VERIFICATION, FABRICATION AND TESTING OF EVEN ORDER BROADBAND MICROSTRIP BALUN CIRCUITS AT 5 GHZ FOR WIRELESS APPLICATIONS

A Project

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by

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Rajat Dhama

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by

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___________________________, Graduate Coordinator ________________
Dr. Preetham B. Kumar Date

Department of Electrical and Electronic Engineering

Abstract

of

VERIFICATION, FABRICATION AND TESTING OF EVEN ORDER BROADBAND MICROSTRIP BALUN CIRCUITS AT 5 GHZ FOR WIRELESS APPLICATIONS

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The objective of this project is a follow-on from earlier work to design and simulate broadband Microstrip Balun circuit at a center frequency of 5 GHz while meeting the specifications for wideband wireless applications. The design of these even order broadband multi-section balun couplers was based on fundamental multi-section theory. Specifically, this project focuses on the verification of the developed designs, fabrication and experimental testing of their microwave properties. The designed circuits were fabricated over microstrip substrate and the characteristic values of the fabricated circuit were measured and compared with the simulated values to verify the specifications of fabricated circuit.

_______________________________, Committee Chair
Dr. Preetham B. Kumar

____
Date

ACKNOWLEDGEMENTS

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True salutations to the Department of Electrical and Electronics Engineering for providing the technical resources and approving us to work on this project. We are thankful to the Office of Graduate Studies to provide us the guidelines for organizing the project plan.

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1. INTRODUCTION

A balun is a form of transformer that converts an ubalanced signal to a balanced signal. The unbalanced, or "single-ended" signal can be microstrip or stripline, the key characteristic is that one of the two conductors is clearly grounded. In a balanced signal, both conductors are equally "hot" with voltage, in reality there is always a true ground somewhere outside of the balun structure, so you almost have to think of it as three conductors [1]. In the structure of a balun, one pair of terminals is balanced, that is, the currents are equal in magnitude but opposite in phase. The other pair of terminals is unbalanced, one side is connected to electrical ground and other carries the signal [2].

1.1 Applications of Balun circuits

- Radio and Television: In television, amateur radio and other antenna installations and connections, to convert between impedances and symmetry feedlines and antennae [3].
- Video transmission: A balun can be used to couple video signals to a twisted-pair cables instead of using coaxial cable. A balun is also used on the video recorder end to convert from the 100 Ω to 75 Ω balanced [3].
- Audio Transmission: In audio applications, baluns convert high impedance unbalanced and low impedance balanced lines. Another application is decoupling of devices (avoidance of earth loops) [3].
- Power Line communications: Baluns are used in coupling signals onto a power line [3].

1.2 Basic structure of Balun circuit

A lumped LC balun is realized using lumped components, two inductors and two capacitors shown in Fig.1. It is also called “lattice type” LC balun. Though a lumped LC balun using discrete components on PCBs is very popular low cost solution for narrow band application, still it had appeared on some RFICs [4].

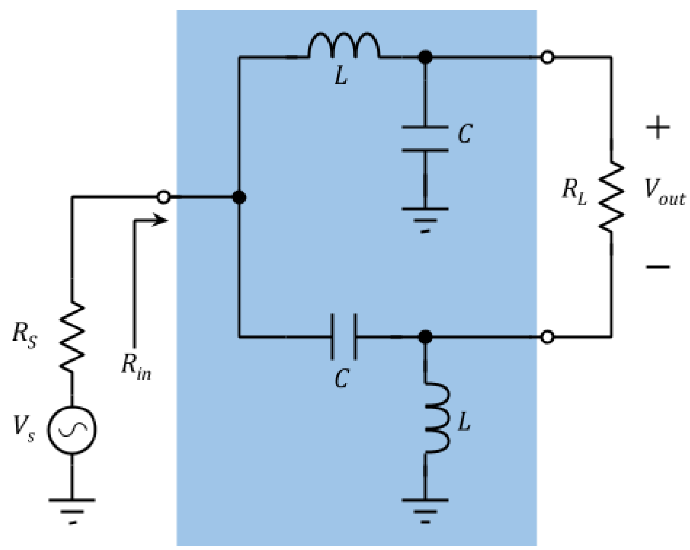

Figure 1. Lumped LC balun circuit

There are many different types of baluns – the different designs that have been developed generally depend on:

- The bandwidth required
- The operating frequency

- The physical architecture of the network (what types of components connected and what configuration) [5].

The objective of the project is to design a 2-section and 4-section balun network on a micro-strip circuit with a center frequency of 5 GHz and bandwidth of ±50% of center frequency.

- The students, who were working on this project earlier had utilized the concepts from micro-strip theory to design the equations for 2, 4 and 6 element multi- section couplers.
- The structural even and odd mode impedances were obtained in the previous steps will be implemented into micro-strip dimensions using the Linecalc tool on the Advance Design System (ADS) software.
- In this part of the project, we will use the dimensions provided from the ADS software and fabricate the design of 2-section as well as 4-section on PCB.
- After the circuits are fabricated, we will tabulate and compare the theoretical and practical values so that we can validate the design.

1.3 Organization of project report

Chapter 1: It gives a brief outline of the project specifications.

Chapter 2: It explains the fundamental theory of micro-strip lines and its role in the fabrication of 2-element and 4-element balun circuits. It will also outline the different types of components used in fabricating the balun circuits and increasing their efficiency.

Chapter 3: It describes the design specifications of the new balun circuits which were evolved from the basic multi-section coupler of network. It will explain the steps involved in the design and simulation of 2-element and 4-element balun couplers using the Line-Calc tool of Advance Design System (ADS).

Chapter 4: This part is concerned with the fabrication of the balun circuit using microstrip line technology. We will also generate the layout of the balun and carry out the proper validation process.

Chapter 5: Finally, we will measure the fabricated design of the balun circuit using VNA and we will also compare the simulated and the actual values for the circuits to draw a conclusion based on that.

Chapter 6: We will be drawing conclusion based on the comparison between the simulation and actual results.

Chapter 7: We enlist the references of the resources that we used to gain the information about the project.

2. FUNDAMENTALS OF MICROSTRIP BALUN COUPLERS

Microstrip is a planar transmission line, similar to stripline and coplanar waveguide. It was developed as a competition to stripline because the fat substrates in striplines allowed non-Transverse mode (TEM) waves to propagate which made the results unpredictable. Microstrip transmission line consist of conductive strip of width “W” and thickness “t” and a wider ground plane, separated by a dielectric layer of thickness “H” as shown in the figure below [6].

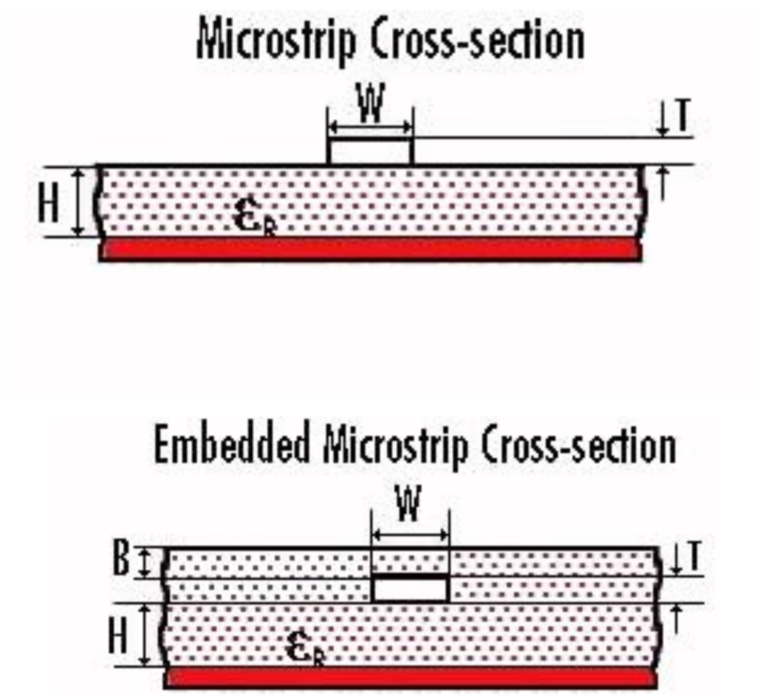

Figure 2. Cross section of microstrip line

Microstrip is by far the most popular microwave transmission line, especially for microwave integrated circuits and Monolithic Integrted Microwave Circuit (MMIC). The major advantage of microstrip over stripline is that all active components can be mounted on top of the board. The disadvantages are that when high isolation is required such as a filter or switch, some external shielding may have to be considered. Given the chance, microstrips can radiate, causing unintended circuit response [6].

A minor issue with microstrip is that it is dispersive, meaning that signals of different frequencies travel at slightly different speeds. Microstrip does not support TEM mode, because of its filling factor. For couple lines, the even and odd modes will not have the same phase velocity. This property causes the asymmetric frequency of microstrip bandpass filters.

2.1 Properties of Microwave Balun circuits

A balun is three port power-splitter, similar to a Wilkinson or resistive power divider. The two outputs will be equal and opposite, this means the outputs have a 180° phase shift in frequency domain. The unbalanced input is matched to the input transmission line impedance. Unlike an isolator or circulator, a balun is a reciprocal device that can be used bi-directionally [7].

The term balun is a portmanteau of balanced and unbalanced, indicating that a balun will transition between a balanced transmission line and an unbalanced transmission line. A balun has equal power outputs just like a Wilkinson power divider, resistive power divider, or quadrature hybrid coupler. However, it has a 180° phase difference between outputs, unlike power-dividers and quad hybrids [7].

The most common application of baluns is to interface an unbalanced signal to a balanced transmission line for long distance communications. Differential signaling on balanced transmission lines is more immune to noise and crosstalk, can use lower voltages, and is lower cost than single-ended signaling on coaxial cables. Hence, it is used for most common intermediate and long distance transmission lines such as RS-422, RS-485, Ethernet over twisted pair, PCI Express, DisplayPort, HDMI, and USB. Therefore, baluns are used to interface local video, audio, and digital signals to long distance transmission lines [7].

The second most important application of baluns is for driving differential antennas. Another extremely high volume application is the use of baluns to create balanced devices such as push-pull amplifiers and balanced mixers [7].

