DESIGN, SIMULATION AND FABRICATION OF IMPROVED WIDEBAND
MICROSTRIP BALUN CIRCUIT AT 5 GHZ


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PROJECT


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DESIGN, SIMULATION AND FABRICATION OF IMPROVED WIDEBAND
MICROSTRIP BALUN CIRCUIT AT 5 GHZ


A Project

by

Jizhen Tang




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Department of Electrical and Electronic Engineering

Abstract

of

DESIGN, SIMULATION AND FABRICATION OF IMPROVED WIDEBAND
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The objective of the project is to design, simulate and fabricate a broadband microstrip
balun operating at a center frequency of 5 GHz and wide bandwidth of 3.5 GHz. In this
project report, I present one design with the capacitor in the middle of coupled lines and
the resistor at the input port. This balun design will find various applications in the
wireless industry such as push-pull configuration and mixers. The Advanced Design
System (ADS) software was used to design and simulate the model. This design is aimed
to provide a coupling of −17 dB at both output ports and a phase difference of 180
degrees between the two output ports over the specified frequency range, and give low
voltage standing wave ratio (VSWR) while maintaining good amplitude balance. The
emphasis is to obtain a high degree of amplitude balance, phase balance and low VSWR,
and keep in tune with high performance demanded by wireless systems.

_____, Committee Chair
Dr. Preetham B. Kumar


_____
Date

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ACKNOWLEDGEMENTS

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Chapter 1

INTRODUCTION

A wideband balun circuit essentially has one input port and two output ports. The balun is designed to have equal power at the both output ports but with a phase difference of 180 degrees. Additionally, for a wideband balun, the latter properties have to be realized over a wide frequency range. The ability of balun to electromagnetically couple an unbalanced input and produce a balanced output is generally to achieve compatibility between systems. Thus it has extensive applications in modern communications, particularly in realizing frequency conversion mixers to make cellular phone and data transmission networks possible. They are also used to convert a carrier signal from coaxial cable to Category five cable types designed for high signal integrity. Planar baluns are used in this project because they have low insertion loss and wide bandwidth compared to other types of balun. Most of the current balun structures are narrowband for specific applications. Therefore, there is a need for wideband matching structure in wideband applications. [1]

This report details the design and simulation of a broadband balun circuit which exhibits improvement in performance from a previous designed miniaturized microstrip coupled line wideband balun.[1] The improvement includes a simplification of the design while still meeting manufacturing requirements, and improved balanced amplitude and phase balance between the outputs over a wide band of frequencies.

This design also shows progress in improving VSWR performance at the input port of the balun. The miniaturized microstrip coupled line wideband balun is designed to operate at a center frequency of 5GHz over a 3.5GHz frequency band.

Chapter 1 of this report focuses on the introduction to the report. Chapter 2 explains the transmission line, scattering parameters, and input output impedance mismatch.

Chapter 3 explains microstrip coupler, directional coupler, coupled line couplers and wideband balun fundamentals. The 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 4 describes the model of balun design. Chapter 5 describes the computer simulations and optimization introduces to obtain final form of wideband balun circuit. Chapter 6 describes the layout of balun circuit. Chapter 7 describes the fabrication the balun circuit in IsoPro T-TECH.

Chapter 8 describes the conclusions of the project and the direction of future work

Chapter 2

TRANSMISSION LINE THEORY AND S-PARAMETERS

2.1   Lossless Transmission Line

A transmission line is a path from one place to another for directing the transmission of energy. It creates a medium that transfers energy such as electromagnetic waves, acoustic waves or electric power transmission. Transmission lines can be wires, coaxial cables, dielectric slabs, optical fibers, electric power lines, and waveguides. [3] Transmission line theory is applicable when it follows the following rule of thumb: If the length of cable wire is greater than one-tenth of the wavelength, then the cable or wire is treated as a transmission line.

The transmission line and its equivalent circuit model are shown in Figure 2.1 and Figure 2.2. The transmission line can be modeled as a two-port network. In the basic model, the network is assumed to be linear. It means output changes linearly with input and the two ports are interchangeable. [3]

In Figure 2.2, the components R, L, C and G are presented per unit length. R is the series resistor, L represents inductance, G is conductance, and C is capacitance. All these quantities are functions of frequency, and they are constant along the transmission line. In lossless transmission lines, R and G are equal to zero.

```
                +----------------+
    O---------| Transmission   |---------o
    Port A    |                |          Port B
    O---------|      Line      |---------o
                +----------------+
```
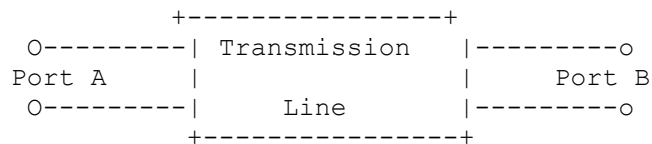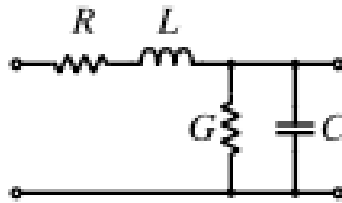Figure 2.1 Basic Transmission Line [3]

Figure 2.2 Lumped Element Model of Transmission Line [2]

Lossless transmission lines mean incident wave will be completely absorbed by the material and there will be no reflection of that wave. However, in the real world, lossless transmission lines do not exist because there will be always loss along the transmission lines. It means, when the energy is incident onto transmission line, it travels along the transmission line with certain phase and amplitude. Due to impedance mismatches, part of incident energy is reflected back and part of energy is transmitted into load where it gets absorbed. It is not practical to make lossless transmission lines but one can create low loss transmission lines. In order to make it low loss transmission line, it is necessary that no energy get reflected from the load. The wave should neither raise nor attenuate with the change in distance and time.

Figure 2.2 diagram illustrates that when an incident wave of form $V_0^+ e^{-j\beta z}$ is generated, where $\beta = \omega \sqrt{(\mu\varepsilon)}$ denotes wave number or phase constant, the total voltage on a line is given by the following equation [4]

$$V(z) = V_0^+ e^{-j\beta z} + V_0^- e^{j\beta z}$$ ……………………………………………..……….. (2.1)

The reflection coefficient is defined as the ratio of reflected wave to incident wave

Voltage Reflection coefficient ($\acute{\Gamma}$) = Reflected wave/Incident wave = $\dfrac{(Z_L - Z_O)}{(Z_L + Z_O)}$

Where $Z_L$ = Load Impedance

and $Z_0$ = Characteristic Impedance

For low loss high frequency design, in that, we have R<< $\omega$L and G << $\omega$C. Applying these approximations to the characteristic impedance $Z_0$ [9].

$$Z_0 = \sqrt{\dfrac{(R + j\omega L)}{(G + j\omega C)}}$$

Which gives $Z_0 = \sqrt{\dfrac{L}{C}}$ [2].

Also, the wavelength is $\lambda = \dfrac{2\pi}{\omega\sqrt{LC}}$ [2].

These approximations are summarized as follow [1].

