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Faculty of Electrical Engineering,
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Investigating Planar Balun Structures with Inherent Impedance Transformation and Power Combining Properties

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MSc. Thesis
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Investigating Planar Balun Structures with Inherent Impedance Transformation and Power Combining Properties

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ABSTRACT

In recent years, to accommodate the needs of wireless communication technologies, radio frequency integrated circuits (RFICs) are using differential configurations in their topologies, because they provide better overall RF performance at a relatively low-cost increment. However, the growth number of portable devices, embedded systems, and Internet of Things (IoT) applications mean that there are a large number of demands for small/tiny, low-power baluns. Moreover, for flexibility and cost reasons, planar versions of balun structures are needed. The goal of this research is to investigate whether a balanced-to-unbalanced (balun) structure can simultaneously be used for impedance transformation and power combination as well. As a result, this research presents the planar version of a 1:4 Guanella balun, a 1:4 Ruthroff balun, and a 1:4 Differential balun. Three proposed structures are implemented at a center frequency of 1.5 GHz. These baluns work as matching networks and power combining between single ended and differential ports. All these balun structures are designed and simulated with Advanced Design System (ADS) from Keysight. For measurement purposes, all structures were fabricated on 0.5 mm printed circuit board (PCB) with I-tera substrate ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$). Based on measurement results, the 1:4 Guanella balun has the biggest fractional bandwidth (FBW) of 175 %. Next, the 1:4 Ruthroff balun comes second with FBW of 85 %. Last, the 1:4 Differential balun has the smallest FBW of 19 %. The results show that planar 1:4 Guanella balun, planar 1:4 Ruthroff balun, and planar 1:4 differential balun can be used in many wireless communication devices for portable devices, embedded systems, and IoT.

Keywords: balun transformers, planar technology, Guanella, Ruthroff, differential, portable devices, IoT, RFIC, embedded system.

UNDERTAKING

Use the following undertaking as it is.

I certify that research work titled "*Investigating Planar Balun Structures with Inherent Impedance Transformation and Power Combining Properties*" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

Signature of Student____________________

Name of Student____________________

Registration Number____________________

I would like to thank Allah for everything

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CHAPTER 1

Introduction

1.1 Motivation

Wireless communication technologies continue to evolve and expand at a very fast pace these days. In recent years, to accommodate the needs of such communication technologies, radio frequency integrated circuits (RF ICs) are using differential configurations in their topologies, because they provide better overall RF performance at a relatively low-cost increment. However, the growth number of portable devices, embedded systems, and Internet of Things (IoT) applications mean that there are a large number of demands for small/tiny, low-power baluns.

Balun structures are a type of electrical transformer that converts balanced electrical signals to unbalanced electrical signals. They have been used since the early ages of wireless telephony to resolve the single-ended/balanced problem [8]. In many cases, a balun is used for impedance matching networks, balanced mixers, push-pull amplifiers, phase shifters, balanced modulator, coaxial antenna feeds, and balanced frequency multipliers. The needs for low noise data transfer and multi-band operations have driven the urgency in the development of the balun structure to its performance at higher frequencies and wideband applications.

1.2 Problem Statement

1.2.1 Research Goal

The goal of this research is to investigate whether a planar balanced-to-unbalanced (balun) structure can simultaneously be used for impedance transformation and power combination.

1.2.2 Methodology

The methodology used for this research can be explain as follows:

a) The first step is performing a literature study of various balun structures from many resources, such as books and scientific papers. Some datasheets of existing balun products from various manufactures are also a valid example for exploring the object in more detail and gain more knowledge about state-of-the-art balun structures.

b) Based on this literature study, the best suitable topologies for planar impedance transforming baluns were identified. Three suitable topologies were further investigated up to the level of their ideal layout. This is explained in chapter 3.

c) A manufacturing technology was chosen. The ideal layouts were adapted to the chosen printed circuit board (PCB) technology. Calibration structures were designed and the boards were manufactured. This is explained in chapter 3 and 4.

d) The balun structures were measured in a calibrated microwave measurement setup. The results were carefully analyzed. This is explained in chapter 5 and 6.

1.2.3 Target Specifications

The target specifications corresponding to the goal of the research can be explained as follows:

a) Planarity: The balun has to be in a planar form to provide greater flexibility, area saving, and better performance.

b) Operating frequency: 1.5 GHz with fractional bandwidth (FBW) > 20 %.

c) Impedance transformation: It works as impedance transformation device with ratio 1:4 between source and load.

d) Impedance matching: Delivers good impedance matching and power combining between single ended and differential port (balanced/unbalanced).

e) Phase difference: It has 180° phase difference at the differential port.

1.3 Contribution

Through the research work of the thesis, several contributions have been made to the field of wireless communications in general, especially in term of planar balun structure design. In this section, summaries of these contributions are presented.

- A comprehensive study of theories, principles, and techniques of wideband baluns as impedance matching networks and power combiners are presented.

- A structure of planar 1:4 Guanella transmission line transformer (TLT) as a preferred design of wideband balun is proposed.

- A structure of planar 1:4 Ruthroff TLT as first alternative design of wideband balun is proposed.

- A structure of planar 1:4 differential balun as comparison design of balun is proposed.

- All planar balun designs are manufactured and measured.

This thesis presents the results of a more comprehensive characterization of all three planar 1:4 balun designs (Guanella TLT, Ruthroff TLT, and differential balun). The electromagnetic simulation and measurement results provide an understanding of their capabilities and limitations. Later, all three balun structure designs are compared and analyzed to see the optimum structure among them for wireless communication applications.

1.4 Organization

This thesis is organized in six chapters. The brief introduction of balun is given in this chapter along with its applications especially in wireless communication. A problem statement for this research and contribution are also defined to describe boundaries and limitations in the designs.

Chapter 2 presents fundamental properties of all three proposed balun structures. It contains of brief explanation, advantage and disadvantage of each balun structure. Also, since the main goal of this research is to design planar version of each balun, the compatibility with planar technology for each balun is defined.

Chapter 3 consists of the design process of each balun structure. It starts with how to derive the planar version from transmission line transformer or coaxial version along with a systematic design procedure. Next, the entire stack layers from each balun design and electromagnetic (EM) simulation results in Momentum Advanced Design System (ADS) from Keysight are explained.

Chapter 4 shows the productions process of planar version for all balun structure. It explains the design process from design sketch in ADS, extraction of its Gerber files, and PCB manufacturing process. Last, all three planar version of balun structures are measured or tested.

The comparison and analysis between simulation and measurement results can be found in chapter 5. Finally, chapter 6 concludes all the research results with its recommendation for further research in the same area.

CHAPTER 2

Fundamental Properties of Baluns

2.1 Introduction

With the rapid development of (future) wireless communication technologies, the demand of low-cost and low profile passive devices is highly increased. One example of this device is a balun. The main function of a balun as a passive device is to match an unbalanced to balanced structure. The signals at the balanced ports are equal in magnitude throughout the frequencies of interest, with 180° phase difference. The other purpose of a balun is for impedance matching. The balun structure designed in this research should fulfill some fundamental functions, such as impedance matching and power combining. This chapter describes all three 1:4 balun structures in detail.

2.2 Balun Transformer

In general, a balun consists of rightfully placed transmission lines or coupled lines with such different configurations and sizes depending on the required operating frequency, bandwidth and architecture of the circuit. A balun also referred as a balanced to unbalanced impedance transformer due to its structure/architecture. The unbalanced port of a balun has a reference signal as a ground, whereas the balanced ports have equal magnitude with 180° phase difference. Figure 1 shows a general circuit diagram of a balun transformer.

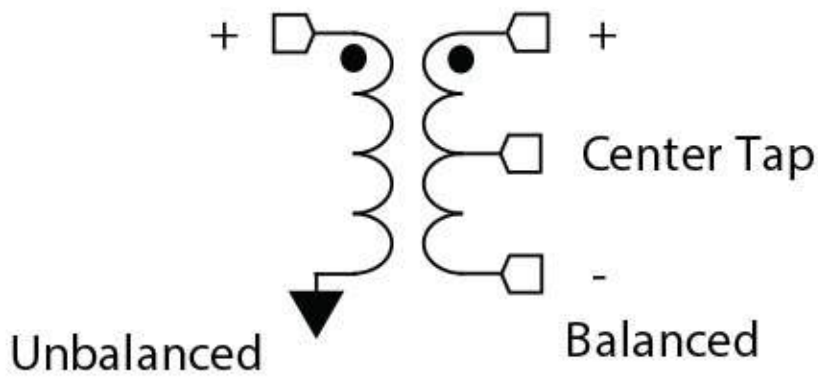


Figure 1. Balun transformer [11]

A balun has equal power outputs similar to the Wilkinson power divider or quadrature hybrid coupler. A balun is a reciprocal device. It means that a balun can be used bi-directionally, unlike a circulator or an isolator. That is the reason why a balun can work both ways in a circuit.

This research investigates three different balun structures that can have 1:4 impedance transformation ratios. These balun structures are the 1:4 Guanella balun, the 1:4 Ruthroff balun and the 1:4 Differential balun. The first two baluns are implemented with transmission line transformers (TLT), the last one is a conventional balun that is commonly use in radio/TV antenna.

2.2.1 1:4 Guanella Balun

The first balun structure for research is a 1:4 Guanella balun, also known as a 1:4 Guanella TLT. This structure introduced by George Guanella in *The Brown Boveri Review* 1944.

2.2.1.1 Overview

A 1:4 Guanella balun is a specific TLT balun, which is derived from a 1:1 balun. Figure 2 shows the schematic of the 1:4 Guanella balun.

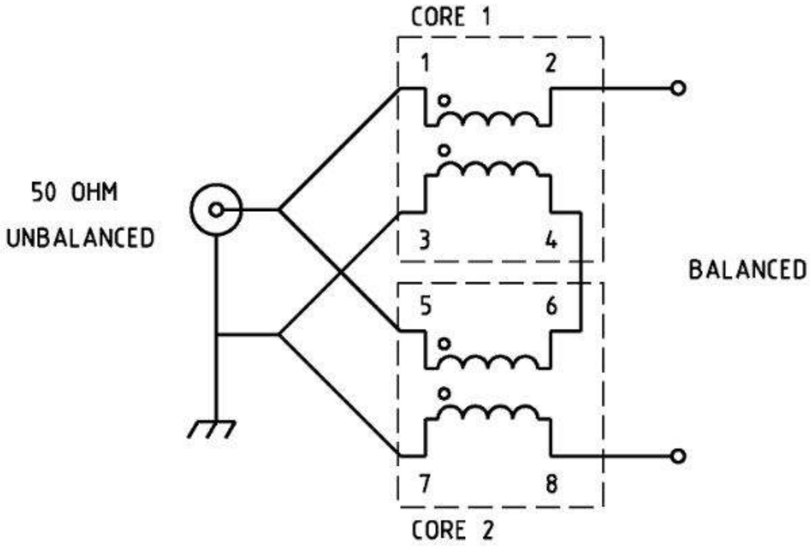


Figure 2. Basic schematic of the 1:4 Guanella balun [29]

The balun in figure 2 can be redrawn as in figure 3 that is going to be used for analysis [3]. If the two-transformers/transmission lines CORE 1 and CORE 2 in figure 2 are tightly coupled and identical, then the winding voltage (V) and currents (i) are the same.

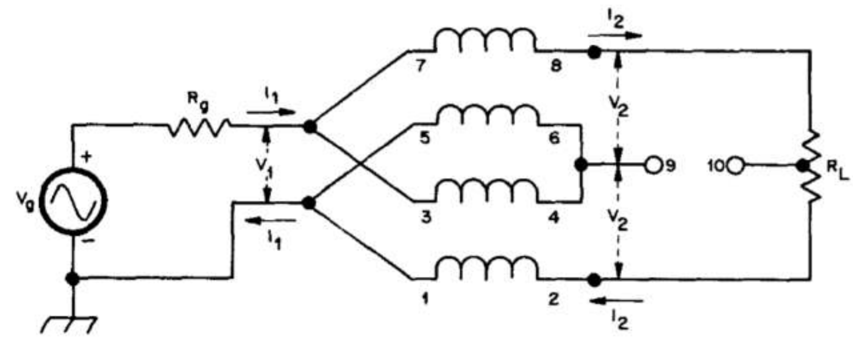


Figure 3. Circuit of a 1:4 Guanella transmission line transformer (balun) [3]

Assume that the signal loss through the balun is small enough to ignore. Whatever voltage is at the input of 1:1 balun is the same at the output. Figure 3 shows that the 1:4 Guanella balun has parallel connection at the input and serial connection at the output. If input impedance (Z_{in}) is set at the input and R_L is set at the output of the balun, the power ratio between input and output of the balun can be calculated with (1).

$$P = \frac{V^2}{R} \tag{2.1}$$

The balun input is connected in parallel. Thus, the voltage (V) is V_1. The power at the input is,

$$P_{in} = \frac{{V_1}^2}{Z_{in}}$$

However, the balun output is connected in series. Thus, the voltage (V) is $2V_2$. The power at the output is,

$$P_{out} = \frac{(2V_2)^2}{R_L} = \frac{4{V_2}^2}{R_L}$$

Assuming that there is no power lost in the balun, the input power (P_{in}) is equal to the output power (P_{out}) or can be written as,

$$P_{in} = P_{out}$$

$$\frac{{V_1}^2}{Z_{in}} = \frac{4{V_2}^2}{R_L}$$

Here, $V_1 = V_2 = V$ then,

$$\frac{V^2}{Z_{in}} = \frac{4V^2}{R_L}$$

$$R_L = 4Z_{in}$$

It concludes the 1:4 impedance ratio between Z_{in} and R_L.

Meanwhile, according to [3], the value of Z_{in} for 1:4 Guanella balun can be calculated as follow,

$$Z_{in} = \frac{Z_0}{2}\left(\frac{Z_L/2 + jZ_0 tan\beta\ell}{Z_0 + jZ_L/2tan\beta\ell}\right) \tag{2.2}$$

where,

Z_{in} = the input impedance of transmission lines.
Z_0 = the characteristic impedance of both transmission lines.
Z_L = the load impedance.
ℓ = the length of transmission line.
β $= \frac{2\pi}{\lambda}$ = phase constant, where λ is the wavelength in transmission line.

With the optimum value of $Z_0 = R_L/2$ for a load, equation (2.2) can be reduced to $Z_{in} = Z_L/4$. However, with more than two transmission lines, it can be rewritten as $Z_{in} = Z_L/n^2$ where n is the number of transmission lines. This overview is a fundamental theory to design a planar 1:4 Guanella balun.

2.2.1.2 Advantages and Disadvantages

There are several advantages of the 1:4 Guanella balun, such as its matching properties and bandwidth. However, the disadvantages of this balun structure are its limited impedance transformation ratios (1:4) and dependency of the planar version on the coupling between transmission line metal layers.

2.2.1.3 Compatibility with Planar Technology

Since the 1:4 Guanella balun structure in its original version (TLT) can be implemented with a coaxial transmission lines, it is also possible to derive the structure into a planar version with microstrip line technology. The configuration of the layer stack of the structure can be made with 2 layers as signal and ground layer. However, because of the connection between terminal 4 and 6 in figure 3, it is not possible to use infinite ground for this balun structure. Regarding to the frequency to cover, there is a drawback for this planar version of the Guanella balun. The planar Guanella balun depends on the length of the transmission lines. It means that longer transmission lines tend to cover lower operating frequency and vice versa.

2.2.2 1:4 Ruthroff Balun

The next balun structure for a planar design is the 1:4 Ruthroff balun or commonly known as 1:4 Ruthroff TLT. This structure firstly introduced by Clyde Ruthroff at *The Bell Labs* and published in 1959 with title "Some Broad-Band Transformers". This type of balun requires only one transmission line, rather than two transmission lines that are required in the Guanella balun. In addition, the signal paths from each balanced ports to ground in Ruthroff balun are more symmetric than in its Guanella counterpart.

2.2.2.1 Overview

A 1:4 Ruthroff balun also known as "voltage" balun is another type of TLT balun. Figure 4 shows the schematic of a Ruthroff balun and figure 5 shows its unbalanced-unbalanced (un-un) version.

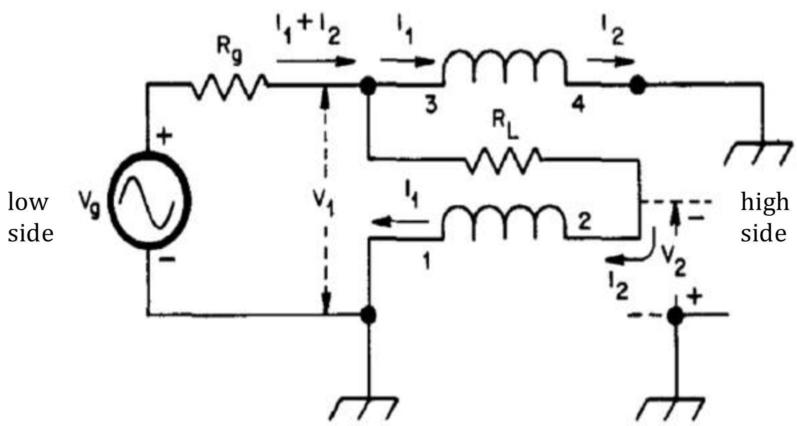


Figure 4. Circuit of a 1:4 Ruthroff transmission line transformer (balun) [3]

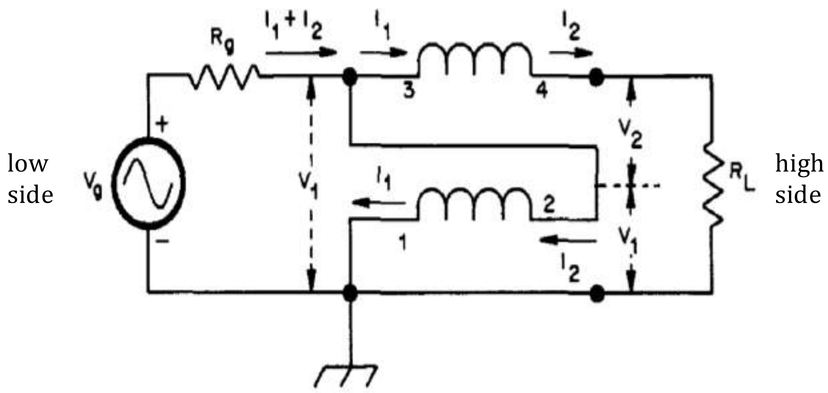


Figure 5. Circuit of 1:4 Ruthroff transmission line transformer (un-un) [3]

As shown in figure 5, in its 1:4 un-un structure, the output of terminal 2 is connected to the input of terminal 3 and raises this transmission line input voltage (V_1), which is called *"Bootstrap Effect"*. By connecting terminal 2 and 3, the output voltage (V_2) is delayed and the transmission line is *lifted-up* by its own *bootstraps* to V_1. The chocking reactance of the windings prevents conventional transformer currents to flow resulting in a voltage of V_1+V_2 across load, R_L.

