DESIGN, SIMULATION, FABRICATION AND TESTING OF IMPROVED HYBRID WIDEBAND MICROSTRIP BALUN CIRCUITS AT 2.4 GHz

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A Project

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Abstract

of

DESIGN, SIMULATION, FABRICATION AND TESTING OF IMPROVED HYBRID WIDEBAND MICROSTRIP BALUN CIRCUITS AT 2.4 GHz

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Microwave baluns are key circuit components in wireless modulator and mixer circuits. The objective of the project is to design, simulate and fabricate an improved version of wideband microwave balun operating at a center frequency of 2.4 GHz. The design is optimized using Advanced Design System (ADS) software of Agilent Technologies. The focus of the project is to design a microstrip circuit with low Voltage Standing Wave Ratio (VSWR), high degree of amplitude balance and phase balance for optimum performance. A resistor at the input port and capacitor at the center of the coupled lines are included to get balanced coupling of -17dB and a phase difference of 180 degrees at the two output ports and a low VSWR. The microstrip design is routed using the IsoPro 2.7 PCB routing software and fabricated using the T-Tech PCB fabricating machine.

______________________ , Committee Chair
Suresh Vadhva, Ph.D.

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We are grateful to all staff and faculty members of College of Engineering and Computer Science, California State University, Sacramento who contributed and helped us to finish this work.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Chapter 1

INTRODUCTION

A balun circuit is a type of electrical transformer which converts balanced electrical signals to unbalanced electrical signals and vice-versa. A balanced or differential signal is the one which has both its conductors having equal voltages and an unbalanced or single-ended signal is the one having one of its conductors grounded [11]. Balun circuits have different configurations depending on bandwidth, operating frequency and physical architecture. Most balun circuits consists sections of transmission lines or coupled lines. A simple transmission line balun consists of a half wavelength transmission line which gives narrow band performance, for improved bandwidths multiple sections of half wavelength lines can be interconnected by quarter wavelengths [2]. A balun circuit is a four port device. It has one input port, two output ports and the fourth port is isolated. A wideband balun is designed to have equal power at both the output ports but with a phase difference of 180 degree over wide frequency range [1].

Baluns find wide applications in the modern communication systems. They are used at the output stages of push-pull amplifiers in radios and televisions, used as key components in balanced mixers and frequency multipliers. They are also used in antenna application for wireless technologies such as Bluetooth and WLAN [1], [2], [4].

This report describes the design, simulation, fabrication and testing of an improved wideband balun circuit operating at a centre frequency of 2.4 GHz. The implemented design achieved better amplitude balance, excellent phase balance between the output ports over 50% of bandwidth and a very low VSWR compared to the previous design of miniaturized microstrip balun operating at 2.45 GHz [1].

Chapter 1 of this report focuses on the introduction to the report. Chapter 2 explains Directional Coupler, Coupled Line Couplers and Wideband Balun fundamentals. This chapter also explains the performance of standard coupler with a coupling level of ~ -17 dB at one output port. The chapter then describes the goals of the new designs and requirements that include small size and equal coupling levels at both output ports and a phase balance of ~180 degrees in the frequency band of interest.

Chapter 3 of the report describes the optimized balun design at 2.4 GHz. Chapter 4 describes the layout and fabrication of the balun circuit using IsoPro T-TECH. Chapter 5 describes the test setup and results. Chapter 6 of the report gives the conclusion of the project and the direction of future work.

Chapter 2

DIRECTION COUPLERS AND BALUNS

2.1 Direction Coupler

A very commonly used basic element in microwave system is the directional coupler. Its basic function is to sample the forward and reverse traveling waves through a transmission line. It is used to measure the power level of transmitted or received signal [8].

The Directional Coupler consists of two transmission lines and a mechanism for coupling signals between them. The directional coupler is shown in fig 2.1. They can be realized from microstrip, stripline, coax, waveguide. There are different types of direction couplers, for example, hybrid couplers and coupled line couplers. In our design, we have focused on coupled line couplers, since the coupled line coupler provides higher bandwidth [6].

The basic of directional coupler is as follows: As shown in fig 2.1, it is a four port device that samples the power flowing into port 1 coupled in to port 3 (the coupled port) with the remainder of the power delivered to port 2 (the through port) and no power delivered to the isolated port 4. It can be described respectively by Coupling(C), Directivity (D) and Isolation (I). Coupling is the ratio of input power to the coupled power. Directivity (D) is the ratio of coupled power to the power at the isolated port. Isolation (I) is the ratio of input power to power out of the isolated port [7], [8].

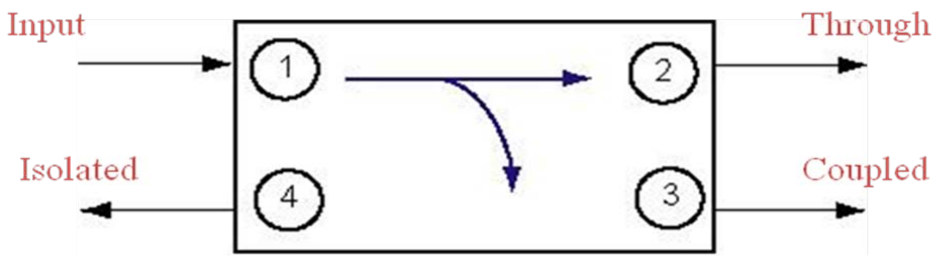


Figure 2.1: Directional Coupler [7], [8]

Hybrid coupler is a special type of directional coupler where the input power is equally divided between two output ports. The coupling factor of hybrid coupler is 3db. There are two types of hybrids.

1) The quadrature hybrid-

   It has a 90 degree phase shift between port 2 and 3 when fed from port 1, with the scattering matrix [S] given by:

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

2) The magic-T hybrid or rat-race hybrid

   It has a 180 degree phase shift between port 2 and 3 when fed from port 4, with the scattering matrix [S] given by:

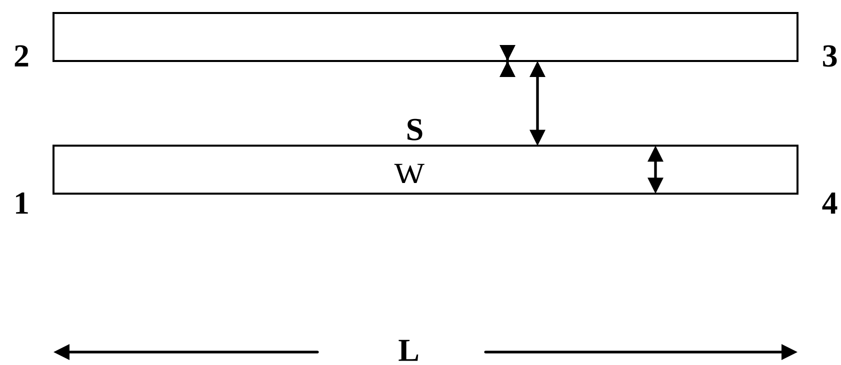
$$[S]=\frac{1}{\sqrt{2}}\begin{bmatrix}0 & 1 & 1 & 0\\ 1 & 0 & 0 & -1\\ 1 & 0 & 0 & 1\\ 0 & -1 & 1 & 0\end{bmatrix}$$

2.2 Coupled Line Couplers

The popular realization technique for directional couplers is the coupled line couplers. The coupled line couplers consist of two quarter wavelength lines with capacitive coupling between them as shown in figure 2.2. Each of the lines has two ports thus creating a four port device [8]. The coupling between the two lines is the result of interaction of electromagnetic fields of each line [5].

