvents and reagents normally used in the etching processes. The low density of the RT/Duroid 5870 also made it a lightweight material for any equipment.

The others advantages of the RT/Duroid 5870 laminate is that it can be made to the thickness that required. The project required the thickness to be 2.54mm and for the Rogers substrate, the thickness is tightly controlled and quality is ensured to be accurate. So, this can ensure the results of the actual produce and the simulation results are very close and accurate.

2.1.3 Effective dielectric strength and Characteristic Impedance in Microstrip

In the microstrip, when a source supplied to the conducting strip, the field will extend within the two media which are the dielectric below the strip and the air above the strip. Due to the inhomogeneous of the dielectric properties, the waves in the microstrip line will have no vanished longitudinal components of electric and magnetic fields. The propagation velocities will depend on the material properties and the physical dimension of the microstrip.

One of the material properties in the microstrip is the effective dielectric constant of the material. To obtain the effective dielectric constant, the Quasi-TEM approximation method had applied. It is a method that when the longitudinal components of the field for the dominant mode of the microstrip line remained much smaller than the transverse component. So, the dominant mode behaves like a TEM mode and the TEM transmission line theory is applicable.

In the quasi-TEM approximation, the inhomogeneous dielectric air and substrate dielectric is replaced with the homogeneous dielectric. Characteristic impedance is the ratio of the amplitudes of a single pair of voltage and current waves propagating along the microstrip line in the absence of reflections. It acts like a resistance where power generated by a source on one end of an infinitely long lossless transmission line is transmitted through the line but it is not dissipated in the line itself. The effective dielectric strength and characteristic impedance can be determined with the two capacitances as followed.

$$\varepsilon_{re} = \frac{Cd}{Ca}$$

$$Z_c = \frac{1}{c\sqrt{CaCd}}$$

Cd is the capacitance per unit length with the dielectric substrate present

Ca is the capacitance per unit length with the dielectric substrate replaced by air

c is velocity of EM waves in free space (c = 3.0 × e8 m/s)

Z_c is the characteristic impedance.

For a very thin of conductors that made up the microstrip transmission line, the value of effective dielectric strength and the characteristic impedance can be calculated by the formula as below.

For $(\frac{W}{H}) < 1$

$$\varepsilon_e = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2} [\{1+12 (\frac{H}{W})\}^{-0.5} + 0.04 \{1- (\frac{W}{H})\}^2]$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon eff}} \ln (8 \frac{H}{W} + 0.25\frac{W}{H})$$

For $(\frac{W}{H}) \geq 1$

$$\varepsilon_e = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2} [1+12 (\frac{H}{W})]^{-0.5}$$

$$Z_0 = \frac{120\Pi}{\sqrt{\varepsilon eff\ x \{\frac{W}{H} + 1.393 + \frac{2}{3}\ln(\frac{W}{H} + 1.444)\}}}$$

$(\frac{W}{H})$ is the ratio of the width and length of the microstrip

Z_o is the characteristic impedance

ε_e is the effective dielectric strength

So, the characteristic impedance and the effective dielectric strength will be affected by the width and length of the microstrip line. When the transmission line is narrow, there is less electric field concentrated on the line, so the effective dielectric strength is less.

In this case, the thickness of the conductor is neglected because the metal conductor is very thin on the substrate and with the ratio of the width and length, the computed answer is not significant to affect the effective dielectric strength and impedance.

In the HFSS simulation software, the system will calculate the actual characteristic impedance and the simulation result is compute based on the effective dielectric strength of the structure. So, the result from the HFSS will be very close to the practical value.

However, in the project, the Software TX Line 2003 used to calculate the width needed for the microstrip line used in the designed for the input and output microstrip line. Impedance matching is required for obtaining the maximum power transfer between the power divider and the external equipment system. The software only required to input the dielectric strength of the substrate, the impedance required for the microstrip line and the thickness of the substrate. Then, it will calculate the width required and it is used in the HFSS for designing the power divider.

2.1.4 Guided Wavelength, Phase Velocity and Electrical Length

The guided wavelength is the wavelength of the wave that travelling in the microstrip that operates in the given frequency. The guided wavelength is different with the wavelength in the air. It can be calculated by the following formula.

$$\lambda = \frac{300}{\sqrt{\varepsilon e}\, f} \text{ mm}$$

f is the operating frequency in GHz

Then, the associate propagation constant and electrical length can be determined by:

$$\beta = \frac{2\pi}{\sqrt{\lambda}}$$

$$\theta = \beta\, l$$

With these formulas, the length that required for the design can be obtained by substituting the operating frequency and $\theta = \pi/2$ for the quarter wavelength microstrip line. In the project, the operating frequency of the first design is set to be 3 GHz and 2 GHz for the second design. When the electrical length increased, the operate frequency will decreased. The approximated electrical length is used to design the structure of the power divider and it will operate in the frequency that desire.

2.1.5 Coupled Lines

Coupled microstrip line as in Figure 2.3 is very common in the microstrip design. When two microstrip lines being parallel coupled or edge coupled with a separation distance, the coupled line structure will supports two quasi-TEM modes, the odd mode and even mode. For the even-mode excitation, it has the same voltage potential resulting in a magnetic wall at the symmetry plane as in Figure 2.4 (a). For the case of odd-mode excitation, both microstrip lines have the opposite voltage potential and hence the symmetric plane is an electric wall as in Figure 2.4 (b). This showed that they propagate with different phase velocities because they experience different relative permittivity.

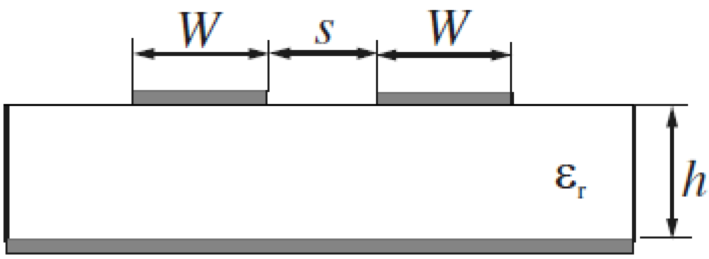


Figure 2.3: Cross section of coupled microstrip line

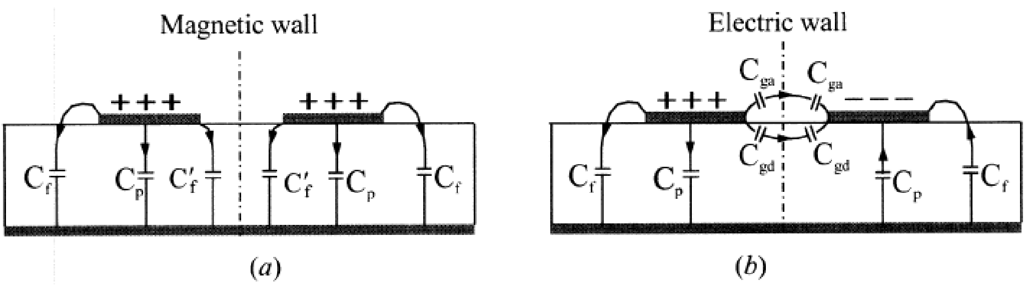


Figure 2.4: Quasi-TEM modes of a pair of coupled microstrip lines: (a) even mode; (b) odd mode

So, when two microstrip lines are coupled, the capacitance effect is different for an even-mode and odd-mode. Other than that, there are some typical microstrip discontinuities and components that will be used when designing filter or power divider with microstrip such as steps, open-ends, bends, gaps and junctions as in

Figure 2.18. The effects of the discontinuity in microstrip need to be simulated in simulation software in order to analyse their effects.

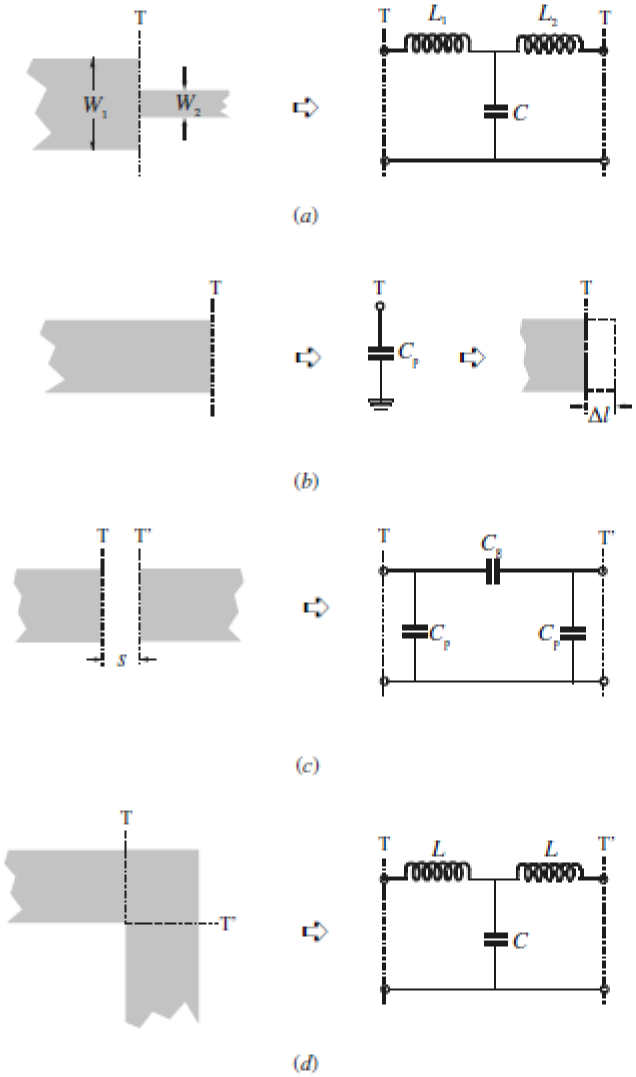


Figure 2.18: (a) step (b) open-end (c) gap (d) bend

In conclusion, designs on the microstrip will consist of different components and it will have different response of the designed system. The choice of individual components depend on the type of filters, fabrication techniques, the acceptable losses or Q factors, the power handling and the operating frequency. The design can be illustrate as equivalent inductors and capacitor in the circuit.

2.2 Wilkinson Power Divider

Wilkinson power divider is the most common power divider that implemented with microstrip. This is mainly due to the Wilkinson divider ideally can be lossless if impedance of all ports is matched.

In the Wilkinson power divider theory, input power can be divided into two or more in-phase signals with the same amplitude. In order to realise this, several parameters need to be taken into account which are the impedance transformers, the characteristic impedance and the lumped isolation resistor. With all these parameters, then the Wilkinson power divider will have matched impedance and high isolation between output ports.

When designing a Wilkinson power divider with output ports more than 2 such as 3 or 4 output ports, the parameter that required designing the power divider is very hard to obtain. So, it is very hard to design an ideal power divider with more ports. Then, if the Wilkinson power divider operates in low frequency, the efficiency of the power divider will drop significantly and the structure will be large in size. From the IEEE journal, many types of design and optimization had been done to overcome such problems such as designing microstrip structure that able to slow down the wave. These shapes include bending structure, circular split design and elliptical design.

There is no much designed in odd number of port Wilkinson power divider. Most of the design of Wilkinson power divider is in even number of ports by cascading the same power divider at the initial power divider but this cannot work in equal odd number of Wilkinson power divider.

2.2.1 A Novel Ka-Band Planar Balun Using Microstrip CPS Microstrip Transition

A balun is a device for converting signals between an unbalanced circuit structure and a balanced circuit structure.

The author reviews Peng Wu, Yong Zhang, Yu-Liang Dong and Qin Zhang paper, entitled “A Novel Ka-Band Planar Balun Using Microstrip CPS Microstrip Transition”. In this paper, a wideband balun employing a three-stage Wilkinson divider is implemented.

Authors in the paper state that the proposed planar balun consists of a Wilkinson divider for power splitting followed by two microstrip-CPS-microstrip transitions for broadband 180 phase shift. It is required to work in the overall Ka-band with excellent isolation and impedance matching, so a two-stage Wilkinson divider is needed. Moreover, if the number of the chip resistors increases, the performance of the millimetre-wave Wilkinson divider will be deteriorated.

The authors in the paper proposed that the design of the wideband millimetre-wave single-stage Wilkinson divider with four branch lines is designed based on the Wilkinson divider in a published journal titled “A novel wideband Wilkinson divider using parallel branch lines”. The branch lines and the resistor serve an essential function in providing wideband match and output-port isolation. The structural design of the power divider is as in Figure 2.5.

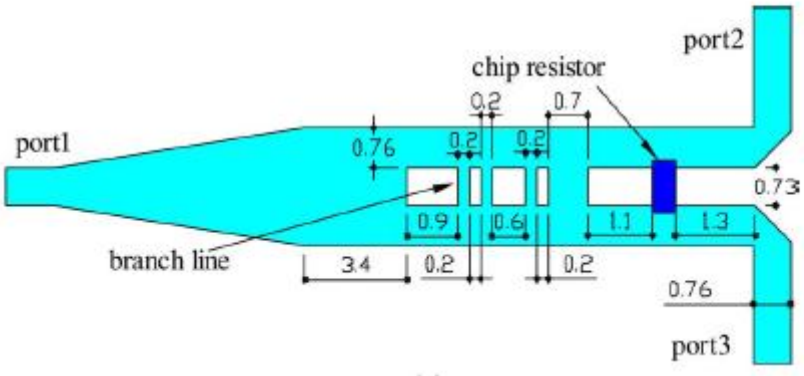


Figure 2.5: Wilkinson power divider

The authors had simulated the power divider by using the HFSS and the results show that return loss and isolation are better than 17.4 and 20.3 dB, respectively, from 26 GHz to 43.5 GHz. The result is shown in Figure 2.6.

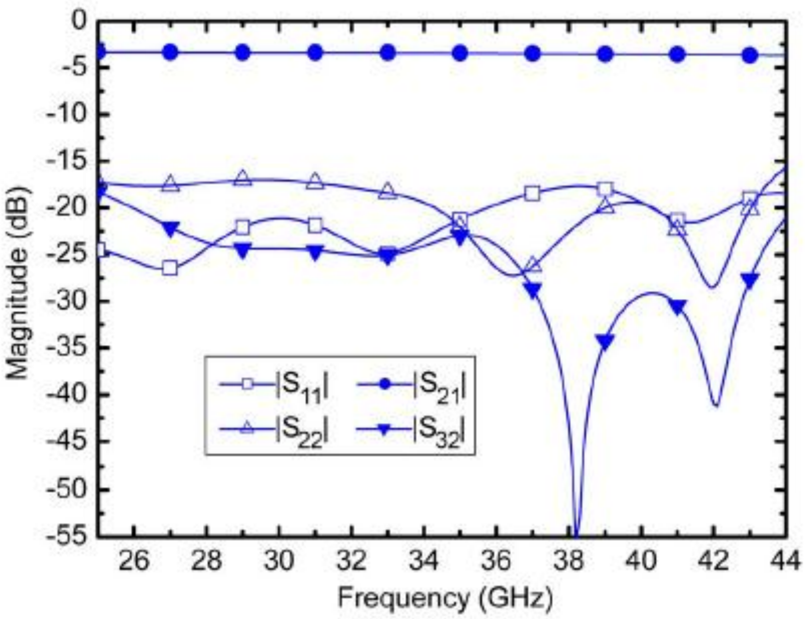


Figure 2.6: Simulated results of the power divider

2.2.2 A Dual-Frequency Wilkinson Power Divider

The author reviews Lei Wu, Zengguang Sun, Hayattin Yilmaz, and Manfred Berroth paper, entitled “A Dual-Frequency Wilkinson Power Divider”. This paper presents a dual frequency power divider with 2 way outputs.

From the journal, a conventional microstrip power divider that consists of two parallel branch lines that terminated at the end of the line with the appropriate active components such as resistor, inductor and capacitor. In this design, the power divider realizes an equal power division at two arbitrary frequencies.

The author of the paper designed and fabricated the power divider as in Figure 2.7. The design of the power divider consists of resistor, inductor and capacitor located before the outputs of the power divider. All the values of the components can calculated with the formula stated in the journal.

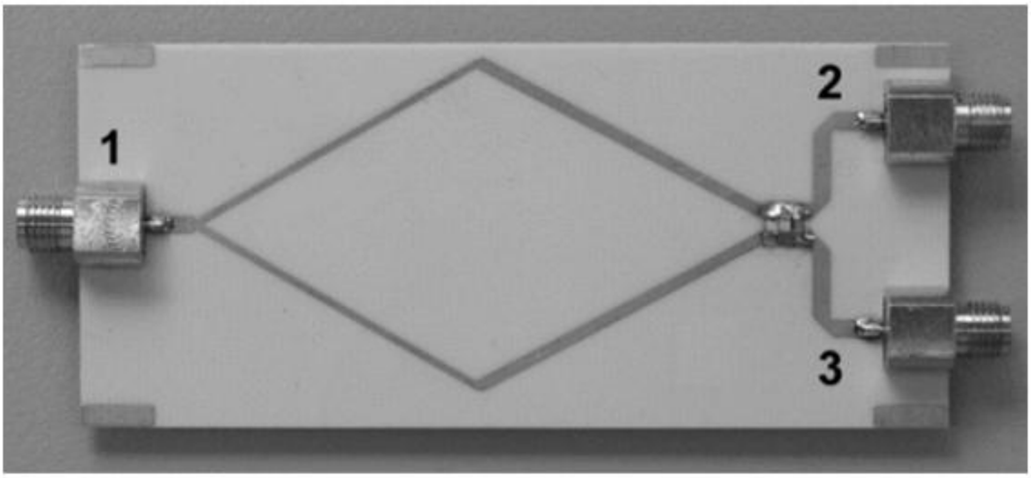


Figure 2.7: Fabricated Power Divider

Authors in the paper have simulated and experiment on the power divider. All the S-parameters of the power divider showed in Figure 2.8. In the Figure 2.8(a), it showed that the input signal is almost equally divided and transmitted to the output ports, both at the frequency of 1 and 1.8 GHz. In the Figure 2.8(b), it shows that the power divider passes the signals at both frequencies very well. A low return loss obtained from the power divider. Good isolation between ports 2 and 3 is also fulfilled at these two frequencies, as shown in Figure 2.8(c). In the Figure 2.8(d), impedance matching at the output ports is realized.

Authors in the paper commented, “The peaks of the curves are slightly shifted away from 1 and 1.8 GHz because of the limited accuracy by the experimental setup and the models of the real lumped components and substrate used for the simulation. The measured power division (S_{21}) for the two-way divider as shown in Figure 2.8 is -3.2 dB (ideal value -3.0 dB), input return loss (S_{11}) is better than 15 dB, while output return loss (S_{22}) is better than 20 dB. The measured isolation between output ports (S_{23}) is also better than 20 dB. The bandwidth of the divider can be controlled by the input coupling gap S_1, likewise single-stage coupled line bandpass filter.”