1. For low loss or lossless transmission lines, $Z_0$, v, $\beta$ and $\lambda$ are approximately the same.

2. At any point in travelling wave, the average power is product of rms voltage and current.

3. Characteristics impedance $Z_0$ is real.

4. Electromagnetic wave is transmitted by transmission line.

2.2  Scattering Parameters

From their definitions, scattering parameters or S-parameters are measured using a matched termination. The S-parameters of a 2-port network is shown figure 2.3. Where,

$a_1$ is incident wave and $b_1$ is reflected wave at port1 and $a_2$ is incident wave and $b_2$ is

reflected wave at port 2.
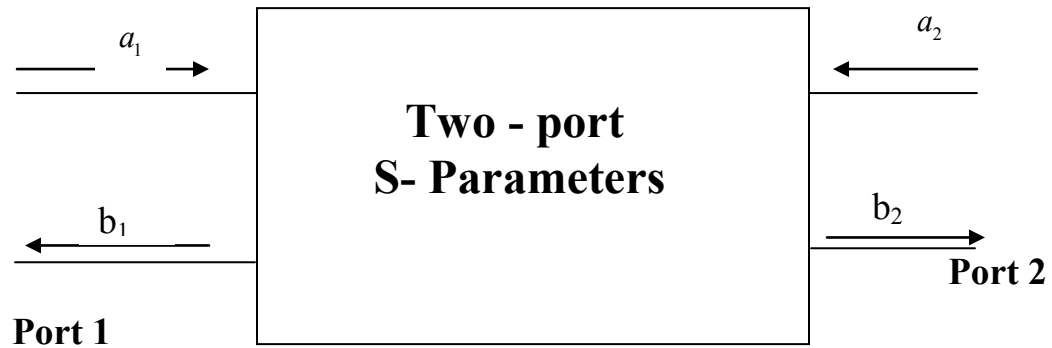


Figure 2.3 S-Parameters 2-port Network. [4]

The above two-port S-parameters network can be derived using the following

matrix formula. Where, [S] is called scattering matrix, and S11, S12, S22 and S21 are

called scattering parameters. [4]

[b] = [S] [ $a$ ]

or

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

The following equations can be derived from the above matrix.

$b_1 = S_{11} a_1 + S_{12} a_2$ ................................................................. (2.3)

$$b_2 = S_{21}\, a_1 + S_{22}\, a_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(2.4)}$$

Where

$S_{11} = \dfrac{b_1}{a_1}\Big|_{a_2=0}$  denotes input reflection coefficient

$S_{22} = \dfrac{b_2}{a_2}\Big|_{a_1=0}$  denotes output reflection coefficient

$S_{12} = \dfrac{b_1}{a_2}\Big|_{a_1=0}$  denotes reverse transmission coefficient

$S_{21} = \dfrac{b_2}{a_1}\Big|_{a_2=0}$  denotes gain or forward transmission coefficient

As shown figure 2.4, for example, if we want to measure $S_{11}$ and $S_{21}$, make $a_2$ equal to zero; terminate the output port with impedance equal to characteristic impedance of transmission line. It will absorb travelling wave incident on the load and no energy will return [4]. Similarly, by terminating the input port with impedance equal to the characteristic impedance, we can measure $S_{22}$ and $S_{12}$ parameters.
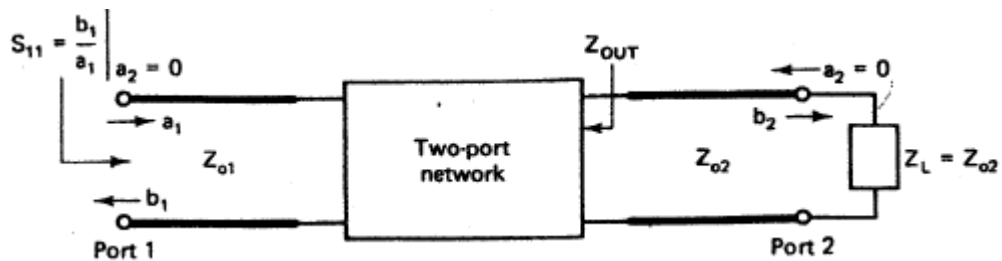


Fig.2.4 Diagram of Two Port Network [4]

2.3   Input Output Impedance Mismatch

Impedance matching is necessary in order to obtain maximum power, high gain and low voltage standing wave ratio (VSWR). We need to match both input and output impedance, and the amount of impedance mismatch can be determined by the complex parameter, known as reflection coefficient, which is defined as the ratio of reflected wave to the incident wave:

Reflection coefficient $(\Gamma) = V_{reflected} / V_{incident}$............................. (2.5)

$\Gamma = 0$ denotes perfect match between the input and output ports.

$\Gamma = 1$ denotes perfect mismatch.

Input Impedance Mismatch:

As shown in fig 2.5, to get maximum power to the 50 ohm load, we must have $Z_s = Z_0$, and the source will absorb entire reflected energy. In case, if $Z_s$ is not equal to $Z_0$, the energy will reflect back towards load. The amount of the reflected incident energy can be determined by the degree mismatch between $Z_0$ and $Z_s$.
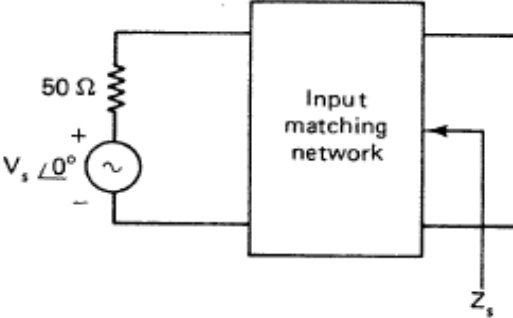


Figure 2.5 Input Impedance Matching Network

Output Impedance Mismatch:

As shown in fig 2.6, to get maximum power to the 50 ohm load, we must have $Z_L$ = $Z_0$, and the load will absorb entire reflected energy. In case, if $Z_L$ is not equal to $Z_0$, the same energy will reflect back towards source. The amount of the reflected incident energy can be determined by the degree mismatch between $Z_L$ and $Z_s$.
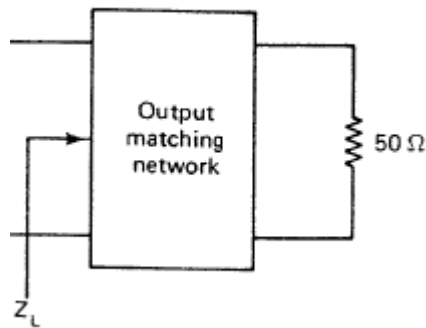


Figure 2.6   Output Impedance Matching Network

2.4 Microstrip Circuits

Miniaturized microwave circuits use stripline and microstrip lines instead of coaxial cables as transmission lines. It helps flexibility and density in design. The stripline structure consists of a flat conductor fixed in a dielectric material and inserted between two ground planes, [4] where the microstrip structure consists of the main conductor and the ground conductor separated by a dielectric material. A schematic of microstrip and stripline structure is as shown in figure 2.7(a) and figure 2.7(b).

Figure 2.7(a) Microstrip Structure [4]



Figure 2.7(b) Stripline Structure [4]

Chapter 3

DIRECTION COUPLERS AND BALUNS

3.1 Direction Coupler

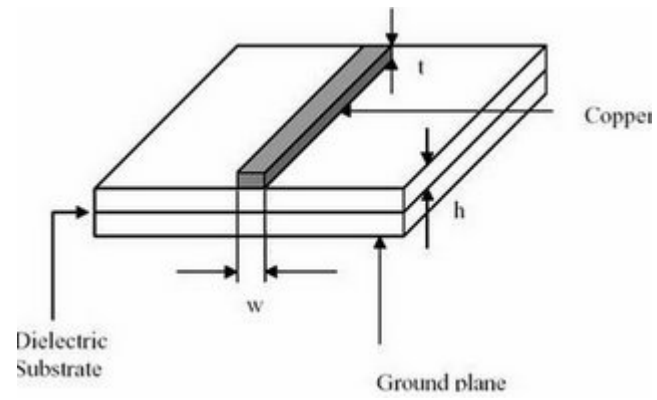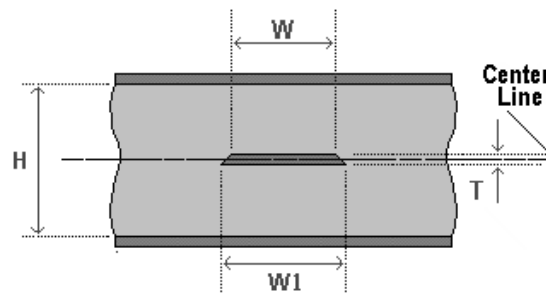There are different types of couplers. Two coupled transmission lines are used to construct a direction coupler as shown in fig 3.1. There are different types of direction couplers, for example, hybrid couplers and coupled line couplers. In my design, I have focused on coupled line couplers, since the coupled line coupler provides higher bandwidth.

