Design of Tri-Band Coupler and Wideband Phase Shifter

By

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Certificate

This is to certify that the thesis titled **"Design of Tri-Band Coupler and Wideband Phase Shifter"** submitted by **Anuradha Ahlawat** for the partial fulfillment of the requirements for the degree of *Master of Technology* in *VLSI & Embedded Systems* is a record of the bonafide work carried out by her under my guidance and supervision in the Security and Privacy group at Indraprastha Institute of Information Technology, Delhi. This work has not been submitted anywhere else for the reward of any other degree/diploma.

August, 2017
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This thesis is dedicated to my family
for their
endless support and encouragement.

Abstract

Branch-line coupler and phase shifter are widely used passive components in RF and microwave communication systems. The designing of circuits operating at multi-band frequencies has the advantage of both compact size and cost. Therefore, it becomes very fascinating to design the RF and microwave circuits with such specifications. This thesis work has been divided into two parts. The first part focuses on the designing of Tri-band coupler with port matching technique in which an architecture of 3-dB tri-band branch line coupler operating at three arbitrary frequencies is presented. It is capable to provide a phase shift of 90° and equal power division at its output ports. To validate the proposed design procedure, a coupler working at 1.8 GHz, 2.4 GHz and 3.5 GHz is prototyped.

The second part of the thesis work focuses on designing and validation of wideband phase shifter circuit with stub loaded transmission lines in which a modified architecture of wideband phase shifter having 90° phase shift is presented. A number of design examples capable of multiple phase shifts up to 90° for a wide bandwidth are presented to demonstrate the effectiveness of the proposed phase shifter. The designed phase shifter have a bandwidth of operation 190MHz around central frequency. To validate the reported design procedure, a 90° phase shifter working at 1.8 GHz is prototyped. The proposed design is able to provide the 90 ° phase difference over a bandwidth of 106 % considering only 3 ° phase ripples. Both design are prototyped on Rogers5880 substrate with thickness of 1.575 mm and dielectric constant of 2.2. All EM Simulated and results measured with VNA are in good agreement with each other.

Relevant Publications

1. Anuradha Ahlawat, Rahul Gupta and Mohammad S Hashmi, "Wideband Phase Shifter with Stub Loaded Transmission Line ", Asia-Pacific Microwave Conference (APMC) 2017, Nov. 13 – 16, Kuala Lumpur, Malaysia.

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List of Abbrevation

RF	Radio Frequency
ADS	Advanced Design System
VNA	Vector Network Analyzer
IL	Insertion Loss
RL	Return Loss
BW	Bandwidth
OCSC	Open Circuit Short Circuit
BLC	Branch Line Coupler
LTE	Long Term Evolution
EM	Electromagnetic Simulation
DGS	Defected Ground Structure
SWS	Slow Wave Structure
D	Directivity
I	Isolation
dB	Decibel
Hz	Hertz
ISM	Industrial Scientific Medical

Chapter 1

Introduction

This chapter provides a background of branch line coupler and phase shifter. Section 1.1 of this chapter explains the various terminologies used in this work. In section 1.2 and section 1.3, coupler and phase shifter overview is discussed is detail with their application. Section 1.4 includes the motivation for carrying out this work as a master thesis. Literature survey of branch line coupler and phase shifter is provided in section 1.5. Finally, section 1.6 presents the organization of this thesis work.

1.1 Terminology

In this section, some important terminologies used in this thesis work are provided along with their definition and mathematical description. Refer figure 1.2 for any port number used in description of any term in this section.

Radio frequency (RF): It is any of the electromagnetic (em) wave frequencies that lie in the range from 3 kHz to 300 GHz. These frequencies are used for communications or radar signals.

Coupling coefficient (C): It is commonly referred as coupling factor. It indicates the fraction of input power that is coupled to coupled port.

For example, a 10 dB coupling factor of a coupler means that the output of coupled port will be 10 dB lower than the signal applied at input port. Mathematically, it can be represented as:

$$C_{dB} = 10log\frac{P_3}{P_1} \tag{1.1}$$

Or

$$C_{dB} = -20log(|S_{31}|) \tag{1.2}$$

where P_1 and P_3 are the input and coupled power.

Directivity (D): Directivity is defined as the power level difference between coupled and isolated port of a coupler. Thus it is a measure of how independent the coupled port and isolated ports are.Mathematically, it can be represented as:

$$D_{dB} = 10log\frac{P_3}{P_4} \tag{1.3}$$

Or

$$D_{dB} = 20log\frac{(|S_{31}|)}{|S_{41}|} \tag{1.4}$$

Isolation (I): The isolation provides the fraction of power that is delivered to isolated port or the power level difference between input and isolated ports. Mathematically, it can be represented as:

$$I_{dB} = -10log\frac{P_4}{P_1} \tag{1.5}$$

Or

$$I_{dB} = -20log(|S_{41}|) \tag{1.6}$$

Return Loss: The total loss of signal reflected back by any type of discontinuity in transmission line is measured as return loss and is expressed in decibel (dB). These discontinuities can be due the impedance mismatch etc. Return loss at port 1 in figure 1.2 is given as:

$$RL_{dB} = -20log(|S_{11}|) \tag{1.7}$$

Insertion Loss: The total loss in signal amplitude from input to the output port is measured as insertion loss. It is expressed in decibels (dB). Ideally there should be no insertion loss. Mathematically, it can be represented as:

$$IL_{dB} = -10log\frac{P_2}{P_1} \tag{1.8}$$

Or

$$IL_{dB} = -20log(|S_{21}|) \tag{1.9}$$

Bandwidth (BW): It is defined as the difference between upper and lower cutoff frequencies. It is also known as passband bandwidth and typically measured in Hertz (Hz).

Amplitude Imbalance (AI): It is defined as the power level difference between the two output ports i.e. coupled and transmitted port. For an ideal circuit, the difference should be 0 dB. Practically, It is a frequency dependent term and thus departs from the ideal 0 dB difference. Mathematically, it can be represented as:

$$AI = |S_{21}| - |S_{31}| \tag{1.10}$$

Phase Range: It is defined as the phase shift range of the device. A design will only be able to provide a phase shift within this range based on the type on its configuration.

Phase Ripple: It is measured as the deviation is phase from the required phase value in phase range. It is expressed in degree (°). It's value should be as small as possible.

For an ideal coupler, the Directivity (D) should be infinite and Isolation (I) should be zero.

Vector Network Analyzer: It is a Keysight instrument used for measuring the results of a fabricated prototype.

1.2 Branch-Line Coupler: Introduction

Branch line couplers are an important part of RF and microwave integrated circuits. They have several applications in the designing of many RF and microwave components such as balance amplifiers, phase shifters, mixers etc. They possess the dividing/combining properties of magnitude and phase so they are widely used in communication systems as well and as a feeding networks in smart antenna array systems. Couplers are passive three or four port components commonly used in RF and microwave designs. These components also provide a phase shift between its output ports i.e. transmitted and coupled port.