The Ruthroff TLT has a different analysis compared to its Guanella counterpart. For the un-un version of Ruthroff TLT in figure 5, they are

$$V_g = (I_1 + I_2)R_g + V_1$$

$$I_2R_L = V_1 + V_2$$

$$V_1 = V_2 cos\beta\ell + jI_1Z_0 sin\beta\ell$$

$$I_1 = I_2 cos\beta\ell + jV_2/Z_0 sin\beta\ell \tag{2.3}$$

Ruthroff in his paper shows that the maximum transfer of power appears when $R_L = 4R_g$ with optimum value of characteristic impedance is $Z_0 = 2R_g$[13]. He also derived equations for the Z_{in} seen at either end of the transmission line.

The equations for Z_{in} that derived in [13] can be written as,

$$Z_{in}(low\ side) = Z_0\left(\frac{Z_L cos\beta\ell + jZ_0 sin\beta\ell}{2Z_0(1+cos\beta\ell)+jZ_L sin\beta\ell}\right) \quad (2.4)$$

$$Z_{in}(high\ side) = Z_0\left(\frac{2Z_L(1+cos\beta\ell)+jZ_0 sin\beta\ell}{Z_0 cos\beta\ell + jZ_L sin\beta\ell}\right) \quad (2.5)$$

The high and low frequency response for balun version of the Ruthroff TLT in figure 4 are similar as in un-un version [10].

2.2.2.2 Advantages and Disadvantages

The advantages for using a 1:4 Ruthroff balun include its matching properties and its bandwidth, even though not as wide as 1:4 Guanella balun. Thus, a planar version of this balun structure is able to save more area in PCB because it only needs one transmission line. However, the disadvantages of this balun structure are its limited impedance transformation ratio (1:4) and dependency of the planar version on the coupling between transmission line metal layers. Last, this type of balun structure is relatively more difficult to build and measure properly because of the connection that causes "*Bootstrap Effect*".

2.2.2.3 Compatibility with Planar Technology

The 1:4 Ruthroff balun structure shares the same condition with the 1:4 Guanella balun structure. It also can be implemented using coaxial transmission line as in its original version (TLT), which makes it possible to derive the structure into a planar version with microstrip line technology. The same configuration of layer stack of the structure also can be made with 2 layers (signal and ground layer). However, since the connection between the input of terminal 3 and the output of terminal 2 that create "*Bootstrap Effect*", it is not possible to use infinite ground for this balun structure.

2.2.3 1:4 Differential Balun

The last balun structure for research is the 1:4 differential balun. This structure can be derived from 1:1 coaxial balun. The 1:1 coaxial balun is a balun made of coaxial cable that can be found in radio or TV antennas. It uses a feed-line at arbitrary electrical length, a quarter wavelength ($\lambda/4$), and a third-quarter wavelength ($3\lambda/4$) adapting sections of coaxial cable with $Z_0 = Z_c = 25\ \Omega$ [26]. If the balun input has the same value with coaxial cables, then the value of the balun output is exactly the same [30]. Figure 6 shows the 1:1 Differential balun structure.

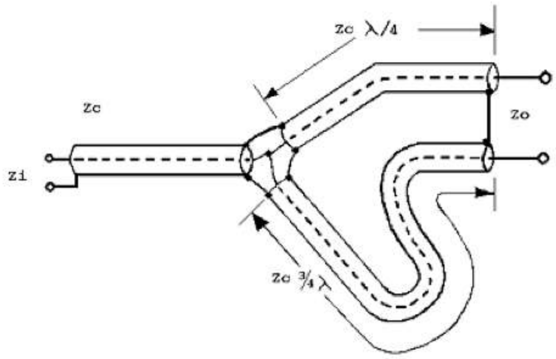


Figure 6. Basic design of the 1:1 Differential balun [26]

The 1:4 Differential balun can be built by eliminating two $\lambda/4$ pairs from both $\lambda/4$ and $3\lambda/4$ adapting sections of coaxial cables with $Z_0 = Z_c = 25\ \Omega$ [26].

2.2.3.1 Overview

A 1:4 differential balun has two outputs at balanced side. The first output (A) connected to the inner before a half-wavelength ($\lambda/2$) of antenna feeder. Meanwhile, the other output (B) is connected to the inner after a half-wavelength ($\lambda/2$) of antenna feeder. However, all the screens of coaxial cable are connected together at one common point. Figure 7 shows the basic design of the 1:4 differential balun.

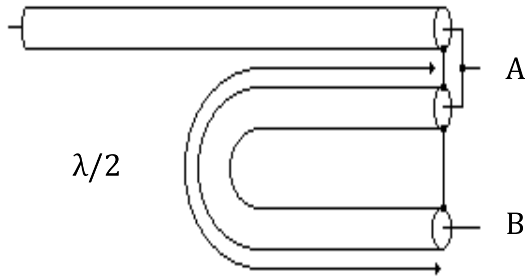


Figure 7. Basic design of the 1:4 differential balun [27]

From this design, there are two observations can be made. If the half-wavelength ($\lambda/2$) part is assumed to near resonant then the impedance will be mostly resistive. Due to the delay brought by the half-wavelength ($\lambda/2$) of the coaxial cable, the second output (B) has $180°$ phase difference with the other output (A). This situation makes output (A) as positive voltage (+V) and output (B) as negative voltage (-V).

The voltage difference at the output makes $V(B) = V - (-V) = 2V$. As the power through the system should be lossless, the output current (I) should drop by half or I(B) = I/2. Since the half-wavelength part in this design structure is near resonant, the impedance change in this balun is $R_L(B) = V(B)/I(B) = (2V)/(I/2) = 4R_g$. This yields the 1:4 ratio in differential balun structure.

2.2.3.2 Advantages and Disadvantages

The advantages for using a 1:4 Differential balun are as follow; this balun is able to perform impedance matching and power combining. This type of balun structure is the easiest structure to analyze since it is built based on coaxial cables. However, the disadvantages of this balun structure are its specific impedance transformation ratio and it works in a narrow bandwidth.

2.2.3.3 Compatibility with Planar Technology

The 1:4 Differential balun has the simplest structure among all three structures for this research. It is also possible to derive the structure into planar version with microstrip line technology. The configuration of layer stack of the structure can be made with 2 layers with infinite ground layer.

2.3 Summary

A balun is an important component in balanced devices, such as push-pull amplifiers, double-balance mixers, and antennas. The main function of a balun as passive device is to match an unbalanced to balanced structure. Thus, the device is used to solve unbalanced-balanced connection problem. For this research, three types of balun are designed. They are Guanella balun, Ruthroff balun, and Differential balun with 1:4 impedance ratios. Each balun has its advantages and disadvantages. However, all types of balun for this research are compatible with planar technology, which means that it can be transformed into microstrip line version to be implemented in integrated circuit (IC) or printed circuit board (PCB).

CHAPTER 3

Design of Balun Structures

3.1 Introduction

This chapter explains about the design approaches taken during the research. Since one of the goals of this research is to investigate whether a balun structure can simultaneously be used for impedance transformation, this research starts from investigating matching network structures. The most practical and easy to build circuit for impedance matching network structure is utilizing quarter-wave transformers (QWT) because they can be used to form balun structures. The number of QWT structures to be used depends on the type of balun. There are three types of planar balun structures designed for this research. These balun structures are the 1:4 Guanella balun, the 1:4 Ruthroff balun, and the 1:4 Differential balun. During the research, all of these structures are designed and simulated in ADS from Keysight.

3.2 Quarter-wave Transformer Design

The design step of QWT structures begins from how to set the parameters for QWT to works fine as impedance matching. The most important thing during the QWT design process is to make sure that the load impedance (Z_L) is matched to the source impedance (Z_o). Figure 8 shows the circuit of QWT matching network transformer.

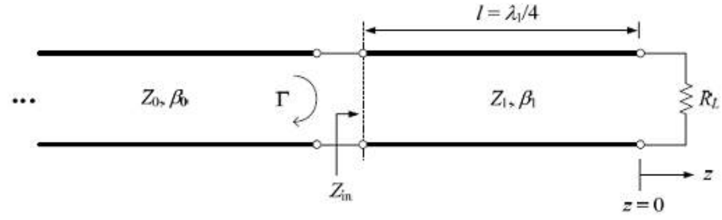


Figure 8. QWT matching transformer [1]

From figure 8, if the load resistance (R_L) is not matched to the source impedance (Z_0), part of the transmitted wave or signal will be reflected back. To make sure full power can be delivered, it is important to make sure that the R_L is matched where one way is add a QWT with characteristic impedance (Z_1) between Z_0 and R_L. All formulas for QWT calculation are mentioned in [1] and [2].

To make sure that the R_L is matched to the Z_0, it is important to set the reflection coefficient of transmission line (*Gamma*) equal to 0 ($\Gamma = 0$). The result of *Gamma* can be calculated with equation (3.1).

$$\Gamma = \frac{Z_{in}-Z_0}{Z_{in}+Z_0} \tag{3.1}$$

Here, the Z_{in} for QWT can be derived from equation (3.2).

$$Z_{in} = Z_0 \frac{Z_L+jZ_0 tan\beta\ell}{Z_0+jZ_L tan\beta\ell} \tag{3.2}$$

$$Z_{in(QWT)} = Z_1 \frac{R_L+jZ_1 tan\beta\ell}{Z_1+jR_L tan\beta\ell}$$

Both equation (3.1) and (3.2) are taken from [1]. To analyze this for $\beta\ell = \pi/2$, assume $\ell = \lambda/4$ and $\beta = 2\pi/\lambda$. By substituting this in $tan\beta\ell$, the Z_{in} for lossless QWT can be written as,

$$Z_{in} = \frac{{Z_1}^2}{R_L}$$

In order to make $\Gamma = 0$, from (3.1) the value of Z_{in} must equal to Z_0 ($Z_{in} = Z_0$). This conclude the Z_1 of QWT in lossless condition as

$$Z_1 = \sqrt{Z_0 \times R_L} \tag{3.3}$$

Assume, the value of $Z_0 = R_L$ = 50 Ω. By using equation (3.3), the value of Z_1 for QWT is 50 Ω. The physical length (ℓ) of QWT can be calculated with (3.4).

$$\lambda(\ell) = \frac{c}{f\sqrt{\varepsilon_r}} \tag{3.4}$$

For example, for an ideal (lossless) QWT in vacuum condition, $c = 3\times10^8\ m/s$, $f = 1.5\times10^9\ Hz$, and $\varepsilon_r = 1$. By using equation (3.4), $\ell = 5\ cm = 50\ mm$. The physical length of transmission line is the length from one end of the connector to the other in real situation.

An ideal QWT is designed and simulated with TLIN model in ADS from Keysight to observe its characteristic. This QWT model is set with Z_0 = 50 Ω and electrical length (E) = 90° $(\lambda/4)$. The electrical length of transmission lines is the length of an electrical conductor in terms of phase shift introduced by a transmission line conductor at a certain frequency. It is simulated with frequency range from 0.01 to 3 GHz. Picture 9 shows the design setup in ADS and picture 10 shows its simulation results.

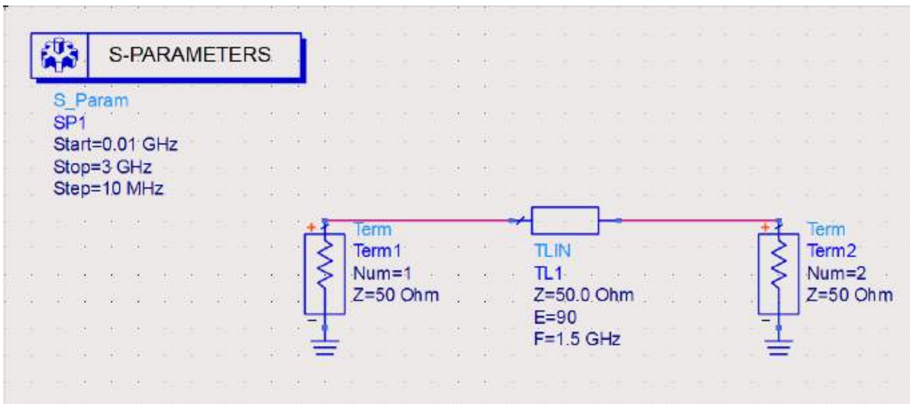


Figure 9. Schematic setup of an ideal QWT structure in TLIN model with ADS

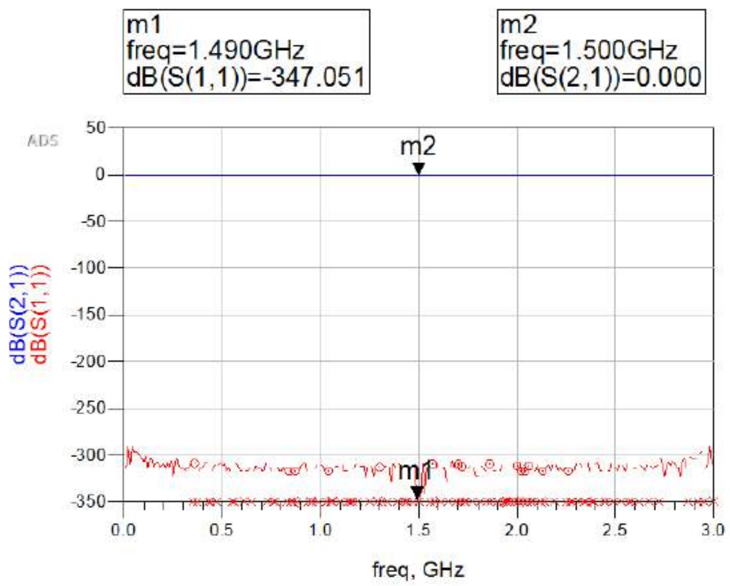


Figure 10. Simulation results of an ideal QWT structure in TLIN model with ADS

The simulation results in figure 10 shows that at center frequency, the S-parameter of return loss (S_{11}) reaches -347.051 dB and insertion loss (S_{21}) reaches 0 dB. It means that all input signal can be transmitted. However, the simulation results for S_{11} never reach infinity (∞). Instead, it only reaches -347.051 dB. The analysis for this situation can be calculated with equation (3.5) taken from [2] as follows,

$$RL\ [dB] = -20\times\log\,(S_{11}) \tag{3.5}$$

$$347.051 = -20\times\log\,(S_{11})$$

$$\log(S_{11}) = -\frac{347.051}{20} = -17.35255$$

$$S_{11} = 10^{-17.35255}$$

$$S_{11} = 4.440685331\times10^{-18}$$

The result for S_{11} can be simply writes as 0 (zero). The reason of this situation is that the ADS software is an EDA software with 64-bit signed integer in computing that has limitation to 9,223,372,036,854,775,807 as maximum number, equivalent to the hexadecimal number $7FFF, FFF, FFF, FFF_{16}$ to show to the nearest simulation results.

Next, an ideal QWT with coax model is designed and simulated in ADS. The coax model is set with $Z_0 = 50\ \Omega$ and electrical length (E) = 90°. A substrate is introduced here as part of coax model with the value of dielectric constant $(\varepsilon_r) = 2.1$. Here, the addition of substrate means an introduction of very small looses in the structure, which makes it a bit difference than TLIN model. By using equation (3.4), this setup makes the physical length of QWT become shorter to,

$$\lambda(\ell) = \frac{3 \times 10^8}{1.5 \times \sqrt{2.1}}$$

$$\lambda(\ell) = 34.4794 \text{ mm}$$

Figure 11 shows the schematic setup and figure 12 shows its simulation results.

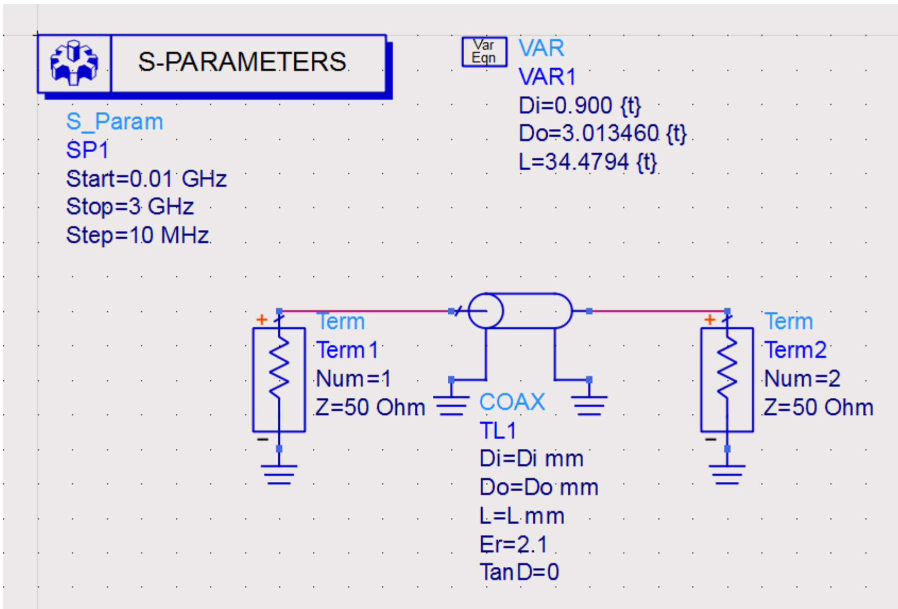


Figure 11. Schematic setup of an ideal QWT structure in coax model with ADS

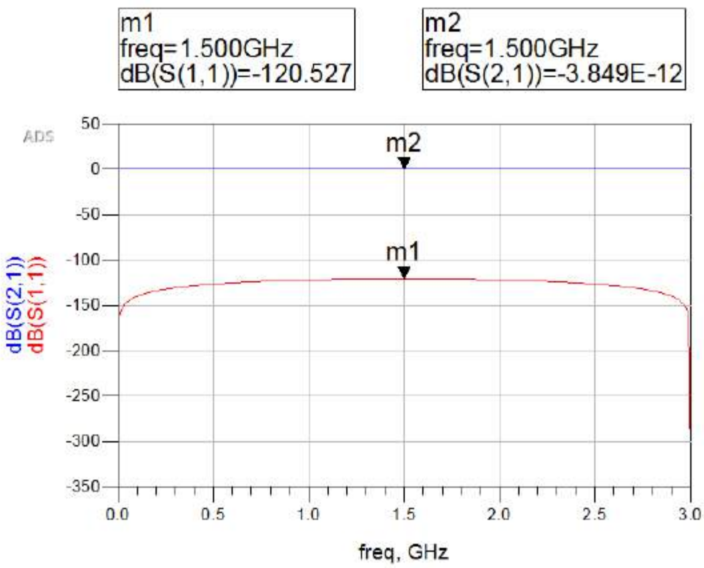


Figure 12. Simulation results of ideal QWT structure in coax model with ADS

Simulation result with ADS in figure 12 shows that the S_{11} reaches -120.527 dB and S_{21} reaches -3.849×10^{-12} dB. It means that there is no attenuation in output port and all power can be transmitted.