The basic of directional coupler is as follows: As shown in fig 3.1, 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. [4]
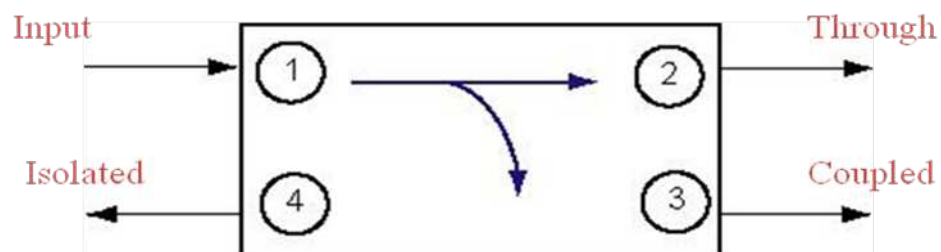


Figure 3.1 Directional Coupler [4]

A special type of directional coupler is the hybrid coupler. 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:

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

3.2 Coupled Line Couplers [4]

The coupled line couplers consist of two lines with capacitive coupling between them as shown in figure 3.2. Each line has two ports thus creating a four port device.

3.3 Design of 3 dB Directional Coupler

Consider a typical 3dB directional coupler that operates at 5 GHz, as shown in figure 3.2, with all four ports are terminated in 50-ohm loads. [5]
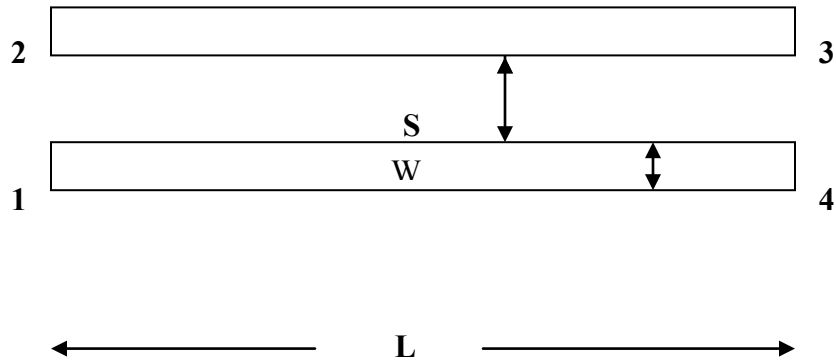


L = Line Length        S = Spacing between lines        W = Width of lines

Figure 3.2   Structure of 3dB Directional Coupler [1]

The given design parameters are:

3dB coupling

Center frequency: 5 GHz

The even mode impedance ($Z_{oe}$) and odd mode impedance ($Z_{oo}$) are calculated from the above given parameters by using the following formulae

$$Z_{0e} = Z_0 \sqrt{\frac{1+C}{1-C}}$$        even mode impedance………………… (2.6)

$$Z_{0O} = Z_0 \sqrt{\frac{1-C}{1+C}}$$        odd mode impedance…………………... (2.7)

Where, C denotes the co-efficient of coupling.

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

When Zo is 50 Ohm, $Z_{oe}$ is 119 Ohm and $Z_{oo}$ is 21 Ohm.

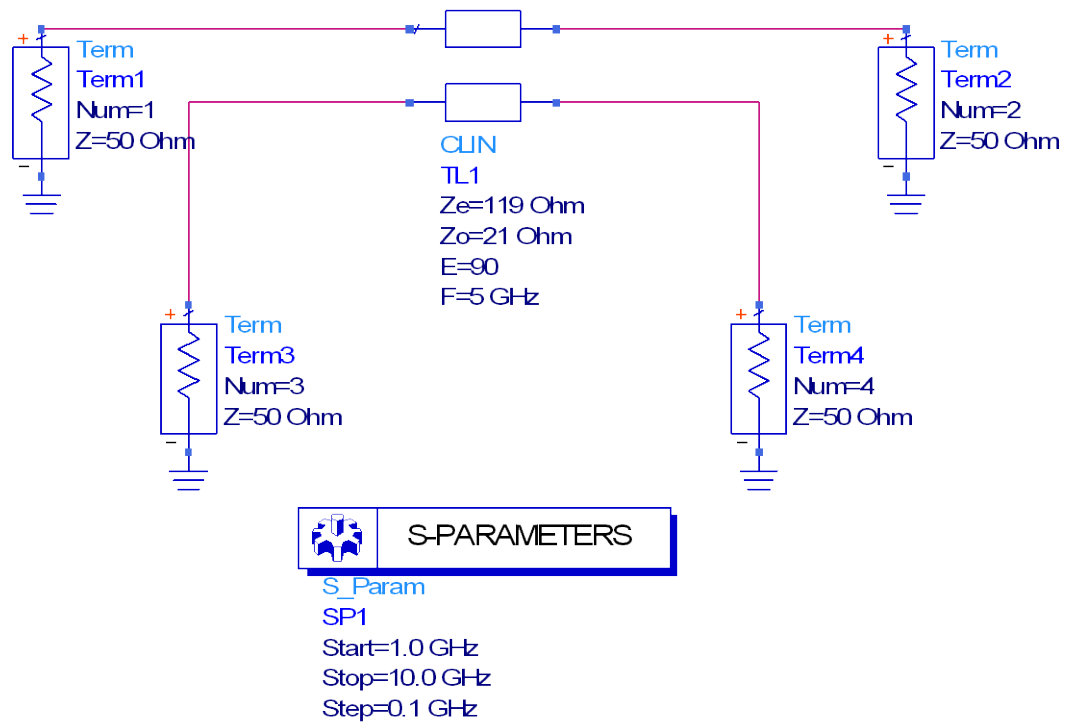

Figure 3.3    ADS Schematic of Coupled Line Design with Center Frequency of 5 GHz.
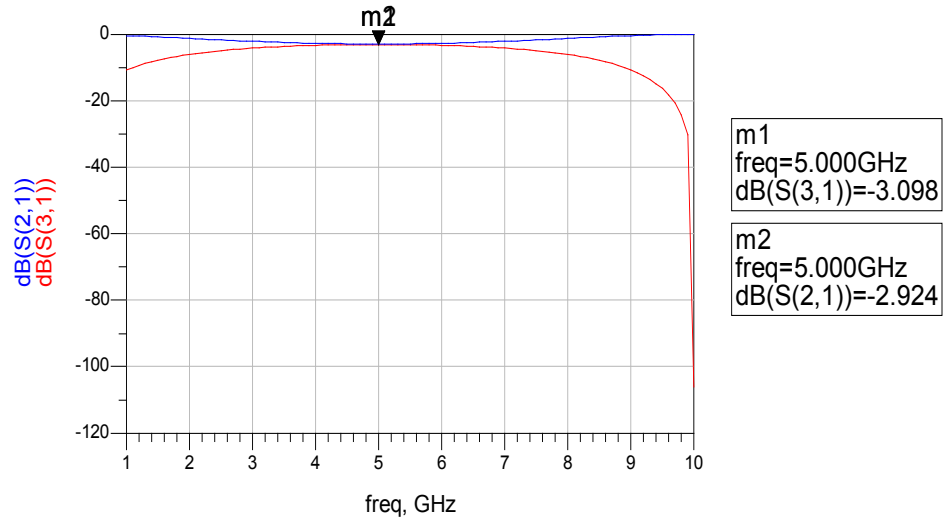
Figure 3.4 Plot of Amplitude

m3
freq=5.000GHz
phase(S(2,1))-phase(S(3,1))=-90.000

m3

-89.9999

-90.0000

-90.0001

-90.0002

-90.0003

-90.0004

-90.0005

phase(S(2,1))-phase(S(3,1))