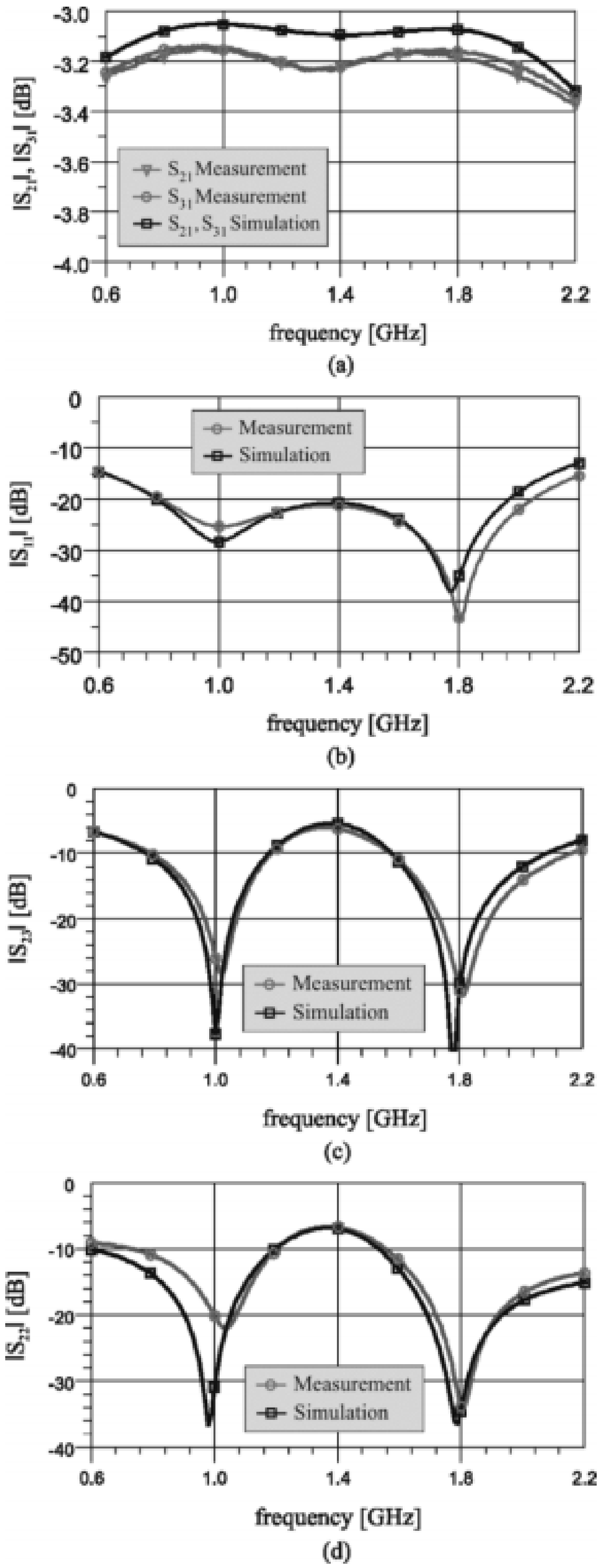


Figure 2.8: S-parameters of simulated and experimental results

2.2.3 Coupled Line Power Divider with Compact Size and Bandpass Response

This is the optimized and an integration of a single stage coupled line bandpass filter and Wilkinson power divider.

The author reviews P.K Singh, S. Basu and Y.H. Wang paper, entitled "Coupled line power divider with compact size and bandpass response". This paper presents a compact power divider that having 2 way and 3 way outputs.

The journal states that, the convention Wilkinson divider provides a fixed bandwidth and passes power at frequency outside the usable bandwidth. However, this can be overcome by implementing the bandpass filter with the miniaturized Wilkinson power divider.

Authors of this paper mentions that, a new coupling scheme used to achieve the compact layout which is the output lines of divider are spaced closely without any performance degradation.

The author of the paper proposed that the design method of the coupled line power divider is showed in Figure 2.9 where the design is equivalent to the series connection of a single stage coupled line bandpass filter and a conventional Wilkinson divider.

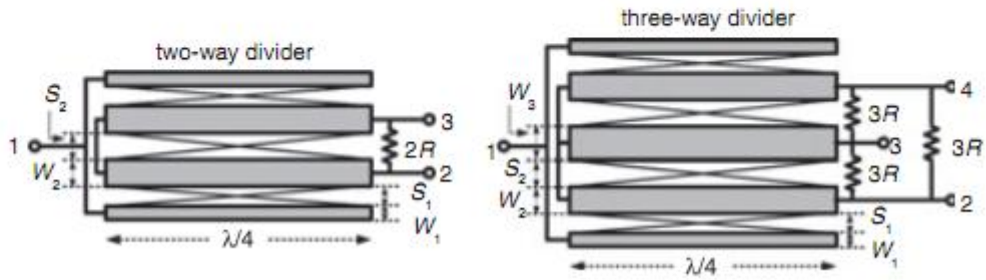


Figure 2.9: Proposed design of the couple line dividers

Authors have simulated the two and three way divider design. The author had reviewed that the layout width of the dividers is greatly reduced in the present design. The measured power division (S_{21}) for the two-way divider as shown in Figure 2.10 is -3.2 dB (ideal value -3.0 dB), input return loss (S_{11}) is better than 15 dB, while output return loss (S_{22}) is better than 20 dB. The measured isolation between output ports (S_{23}) is also better than 20 dB. The bandwidth of the divider can be controlled by the input coupling gap S_1, likewise single-stage coupled line bandpass filter.

For the three way divider design, the author reviewed that the results of the simulation shown in Figure 2.11. The measured power division is -5 dB (ideal value -4.8 dB), and return losses are better than 20 dB at the centre frequency. Output port isolations are 20 dB or better.

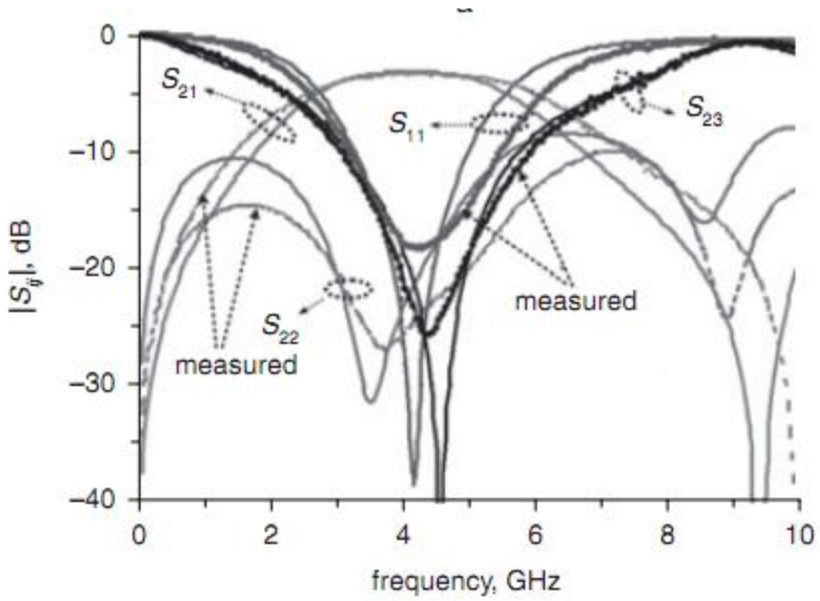


Figure 2.10: Simulated results of the 2 ways coupled line dividers

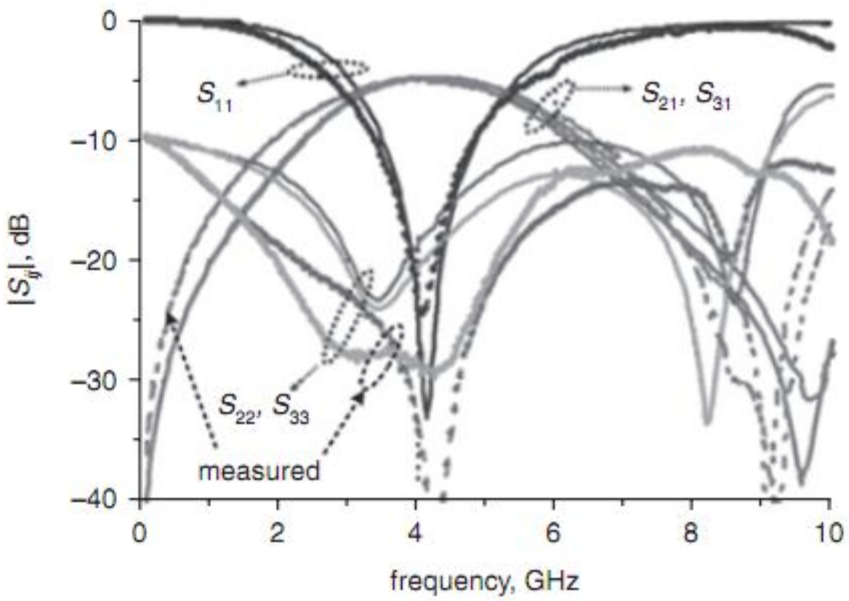


Figure 2.11: Simulated results of the 3 ways coupled line dividers

From the results, the author of the journal concluded that a new power divider using coupled microstrip lines is proposed to improve bandpass frequency response and compact size. The circuit is miniaturised when considered as an integration of a bandpass filter and conventional Wilkinson power divider.

2.3 Modified 3-Way Bagley Rectangular Power Divider

The author reviews Homayoon Oraizi and Seyyed-Amir Ayati paper, entitled "Optimum Design of A Modified 3-Way Bagley Rectangular Power Divider". In this paper, a novel 3 way rectangular power divider is proposed which is a modified version of Bagley power divider. The method of least square is developed for its design and optimization which determine the line section length and widths.

Authors in the paper mention that, the design specifications are made on the desired values of scattering parameters, which tend to minimize the input reflection coefficient and realize the desire power division ratios.

Authors states that although it has a relatively good transmission bandwidth from the input to output ports but the isolation among its output may not perform equally well. Several configurations have been proposed by the authors to improve its performance in the literature such as application of transmission lines with different characteristic impedance to reduce its geometrical configuration, use of open circuited lines to reduce its size and use of right-handed materials and left-handed Meta materials to miniaturize it and obtain a dual band power division response.

The authors decide to present the idea to design and optimization procedure based on the method of least squares, which realizes the optimum performance for the best impedance matching at the input, the best realization of specified power division ratios and isolation among the output ports. Then, an accurate equivalent circuit is obtained for the proposed modified rectangular 3-way power divider and its admittance matrix among its terminal ports is derived. Then, its scattering matrix is obtained, which is used for the construction of an error function in terms of its geometrical dimensions. The minimization of the error function leads to the optimum design of the divider.

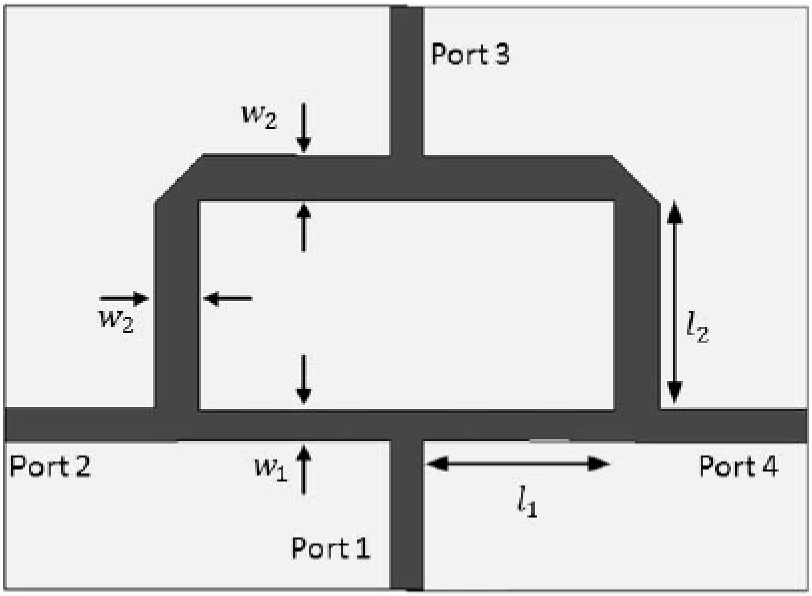


Figure 2.12: Modified 3 way Bagley rectangular power divider

In the optimization process, the author put the design into equivalent line sections, bends, and LC component and divided into several sections as in Figure 2.13. This is to help the author to obtain the transmission matrix of each section and then transform them into equivalent admittance matrices as in Figure 2.14. With the use of Kirchhoff current law, the relation of currents and voltages in the admittance matrix are obtained for each part. Finally, the scattering matrix is determined.

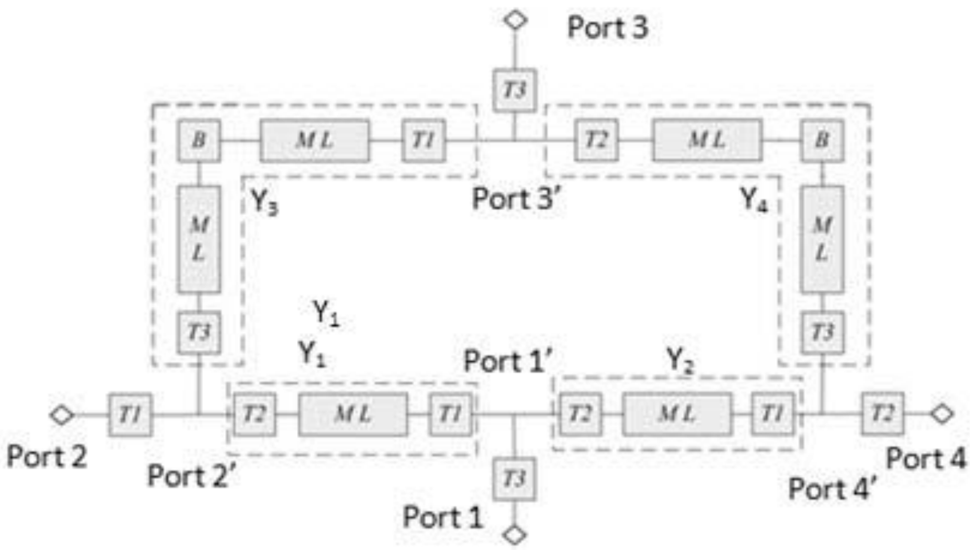


Figure 2.13: Modified 3 ways Bagley rectangular power divider divided into line section and combined appropriate blocks

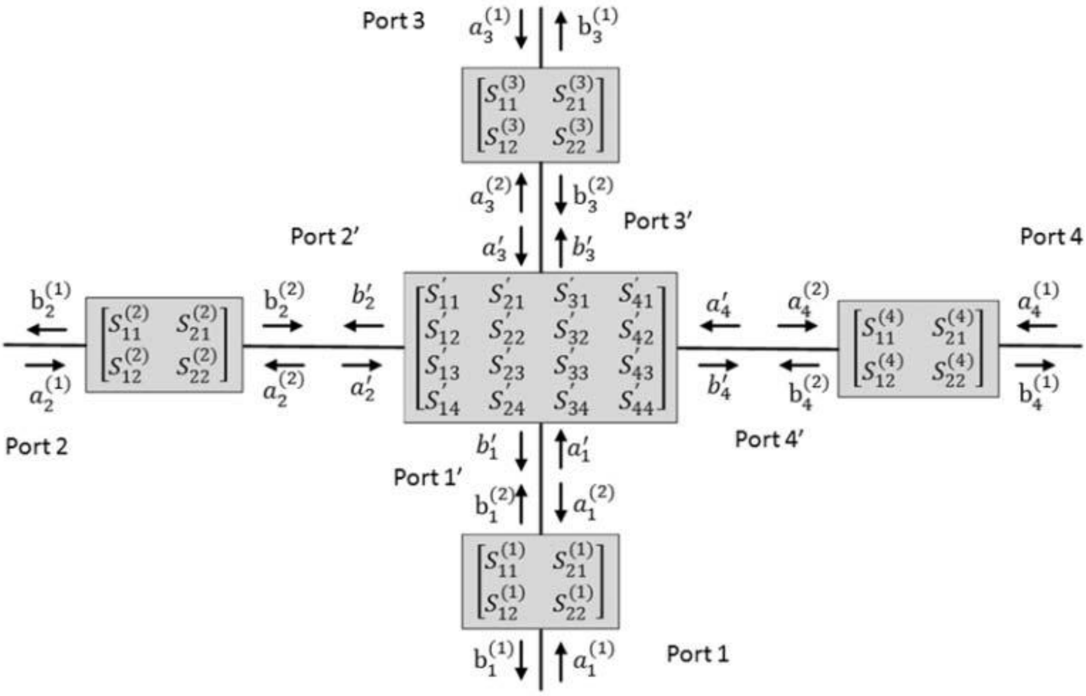


Figure 2.14: Incident and scattered voltage waves on each block

$$[A]=\begin{bmatrix}\frac{1}{S_{21}^{(1)}} & 0 & 0 & 0\\ 0 & \frac{1}{S_{21}^{(2)}} & 0 & 0\\ 0 & 0 & \frac{1}{S_{21}^{(3)}} & 0\\ 0 & 0 & 0 & \frac{1}{S_{21}^{(4)}}\end{bmatrix},\quad [B]=\begin{bmatrix}\frac{S_{11}^{(1)}}{S_{21}^{(1)}} & 0 & 0 & 0\\ 0 & \frac{S_{11}^{(2)}}{S_{21}^{(2)}} & 0 & 0\\ 0 & 0 & \frac{S_{11}^{(3)}}{S_{21}^{(3)}} & 0\\ 0 & 0 & 0 & \frac{S_{11}^{(4)}}{S_{21}^{(4)}}\end{bmatrix}$$

$$[C]=\begin{bmatrix}\frac{S_{22}^{(1)}}{S_{21}^{(1)}} & 0 & 0 & 0\\ 0 & \frac{S_{22}^{(2)}}{S_{21}^{(2)}} & 0 & 0\\ 0 & 0 & \frac{S_{22}^{(3)}}{S_{21}^{(3)}} & 0\\ 0 & 0 & 0 & \frac{S_{22}^{(4)}}{S_{21}^{(4)}}\end{bmatrix},[D]=\begin{bmatrix}\frac{\Delta_1}{S_{21}^{(1)}} & 0 & 0 & 0\\ 0 & \frac{\Delta_2}{S_{21}^{(2)}} & 0 & 0\\ 0 & 0 & \frac{\Delta_3}{S_{21}^{(3)}} & 0\\ 0 & 0 & 0 & \frac{\Delta_4}{S_{21}^{(4)}}\end{bmatrix}$$

$$error=\sum_K\sum_{m=1}^{4}\sum_{n=m+1}^{4}W_{t\,mn}(S_{mn}-G_{mn})^2+\sum_K W_{t1}(S_{11}-G_{11})^2$$

Figure 2.15: The develop function for optimization

In the end, the author developed an algorithm based on the method of least squares for optimizing the Bagley power divider. This algorithm will calculate the error in the system and it is based on the width and lengths of the line section as in Figure 2.12. The author also states that they used the combination of genetic algorithm and conjugate gradient method for minimization of error function as in Figure 2.15.