Last, the coax model is converted to microstrip line model. For converting the transmission line from coax to microstrip line technology, it has to consider the relation of ε_r, f, and λ as shown in equation (3.4) to derive microstrip dimensions (width (W) and length (L)).

The formulas to calculate the dimensions of microstrip line are mentioned in [1] and can be seen in equation (3.6) and (3.7).

$$Z_0 = \begin{cases} \dfrac{60}{\epsilon_{eff}} \ln\left(\dfrac{8d}{w} + \dfrac{w}{4d}\right) & for\,\dfrac{w}{d} \leq 1 \\ \dfrac{120}{\sqrt{\epsilon_{eff}}\ \left(\frac{w}{d}\right)+1.393+0.667\ln\left(\left(\frac{w}{d}\right)+1.44\right)} & for\,\dfrac{w}{d} \geq 1 \end{cases} \tag{3.6}$$

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2} + \frac{1}{\sqrt{1+12(\frac{d}{w})}} \tag{3.7}$$

where,

Z_0 = the characteristic impedance of microstrip lines.

ϵ_{eff} = the effective dielectric constant.

d = the substrate thickness.

W = the width of microstrip line conductor.

By using equations (3.4), (3.6), and (3.7), the values of W and L of the microstrip line with Z_0 = 50 Ω can be calculated. For simulation and analysis purpose, the value of conductor conductivity is set to 1.0×10^{50} for ideal microstrip line. This setup purpose is to eliminate any possible noise that may appear in the substrate. Last, the schematic design of microstrip line model is simulated with frequency range from 0.01 to 3 GHz. Figure 13 shows the schematic setup and figure 14 shows the simulation result. This simulation results, later will be compared with EM simulation when this microstrip line schematic converted into layout in Momentum.

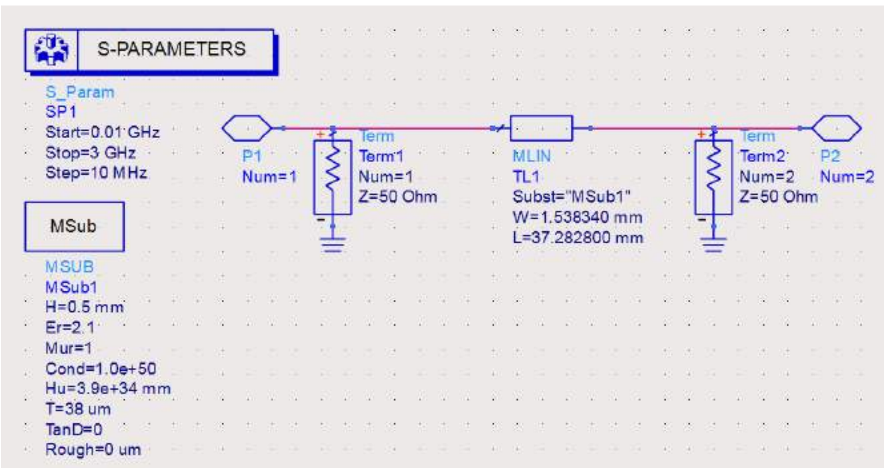


Figure 13. Schematic setup of ideal QWT structure in microstrip line model with ADS

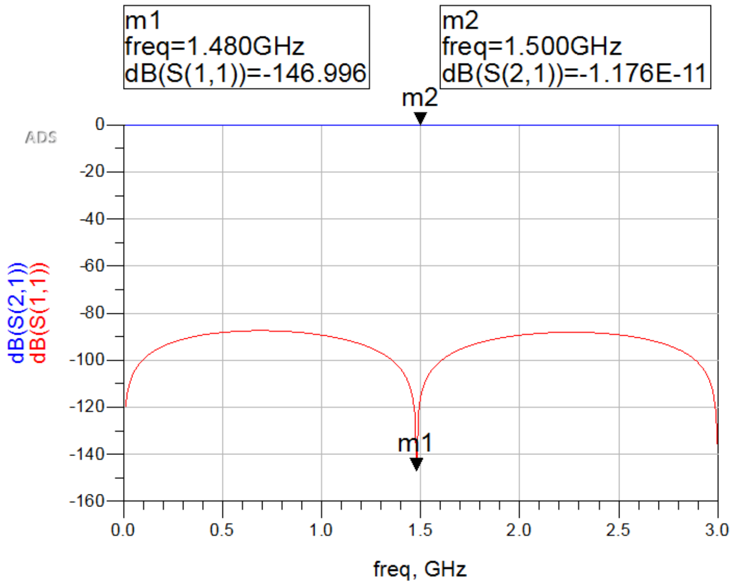


Figure 14. Simulation results of QWT structure in microstrip line model with ADS

The layout design derivation of ideal microstrip line is by generated it from schematic version. Figure 15 shows the 3D view of the design with Momentum and figure 16 shows the EM simulation result.

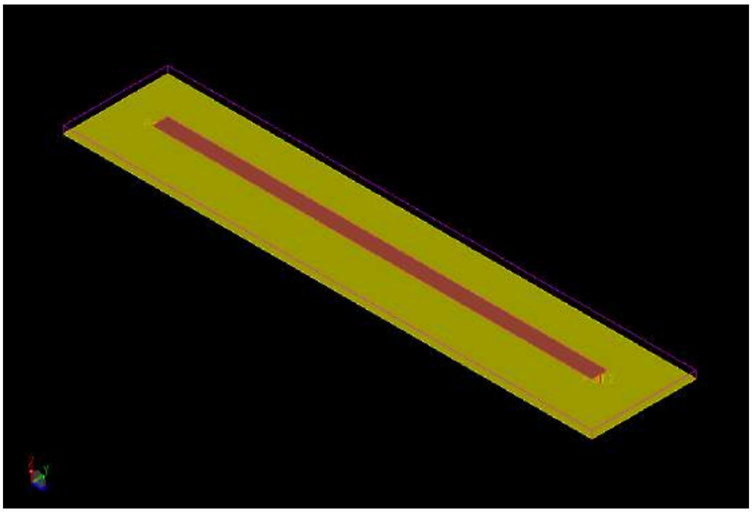


Figure 15. 3D view of ideal microstrip line model with Momentum ADS

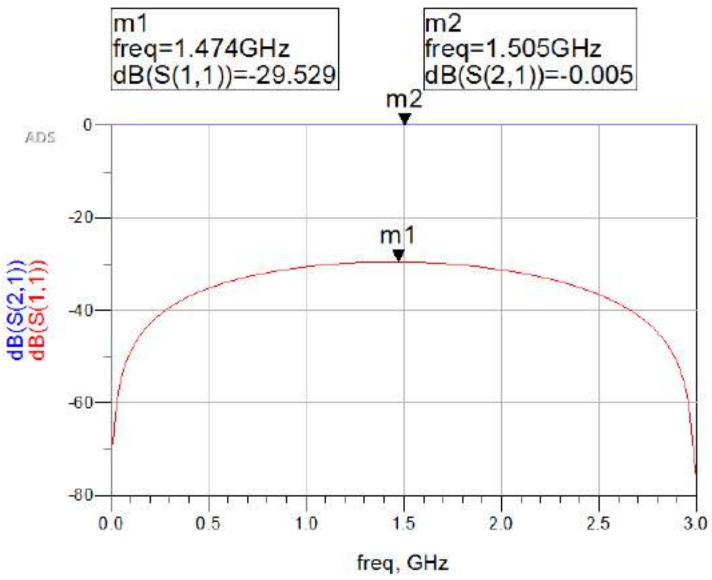


Figure 16. EM simulation results of ideal microstrip line model with Momentum ADS

The simulation results in schematic and Momentum of ideal microstrip line show a huge differences as can be seen in figure 14 and 16. The simulation results in schematic show that there is a slightly increase in higher frequency. However, when performing EM simulation in Momentum, the result is totally different. EM simulation result shows that at center frequency, the S_{11} reaches -29.529 dB. This result shows that the value of Z_0 is not equal to 50 Ω. Thus, the real value of Z_0 can be calculated with equation (3.1) and (3.5) as follows,

$$29.53 = -20 \times \log(S_{11})$$

$$\log(S_{11}) = -1.47645$$

$$S_{11} = 10^{-1.47645}$$

$$S_{11} = 0.032$$

Here $S_{11} = \Gamma$ and $Z_L = Z_0$ then,

$$S_{11} = \frac{Z_0 - Z_S}{Z_0 + Z_S}$$

$$0.032 = \frac{Z_0 - 50}{Z_0 + 50}$$

$$0.032 \times (Z_0 + 50) = Z_0 - 50$$

$$0.032Z_0 + 1.6 = Z_0 - 50$$

$$Z_C - 0.032Z_0 = 50 + 1.6$$

$$0.968\, Z_0 = 51.6$$

$$Z_0 = \frac{51.6}{0.968}$$

$$Z_0 = 53\ \Omega$$

The analytic result shows that the characteristic impedance of microstrip line design in Momentum is $Z_0 = 53\ \Omega$, which is bigger than the result in schematic design ($Z_0 = 50\ \Omega$). The differences between schematic and Momentum (layout) results caused by many factors such as introduction of substrate, quasy-TEM effect in this microstrip line, and the dimension of conductor. It occurs because of the EM simulation in Momentum compute not only S-parameters, but also surface current, and fields effect that make it closer to physical design. To eliminate the differences, a design tuning is needed. For tuning purpose, the Z_0 value is taken from its S-parameters. For Return Loss (RL), the value of S_{11} can be calculated with equation (3.5) taken from [2] as follows,

$$RL\ [dB] = -20 \times \log\,(S_{11})$$

$$-29.53 = 20 \times \log\,(S_{11})$$

where S_{11}= Γ_{in} then,

$$\Gamma_{in} = 10^{-1.5} = 0.032$$

For Insertion Loss (IL), the value of S_{21} can be calculated with equation (3.8) taken from [2] as follows,

$$IL\,[dB] = -20\times\log(S_{21}) \tag{3.8}$$

$$-0.005 = 20\times\log(S_{21})$$

$$S_{21} = 10^{0} = 1$$

The S-matrix of this microstrip line is

$$S = \begin{bmatrix} 0.032 & 1 \\ 1 & 0.032 \end{bmatrix}$$

Here, the S-matrix is transformed to ABCD-matrix with equation (3.9) to (3.12) taken from [1] and [2].

$$A = \frac{(1+S11)(1-S22)+S12S21}{2\times S21} \tag{3.9}$$

$$B = \frac{(1+S11)(1+S22)-S12S21}{2\times S21} \tag{3.10}$$

$$C = \frac{(1-S11)(1-S22)-S12S21}{2\times S21} \tag{3.11}$$

$$D = \frac{(1-S11)(1+S22)+S12S21}{2\times S21} \tag{3.12}$$

The ABCD-matrix of this microstrip line is

$$ABCD = \begin{bmatrix} 0.999488 & 0.032512 \\ -0.031448 & 0.999488 \end{bmatrix}$$

For transmission line with length (ℓ), the ABCD-matrix can also be calculated with equation (3.13) to (3.16) taken from [1] and [2].

$$A = cos\beta\ell \tag{3.13}$$

$$B = jZ_0 sin\beta\ell \tag{3.14}$$

$$C = jY_0 sin\beta\ell \tag{3.15}$$

$$D = cos\beta\ell \tag{3.16}$$

The propagation constant $(\gamma) = \alpha + j\beta$, where for transmission lines in a lossless situation the attenuation constant $(\alpha) = 0$ and phase constant $(\beta) = \sqrt{\epsilon_{eff}} \times k_0$. By using equation (3.14), the correct Z_o value of microstrip line in Momentum can be achieved. In addition, based on the lossless transmission line equation (3.17), the reduction of Z_0 value can be achieved by increasing the capacitance in the transmission line.

$$Z_0 = \sqrt{\frac{L}{C}} \tag{3.17}$$

However, even though there is a slightly difference of the Z_o value, because of the S_{11} value in this microstrip line is far less than – 20 dB, the value of S_{11} and S_{21} in this microstrip line become very sensitive and it is very difficult to design microstrip line with Z_0 = 50 Ω. Figure 17 shows the result of ideal microstrip line EM simulation after adjustment in width (W = 1.7086986 mm) of microstrip line model in Momentum ADS.

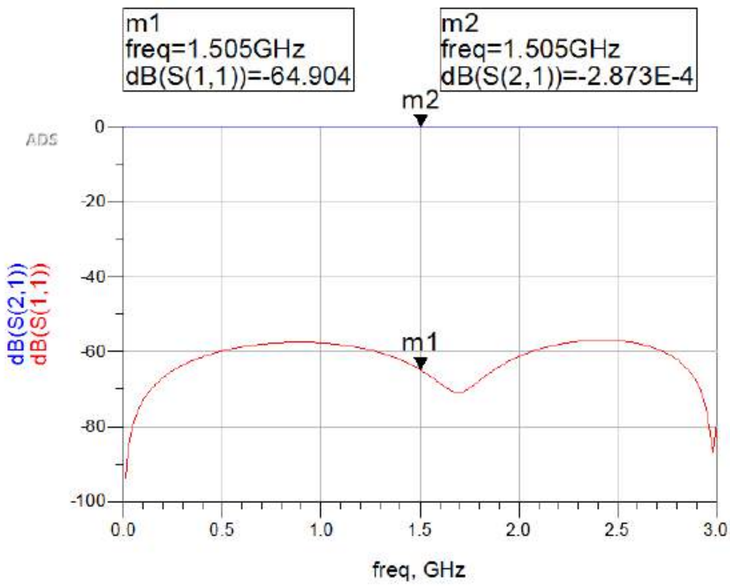


Figure 17. EM simulation results of ideal microstrip line model in Momentum ADS after adjustment

After the adjustment of the width in microstrip line design, the EM Simulation results in figure 17 shows that the S_{11} reaches -64.904 dB and S_{21} reaches $-2.873{\times}10^{-4}$ dB at center frequency. It shows that the characteristic impedance of microstrip line is close to 50 Ω.

3.3 Balun Design

Based on QWT structure, three topologies on balun structure are designed both in ideal (lossless) and non-ideal (losses) condition. Each balun is designed and simulated in planar version with microstrip line technology in ADS from Keysight.

3.3.1 1:4 Guanella Balun

The design of the 1:4 Guanella balun from figure 2 shows that it is possible to use two QWT structures that have parallel input and serial output. The analysis for impedance matching, Z_0, and Γ can be done as in section 2.1. First, the value of Z_{in} is calculated. It can be done by derived ABCD parameter based on figure 18.

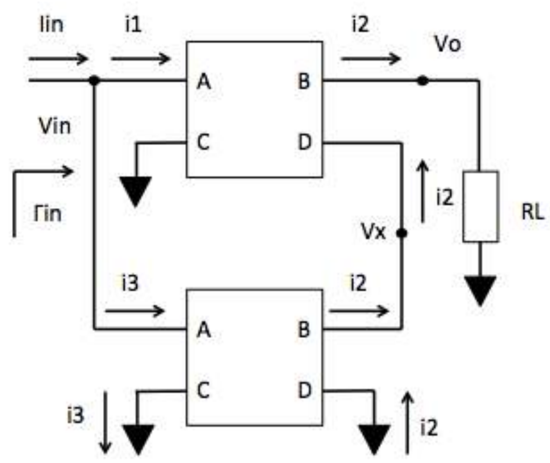


Figure 18. 1:4 Guanella balun circuit

In order to derive Z_{in} for this balun, ABCD matrix can need to be derived as stated in equation (3.18) and (3.19) as follows,

$$\begin{bmatrix} V_{in} \\ i_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_o - V_x \\ i_2 \end{bmatrix} \tag{3.18}$$

$$\begin{bmatrix} V_{in} \\ i_3 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_x \\ i_2 \end{bmatrix} \tag{3.19}$$

Where $i_{in} = i_1 + i_3$ and $V_o = i_2 \times R_L$. Equation (3.18) and (3.19) can be rewrite as

$$V_{in} = AV_o - AV_x + Bi_2$$

$$i_1 = CV_o - CV_x + Di_2$$

$$V_{in} = AV_x + Bi_2$$

$$i_3 = CV_x + Bi_2$$

$$i_{in} = i_1 + i_3$$

$$V_o = i_2 R_L$$

With simple substitution and elimination, the parameters for V_{in} and i_{in} can be achieved. The parameters for Z_{in} can be calculated with equation (3.20) as follows,

$$Z_{in} = \frac{V_{in}}{i_{in}} \tag{3.20}$$

$$Z_{in} = \frac{1}{2} \times \frac{(A \times RL) + 2B}{(C \times RL) + 2D}$$

The behavior of the 1:4 Guanella balun structure in ideal condition (lossless) can be analyzed with mathematical software Matlab (see appendix A and B).

The variety of Z_o and ℓ values of the balun circuit can be change and see the effect to the balun behavior in ideal simulation. Figure 19 shows the simulation result in Matlab if the value of Z_o is 50 Ω and a few samples of results as shown in figure 20 if the value of Z_o is 49.999 Ω and figure 21 if the value of Z_o is 50.001 Ω.