2.3 Design of 3 dB Directional Coupler

Consider a typical 3dB directional coupler that operates at 2.4 GHz, as shown in figure 2.2, with all four ports are terminated in 50-ohm loads [10].



L = Line Length S = Spacing between lines W = Width of lines

Figure 2.2: Structure of 3dB directional coupler [10]

The given design parameters are:

3dB coupling

Center frequency: 2.4 GHz

The even mode impedance (Z_{oe}) and odd mode impedance (Z_{oo}) are calculated from the above parameters using the following formulae [3]

$Z_{0e} = Z_0 \, [(1+C)/(1-C)]^{1/2}$ even mode impedance…………………(2.6)

$Z_{0o} = Z_0 \, [(1-C/(1+C)]^{1/2}$ odd mode impedance…………………...(2.7)

Where, C denotes the co-efficient of coupling.

For a 3 dB coupler, $C = 10^{-3/20} = 0.70$

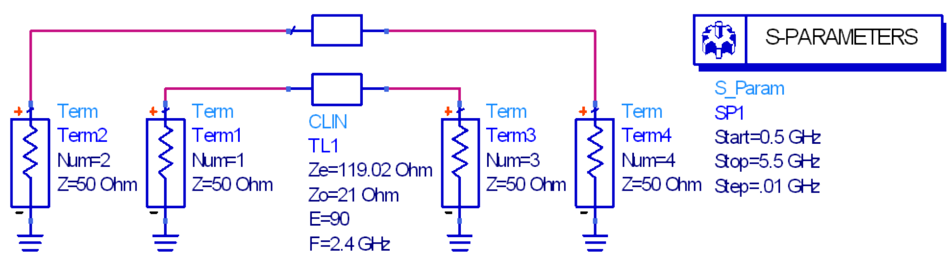


Figure 2.3: ADS Schematic of Coupled Line Design with Center Frequency of 2.4 GHz.

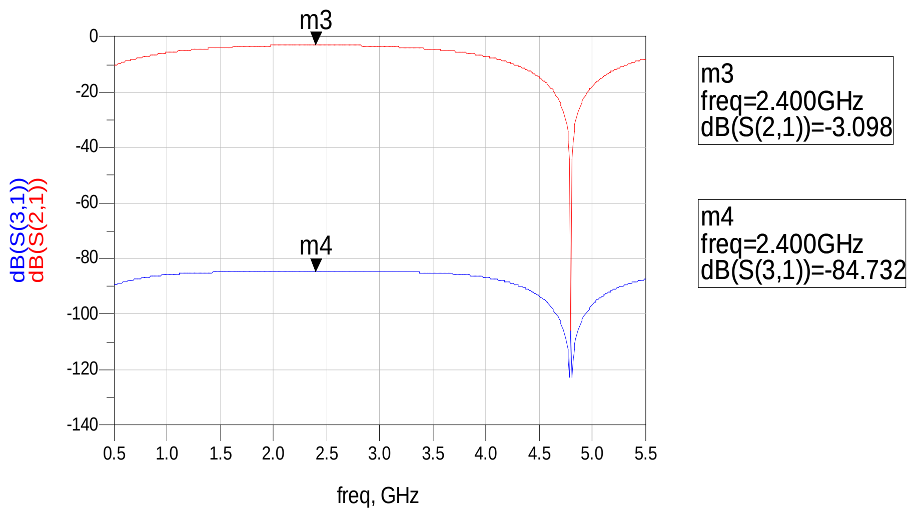


Figure 2.4: Plot of S(2,1) and S(3,1) vs. Frequency

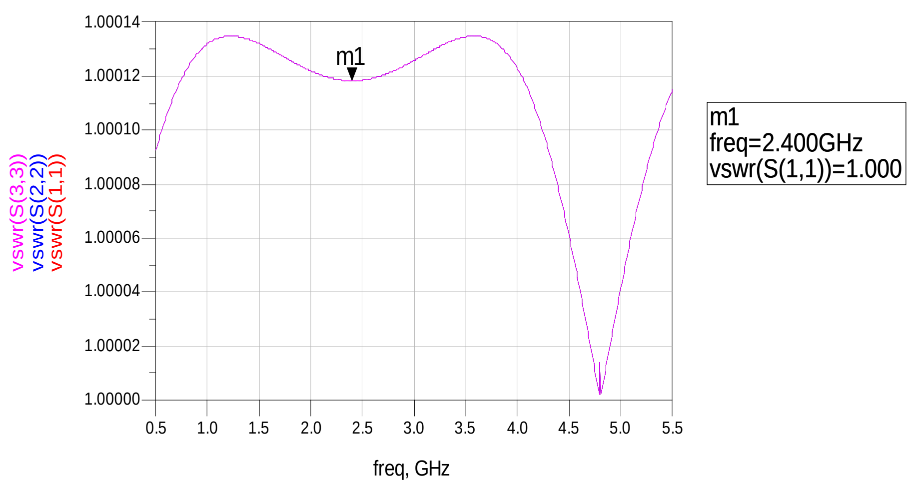


Figure 2.5: Plot of VSWR of S(1,1), S(2,2) and S(3,3) vs. Frequency

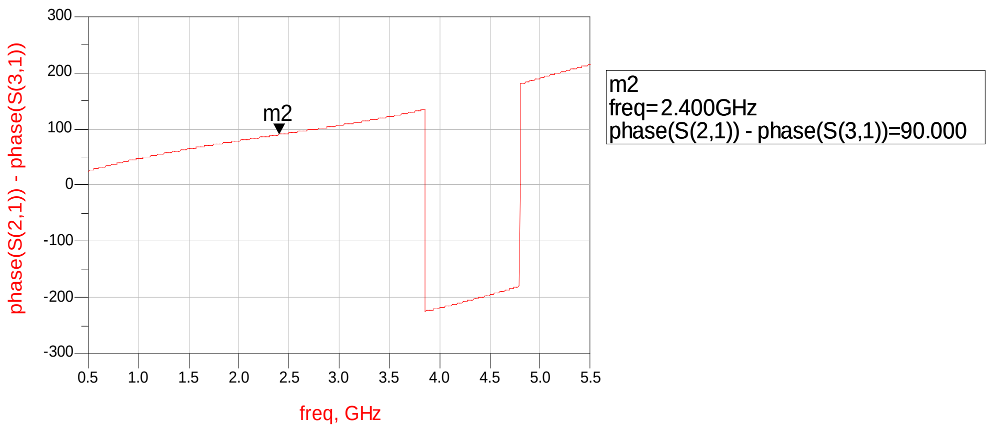


Figure 2.6: Plot of S(2,1) Phase and S(3,1) Phase Difference vs. Frequency

The simulation of the circuit shown in figure 2.3 was carried out using Advanced Design System (ADS) software. The simulation results are shown in Figures 2.4 –2.6. Figure 2.4 shows the maximum coupling (|S21|~ -3) dB at the center frequency of 2.4 GHz, insertion loss being minimum (|S31| ~ -84) dB as shown in the figure 2.4. It shows that amplitude plot is not flat as we required in wideband range. The VSWR at a port is shown in figure 2.5 that is ideally at ~ 1 at the center frequency. The phase balance is not flat over the frequency band as shown in figure 2.6.

