DESIGN OF FOUR-PORT WILKINSON POWER DIVIDER USING CIRCULAR SPLIT RING RESONATOR

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by

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"In the name of Allah, Most Gracious and Merciful"

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SYMBOLS

c	Width of copper ring
d	Distance between SRR ring
dB	Decibel
ε_r	Dielectric constant
ε_o	Permittivity constant, $8.85 \times 10^{-12} Fm^{-2}$
ε_{eff}	Electrical length
f_o	Central frequency
GHz	Giga Hertz
H	Thickness of substrate
g	Gap SRR
λ	Wavelength
Γ	Reflection coefficient
t	Thickness of copper
tan δ	Loss tangent
μ_{eff}	Effective permeability

ω	Resonant frequency
Z_o	Characteristic impedance
Z_{in}	Input impedance

ABBREVIATIONS

ADS	Advanced Design System
NIM	Negative Index Material
LHM	Left-Handed Material
SRR	Split Ring Resonator
VSWR	Voltage Standing Wave Ratio
WPD	Wilkinson Power Divider

DESIGN OF FOUR-PORT WILKINSON POWER DIVIDER USING CIRCULAR SPLIT RING RESONATOR

ABSTRAK

Kuasa pembahagi adalah alat yang berpecah kuasa input kepada kuasa output sama rata tanpa mengira berapa banyak pelabuhan ia mempunyai. Ia biasanya digunakan untuk sistem antena, penguat kuasa, resonator dan pembancuh. Dalama projek ini, ia memberi tumpuan kepada bagaimana untuk mereka cipta empat liang kuasa pembahagi Wilkinson (WPD) dengan penyalun gelang belah bulat (SRR) dengan mengunnakan ADS. Fungsi penyalun gelang belah bulat (SRR) adalah untuk mningkatkan prestasi empat liang kuasa pembahagi Wilkinson (WPD) apabila saiz dikurangkan. Kuasa pembahagi yang dicadangkan digunakan untuk merancang pemisahan kuasa yang sama dan hampir sama baik di semua liang. Oleh itu, ia membuatkan peranti untuk melaksanakan dengan prestasi yang lebih baik. Dalam laporan ini, ia adalah terutamanya memberi tumpuan kepada bagaimana untuk mengurangkan saiz empat liang WPD supaya ia akan mendapatkan yang baik bacaan S-parameter. Reka bentuk yang dicadangkan itu direka menggunakan papan litar Rogers RO4003C dicetak dengan pemalar dielektrik, εr yang mepunyai ketebalan substrat, H, 0.813 mm dan ketebalan tembaga, t, 0.035 mm. Reka bentuk yang dicadangkan boleh beroperasi dalam julat frekuensi S-band yang ada di antara 2 hingga 4 GHz. Keputusan perbezaan menunjukkan kuasa pebahagi boleh beroperasi pada 2.4 GHz dengan membandingkan keputusan reka cipta asa dan gabungan. Masing-masing mempunyai keputusan are – 38.13 dB dan -14.78 dB dengan penurunan saiz sebanyak 20%.

DESIGN OF FOUR-PORT WILKINSON POWER DIVIDER USING CIRCULAR SPLIT RING RESONATOR

ABSTRACT

Power divider is a device that split the input power to output power equally regardless how many ports it has. It is commonly applied to the antenna system, power amplifier, resonator, and mixers. In this project, it is focuses on how to design four-port Wilkinson power divider (WPD) with circular split ring resonator (SRR) by using the ADS. The function of circular SRR in this project is to increase the performance of four-port Wilkinson power divider (WPD) when the size is reduced. The proposed power divider is used to show equal power splitting and good matching at all ports. Thus, it makes the device to perform with better performance. In this work, it is mainly focused on how to reduce the size of four-port WPD so that it will obtain good S-Parameters readings. Circular SRR is loaded onto the conventional WPD. The proposed design is fabricated using Rogers RO4003C printed circuit board with dielectric constant of ε_r, thickness of substrate, *H*, 0.813 mm and thickness of copper, *t*, 0.035 mm. The proposed design can be operated within S-band frequency range which is between 2 and 4 GHz. The simulation result were analyzed and compared theoretically and practically so that it achieve the requirement of S-Parameters. By comparing the results of conventional and combined design, the return loss of both designs are – 38.13 dB and -14.78, respectively with regards to 20% of size reduction from conventional design.

CHAPTER 1

INTRODUCTION

1.1 Background

N-port WPD forms a fundamental block in microwave circuits that divide the input radio frequency power by arbitrary ratios. The power divider is a device that split the input power to output power equally regardless how many ports it has. The power divider is commonly applied to the antenna system, power amplifier, resonator, and mixers.

In order to achieve a good performance of power divider, once must have high isolation at the output ports, good coupling factor, low insertion loss, compact in size and broad bandwidth. On top of that, with the good performance of Wilkinson power divider, it gives a better signal and has low economical cost.