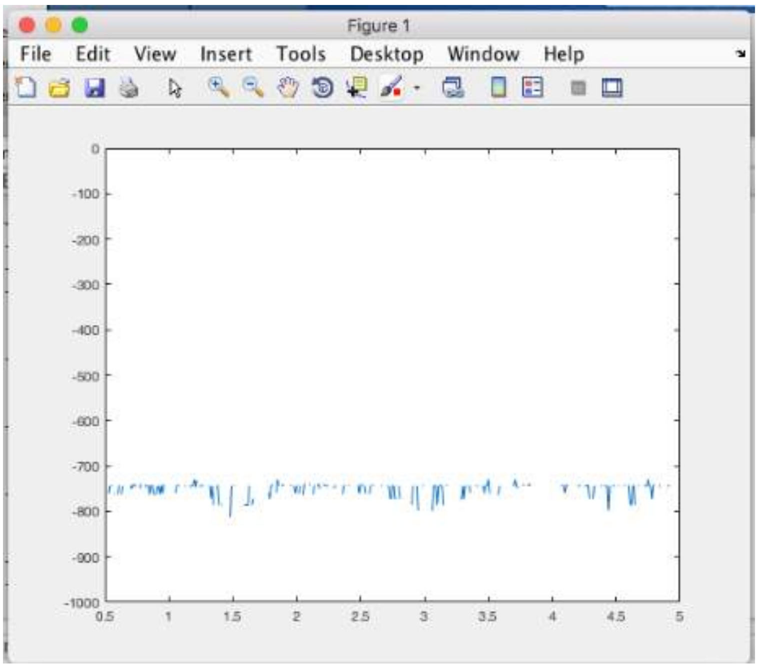


Figure 19. Matlab simulation result (Z_o = 50 Ω)

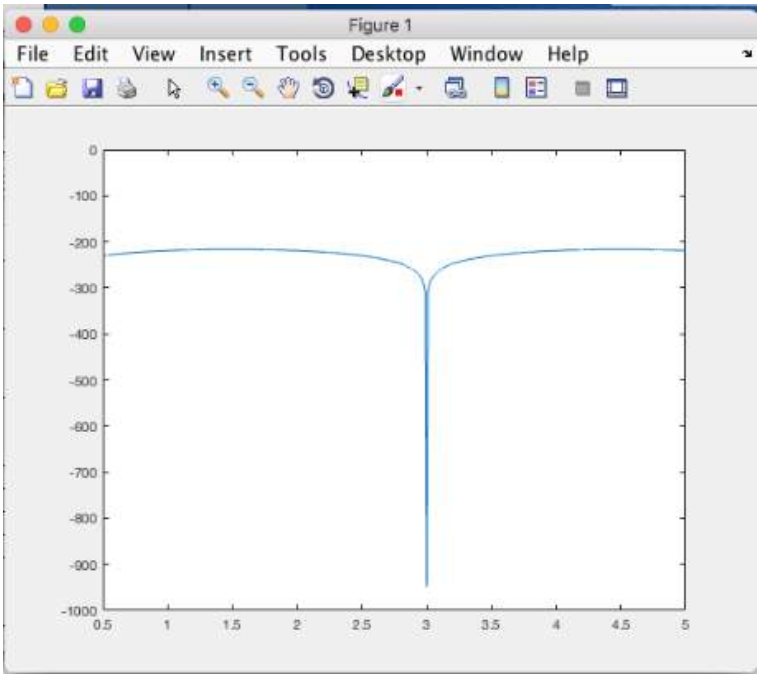


Figure 20. Matlab simulation result (Z_o = 49.999 Ω)

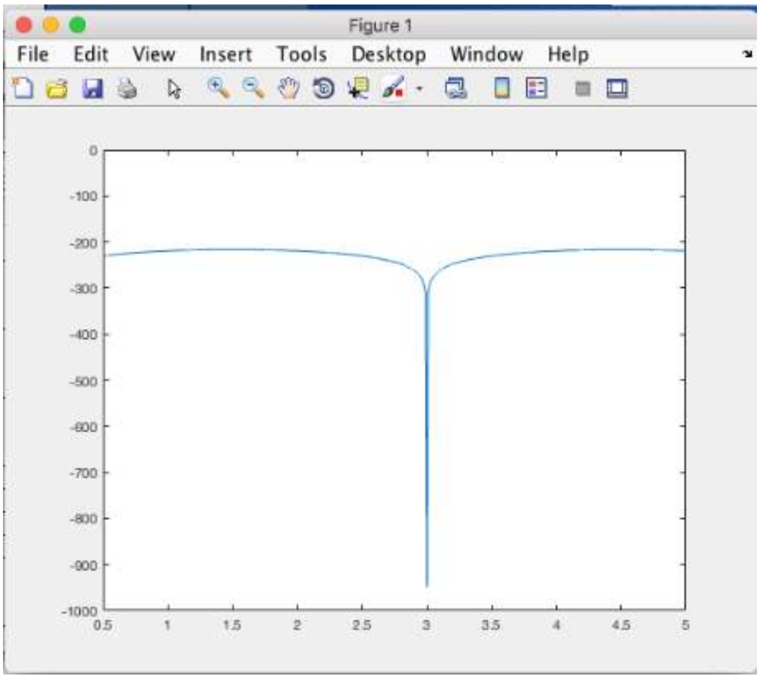


Figure 21. Matlab simulation result (Z_o = 50.001 Ω)

Figure 20 and 21 show that it is crucial to make the value of Z_o = 50 Ω. Changes in behavior can occur even with slightly changes in Z_o value. This situation is hard to reach specially when designing the planar version with microstrip line technology because it does not have an ideal TEM mode due to the existence of second substrate (AIR with $\varepsilon_r = 1$) in the design.

3.3.1.1 Design Derivation with Planar Technology

The design of planar 1:4 Guanella balun can be achieved in several steps. Figure 22 shows the derivation of 1:4 Guanella balun from its original structure as mentioned in figure 2 to planar version with microstrip line technology.

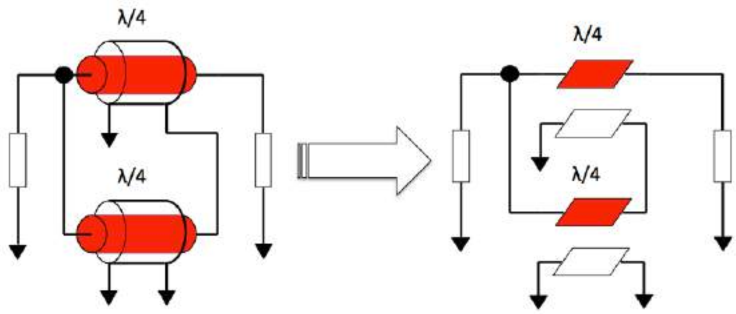


Figure 22. The design derivation of planar 1:4 Guanella balun

Figure 22 shows that planar 1:4 Guanella balun structure can be designed with coaxial cable model. First, two toroid cores are replaced by two coaxial cables with electrical length of $\lambda/4$ as in QWT. This electrical length is chosen because the balun structure has to be work as impedance matching network. Next, these cables are connected as shown in figure 22 to create a balun structure with 1:4 impedance ratios between source and load. Based on this structure, the derivation with microstrip line technology can be applied.

3.3.1.2 Layer Stack and Dimensions of Planar Design

The design of planar 1:4 Guanella balun started by defining the multi-layer substrate with finite ground layer (described with certain dimension). Finite ground layer is chosen because the balun structure cannot utilize common ground at the output of the structure. Planar 1:4 Guanella balun structure output has a unique connection at the output, which is the output of signal layer from one microstrip line has to be connected to ground layer from another microstrip line. This situation makes the usage of infinite ground layer is not possible.

Due to the usage of finite ground layer, it is necessary to assign pin inside a port in a specific way. The setup for this balun structure is pin 3 sets as negative pin for pin 1 for input port (PORT1) and pin 4 sets as negative pin for pin 2 for output port (PORT2). The substrate setup for this structure design is using MLSUBSTRATE2 (substrate for 2 layers with bottom layer as universal ground layer) and set all parameters to be lossless ($\varepsilon_r = 2.1$, $tan\delta = 0$, and conductor conductivity = 1.0×10^{50}). Figure 23 shows the configuration for 2 layers microstrip line for planar 1:4 Guanella balun structure with finite ground layer.

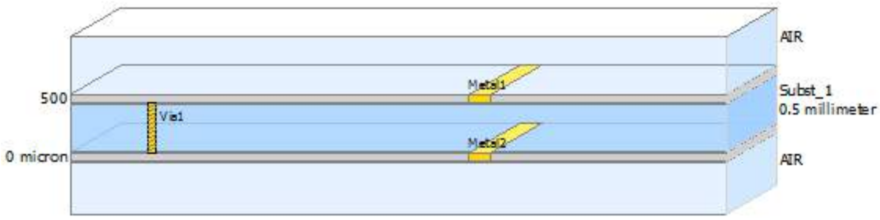


Figure 23. Layer stack for planar 1:4 Guanella balun structure

The plane dimensions for this design are as follows:

- Layer 1: W = 1.7 mm, L = 30.1 mm, Port 1 = P1 (+) and P3 (-).
- Layer 2: W = 3.5 mm, L = 30.1 mm, Port 2 = P2 (+) and P4 (-).

Here, the value of both W and L is rounded to single digit after comma to ease manufacturing process.

3.3.1.3 Planar Design and Simulations

For electromagnetic (EM) simulation, layout of planar 1:4 Guanella balun is designed in Momentum ADS. It simulated with frequency range from 0.01 to 3

GHz. Figure 24 shows the 3D view of two layers design and figure 25 shows its simulation results in Momentum ADS.

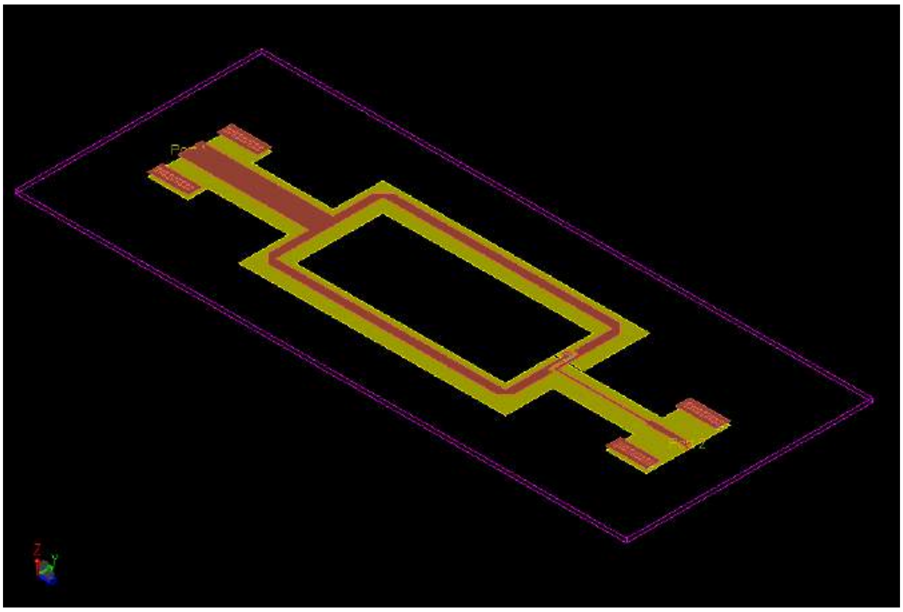


Figure 24. 3D view of ideal planar 1:4 Guanella balun in Momentum ADS

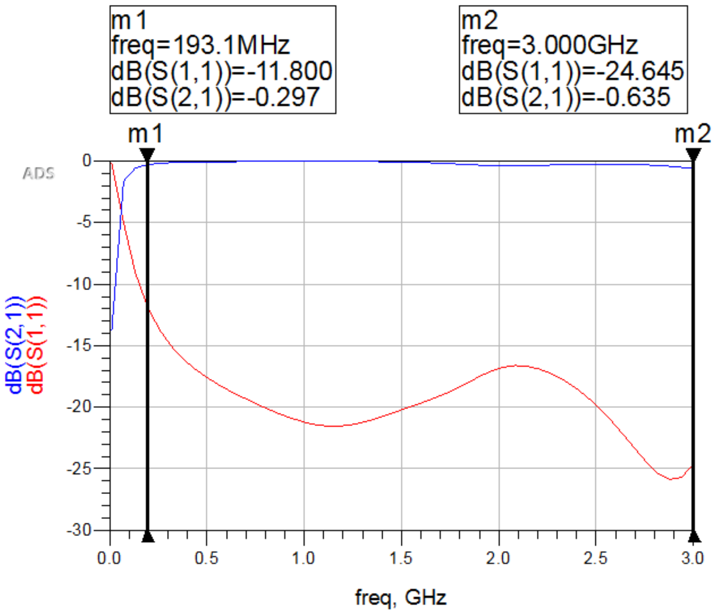


Figure 25. EM simulation results of ideal planar 1:4 Guanella balun with Momentum ADS

The EM simulation results show that the design of ideal planar 1:4 Guanella balun structure achieves the value of S_{11} lower than -10 dB and S_{21} higher that -1 dB from 0.193 to 3 GHz with fractional bandwidth (FBW) 175 %. Based on the FBW percentage achieved, this balun structure is considered as a wideband balun.

3.3.2 1:4 Ruthroff Balun

The design of 1:4 Ruthroff balun from figure 4 and 5 show that it is possible to use single QWT structures and make it in planar version using microstrip line. However, unlike Guanella's balun structure that can practically be analyzed by inspection of current and voltage, Ruthroff balun structure trapped to loop and use equations (3) to (6) to solve the power in the load [10][13].

3.3.2.1 Design Derivation with Planar Technology

The design of planar 1:4 Ruthroff balun can be achieved in several steps. Figure 26 shows the derivation of 1:4 Ruthroff balun from its original structure as mentioned in figure 4 and 5 to planar version with microstrip line technology.

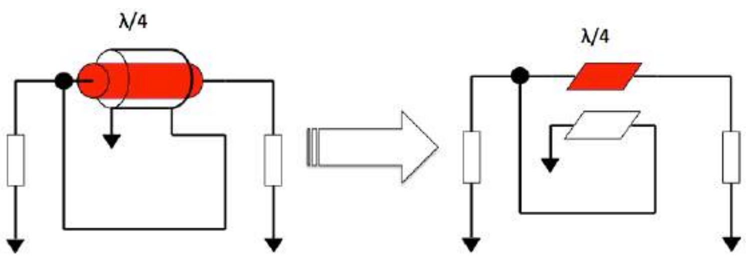


Figure 26. The design derivation of planar 1:4 Ruthroff balun

First, single toroid core is replaced by a coaxial cables with electrical length of $\lambda/4$ as in QWT. This electrical length is chosen because the balun structure has to be work as impedance matching network. This coaxial cable is connected as shown in figure 26 to create a balun structure with 1:4 impedance ratios between source and load. Based on this structure, the derivation with microstrip line technology can be applied as in QWT design.

3.3.2.2 Layer Stack and Dimensions of Planar Design

The layer stack for planar 1:4 Ruthroff balun has the same configuration with planar 1:4 Guanella balun and set all parameters to be lossless ($\varepsilon_r = 2.1$, $tan\delta = 0$, and conductor conductivity = $1.0{\times}10^{50}$). Figure 27 shows the configuration for 2 layers microstrip line for planar 1:4 Ruthroff balun structure.

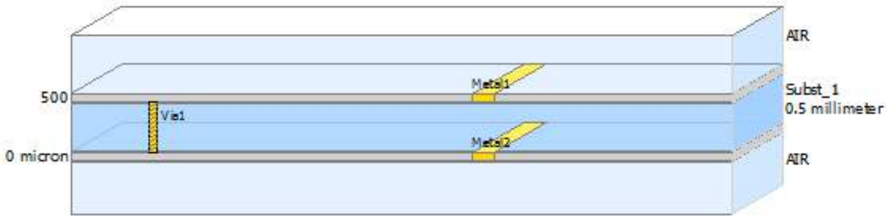


Figure 27. Layer stack for planar 1:4 Ruthroff balun structure

The plane dimensions for this design are as follows:

- Layer 1: W = 1.7 mm, L = 30.1 mm, Port 1 = P1 (+) and P3 (-).
- Layer 2: W = 3.5 mm, L = 30.1 mm, Port 2 = P2 (+) and P4 (-).

Here, the value of both W and L is rounded to single digit after comma to ease manufacturing process.

3.3.2.3 Planar Design and Simulations

For EM simulation, layout of planar 1:4 Ruthroff balun is designed in momentum ADS. It simulated with frequency range from 0.01 to 3 GHz. Figure 28 shows the 3D view of two layers design and figure 29 shows its simulation results in Momentum ADS.