2.4 Design Expectations of Balun

Baluns are designed to have a precise 180 degree phase shift with minimum loss and equal balanced impedances. Design of a balun consists of two 90 degree phasing lines that provide required 180 degree split and this involves quarter wavelengths and half wavelengths [12].

The Coupler configuration described in the previous section is simple but does not meet the balun requirement as it does not give equal power at the output ports with a phase difference of 180 degrees [1]. The amplitude and phase balance of the output ports are shown in figure 2.4 and figure 2.5 respectively.

The requirements for the desired balun represented in this report are as follows:

1. The wideband frequency range should be centered at 2.4 GHz with a 50 % bandwidth.
2. The amplitude balance should be maintained at the both the output port at ~- 17dB in the prescribed wideband frequency range.
3. The phase balance $/S_{21}$-$/S_{31}$ should be precise at ~180 degrees over the wideband frequency range.
4. The Balun design should be very small in size, in the range of approximately 650 mils x 850 mils.

In order to reach the above-mentioned requirements over the wideband frequency range, we need to do considerable changes in the standard coupler design as well as the balun design. The next chapter describes the changes and the steps that were taken to design miniaturized wideband balun.

2.5. Balun Applications

A balun's function is to achieve compatibility between systems, and has wide application in modern communications. They are used in balance mixers, push pull amplifiers, balanced frequency multipliers, phase shifters, balanced modulators, dipole antenna feeds. Basically used whenever a circuit design requires signals on two lines with equal magnitude and 180 degrees out of phase [2], [9].

Chapter 3

IMPROVED MINIATURIZED WIDEBAND BALUN DESIGN AT 2.4 GHz

3.1 Basic Topology of Balun Design

In this chapter, an improved miniature wideband balun design working at 2.4 GHz is presented. This design is an improved version of an earlier project that dealt with design of a wideband balun circuit operating at 2.45 GHz [1].

A standard balun design works on the principle of center tapper transformer as shown in the figure 3.1. A coupling element is used for obtaining balanced output and taps provide the coupling of signals to generate the outputs [12].

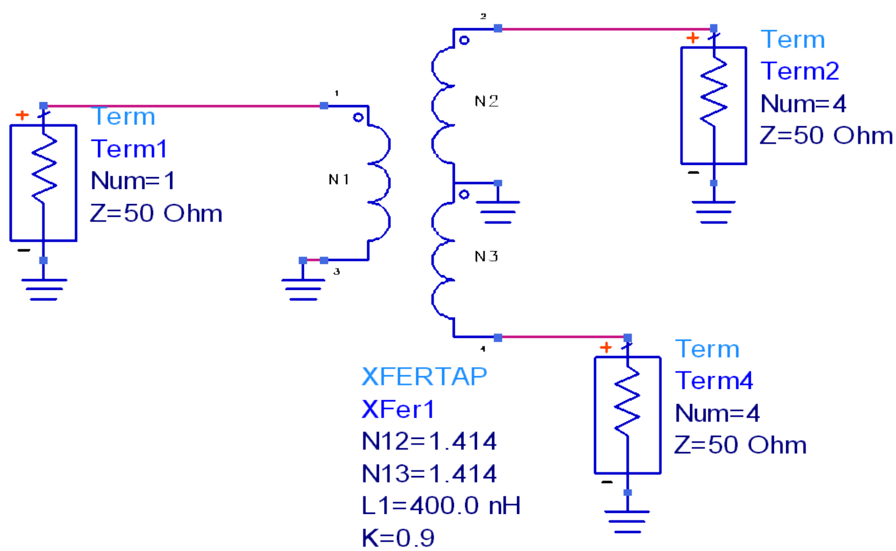


Figure 3.1: Center Tapped Transformer [12]

3.2 Optimized Wideband Balun Design

The optimized wideband balun design using ADS is shown in the figure 3.2. It has four coupled lines. The dimensions of coupled lines, transmission lines and other components used are given in the table 3.3.