The block diagrams of power divider and power combiners are shown in figure 1.1. In power divider, an input signal is splitted into two output signals of lesser power. α denotes the power division ratio and it may have value in between 0 and 1. Thus depending on the value of α, design may be lossy or lossless.

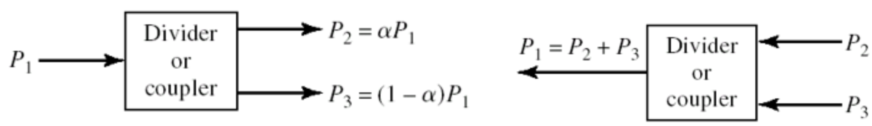

Figure 1.1: Power division and power combiner [1]

A power combiner has two or more input signals and produces an single signal at output port. Power combiner and divider devices are generally three port networks. However, four-port networks such as directional couplers are very widely used. The main difference between coupler and power divider is that coupler provides a particular phase shift at output ports and power dividers provide zero phase shift. Microstrip couplers are able to provide a phase of 90 ° or 180 ° phase shifts [2] but couplers having arbitrary phase shifts are also possible. Because of the reciprocity characteristics of these devices, the same device can be used to perform both combining and diving operation. Therefore, in this work a symmetrical coupler structure has been designed. A four port symmetric network of coupler is shown in figure 1.2. In this figure, port 1 (input port) and port 2 (transmitted port) are known as primary ports while isolated (port 4) and coupled ports (port 3) are secondary ports. Ideally couplers are perfectly matched, lossless, reciprocal and provide a phase difference of 90 or 180 in between its output ports. In figure 1.2, assuming input power signal is applied at port 1 and evenly divided between its output ports (port 2 and port 3) as in case of 3-dB coupler with a phase difference of 90 degree between these output ports. No power will be delivered to the isolated port of coupler. As the couplers are symmetric devices, so any of the port can be defined as input port and thus according to that port, through, coupled and isolation ports can be defined appropriately. Lets assume input power of P1 is applied at port 1 then this power signal will be coupled to port 3 with coupling coefficient ofβ^2. At port 2, also known as throughput port or transmitted port, the power is obtained with a coefficient of α.

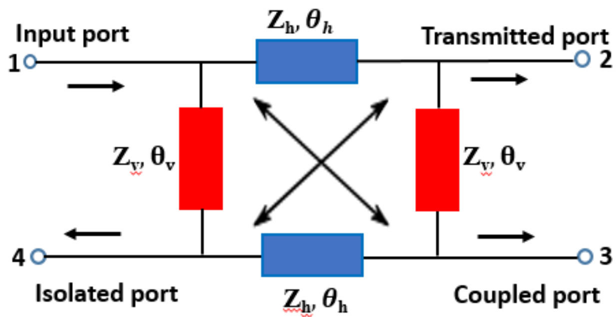

Figure 1.2: Conventional Branch line coupler

The relation between α and β is given by:

$$\alpha = \beta^2$$

The power at transmitted port will be:

$$P2 = (1{-}\beta^2) \times \text{P1}$$

and power at coupled port will be:

$$P3 = (\beta^2) \times \text{P1}$$

The most adopted method of analysis of a four port symmetric network like branch line coupler, is even and odd mode analysis. Branch line couplers (BLCs) have entirely planar structure with very simple and robust design. They are the basic building blocks in many of the communication application. The bandwidth of a single stage branch line coupler is mainly limited by its electrical length (θ). And due to low bandwidth, a single stage branch line coupler is not suitable to wideband operation.

Bandwidth of a coupler can be increased by cascading more sections together but it will also increases the physical size of chip. Cascading of many sections of transmission line may also complicate the fabrication process. These can be categorized into two main categories listed below.
a. Waveguide Couplers
b. Microstrip Couplers

Generally, waveguide couplers have one or more holes between them for coupling. The most basic type of waveguide coupler is the Bethe hole coupler. Bethe hole coupler have one small hole to couple two waveguide transmission lines. Similarly, the multihole coupler can be designed by using two waveguides coupled by two or more holes. Other waveguide couplers are Moreno crossed-guide coupler, Riblet short-slot coupler, Schwinger reversed-phase coupler etc.

The second type of commonly used RF couplers are microstrip coupler. Branch line and rat-race couplers are the two most widely used couplers that uses microstrip transmission lines in their designing. The main specification of these type of couplers are to achieve phase shift and equal power division at output ports. These are 3 dB couplers i.e. half of the input power should be output at the transmitted (port 2) and other half should be at the coupled port (port 3). For achieving wider bandwidths and lower coupling, coupled line couplers with tight coupling are common. These couplers uses proximity of the microstrip transmission lines to achieve the tight coupling e.g. single-section coupled line coupler or the Lange coupler.

1.3 Phase Shifter: Introduction

The phase shifter block introduce an amount of time delay in the signal passing through it. RF phase shifter are used to change the transmission phase angle (S_{21}) of an input signal. Ideally these network provides an output signal which has equal amplitude to that of the input signal but have different phase. Any loss in amplitude from input to output signal is accounted as the insertion loss of the design. They modifies the phase of input signal and provides as an output signal. Amount of change in phase of any phase shifter is controlled by its logic circuit. The shifting of input signal in phase at output depends on the configuration of phase shifter selected. Phase shifter has a numerous applications

in RF and microwave integrated circuits but it finds the most important application as an electronic beam steering in phased array antenna as shown in figure 1.3.
Radio frequency components are widely used in wireless communication systems and phase shifter is a major component used in RF transmitter circuits. Every RF signal transmitter used in communication system has the following blocks:
Signal Generator
Phase Shifter
Variable Gain Amplifier (VGA)
Power Amplifier
Transmitting Antenna

In radio communication network, phase shifters along with VGA are used as a electronic beam steering of transmitted RF signals as shown in figure 1.3. To minimize the losses in a receiving signal at receiver end, its radiation should be controlled in a proper direction and it is known as beam steering. In this application of beam steering, phase shifters are required to control both the amplitude and the phase of signal radiation radiated by each RF antenna. Both amplitude and phase control is used to adjust side lobe levels more properly as compared to side lobe level achieved only by phase control. As shown in figure 1.3, a number of antennas radiating signals coming from power distributed network with different phase shifts. From this figure it can be seen that beam of radiated signal is being steered in a particular direction depending on the phase of that signal.