There is one step to achieve the good performance of power divider by minimizing the dimension of the device. Therefore, a circular SRR will be loaded onto four-port WPD and it allows reducing the size of the device. Then, the four-port WPD will achieve a good power division and its matched at all ports.

1.2 Problem Statement

In this new wireless communication system, power divider is one of the essential tools used for power division. However, one of the major drawbacks of the device is its bigger dimension at low-frequency range, such as S-band. Therefore, studies proposed a method to reduce the size of the power divider.

To overcome the problem, the size of power divider needs to be reduced into a compact size. A circular SRR is implemented with four-port WPD. The presence of circular SRR in the design will help to reduce the size of four-port WPD as well as gives better performance in S-Parameters such as high isolation, matched at all ports and good resonant frequency for circular SRR.

Reduction size of power divider can be achieved when the resonator is loaded with its design. The resonator is a metamaterial structure that shows its negative permittivity and permeability values close to the set frequency range. Negative permeability allows the development of novel devices. The circular SRR can be excited by time-varying electric and magnetic field. The circular SRR reduce the dimension of WPD which is smaller than a wavelength at the resonant frequency. Hence, by loading the circular SRR to four-port WPD, it exhibits a better performance of four-port WPD.

1.3 Objectives

In this research, three objectives are set to be achieved:

i. To design a four-port WPD with circular SRR by using ADS
ii. To simulate and measure the S-parameters for the proposed design at a cut-off frequency of 2.4 GHz
iii. To test, measure and analyze the S-parameters of conventional WPD with the combined design by using VNA.

1.4 Scope of project

The scope of this project is to design, simulate and analyze a combined design of four-port WPD with circular SRR. The design of each component was simulated by using

ADS and CST respectively while the combined design was simulated by using ADS at the operational frequency of 2.4 GHz which under the S-Band frequency range. The circular SRR is designed and will be loaded at the 50 Ω input transmission line of four-port WPD. Subsequently, the combined design is fabricated using RO 4003C with following parameters:

i. Thickness of substrate, *h*: 0.813 mm

ii. Relative permittivity of substrate, ε_r: 3.38

iii. Tangent loss, tan δ: 0.0027

iv. Thickness of conductor, *t*: 0.035 mm

1.5 Thesis Outline

The report has been divided into five main chapters. The topics covered mainly focus on design and fabrication of proposed four-port WPD using circular SRR.

Chapter 2 is dedicated to illustrating the relevant literature and the new works related to the study performed by other researchers. The content includes the theoretical background of the project which consists of the basic understanding of power divider, the study of Wilkinson power divider, a basic understanding of split ring resonator and performance of WPD with SRR using in this project.

Chapter 3 focuses on methodologies adopted for the study. It consists of explanation for the components parameters of power dividers and split ring resonator. The project flow chart is included to show pictorially the decision and progress of each task involved during performs the project. Furthermore, the chapter includes the design of power divider which is the conventional power divider and four-port WPD as well as circular SRR by using CST and ADS software including the layout designs.

Chapter 4 presents the simulation results obtained from ADS software and measured from the network analyzer. Results obtained are measured by referring on magnitudes of S-parameters and reflection coefficients. The obtained results also are then discussed and analyzed thoroughly.

Lastly, Chapter 5 gives the conclusion of the study of the project. Some recommendations are proposed for future works in order to improvise the performance of the proposed design.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the general outline of the theoretical background of the proposed project is given in this chapter. The relevant particular issues or theories of four-port WPD using circular SRR are discussed in depth. Besides, the design of four-port WPD using circular SRR will be mentioned in this chapter. Several comparisons on specifications and performance are made.

2.2 Power Divider

Power divider and power splitter are two types of passive components. Both of the components are extensively used in radio frequency and microwave applications. The devices allow distributes power among various paths equally. The configuration of resistor used by both devices is different from each other [2]. Both of the devices can be presented using lumped element and microstrip lines.

A basic power divider is constructed by using three resistors while power splitter is using two resistors. In this study, we chose power divider as the main design as it is equal and a bi-directional device which allows being used in power combiner. By referring to Figure 2.1, it shows the lumped element configuration of both devices.

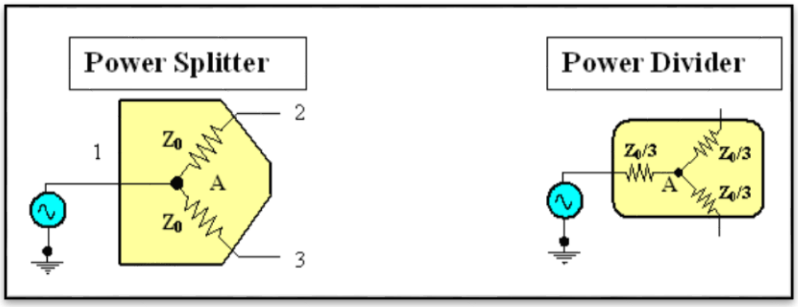

Figure 2. 1: The lumped element configuration of power splitter and power divider [3]

In addition, the block diagram describes the ports network used in power divider [4]. Power divider contains one input power, P_1 and two output powers, P_2 and P_3. However, the block diagram as in Figure 2.2 of power combiner is the opposite configuration of power divider. It has a combination of two input powers, P_1 and P_2 as well as P_3 as the output power.