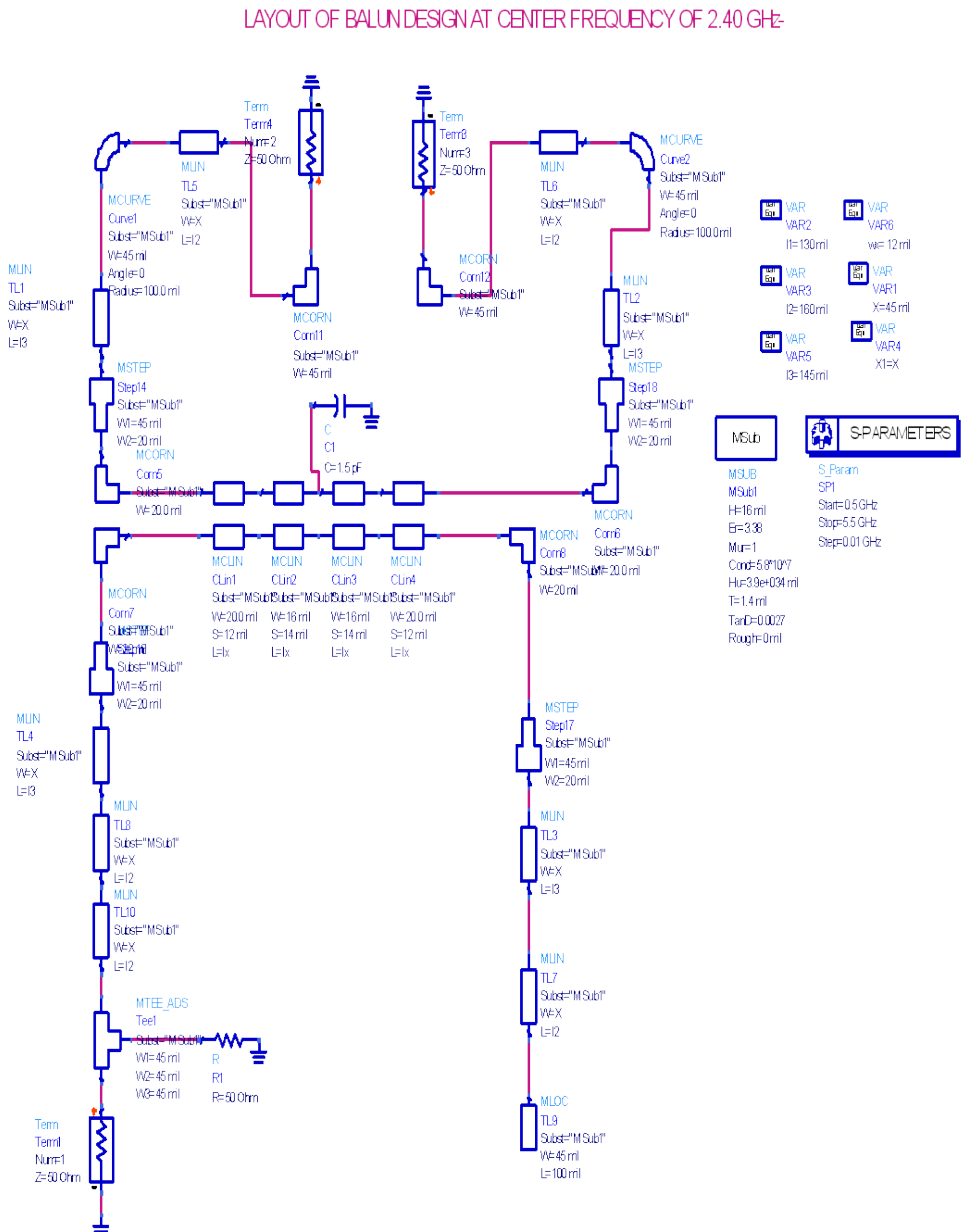


Figure 3.2: Design of Wideband Microstrip Balun Circuit at 2.4 GHz

L1	**130Mils**
L2	**160Mils**
L3	**145 Mils**
L4	**140 Mils**
W1	**45 Mils**
W2	**20 Mils**
W3	**20 Mils**
S1	**14 Mils**
S2	**12 Mils**
R	**50 Ohm**
C	**1.5 pF**

Table 3.3: Dimensions of Optimized Balun Circuit

The earlier project 'Design of a Miniaturized Microstrip Balun at 2.45 GHz had a reasonable amplitude balance but had a very high VSWR [1]. The phase balance at the output ports was not 180 degrees flat over the frequency band. These factors are addressed in our design operating at 2.4 GHz.

The initial design of the balun circuit operating at 2.4 GHz consisted of four coupled - line sections and binomial multisection matching circuit. This lowered the VSWR at the output ports but the phase balance was not close to 180 degrees over the frequency band.

Hence a few changes were made to the initial design. A capacitor of 1.5 pF was placed at the center of the coupled lines. This gave a constant phase difference of 180 degrees at the output ports.

To optimize the design further the lengths of the coupling lines were reduced so that the total length equals to 580 mils.

By varying the lengths and widths of transmission lines and coupling lines the VSWR at the output ports was reduced considerably but the input VSWR was still high. Hence a resistor of 50 ohms was placed at the input port, thus bringing the input VSWR close to one.

Chapter 4

LAYOUT AND FABRICATION PROCESS

4.1 Layout:

The first step in the fabrication process was the generation of layout from the schematic. The layout of the balun design was generated in ADS. The layout is shown in figure 4.1.

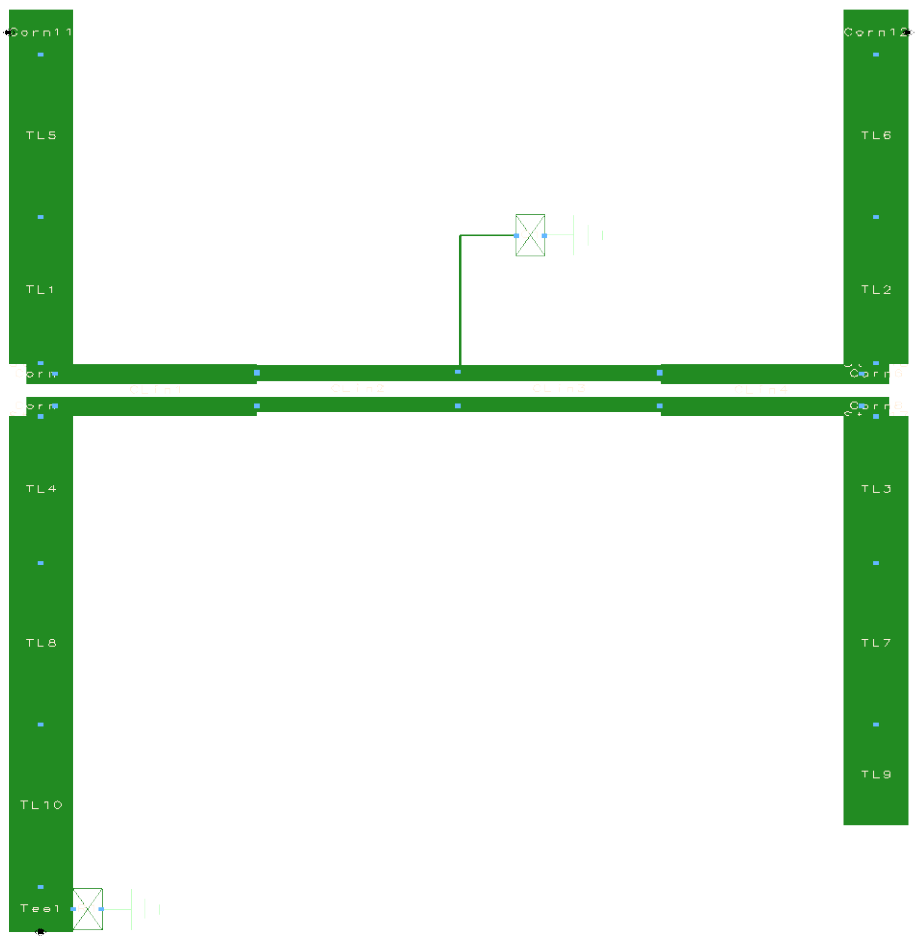


Figure 4.1: Layout of Wideband Balun Circuit

4.2 PCB Routing Using Iso Pro 2.7

The generated layout in ADS was exported to a Gerber file format so that it could be recognized by the Iso Pro PCB routing software. The Gerber file is shown in figure 4.2.1. The gerber file thus obtained was imported onto the ISO Pro software. Then the traces were repositioned to the location where the circuit was to be routed with respect to the T-Tech milling table.