2.2 Fundamentals of Balun design

There are different types of Balun designs: Lumped L-C Baluns, distributed transmission line and Microstrip designs, however Microstrip design is the main focus for this project. There is a wide range of printed Microstrip Balun topologies which have the advantage of being inexpensive, realized as they are on the Printed Circuit board (PCB) or Microwave Integrated Circuit (MIC) substrate. An example of a simple coupled line Balun is shown below in Figure 3, while Figure 4 shows a coupled line Balun with broadside coupler structure [8].

Figure 3. Simple Coupled Line Balun [10]

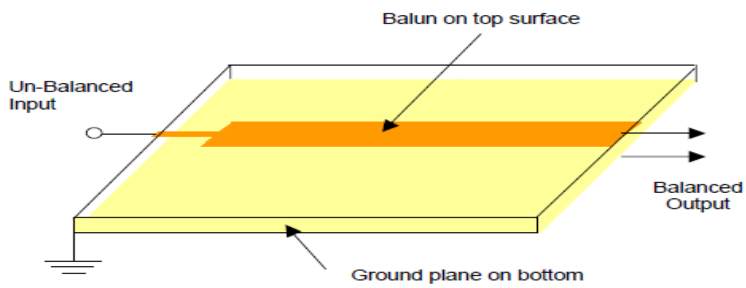

Figure 4. Simple Coupled Line Balun, Using Broadside Coupler Structure [10]

2.3 Advantages of using Microstrip line

Microstrip line is low in cost, lighter and compact compare to waveguide technology. Microstrip is widely used microwave transmission line, exclusively for Microwave Monolithic Integrated Circuits (MMICs) [9]. The major benefit of microstrip above stripline is that, on top of the board you can mount all active components. Specific reasons why microstrip lines are used in the final designs are as follows:

- Microstrip lines can be easily fabricated and accommodated using the latest PCB routing or chemical etching techniques which can produce circuits in bulk. Hence, network interconnections can be easily accommodated on the surface.
- It is considered as the most convenient form of transmission line structure for obtaining reliable voltage, current and other RF Circuit Parameters.
- Microstrip lines can be easily used in integrated semiconductor form with interconnections done to microwave integrated circuits [9].

3. DESIGN AND SIMULATION VERIFICATION OF MULTI-SECTION BALUN COUPLER DESIGNS

This chapter details the theoretical and software verification of the microstrip balun transmission properties. These 2 section and 4 section balun circuits were developed and designed in two earlier project reports [13,14], and based on initial groundwork completed in other projects [10,11,12].

3.1 Design specification verification

The requirements for the desired Balun characteristics are as follows:

- The wideband frequency range should be between 2.5 GHz – 7.5 GHz, with a center frequency of ~ 5 GHz.
- The amplitude balance should be maintained between 10 to 20 dB at both the output ports in wideband frequency range.
- The phase balance should be maintained at ~180 degrees over the wideband frequency range.
- The design should be completely distributed, built in Microstrip material without any lumped elements to be soldered on to the circuit.
- The Balun design should be very small in size, in the range of approximately 200-300 mils or ~ a quarter inch, to conform to wireless device applications.

In order to obtain the above specifications for the Balun, we derived the theoretical design equations of the even order Balun, and then proceeded to the Microstrip structure [11].

3.2 Theoretical Analysis Verification of 2 and 4 section couplers

As reported in the earlier project [12], the standard design procedure required to obtain the final Microstrip Balun design is a multi-section approach, which is represented by Figure 5 below.

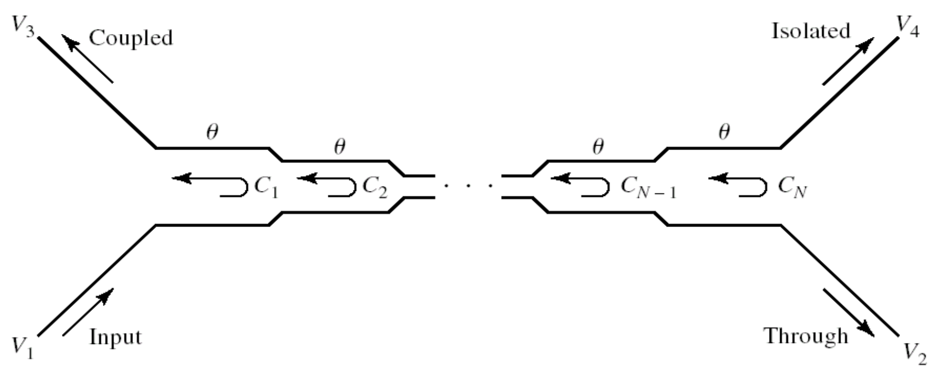

Figure 5. N-Section Coupled Line Coupler [7]

Coupling equation for even order coupler*:*

V_3 = jV_1 $\sin\theta e^{-j\theta}$ [C_1(1+$e^{-2j(N-1)\theta}$) + $C_2(e^{-2j\theta} + e^{-2j(N-2)\theta})$ + …+ C_M]

= 2 jV_1 $\sin\theta e^{-jN\theta}[C_1\cos(N-1)\theta$ + $C_2\cos(N-3)\theta$ +….+ C_M]

Where $C_M = \frac{N}{2}$ (1)

3.2.1 Calculation

The default Microstrip dimensions are calculated by using standard procedure as detailed below [15]. The example shown below is the theoretical approach; however modern tools like LINECALC can be utilized to obtain the impedances of the coupled lines in the multi-section structure.

- *Coupling coefficients of 2-section coupler:*

At the coupler center frequency, the coupling ratio

C = C_0 = $2\sin(\theta)[C_1 \cos(N-1)\,\theta]$

and assuming the following parameters:

N=2, $\theta = \pi/3$ and C_0 = -10 dB or a magnitude of $10^{-10/20}$ = 0.3162

we obtain **C_1 = 0.365**

Calculating above value in dB,

C_1 = 20*log(0.365) = **-8.75 dB**

- *Coupling coefficients of 4-section coupler:*

Therefore, at the coupler center frequency, we have:

C_0 = $2\sin(\theta)[C_1 \cos(N-1)\,\theta + C_2\cos(N-3)\theta]$ ---------> (2)

For 4-coupler we will consider,

N=4, $\theta = \pi/6$ and C_0 = -10 dB or a magnitude of $10^{-10/20}$ = 0.3162

After solving above equation for $\theta = \frac{\pi}{6}$, we obtain:

C_1 = 0.1217

C_2 = 0.3651

Calculating above values in dB,

C_1 = 20*log(0.1217) = **-18.3 dB**

C_2 = 20*log(0.3651) = **-8.75 dB**

3.2.2 Calculation of even and odd mode impedance

Equation for calculating even and odd mode impedances for a coupler are as follows:

$$Even - Mode\ Impedance, \qquad Zoe = \left(\sqrt{\frac{1+C}{1-C}}\right) * Zo$$

$$Odd - Mode\ Impedance, \qquad Zoo = \left(\sqrt{\frac{1-C}{1+C}}\right) * Zo$$

A good sanity check for the even and odd mode impedance calculations is the following:

Rule of thumb: Zoe > Zo, and Zoo < Zo

3.2.2.1 Even and Odd mode impedance for 2 section BALUN coupler

$$Even - Mode\ Impedance, \qquad Zoe = \left(\sqrt{\frac{1+0.365}{1-0.365}}\right) * 50 = \mathbf{73.31\ \Omega}$$

$$Odd - Mode\ Impedance, \qquad Zoo = \left(\sqrt{\frac{1-0.365}{1+0.365}}\right) * 50 = \mathbf{34.10\ \Omega}$$

3.2.2.2 Even and Odd mode impedance for 4 section BALUN coupler

- For coupled sections C1 and C4

$$Even - Mode\ Impedance, \qquad Zoe = \left(\sqrt{\frac{1+0.365}{1-0.365}}\right) * 50 = \mathbf{73.31\ \Omega}$$

$$Odd - Mode\ Impedance, \qquad Zoo = \left(\sqrt{\frac{1-0.365}{1+0.365}}\right) * 50 = \mathbf{34.10\ \Omega}$$

- For coupled sections C2 and C3

$$Even - Mode\ Impedance, \qquad Zoe = \left(\sqrt{\frac{1+0.1217}{1-0.1217}}\right) * 50 = \mathbf{56.51\ \Omega}$$

$$Odd - Mode\ Impedance, \qquad Zoo = \left(\sqrt{\frac{1-0.1217}{1+0.1217}}\right) * 50 = \mathbf{44.24\ \Omega}$$

3.3 Design verification of 2 and 4 section multi-section couplers

The prerequisite to design the BALUN coupler circuit over the Microstrip line was to research the properties of the laminate materials available in the lab. After carefully studying the properties of all the available materials we decided to use and Rogers 4003C (RO4003C) substrate for our design and fabrication.

The information above can be found at the Rogers Corp. website (http://www.rogerscorp.com/) under their “Products” tab. Within the website one can find various links to the various substrate materials that Rogers fabricates.