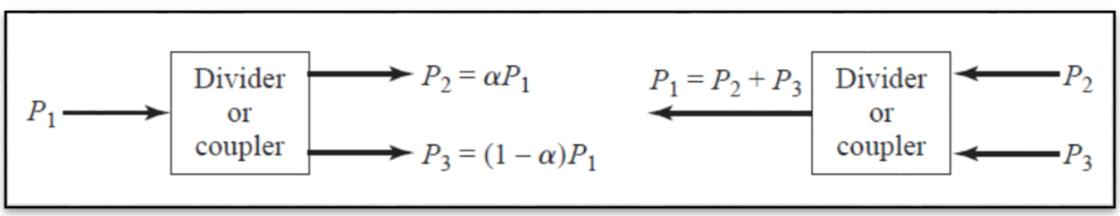

Figure 2. 2: Power divider (left), Power combiner (right)

Commonly, power dividers are come out with three-port, 4-port or N-port network in either lossy or lossless condition. However, a two-port divider has equal division loss of 3 dB between the output ports [5]. Many studies said that to maintain a good performance of power divider, some characteristics that need to take into account are good return loss, low insertion loss, high bandwidth and small in size [4, 6, 7]. Therefore, to investigate the characteristics, we study several types of power dividers such as Resistive, T-junction and Wilkinson power dividers.

2.2.1 Resistive Power Divider

A resistive power divider is a lossy divider but it can be made to be matched at all ports even though the two-port network may not be isolated [4]. Figure 2.3 shows an equal split (-3 dB) resistive power divider using lumped elements resistors.

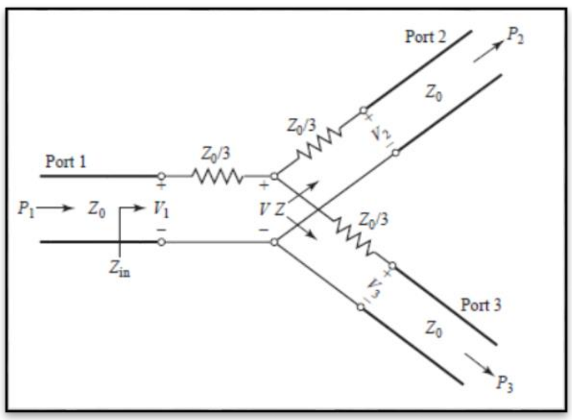

Figure 2. 3: An equal split three-port resistive power divider [4]

Analysis of the power divider can be applied using fundamental of circuit theory obtained in [4]. From [4], we can assume that the three ports are terminated with characteristic impedance, Z_o, then the impedance, Z is look out to $\frac{Z_o}{3}$ resistor as follows:

$$Z = \frac{Z_o}{3} + Z_o = \frac{4Z_o}{3} \tag{2.1}$$

The input impedance Z_{in} is given by:

$$Z_{in} = \frac{Z_o}{3} + \frac{2Z_o}{3} = Z_o \tag{2.2}$$

Equations below obtained from [4] shows that the input and output ports are matched, $S_{11} = S_{22} = S_{33} = 0$. Given that, voltage, V at the center is,

$$V = V_1 \frac{\frac{2Z_O}{3}}{\frac{Z_O}{3}+\frac{2Z_O}{3}} = \frac{2}{3}V_1 \tag{2.3}$$

Meanwhile, the output voltage for P_1 and P_2 are equal,

$$V_2 = V_3 = V \frac{Z_o}{Z_o+\frac{Z_O}{3}} = \frac{3}{4}V = \frac{1}{2}V_1 \tag{2.4}$$

Thus, $S_{21} = S_{31} = S_{23} = -6$ dB. It shows that the power level at port 2 and 3 are 6 dB below the input power at port 1. Since the network is reciprocal n symmetrical, the S-matrix is as below [4]:

$$[S] = 1/2 \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \tag{2.5}$$

The input and output powers are distinguished be equation below respectively:

$$P_{in} = \frac{1}{2}\frac{{V_1}^2}{Z_o} \tag{2.6}$$

$$P_2 = P_3 = \frac{1}{2}\frac{\left(\frac{1}{2}V_1\right)^2}{Z_o} = \frac{1}{8}\frac{{V_1}^2}{Z_o} = \frac{1}{4}P_{in} \tag{2.7}$$

2.2.2 T-Junction Power Divider

T-junction power divider has a simple three-port network configuration. There are several types of T-junction power divider that been used in radio frequency applications as in Figure 2.4:

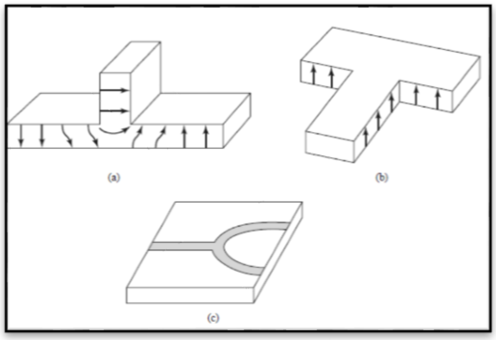

Figure 2. 4: Different type of T-junction power divider, a) E-plane waveguide, b) H-plane guide, Microstrip T-junction [4]

In Figure 2.5, the lossless T-junction can all be constructed as a junction of three transmission line.

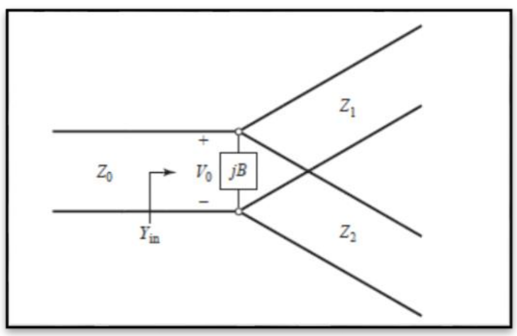

Figure 2. 5: Transmission line of T-junction [4]

The presence of fringe fields and high-order modes are related with the discontinuity at such a junction, which it's lead to store energy that considered for by lumped susceptance, B. The divider is matched when,

$$Y_{in} = jB = \frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_o} \quad (2.8)$$

The equation is reduced when the transmission line is lossless, characteristic impedance, Z_o = 0 and B = 0,

$$\frac{1}{Z_1} + \frac{1}{Z_2} = \frac{1}{Z_o} \qquad (2.9)$$

The output of $Z_1$and Z_2 can be selected to give different power divider ratios. The isolation between two-output port are not happen if the output lines are matched but it is happen when input line is matched. Therefore, output ports will have mismatched ports.

2.2.3 Wilkinson Power Divider

From the previous design, we can see that T-junction power divider is one of the simple three-port channels. Unfortunately, the drawback of it is it cannot be matched at all ports. Hence, no isolation occurred between the output ports. For resistive power divider, it can be matched at all ports but it is not lossless, yet the isolation still can be achieved [4]. Some writings stated that to prevent crosstalk between the channels, there must be isolation between ports [10]. Therefore, the performance of power divider can be increased.

Wilkinson power divider is a most common device that uses for power splitting and power combining. It is a three-port network that is lossless when the output ports are matched if and only if reflected power is dissipated [4,10,11]. In two-port Wilkinson power divider requires $\frac{\lambda}{4}$ impedance transformer which has $\sqrt{2Z_o}$ of characteristic impedance and lumped isolation of $2Z_o$with all three-port matched, high isolation between output ports are achieved [11,13]. Figure 2.6 shows the Wilkinson power divider both in micro strip and transmission line circuits.

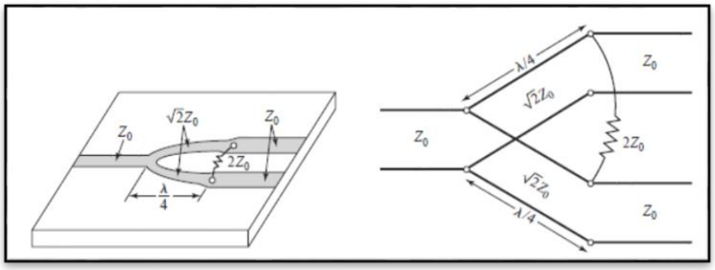

Figure 2. 6: From the left side is Microstrip circuit followed by Transmission line circuit [4]

Wilkinson power divider can be analyzed using even-odd mode analysis [12]. Even-odd mode analysis must obey two principles which are superposition and circuit symmetry. Initially, we redrew the circuit in Figure 2.6 with all impedance normalized to Z_o. The redrawn circuit is in Figure 2.7.

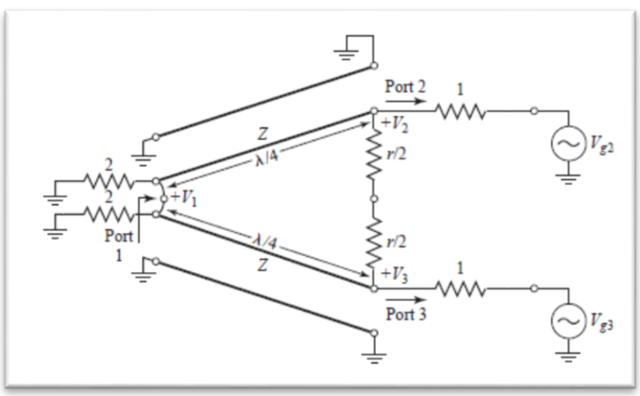

Figure 2. 7: Wilkinson power divider in normalized and symmetric form [4]