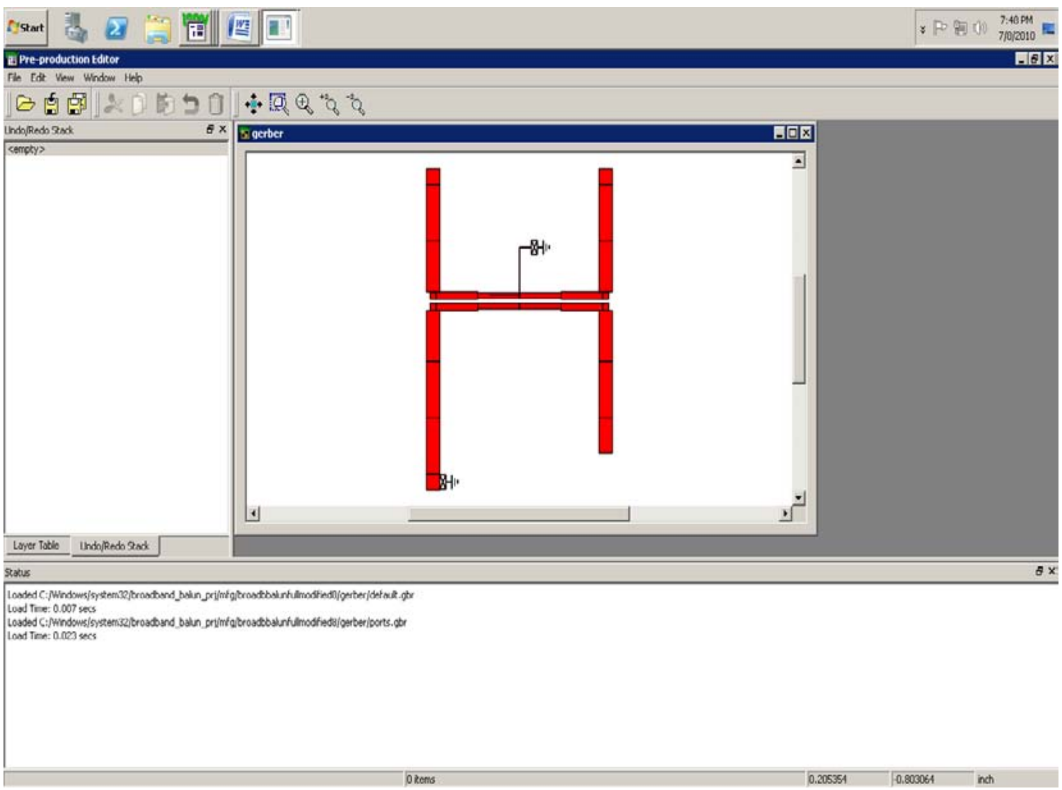


Figure 4.2.1: Layout of Wideband Balun Circuit in the Gerber file

The traces of the design were isolated by creating the isolation layer. After this a new contour layer was created which specified the outer boundary of the printed circuit board. Tabs were created in the contour to help the board stay in place when the board was being routed. Next a rubout layer was created to rubout the excess area. The IsoPro layout is show in figure 4.2.2.

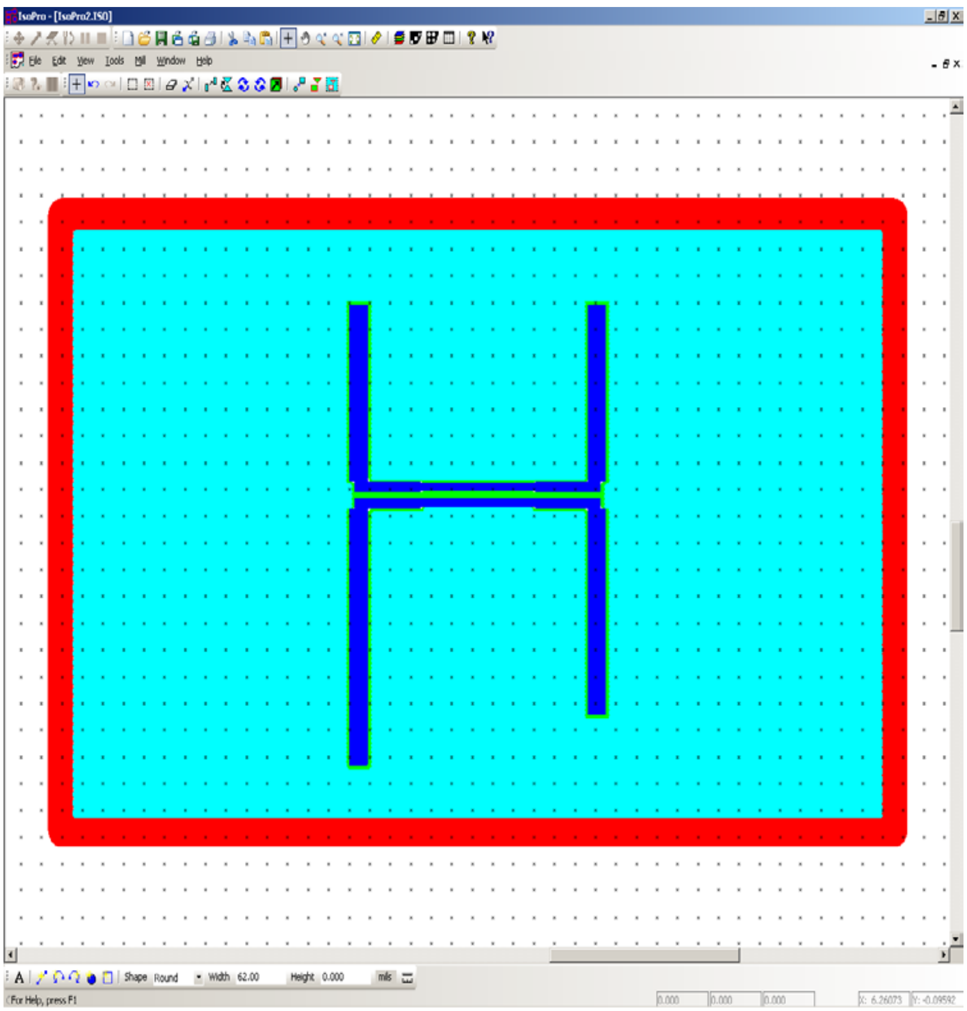


Figure 4.2.2: Layout of Wideband Balun without Capacitor and Resistor in IsoPro

A microstrip laminate was used to fabricate the circuit. It is low in cost, small in size and it has the ability to easily integrate active and devices [5]. The printed circuit board used was an RT Duriod Microwave Laminate RO 4003 QLAM developed by Rogers Corporation. The specifications of the laminate are given in table 4.2.3.

Name	**RO 4003 QLAM**
Dielectric Constant ε_r	3.38
M_{ur}	1
Dielectric Thickness H (mils)	16
H_u	3.9×10^{34}
Conductor Thickness T (mils)	1.4
Conductivity	5.8×10^7
TanD	0.0027
Rough RMS (mm)	95 (2.4)

Table 4.2.3: Specifications of RT/DUROID Microwave Laminate QLAM 4003

After the layers are thus set, the printed circuit board was placed on the T-Tech machine and the power was switched on. First, the isolation layer was routed creating traces around the actual circuit. Then the rubout was performed to etch out all of the excess copper on the printed circuit board. The contour layer was then routed, creating contours at the ends of the circuit. A chisel was used to break the taps and take the circuit out.

Chapter 5

TESTING OF BALUN CIRCUITS AND RESULTS

5.1 Test Setup

The fabricated balun circuit was very thin and delicate. It would not be able to withstand the pressure applied by the arms of network analyzer and SMA Connectors. So an aluminum metal base structure was constructed to make the circuit more robust. The fabricated balun circuit was placed on the aluminum base and then SMA connectors were soldered onto to the input and two output ports.

To begin testing, the network analyzer was calibrated to operate in the frequency range of 0.5 to 5.5 GHz. Next, port 1 of network analyzer was connected to the input port of the balun while port 2 was connected to the output port 2 of the balun circuit and a 50 ohm wideband load was connected to output port 3. The various S- Parameters were measured and the results imported onto ADS. Similarly, this input is maintained the same but the port 2 of the network analyzer was connected to the output port 3 of the balun circuit and a wideband load of 50 ohms was connected to the output port 2 of balun circuit. The various S- Parameters at these ports were measured and the results imported onto ADS.