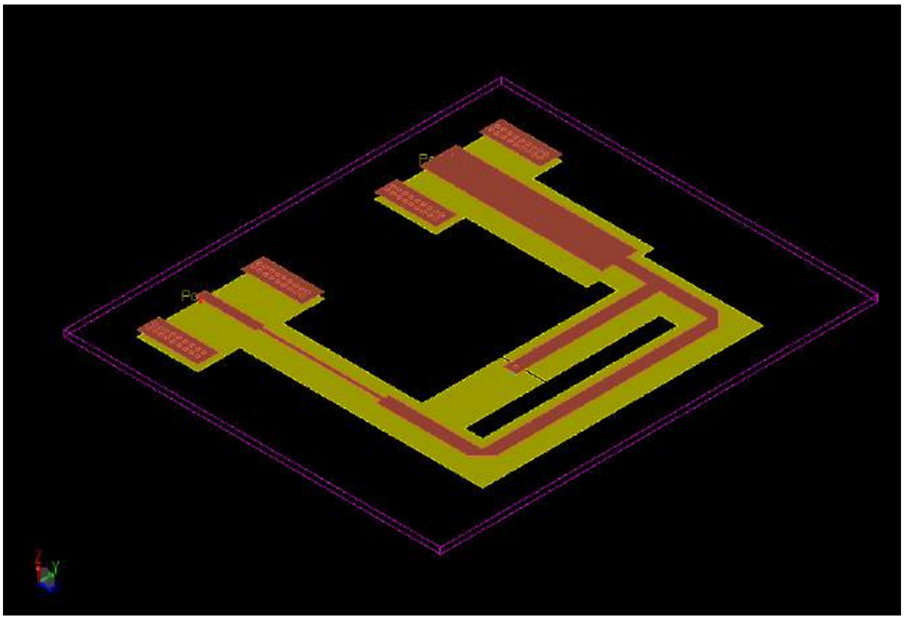


Figure 28. 3D view of ideal planar 1:4 Ruthroff balun with Momentum ADS

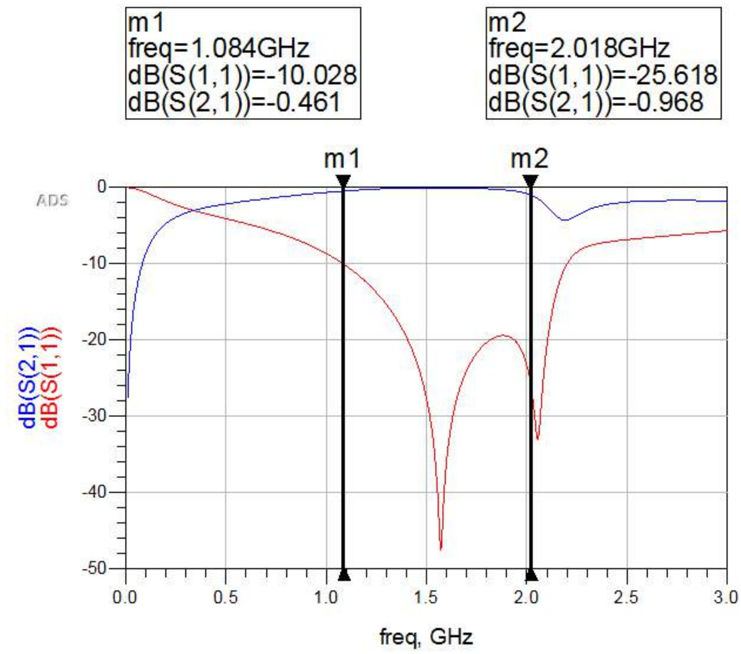


Figure 29. EM simulation results of ideal planar 1:4 Ruthroff balun with Momentum ADS

The EM simulation results show that the design of ideal planar 1:4 Ruthroff balun structure achieves the value of S_{11} lower than -10 dB and S_{21} higher that -1 dB from 1.084 GHz to 2.018 GHz with fractional bandwidth (FBW) 67%. The additional of matching lines and the usage of SMA connectors at input and output of the balun for measurement purpose cause the lower percentage in FBW. As mentioned in chapter 2 that a 1:4 Ruthroff balun is able to give its best results at shorter. However, even tough it does not reach its best results, the FBW percentage in this structure still make this balun structure considered as a wideband balun.

3.3.3 1:4 Differential Balun

The design of 1:4 Differential balun from figure 6 shows that the balun structure uses coaxial cable. This structure eases the derivation to planar version using microstrip line. The balun structure itself can be derived from 1:1 Differential balun consist of two coaxial cables with different electrical length ($\lambda/4$ and $3\lambda/4$) to make a delay line with $180°$ phase difference at the outputs as mentioned in chapter 2.

3.3.3.1 Design Derivation with Planar Technology

The design of planar 1:4 Differential balun can be achieved in several steps. Figure 30 shows the derivation of 1:4 Differential balun from its original structure with coaxial cable as mentioned in figure 7 to planar version with microstrip line technology.

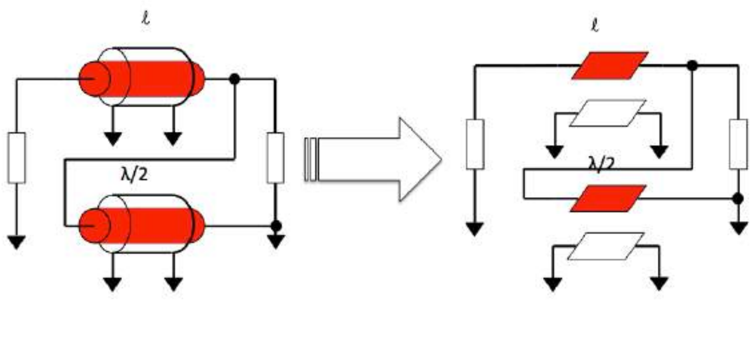


Figure 30. The design derivation of planar 1:4 Differential balun

A coaxial cable version of 1:4 Differential balun is replaced by microstrip line with electrical length of $\lambda/2$. This coaxial cable consist of a feed-line with any length and a coaxial cable with $\lambda/2$ to create delay with $180°$ phase difference at the outputs.

3.3.3.2 Layer Stack and Dimensions of Planar Design

The layer stack for planar 1:4 Differential balun has the same configuration with two previous balun designs and set all parameters to be lossless ($\varepsilon_r = 2.1$, $tan\delta = 0$, and conductor conductivity = 1.0×10^{50}). Figure 31 shows the configuration for 2 layers microstrip line for planar 1:4 Differential balun structure.

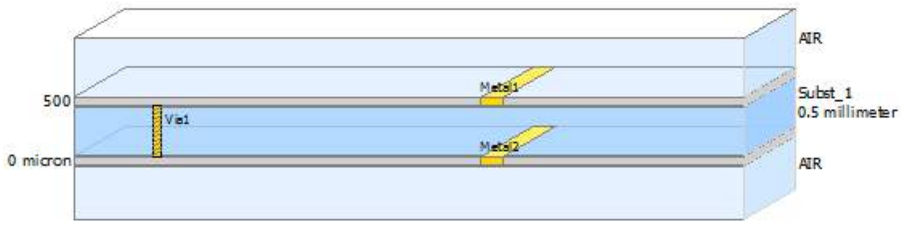


Figure 31. Layer stack for planar 1:4 Differential balun structure

The plane dimensions for this design are as follows:

- Layer 1: W = 3 mm, L = 60 mm, P1 (+), P2 (+), and P3 (+).
- Layer 2: W = 6 mm, L = 60 mm, P4 (-), P5 (-) and P6 (-).

Here, the value of both W and L is rounded to single digit after comma to ease manufacturing process.

3.3.3.3 Planar Design and Simulations

For EM simulation, layout of planar 1:4 Differential balun is designed in momentum ADS. It simulated with frequency range from 0.01 to 3 GHz. Figure

32 shows the 3D view of two layers design and figure 33 shows its simulation results in Momentum ADS.

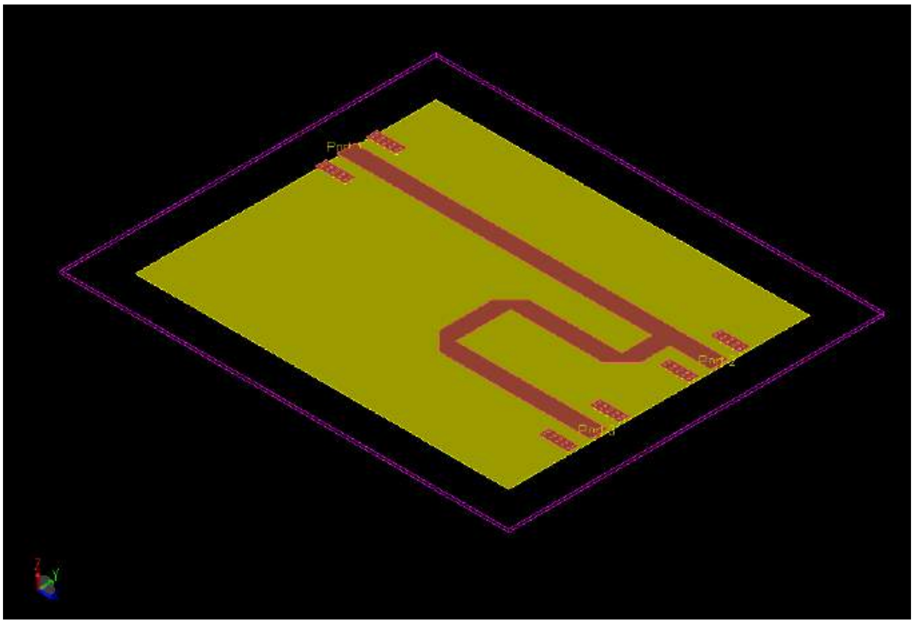


Figure 32. 3D view of ideal planar 1:4 Differential balun with Momentum ADS

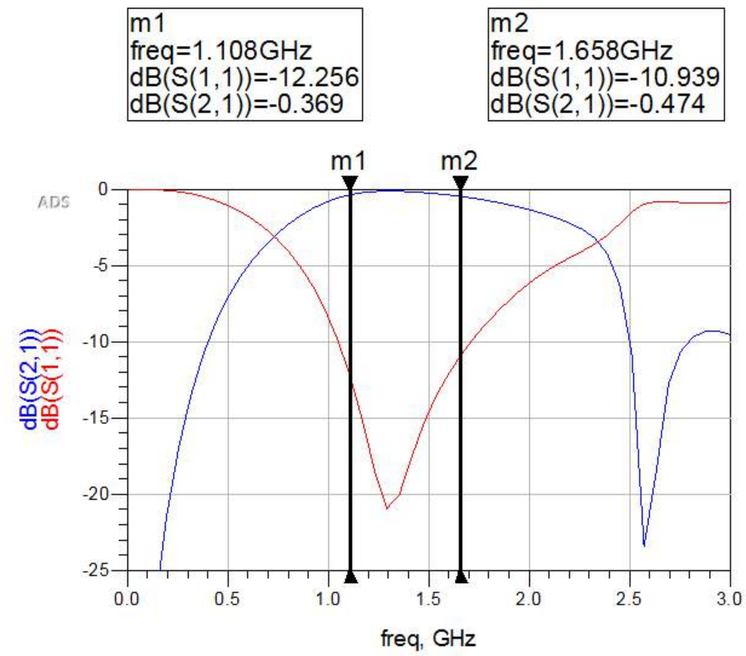


Figure 33. EM simulation results of planar 1:4 Differential balun with Momentum ADS

The EM simulation results show that the design of ideal planar 1:4 Differential balun structure achieves the value of S_{11} lower than -10 dB and S_{21} higher that -1 dB from 1.108 GHz to 1.658 GHz with fractional bandwidth (FBW) 39 %. Based on the FBW percentage achieved, this balun structure has the narrowest bandwidth among all balun structures in this research.

3.4 Summary

Three topologies of balun have been designed in microstrip line technology for this research. There are Guanella balun, Ruthroff balun, and Differential balun with 1:4 impedance transformation ratios. A QWT structure is designed as basic foundation of the balun because it is the most practical and easy to build impedance matching network structure. This step has to be done properly since all balun structure needs to be worked as impedance matching network.

All three baluns are designed in ideal conditions. It means that there is no loss in transmission line that potentially blocks the signal. The design and simulation is done in ADS from Keysight. Based on the results, all planar version of balun are able to perform as expected with 1:4 Guanella balun has the widest bandwidth and 1:4 Differential balun has the narrowest one. These results set the basic comparison parameters for further design.

CHAPTER 4

Manufacturing and Measurement

4.1 Introduction

This chapter explains about the manufacturing and measurement taken during the research. The previous chapter explains about the design process in ideal condition for all three balun structures. However, since ideal condition never exist in real environment, it is necessary to add some losses into the structure. Thus, there are some additional specifications have to be taken for manufacturing process, such as the usage of I-tera substrate ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$) with thickness 0.5 mm and copper (Cu) as conductor for signal and ground layer with thickness 18 um. The balun structures are re-designed and simulated in ADS from Keysight to make sure that all of the structures still hold the target specification for this research.

4.2 Balun Manufacture and Measurement

For manufacturing process, all balun structures are re-designed with the additional of losses in conductor and a new substrate that have to meet minimum requirements set by the manufacture company. Thus, it continues with the comparison of simulation results between lossless and losses structures. Three topologies of planar balun structure manufactured into PCB and measured with vector network analyzer (VNA) for behavior analysis.

The measurements of all planar balun structures held in MCT lab of Integrated Circuit Design group. The value of S_{11} and S_{21} are two parameters that need to be measured. The ZVB20 10 MHz – 20 GHz VNA from Rohde & Schwarz (R&S) is used to measure all parameters in this research. The frequency range for this measurement is from 0.01 to 3 GHz.

Before measurement with this VNA, the first thing to do is to create reference planes from which the measurement results can be analyzed. Therefore calibration has to be carried out on the maximum number of ports to be used, which are 2 ports for this research. TOSM (through, open, short, and match/load) calibration is implemented with existed calibration kit (Cal kit 85052B) to connect to 50 Ω 3.5 mm SMA connectors.

To acquire good results, there are two measurement techniques. These techniques are as follows:

- Measures only the planar balun structure and exclude it from 25 Ω and 100 Ω matching lines with de-embedding technique. This measurement techniques targetted only the balun structure.

- Measures the planar balun structure with 25 Ω and 100 Ω matching lines. By utilizing this measurement technique, there is an additional phase shifting at the measurement results. However, the results itself is acceptable because no significant difference compare to the de-embedding technique.

The measurement technique without de-embedding technique is chosen for this research because of the usage of 50 Ω 3.5 mm SMA connector and it ease the measurement process. By utilizing this technique, it includes the 25 Ω and 100 Ω matching lines and the effect can be seen by the additional phase shifting at the measurement results. However, this technique is able to reach target specification for S_{11} lower than -10 dB and S_{21} higher that -1 dB.

4.2.1 1:4 Guanella Balun

Planar 1:4 Guanella balun structure has been re-designed in Momentum ADS by changing the substrate to I-tera ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$) with 0.5 mm thickness and conductor to copper (Cu) with 0.18 mm thickness to add losses into structure. All other parameters such as layer stack, simulation setup, and frequency range remain the same with ideal structure. However, the dimensions of the balun are changed due to the introduction of losses. New dimensions for planar 1:4 Guanella balun are width (W) = 1.1 mm and length (L) = 30 mm.

4.2.1.1 Design Manufacture

New EM simulation is set based on new structure design with additional losses. It is simulated with frequency range from 0.01 to 3 GHz. Figure 34 shows its simulation results in Momentum ADS.

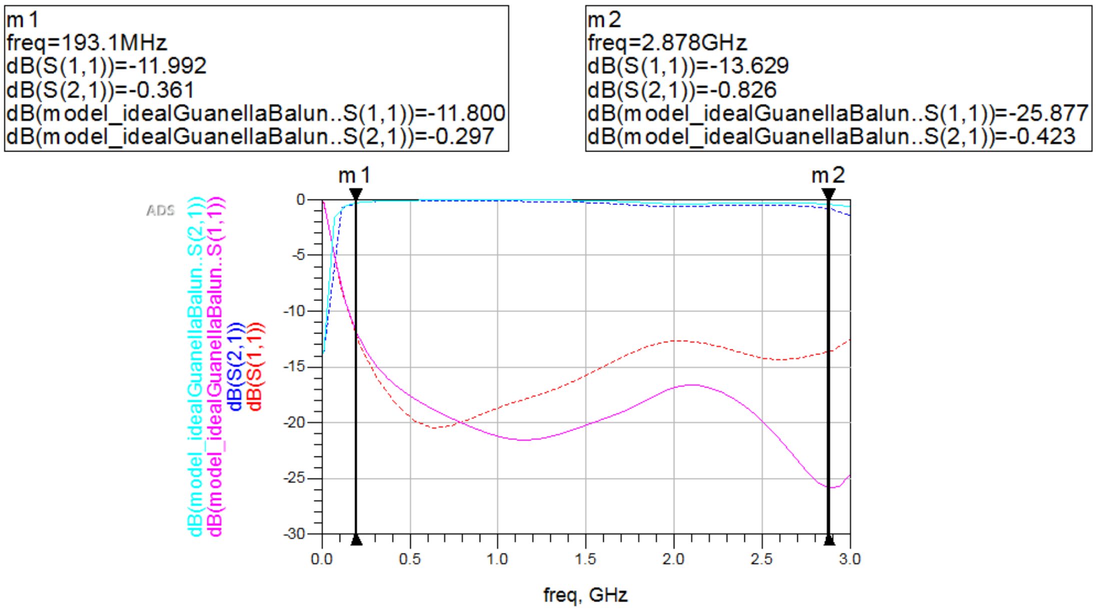
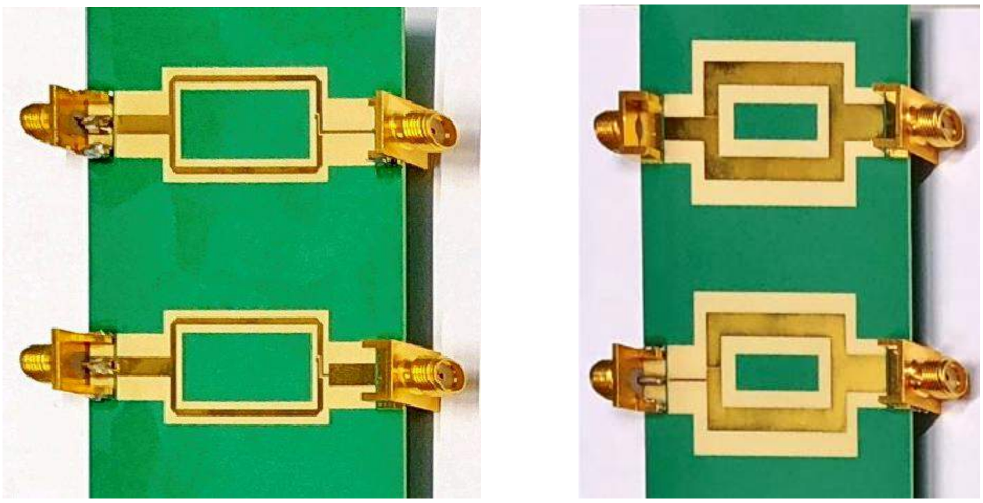


Figure 34. EM simulation results of planar 1:4 Guanella balun with additional losses in Momentum ADS (solid line = lossless; short dash = with losses)

The EM simulation results show that the design of planar 1:4 Guanella balun structure achieves the value of S_{11} lower than -10 dB and S_{21} higher that -1 dB from 0.193 to 2.878 GHz with fractional bandwidth (FBW) 175 %. Figure 34 also shows some degradation in return loss results for losses structure. However, based on the FBW percentage, this balun can be considered as a wideband balun. Next, the design structure is sent to manufacture company. Figure 35 shows planar 1:4 Guanella balun in PCB.