The important properties considered for choosing the best possible available substrate material were:

Property	RO4003C
Dielectric Constant (ε_r)	3.550
Substrate Thickness (in)	0.032
Cladding Thickness (µm)	35.000
Dissipation Factor (tan δ)	0.0027
Surface Roughness, Electrodeposited (µm)	3.200

Table 1. Properties of RO4003C substrate material

3.3.1 Line-Calc to synthesize coupled Microstrip Line

Once all the required substrate properties were extracted from the laminate data sheet, the substrate parameters along with the desired electrical properties of coupled lines calculated in previous chapter were punched into the Line-Calc tool available in ADS to synthesize the physical properties of coupled lines which serves as basic building blocks of final BALUN coupler design viz. Width (W), Spacing (S) and Length (L)

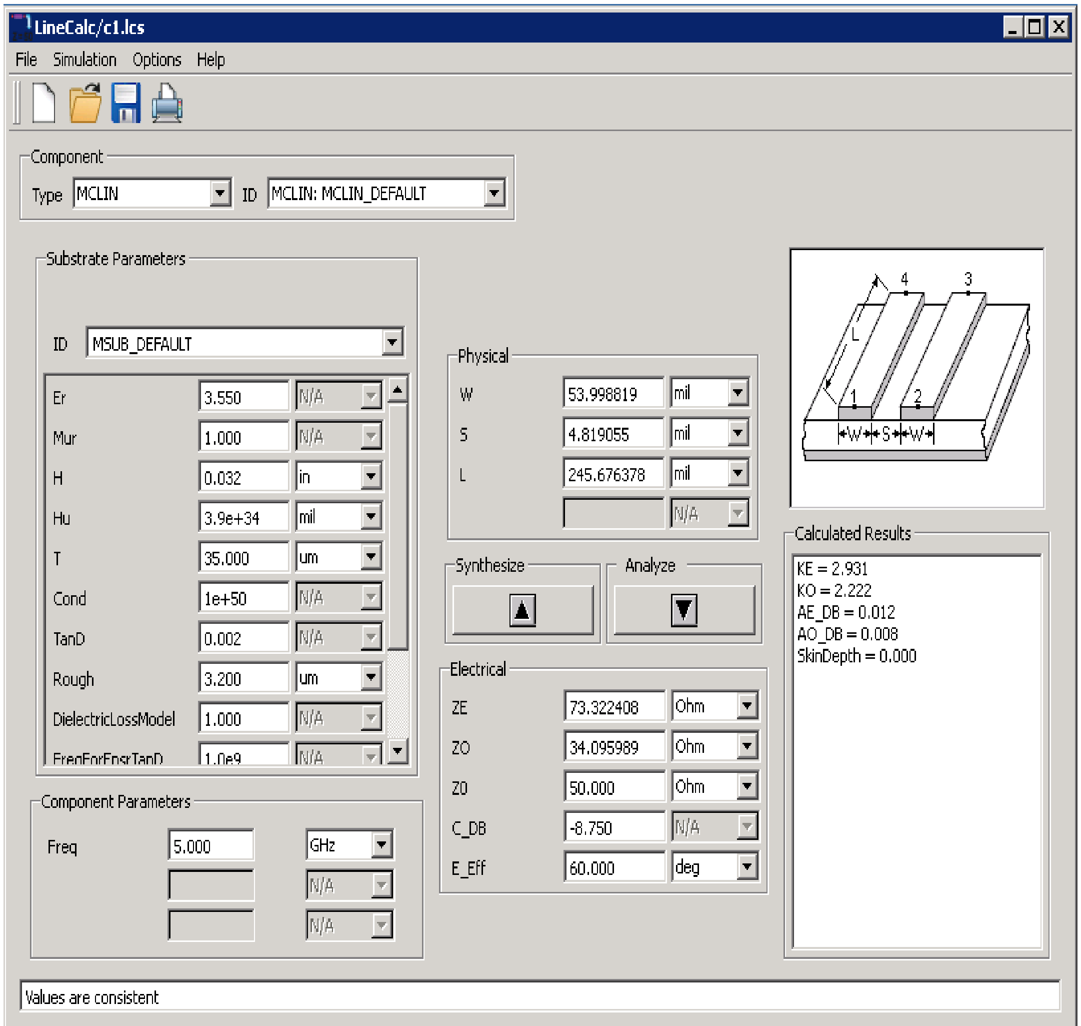

Figure 6. ADS Line-Calc tool

The physical properties of the coupled microstrip lines for individual 2 and 4 section designs were synthesized using Line-Calc and the results are displayed below-

```
LineCalc (*) 430.shp Dec  3 2014


Tue Nov 15 21:21:19 2016

Element type: MCLIN
Element ID: MCLIN_DEFAULT

Units
   Freq = GHz
   Length = mil
   Res = Ohm
   Angle = deg

Frequency = 5.000

Shared Parameters:
   Substrate: MSUB = MSUB_DEFAULT
      Er = 3.550
      Mur = 1.000
      H = 0.032 in
      Hu = 3.9e+34 mil
      T = 35.000 um
      Cond = 1e+50
      TanD = 0.002
      Rough = 3.200 um
      DielectricLossModel = 1.000
      FreqForEpsrTanD = 1.0e9
      LowFreqForTanD = 1.0e3
      HighFreqForTanD = 1.0e12

Physical Parameters
   W = 53.998 mil
   S = 4.819 mil
   L = 245.676 mil

Electrical Parameters
   ZE = 73.322 Ohm
   ZO = 34.095 Ohm
   Z0 = 50.000 Ohm
   C_DB = -8.750
   E_Eff = 60.000 deg

Result Parameters
   KE = 2.931
   KO = 2.222
   AE_DB = 0.012
   AO_DB = 0.008
   SkinDepth = 0.000 mil
```

Figure 7. Physical parameters of coupled lines (C1 and C2) for 2-section BALUN coupler

LineCalc (*) 430.shp Dec 3 2014

Tue Nov 15 21:49:24 2016

Element type: MCLIN
Element ID: MCLIN_DEFAULT

Units
  Freq = GHz
  Length = mil
  Res = Ohm
  Angle = deg

Frequency = 5.000

Shared Parameters:
  Substrate: MSUB = MSUB_DEFAULT
    Er = 3.550
    Mur = 1.000
    H = 0.032 in
    Hu = 3.9e+34 mil
    T = 35.000 um
    Cond = 1e+50
    TanD = 0.002
    Rough = 3.200 um
    DielectricLossModel = 1.000
    FreqForEpsrTanD = 1.0e9
    LowFreqForTanD = 1.0e3
    HighFreqForTanD = 1.0e12

Physical Parameters
  W = 53.998 mil
  S = 4.819 mil
  L = 122.838 mil

Electrical Parameters
  ZE = 73.322 Ohm
  ZO = 34.095 Ohm
  Z0 = 50.000 Ohm
  C_DB = -8.750
  E_Eff = 30.000 deg

Result Parameters
  KE = 2.931
  KO = 2.222
  AE_DB = 0.006
  AO_DB = 0.004
  SkinDepth = 0.000 mil

Figure 8. Physical parameters of coupled lines (C1 and C4) for 4-section BALUN coupler

```
Tue Nov 15 21:37:55 2016

Element type: MCLIN
Element ID: MCLIN_DEFAULT

Units
  Freq = GHz
  Length = mil
  Res = Ohm
  Angle = deg

Frequency = 5.000

Shared Parameters:
  Substrate: MSUB = MSUB_DEFAULT
    Er = 3.550
    Mur = 1.000
    H = 0.032 in
    Hu = 3.9e+34 mil
    T = 35.000 um
    Cond = 1e+50
    TanD = 0.002
    Rough = 3.200 um
    DielectricLossModel = 1.000
    FreqForEpsrTanD = 1.0e9
    LowFreqForTanD = 1.0e3
    HighFreqForTanD = 1.0e12

Physical Parameters
  W = 67.905 mil
  S = 34.733 mil
  L = 118.555 mil

Electrical Parameters
  ZE = 56.500 Ohm
  ZO = 44.247 Ohm
  Z0 = 50.000 Ohm
  C_DB = -18.300
  E_Eff = 30.000 deg

Result Parameters
  KE = 2.986
  KO = 2.529
  AE_DB = 0.005
  AO_DB = 0.004
  SkinDepth = 0.000 mil
```

Figure 9. Physical parameters of coupled lines (C2 and C3) for 4-section BALUN coupler

3.4 Performance verification of 2-section Microstrip Balun design

The design consists primarily of two coupled-line sections, with a center-tap at the output coupled line, as shown Figure 10. The physical parameters of the coupled lines are synthesized using Line-Calc tool and theoretical design procedure detailed in previous section.

As seen in the Figure 10, the input impedance at Port 1 and output impedances at Port 2 and 3 are kept constant at 50 Ω which follows the principle of center tap transformer used for coupling, while the Port 4 is terminated using 50 Ω resistor to match the input impedance and avoid the reflection of signals from the through port output to avoid ringing effect over the transmission line and to get steady output response.

A transmission line was inserted at output port 2 of the coupled line to increase the phase difference between the outputs since the effective electrical length considered during coupling voltage calculation was 60° to conform specifications for dimensions of the design.

The simulation study below involves verification of amplitude balance, phase difference and return loss of the implemented 2-section balun coupler design.

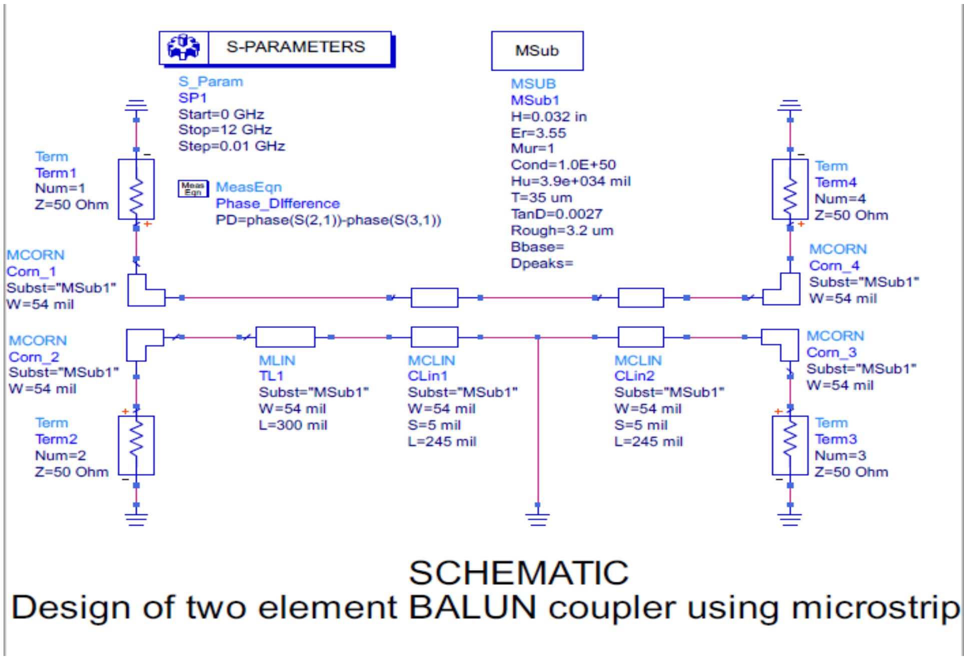

Figure 10. Schematic of 2-section Microstrip Balun design

3.4.1 Simulation verification for 2-section Balun design

The first part of the simulation studies detailed below involves comparing the magnitude of the balanced output signals followed by simulation of phase difference between the two outputs. Finally, the return loss was simulated for the input port to check whether value of VSWR is within acceptable value.