Now a capacitor of 1.5 pF was soldered onto the center of the coupled lines of the balun and a resistor of 50 ohms is soldered onto the input port of the balun. The S-Parameters were measured on the network analyzer as described in the previous paragraph and the results were imported on to ADS. The final circuit with aluminum base and SMA connectors is shown in the figure 5.1.

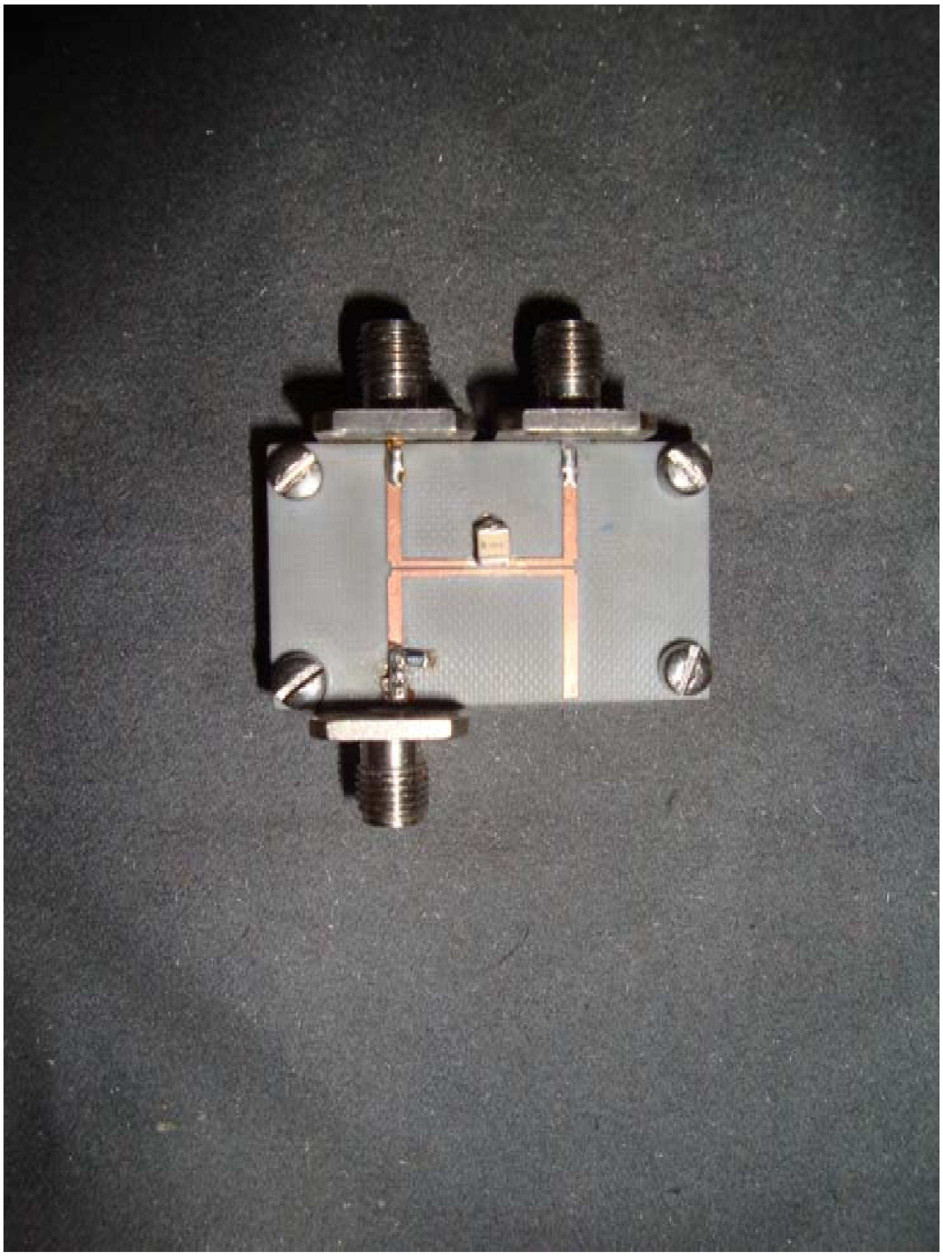


Figure 5.1: Final Fabricated Balun Circuit with Resistor, Capacitor and Connectors (630 mils x 830 mils)

5.2. Results

5.2.1 Simulation Results

The simulation was carried out on the ADS (Advanced Design System) software by Agilent Technologies. This section describes the simulation results on the model shown in Figure 3.2.1.

Figure 5.2.1a shows the amplitude balance between two output ports.

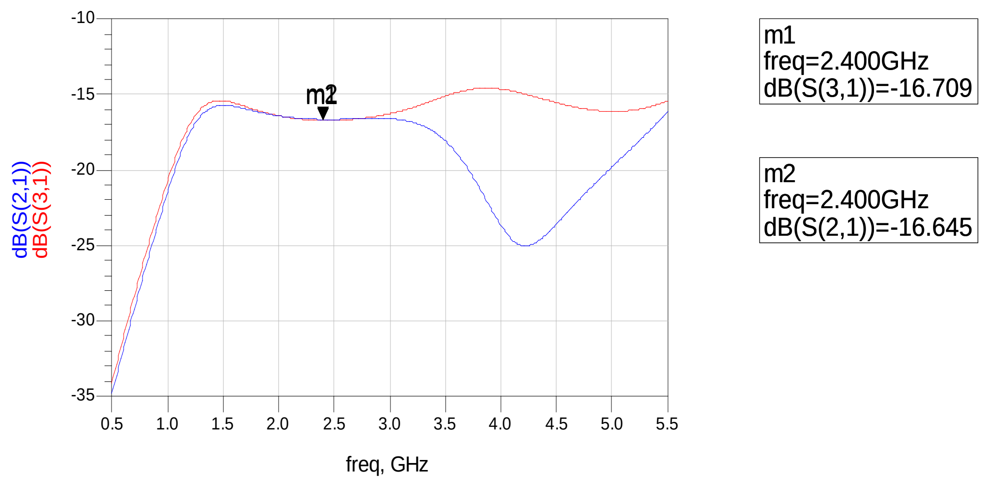


Figure 5.2.1a: Plot of S(2,1) and S(3,1) vs. Frequency

Figure 5.2.1b shows the phase balance between the two output ports.