Then, from the paper, authors selected the substrate RO 4003 with dielectric constant of 3.55, thickness of 20 mil and loss tangent 0.0027. The frequency interval is 10-14 GHz. With the defined design specification, the optimization process is run and the optimum length and width are obtained and designed in simulation software, HFSS and AWR.

The author reviewed the results obtained as the return loss as S11 versus frequency is drawn in Figure 2.16. The transmission coefficients to ports 2, 3 and 4 (as S12, S13 and S14) are drawn in Figure 2.17. The 1-dB bandwidth of transmission coefficients at port 2 and 4 are about 50% which are 10% greater than that of the reflection coefficient at the input port1. The bandwidth of S13 is about 43%. The isolation among ports (2, 3), (3, 4) and (2, 4) as S23, S34 and S24 are drawn in Figure 2.19. The isolation among ports is the phase difference among the signals passing through different path length. The signal phase differences between the input port and output ports are drawn in Figure 2.20 (a). The group delays between the input port and the output ports are drawn in Figure 2.20 (b).

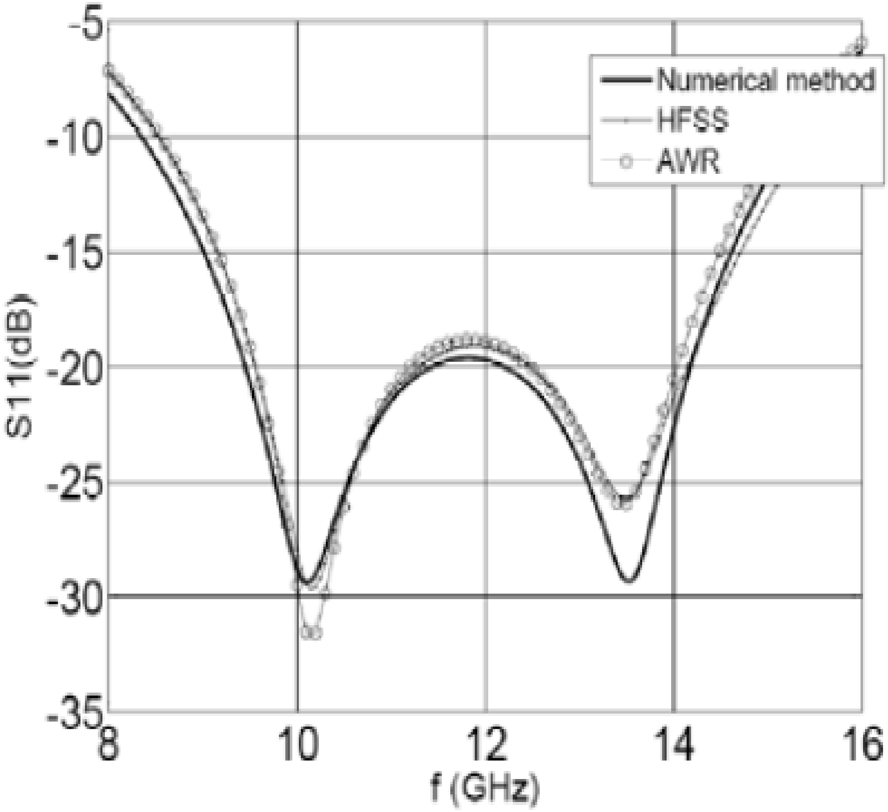
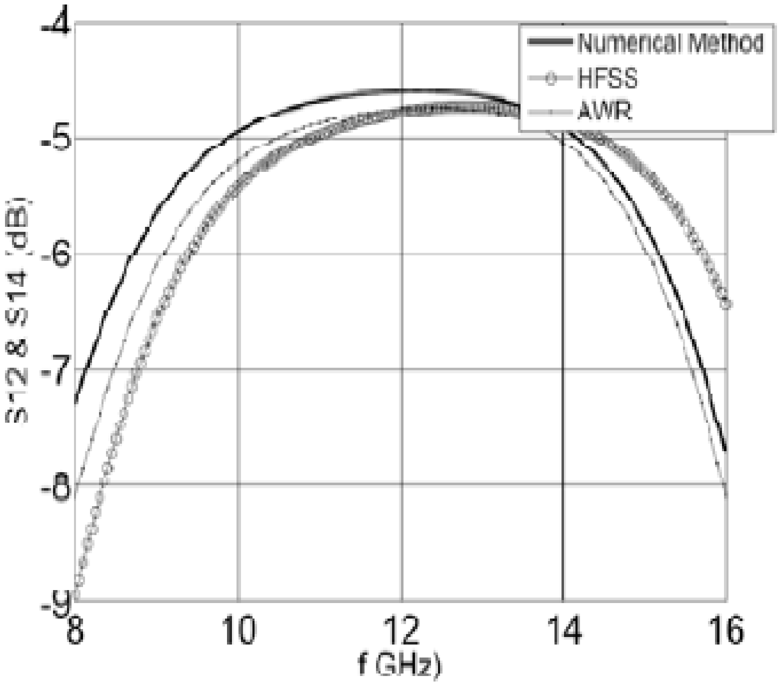


Figure 2.16: The Return Loss

(a)



(b)

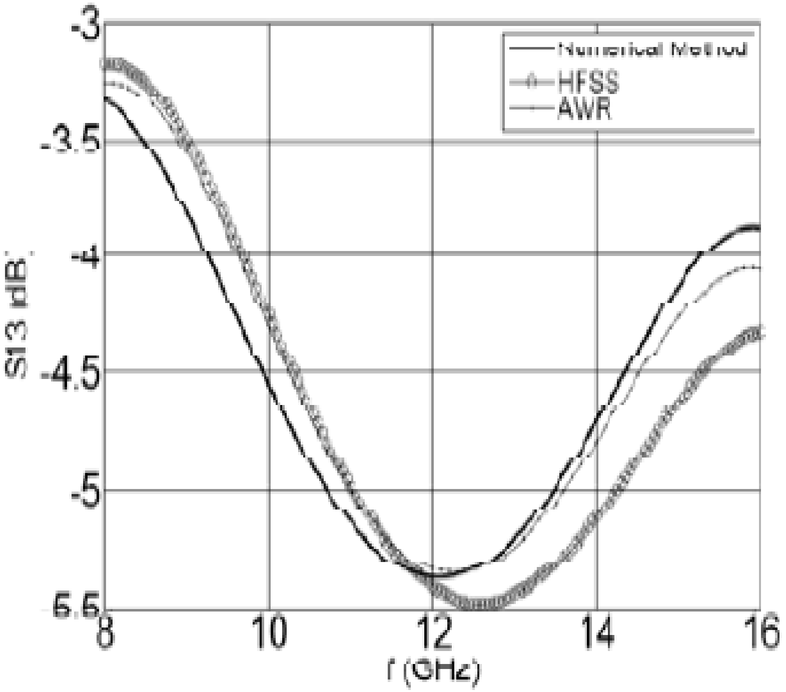


Figure 2.17: (a) Transmission coefficients to ports 2 and 4

(b) Transmission coefficients to port 3

(a)

(b)

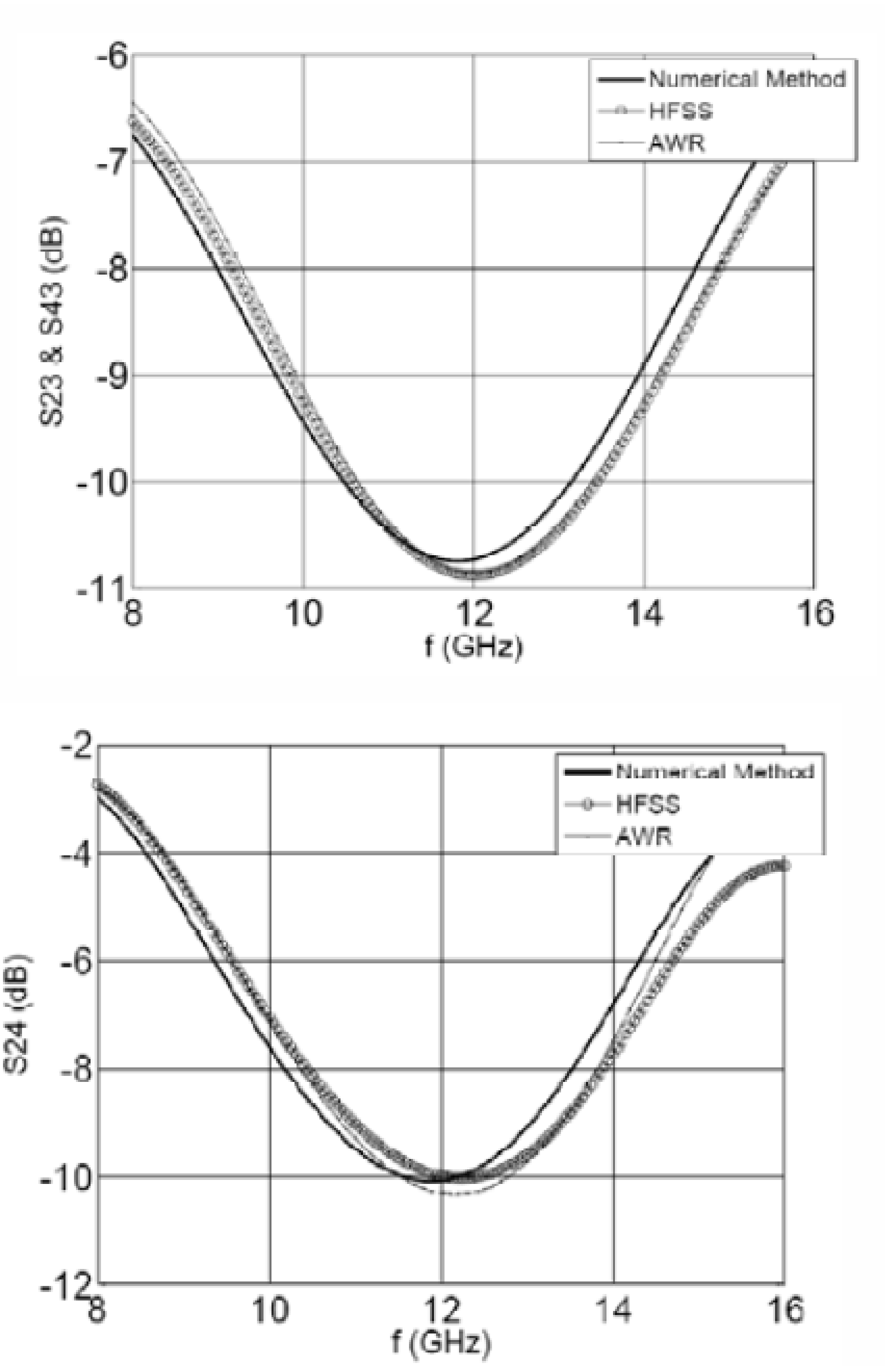


Figure 2.19: (a) Isolation among ports (2, 3) and (3, 4)

(b) Isolation among ports (2, 4)

(a)

(b)

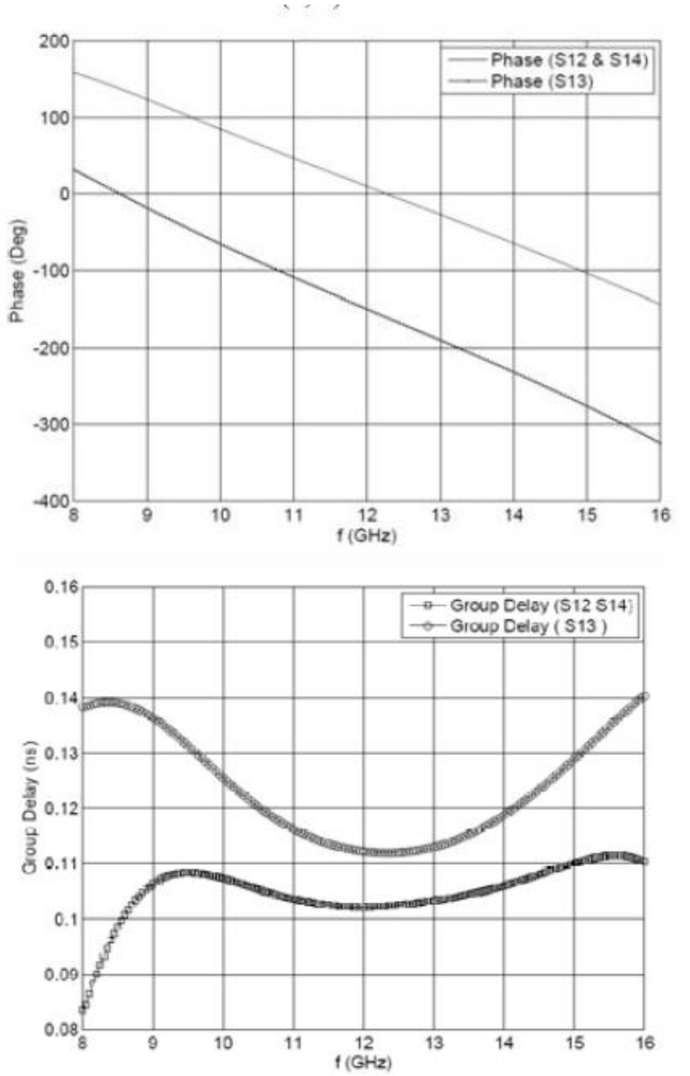


Figure 2.20: (a) Signal phase differences between the input port and output ports (b) Group delays between the input port and the output ports

By analysing the Modified Bagley Rectangular power divider, the return loss from port 1 showed that the dual mode occurred at approximate 10 GHz and 13.5 GHz and having the bandwidth of more than 4 GHz but the transmission coefficient is not equal among the 3 ports. Only the port 2 and port 4 sharing the same characteristic while the port 3 having different transmission coefficient characteristic. This is due to the phase different of the port 3 with the port 2 and 4. For the transmission coefficient of port 2 and port 4, it does not had a flat response along the operate frequency and the transmitted power is not too strong and high rolled off frequency.

There is limitation in the design of this power divider although the isolation among each port in the power divider had been optimized. The author of the paper also noted that there are possibilities of incorporating the impedance matching functions among all the ports into the design procedure. But, this power divider suffered the problem of modification to the number of output port and the it is not a equal 3-ways power divider although it has a total of 4 ports.

2.4 A Multi-Layer Coupled-Line Power Divider

The author reviews Sheng-Jie You and Wen-jiao Liao paper, entitled “A Multi-Layer Coupled Line Power Divider”. This paper presents a coupled line power divider, consists of three layers of traces and two slabs of substrates with 2 way outputs.

From the paper, the top and bottom layer are microstrip line while the middle layer is the common ground. At the power divider location, there is an elliptical metal patch on the both top and bottom layers of the substrate while an elliptical aperture is present on the ground plane. By adjusting the size of the metal patches and the aperture, the power-dividing ratio is controllable. The author of this paper adopted the multi-layer directional coupler structure to formulate a power divider with wider dividing ratio range. In this design, it allows large amount of coupling.

The author of the paper designed the power divider as in Figure 2.21. The overall dimensions of the power divider are 40mm, 20mm and 0.8mm in length, width and height. The operational frequency band is 2 to 3 GHz. For the elliptical design, the axial ratio of the ellipse is 2.17 and the minor radius of the top patch is 2.76mm, the middle aperture is 3mm and the bottom minor radius is 2.2mm in order to obtain the maximum coupling effect.

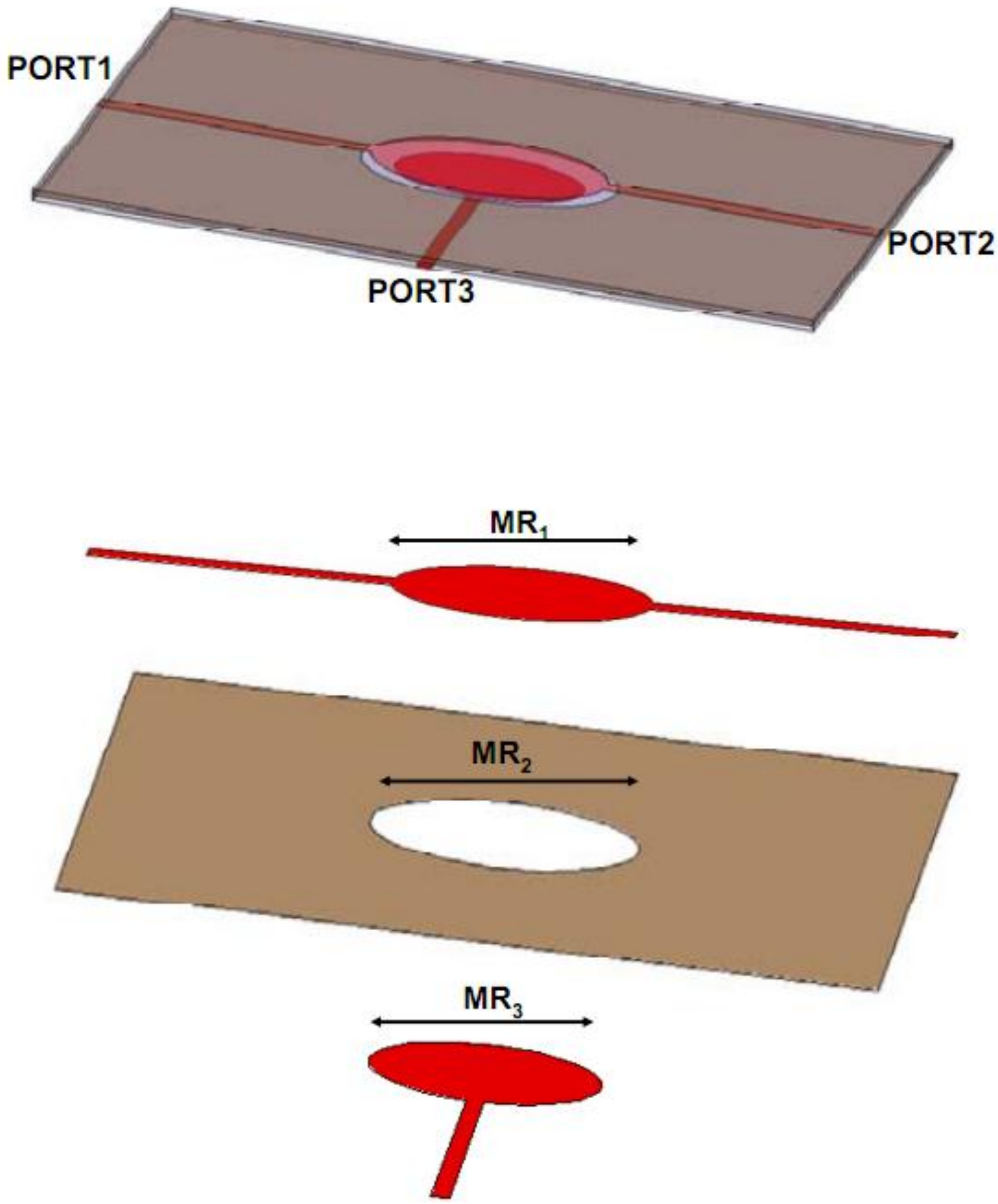


Figure 2.21: The design of multi-layer coupled line power divider

In the Figure 2.22, it shows the fabricated power divider by the authors in the paper. The Figure 2.22(a) showed the top layer of the power divider with an elliptical patch while (b) is the bottom layer of the power divider. The substrate used is FR4 substrate with a thickness of 0.4mm.