By referring to Pozar [4], S-matrix can be described as follows:

- $S_{22} = S_{33} = 0$ (Port 2 and 3 matched for even-odd modes)
- $S_{12} = S_{21} = -j0.707$ (symmetrical since its reciprocal)
- $S_{13} = S_{31} = -j0.707$ (symmetrical since its reciprocal)

- $S_{23} = S_{32} = 0$ (because of short and open bisections)

2.2.3.1 N-port Wilkinson Power Divider

Generally, the concept of two-port power divider with N-port power divider is nearly the same. In this work, four-port WPD is chosen as the main element in the design. The greater the N-, more complicated the design is. To achieve good performance of Wilkinson power divider, it is better to use more N as the design. An N-port Wilkinson power divider consists of quarter-wave long transmission lines and isolation resistors, where the transmission lines should be placed sufficiently apart from each other to minimize the coupling effect. Therefore, it is difficult to fabricate a multi-port Wilkinson power divider in planar form due to the layout limitation [4].

2.3 Performance Matrix of Power Divider

Several related theoretical backgrounds will be discussed further such as scattering parameters, return loss, insertion loss, matching properties, and bandwidth as well as frequency response. Along with that, the formulas are also provided.

2.3.1 Scattering Parameters (S-Parameters)

Generally, S-Parameters are related to power traveling waves in order to avoid the concept of voltage and current are complicated to relate to network performance. Before the S-Parameters were introduced, the Y and Z parameters were coming with the mentioned concept.

S-Parameters are displays in a matrix format which comes in a row and column spaces as it describes the input and output relationship at the number of ports in the network system. In the electrical system, the elementsS_{11}, S_{12}, S_{21}, S_{22} are represents the

S-Parameters. S_{11} and S_{22} indicate the reflection coefficients, Γ while $S_{12}$and S_{21}indicate the transmission coefficients, T. Reflection coefficient Γ is the ratio of the reflected wave and incident wave while transmission coefficient, T is the ratio of transmitted wave and incident wave.

S-Parameters can be represented by S_{ab} which *a* denotes the power wave going into the port while *b* denotes the power wave leaves from the port. For example is two-port network is used, S_{21}, it is means power wave is transmitted from port 1 to port 2.

In addition, each of the parameters involved mentioned above gives its own definition as below:

- S_{11}shows the input reflection coefficient at port 1
- S_{12} shows the reverse transmission coefficient from port 2 to port 1
- S_{21} shows the forward transmission coefficient from port 1 to port 2
- S_{22} shows the output reflection coefficient at port 2

From the above list, some related parameters can be represented by them. Firstly, S_{11} denotes as return loss,Γ , S_{21} denotes as transmission loss, T, and S_{12} is denotes as isolation loss. Both of the return and isolation losses can be calculated from the reflection coefficient with the equation in (2.10) and (2.11) [4]:

$$Return\ loss, RL = -20\log|\Gamma| \tag{2.10}$$

$$Isolation\ loss, IL = -20\log|T| \quad (211)$$

Referring to Figure 2.8, it is an illustration of wave function used in S-Parameters for a two-port network. Denotes that *a* is the power wave going into the port while *b* is the power wave leaves from the port. Both *a* and *b* are resembled the incident and reflected waves respectively.

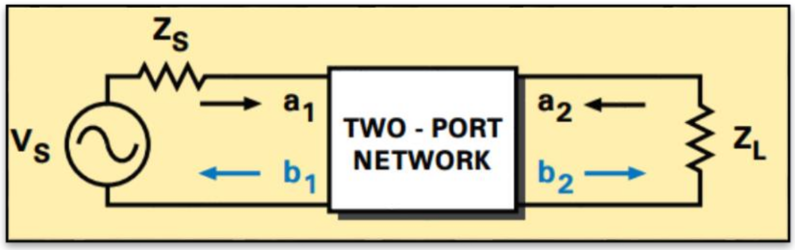

Figure 2. 8: Photo of two-port network [1]

2.3.2 Return Loss

Return loss is an amount of signal that reflected back towards the signal source by a device due to impedance mismatch. The amount of reflected power is represented by dB. The higher the number of gains measured in negative value, the smaller number of power that reflected out. From return loss equation, the reflection coefficient can be determined. Thus, VSWR and percentage reflected power can be calculated to determine the match properties of the design. The equation can be obtained as follows [4]:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{2.12}$$

$$Return\ loss, RL = -20\log|\Gamma| \tag{2.13}$$

$$\Gamma = 10^{\frac{-RL}{20}} \tag{2.14}$$

$$Percentage\ of\ reflected\ power, \% = (100)(|\Gamma|^2) \tag{2.15}$$

2.3.3 Insertion Loss

Insertion loss is a loss in power that attenuates the device in dB. It allows the input power to be declined at the output port equally. Hence the power at the output port is equal to each other. It can be expressed as follows [4]:

$$Insertion\ loss, IL = 10 \log \frac{P_{out}}{P_{in}} \tag{2.16}$$

2.3.4 Matching properties

Impedance matching shows that the minimum reflection happened at each port. The network is matched if the coefficients $S_{ab} = S_{ba}$ when i = j. For reciprocal network, [S] matrix is symmetry and $S_{ab} = S_{ba}$. Hence, there is no loss of power, network is loss less and matched at all ports. The [S] matrix can be written as [4]:

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{21} & 0 & S_{23} \\ S_{31} & S_{32} & 0 \end{bmatrix} \tag{2.17}$$

2.3.5 Bandwidth

The operational bandwidth is one of the important parameters in power divider. Bandwidth allows determining the performance of the device under the desired frequency range. The percentage of bandwidth can be determined by [4]:

$$\text{Bandwidth} = \frac{f_H - f_L}{f_C} \times 100\ \% \tag{2.18}$$

f_H, f_L, f_C are higher cut-off frequency, lower cut-off frequency and central frequency respectively.

2.3.6 Frequency response of Wilkinson power divider

From Figure 2.9, what can we analyzed is S_{11} and S_{22} is the return loss at output port 1 and 2. Isolation loss is at S_{23} which happen between output port 2 and 3 while the coupling happens between port 1 and 2 of S_{12}. The frequency response over 0.5-1.5 GHz of return loss, isolation loss as well as the coupling between the output ports has nearly to negative infinity at the f_o.

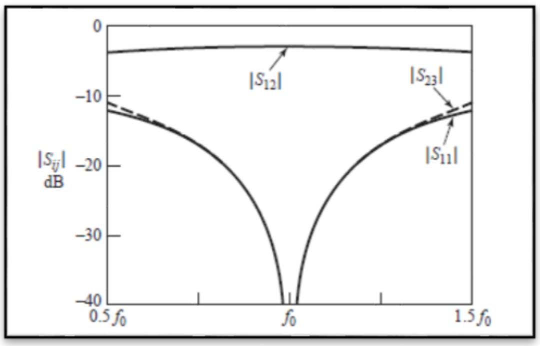

Figure 2. 9: Frequency response of an equal split Wilkinson power divider [4]

2.4 Comparison between Passive Power Divider

There is three type of passive power dividers which is widely used among researchers. Table 1 is a summarization of all the advantages and drawbacks between all the power divider.

Table 2. 1: Advantages and drawbacks of power dividers [4]

Power Divider	Advantage(s)	Drawback(s)
Resistive	- Matched at all ports	- Lossy condition - No isolation happens between output ports
T-junction	- Lossless	- No isolation happens at output ports - No matched at all ports
Wilkinson	- Lossless (if only if matched at all ports) - High isolation - Narrow bandwidth	- Reflected power dissipated through isolation resistor if mismatched)

Therefore, Wilkinson power divider highlights all the ideal parameters characteristic such as lossless, reciprocal and matched. It is the best choice to use for the proposed design in this work.

2.5 Split ring resonator (SRR)

The left-hand metamaterial (LHM) or negative index metamaterial (NIM) is a composite structure that used to change the electromagnetic properties of materials. It has been extensively used among researchers to determine permittivity, ε and permeability, μ [14].

In order to obtain the characteristic of LHM and NIM, the structure of permittivity and permeability are realized using conducting wires and SRR, respectively [15]. Previous works have focused on two type of SRR structure which is circle and square SRRs [15-17]. Both of the SRRs obtained high magnetic polarizability and show negative effective permeability($\mu_{eff} < 0$) when center frequency, f_o is close to resonant frequency, ω [18]. This approach has been on demand among researchers for miniaturizing the size if the device.

In designing SRR structure, it usually comes out by using electromagnetic (EM) software. SRR can be designed by using High-Frequency Structure Simulator (HFSS), CST Microwave Studio (CST) or Advanced Design System (ADS). Therefore, the resonant frequency is an important parameter that needs to be considered in designing the resonator. It is important to obtain a good performance of the SRR.

2.5.1 Theory of Split Ring Resonator (SRR)

During recent years, split ring resonators had been studied by many researchers to investigate the magnetic material and determine the performance SRR as perturbations for different passive planar circuit design [20]. There are several geometrical shapes that have been investigated by researchers such as circular SRR, square SRR, hexagonal SRR and several other shapes.

SRR has two types of polarization modes. The Transverse Electric (TE) polarization mode which is the electric, E-field is parallel to the x-axis. In this situation, the electric field coupled with the capacitance of SRR and it generates circulating current around it [24]. The external magnitude field penetrates through the rings and current are induced. Besides, the current interacts with the external field to produce magnetic resonance called LC resonance as studied by Linden et al [27]. For Transverse Magnetic (TM) mode, E-field is perpendicular to the y-axis. E field cannot be coupled to the capacitor of SRR and it only produces electric resonances [24-25].