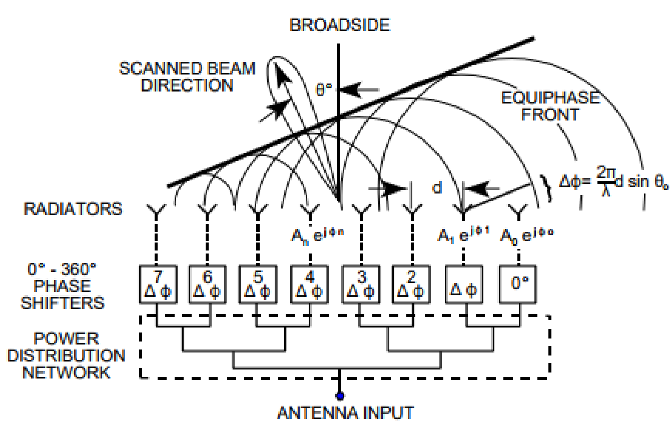

Figure 1.3: Phase shifter for beam steering application [2]

They can also be used in radar systems for multi-target tracking. An American company is working on a high tech commercial application where an phased array can be used to calculate the blind stops on road while vehicle is in motion and this makes the driving safer. Therefore, phase shifter circuits as a phased array has a wide applications in both defence and in daily life. Other applications are in frequency translator, phase modulator, radio communications, remote controlled applications, aircraft, defence etc.

1.3.1 Topologies of phase shifter

Phase shifters can be passive or active with digital or analog signal.Analog phase shifters provide a continuous phase shift such as voltage controlled phase shifter in which phase is controlled by varactor diodes. Digital phase shifters provide a discrete phase shift and these are realized by switches. In this thesis work, only passive phase shifters are considered. There have been several methods adopted to implement phase shifter, some of those configurations are described in this subsection.

1. Reflection type phase shifter

This is the first type of phase shifter which was initially presented in [3]. The basic building block of this topology is a branch line coupler loaded with frequency dependent load impedances (vary with frequency) is shown in figure 1.4. It consists of a branch line coupler loaded by two variable impedances Z_L. The reflected signals from Z_L are phase

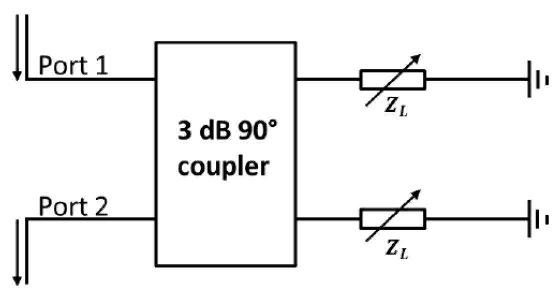

Figure 1.4: Reflection type Phase shifter [3]

shifted and combined at output port. The phase difference between port 1 and port 2 of figure 1.4 is given by equation 1.11:

$$\text{Phase Difference} = \pi - 2\tan^{-1}\left(\frac{Z_L}{Z_o}\right) \tag{1.11}$$

where Z_L is variable load impedance and Z_o is the port impedance.

2. Passive vector modulator phase shifter

A passive vector modulator was first implemented in [4] using GaAs MESFET process. The configuration of this type of phase shifter is shown in the figure 1.5 in which three control voltages (V_{LP}, V_{HP} and V_o) are shown. By changing these control voltages in a specified range, amplitude of the signal can be changed and therefore, required phase shift can be achieved at a particular operating frequency.

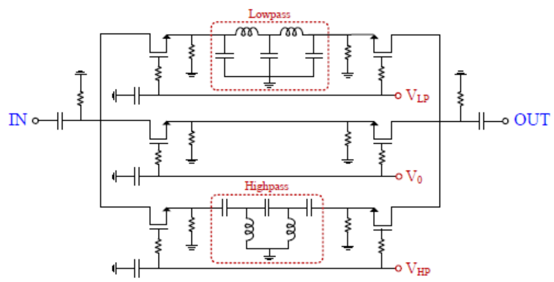

Figure 1.5: Passive vector modulator [4]

3. Switched network phase shifter

In this type of phase shifter, the output phase is obtained by varying the switching frequency between two phase shifter networks and is also known as switched delay line phase shifter. One network is known as phase shifting circuit and the other one is called phase reference circuit. A basic diagram for this topology using two single-pole double-throw (SPDT) switches is shown in figure 1.6. They can be implemented using the combination of low pass and high pass filter, and produces differential phase shift.

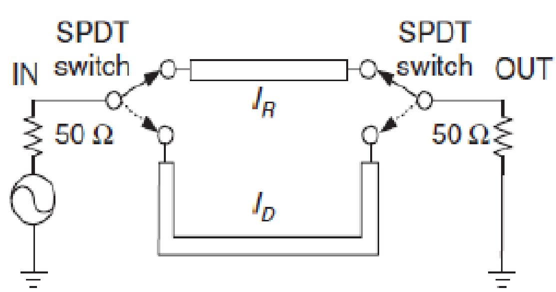

Figure 1.6: Switched network phase shifter [5]

The main disadvantage of these type of phase shifters is that the transmitted signal can be interrupted and this may create problem in communication systems.

4. Loaded line phase shifter

In these type of phase shifters design, a shunt reactance (an inductor or a capacitor) is added to the microstrip transmission line which cause the input signal to undergo a phase shift. In micro-strip transmission line, the reactive components can be formed by using microstrip open and short stub transmission line. This topology is used to tune the characteristics of a transmission line. The basic block diagram of loaded line phase shifter is shown in figure 1.7.

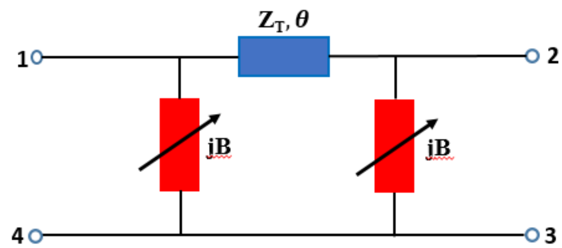

Figure 1.7: Loaded line phase shifter

The total phase shift and insertion loss of this type of phase shifter will be given by equation 1.12 and 1.13 respectively.

$$\text{Phase shift} = -\tan^{-1}\left(\frac{b}{2}\right) \tag{1.12}$$

and

$$\text{IL} = 10\log\frac{1+b^2}{4} \tag{1.13}$$

From equation 1.12, it is clear that for obtaining larger phase shift, value of constant 'b' should be high. And large value of 'b' will increase the insertion loss. Return loss of these phase shifter is also very poor. Therefore a **Modified loaded line phase shifter** with some extra circuitry also came into the picture. In this design, the return losses of loaded line phase shifter can be improved by using two shunt susceptance which are separated by 90 ° phase. In the implementation of these design, a transmission line is loaded with symmetric pair of reactive elements at its both ends. In this thesis work to design a wideband phase shifter, the configuration of loaded line phase shifter is used. It consists of a main line with a T shaped network and a modified conventional reference line with an L shaped network.