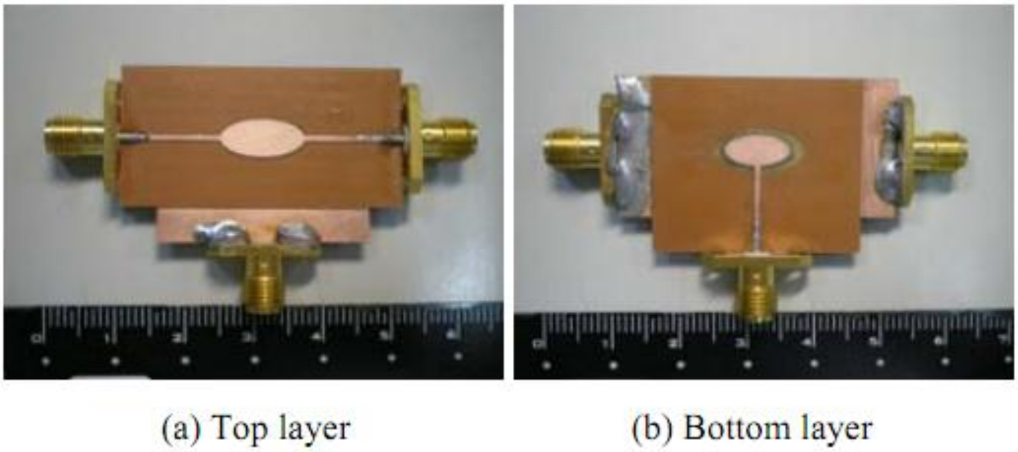


Figure 2.22: Fabricated Power Divider

The authors in the paper simulated and reviewed the result of the power divider. In the Figure 2.23, the graph showed the return loss of the power divider in simulated and experimental results. The S21 and S31, which are the coupled energy or insertion loss, showed in Figure 2.24. Discrepancy found in the measurement and simulation results. The authors in the paper commented that the S parameters are more sensitive to the changes in frequency that can be attributed to defects during the fabrication process.

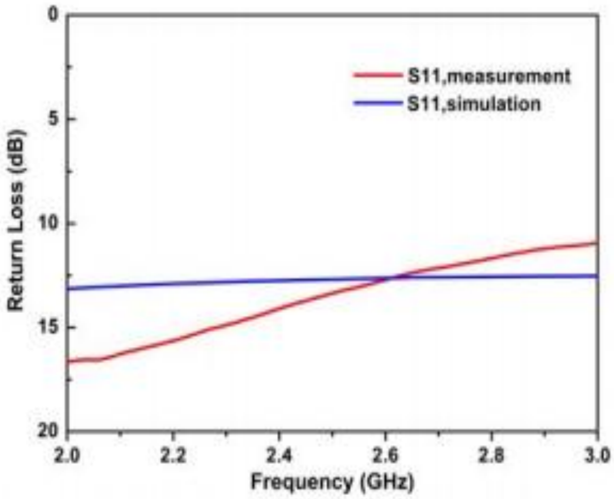


Figure 2.23: Return Loss of the Power Divider

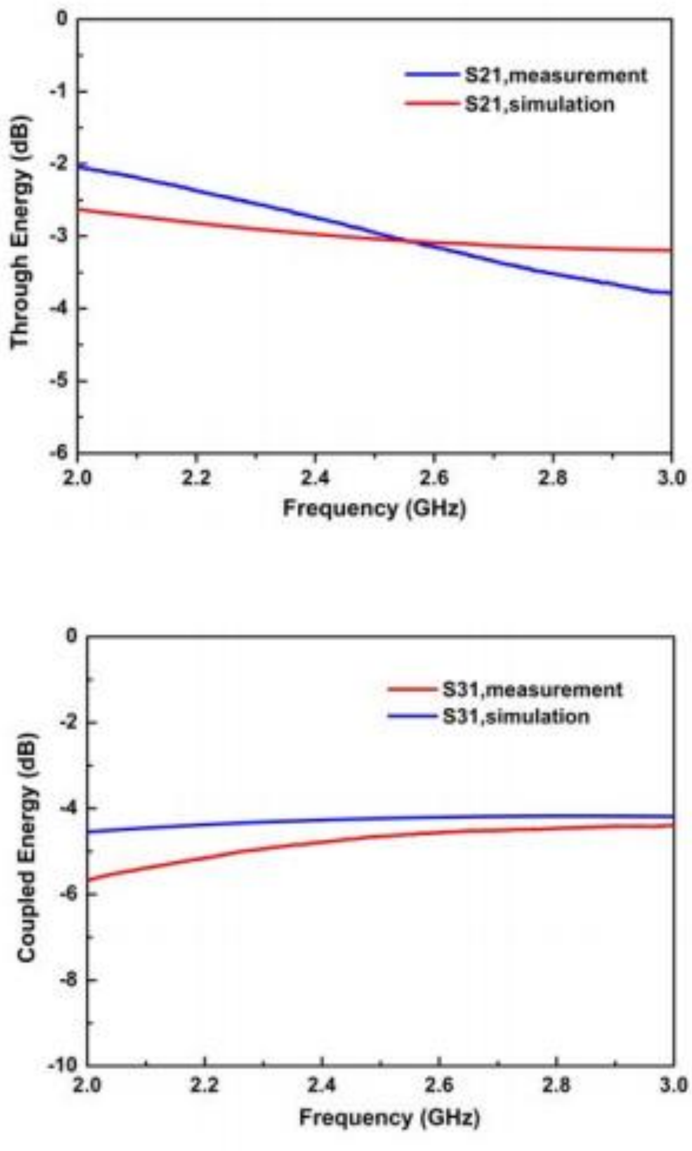


Figure 2.24: Coupled Energy of the Power Divider

CHAPTER 3

METHODOLOGY

3.1 Two-ways Capacitive Coupled Power Divider

The fundamental idea of the Two-ways capacitive coupled power divider is based on paper “Coupled line power divider with compact size and bandpass response” by P.K Singh, S. Basu and Y.H. Wang. In this paper, a power divider integrated with a bandpass filter is present.

In the paper, it showed a working power divider that only enable certain frequency to pass through it and reject the signal outside the frequency range. This is a very useful idea as the design can implement on a system that only want to divide the signal in certain frequency range and filter out the unwanted signal.

The proposed power divider with bandpassing characteristic do show its advantage but also had disadvantages where the design is hard to modified to work in others frequency and the bandpass filter bandwidth is small. Moreover, there is a big difference between the measured result and the simulation result and it is complex to have interconnected wire for grounding the odd mode.

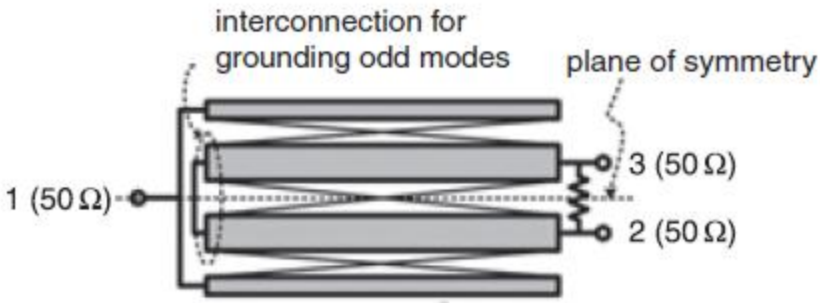


Figure 3.1: Couple line design in paper

Then, from the journal titled "Modified 3-Way Bagley Rectangular Power Divider" by Homayoon Oraizi and Seyyed-Amir Ayati, it shows that the power divider can be in the form of rectangular ring and the length and width of the ring will affect its power transfer characteristics.

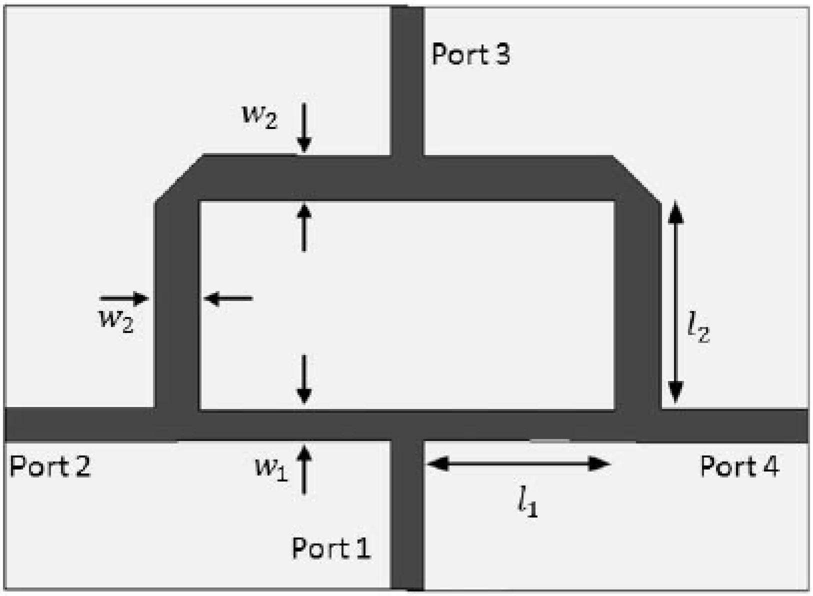


Figure 3.2: Bagley Rectangular Power Divider

3.1.1 Research Methodology

The journals reviewed are useful for author when designing the power divider with bandpass filter. These information and ideas are analyzed in order to come out with a new idea of capacitive coupled power divider. There are three main stages in power divider design, which are simulation stage, fabrication stage, and experiment stage. Different problems arise in each stages and a lot of time is used to obtain precise and accurate result.

3.1.2 Design and Simulation Stages

The software which used in the simulation is the HFSS (High Frequency Structure Simulator). It enables the fast and accurate analysis of high frequency devices such as antennas, filters, couplers, planar and multi-layer structure and SI and EMC effects. Moreover, HFSS is the industry-standard simulation tool for 3D full-wave electromagnetic field simulation and is essential for the design of high-frequency and high-speed component design. The HFSS solver is based on powerful, automated solution process where users are only required to specify geometry, material properties and the simulation settings. Then, HFSS will generate the appropriate solution and accurate mesh for solving the problem using the proven finite elemental method. The software can complete the complex simulation in hours.

In the first step, the author needs to learn how to use the HFSS simulation tool by referring to several tutorials and practical exercises on how to simulate a design with HFSS. These tutorials studied include “Ansoft HFSS Training Example: Aperture-Coupled Patch Antenna” and “Ansoft HFSS Software Demonstration Example: Microstrip Transmission Line”. The author needs to follow instructions and steps listed to plot the simulated result. Not only that, another Ansoft HFSS Training Workbook: Slot Antenna” is reviewed to learn more details into the Ansoft Simulation software. However, there are some small differences in simulation result with the training manual. The variation of results might due to different version of simulation software has been used. So the simulated result generated by HFSS is still acceptable.

After knowing the basic control and functions in the HFSS, supervisor handed a paper titled “A Novel Ka-Band Planar Balun Using Microstrip CPS Microstrip Transition” to the author. The purpose of the task is to analyse and familiarise on how to design and simulate in the HFSS. This is due to in the paper, there is only structure of the design and some importance parameters are given. The author had to think and implement it in the HFSS and simulate the result. With this task, it can ensure and further enhance the author’s knowledge on HFSS software.

Then, supervisor had given several ideas on the design for designing the capacitive coupled power divider such as square ring and rectangular ring design. With the clear understanding on how a power divider works, there is a need to find the resonant frequency of the ring that couple together. The rectangular ring is chosen because from the rectangular shape, the output ring can be easily coupled to the input ring. The resonant frequency of the rectangular ring is obtained by calculate with the formula to find the electrical length. The estimated length is then transformed into the rectangular ring total side length as in the Figure 3.3. The result is analysed by coupling two symmetrical rectangular rings side by side in HFSS. From the results, it showed that the resonant frequency is approximate 3 GHz as in Figure 3.4. This showed that the calculation is correct.

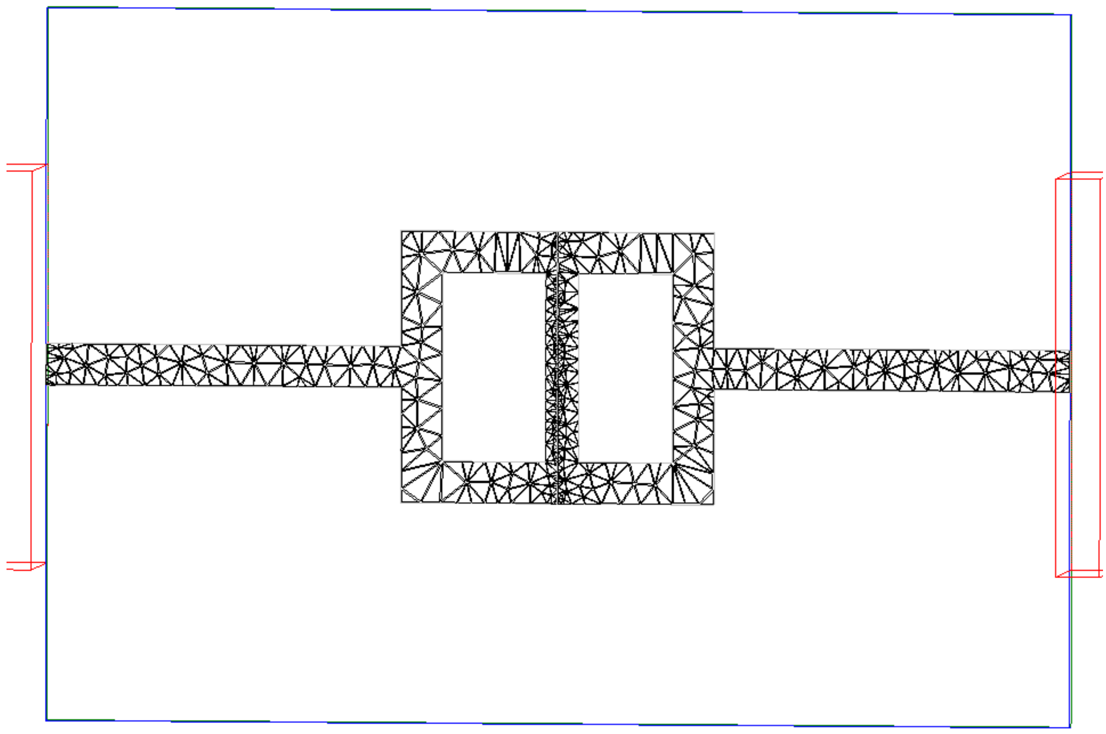


Figure 3.3: Design of the rectangular ring

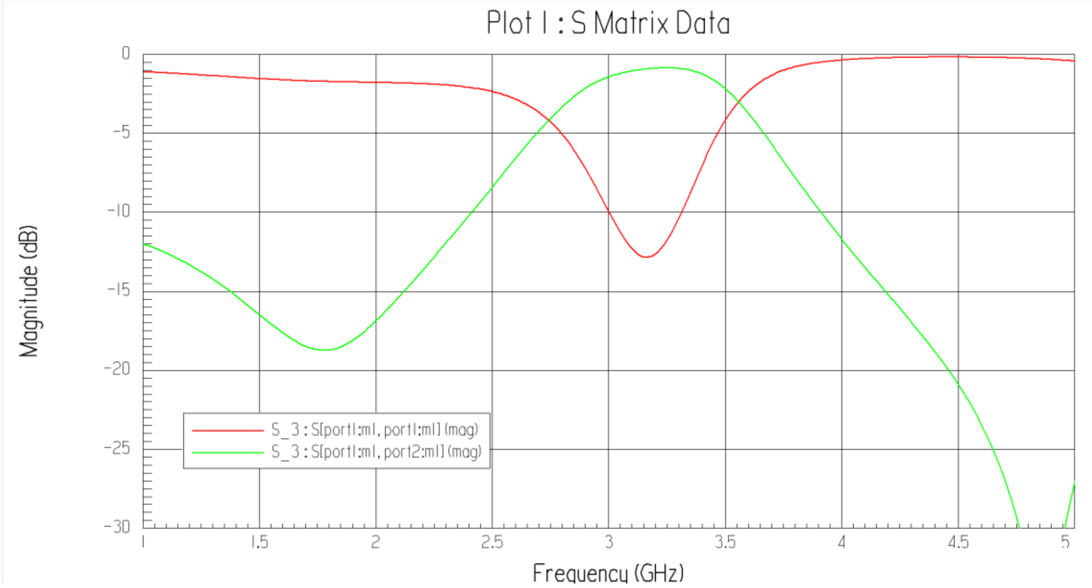


Figure 3.4: Simulation result

Next, two output rectangular rings that coupled to the input rectangular ring is designed in order to make a two-ways power divider with bandpassing characteristic. The main purpose in the design is to obtain the result of good isolation between output ports, high insertion loss, low return loss and reasonable bandwidth in the design. The design is carry out by varying the parameters in the design such as changing the dimension of the rectangular ring, the gaps between each rectangular ring, the location of each port at the rectangular ring and the width at the centre of the ring. Many simulations had done in order to obtain good result.

The weak coupling effect is faced by the author during the design and simulation stage. When there is weak coupling, the reflection coefficient in port 1 is high and less power coupled to the output ports. Moreover, the small bandwidth of the bandpassing characteristic faced by the author. The power divider should design to operate in sufficient bandwidth of approximate 1 GHz.