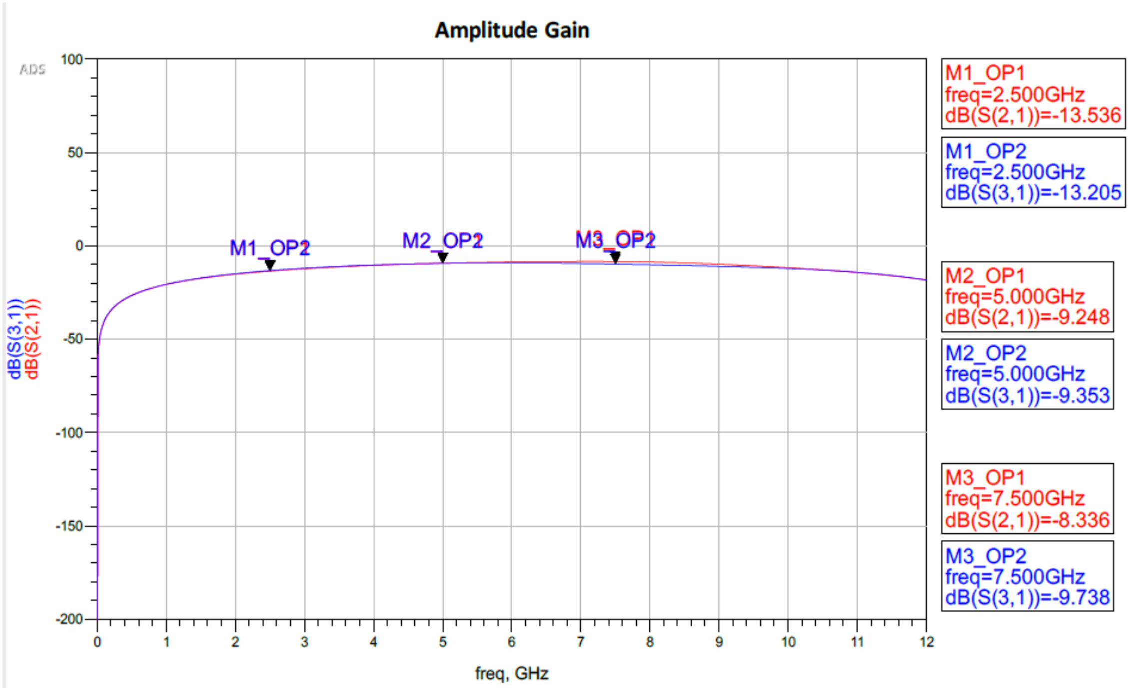

Figure 11. Amplitude Balance (2-section)

From the simulated results displayed in the graph above, it can be seen that the magnitudes of both output signals at Port 2 and port 3 resp. are almost equal in magnitude for desired range of frequency band which is 2.5 GHz to 7.5 GHz and thus it can be concluded from the simulation results that amplitude of the signals at their respective output ports are well balanced and meets the specification of balun circuit discussed in chapter 3.

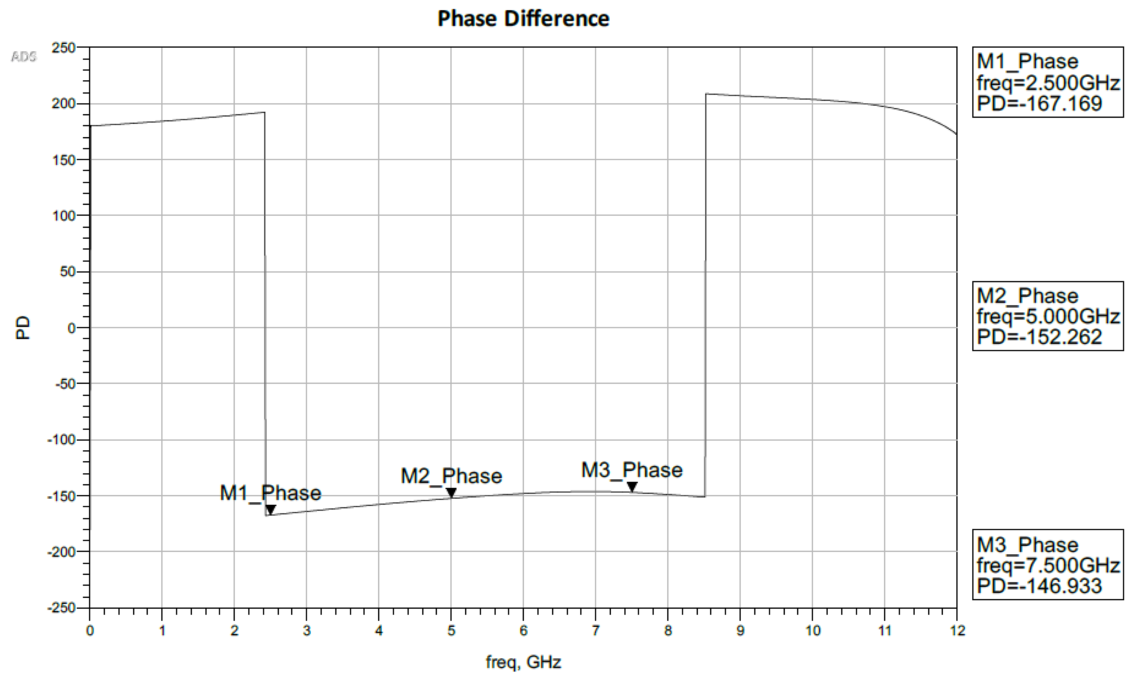

Figure 12. Phase Balance (2-section)

From the simulated results displayed in the graph above, it can be seen that the phase difference between the signals at output ports, Port 2 and Port 3 resp. is stable for the desired range of frequency band which is 2.5 GHz to 7.5 GHz, however the phase difference is not close to 180°. The results were expected to be improved in 4-section balun coupler design. Thus, it can be concluded from the simulation results that the phase difference between the output signals meets the desired the specification of balun circuit discussed in chapter 3.

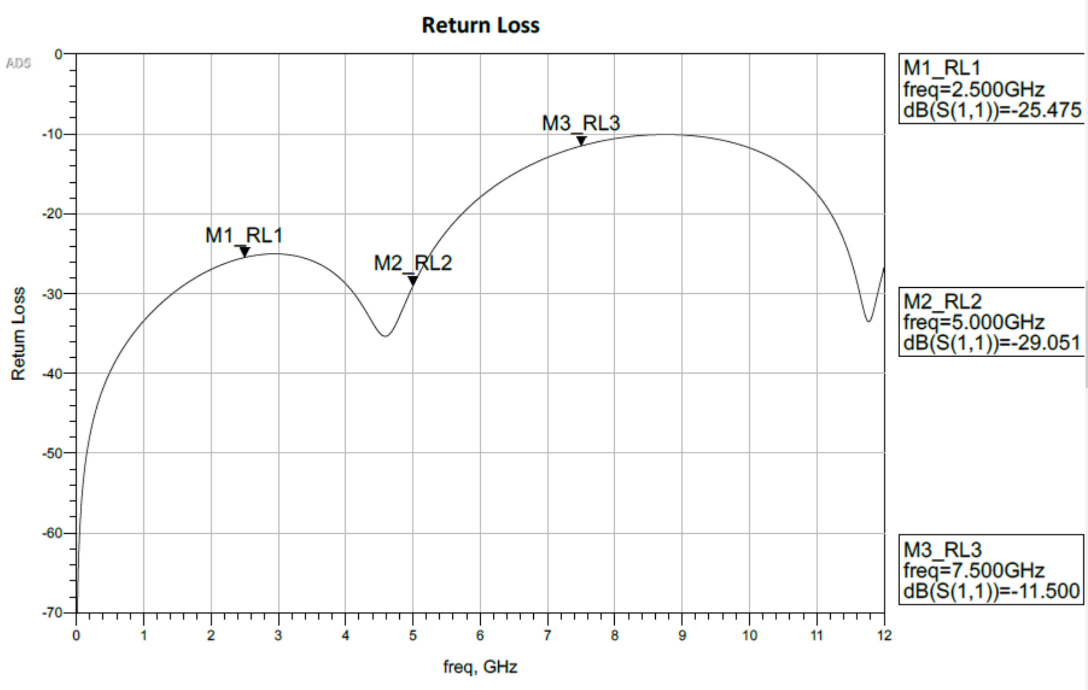

Figure 13. Return Loss (2-section)

From the simulated results displayed in the graph above, it can be seen that the Return Loss at the center frequency of 5 GHz is -29.051 dB which translates to VSWR value close to 1.07 which is considered to be good enough for any industrial wireless application. The return loss for the desired frequency range is within the acceptable range and thus it can be concluded from the above results that simulated circuit meets the specification of balun coupler circuit discussed in chapter 3.

3.5 Performance Verification of 4-section Microstrip Balun Design

The design consists primarily of four coupled-line sections, with a center-tap at the output coupled line, as shown below in figure below. The physical parameters of the coupled lines are synthesized using Line-Calc tool and theoretical design procedure detailed in previous section.

As seen in the design below we have used 4 coupled lines and the input impedance at Port 1 and output impedances at Port 2 and 3 are kept at a constant 50 Ω which follows the principle of center tap transformer used for coupling. As in the two-section and four-section cases, Port 4 is terminated using 50 Ω resistor to match the input impedance and avoid the reflection of signals from far end of the line.

A transmission line was inserted at output port 2 of the coupled line to increase the phase difference between the outputs since the effective electrical length considered during coupling voltage calculation was 60° to conform specifications for dimensions of design.

The simulation study below involves verification of amplitude balance, phase difference and return loss of the implemented 2-section balun coupler design.