1.4 Motivation

I am writing to express my interest in pursuing my Master Thesis in RF Design on **Designing of Tri Band Coupler and Wideband Phase Shifter** starting in May 2016. I have been active member of the "RF and Microwave design Lab" group of IIIT Delhi, where I have been involved in several RF projects. I have also been involved in many workshops and seminars in this field. The reason for choosing this specific field comes from the fact that in the near future I would like to get to know many things and how they work in such a high frequency.

In past few decades, there has been a lot of innovations using RF waves as the growth in Radio Frequency (RF) wave research is evolving very fast because of its use in radio communications and other applications. In order to expand communication applications of RF waves, there is more demand for basic RF passive components which makes the communication efficiently and on a broad scale such as couplers, phase shifters, power dividers, mixers etc. The specification required for these components are that they should have high performance with very less cost, larger bandwidth, small size and also very less power consumption. Phase shifters has a several number of applications like in Radar system for multi-target tracking, in communication system as a RF transmitter, in high speed modulation, in aircraft and defence system etc.

Now a days, modern communication system requires the use of low cost, bandwidth efficient, compact size and multi band components. The designs operating at multi band frequencies has the advantage of both compact size and cost. Therefore, it becomes very fascinating to design the RF and microwave circuits with such specifications.

Moreover I can say that I would like to continue my research in this field in order to enhance my domain knowledge and I believe a Master Thesis in RF design would offer me the possibility of receiving a picture of some aspects of this field.

1.5 Literature Survey

In this section literature study for both branch line coupler and phase shifter components has been provided.

1.5.1 Branch Line Coupler

Till now, only a few number of works dealing with multi-frequency operation has been reported in the open source. Most of the research describes the devices with narrow band and dual band operation. The first basic analysis of a symmetric structure is provided in [6] but conventional branch line coupler consisting of only one section [7] [8] suffers with very narrow bandwidth. The bandwidth of a single stage branch line coupler is mainly limited by its electrical length and due to low bandwidth, a single stage branch line coupler is not suitable to wideband operation. Bandwidth can be increased by cascading more sections together presented in [9] but it will also increases the physical size of chip. Cascading many sections of transmission lines may also complicate the fabrication process. A lot of dual band coupler structures were also reported in [10] [11] [12]. Now a days, modern communication system requires the use of low cost, bandwidth efficient, compact size and multi band components. In [13], a design of branch line coupler using open stubs with high impedances was presented to obtain miniaturized size. The size reduction in this research was around 65 % as compared to that of conventional branch line coupler. But in this design, performance degrades. Another design of 10 dB coupler using DGS was provided in [14] to increase its bandwidth. After adding DGS in a structure, it introduces some inductance and increase the effective electrical length (θ) of the microstrip transmission line. Thus it provides slow wave characteristics and enhance the operational bandwidth.

A coupler having very flat coupling property is first realized in [15] using analytical equivalent admittance approach. In [15], Riblet proves that coupling of an externally matched branch line coupler is independent of frequency and depends on the impedance ratio of in and branch arm. In [16], tri band coupler is designed with compensation technique to achieve matching in pass band region. This design is capable of operating three arbitrary frequencies but it also involve the use of lumped components which restricts its use at high frequencies due to more parasitic effects. Another tri band coupler structure is presented in [17] consisting of an external matching network connected at each port of conventional

coupler. But in this design, there can be chosen only two arbitrary frequencies and third will the center of other two. Also this design doesn't give any information about phase at output ports. Its a 10 dB coupler, so equal power division is also not there at output ports.
In this thesis work, a tri band directional coupler is proposed operating at three arbitrary frequencies with equal power division and 90 ° phase difference at output ports. The reported coupler design possesses additional design variables and this provides it the flexibility to scale it to wideband operations.

1.5.2 Phase Shifter

Phase shifter is one of the most useful passive components in RF and microwave integrated circuits. Active phase shifters have more gain but they introduce high non-linearity to the system [18]- [19]. Passive phase shifters have better performance but they suffers from insertion loss [20]- [21]. In practical applications, phase shifter with large fractional bandwidth, low return loss are required and these specifications can be achieved by using various configurations. The concept of broadband phase shifters were first introduced by Schiffman [22] that the designing of wideband and matched differential phase shifter can be possible by using coupled transmission lines. After Shiffman, many improvements were achieved and there have been several reports [22]- [23] suggesting different architectures for the passive phase shifter working for a wide range of frequencies. Among the earlier reports are Schiffman phase shifter [22] which consists of a coupled line structure exhibiting a bandwidth of approximately 80 % with a phase ripple of 10 °. By proper selecting the length of lines and coupling factor, required phase difference can be achieved constant over a wide bandwidth. Schiffman phase shifter also requires a long reference line and tight coupling in coupled lines which is difficult to realize unless a very expensive thin film technology is used. The modifications in Schiffman phase shifter exhibit good performance but suffers from unequal odd and even mode velocities and design complexities [24] [25]. In one improvement, multisection coupled lines are used to compensate the difference in odd-even mode velocities [19] but these designs again requires tight coupling which is difficult to fabricate. Another multisection phase shifter design provided in [26] which has good return loss over more than 90 % bandwidth but has the limitation of small phase ripples. These designs still require narrow gap in coupled lines and high characteristics impedance. In [27], a structure of phase shifer using TEM transmission line for obtaining ultra wideband differential phase shift is presented. The design consists of a cascade of two blocks whereas each block is a single section coupled line with parallel transmission lines connected at each end. To obtain a wideband phase shifter structure, a switching network was combined with basic Shiffman phase shifter in [5]. The switching network consists of a half wavelength coupled line and 45 ° open and short stubs which are connected at edge of coupled line respectively. In [28], Garver presents phase shifter designs such as switched line, high-pass low-pass filter, reflection and loaded line phase shifters using different types of PIN diodes as a switching elements. In [29], various phase shifter topologies were presented to reduce the resonance effects.

The alternative simple designs with miniaturize structures possess slightly lower bandwidth i.e. approximately 80 % [30] [31]. Another structure [23] proposed for the wide band applications employs loaded inductor and capacitor. But due to the presence of lumped components, this type of phase shifters can work only at lower frequencies. A detailed synthesis procedure for symmetrically loaded RC bridge circuits were presented in [32]. In this phase shift is obtained by switching between two RC networks of second order. Another modification of Schiffman phase shifter in which slot under the coupled lines was cut on the ground plane and a rectangular conductor was inserted under the coupled line to act as a capacitor [25]. Phase imbalance of this design was within 5 ° over a wide bandwidth of 1.5 to 3.1 GHz. However, tight coupling and high impedance transmission lines are still needed which makes makes fabrication process more complicated. Latest improvement on Shiffman design was presented in [33] in which a broadband dumb-bell shaped 45 ° phase shifter was constructed using a parallel combination of OCSC stubs. The proposed phase shifer design in this research results in smaller size and wider bandwidth as compared to conventional phase shifter.