(a) (b)

Figure 35. (a) Top (b) Bottom view of Planar 1:4 Guanella balun in a PCB

4.2.1.2 Measurements

The measurements for planar 1:4 Guanella balun held by connecting the balun as device under test (DUT) with 50 Ω 3.5 mm SMA connectors to VNA. Because the VNA measures the balun structure with two 50 Ω reference planes, the measurement results are saved in *.s2p files and simulate in ADS with 25 Ω and 100 Ω loads. Figure 36 shows the measurement setup and Figure 37 shows comparison of measurement and simulation results of planar 1:4 Guanella balun.

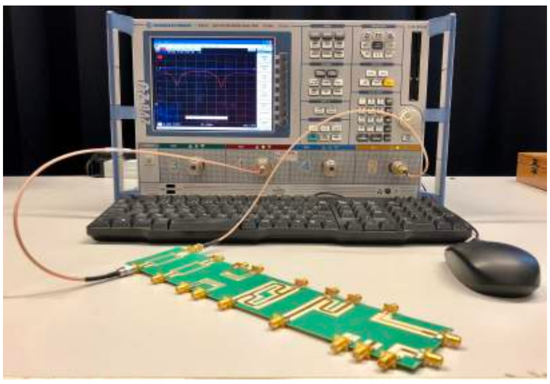


Figure 36. Measurement setup of planar 1:4 Guanella balun
with R&S ZVB20 10 MHz – 20 GHz VNA

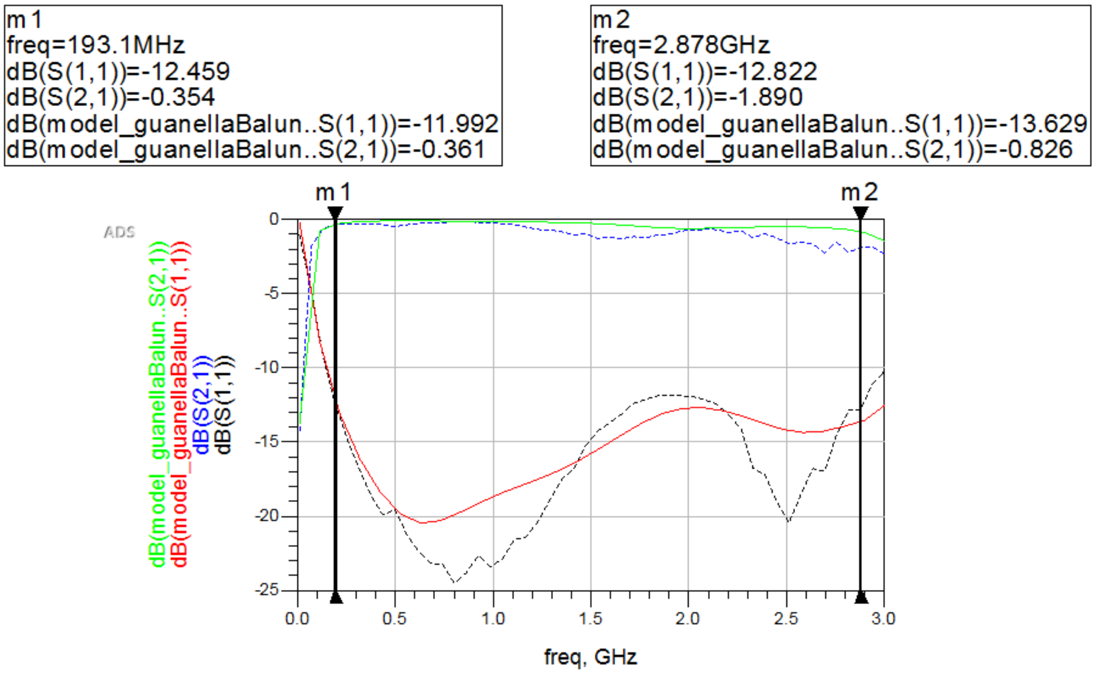


Figure 37. Measurement results of planar 1:4 Guanella balun with VNA (solid line = simulation; short dash = measurement)

The measurement results show that the design of planar 1:4 Ruthroff balun structure achieves the value of S_{11} better than -10 dB and S_{21} better that -1 dB from 0.193 to 2.878 GHz with fractional bandwidth (FBW) 175 %.

4.2.2 1:4 Ruthroff Balun

Planar 1:4 Ruthroff balun has been re-designed in Momentum ADS by changing the substrate to I-tera ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$) with 0.5 mm thickness and conductor to copper (Cu) with 0.18 mm thickness to add losses into structure. All other parameters such as layer stack, simulation setup, and frequency range remain the same with ideal structure. However, the dimensions of the balun are changed. New dimensions for planar 1:4 Ruthroff balun are width (W) = 1.1 mm and length (L) = 30 mm.

4.2.2.1 Design Manufacture

New EM simulation is set based on new structure design with additional losses. It is simulated with frequency range from 0.01 to 3 GHz. Figure 38 shows its simulation results in Momentum ADS.

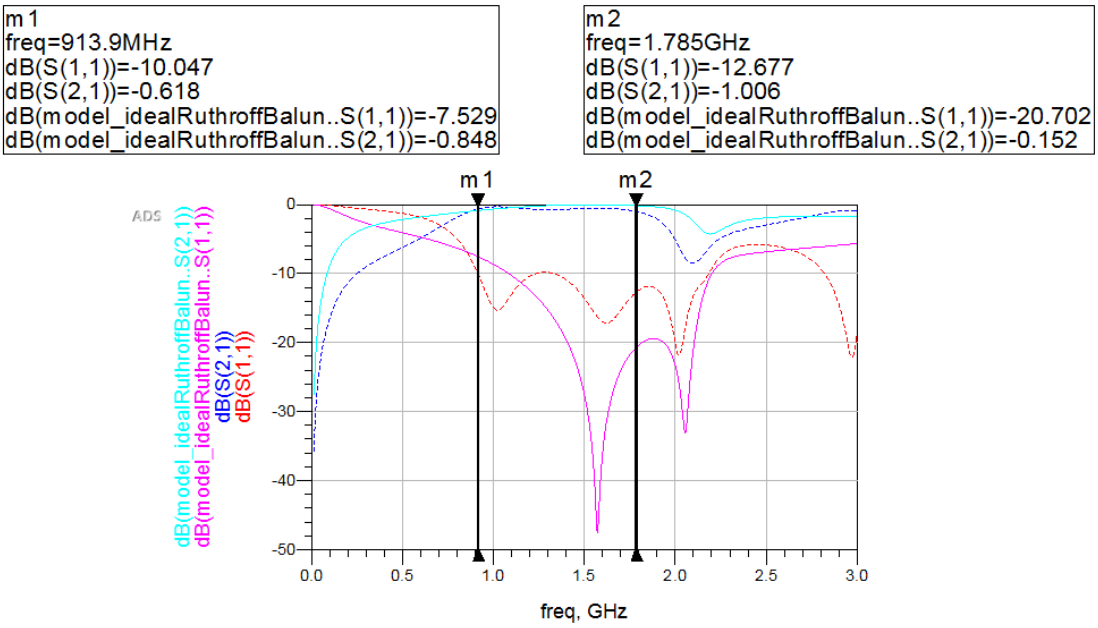
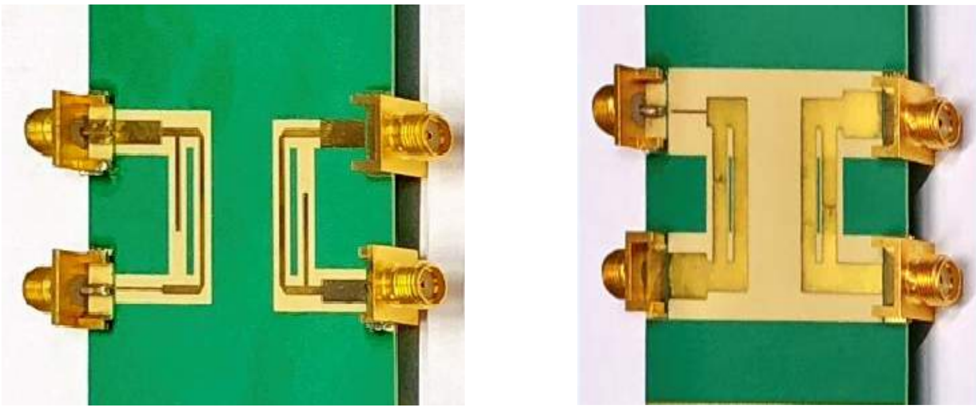


Figure 38. EM simulation results of planar 1:4 Ruthroff balun with additional losses in Momentum ADS (solid line = lossless; short dash = with losses)

Figure 38 shows its EM simulation results in Momentum ADS. The simulation shows that the design of planar 1:4 Ruthroff balun achieves S_{11} lower than -10 dB and S_{21} higher that -1 dB from 0.914 to 1.785 GHz with fractional bandwidth (FBW) 65 %. Figure 38 also shows some degradation in return loss results for losses structure. However, based on the FBW percentage achieved, this balun has wide bandwidth just in between 1:4 Guanella balun and 1:4 Differential balun in this research. Next, the design structure is sent to manufacture company. Figure 39 shows planar 1:4 Ruthroff balun in PCB with I-tera substrate ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$).



(a) (b)

Figure 39. (a) Top (b) Bottom view of Planar 1:4 Ruthroff balun in a PCB

4.2.2.2 Measurements

The measurements for planar 1:4 Ruthroff balun held by connecting the balun as device under test (DUT) with 50 Ω 3.5 mm SMA connectors to VNA. Because the VNA measures the balun structure with two 50 Ω reference planes, the measurement results are saved in *.s2p files and simulate in ADS with 25 Ω and 100 Ω loads. Figure 40 shows the measurement setup and Figure 41 shows comparison of measurement and simulation results of planar 1:4 Ruthroff balun.

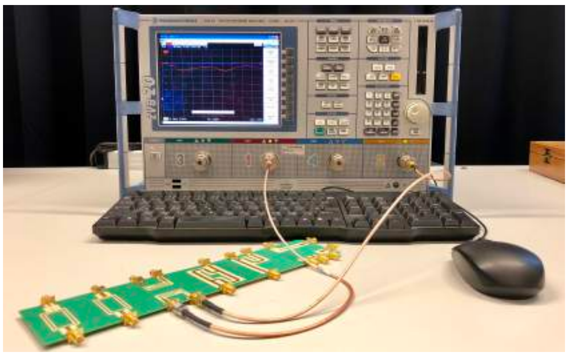


Figure 40. Measurement setup of planar 1:4 Guanella balun
with R&S ZVB20 10 MHz – 20 GHz VNA

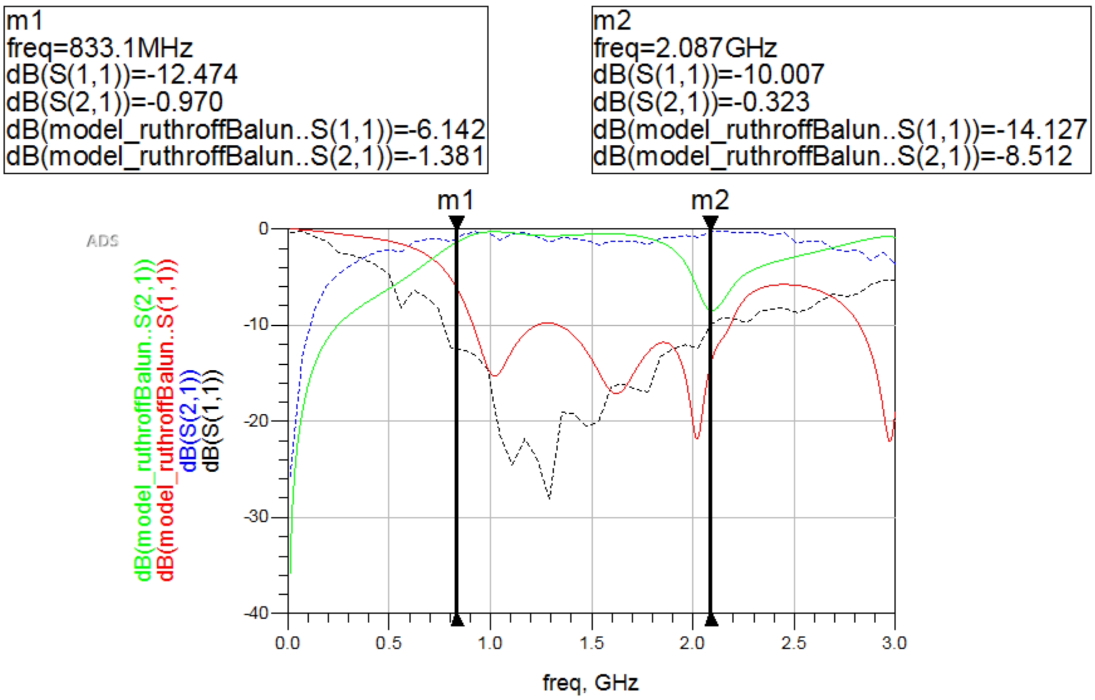


Figure 41. Measurement results of planar 1:4 Ruthroff balun with VNA (solid line = simulation; short dash = measurement)

Figure 41 shows comparison of measurement and simulation results of 1:4 Ruthroff balun. The measurement results show that the design of planar 1:4 Ruthroff balun achieves S_{11} lower than -10 dB and S_{21} higher that -1 dB from 0.833 to 2.087 GHz with fractional bandwidth (FBW) 85 %.

4.2.3 1:4 Differential Balun

Planar 1:4 Differential balun has been re-designed in Momentum ADS by changing the substrate to I-tera ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$) with 0.5 mm thickness and conductor to copper (Cu) with 0.18 mm thickness to add losses into structure. All other parameters such as layer stack, simulation setup, and frequency range remain the same with ideal structure. However, the dimensions of the balun are changed. New dimensions for planar 1:4 Differential balun are width (W) = 3 mm and length (L) = 60 mm for the half wavelength ($\lambda/2$) line and length (L) = 22 mm for feed line.

4.2.3.1 Design Manufacture

New EM simulation is set based on new structure design with additional losses. It simulated with frequency range from 0.01 to 3 GHz. Figure 42 shows its simulation results in Momentum ADS.

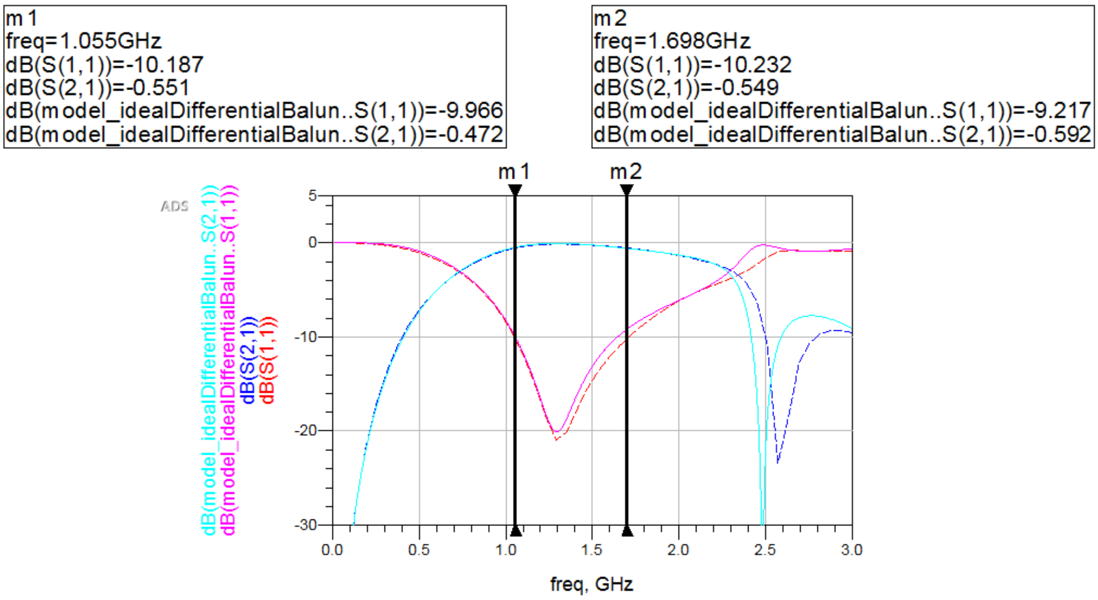
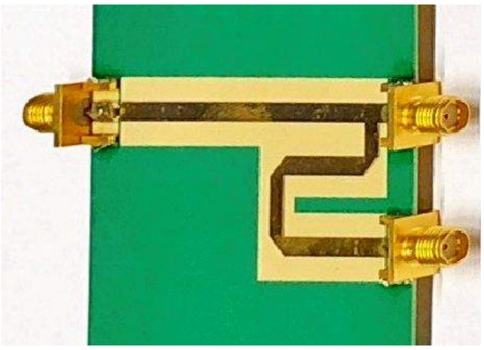
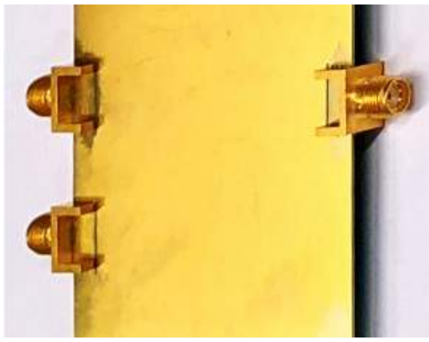


Figure 42. EM simulation results of planar 1:4 Differential balun with additional losses in Momentum ADS (solid line = lossless; short dash = with losses)

The simulation shows that the design of planar 1:4 Differential balun structure achieves S_{11} lower than -10 dB and S_{21} higher that -1 dB from 1.055 to 1.698 GHz with fractional bandwidth (FBW) 37 %. Figure 42 also shows some degradation in return loss results for losses structure. However, based on the FBW percentage, this balun has the narrowest bandwidth among all balun structures in this research. Next, the design structure is sent to manufacture company. Figure 43 shows planar 1:4 Differential balun in PCB.