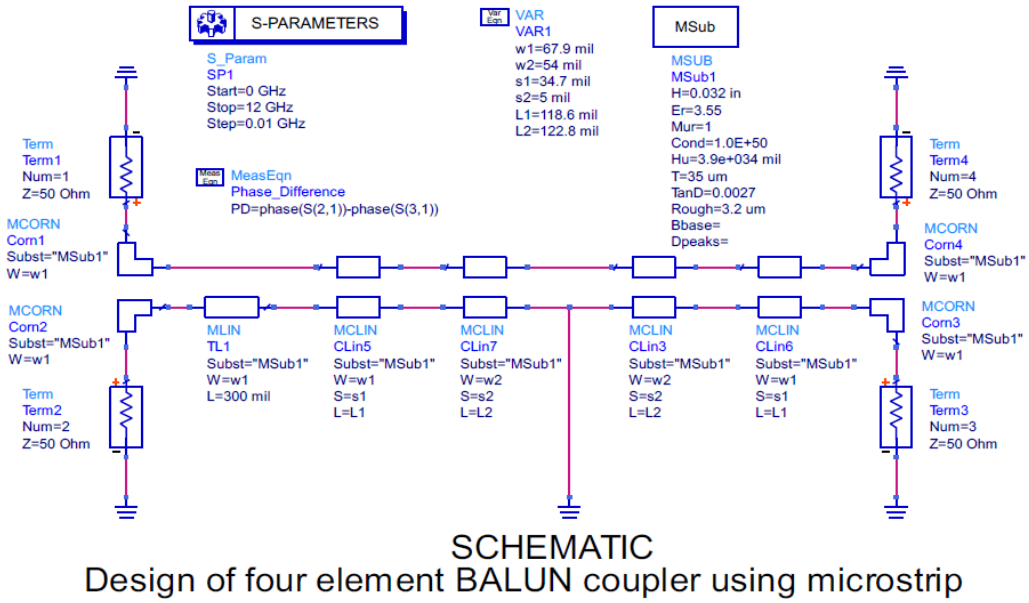

Figure 14. Schematic of 4-section Balun Circuit

3.5.1 Simulation verification for 4-section Balun design

The first part of the simulation studies detailed below involves comparing the magnitude of the balanced output signals followed by simulation of phase difference between the two outputs. Finally, the return loss was simulated for the input port to check whether value of VSWR is within acceptable value.

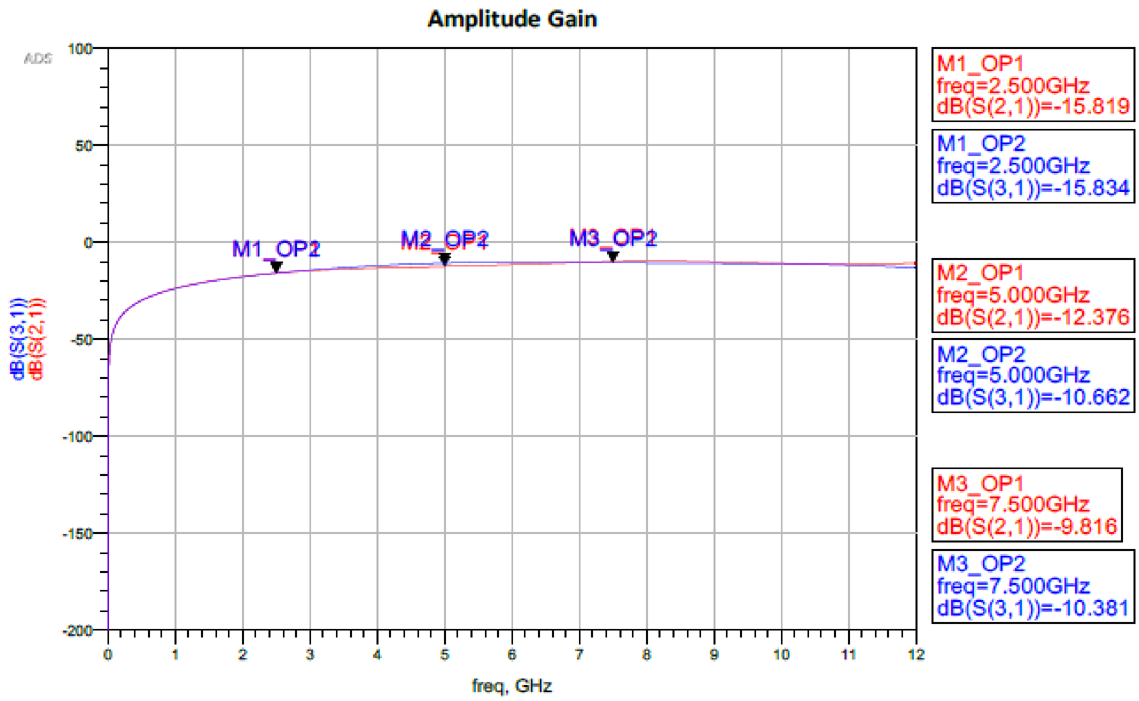

Figure 15. Amplitude Balance

From the simulated results displayed in the graph above, it can be seen that the magnitudes of both output signals at Port 2 and Port 3 resp. are almost equal in magnitude for desired range of frequency band which is 2.5 GHz to 7.5 GHz. Also, the amplitude gain for both the output signals is increased significantly compared to the two section balun coupler design. Thus, it can be concluded from the simulation results that amplitude of the signals at their respective output ports are well balanced and meet the specification of balun circuit discussed in chapter 3.

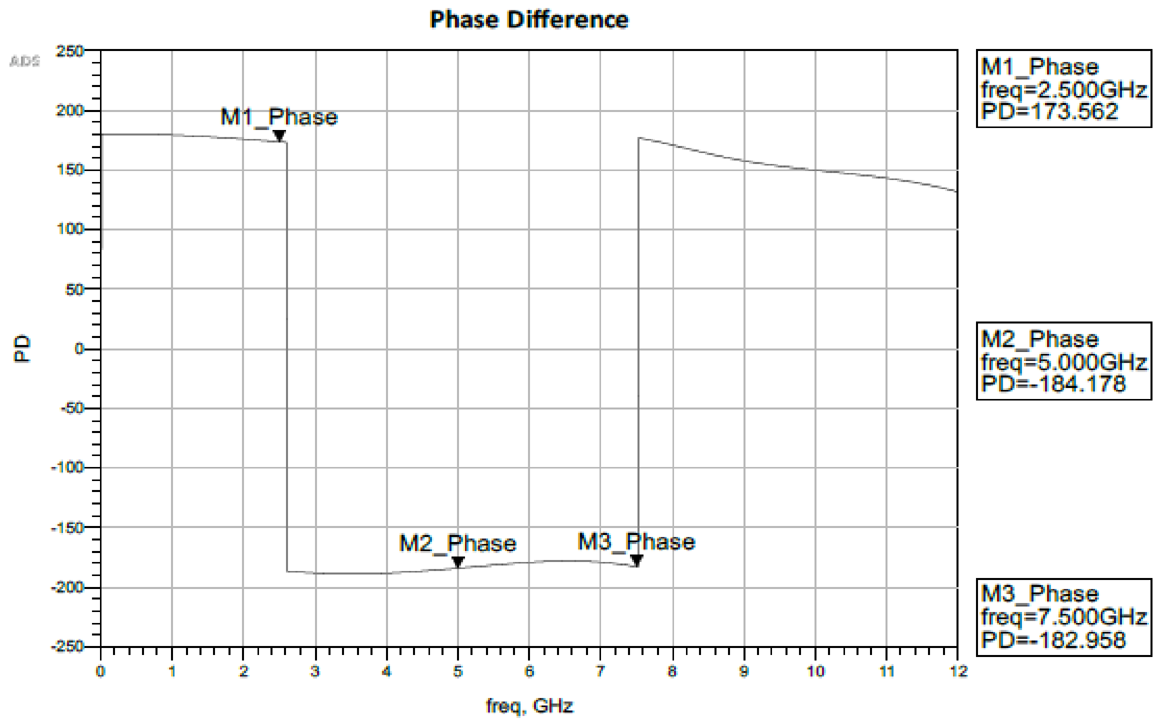

Figure 16. Phase Balance

From the simulated results displayed in the graph above, it can be seen that the phase difference between the signals at the output ports, Port 2 and Port 3 resp. is close to -180° for desired range of frequency band which is 2.5 GHz to 7.5 GHz and thus it can be concluded from the simulation results that the phase difference between the output signals meets the desired specification of balun circuit discussed in chapter 3.

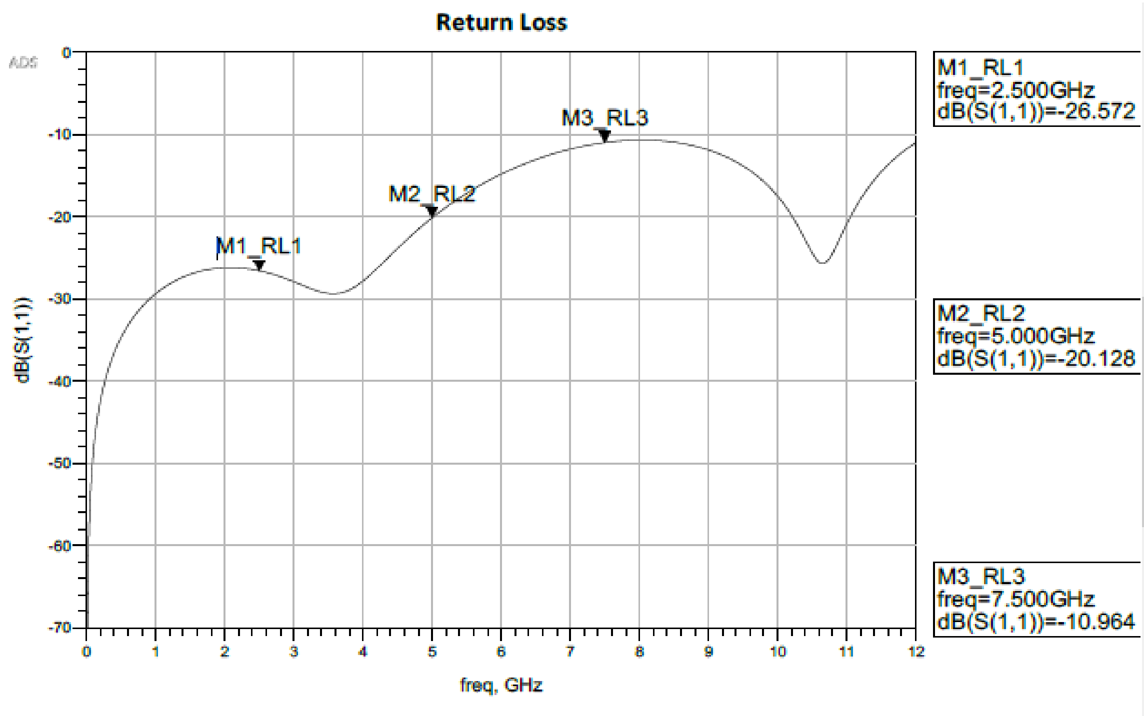

Figure 17. Return Loss

From the simulated results displayed in the graph above, it can be seen that the Return Loss at the center frequency of 5 GHz is -20.128 dB which translates to VSWR value close to 1.22 which is considered to be good enough for any industrial wireless application. The return loss for the desired frequency range is within the acceptable range and thus it can be concluded from the above results that simulated circuit meets the specification of balun coupler circuit discussed in chapter 3.