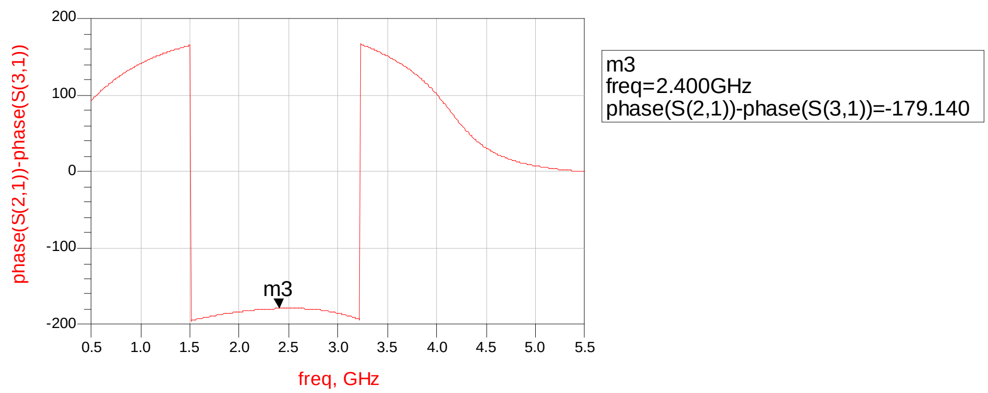


Figure 5.2.1b: Plot of S(2,1) and S(3,1) Phase Difference vs. Frequency

Figure 5.2.1c shows the VSWR at the input port and two output ports.

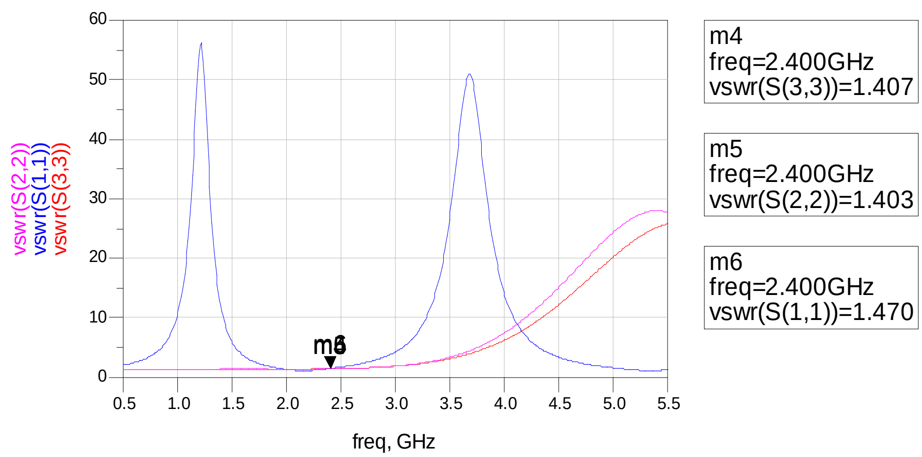


Figure 5.2.1c: Plot of VSWR of S(1,1), S(2,2) and S(3,3) vs. Frequency

There is an excellent amplitude balance with a coupling of -17 dB between the output ports. There is a flat 180 degrees phase difference over the frequency band between the output ports. The VSWR at the input and two output ports is close to 1.

5.2.2 Results of Fabricated circuit without Resistor and Capacitor

5.2.2 Measured Results without Capacitor and Resistor: This section describes the measured results on the fabricated balun circuit without the resistor and capacitor soldered on to it.

Figure 5.2.2a shows the amplitude balance at the two output ports.

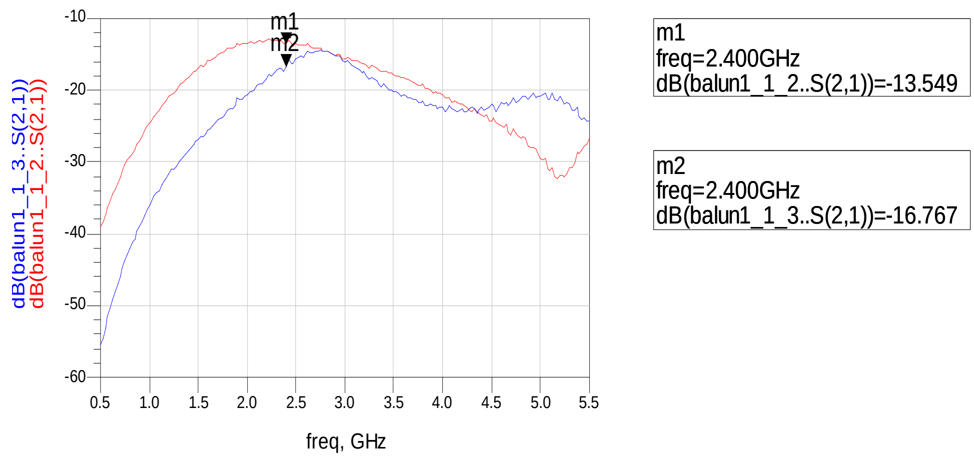


Figure 5.2.2a: Plot of S(2,1) and S(3,1) amplitude vs. Frequency

Figure 5.2.2b shows the phase balance between the two output ports.

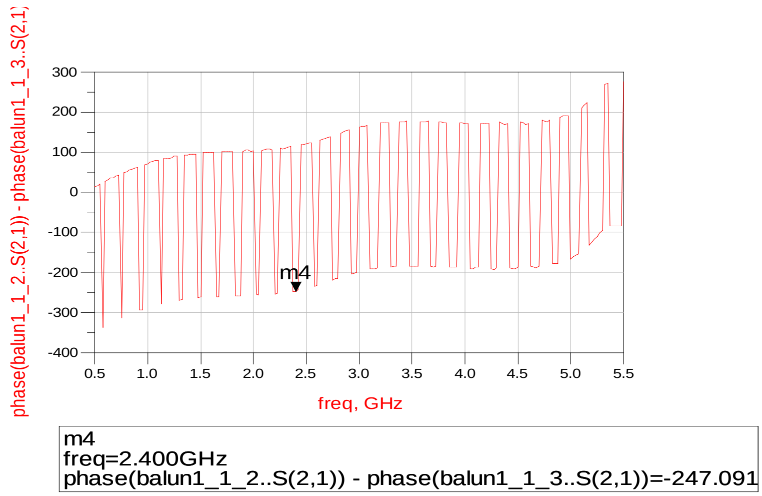


Figure 5.2.2b: Plot of S(2,1) Phase and S(3,1) Phase Difference vs. Frequency

Figure 5.2.2c shows the measured VSWR at the input and two output ports

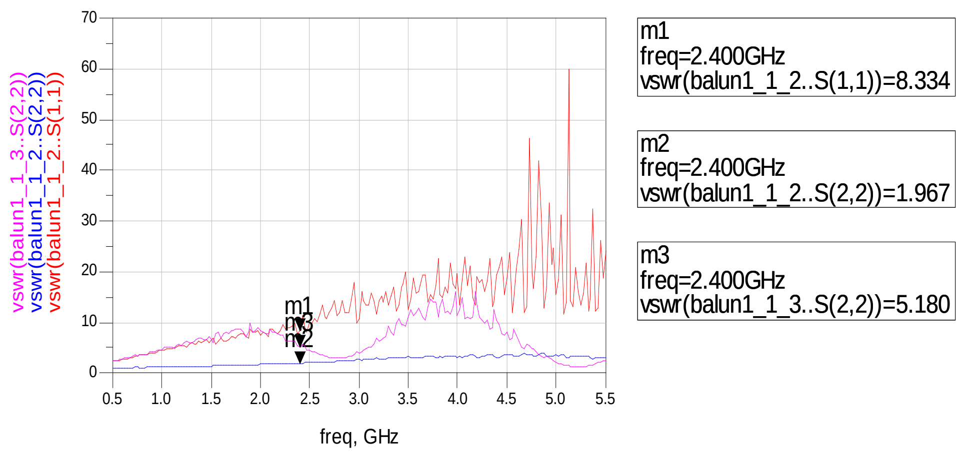


Figure 5.2.2c: Plot of VSWR of S(1,1), S(2,2) and S(3,3) vs. Frequency

The results of the fabricated circuit are as shown in the figures above. The amplitude of S(2,1) and S(3,1) are not balanced with a difference of 3dB between them. The phase difference between the output ports is 247 degrees which is not desirable. The input and output VSWR are also quite high at 8.3, 1.9 and 5.18 respectively..