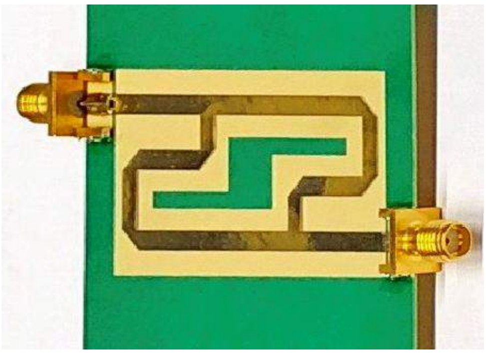


Top view

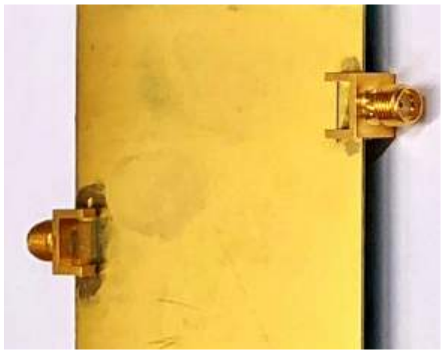


Bottom view

(a)



Top view



Bottom view

(b)

Figure 43. (a) single (b) back-to-back structure of planar 1:4 Differential balun in a PCB

Since planar 1:4 Differential balun has 2 ports at the output, it makes the measurement process difficult because the measurement in VNA set to only 2 ports network. It needs additional balun externally to deal with 2 ports network measurement. Using external balun could cause additional problem due to losses, compatibility, and availability with certain impedance ratio. However, there is a solution for the problem.

By utilizing identical balun back-to-back in single PCB, it solves the 2 ports network measurement for planar 1:4 Differential balun. This structure can be used since the results of return and insertion loss remain the same. Figure 43 (b) shows the back-to-back balun structure in single PCB design for measurement.

4.2.3.2 Measurements

The measurements for planar 1:4 Differential balun held by connecting the balun as device under test (DUT) with 50 Ω 3.5 mm SMA connectors to VNA. Because the VNA measures the balun structure with two 50 Ω reference planes, the measurement results are saved in *.s2p files and simulate in ADS with 25 Ω and 25 Ω loads.

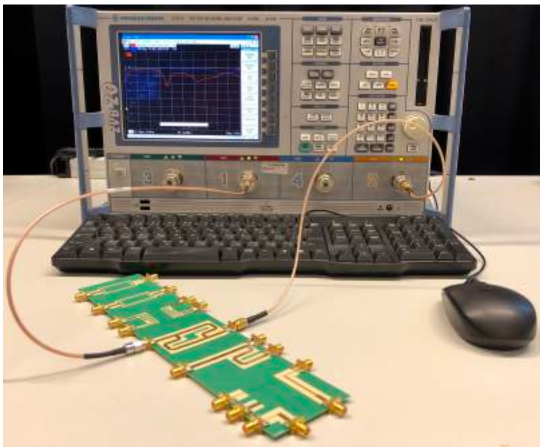


Figure 44. Measurement setup of planar 1:4 Differential balun
with R&S ZVB20 10 MHz – 20 GHz VNA

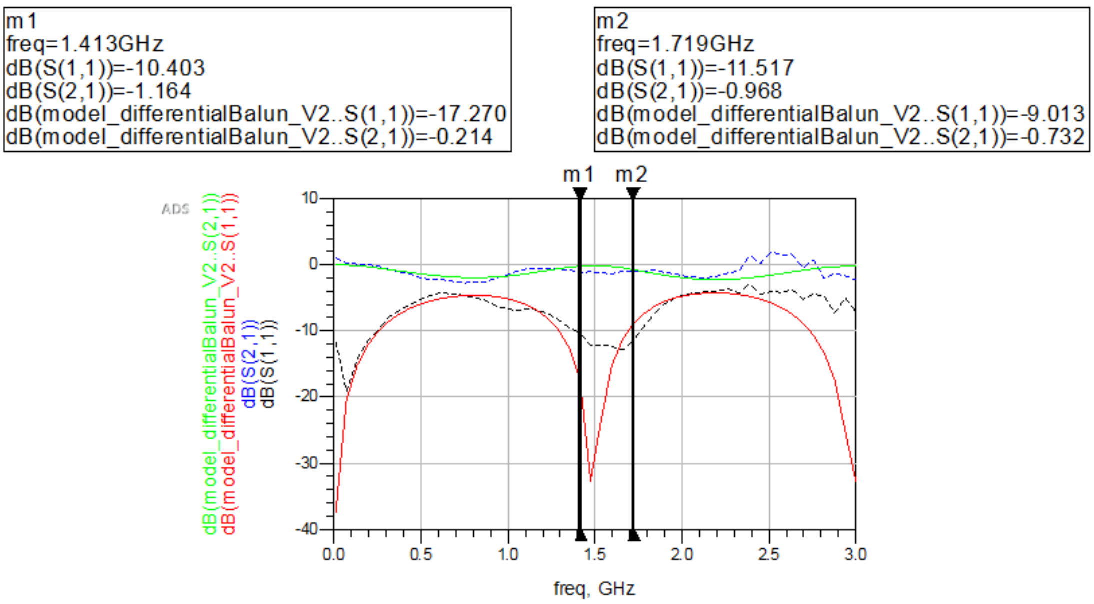


Figure 45. Measurement results of planar 1:4 Differential balun with VNA
(solid line = simulation; short dash = measurement)

Figure 44 shows the measurement setup and Figure 45 shows comparison of measurement and simulation results of planar 1:4 Differential balun. The measurement results show that the design of planar 1:4 Differential balun structure achieves S_{11} lower than -10 dB and S_{21} higher than -1 dB from 1.413 to 1.719 GHz with fractional bandwidth (FBW) 19 %.

4.2.4 Back-to-back 1:4 Guanella Balun

The planar back-to-back 1:4 Guanella balun structure measurement is held to make sure that the structure is applicable as a balun. This is can be done by combining two planar 1:4 Guanella balun with normal outputs (figure 35 (a) top) and with inverted output (figure 35 (a) bottom). The planar 1:4 Guanella balun has been chosen as a sample for this measurement since it has the biggest FBW among all other balun structures in this research.

4.2.4.1 Design Manufacture

New EM simulation is set based on new structure design with additional losses. It simulated with frequency range from 0.01 to 3 GHz. Figure 46 shows its simulation results in momentum ADS.

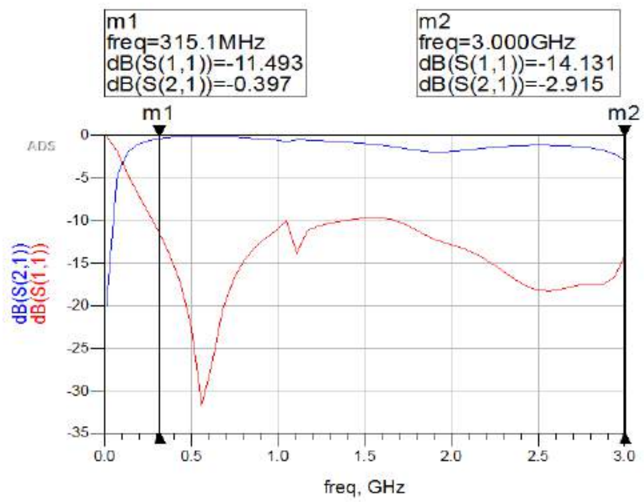


Figure 46. EM simulation results of planar back-to-back 1:4 Guanella balun with additional losses in Momentum ADS

There are some compromises in target specifications that have to be made for this structure. The value of S_{11} and S_{21} are better that -3 dB. The EM simulation results show that the design of planar back-to-back 1:4 Guanella balun structure achieves its best results for S_{11} and S_{21} from 0.315 to 3 GHz with fractional bandwidth (FBW) 165 %. Later, this simulation is compared with measurements results. The purpose of this comparison is to make sure that it matches with the actual hardware with external connectors. Figure 47 shows planar back-to-back 1:4 Differential balun in PCB.

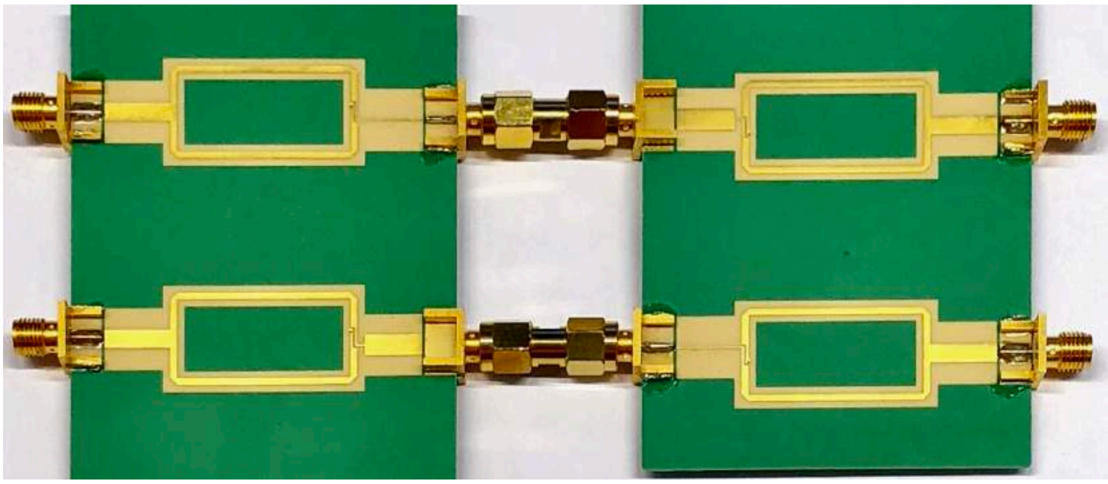


Figure 47. Planar back-to-back 1:4 Guanella balun in a PCB

4.2.4.2 Measurements

The measurements for planar back-to-back 1:4 Guanella balun held by connecting the balun as device under test (DUT) with 50 Ω 3.5 mm SMA connectors to VNA. Because the VNA measures the balun structure with two 50 Ω reference planes, the measurement results are saved in *.s2p files and simulate in ADS with 25 Ω and 25 Ω loads. Figure 48 shows the measurement setup and Figure 49 shows comparison of measurement and simulation results of planar back-to-back 1:4 Guanella balun.

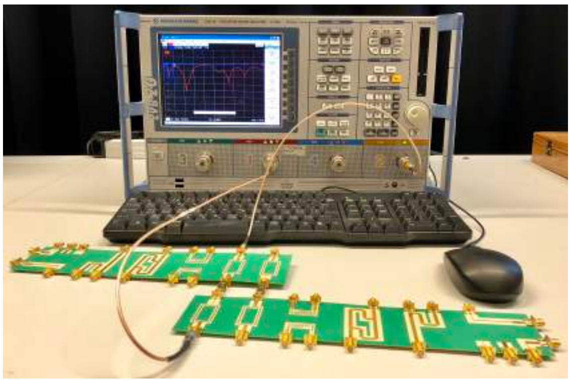


Figure 48. Measurement setup of back-to-back planar 1:4 Guanella balun with R&S ZVB20 10 MHz – 20 GHz VNA

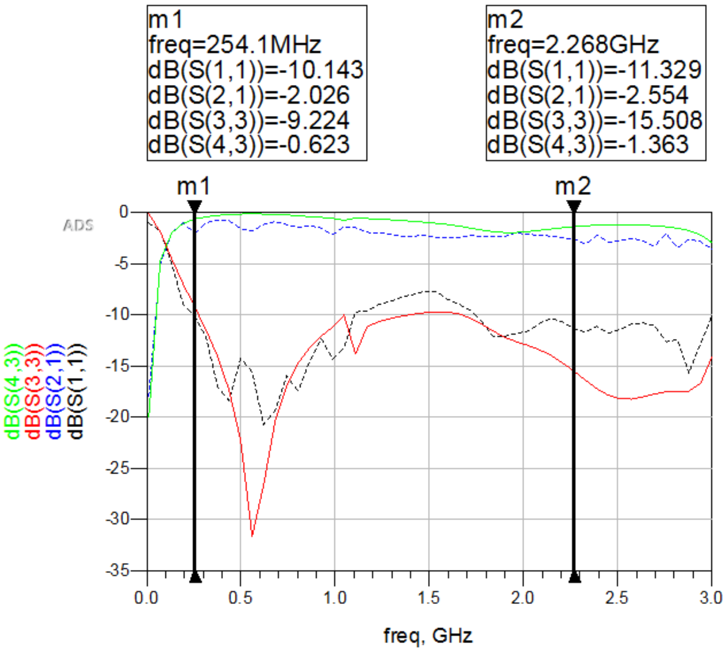


Figure 49. Measurement results of planar back-to-back 1:4 Guanella balun with VNA

(solid line = simulation; short dash = measurement)

The measurement results show that the planar back-to-back 1:4 Guanella balun achieves its best result for S_{11} and S_{21} from 0.254 to 2.268 GHz with fractional bandwidth (FBW) 160 %.

4.3 Summary

Three topologies of planar balun structure have been manufactured in I-tera substrate ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$) with 0.5 mm thickness and conductor copper (Cu) with 0.18 mm thickness based on the design with additional losses in a PCB. All balun structures are measured with R&S ZVB20 10 MHz – 20 GHz VNA. Before measurement process, TOSM calibration is implemented to acquire accurate results. There are two parameters to measure, return loss (S_{11}) and insertion loss (S_{21}) for each balun structure. Later, measurement results from all balun structure are compared with simulation results. Based on measurement results, planar 1:4 Guanella balun has the biggest FBW with 175 % and planar 1:4 Differential balun has the smallest one with 19 % of FBW.

To make sure that all designs are applicable as a balun, a measurement of planar back-to-back 1:4 Guanella balun is held. Planar 1:4 Guanella balun structure has been chosen because it has the biggest FBW results among all other balun in this research. However, some changes in target specification have to be made to accommodate compromises for planar back-to-back 1:4 Guanella balun design. Due to this reason, the return loss and insertion loss is set to -3 dB. The analysis about why the compromises occur in back-to-back balun structure will be explained in chapter 5.

CHAPTER 5

Results Comparison and Analysis

5.1 Introduction

This chapter explains about comparison and analysis between simulation and measurement results. After measuring the PCB that consists of various types of balun with VNA, the measurement results data can be saved as *.s2p files and run in ADS with proper loads to ease comparison process. By comparing all measurement with simulation results, it is possible to see if there is any match or mismatch between theory and real application. There are two parameters (S_{11} and S_{21}) that can be compared and analyze.

5.2 Design Comparisons and Analysis

5.2.1 1:4 Guanella Balun

The planar 1:4 Guanella balun structure design has been manufactured with 0.5 mm thickness of I-tera substrate ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$) and 0.18 mm thickness of copper (Cu) as conductor for both signal and ground plane. There are two parameters that have to be measured, such as S_{11} and S_{21}. Later, the measurement results are compared with simulation results.

5.2.1.1 Simulations and Measurements comparison

For comparison purpose, all measurements setup in VNA for planar 1:4 Guanella balun is set with the same frequency range as simulation frequency range in ADS, which is from 0.01 to 3 GHz. Table 1 shows comparison between measurement and simulation results for planar 1:4 Guanella balun.

Table 1. Comparison of measurement and simulation of planar 1:4 Guanella balun

No	Parameters	Ideal Structure	Losses Structure	Manufactured Structure
1	Frequency Range (GHz)	0.193 – 3	0.193 – 2.878	0.193 – 2.878
2	Return loss (S_{11}) (dB)	< -10	< -10	< -10
3	Insertion loss (S_{21}) (dB)	> -1	> -1	> -1
4	FBW (%)	175	175	175

5.2.1.2 Analysis

Table 1 shows the comparison of measurement and simulation of planar 1:4 Guanella balun. For additional data, there are also simulation results for ideal (lossless) structure. Regarding to measurement results, planar 1:4 Guanella balun performs as a wideband balun. This balun operates from 0.193 to 2.878 GHz with FBW 175 %. Meanwhile, figure 34 clearly shows that the addition of losses in the structure gives some effects to simulation results. It is slightly worse for losses structure. Thus, from figure 37 shows that there are differences between simulation and measurement results.

These results appear because of the difference between the actual hardware structure and the structure in the design tools. Even though losses are introduced into the structure, it is not possible to achieve identical results during measurements. Environment and materials differences between simulation and measurement are the main possible reason that could cause such differences between measurement and simulation results.

5.2.2 1:4 Ruthroff Balun

The planar 1:4 Ruthroff balun structure also manufactured with 0.5 mm thickness of I-tera substrate ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$) and 0.18 mm thickness of copper (Cu) as conductor for both signal and ground plane. Similar with 1:4

Guanella balun, there are two parameters that have to be measured, such as S_{11} and S_{21}. Last, the measurement results are compared with simulation results.

5.2.2.1 Simulations and Measurements Comparison

All measurements setup in VNA for planar 1:4 Ruthroff balun design is set with the same frequency range as simulation frequency range in ADS, from 0.01 to 3 GHz. Table 2 shows comparison between measurement and simulation results for planar 1:4 Ruthroff balun.

Table 2. Comparison of measurement and simulation of planar 1:4 Ruthroff balun

No	Parameters	Ideal Structure	Losses Structure	Manufactured Structure
1	Frequency Range (GHz)	1.084 – 2.018	0.914 – 1.785	0.833 – 2.087
2	Return loss (S_{11}) (dB)	< -10	< -10	< -10
3	Insertion loss (S_{21}) (dB)	> -1	> -1	> -1
4	FBW (%)	68	65	85

5.2.2.2 Analysis

Table 2 shows the comparison of measurement and simulation of planar 1:4 Ruthroff balun. Also, there is a simulation results for ideal (lossless) structure for additional comparison. Regarding to these results, the planar 1:4 Ruthroff balun performs in a wide bandwidth, even though not as wide as planar 1:4 Guanella balun. The planar 1:4 Ruthroff balun has frequency range from 0.833 to 2.087 GHz depends on the structure (lossless, losses, and manufactured). Table 2 also shows that there is some differences occur when losses are introduced into the structure.

The most significant differences can be seen from frequency range. Figure 38 and 41 clearly show that by introducing losses into the structure gives effect to simulation results, which is slightly worse for losses structure. Manufactured structure achieved the largest FBW with 85 %. These results appear because of the difference between actual hardware structure and the structure in the design tools. It is not possible to achieve identical results during measurements for actual hardware. Environment and materials differences are the main possible reason that could cause such differences between measurement and simulation results.