1    2    3    4    5    6    7    8    9   10

freq, GHz

Fig 3.5 Plot of Frequency vs. Phase

m1
freq=5.000GHz
vswr(S(1,1))=1.000
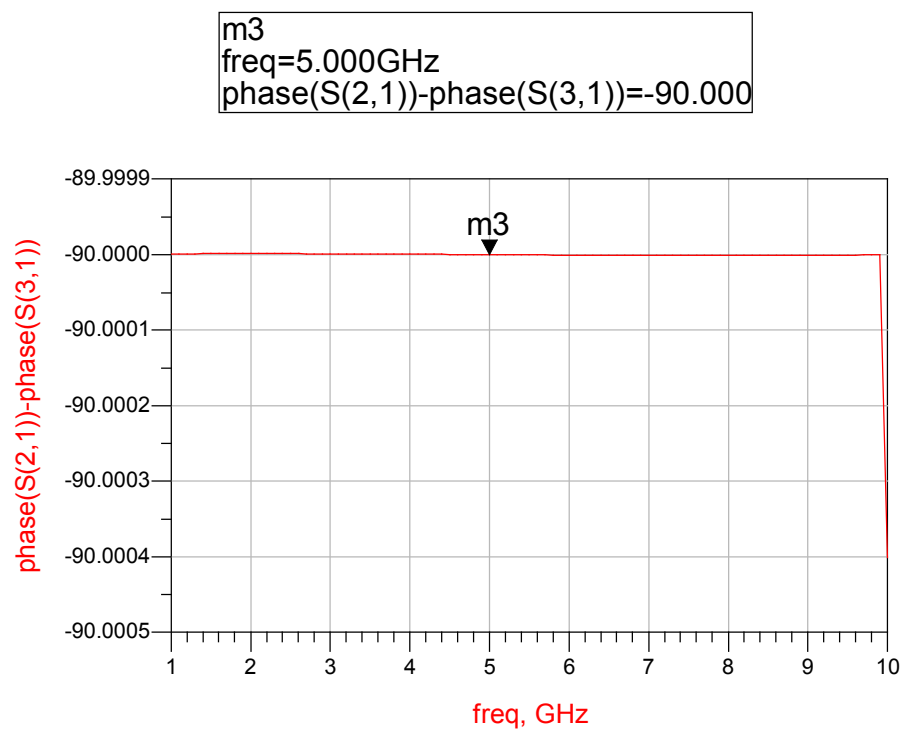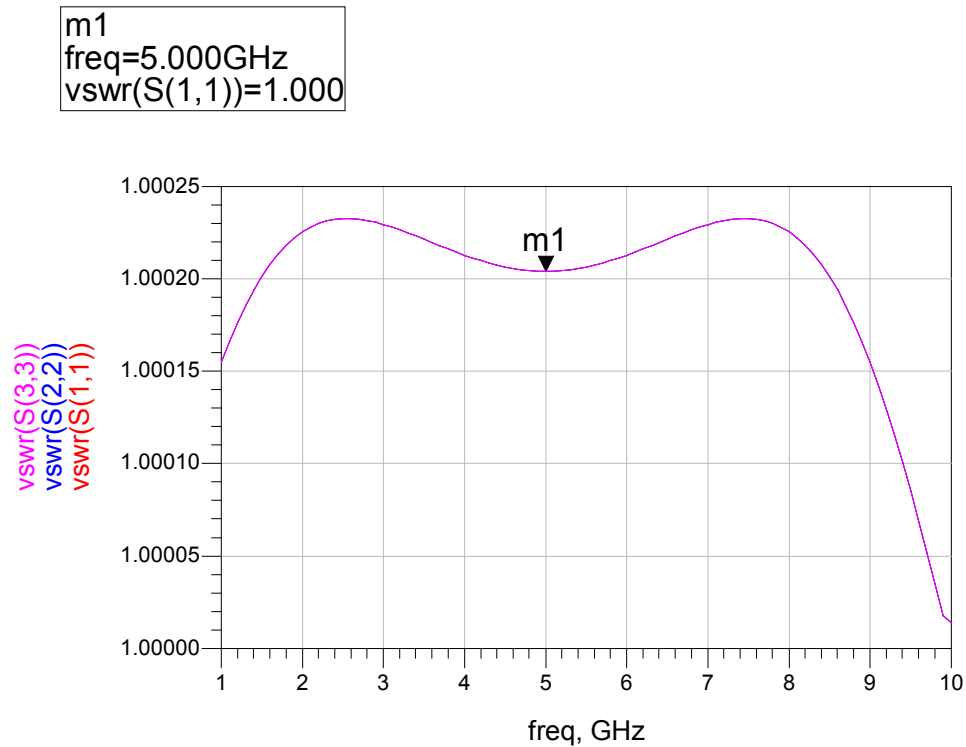


Figure 3.6 Plot of VSWR

As a sample simulation, Advanced Design System (ADS) software was used in order to get the simulated response of the circuit whose layout is shown in Figure 3.3. The simulated responses of the circuit are shown in Figures 3.4 –3.6. Figure 3.4 reflects the maximum coupling (|S21|~ -2.9) dB at the center frequency of 5 GHz, insertion loss being minimum (|S31| ~ -3) dB as shown in the figure 3.4. It shows that amplitude plot is not flat as we required in broadband range. The VSWR at a port is shown in figure 3.6

that is ideally at ~ 1 at the center frequency. Also, phase plot as shown in figure 3.5 is nice with required phase difference of 90 degrees.

3.4 Design Expectations of Balun

A balun is a passive electronic device that translates between balanced and unbalanced electrical signals and changes impedance. It can take many forms and their presence is not always obvious. They always hold some form of electromagnetic coupling. [6]

The Coupler configuration described above is simple and very useful, but the design is not sufficient for the balun requirements of equal power at both the ports with phase difference of 180. The balun requirements of equal power at both the output ports with phase difference of 180 degrees. Also, as shown in fig 3.4 and fig 3.5, $|S_{21}|$ is equal to $|S_{31}|$ for a standard coupler design. Moreover, this does not meet the requirements of the balun design for wideband wireless communication applications.

3.5. Balun Applications

A balun's function is to achieve compatibility between systems, and has wide application in modern communications. It helps in realizing frequency conversion mixers to make cellular phone and data transmission networks possible. It is used in radio, video and audio applications. They are used in for push-pull amplifier, balanced mixers and antenna feeds. [5]

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

1.  The wideband frequency range should be between 1GHz and 10GHz.

2.  The amplitude balance should be maintained at the both the output port at ~17dB in wideband frequency range.

3.  The phase balance /$S_{21}$-/$S_{31}$ should be at ~180 degrees over the band.

4.  The VSWR at input and both output is ideally at ~ 1 at the center frequency 5 GHz.

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

Chapter 4

IMPROVED MINIATURIZED WIDEBAND BALUN DESIGN AT 5 GHZ

4.1 Basic Topology of Balun Design

In the previous chapters, I have covered the concept of coupled lines and Baluns. This chapter will focus on the two Balun designs that work over a broadband range of frequency, and gives flat equal amplitude with precise 180 degrees of phase shift, which is the main goal of this project. This work is based on earlier project design of balun for wideband frequency at 8 GHz [2]. However, the earlier design did not have very flat amplitude and phase balance and had very high VSWR at the input port. The aim of the two balun designs reported in the work are centered at the operating frequency of 5 GHz with flat balanced amplitude of -17dB and phase shift of 180. This design is simpler than earlier design which helps in fabrication, and also reduces size and cost of fabrication