4. FABRICATION OF BALUN CIRCUITS

After the validating the balun coupler designs for the required specification by simulating the designs and verifying the s-parameters for amplitude, phase and VSWR discussed in previous chapter the designs were fabricated on laminate sheets available in the lab. The steps involved in fabrication process are discussed in consecutive sub-sections below.

4.1 Layout-Generation and Verification

The layouts for both 2 and 4 section balun coupler designs were generated from their respective schematics designed in ADS software. Figures 18 and 19 show the generated layout for the respective designs.

Figure 18. Layout (2-section)

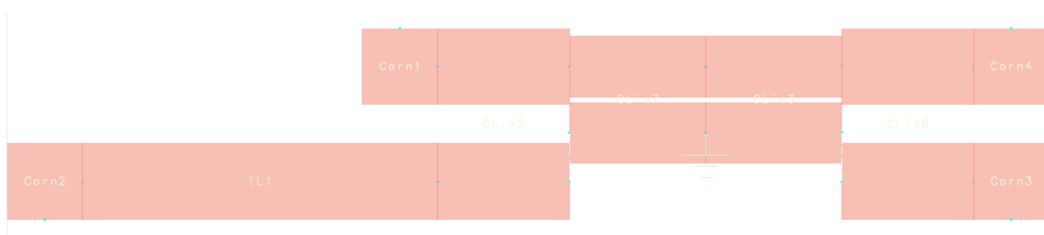

Figure 19. Layout (4-section)

Once the layouts were obtained from ADS, the physical dimensions of the coupled lines were measured to compare them with the schematic values as shown in Figures 20 and 21.

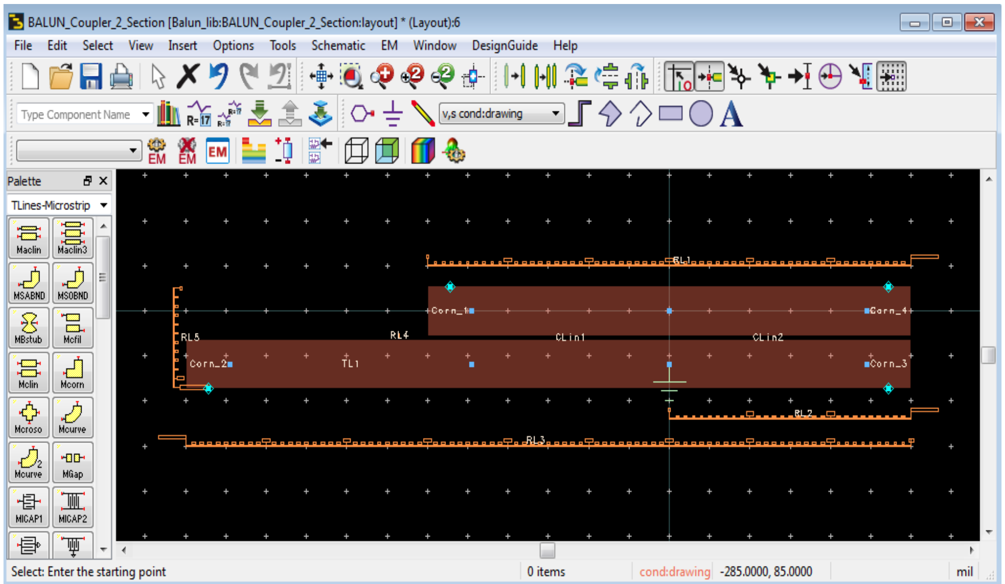

Figure 20. Verification of Layout (2-section balun)

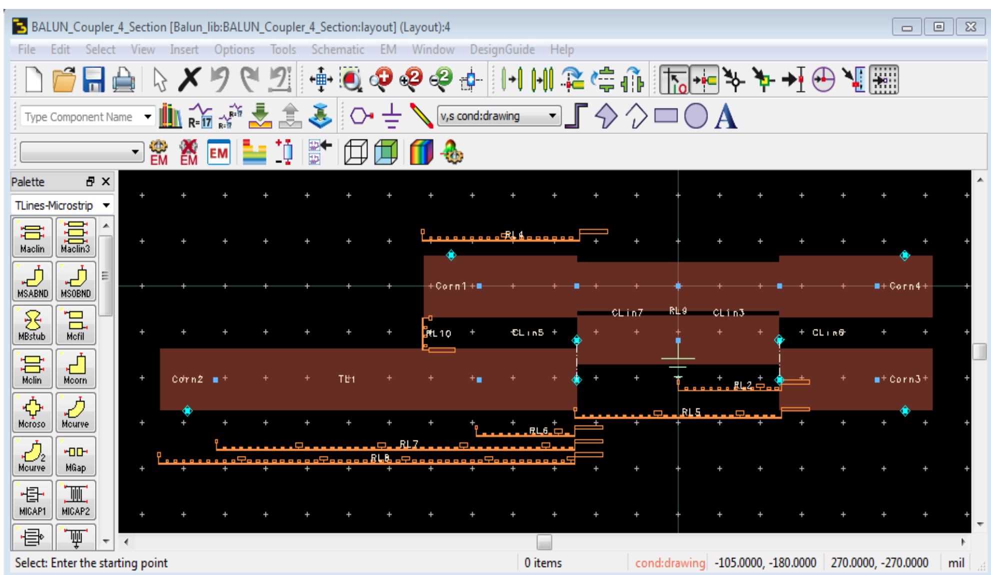

Figure 21. Verification of Layout (4-section balun)

4.2 Fabrication

After verification of physical dimensions, gerber files were extracted from the layouts for both the circuits which were used as input file for the T-Tech router software, routing machine which was used for fabricating the layout over the laminate sheet (RO4003C).

Once the edges of the circuit were carved out from the substrate using the router the excess copper material was peeled of using a sharp blade to avoid chemical etching process which generated toxic chemicals and hence considered harmful.

The base metal layer and was added to the circuit to provide mechanical support to connectors and make the design sturdy for industrial applications. The connectors for the input and output ports were soldered onto the board and a 50 Ω resistor was connected to the unused port of the balun coupler as explained in the previous chapter. Also, center tap on the output line was grounded by soldering wire from center tap to the ground of design.

The images for 2 and 4-section balun circuits are shown in Figures 22 and 23 below.

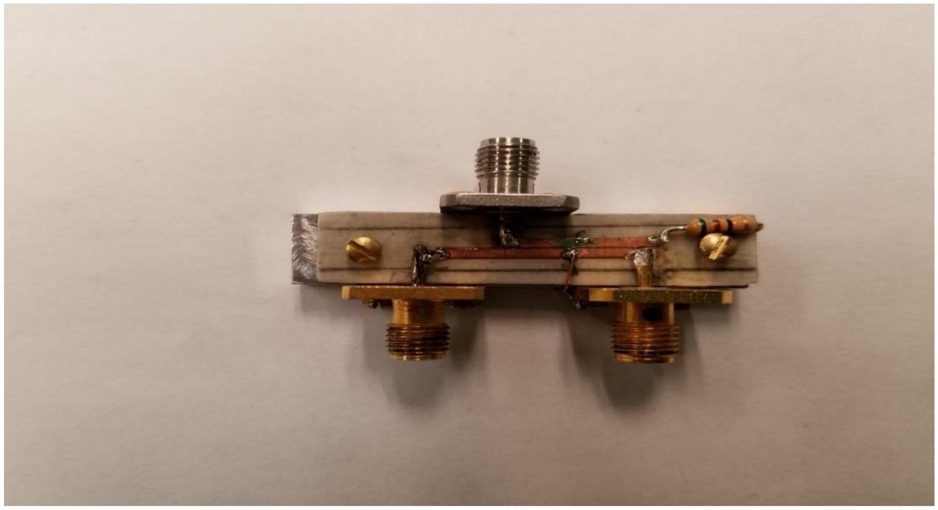

Figure 22. Fabricated balun coupler circuit (2-section)

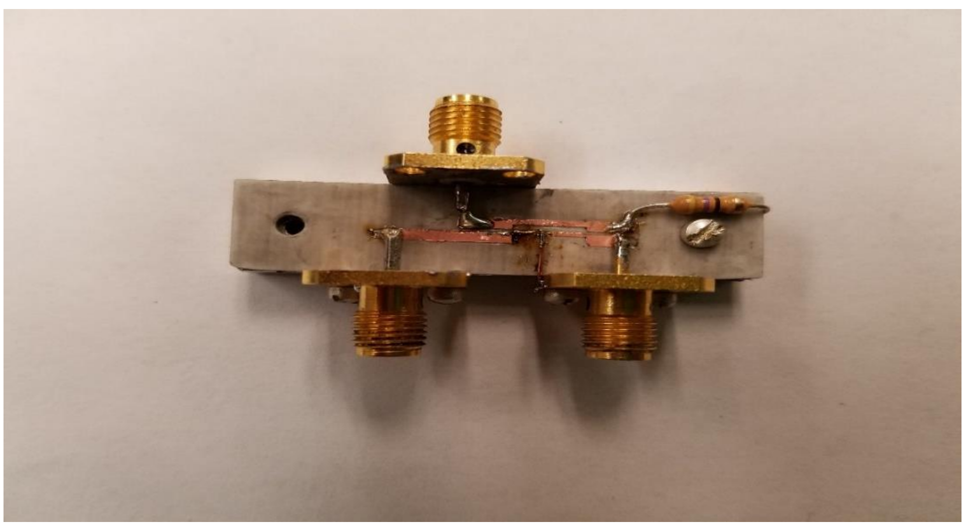

Figure 23. Fabricated balun coupler circuit (4-section)

5. MEASUREMENT OF FABRICATED BALUN DESIGNS

Since a 4-Port VNA was not available, we used a 2-Port VNA to conduct the measurements. We connected an RF test cable from Port 1 of the VNA to Port 1 of the coupler, and then connected another RF test cable from Port 2 of the VNA to Port 2 of the coupler. This measurement gave us the required s-parameters for Port 2 of balun coupler circuit. While these measurements were taken, the unused Port 3 was terminated with a 50 Ω load.