However, manufactured structure shows larger FBW than the simulation FBW (both lossless and losses). This situation occurs due to the effect of the ground layer and the existence of transmission line between the output of ground layer and the input of signal layer (the one that gives Bootstrap effect) in the structure. Thus, the use of 50 Ω 3.5 mm SMA connector for measurements also causes a problem that gives limitation to the balun structure. By using 50 Ω 3.5 mm SMA connector, it introduces additional length into the structure that changes the behavior of balun structure.

5.2.3 1:4 Differential Balun

The planar 1:4 Differential balun structure manufactured with 0.5 mm thickness of I-tera substrate ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$) and 0.18 mm thickness of copper (Cu) as conductor for both signal and ground plane. Similar with two previous balun structures, there are two parameters that have to be measured, such as S_{11} and S_{21}. Last, the measurement results are compared with simulation results.

5.2.3.1 Simulations and Measurements Comparison

For all measurements setup in VNA for planar 1:4 Differential balun design is set with the same frequency range as simulation frequency range in ADS, which is from 0.01 to 3 GHz. Table 3 shows comparison between measurement and simulation results for planar 1:4 Differential balun.

Table 3. Comparison of measurement and simulation of planar 1:4 Differential balun

No	Parameters	Ideal Structure	Losses Structure	Manufactured Structure
1	Frequency Range (GHz)	1.108 – 1.658	1.055 – 1.698	1.413 – 1.719
2	Return loss (S_{11}) (dB)	< -10	< -10	< -10
3	Insertion loss (S_{21}) (dB)	> -1	> -1	> -1
4	FBW (%)	39	37	19

5.2.3.2 Analysis

Table 3 shows the comparison of measurement and simulation of planar 1:4 Differential balun. Also, there is a simulation results for ideal (lossless) structure for additional comparison. Regarding to these results, the planar 1:4 Differential balun has the narrowest bandwidth among all balun structure in this research. Planar 1:4 Differential balun has frequency range from 1.052 to 1.72 GHz depends on the structure (lossless, losses, and manufactured). Table 3 also shows that there is differences occur when losses are introduced into the structure.

The most significant differences can be seen from frequency range. Manufactured structure achieved the smallest FBW with 19 %. It proves that planar 1:4 Differential balun only applicable for any single frequency devices. From figure 42 and 45 clearly show that by introducing losses into the structure gives effect to simulation results, which is slightly worse for losses structure.

These results appear because of the difference between actual hardware structure and the structure in the design tools. Even though losses are introduced into the structure, it is not possible to achieve identical results during measurements. Environment and materials differences are the main possible reason that could cause such differences between measurement and simulation results.

5.2.4 Back-to-back 1:4 Guanella balun

The planar back-to-back 1:4 Guanella balun structure design can be achieved by connecting two planar 1:4 Guanella baluns that have different outputs. One balun structure has normal output with 100 Ω matching line when the other one has the upside down version of 100 Ω matching line. The combination of those two outputs in term of phase difference is $180°$. This phase difference fulfills the target specification of balun. However, to make sure that this structure is applicable as a balun, the measurement with real hardware is needed. Similar with previous balun analysis, there are two parameters that have to be measured, such as S_{11} and S_{21}. Last, the measurement results are compared with simulation results.

5.2.4.1 Simulations and Measurements Comparison

All measurements setup in VNA for planar back-to-back 1:4 Guanella balun is set with the same frequency range as simulation frequency range in ADS, which is from 0.01 to 3 GHz. Table 4 shows comparison between measurement and simulation results for planar back-to-back 1:4 Guanella balun. However, because of compromises occur during simulation and measurement, the target specification for S_{11} and S_{21} are changed to -3 dB.

Table 4. Comparison of measurement and simulation of planar back-to-back 1:4 Guanella balun

No	Parameters	Losses Structure	Manufactured Structure
1	Frequency Range (GHz)	0.315 – 3	0.254 – 2.268
2	Return loss (S_{11}) (dB)	< -3	< -3
3	Insertion loss (S_{21}) (dB)	> -3	> -3
4	FBW (%)	165	160

5.2.4.2 Analysis

Table 4 shows the comparison between measurement and simulation of planar back-to-back 1:4 Guanella balun. Regarding to these results, the planar 1:4 Guanella balun design is applicable as a balun. Even though it has some compromises in the results, the balun is able to transmit power to the load. Table 4 also shows that there are some differences occur between design simulation and actual hardware measurements. As mentioned in previous design analysis, it is not possible to achieve identical results during measurements. Environment and materials differences are the main possible reason that could cause such differences between measurement and simulation results.

The simulation results show that there are some compromises that need to be taken for planar back-to-back 1:4 Guanella balun structure. It is caused by the drastic transition between narrow to wide line (or vice versa) between 2 baluns and reflection due to the usage of 50 Ω 3.5 mm SMA connector. Also, the 100 Ω matching lines at the reverse version of planar 1:4 Guanella balun add another reflection to the structure. Because of the connection between these two baluns is handled by external 50 Ω connector, there is also a possibility that another reflections might occur. These reflections especially give an effect to 100 Ω microstrip lines in each balun. This situation could leads into some degradation in terms of performance of the balun.

The other possible reason is because of the balun may not have isolation, which would cause an input signal in one differential port also show up in the other differential port. This case might be happening since a balun does not have any constrain on S_{23}, so the output may or may not have isolation [11]. The “no isolation” case would cause some resonance in the S-parameters that shown as performance degradation that can be seen in figure 49.

Thus, regarding to measurement results, that few compromises in the design that can be seen in simulation results also affecting the actual balun hardware. Here, the return loss and insertion loss results cannot fulfill target specification. However, insertion loss is still better than -3 dB.

5.3 Summary

The comparison of measurement and simulation results of three topologies of planar balun has been implemented in this chapter. All balun structures comparison consists of three conditions. These structures are Lossless, losses, and manufactured structure. There are four parameters to be compared for whole structures, such as frequency range (GHz), return loss (S_{11}) (dB), insertion loss (S_{21}) (dB), and FBW (%). Regarding to comparison results in table 1 to 3, planar 1:4 Guanella balun has the biggest FBW with 175 % and planar 1:4 Differential balun has the smallest one with 19 % of FBW.

There are many reasons that make the differences occur between simulation and measurement. Environment and material differences give the biggest impact to the difference of behavior of the balun structure. It is not possible to achieve measurement results that identical with simulation results, even though losses are introduced into the structure during design process. Based on comparison results among all three topologies of planar balun structure, there is a match between design and manufactured structure. It means that the design of all planar balun structure performs and behaves as expected. For verification purpose of balun performance, a back-to-back planar balun has been measured by connecting two balun structures. The results show that the structures are able to perform as a balun.

CHAPTER 6

Conclusion and Recommendation

6.1 Conclusion

The goal of this research is to investigate whether a balanced-to-unbalanced (balun) structure can simultaneously be used for impedance transformation and power combination. As a result, three types of balun structures are developed with microstrip technology. It is a planar version of 1:4 Guanella balun, 1:4 Ruthroff balun, and 1:4 Differential balun.

In this research, first the fundamental properties of a balun are explained. Next, the design of each balun structure is proposed based on the previously explained fundamental properties of a balun structure. The target specification for each balun structure is to achieve the value of S_{11} less than -10 dB and S_{21} bigger than -1 dB with operating frequency 1.5 GHz. All balun structures are manufactured in a company and measured in the lab. The goal of this measurement process is to check either the balun structure meet the target specification and match with the design simulation results by measurement and simulation results comparison.

The most practical and effective structure for matching network is by utilizing QWT structure. Since the balun structure has to be able to perform as a matching network between two systems, a balun structure could adopt QWT structure as a starting point. As explained in chapter 2, it is possible to design three topologies of balun for this research with QWT structure. Moreover, two of three of balun structure for this research are basically made of TLT. This approach eases the design process as long as it suits the fundamental and target specification of a balun structure for this research.

In chapter 3, the design derivation with planar (microstrip) technology of each balun structure starts from coaxial cable form of balun structure is explained. The design process held in ADS from Keysight. It simulates all parameters needed for further analysis such as S_{11}, S_{21}, and phase difference. The planar version of each balun structure has been build with 2 layers stack microstrip line. It uses a low losses substrate I-tera ($\varepsilon_r = 3.38$ and $tan\delta = 0.0028$) with 0.5 mm of thickness and copper (Cu) with 0.18 mm thickness as conductors for both signal and ground layer.

Based on the design structure, all balun structures are manufactured in a single PCB. The actual hardware with all balun structure is measured in the lab with R&S ZVB20 10 MHz – 20 GHz VNA to check and analyze the behavior of each balun structure in real environment. The measurements then compared with simulation results and analyze the difference among them. Theoretically, it is not possible to have measurement results identic with simulation results because of many reasons, such as environment and material differences between simulator and the real one. Tables 1 to 3 show the comparison between measurement and simulation results for all balun structures. It is concluded that there is some differences between simulation and measurement results. Thus, the differences are still in the tolerable range. Moreover, tables 5 to 7 summarize the research output, which is inspecting planar balun structures.

Table 5. Comparison of simulation results for ideal (lossless) balun structure

No	Parameters	1:4 Guanella Balun	1:4 Ruthroff Balun	1:4 Differential Balun
1	Frequency Range (GHz)	0.193 – 3	1.084 – 2.018	1.108 – 1.658
2	Return loss (S_{11}) (dB)	< -10	< -10	< -10
3	Insertion loss (S_{21}) (dB)	> -1	> -1	> -1
4	FBW (%)	175	68	39

Table 6. Comparison of simulation results for losses balun structure

No	Parameters	1:4 Guanella Balun	1:4 Ruthroff Balun	1:4 Differential Balun
1	Frequency Range (GHz)	0.193 – 2.878	0.914 – 1.785	1.055 – 1.698
2	Return loss (S_{11}) (dB)	< -10	< -10	< -10
3	Insertion loss (S_{21}) (dB)	> -1	> -1	> -1
4	FBW (%)	175	65	37

Table 7. Comparison of measurement results for manufactured balun structure

No	Parameters	1:4 Guanella Balun	1:4 Ruthroff Balun	1:4 Differential Balun
1	Frequency Range (GHz)	0.193 – 2.878	0.833 – 2.087	1.413 – 1.719
2	Return loss (S_{11}) (dB)	< -10	< -10	< -10
3	Insertion loss (S_{21}) (dB)	> -1	> -1	> -1
4	FBW (%)	175	85	19

Based on the results in tables 5 to 7, the planar 1:4 Guanella balun has the biggest FBW with 175 % and the planar 1:4 Ruthroff balun comes second with 85 % of FBW. Multiple frequency devices can use both of these balun structures. However, planar 1:4 Differential balun has the smallest FBW with 19 %, makes it can only be used by single frequency devices. All of these three results consistently show match outputs from lossless to manufactured balun structure and from simulations to measurements. It shows that the design processes for this research are correctly done.

6.2 Recommendation for Future Directions

There are a few recommendations that can add further values to this design. They are as follows:

Optimization in the design of ground layer

Since the design of planar 1:4 Guanella balun and planar 1:4 Ruthroff balun cannot use common ground layer as in planar 1:4 Differential balun, it is necessary to optimize the dimensions of ground layer for these two balun structures. The optimization should be in high precision, because slightly change in term of dimension could lead to unwanted behavior in simulation and measurement. Also, because of 50 Ω 3.5 mm SMA connector is the main connector to use for measurement, it is necessary to include the dimension of this connector from the beginning of the design.

Different design approach

This research acknowledge the use of simple microstrip line technology to develop planar 1:4 Guanella balun, planar 1:4 Ruthroff balun, and planar 1:4 Differential balun. There is any other planar technology that can be used to build such structures. The form of broadside coupled stripline and coplanar waveguide (CPW) are few examples of such design approach that can be use for further research. Later, the outputs (simulations and measurements) can be compared and see which design approach has the best results.

REFERENCES

[1] D.M. Pozar, *Microwave Engineering*. 4th edition, John Wiley & Sons, New York, 2012.

[2] D.M. Pozar, *Microwave and RF Design of Wireless Systems*, John Wiley & Sons, New York, 2000.

[3] B. Henderson and E. Camargo, *Microwave Mixer Technology and Applications*, Artech House, London, 2013.

[4] P.A. Rizzi, *Microwave Engineering (Passive Circuit)*, Prentice-Hall International, Upper Saddle River, NJ, 1988.

[5] H. Howe, Jr., *Stripline Circuit Design*, Microwave Associates, Lowell, MA, 1974.

[6] C.A. Balanis, *Antenna Theory: Analysis and Design*, John Wiley & Sons, New York, 2016.

[7] G. Gonzales, *Microwave Transistor Amplifier: Analysis and Design*, Prentice-Hall, Upper Saddle River, NJ, 1997.

[8] R. Mongia, I. Bahl, P. Bhartia, *RF and Microwave Coupled Line Circuits*, Artech House, London, 1999.

[9] T.H. Lee, *Planar Microwave Engineering*, Cambridge University Press, Cambridge, 2004.

[10] J. Sevick, *Transmission Line Transformers*, Noble Publishing Corporation, London, 2001.

[11] D. Jorgesen and C. Marki, “Balun Basic Primer”, Marki Microwave.

[12] A. Grebennikov, "Power Combiners, Impedance Transformers, and Directional Couplers", *High Frequency Electronics*, pp. 20-38, Dec. 2007.

[13] C.L. Ruthroff, "Some Broadband Transformers", *Proceedings of the* IRE, vol. 47, no.8, pp. 1337-1342, Aug.1959.

[14] G. Guanella, "New Method of Impedance Matching in Radio-Frequency Circuits", *Brown Boveri Rev*., vol. 31, pp. 125-127, Sep. 1944.

[15] Z. Zhang, M.T. Arnous, G. Boeck "Ultra-Broadband GaN Power Amplifier Utilizing Planar Guanella Transformer", 17th *International Conference on Transparent Optical Network* (ICTON), pp. 1-4, 2015.

[16] Z. Zhang and G. Boeck, "Broadside-Coupled Multi-Octave Impedance Transformers", Proceedings of the 44th *European Microwave Conference*, pp. 37-40, Oct. 2014.

[17] H.Y. Chung, H.K. Chiou, Y.C. Hsu, T.Y. Yang, C.L. Chang, "Design of Step-Down Broadband and Low-Loss Ruthroff-Type Baluns Using IPD Technology", IEEE *Transactions on packaging and manufacturing technology*, vol. 4, pp. 967-974, June 2014.

[18] S. Liu, "Planar Transmission Line Transformer Using Coupled Microstrip Lines", IEEE MTT-S Int. Microwave Symposium Digest, pp. 789-792, Jun. 1998.

[19] C.F. Campbell, "Galium Nitride Power MMICs – Promise and Problems", *Integrated Nonlinear Microwave and Millimeter-wave Circuits Workshop* (INMMiC), pp. 1-6, 2015.

[20] H.C. Park, S. Daneshgar, J.C. Rode, Z. Griffith, M. Urtega, B.S. Kim, M. Rodwell, "30% PAE W-band InP Power Amplifiers using Sub-quarter-wavelength Baluns for Series-connected Power Combining", IEEE *Compound Semiconductor Integrated Circuit Symposium* (CSICS), pp. 1-4, 2013.

[21] J. Horn, G. Beock, "Ultra Broadband Ferrite Transmission Line Transformers", IEEE MTT-S *Int. Microwave Symposium Digest*, pp. 433-436, Jun. 2003.

[22] P. Gomez-Jimenez, P. Otero, E. Marquez-Segura, "Analysis and Design Procedure of Transmission Line Transformers", IEEE *Trans. Microwave Theory Tech.*, vol. 56, no.1, pp. 163-171, Jan. 2008.

[23] J.H. Kim, D.W. Woo, G.Y. Jo, W.S. Park, "Microstrip Phase Inverter using Slotted Ground", IEEE *Antennas and Propagation Society International Symposium*, pp. 1-4, 2010.

[24] Z. Liao, X. Zhang, "Frequency-Tunable Phase Inverter Based on Slot-Line Resonator", *Progress In Electromagnetics Research Letters*, vol. 66, pp. 9-14, 2017.

[25] K. Hagiwara, H. Arai, "Wideband Unbalanced Fed 180-degree Phase Shifter using Phase Inverter", IEEE *International Workshop on Electromagnetics, Applications and Student Innovation Competition*, pp. 76-77, 2013.

[26] KLIMA CO.USA. (2014). *A multi-band wire antenna that performs exceptionally well even though it confounds antenna modeling software*. Retrieved from http://www.klimaco.com/HAMRADIOPAGES/hf_antennas.htm

[27] J Hare. *The 4:1 Half-wave coax balun*. Retrieved from http://www.creative-science.org.uk/balun.html

[28] I.J. Bahl and D.K. Trivedi (1977, May). *Microstrip*. Retrieved from https://www.microwaves101.com/encyclopedias/microstrip

[29] P. Miles. (2016, June 30). *1:4 Guanella current balun*. Retrieved from https://vk6ysf.com/balun_guanella_current_1-4.htm

[30] N. Smith. (2017, October 28). *I0QM 1:1 Coax balun test*. Retrieved from http://www.g4dbn.uk/?p=691

APPENDIX A

Matlab code for quarter-wave transformer with ABCD - matrix:

```
% frequency range
f =0.5:0.01:5;

% load resistance
RL=50;

% characteristic impedance
Z0=50;

% ABCD matrix
A=cos(pi/3*f);
clear j
B=j*Z0*sin(pi/3*f);
C=j*(1/Z0)*sin(pi/3*f);
D=cos(pi/3*f);

% input impedance
Zin=(A*RL+B)./(C*RL+D);

% Gamma IN
Gin=(Zin-50)./(Zin+50);

% Reflection wave
S_11=20*log(abs(Gin));

% plot graph
plot(f,S_11)
% axis([0.5 5 -300 0])
hold on
```

APPENDIX B

Matlab code for 1:4 Guanella balun with ABCD - matrix:

```
% frequency range
f =0.01:0.01:3;

% load resistance
RL=100;

% characteristic impedance
Z0=50;

% ABCD matrix
A=cos((2*pi)/3*f);
clear j
B=j*Z0*sin((2*pi)/3*f);
C=j*(1/Z0)*sin((2*pi)/3*f);
D=cos((2*pi)/3*f);

% input impedance
Zin=((A*RL+2*B)./(C*RL+2*D))/2;

% Gamma IN
Gin=(Zin-25)./(Zin+25);

% Reflection wave
S_11=20*log(abs(Gin));

% plot graph
plot(f,S_11)
% axis([0.5 5 -300 0])
hold on
```