The central principle behind a standard balun design is the center-tapped transformer as shown in Figure 4.1 It uses the coupling element for a balanced output and taps are used for coupling of the signals to generate balun outputs [9]. In the new designs, I added a capacitor at the middle of coupled line to get equal amplitude balance and a resistor at the input port to lower VSWR, and changed the size of transmission lines to obtain phase difference of 180 degrees.
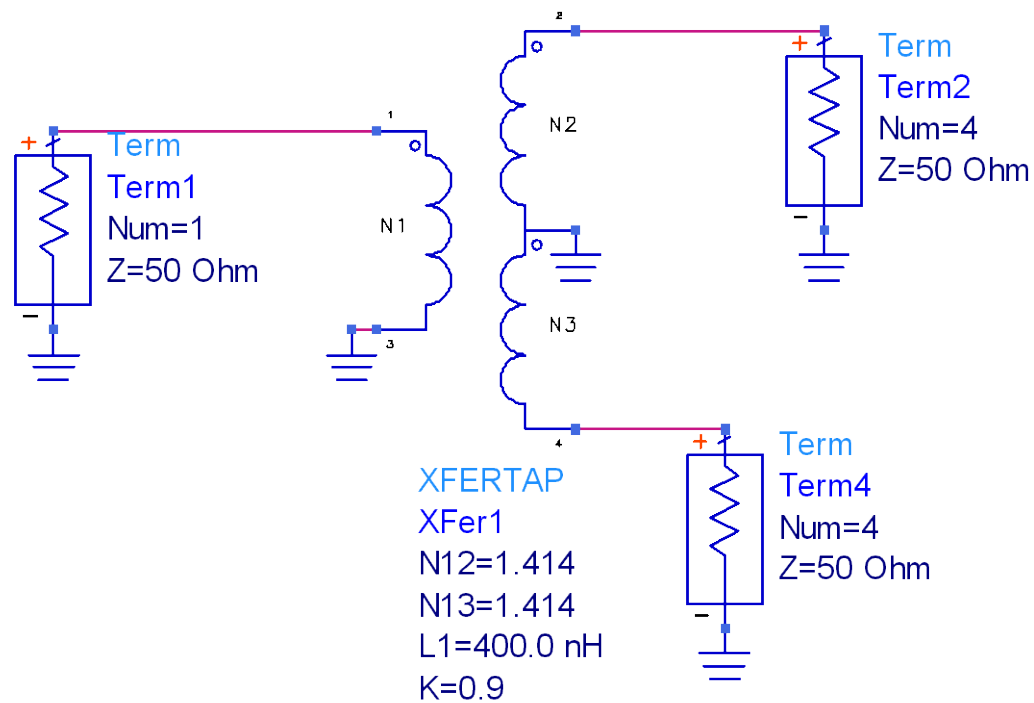
Figure 4.1: Center Tapped Transformer [9]

## 4.2 Broadband Balun Design

The final ADS schematic of the first balun circuit is shown in Figure 4.2, with current dimensions as shown in Table 4.1. It essentially consists of a six coupled line sections with center tapped capacitor at the coupled line. This design has resistor with Binomial multisection matching circuit at the input port to get equal amplitude with low VSWR but with reasonably good phase difference of 180 degrees.
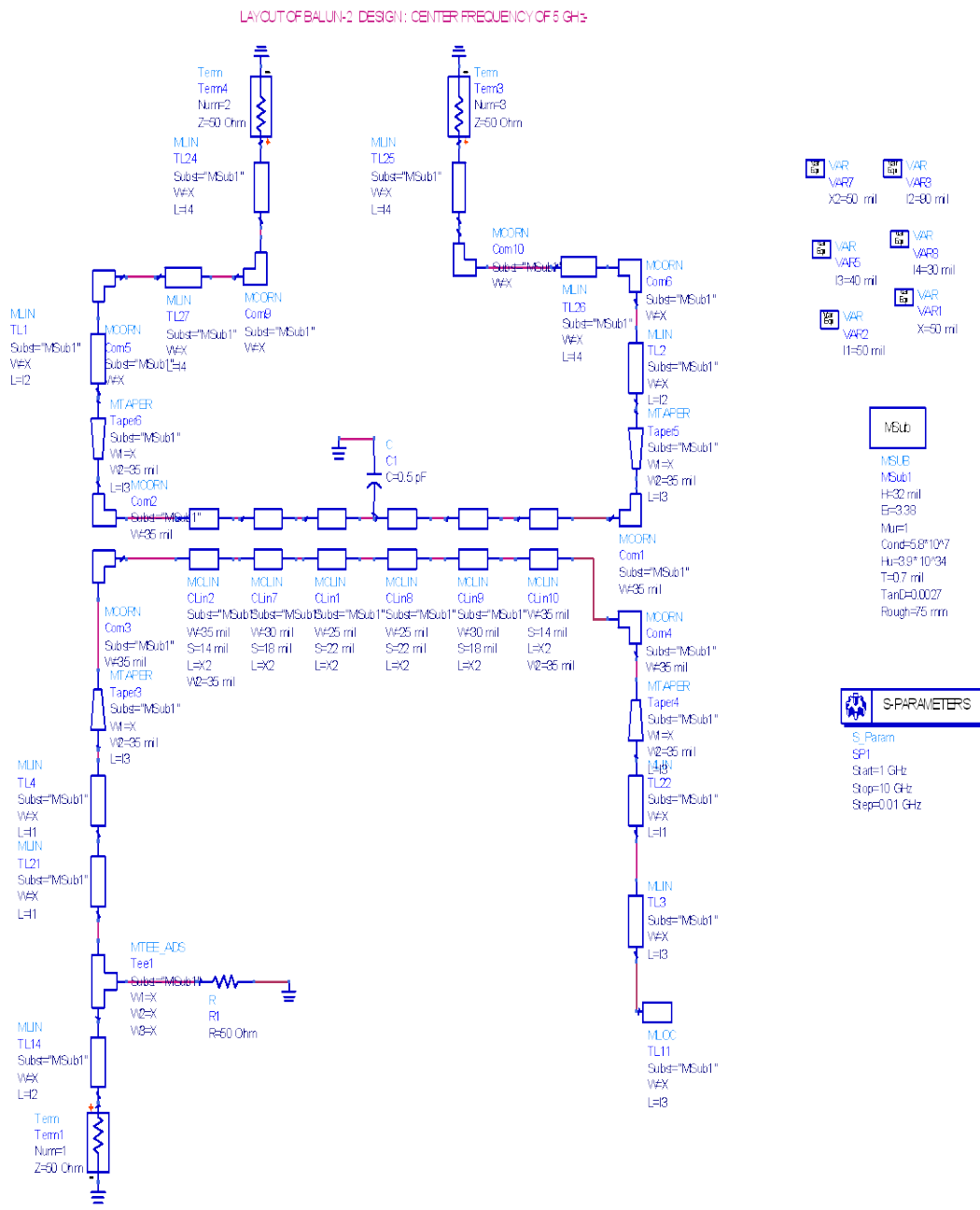
Figure 4.2: Design of Microstrip Wideband Balun

Following are the parameters of the Microstrip Balun Circuit given us to design: from left to right for coupled lined

| | |
|---|---|
| X | 50 mils |
| X2 | 50 mils |
| l1 | 50 mils |
| l2 | 90 mils |
| l3 | 40 mils |
| l4 | 30 mils |
| Taper3,4,5,6___W1 | X |
| Taper3,4,5,6___W2 | 35 mils |
| Taper3,4,5,6___L | l3 |
| Corn1,2,3,4___W | 35 mils |
| Corn5,6,9,10___W | X |
| TL1,2___W | X |
| TL1,2___L | l2 |
| TL24,25,26,27___W | X |
| TL24,25,26,27___L | l4 |
| TL4,21,22___W | X |
| TL4,21,22___L | l1 |

| | |
|---|---|
| TL3,11___W | X |
| TL3,11___L | l3 |
| TL14___W | X |
| TL14___L | l2 |
| Tee1___W1,W2,W3 | X |
| CLin2,10___W | 35 mils |
| CLin2,10___S | 14 mils |
| CLin1,2,7,8,9,10___L | X2 |
| CLin7,9___W | 30 mils |
| CLin7,9___S | 18 mils |
| CLin1,8___W | 25 mils |
| CLin1,8___S | 22 mils |
| R1 | 50 ohm |
| C1 | 0.5 pF |

Table 4.1 Dimension of the Microstrip Balun Circuit

There is a trade-off between amplitude, phase and VSWR. In the previous design the students achieved equal amplitude with high VSWR and not precise phase balance. When I started improving this Microstrip Balun Circuit, first I built Binomial multisection matching circuit at the input to get wide bandwidth and flat curve. In order to get stable phase balance, I put a capacitor at the middle of coupled line. It was easy to

get low VSWR for outputs by tuning the length and width of transmission lines at the

output, input, terminal four and coupled lines. But the low VSWR at input was hard to

get under the goal of this project. After a trade-off between amplitude, phase and VSWR,

I decided to put a 50 ohm resister at the input to decrease the VSWR.