1.6 Organization of thesis work

This thesis work is organized as follows: In Chapter 2, proposed deisgn of Tri-band coupler and its analysis with result is discussed. Chapter 3 discusses about the proposed design of wideband phase shifter and its analysis in details. Finally, chapter 4 concludes the work done with comparing the proposed designs with the state of art designs.

Chapter 2

Design of Tri Band Branch Line Coupler

In this chapter, the proposed architecture for tri band BLC with its detailed analysis and different matching networks has been presented.

2.1 Matching Networks

Impedance matching networks are the blocks which are used for maximum power transfer from one network to another network and are mostly used in all RF/Microwave circuits. Power delivered from one network to other will be maximum when the load impedances matches with the source impedance i.e. $R_L = R_S$. This is also known as the condition of the maximum power transfer theorem. Matching networks are used to match a load impedance to source impedance. The load impedance and source impedance can be either of the real or complex. We mostly take source impedance (Z_S) a standard real impedance i.e. 50 Ω.

There are different type of matching network configuration depending on the requirement of number of operating frequencies. It can be dual, tri, quad or multi band matching network. **Dual band matching networks** are used in the circuits which are designed to operate at two arbitrary frequencies. A huge amount of research work on matching networks are focused on dual band frequency application. In this thesis work, a dual band matching circuit is used to match the complex load (obtained at the port of coupler) to the real 50 Ω impedance. The two operating frequencies for this are f1 (1.8 GHz) and f2 (2.4 GHz). A T-type network [34] has been used for this application. It is evident from the literature survey that designing of multi band matching network is very challenging as we increase the number of operating frequency of a design then its bandwidth gets divided. The designs operating at multi band frequencies has the advantage of both compact size and cost. Therefore, it becomes very fascinating to design the RF and microwave circuits with such specifications. Therefore, in this thesis work, a branch line coupler has been designed operating at three arbitrary frequencies. For port matching of coupler, a **Tri band matching network** is proposed operating at 1.8 GHz, 2.4 GHz and 3.5 GHz frequencies.

2.2 Proposed Design

The proposed design has symmetricity around all the four ports. The basic block diagram of the proposed design is shown in the figure 2.1. It consists of a core of conventional branch line coupler and external matching network at all the four ports. Dual and tri band matching circuit are used in matching network at each port to achieve good matching at all operating frequencies of the proposed design. The proposed architecture is capable to provide a phase shift of 90 ° and equal power division between through and coupled port. Due to symmetric structure, odd-even mode analysis can be easily applied for analytical design equation.

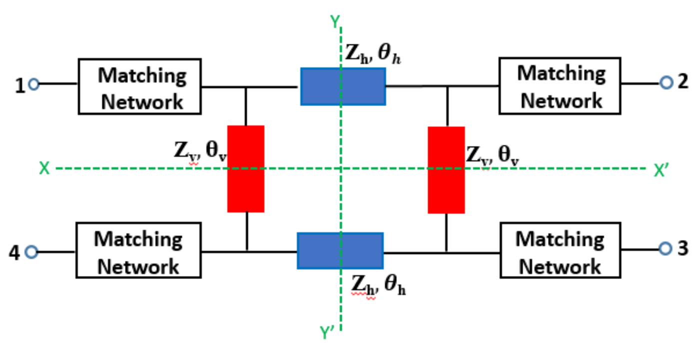

Figure 2.1: Basic Block Diagram of Proposed Design

Matching network as shown in figure 2.2 is a combination of dual and dual to tri band matching circuit to achieve good matching at all ports. Dual band matching consists of a T shaped network [34] and dual to tri band matching consists of a parallel combination of

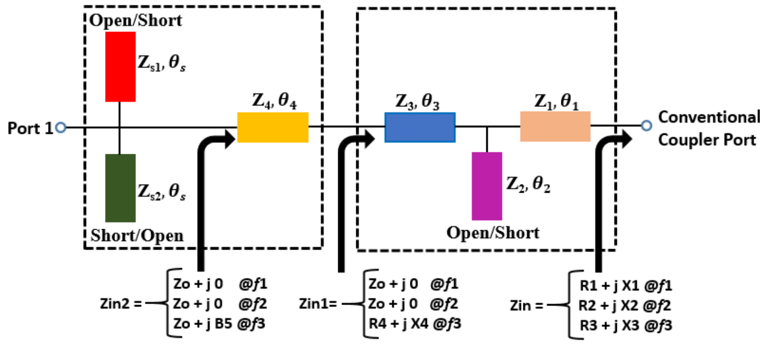

Figure 2.2: Matching Network

open and short stubs. A parallel combination of open and short stubs is used to provide matching at third frequency without disturbing matching at first two frequencies.

2.3 Design Analysis

The design parameters of the proposed circuit are determined with a systematic analytical procedure using even-odd mode analysis [6]. The microstrip transmission line is assumed to be nondispersive that is its characteristics impedance is independent of frequency and the electrical length is directly proportional to the frequency.

$$\theta = f \tag{2.1}$$

Thus according to equation 2.1, the electrical length (θ) at three operating frequencies 1.8 GHz, 2.4 GHz and 3.5 GHz are 90 °, 120 ° and 175 ° respectively.

The equivalent admittance of the coupler at its port is calculated using odd-even mode analysis. For simplicity, MATLAB is used for computing the impedance at each port of the coupler. The analytical equations for port impedance are given below [15]:

$$Y_{in} = \frac{Y_v \times \sqrt{(Y_o{}^2 - 1)}}{sin\theta} - Y_v(1 + Y_o)cot\theta \tag{2.2}$$

where $Y_o = Y_h/Y_v$ and $\theta_h = \theta_v = \theta$

The value of port impedances calculated from equation 2.2 will behave as a load impedance for the matching network. Now, first this load impedance is matched at f1 and f2 by using the dual band matching design procedure as explained in [34]. In this design, the parameters of left most transmission line is calculated in such a way that it gives conjugate impedances at f1 and f2 frequencies then a T shaped open circuited stub is used to cancel the imaginary part of this conjugate impedance and finally a transmission line is used to match the remaining real impedance to 50 Ω. In this way, the port impedance is matched at first two operating frequencies. The various design parameters of each transmisison line are listed in design parameter section of this chapter. Now after dual band matching, a parallel combination of Open Circuit Short Circuit (OCSC) stubs is used to obtain the matching at third design frequency. Design parameter of a OCSC is chosen in such a way that it provides infinite impedance at first two frequencies and for this to happen following conditions of equation 2.3 and 2.4 must be satisfied.

$$Z_{s1} = Z_{s2} \times tan^2\theta_s \tag{2.3}$$

and

$$\theta_s = \tfrac{(1+n)\pi}{1+r} \tag{2.4}$$

where, Z_{s1} and Z_{s2} are OCSC stub impedances as shown in the figure 2.2,
r = $f3/f2$ and 'n' is any integer.