The basic configuration of SRR is it consists of two concentric rings with a split at both opposite ends and gap between two rings. The copper layer is used to constructs the ring shape. Figure 2.10 shows the different shapes of SRR. Different applications can be applied with different shape of SRR.

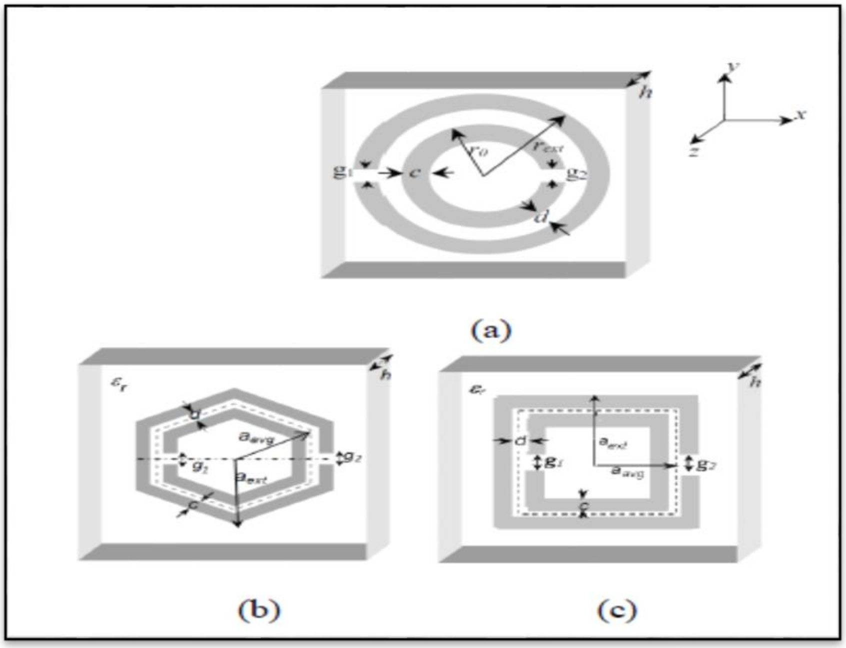

Figure 2. 10: Schematic view of a) circular SRR b) hexagonal SRR c) square SRR [20]

In Figure 2.10 it shows the schematic view of three different SRR which is circle, hexagonal and square. Each of the structure has a width, *c*, and spacing, *d* between the rings. The gap, g_1 is represents the inner ring while g_2 is represents the outer ring. It will be printed on substrate with dielectric constant, ε_r with thickness, *h*. All of the parameters are important to determine the frequency response of SRR.

Next, the behavior of the current is it flows from the inner ring to the outer ring under the exposure of external electromagnetic force around the SRR [20]. Figure 2.11 represents the equivalent circuit of SRR shown in Figure 2.10. The equivalent circuit of SRR consists of a series connection of self-inductance, L and parallel connection of capacitance.

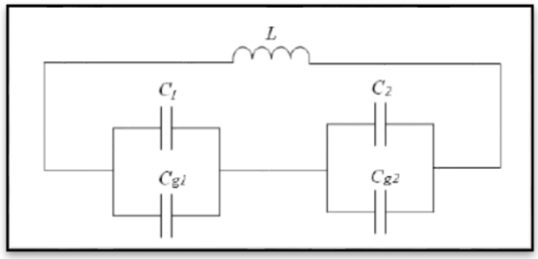

Figure 2. 11: Equivalent circuit of C-SRR, H-SRR, and S-SRR [20]

2.5.1. Circular Split Ring Resonator (circular SRR)

To determine the frequency response, we refer to [20], the formula of the resonant frequency of C-SRR is given by:

$$f_0 = \frac{1}{2\pi\sqrt{L_T C_{eq}}} \tag{2.19}$$

$$L_T = 0.00508l\ (2.303 \log\frac{4l}{d} - 2.451) \tag{2.20}$$

$$l = 2\pi r_{ext} - g \tag{2.21}$$

where the L_T is the total inductance of C-SRR and C_{eq} is the equivalent capacitance of the structure.

$$C_{eq} = \frac{(\pi r_{avg} - g)C_{pul}}{2} + \frac{\varepsilon_o c h}{2g} \tag{2.22}$$

$$C_{pul} = \sqrt{\varepsilon_r}\Big/ c_o Z_o \tag{2.23}$$

where the C_{pul} is the per unit length capacitance, between rings and $c_o = 3 \times 10^8\ ms$ while the average radius, r_{avg} is given by [20]:

$$r_{avg} = r_{ext} - c - \frac{d}{2} \quad (2.24)$$

All the calculation above used to obtain the resonant frequency for circular SRR.