Chapter 5

SIMULATION STUDY OF BALUN DESIGN

The simulated results of wideband balun design are shown in Figures 5.1 to 5.6. The design and simulations were run in Advanced Design System (ADS). The optimized results are shown in the figure after designing several different circuit using different components.

5.1 Simulation Results of Balun Design

This section gives the simulated results for balun design. The amplitude balance, phase response and VSWR of design are shown in figures 5.1 to 5.3. Figure 5.1 shows amplitude balance at both output ports.
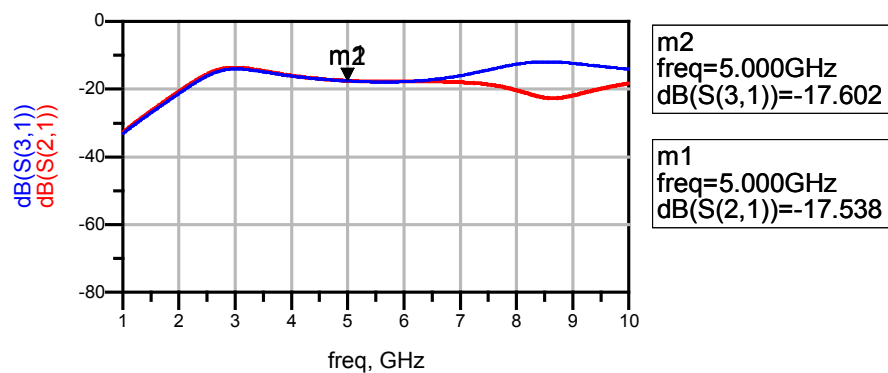
Figure 5.1: Plot of Frequency vs. Amplitude

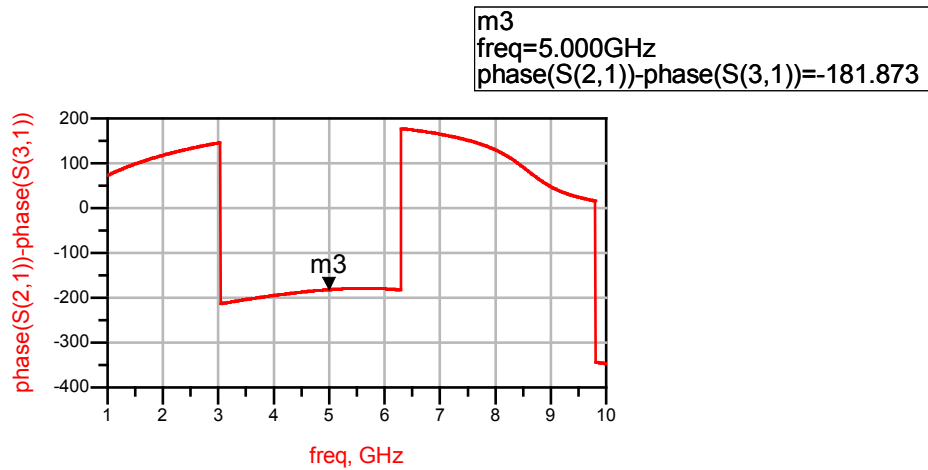Figure 5.2 shows phase balance at the two output ports.



Figure 5.2: Plot of Frequency vs. Phase

Figure 5.3 shows the VSWR at the input ports (vswr(S (1, 1)) and output ports (vswr(S (2, 2)) and vswr(S (3, 3))). While the VSWR at the two output ports is ~1.3. The input VSWR is 1.426. The curve for input VSWR which needs to be improved is not as flat as I want.

m4
freq=5.000GHz
vswr(S(3,3))=1.368

m5
freq=5.000GHz
vswr(S(1,1))=1.426

m6
freq=5.000GHz
vswr(S(2,2))=1.366

vswr(S(3,3))
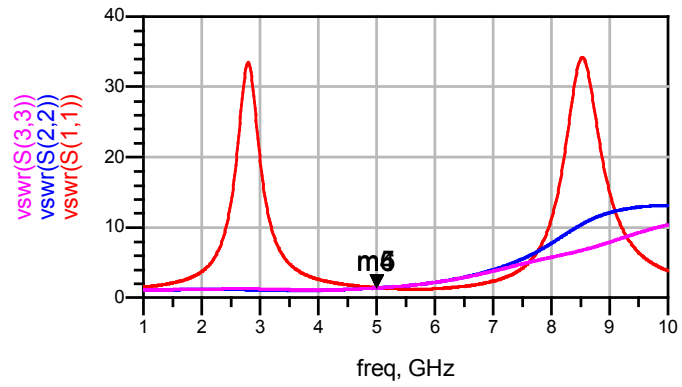vswr(S(2,2))
vswr(S(1,1))