Once these measurements were taken we disconnected the RF test cable from port 2 and connected it to port 3 of the balun coupler and Port was terminated with a 50 Ω load. This measurement gave us the required s-parameters for the Port 3 of balun coupler circuit.

Figure below shows a test diagram of how we took the measurements. The dashed lines imply that it is the RF test cable connected to port 2 on the VNA and how it needed to be connected to ports 2 through 4 on the directional coupler. Anytime an RF test cable was not connected to a port it would be terminated with a 50 Ω load.

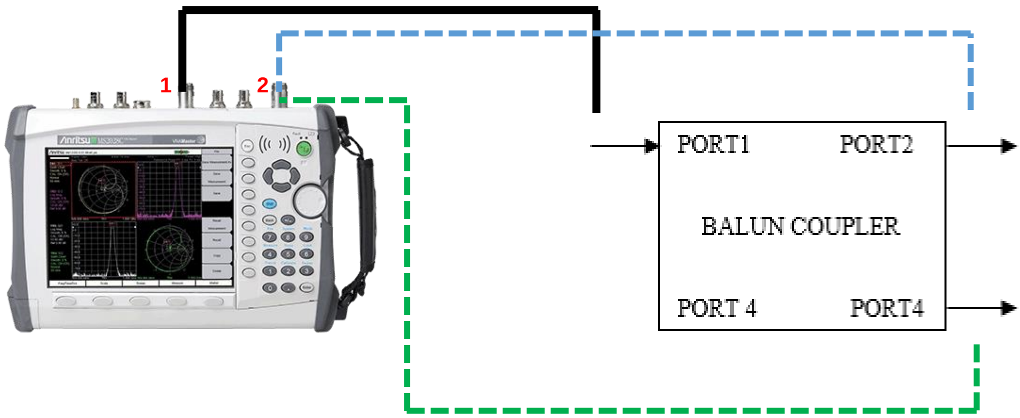

Figure 24. VNA setup for measurement

The figures shown below are the images of VNA display window captured while measuring the required s-parameters for 2 and 4 section Balun coupler design. The phase difference between two output signals was calculated by subtracting the phase of s(3, 1) from s(2, 1) which were measured individually.

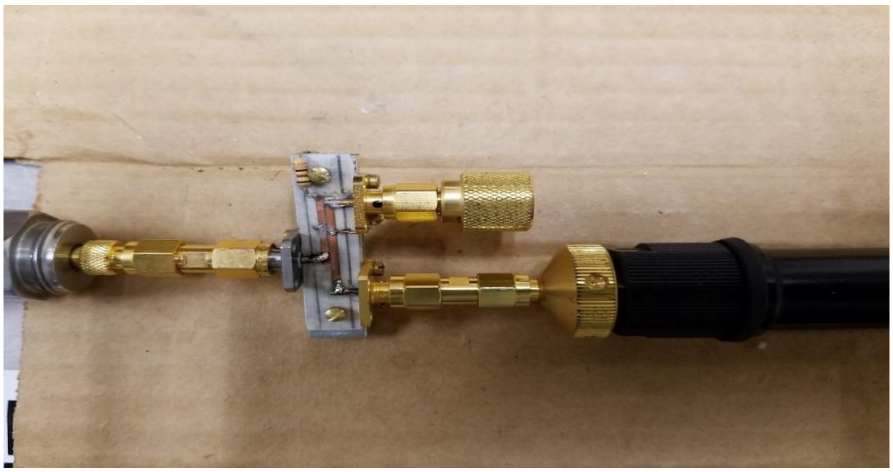

Figure 25. Connection of VNA RF wires with input and output port of circuit

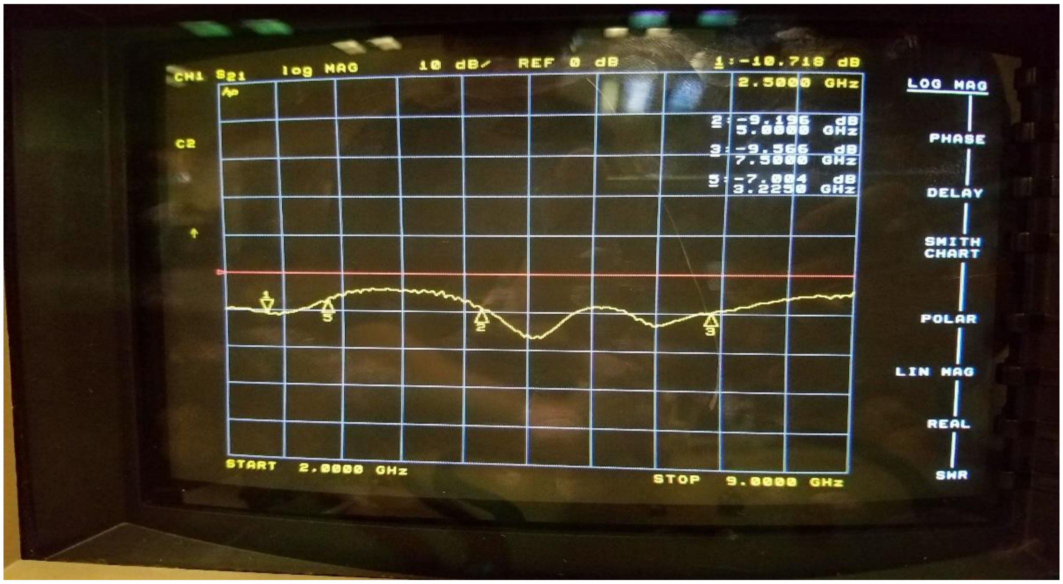

Figure 26. Amplitude Gain for Port 2 (2-section)

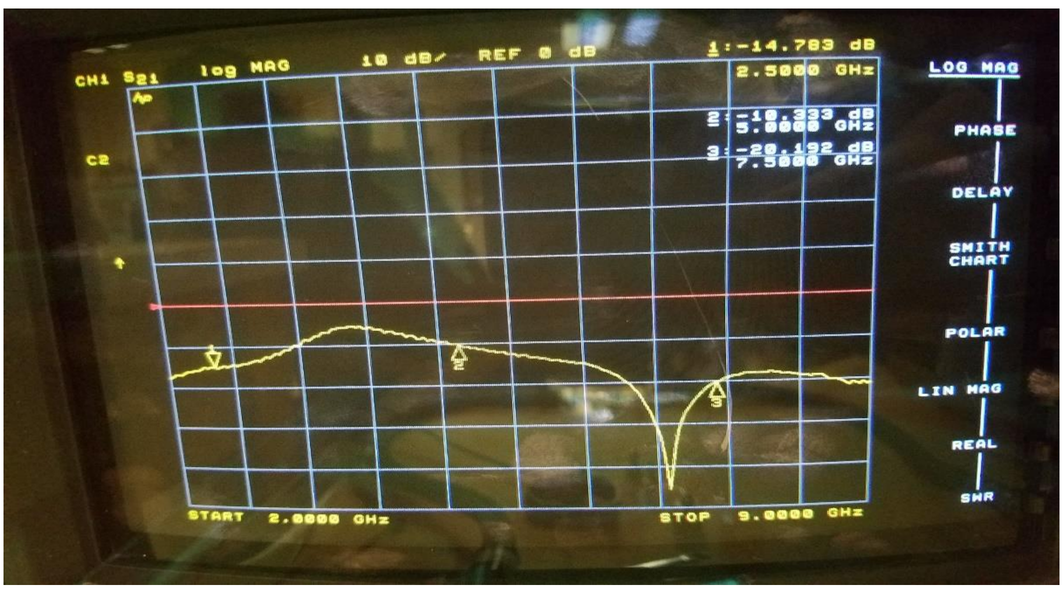

Figure 27. Amplitude Gain for Port 3 (2-section)

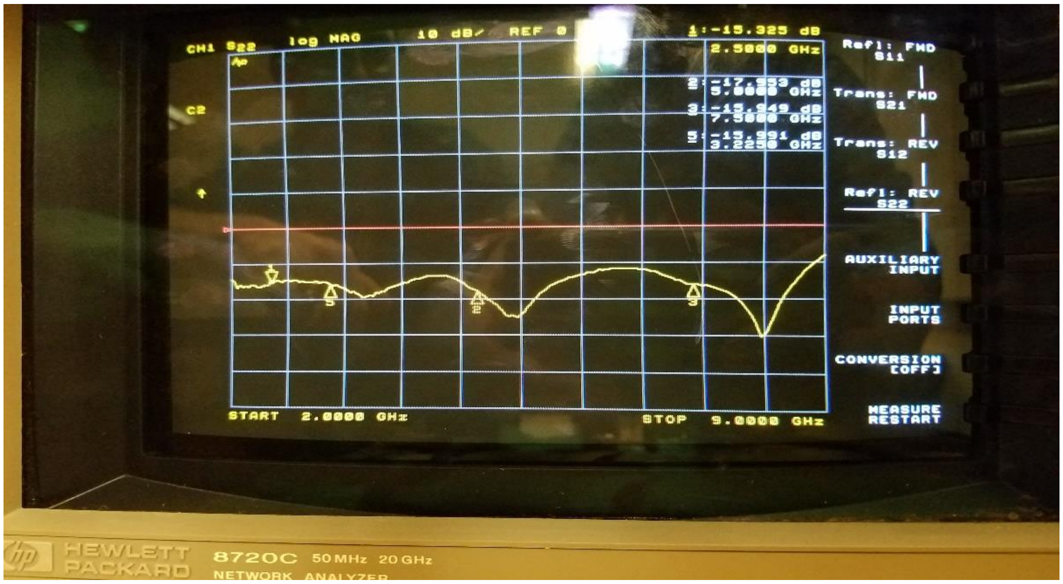

Figure 28. Return Loss for Port 1 (2-section)