In the end the final design of the two-way capacitive coupled power divider is as in Figure 3.5. Even a simple simulation may need an hour to complete. Hence, it consumes a lot of author's time. The substrate has a dielectric constant of ε_r = 2.33 and substrate thickness of 1.54mm.

Dimensions of the power divider: g_1 =50 mm, g_2 =0.6 mm, s_1 =6.235 mm, W_1 =2.54 mm, W_2 =5 mm, W_3 =6 mm, W_4 =4.7 mm, W_5 =2.1 mm, W_6 =2.3 mm, W_7 =3.2 mm, d_1 =30.54 mm, d_2 =15.54 mm, d_3 =14.97 mm

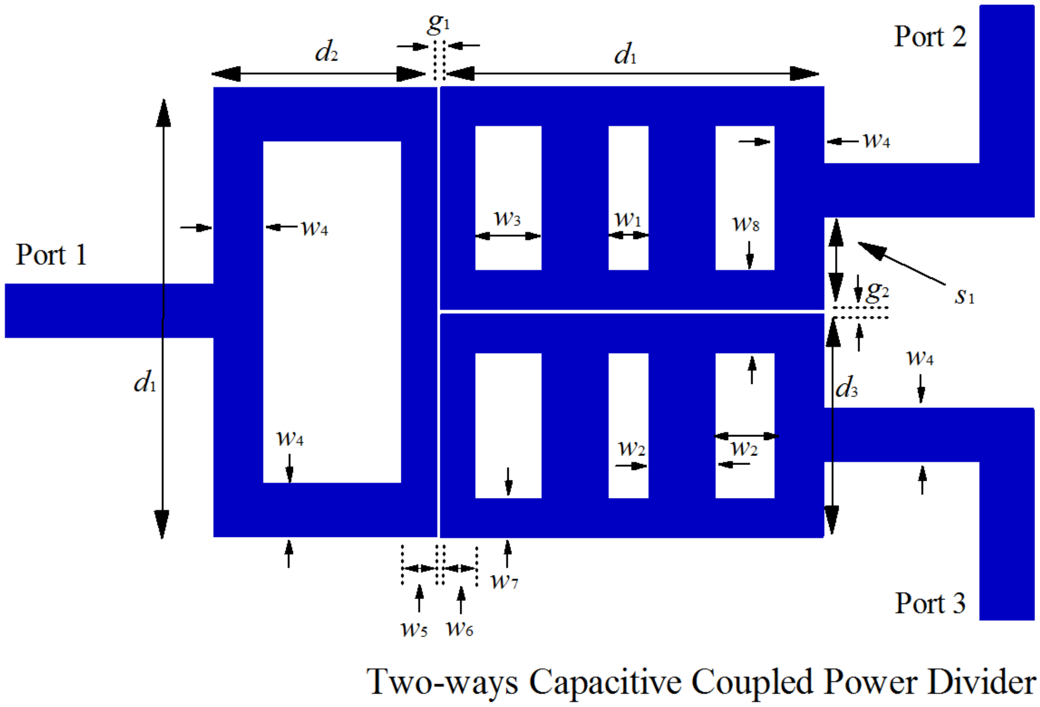


Figure 3.5: Proposed design of two-way capacitively coupled power divider

3.2 Three-ways Capacitive Coupled Power Divider

With the successful design of Two-way Capacitive Coupled Power Divider, the design of the power divider is modified to have a three-way power divider. In this power divider, it coupled the input to three outputs and dividing the input signal equally in the output ports.

In this design, frequency is changed in order to prove that the design could work in others frequency. The process of design and simulation is repeated as in the two-ways power divider but with odd number of outputs, the design is being much difficult to optimize and design. There are many difficulties and challenges faced in the design stages.

The problem faced by author is the unbalance power output among the output ports. More output power is concentrated on the center port among the three output port. Other than that, very weak coupling power is suffered by the design with more output port. The design also suffered high input voltage reflection coefficient and very small bandwidth in the bandpassing characteristic.

In the end the final design of the two-ways capacitive coupled power divider is as in Figure 3.6. The substrate has a dielectric constant of ε_r = 2.33 and substrate thickness of 1.54mm.

Dimensions of the power divider: g_1 =0.1 mm, g_2 =0.1 mm, s_1 =4.535 mm, s_2 =6.135 mm, W_1 =9.7 mm, W_2 =3.73 mm, W_3 =4.7 mm, W_4 =3.355 mm, W_5 =2.4 mm, W_6 =3.3 mm, W_7 =7.49 mm, W_8 =6.69 mm, W_9 =1.93 mm, W_{10} =3.69 mm, W_{11} =3.27 mm, W_{12} =1.6 mm, d_1 =46.11 mm, d_2 =15.54 mm, , d_3 =50.11 mm

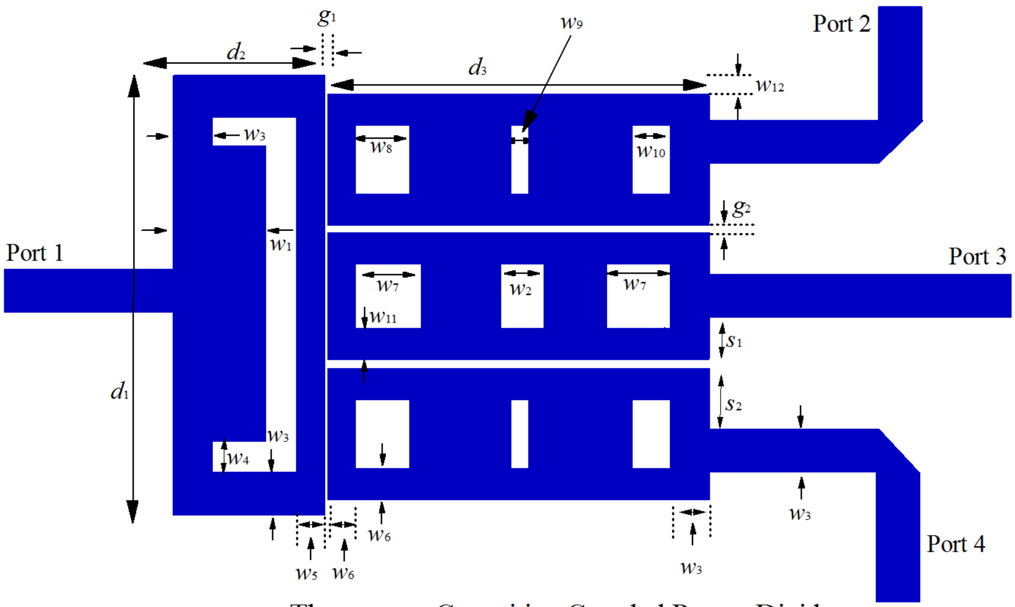


Figure 3.6: Proposed design of three-way capacitive couple power divider

3.3 Fabrication Stage

After the design and simulation stages, the design had to fabricate on the Rogers RT/Duroid substrate. Repeated simulation results are obtained for all the confirmed useful design to ensure there is nothing wrong in the design. This is due to the substrate is very expensive and it should not be wasted on designed flaw. Each fabricated design will cost about RM300 for the substrate board. Hence it is very important for author to optimize and confirm the simulated result before proceeding into this stage. The substrate used in both design is Rogers RT/Duroid 5870 with the dielectric constant of 2.33 with the thickness of 1.54 mm.

3.3.1 Fabrication Method

In order to fabricate the design, photo resist method is used to transfer the design in HFSS to the substrate. The Rogers RT/Duroid 5870 is an UV negative photoresist material. For the negative photoresist material, the UV exposed region will become hardened while the unexposed region is removed in the development process. So, the design appeared on the substrate by the remaining photoresist material.

The working principle of the negative photoresist material is as in Figure 3.7.

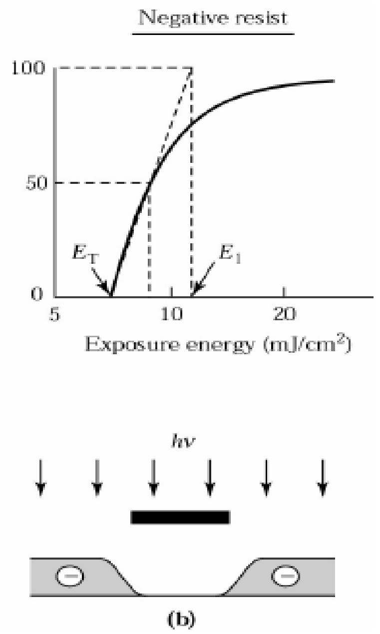
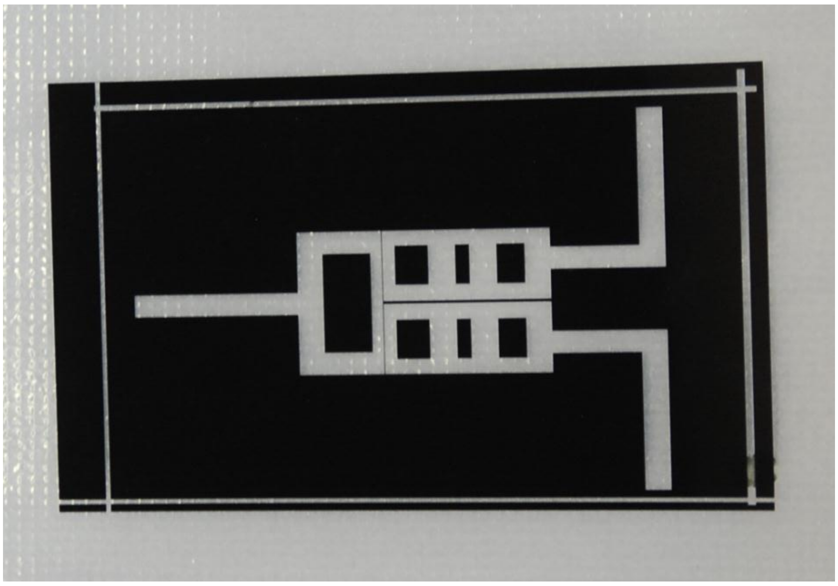


Figure 3.7: Exposure response curve and cross section of the negative resist image after development

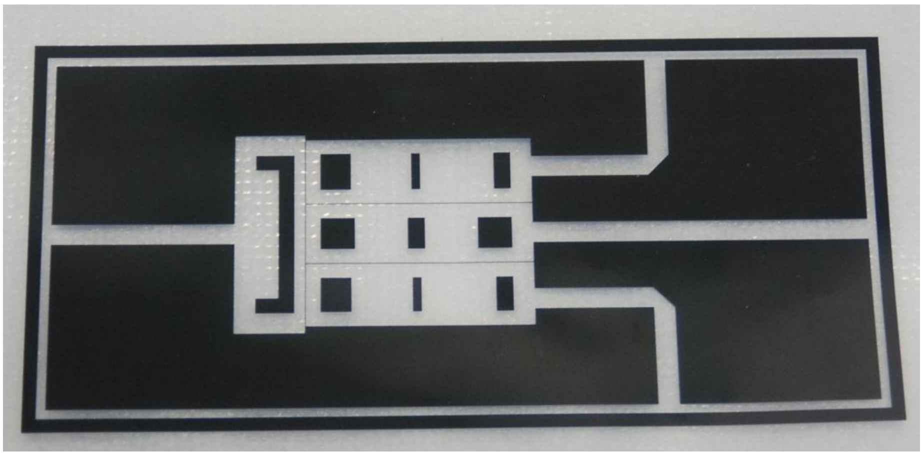
After the development process, the substrate will undergo the etching process. The unprotected area by the photoresist will be etched away during the etching process. So, the mask is needed for the fabrication to be done on the substrate.

First, the substrate is cut to the approximate size of the final design. Next, the design is transferred to a CST Studio Suit software. This is done in order to make a conversion of format from HFSS to the format that recognise by the EAGLE CadSoft software. The EAGLE CadSoft is a powerful tool for designing printed circuit boards due to it can supports up to resolution of 1/10000mm (0.1micro), so this software can print out the exact dimension of the design on the mask. On the other hand, only the top layer of the design is maintained in HFSS during the process of conversion of format. The substrate, ground plane, air box and ports are removed in the HFSS. Then, the top layer design is exported to a file format which the EAGLE CadSoft recognise. All dimensions of the design are maintained during the conversion process.

Then, design in EAGLE CadSoft is printed out on a special type of transparency paper. The transparency paper had two faces, one smooth and one sticky face. The design is printed on the sticky face with a printer. Printer setting is set to the maximum resolution of 2400 X 2400 dpi when printing the mask for the design. This is done so as to reduce the chances of having inaccurate dimension with the design. The dimension of the design is critical in the power divider as the different of 0.1 mm will reflect a big different in the performance of the power divider. The printed mask is shown in Figure 3.8.



(a)



(b)

Figure 3.8: Mask for the design

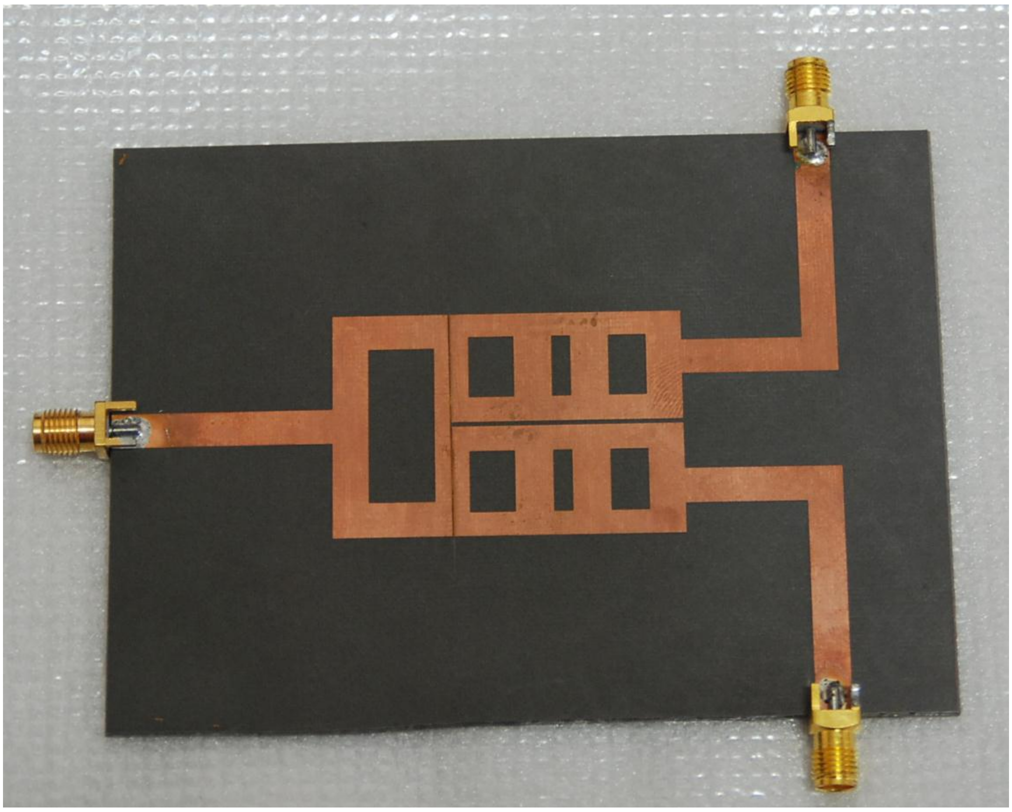
a) Mask for Two-way Capacitive coupled Power Divider
b) Mask for Three-way Capacitive coupled Power Divider

Next, pattern transfer process is done in a dark room to transfer the mask that printed onto the substrate. The process begin with the laminating both side of the substrate with the photoresist material. Care is taken to avoid any air trap between the substrate and the photoresist. The laminating of photoresist is done with a laminating machine with temperature of 110 degree Celsius. Then, the laminated substrate is placed in the UV light exposure box with the mask lying on the substrate. Alignment is carefully done between the mask and the substrate. After that, substrate exposed to UV light with time setting 20 seconds. After exposure, chemical used to etch away the soft photoresist with the remains of hardened photoresist. Designed power divider left on the substrate.

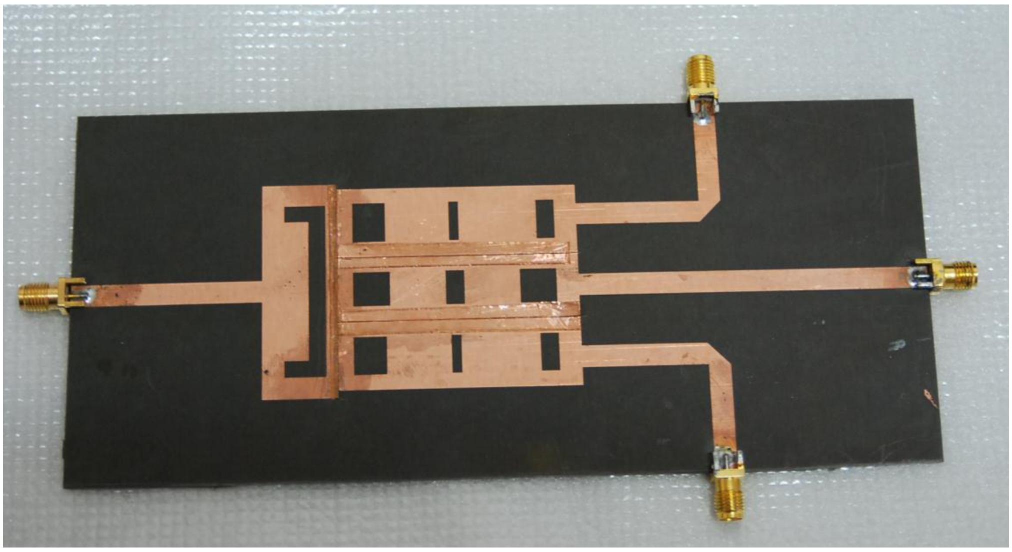
3.3.2 Etching Method

Etching process is carried out after development process. Wet etching is used and the process will chemically remove the copper at the unprotected area of the surface of the substrate. Etching is a carefully done due to over etching the board will make the design useless and it wasted the expensive substrate and time. Time control and patient is the path of success for the etching process. In the both two-ways and three-ways power divider, big challenge faced during the etching process where all the small gaps especially the 0.1mm gaps are very difficult to be etch away. After the wet etching, the photoresist material that remained on the material is cleaned away with chemical. The designed power divider is obtained.

In the two-ways power divider, the unsuccessful etching of gap is carefully cut with penknife to create the gap. Furthermore, the fabrication process had done several times for the two-ways power divider to obtain good experiment results. Same problem faced when fabricating the three-ways power divider. The fabricated two-ways and three-ways capacitive coupled power divider is shown as in Figure 3.9.