m6
m5

freq, GHz

Figure 5.3 Plot of Frequency vs. VSWR

Chapter 6

DESIGN LAYOUT OF WIDEBAND BALUN CIRCUIT IN ADS

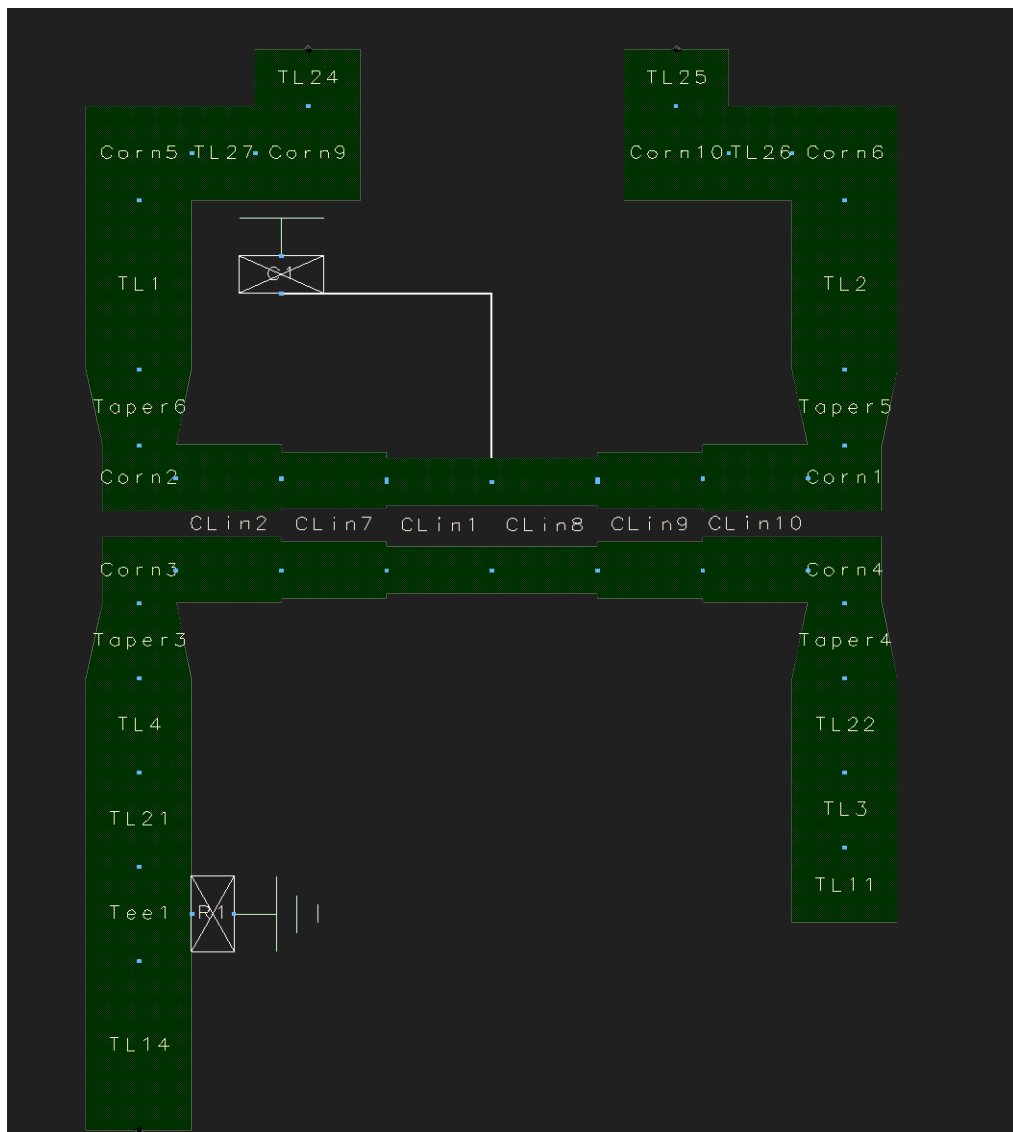The wideband balun circuit laid out in ADS is as shown:



Figure 6.1 Layout of Wideband Balun Circuit

Chapter 7

FABRICATION OF BALUN CIRCUIT  IN ISOPRO T-TECH

I exported the layout file as a Gerber file which is generated in the project

directory.



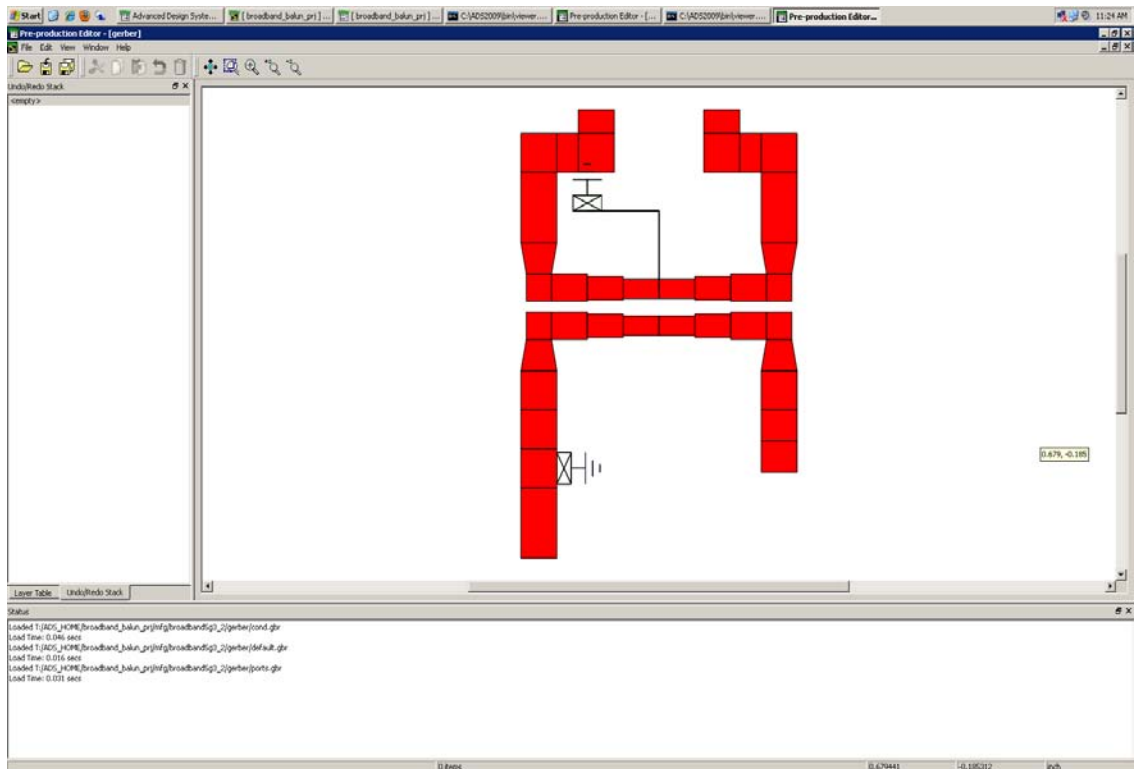Figure 7.1 Layout of Wideband Balun Circuit in the Gerger file

Then I used Isoro 2.7 T-TECH to import gerber file. The first step was to isolate

the traces of the balun design. The green layer around the blue traces is the new isolation

layer. The second step was to create a contour, the outer boundary of the pc board. Then I

created tabs in the contour to help the board stay in place while the board was being

routed The third step was to perform a rubout for the excess areas. The red layer is the areas where I wanted to do the rubout as is shown in Figure 7.2.

The wideband balun circuit is shown in IsoPro 2.7 as follows:
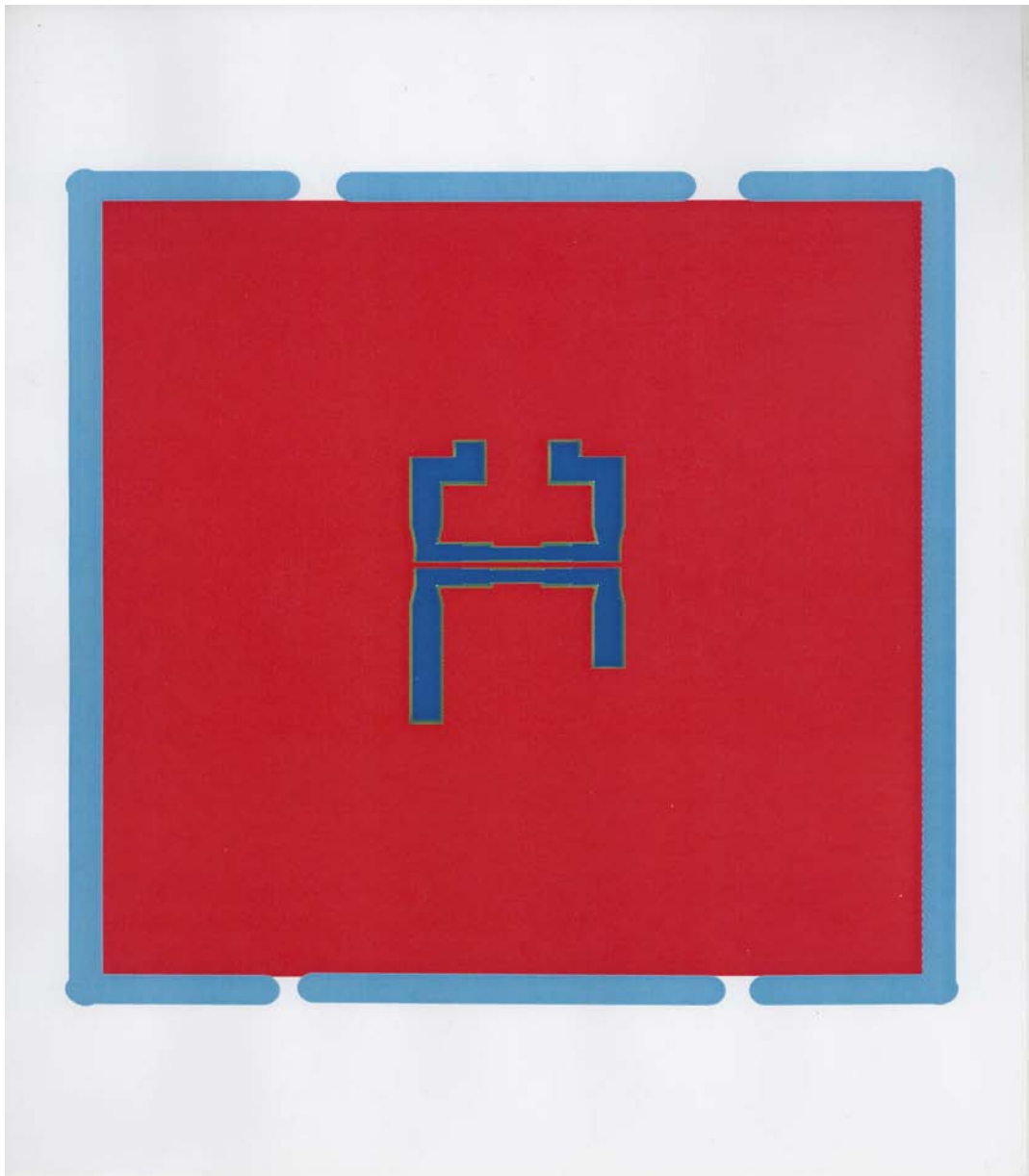