Figure 29. Amplitude Gain for Port 2 (4-section)

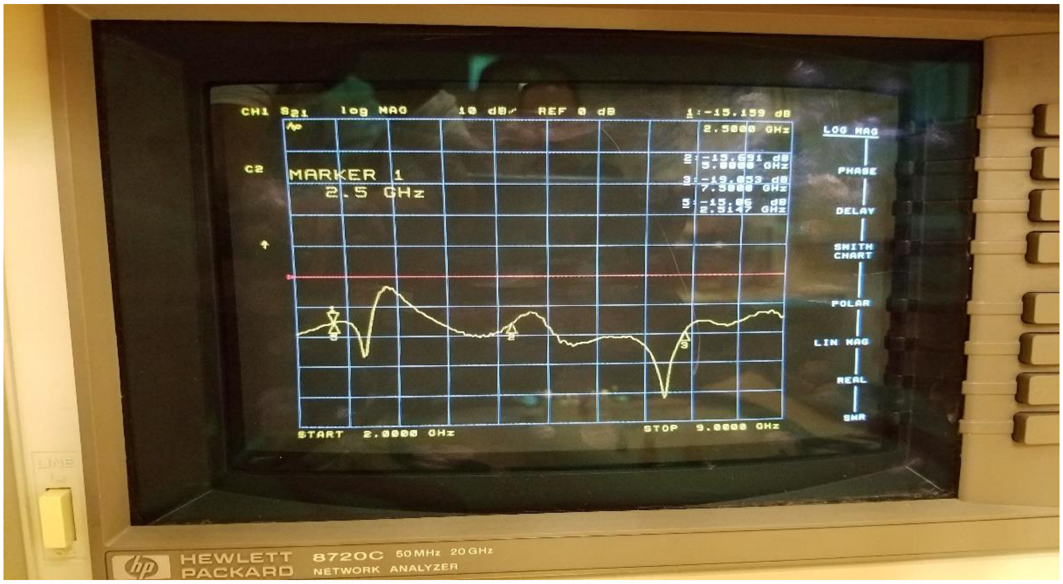

Figure 30. Amplitude Gain for Port 3 (4-section)

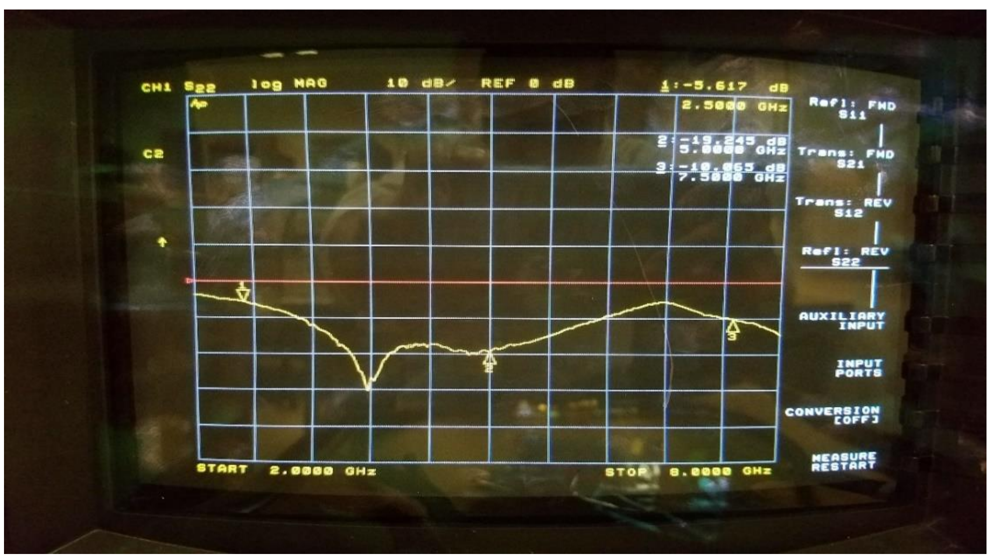

Figure 31. Return Loss for Port 1 (4-section)

Comparison of characteristic values with simulated values for 2-section Balun coupler

Frequency (GHz)	Amplitude Gain (dB) Simulation		Amplitude Gain (dB) Circuit	
	Port 2 [s(2,1)]	Port 3 [s(3,1)]	Port 2 [s(2,1)]	Port 3 [s(3,1)]
Low (2.5)	-13.536	-13.205	-10.718	-14.783
Center/Mid (5)	-9.248	-9.353	-9.196	-10.333
High (7.5)	-8.336	-9.738	-9.566	-20.192

Table 2. Comparison of Amplitude Balance for 2-section Balun coupler

Frequency (GHz)	Phase Difference (°) Simulation [s(2,1)-s(3,1)]	Phase Difference (°) Circuit [s(2,1)-s(3,1)]
Low (2.5)	-167.169	-142.327
Center/Mid (5)	-152.262	-136.921
High (7.5)	-146.933	-130.747

Table 3. Comparison of Phase Difference for 2-section Balun coupler

Frequency (GHz)	Return Loss (dB) Simulation [s(1,1)]	Return Loss (dB) Circuit [s(1,1)]
Low (2.5)	-25.475	-15.325
Center/Mid (5)	-29.051	-17.953
High (7.5)	-11.500	-15.949

Table 4. Comparison of Return Loss for 2-section Balun coupler

Comparison of characteristic values with simulated values for 2-section Balun coupler

Frequency (GHz)	Amplitude Gain (dB) Simulation		Amplitude Gain (dB) Circuit	
	Port 2 [s(2,1)]	Port 3 [s(3,1)]	Port 2 [s(2,1)]	Port 3 [s(3,1)]
Low (2.5)	-15.819	-15.834	-14.602	-15.159
Center/Mid (5)	-12.376	-10.662	-11.357	-15.691
High (7.5)	-9.816	-10.381	-8.951	-19.053

Table 5. Comparison of Amplitude Balance for 4-section Balun coupler

Frequency (GHz)	Phase Difference (°) Simulation [s(2,1)-s(3,1)]	Phase Difference (°) Circuit [s(2,1)-s(3,1)]
Low (2.5)	173.562	158.638
Center/Mid (5)	-184.178	-173.845
High (7.5)	-182.958	-178.137

Table 6. Comparison of Phase Difference for 4-section Balun coupler

Frequency (GHz)	Return Loss (dB) Simulation [s(1,1)]	Return Loss (dB) Circuit [s(1,1)]
Low (2.5)	-26.572	-15.617
Center/Mid (5)	-20.128	-19.245
High (7.5)	-10.964	-10.065

Table 7. Comparison of Return Loss for 4-section Balun coupler

6. CONCLUSIONS

After rectification of previous 4-section Balun coupler design in ADS, verification of the simulated results and comparing the characteristic outputs of fabricated circuits with simulated values, we can conclude that the results of the fabricated circuits follows closely with the simulated results, however results for the actual circuit deviates from the simulated by a negligible margin for the following reasons-

- The simulation results show the s-parameter values for ideal substrate which do not account for physical or chemical damages to the substrate material caused during fabrication and which tend to change the intrinsic properties of the substrate.
- The drill bit used for fabricating the design on router was 11 mils wide while the required spacing between the coupled lines used in both the circuits required a spacing of 5 mils which results in deviation of the calculated values from the simulated values.
- The wires used for connecting the transmission lines with connector and center tap to ground adds additional reactance at the input and output ports by adding extra length of conducting wire to the design.

Thus, the ultimate goal of fabrication, measurement and comparison of the results for Balun Coupler circuit was achieved successfully.

References

[1] https://www.microwaves101.com/encyclopedias/baluns (26th Oct, 2016)

[2] http://searchnetworking.techtarget.com/definition/balun (26th Oct, 2016)

[3] https://en.wikipedia.org/wiki/Balun (26th Oct, 2016)

[4] http://analog.intgckts.com/impedance-matching/lumped-lc-balun/ (10th Nov, 2016)

[5] http://web.ecs.baylor.edu/faculty/baylis/EEL4421/baluns-f07.pdf (10th Nov, 2016)

[6] https://www.microwaves101.com/encyclopedias/microstrip (12th Nov, 2016)

[7] https://www.markimicrowave.com/Assets/appnotes/balun_basics_primer.pdf (12th Nov, 2016)

[8] http://www.odyseus.nildram.co.uk/RFMicrowave_Circuits_Files/Balun%20Design.pdf (15th Nov, 2016)

[9] Chung-Hao Tsai, Iat-In Ao Leong, Hung-Chuan Chen, Tzong-Lin Wu "A Miniaturized and Broadband Balun Using Artificial Coupled Line With Imaginary Even-Mode Impedance" Microwave Theory and Techniques, IEEE Transactions on Year: 2011, Volume: 59, Issue: 9

[10] Elizabeth Kelangi and Danny H. Dang, Design, 'Simulation and Fabrication of Improved Wideband Microstrip Balun Circuit at 5 GHz', M.S. Thesis, California State University, Sacramento, Fall 2010.

[11] Sayidas Mallesha Babu, Optimized Design, Simulation and Testing of Broadband Microstrip Balun Circuit at 5 GHz, California State University, Sacramento, Fall 2014.

[12] Design of the broadband microstrip balun in 6 GHz wireless band, by Christopher Anthony Ghabris, California State University, Sacramento, 2003.

[13] Design and Simulation of Two, Four and Six element broadband microstrip balun circuit at 5 Ghz for wireless application, project by Suvarna Mahale CSUS 2015

[14] Theory, Design and Simulation of even order wideband Microstrip balun circuits at 5 GHz for wireless applications, project by Praveen Veeranki Krishna and Swapnil Wankhede

[15] Theory and Tables of Optimum Symmetrical TEM-Mode Coupled-Transmission- Line Directional Couplers, Cristal, E.G. ; Young, L., Volume:13 , Issue: 5 , Sep 1965.