(a)



(b)

Figure 3.9: Final Product

a) Two-way Capacitive coupled Power Divider
b) Three-way Capacitive coupled Power Divider

3.4 Experiment Stage

Experiment stage is the last stage. In this stage, the power divider is tested for its frequency response. Before the measurement is made, the SMA connector is soldiered at each ports of the fabricated substrate. The SMA ports are aligned at the centre of the input and output line as in Figure 3.10. This is done to avoid any error in the measurement results.

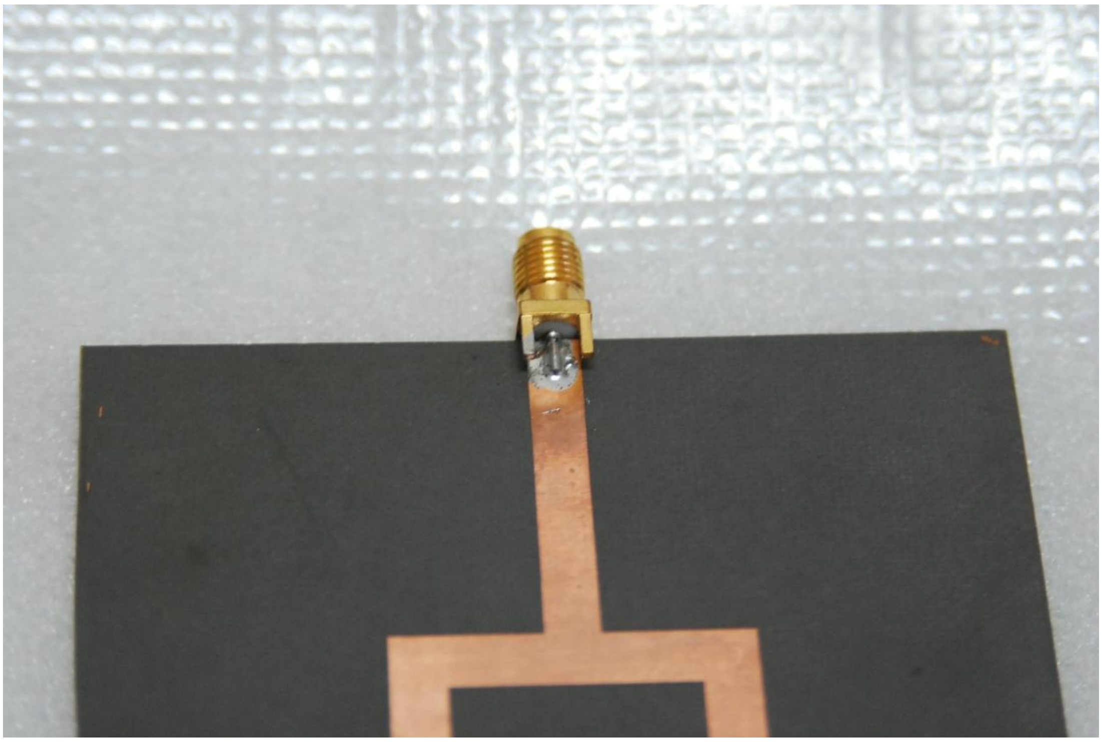


Figure 3.10: SMA connector

Then the Rohde & Schwarz ZVB8 Vector Network Analyser (VNA) as in Figure 3.11 used to measure the results of the capacitive coupled power divider. The VNA is able to detect the frequency range of any device from 300 kHz to 8 GHz and it had two measuring channels.

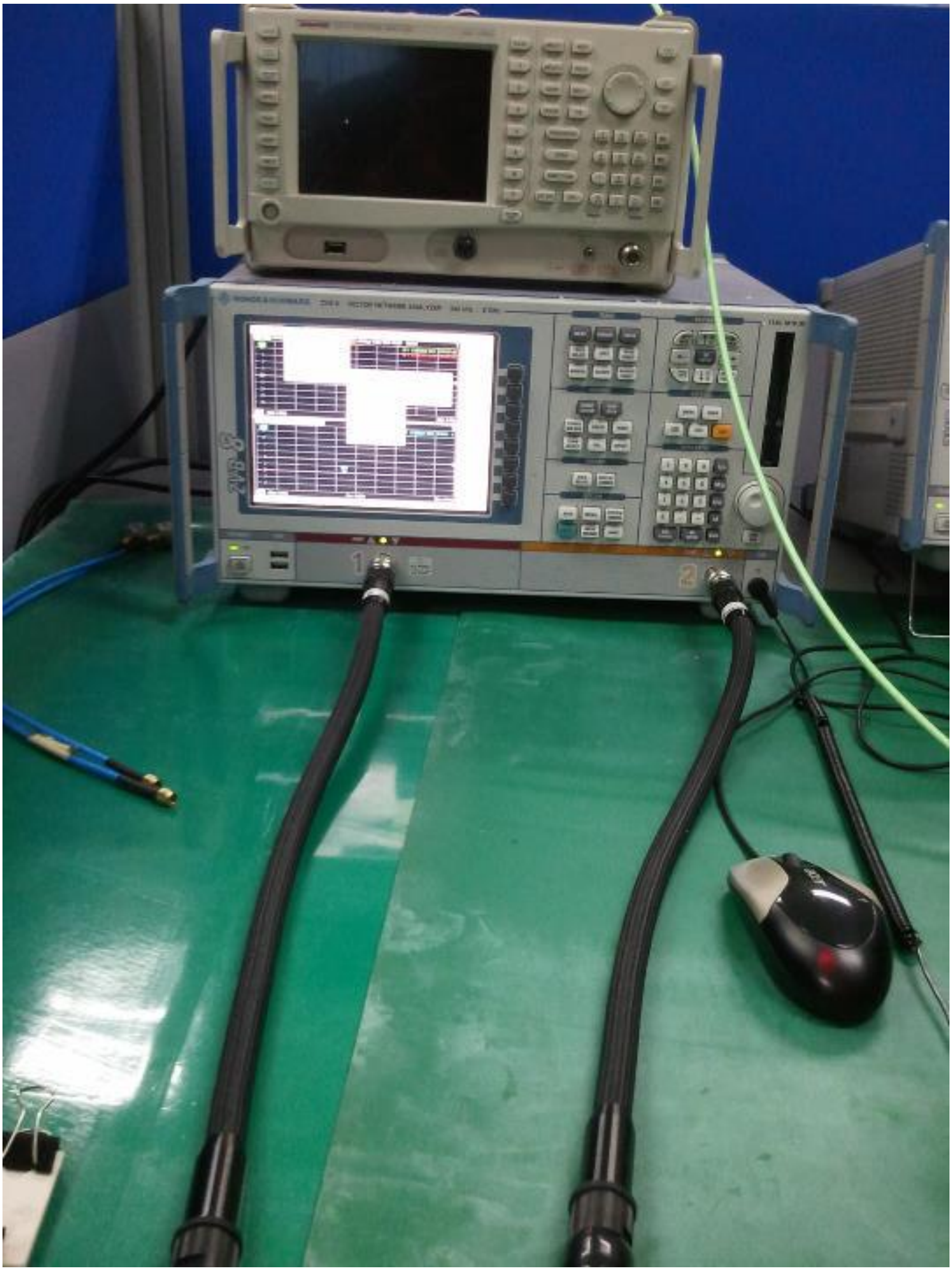


Figure 3.11: Rohde & Schwarz ZVB8 Vector Network Analyser (VNA)

Before the measurement is made, the VNA is calibrated with the Agilent Calibration Kit set as in Figure 3.12. The main purpose of the calibration process is to offset the effect of cable on the measurement. When the VNA is making the measurement of S-parameter, it measured the transmitted and reflected wave. If calibration is not carried out properly, the effect of the waves in cable will be taken into the calculation to generate the S-parameters. In the calibration process, there are 4 types of calibration done which are the open load test, short load test and the matching load test and pass-thru test. The first 3 calibration is done for each of the channel. Then, the VNA measured the accurate results on the power divider. The calibrated setting of the VNA is saved in the device and measurement is begun.

Figure 3.12: Agilent Calibration Kit

Then, the frequency range as in the simulated result of HFSS is set in the VNA and the number of steps is change to 801 in the VNA to obtain accurate results. The measurement is done one by one at the output ports to collect the S-parameters for each port. The results in the VNA then exported out to pendrive and the obtained data are plotted with the freelance graphic software with the result exported from the HFSS simulation. Comparison and analysis carried out between the results. If the power divider perfectly built, the characteristic and response of the power divider should be the same as the simulation results. If there is big variant in the result, then, the fabricated power divider failed and the fabrication process repeated to create the power divider again in order to make measurement again.

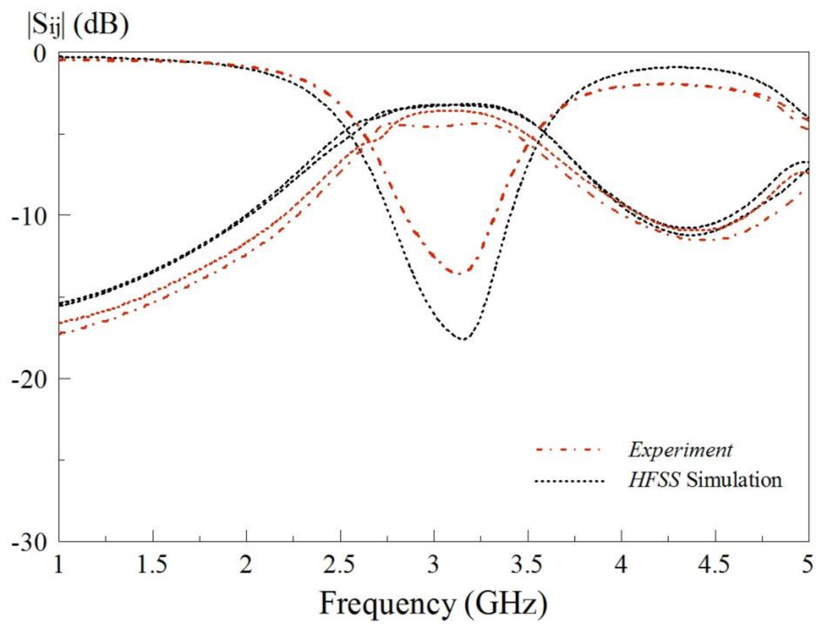
CHAPTER 4

Results and Discussion

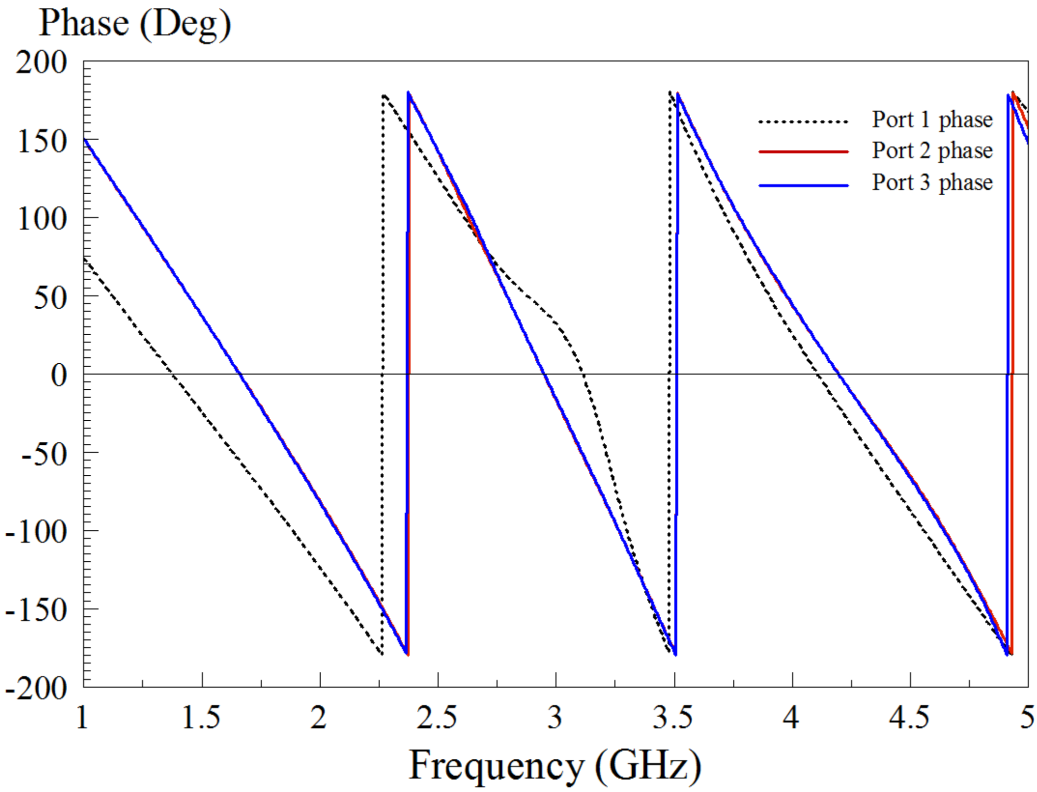
4.1 Result of Two-ways capacitive coupled Power Divider

4.1.1 Result and Discussion

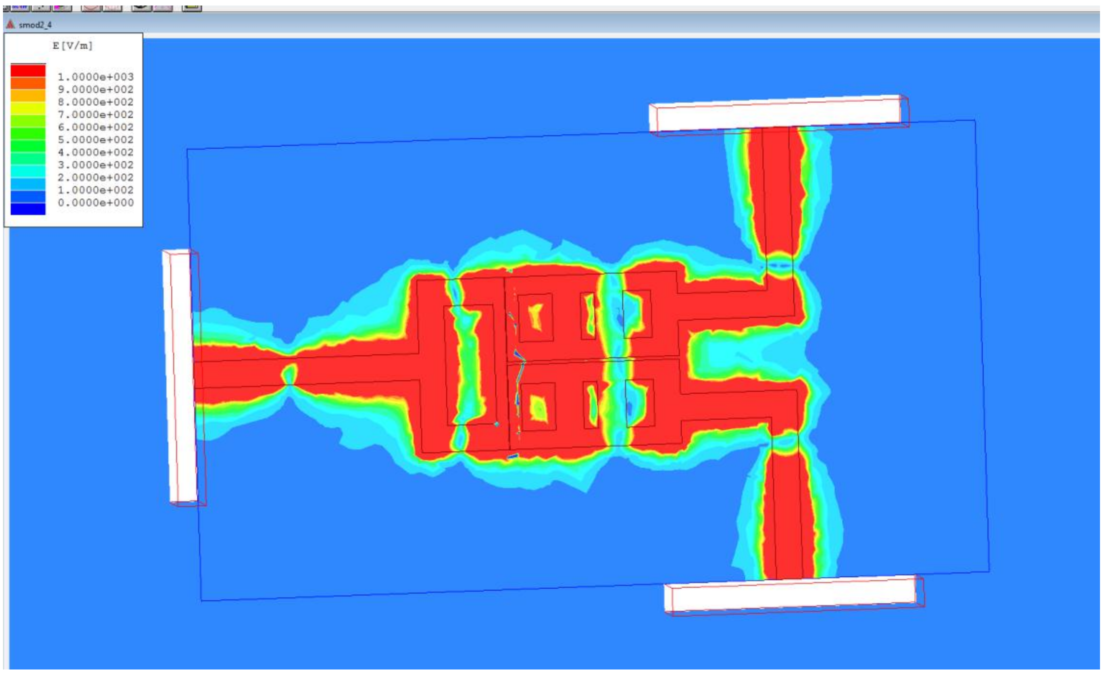
The results obtained by Rohde & Schwarz Vector Network Analyzer ZVB8 (VNA) and the HFSS are plotted together with the Freelance Graphic suite software as in Figure 4.1. Analysis on the S-parameters is carried out on the result. It showed that both result is very similar and only had small difference between the two.



(a)



(b)



(c)

Figure 4.1: a) S-parameter of two-ways power divider

b) Phase different between input port and output ports

c) Electric field distribution

From the Figure 4.1(a), the power is divided in the two output ports and it has a bandpass filter characteristic where the pass-band in the range of 2.625 GHz to 3.5 GHz. From the Figure 4.1(b), it shows that both the output ports are in phase with each other while there is slightly phase different with the input port. From the Figure 4.1(c), the electric field distribution of the power divider at the center frequency plotted in the HFSS simulation software. It shows that the input and outputs port of the power divider are having strong electrical coupling effect.

Then the center frequency, maximum insertion loss, minimum return loss, bandwidth and percentage error between simulation and experiment result is calculated and summarized in the table below.

$$\text{Center frequency} = \frac{\text{Lower Frequency,}fL\text{+ High Frequency,}fH}{2}$$

$$\text{Bandwidth} = \frac{\text{High Frequency,}fH\text{− Lowe Frequency,}fL}{\text{center frequency,}fc} \text{ X } 100\%$$

$$\text{Error} = \frac{|fc\ (measured) - fc\ (simulated)|}{fc\ (measured)} \text{ X } 100\%$$

Table 4.2: Comparison for the results

	Measured	HFSS	% Error
Maximum Insertion Loss (dB)	-3.50	-3.20	9.375
Minimum Return loss (dB)	-13.42	-17.60	23.75
f_L (GHz) / f_H (GHz)	2.625 / 3.5	2.56 / 3.58	2.54 / 2.23
f_c (GHz)	3.0625	3.07	0.24
Bandwidth (%)	28.57	33.22	13.99

From the table 4.2, the maximum insertion loss, high frequency, low frequency and centre frequency is within the 10% difference with the HFSS simulation results. There are discrepancies in percentage of error at the minimum return loss and the bandwidth. This is due to the gap distance between each coupling rectangular is not perfectly fabricated to 0.1mm. The wet etching method is making it hard to etch away the exact dimension of 0.1mm gap and instead the gap will be more then 0.1mm. Then, it caused the weaker capacitive coupling effect between the ports and caused reduced in the minimum return loss and reduced the bandwidth.

4.1.2 Detailed Studies of the power divider

Parametric analysis is studied in this section. Some of the important parameters varied in order to study the effect of power divider with the changed parameter. The result is simulated in the HFSS with the same simulation settings and the result is plotted on the graph. Moreover, it can verify and prove that values selected in configuration are able to perform better compare with other values. However, only one parameter is changed at one time.

4.1.2.1 Gap Distance

In the proposed design, the gap distance, *g1* between the input rectangular ring and both the output rectangular rings is 0.1mm and simulated result represented in the black colour dotted line in Figure 4.3. The gap distance will determine the capacitive coupled effect between the input and outputs. It also affects the bandpass filter characteristic of the power divider. From the result, when the gap distance reduced to 0.07mm, the S-parameter of the S_{11} became approximate -5dB where there is a weak power transfers. Then, when the gap distance increased to 0.2mm, S-parameter of the S_{11} became approximate -10dB. Therefore, the best gap distance is at 0.1mm where the return loss of is at the lowest at approximate -20dB.