Thus, this condition will cancel out the imaginary part of impedance obtained at third operating frequency without effecting matching at f1 and f2 and a transmission line is used to match real impedance at f3 to source impedance i.e. 50 Ω.

2.4 Design Parameters

Now following the design analysis provided in previous section, different design parameters of a tri band coupler working at 1.8 GHz, 2.4 GHz and 3.5 GHz are calculated. The fundamental frequency of the proposed design is 1.8 GHz. The port impedance of a conventional coupler calculated using equation 2.2 at three operating frequencies and is provided in equation 2.5.

$$Z_{in} = \begin{cases} 51.02 + i0.0, \text{ f1} \\ 17.67 - i21.65, \text{ f2} \\ 0.6391 - i1.560, \text{ f3} \end{cases} \tag{2.5}$$

The impedance calculated after T-shaped dual band circuit as shown in the figure 2.2 is Z_{in1} and provided in equation 2.6.

$$Z_{in1} = \begin{cases} 50.07 + i0.59, \text{ f1} \\ 50.05 - i0.50, \text{ f2} \\ 1.579 + i29.443, \text{ f3} \end{cases} \tag{2.6}$$

Various design parameters of matching network are calculated using the design procedure provided in previous section are listed in table 2.1.

Table 2.1: Design parameters of matching network

Parameter	Value	Parameter	Value
Z_1 (Ω)	21.80	Z_4 (Ω)	50.00
Z_2 (Ω)	44.00	Z_{s1} (Ω)	29.48
Z_3 (Ω)	53.23	Z_{s2} (Ω)	127.07
θ_1 ($^\circ$)	144.72	θ_4 ($^\circ$)	144.24
θ_2 ($^\circ$)	77.14	θ_{s1} ($^\circ$)	154.28
θ_3 ($^\circ$)	77.14	θ_{s2} ($^\circ$)	154.28

where Z is the characteristics impedance of transmission line and θ is its electrical length.

2.5 Simulation and Measurement Results

All the simulation of proposed design are carried out in Keysight ADS tool and the fabricated prototype results are measured using Keysight VNA (Vector Network Analyzer). Electro-Magnetic (EM) simulation and measured results for various scattering parameters are plotted and analyzed in details. The return loss (S_{11} parameter) are shown in Fig. 2.3. From Fig. 2.3 it is clear that the return loss at all the three operating frequencies is less than -38 dB for EM simulation and approximately -32 dB for measured results.

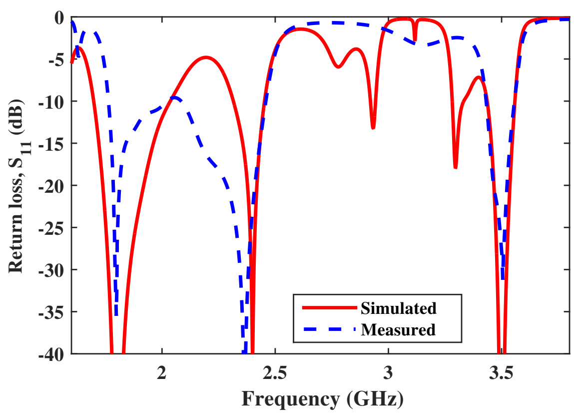

Figure 2.3: Return loss, S_{11} (dB)

Insertion loss (S_{21} parameter) is shown in figure 2.4 also known as transmission parameter and S_{31} is shown in figure 2.5, having value around 3 dB (2 to 4 dB) at all operating frequencies which shows transmission is taking place and also equal power division at output ports of designed coupler.

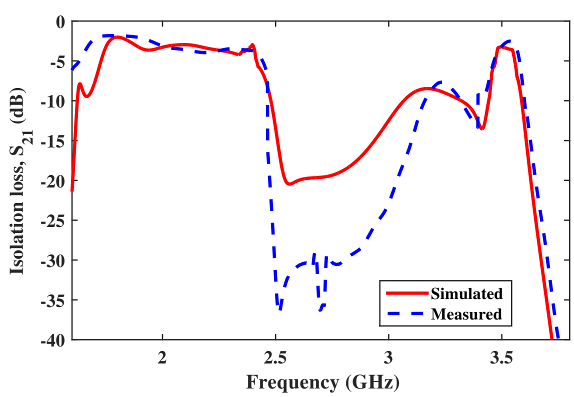

Figure 2.4: Insertion loss, S_{21} (dB)

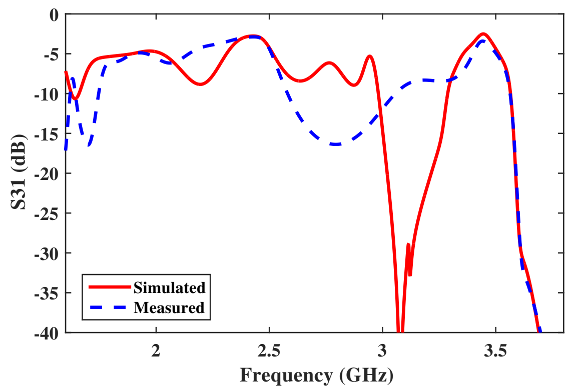

Figure 2.5: S_{31} parameter (dB)

Figure 2.6 shows the S_{41} parameter or isolation losses of designed coupler. From this figure, it is clear that the design provides good isolation at isolated port (port 4) as the value of S_{41} at all operating frequencies is less than -38 dB for both em simulated and measured results. The bandwidth obtained at the operating frequencies is approximately 120 MHz which is better than state of art bandwidth for tri band circuits.

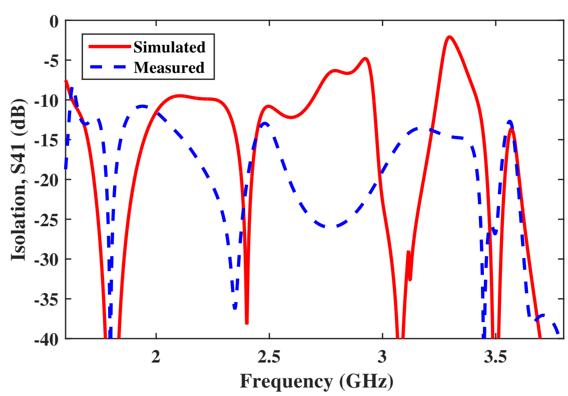

Figure 2.6: Isolation, S_{41} (dB)

The proposed design is able to provide a phase difference of 90° at all operating frequencies. The em simulated and measured phase difference between output ports i.e. transmitted port and coupled port is shown in the figure 2.7. From this figure, it is clear that the simulated and measured phase matches well and provides 90° phase at all operating frequencies. The fabricated prototype of the design is shown in the figure 2.8. This proposed design of coupler is also compared with the state of art techniques in table 4.1 provided in last chapter of this thesis.