5.2.3 Measured Results with Capacitor and Resistor: This section describes the measured results on the fabricated balun circuit with resistor and capacitor soldered onto it.

Figure 5.2.3a shows the amplitude balance between the two output ports.

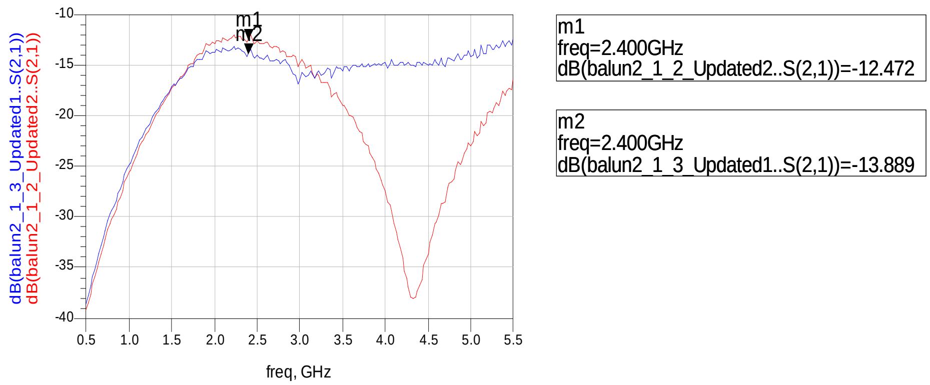


Figure 5.2.3a: Plot of S(2,1) and S(3,1) vs. Frequency

Figure 5.2.3b shows the Phase Balance between the Output Ports

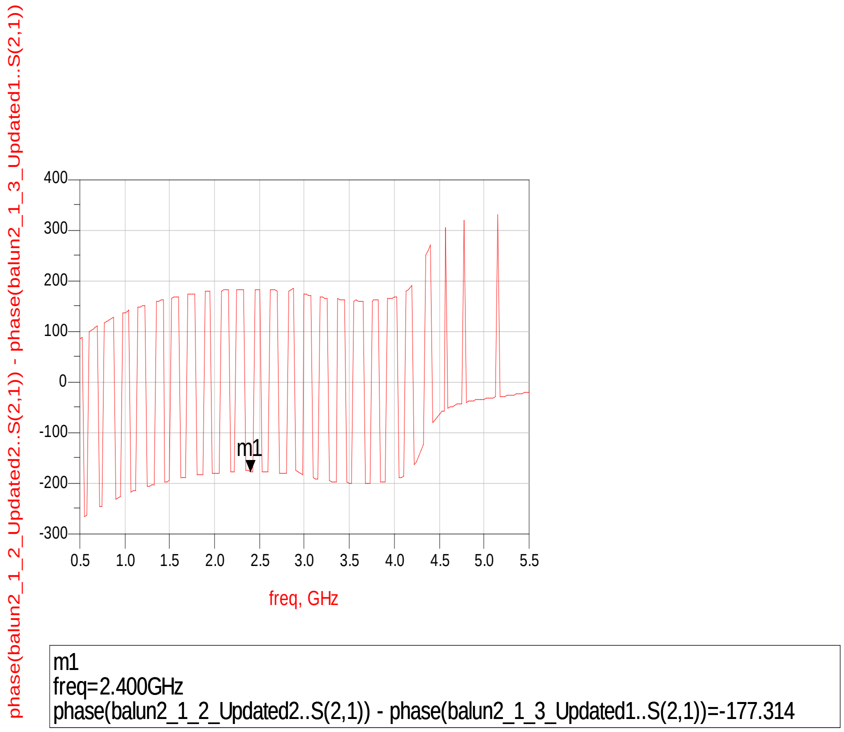


Figure 5.2.3b: Plot of S(2,1) Phase and S(3,1) Phase Difference vs. Frequency

Figure 5.2.3c shows the measured VSWR at input and two output ports

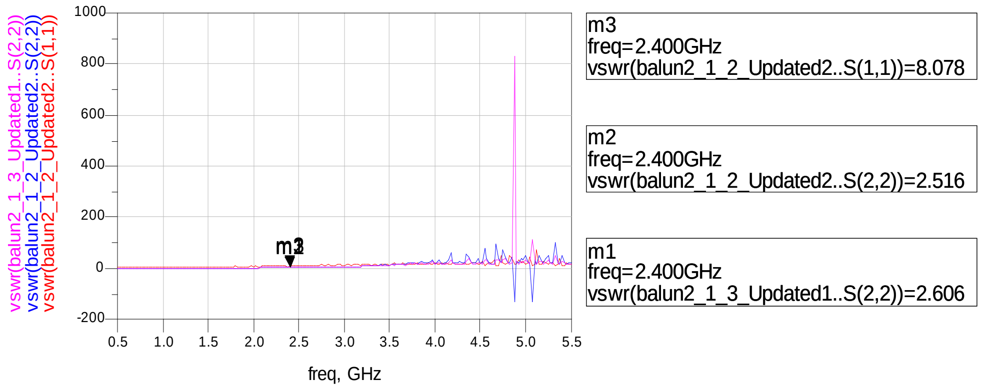


Figure 5.2.3c: Plot of VSWR of S(1,1), S(2,2) and S(3,3) vs. Frequency

The results of the fabricated circuit after soldering a capacitor and a resistor are as shown in the above figures. There is a good amplitude balance between the output ports but with a coupling close to 13 dB. The phase difference between the output ports is close to 180 degrees but is not flat throughout the frequency band. The VSWR at the output ports are very low, close to 2. But the input VSWR is a little high at 8.

Chapter 6

CONCLUSION

An improved miniature wideband balun design operating at 2.4 GHz is presented. The schematic design and simulation were done using ADS. The circuit was routed using the IsoPro 2.7 software and the T-Tech printed circuit board fabrication machine was used to fabricate the circuit. The amplitude balance, phase balance and VSWR performance of the fabricated circuit were improved by soldering a capacitor and a resistor to it. The fabricated circuit was tested on a network analyzer and the results were compared with simulated results using the Advanced Design System (ADS) software.

The proposed design gives a low VSWR, good phase balance of 180 degrees and reasonable amplitude balance between the output ports. There is reasonable match between the simulated results and actual fabricated results. The output VSWR is quite low for the fabricated circuit but the input VSWR is a little high. Although the phase balance at the output ports is close to 180 degrees, it is not constant throughout the band.

The future work on the project would deal with improving the fabricated circuit so that its results closely match that of the simulation. The input VSWR has to be lowered further and a phase balance of 180 degrees has to be achieved through out the band.

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