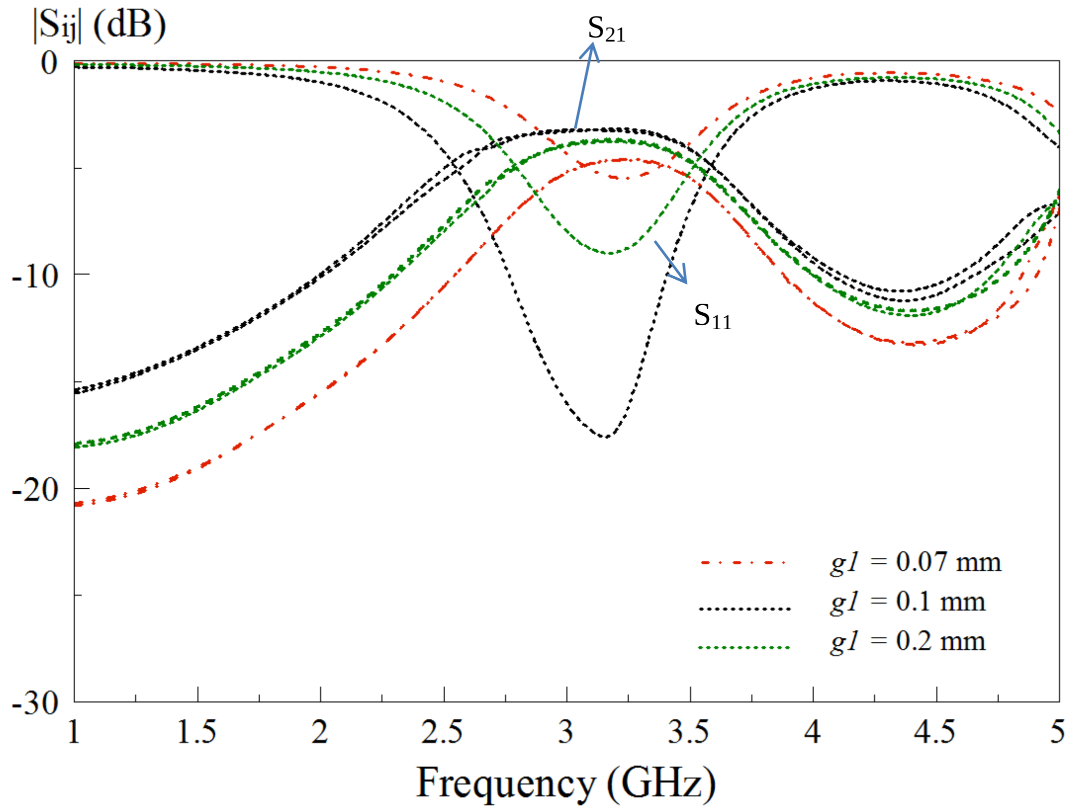


Figure 4.3: Effect of changing gap distance *g1*

In the proposed design, the gap distance, *g2* between both the output rectangular rings is 0.6mm and simulated result represented in the black colour dotted line in Figure 4.4. The gap distance will determine the capacitive coupled effect between the input and output. When changing the gap distance it affect the isolation effect between the output port and causing different return loss. From the result, when the gap distance increased or reduced by 0.1mm, the S-parameter of the S_{11} became less than -5dB where the return loss is high.

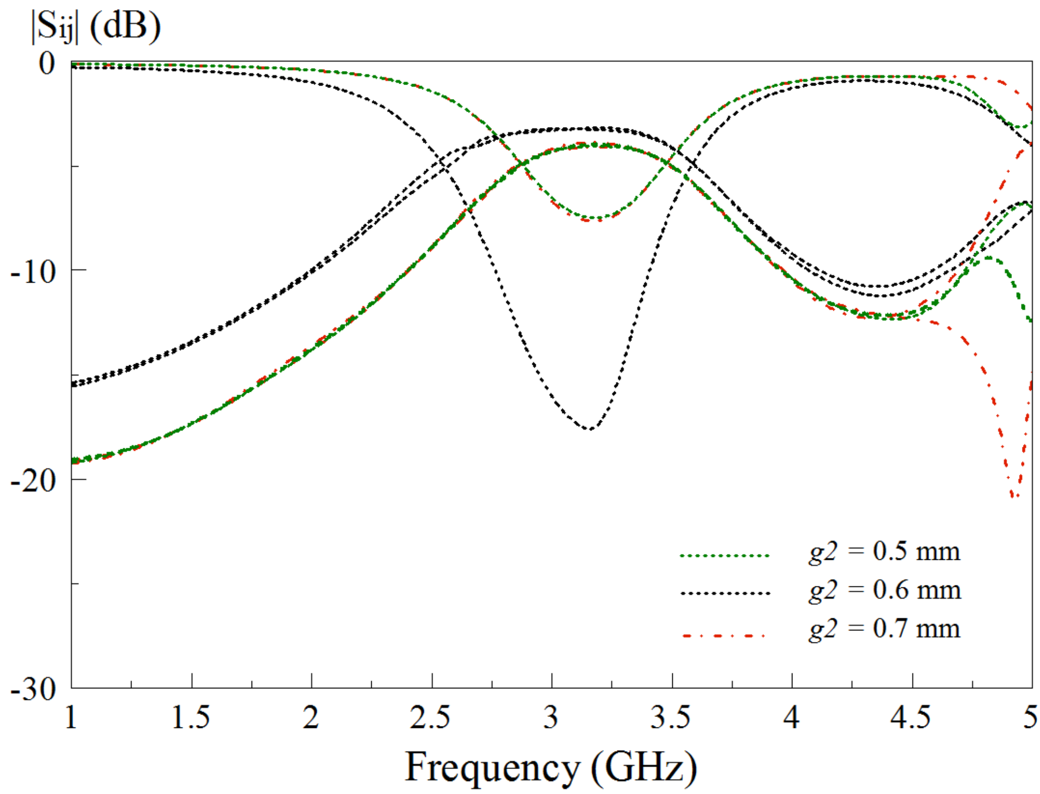


Figure 4.4: Effect of changing gap distance *g2*

4.1.2.2 Width of cavity

In the proposed design, there is a cavity in the center of the two output rectangular ring, *w3*. The width is 2.54mm. The simulated result is represented in the black colour dotted line in Figure 4.5. From the result, it showed that when the width reduced to 2.44mm, the S-parameter of the S_{11} had a flatter bottom and wider bandpass frequency but the S_{21} and S_{31} became unequal. This is something that should not appear in the power divider while increasing the width caused the weaker response of the power divider.

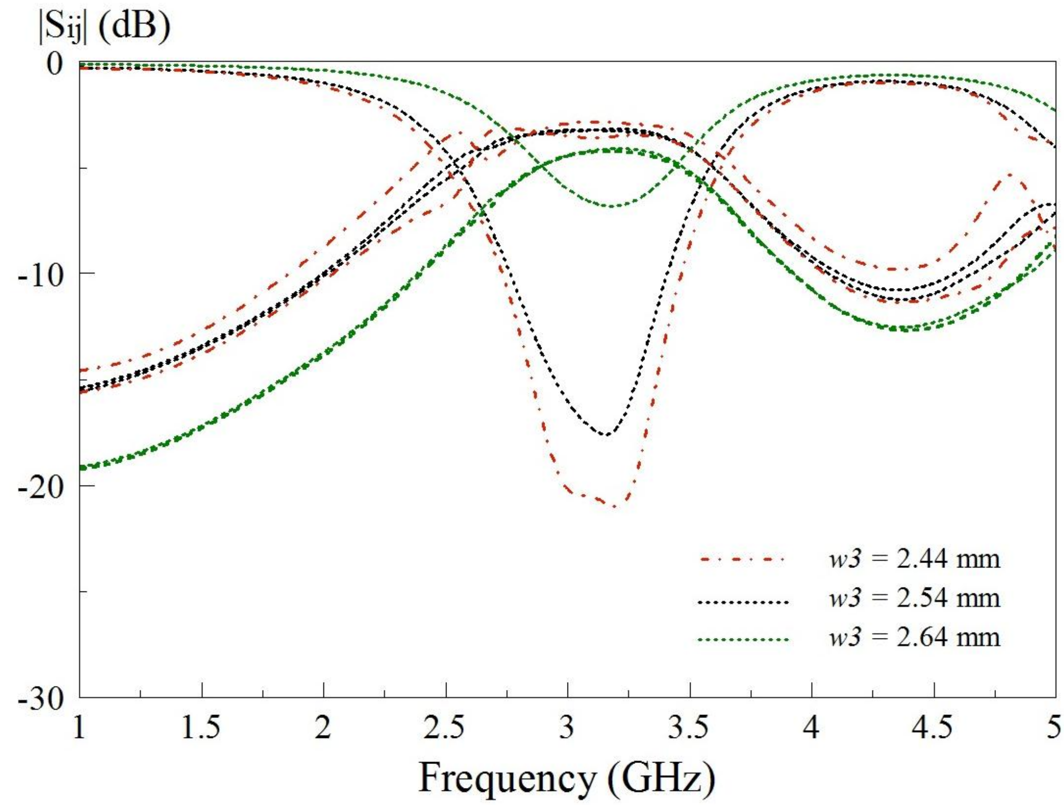
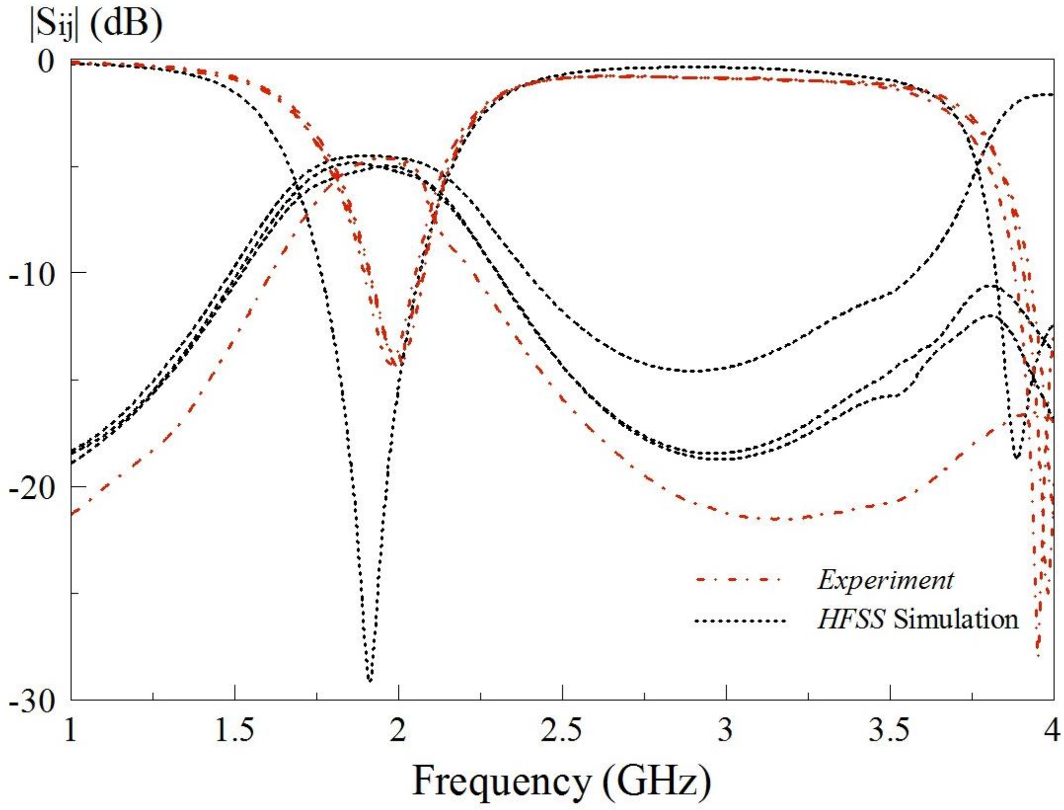


Figure 4.5: Effect of changing gap distance *w3*

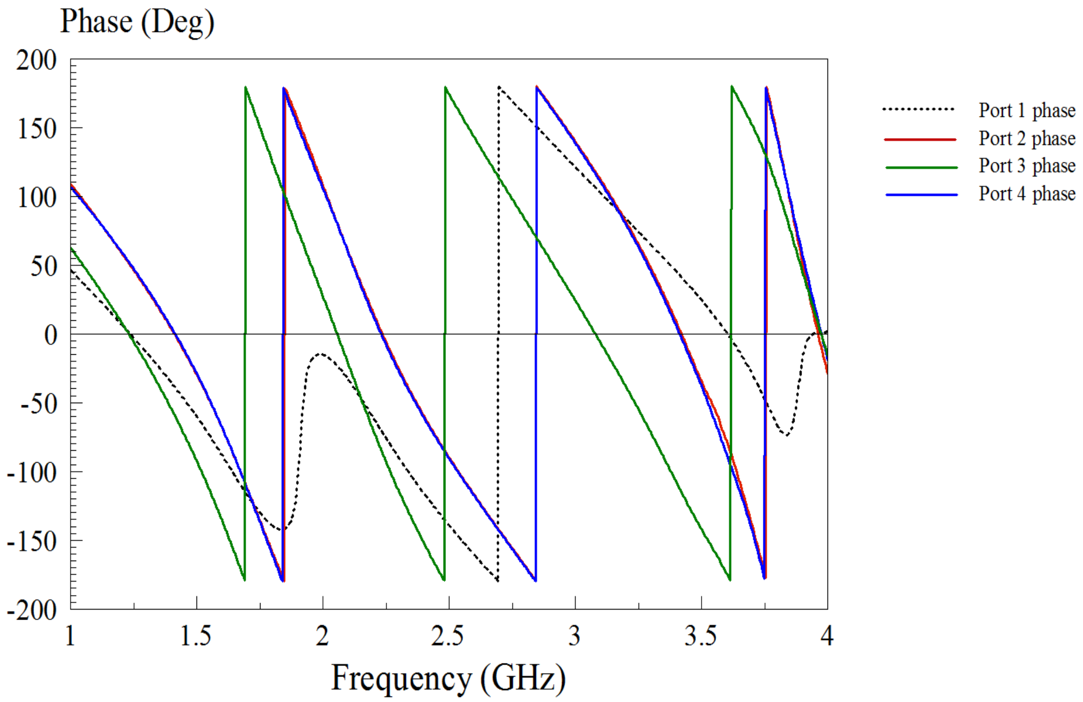
4.2 Result of Three-ways capacitive coupled Power Divider

4.2.1 Result and Discussion

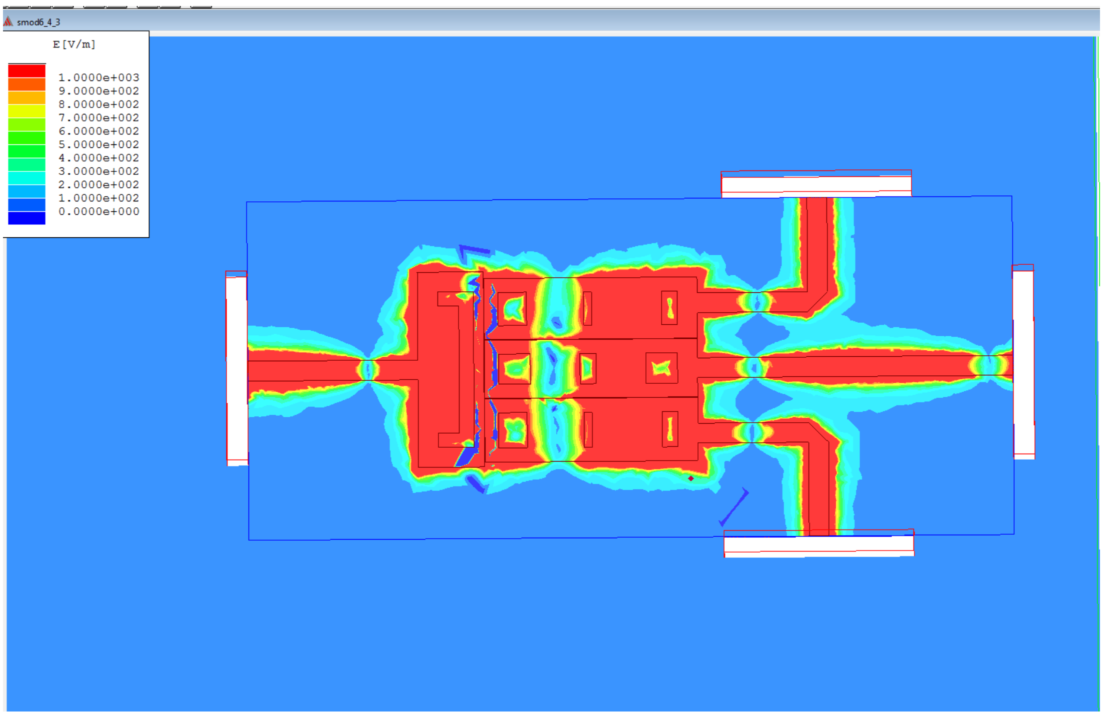
The results obtained by Rohde & Schwarz Vector Network Analyzer ZVB8 (VNA) and the HFSS are plotted together with the Freelance Graphic suite software as in Figure 4.6. Analysis on the S-parameters carried out with the results. It showed that there are some differences between the two results.



(a)



(b)



(c)

Figure 4.6: a) S-parameter of three-ways power divider

b) Phase different between input port and output ports

c) Electric field Distribution

From the Figure 4.6 (a), the power is divided among the three output ports and it has a bandpassing characteristic where the passband frequency is in the range of 1.8125 GHz to 2.125 GHz. In the Figure 4.6 (b), the port two and port three signals are in phase but not in phase with port four. Then the center frequency, maximum insertion loss, minimum return loss, bandwidth and percentage error between simulation and experiment result is calculated and summarized in the table below. From the Figure 4.1(c), the electric field distribution of the power divider at the center frequency plotted in the HFSS simulation software. It shows that the input and outputs port of the power divider are having strong electrical coupling effect.

$$\text{Center frequency} = \frac{\text{Lower Frequency}, fL + \text{High Frequency}, fH}{2}$$

$$\text{Bandwidth} = \frac{\text{High Frequency}, fH - \text{Lowe Frequency}, fL}{\text{center frequency}, fc} \text{ X } 100\%$$

$$\text{Error} = \frac{|fc\ (measured) - fc\ (simulated)|}{fc\ (measured)} \text{ X } 100\%$$

Table 4.7: Comparison for the results

	Measured	HFSS	% Error
Maximum Insertion Loss (dB)	-3.80	-4.51	15.74
Minimum Return loss (dB)	-14.81	-29.18	49.24
f_L (GHz) / f_H (GHz)	1.8125 / 2.125	1.69 / 2.13	7.39 / 0.234
f_c (GHz)	1.968	1.91	3.04
Bandwidth (%)	15.88	23.03	31.04

From the table 4.7, only the pass-band frequency and the centre frequency had a percentage error that less than 10% between the simulation results and the experimental results. The discrepancy in simulation results is mainly due to the gaps distance of the structure. In the design of the three-way power divider, the design is being pushed to the very limit to obtain the good result. There are more 0.1mm gaps in the design compared to the two-ways power divider. Two-repeated fabrication carried out on the design to obtain the good result, but the gaps in the fabricated power dividers are still not the exact dimension and caused the unsatisfying results. The only way of getting the good result is using the laser trimming method where the exact gap distance is trimmed by laser cutter but this equipment is not available in UTAR facilities.