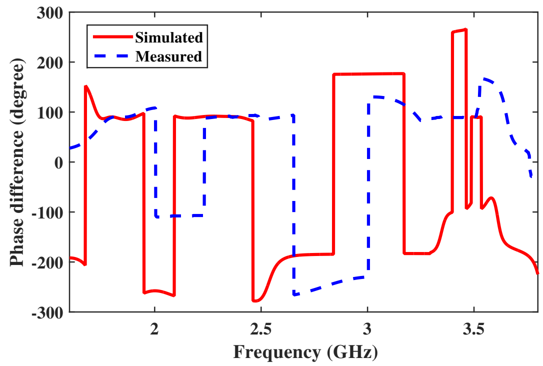

Figure 2.7: Phase difference

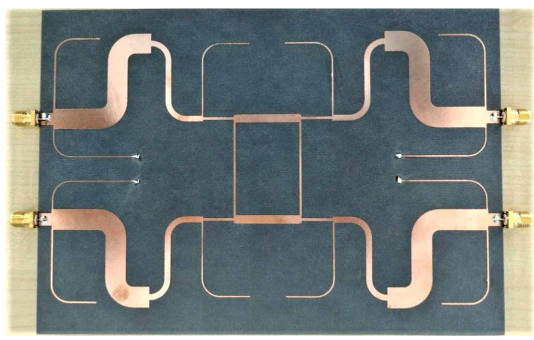

Figure 2.8: The fabricated coupler design prototype

2.6 Conclusion

A modified architecture of 3dB tri band branch line coupler working at three arbitrary frequencies is proposed in this work. External port matching technique is used at each port of the coupler to achieve good matching at all operating frequencies of the design. This architecture of coupler is capable to provide a phase shift of 90 ° and equal power division between through and coupled port. This design also gives good return loss and insertion loss at all design frequencies. To verify this reported design procedure, the design parameters of the coupler are computed for 1.8 GHz, 2.4 GHz and 3.5 GHz arbitrary frequencies. For validation of the proposed methodology, the prototype is fabricated using ROGER5880 substrate of thickness 1.575 and permittivity of 2.2. The measured results and the simulated results matches well and thus validates the deign. A comparison with state of art is provided in chapter 4 of this work which shows the advantages of this proposed design.

Chapter 3

Design of Wideband Phase Shifter

3.1 Proposed Design

The proposed wideband phase shifter in this thesis work is developed around two simple microstrip transmission lines. The basic building block for the proposed phase shifter shown in figure 3.1 consists of two microstrip line sections. One section is referred as the main line and other one is referred as reference line.

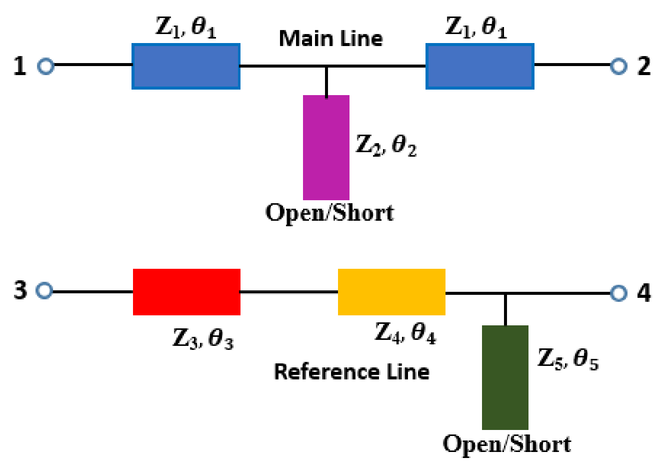

Figure 3.1: Architecture of proposed phase shifter

Here, the main line is a symmetric two-section transmission line [35] with a center tapped stub that forms a T-network. Whereas the reference line is a two-section transmission line tapped by a stub at the edge and this forms into an L-network.

Here, an open stub is used in the main line and a short stub is used in the reference line. The reported phase shifter design possesses additional design variables and this provides it the flexibility to scale it to wideband operations. The proposed concept is validated through a 90 ° phase shifter working at 1.8 GHz and prototyped on Rogers 5880 with substrate thickness of 1.575 mm and dielectric constant of 2.2. The prototype is able to provide a phase difference of 90 ° over a bandwidth of 106 % if phase ripple of 3 ° is considered. The characteristics impedance and the electrical length of all the transmission lines are denoted by Z_i in Ω and θ_i, in degrees (°) where i= 1,2,..,5. The required phase difference for this architecture is the transmission phase difference between the main line and the reference line.

3.2 Design Analysis

The microstrip transmission line is assumed to be non-dispersive that is its characteristics impedance is independent of frequency. The design parameters of the proposed circuit are determined with a systematic analytical procedure using ABCD parameters. The overall ABCD matrix of the main line and for reference line are provided in below expressions:

$$\begin{bmatrix} A_m & B_m \\ C_m & D_m \end{bmatrix} = \begin{bmatrix} \cos_{\theta_1} & jZ_1 \sin_{\theta_1} \\ jY_1 \sin_{\theta_1} & \cos_{\theta_1} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY_2 \sin_{\theta_2} & 1 \end{bmatrix} \begin{bmatrix} \cos_{\theta_1} & jZ_1 \sin_{\theta_1} \\ jY_1 \sin_{\theta_1} & \cos_{\theta_1} \end{bmatrix}$$

$$\begin{bmatrix} A_r & B_r \\ C_r & D_r \end{bmatrix} = \begin{bmatrix} \cos_{\theta_3} & jZ_3 \sin_{\theta_3} \\ jY_3 \sin_{\theta_3} & \cos_{\theta_3} \end{bmatrix} \begin{bmatrix} \cos_{\theta_4} & jZ_4 \sin_{\theta_4} \\ jY_4 \sin_{\theta_4} & \cos_{\theta_4} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -jY_5 \sin_{\theta_5} & 1 \end{bmatrix}$$

Here, "Y_i" denotes respective admittance value. The subscript "m" is used for the main line and "r" is used for the reference line throughout the paper.