Figure 7.2 Layout of Wideband Balun without Capacitor and Resistor

Next I was ready to route my pc board. After I turned on the T-Tech machine, the first step was to route the isolation layer and then rubout layer. The second step was to run contour layer and broke the taps by using a chisel. Then I got my wideband Balun circuit without soldering capacitor and resistor as is shown in Figure 7.3.
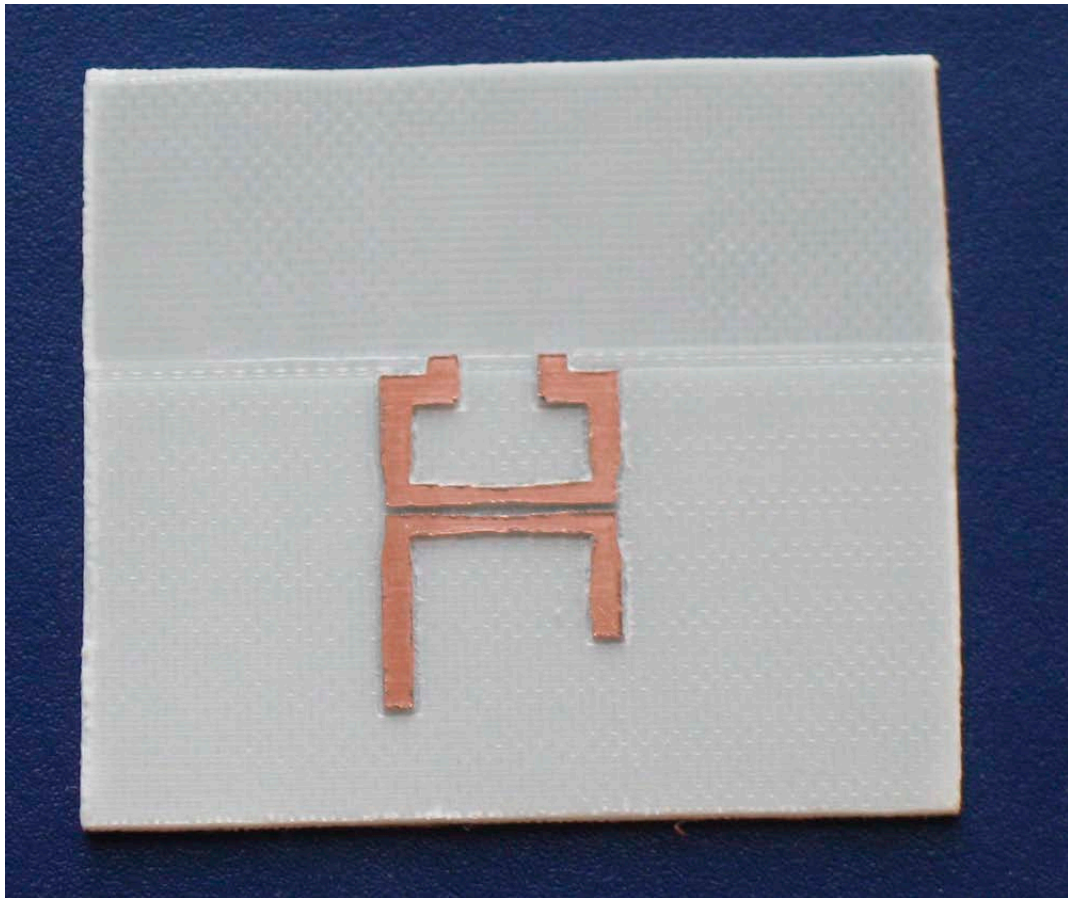


Figure 7.3 Wideband Balun Circuit without Soldering Capacitor and Resistor.

We can see that the copper is on the top and dielectric substrate under it. When I fabricated my wideband microstrip balun circuit I chose RT/DUROID microwave laminates RO4003 as the following:

|  | 5870 | 6002 | 6006 | RO 4003 | RO 4003 QLAM |
|---|---|---|---|---|---|
| Dielectric Constant $\varepsilon_r$ | 2.33 | 2.94 | 6.15 | 3.38 | 3.38 |
| $M_{ur}$ | 1 | 1 | 1 | 1 | 1 |
| Dielectric Thickness H (mils) | 20 | 50 | 50 | 32 | 16 |
| $H_u$ | $3.9*10^{34}$ | $3.9*10^{34}$ | $3.9*10^{34}$ | $3.9*10^{34}$ | $3.9*10^{34}$ |
| Conductivity | $5.8*10^7$ | $5.8*10^7$ | $5.8*10^7$ | $5.8*10^7$ | $5.8*10^7$ |
| TanD | 0.0012 | 0.0012 | 0.0027 | 0.0027 | 0.0027 |
| Rough RMS (mm) | 115 (3) | 95 (2.4) | 95 (2.4) | 75 (1.9) | 95 (2.4) |

Table 7.1 Specifications of RT/DUROID Microwave Laminates

Chapter 8

CONCLUSIONS

This report is focused on an improved miniaturized wideband microstrip Balun designed at the center frequency of 5GHz with bandwidth range of 1-10GHz. There is one resistor at the input to achieve lower VSWR and both output ports are ideally at ~1 around the center frequency. One capacitor was put in the middle of coupled line to get phase balance of around 180 degrees at the output ports. Binomial multisection matching circuit at the input port was used to enable wide bandwidth. The size of microstrip transmission lines were also changed in order to get equal amplitude at two output ports.

This design was based mostly on the coupled line coupler design. However, fundamental changes were required in order to obtain the specified balun characteristics of equal amplitude at the two output ports with a phase difference of exactly 180 degrees over the specified working bandwidth. The simulation results showed that both balun designs maintained a roughly flat equal amplitude balance of ~17dB at the two output ports, with a phase difference of ~181 degrees over the frequency range of 1-10 GHz. The VSWR at the two output ports and input port are significant lower around 1. In order to get the above simulation results, there were some trade-offs among amplitude, phase and VSWR. In addition, I had to make sure that the widths between the two transmission lines were matched except for the coupled lines.

Future work that I will need to do is to put three SMA connectors at one input port and two output parts and solder the capacitor and resistor on the wideband microstrip balun circuit; and then test on the network analyzer to validate the design.

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