4.2.2 Detailed Studies of the power divider

The parametric analysis will be studied in this section. In this section, some of the important parameters are varied in order to study the effect of power divider with the changed parameters. The result is simulated in the HFSS with the same simulation settings and the result is plotted on the graph. Moreover, it can verify and prove that values selected in configuration are able to perform better compared with other values. However, only one parameter is changed at a time.

4.2.2.1 Changes of width

In the proposed design, the width, *w1* at the input rectangular ring is 9.7mm and simulated result represented in the black colour dotted line in Figure 4.8. This width is added to add its capacitive effect to be coupled to the output port. When this width is varied, it has small effect to the reflection coefficient of the S_{11} but only affect the S_{12}, S_{13} and S_{14}. It caused the unequal power division among the output ports.

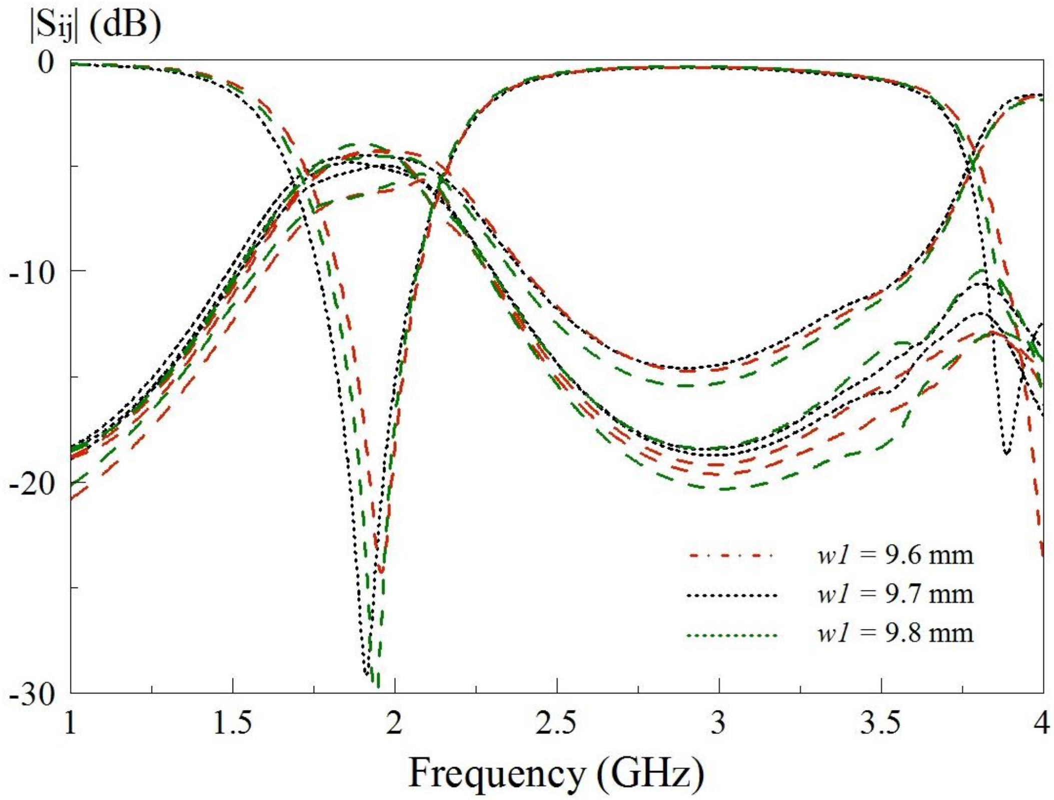


Figure 4.8: Effect of changing gap distance *w1*

In the proposed design, there is a cavity in the center of the middle output rectangular ring, *w2*. The width is 3.73mm. The simulated result is represented in the black colour dotted line in Figure 4.9. From the result, it showed that when the width reduced to 1.93mm, where it is the same width as the other two output port, it caused the unequal power division in the power divider. On the other hand, increasing the width by 0.2mm, the S-parameter of the S_{12}, S_{13} and S_{14} had less changes and the resonant frequency had slightly shifted to right.

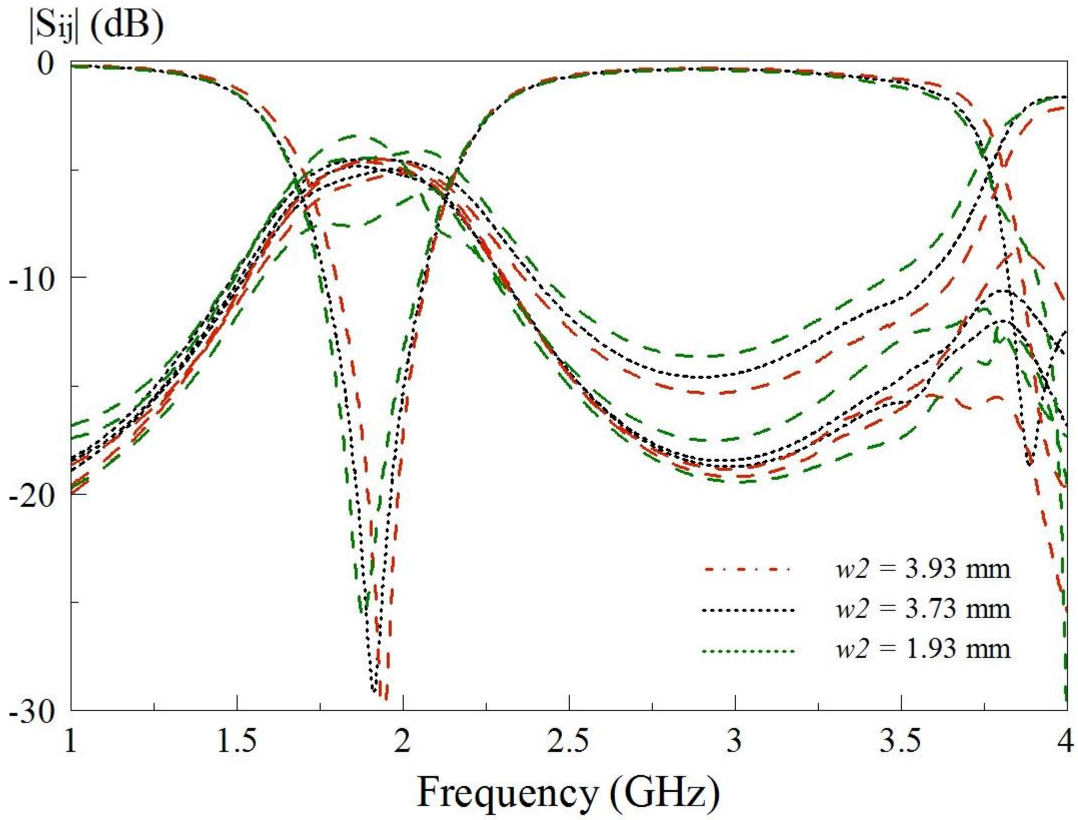


Figure 4.9: Effect of changing gap distance *w2*

4.2.2.2 Gap Distance

In the proposed design, the gap distance, *g1* between the input rectangular ring and both the output rectangular ring is 0.1mm and simulated result represented in the black colour dotted line in Figure 4.10. The gap distance will determine the capacitive coupled effect between the input and output and the resonant frequency. It also affects the bandpass filter characteristic of the power divider. From the result, when the gap distance increased to 0.15mm, the S-parameter of the S_{11} became approximate -20dB where it increases the return loss, reducing the performance. Then, when the gap distance increased to 0.2mm, S-parameter of the S_{11} became approximate -15dB. So, the best gap distance is at 0.1mm where the return loss of S_{11} is at the lowest at approximate -30dB and with the widest bandpassing characteristic.

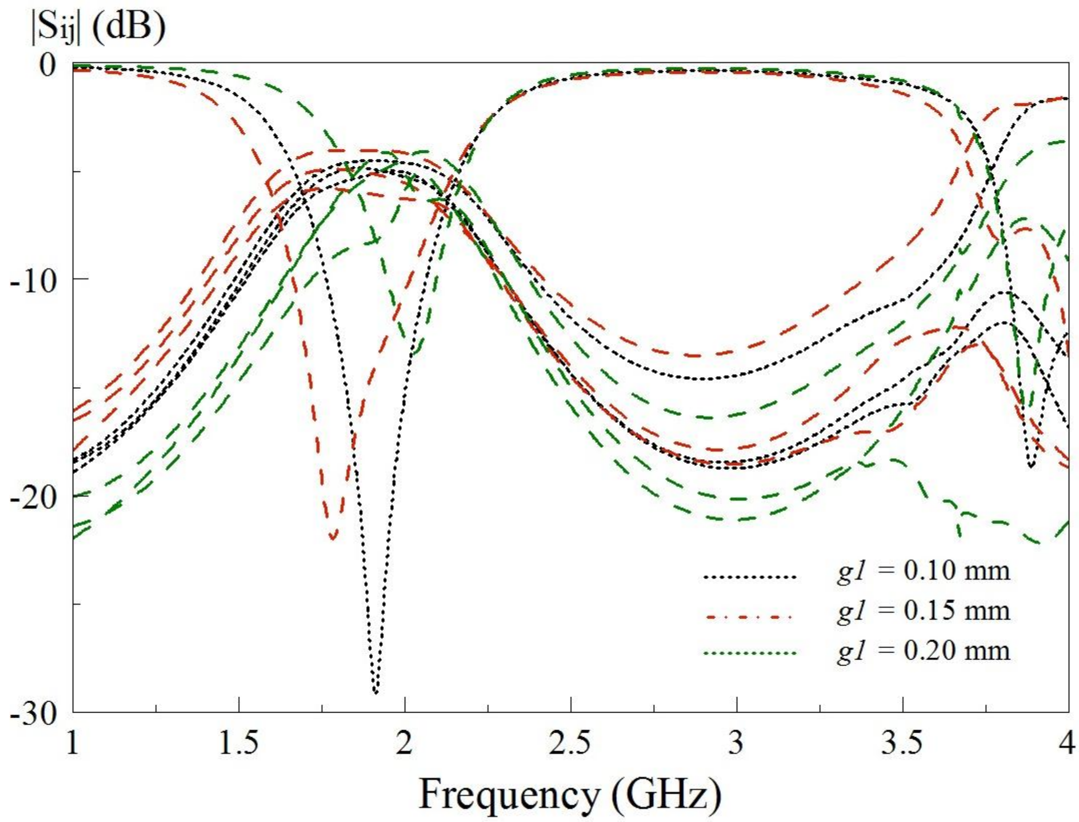


Figure 4.10: Effect of changing gap distance *g1*

In the proposed design, the gap distance, *g2* between both the output rectangular rings is 0.10 mm and simulated result represented in the black colour dotted line in Figure 4.11. The gap distance will determine the capacitive coupled effect between the input and output. When increasing the gap distance, it affects output power of the middle output port, the output power tend to concentrate more on the middle output port.

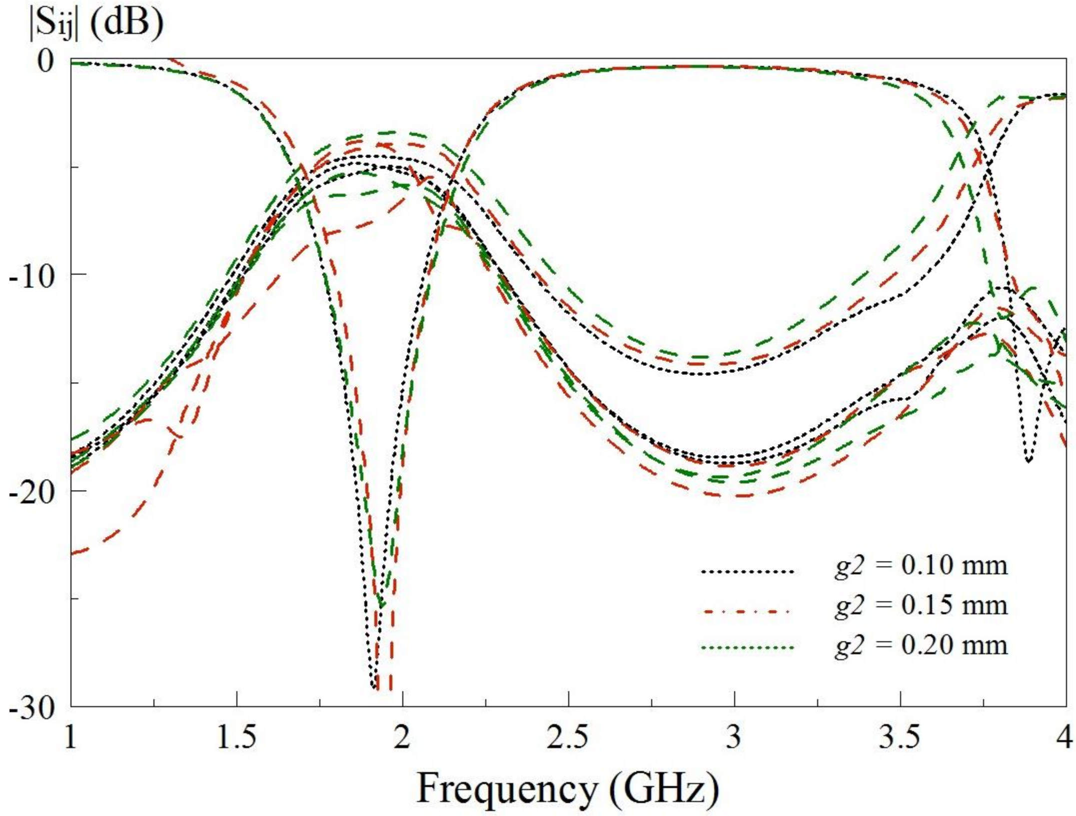


Figure 4.11: Effect of changing gap distance *g2*

4.2.2.3 Location of ports

In the proposed design, the *s2* is 4.175 mm. When the output line tend to move toward the middle port, the output response of the power divider will change and cause 3 different level of output power as in Figure 4.12. The *s2* used to optimize the insertion loss of the outputs.

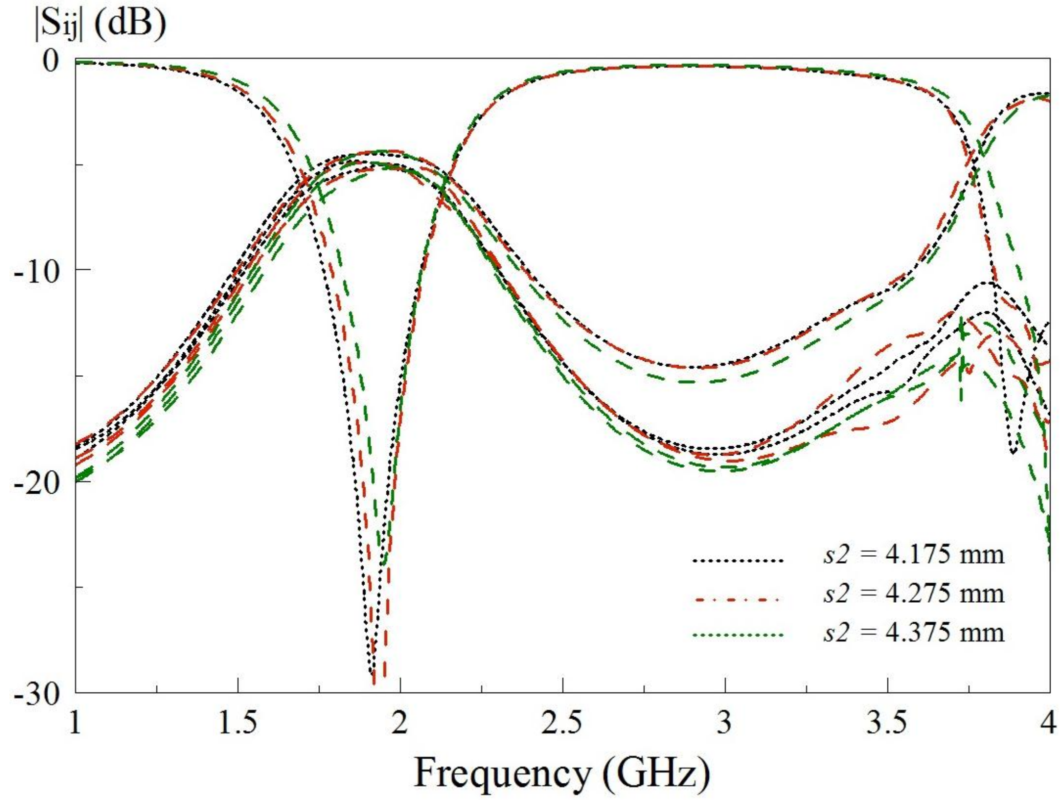


Figure 4.12: Effect of changing gap distance *s2*

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this project, the idea of capacitive coupled power divider is proposed. It can implement as two-way and three-way power divider. It also has the bandpassing characteristic where we can filter a signal and as a power divider at the same time. It is proved in the case study. The design is very new and no people had implement power divider in this way. Ansoft HFSS simulation software is mainly used to carry out the design and simulation stage. The experimental results agree reasonably well with simulation results. The fabrication stage is the main quality control in this design in order to make the power divider to operate perfectly. With slight different in dimension it could altered the response of the power divider and bandpass filter characteristic.

In conclusion, a two-ways and three-ways capacitive coupled power divider has been studied. Software and hardware are designed successfully. The reasonable agreement between the measured and simulated results is obtained. The objectives of this project have been achieved.

5.2 Recommendation

The microstrip that designed and fabricated can be reduced in size with using substrate that having high dielectric strength. The dimension of the power divider can be greatly reduced but the down side is the fabrication process will be more challenging as the gaps, width and length will be reduced as well. Moreover, for power divider to work in higher frequency, the dimension of the power divider had to be reduced as well. In order to obtain outputs more than three ports, it is recommended to implement the power divider by cascading several power dividers together. So, the output from a power divider will be connected to input of second power divider.

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