2.6 Performance Matrices

In this section, theoretical background of split ring resonator will be covered. It includes the S-Parameters, returns loss, insertion loss, resonant frequency and the dielectric constant.

2.6.1 S-Parameters

S-parameters are a mathematical construct that determines the RF energy propagates through a multi-port network. S-parameters describe the response of an N-port network to signal incident to any or all ports [29]. There are four S-Parameters in two-port network which are S_{11}, S_{21},. S_{12} and S_{22}. Figure 2.12 shows the model of two-port network with the input and output ports.

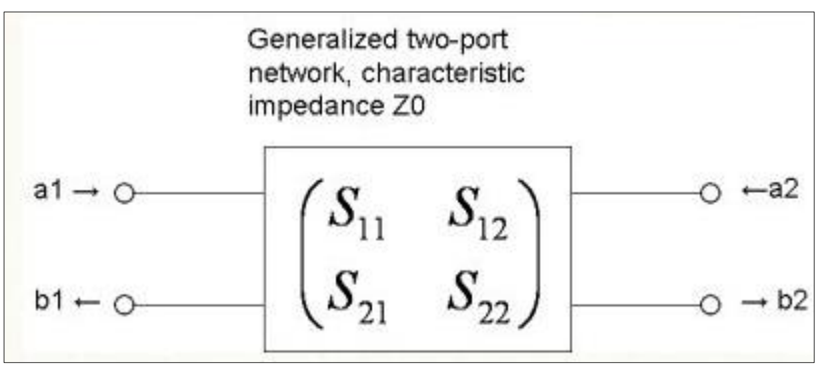

Figure 2. 12: Model of two-port network [29]

From Figure 2.12, a indicates the power going into the port while b indicates the power leave from the port. Furthermore, S_{11} implies that how much power injected at port 1 and resulting signal from port 1 is measured. For S_{21} it means the signal injected at port 1 and the resulting signal exist at port 2 is measured. All of the equations below show the equations of two-port network [4].

$$b_1 = S_{11} * a_1 + S_{21} * a_2 \quad (2.25)$$

$$b_2 = S_{21} * a_1 + S_{22} * a_2 \quad (2.26)$$

$$S_{11} = \frac{b_1}{a_1}\bigg| a_2 = 0 = \quad (2.27)$$

$$S_{21} = \frac{b_2}{a_1}\bigg| a_2 = 0 \quad (2.28)$$

$$S_{12} = \frac{b_1}{a_2}\bigg| a_1 = 0 \quad (2.29)$$

$$S_{22} = \frac{b_2}{a_2}\bigg| a_1 = 0 \quad (2.30)$$

2.6.2 Return Loss

Return loss can be denoted as S_{11}. It is one of the important parameters to be measured. It means that the difference between transmitted signal power and the power signal reflections caused by matching impedance. An ideal network will have a minimum return loss approaching to zero which is the return loss should be a higher negative value at its resonance frequency. S_{11} is measured in decibel (dB) as in Eq. 2.31 [4]:

$$Return\ loss = S_{11} = 20 \log|S_{11}| \text{ in dB} \quad (2.31)$$

2.6.3 Insertion Loss

Another important parameter is the insertion loss, S_{21}. It is indicate that the wave transmitted from port 1 to port 2. S_{21} is a forward transmission gain with the output port terminated at a matched load. The magnitude of insertion loss should be approaching to zero which means the signal measured at port 2 will approximately equal to injected signal at port 1. The equation is defined as in Eq. 2.32[4]. Figure 2.13 shows the ideal S_{11} and S_{21} in dB.

$$Insertion\ loss = S_{21} = 20\log|S_{21}| \text{ in dB} \quad (2.32)$$

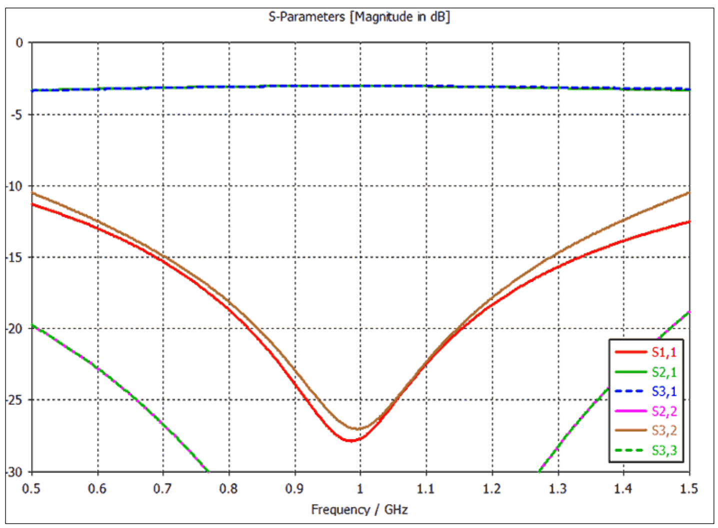

Figure 2. 13: S11 and S21 in decibel (dB) [30]