It is convenient from these parameters to determine the S-parameters as given in equations 3.1 and 3.2. As the main line is symmetric, so it should have $S_{11} = S_{22}$, and $S_{21} = S_{12}$.

$$S_{11/33} = S_{22/44} = \frac{B_{m/r} + Z_0(A_{m/r} - D_{m/r}) - Z_0^2 C_{m/r}}{B_{m/r} + Z_0(A_{m/r} - D_{m/r}) + Z_0^2 C_{m/r}} \tag{3.1}$$

$$S_{12/34} = S_{21/43} = \frac{2Z_0}{B_{m/r} + Z_0(A_{m/r} - D_{m/r}) + Z_0^2 C_{m/r}} \tag{3.2}$$

where,

$$A_m = \cos 2\theta_1 - 0.5 Z_1 Y_2 \sin 2\theta_1 \tan\theta_2 \tag{3.3}$$

$$B_m = j(Z_1 \sin 2\theta_1 - Z_1^2 Y_2 \sin^2\theta_1 \tan\theta_2) \tag{3.4}$$

$$C_m = j(Y_1 \sin 2\theta_1 + Y_2 \cos^2\theta_1 \tan\theta_2) \tag{3.5}$$

$$D_m = \cos 2\theta_1 - 0.5 Z_1 Y_2 \sin 2\theta_1 \tan\theta_2 \tag{3.6}$$

$$A_r = \cos\theta_3 \cos\theta_4 - Z_3 Y_3 \sin\theta_3 \sin\theta_4 + Y_5(Z_3 \sin\theta_3 \cos\theta_4 + Z_4 \cos\theta_3 \sin\theta_4)\cot\theta_5 \tag{3.7}$$

$$B_r = j(Z_3 \sin\theta_3 \cos\theta_4 + Z_4 \cos\theta_3 \sin\theta_4) \tag{3.8}$$

$$C_r = j(Y_3 \sin\theta_3 \cos\theta_4 + Y_4 \cos\theta_3 \sin\theta_4 - Y_5(Y_3 Z_4 \sin\theta_3 \sin\theta_4 + Z_4 \cos\theta_3 \cos\theta_4)\cot\theta_5) \tag{3.9}$$

$$D_r = -Y_3 Z_4 \sin\theta_3 \sin\theta_4 + \cos\theta_3 \cos\theta_4 \tag{3.10}$$

Now, the phase shift of main line and reference line in terms of ABCD parameters can be given by equations 3.11 and 3.12 respectively.

$$Phase(S_{21}) = -\tan\left[\frac{B_{m'} + C_{m'} Z_0^2}{Z_0(A_m + D_m)}\right] \tag{3.11}$$

$$Phase(S_{43}) = -\tan\left[\frac{B_{r'} + C_{r'} Z_0^2}{Z_0(A_r + D_r)}\right] \tag{3.12}$$

$where\ B_{m'} = jB_m\ and\ C_{m'} = jC_m$

For any phase shifter, the following conditions must be satisfied:

$$\begin{aligned} |S_{11}| = 0;\ |S_{33}| = 0 \\ |S_{21}| = 1;\ |S_{43}| = 1 \end{aligned} \tag{3.13}$$

Finally, the phase shift at the operating frequency can be calculated as:

$$\text{Required phase shift} = Phase(S_{21}) - Phase(S_{43}) \tag{3.14}$$

The electrical length of the transmission line is directly proportional to the operating frequency of a transmission line.

$$\theta_f = \theta_{f0} \frac{f}{f_0} \tag{3.15}$$

where, θ_{f0} is the electrical length defined at operating frequency f_0.

Now, as the phase shift between the two transmission paths, i.e. the main line and the reference line, should be constant, the difference between the two phase slopes must be zero.

$$\frac{dPhase(S_{21})}{df} - \frac{dPhase(S_{43})}{df} = 0 \tag{3.16}$$

Equations 3.13, 3.15, and 3.16 can be used to obtain the value of various design parameters.

3.3 Design Example

Based on the design analysis provided in above section 3.2, four different cases of the phase shifters, working for 30 °, 45 °, 60 ° and 90 ° have been designed and simulated in ADS. The operating frequency for all the cases is 1.8 GHz. The design parameters of all the main line elements are provided in table 3.1 whereas table 3.2 contains the design parameters for the reference line.

Where, Z is the characteristics impedance and θ is the electrical length of transmission line.

Table 3.1: Design parameter of main line

Design Example	Phase Shift	$Z_1(\Omega)$	$Z_2(\Omega)$	$\theta_1(^\circ)$	$\theta_2(^\circ)$
Case 1	30 °	33.8	94.10	130.1	58.00
Case 2	45 °	69	105.6	57.00	49.30
Case 3	60 °	79.8	83.2	84.5	179.2
Case 4	90 °	61.9	75.0	130.2	166

Table 3.2: Design parameter of reference line

Design Example	Phase Shift	$Z_3(\Omega)$	$Z_4(\Omega)$	$Z_5(\Omega)$	$\theta_3(^\circ)$	$\theta_4(^\circ)$	$\theta_5(^\circ)$
Case 1	30 °	49.8	136.0	125.0	199.7	116.0	87.5
Case 2	45 °	34.0	130.0	122.0	102.7	79.70	87.90
Case 3	60 °	64.0	30.80	108.0	40.70	209.0	24.50
Case 4	90 °	29.5	100.0	95.00	225.6	108.0	110.6

3.4 Simulation and Measurement Results

All the four cases are designed in the Keysight ADS simulation environment and the performance is evaluated and demonstrated. Simulated return loss and insertion loss of main line for all cases are shown in figure 3.2 and 3.3 respectively.
From these results, it can be seen that return loss value is less than -40 dB at central frequency for all the four design cases and insertion loss value is unity throughout the required frequency range.

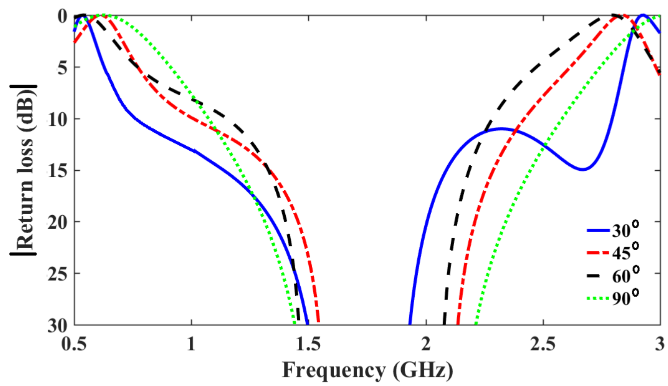

Figure 3.2: Simulated return loss for all design cases

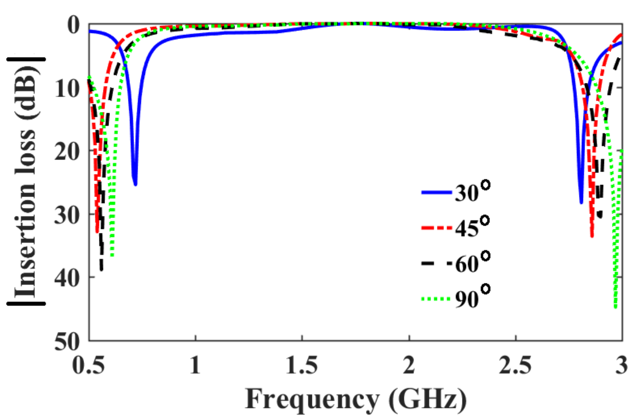

Figure 3.3: Simulated insertion loss for all design cases

Figure 3.4 shows the simulated phase difference for various design cases which provides a constant phase shift with 3 ° phase ripple throughout the required frequency range. As we increases the value of required phase shift then its bandwidth goes on decreases.

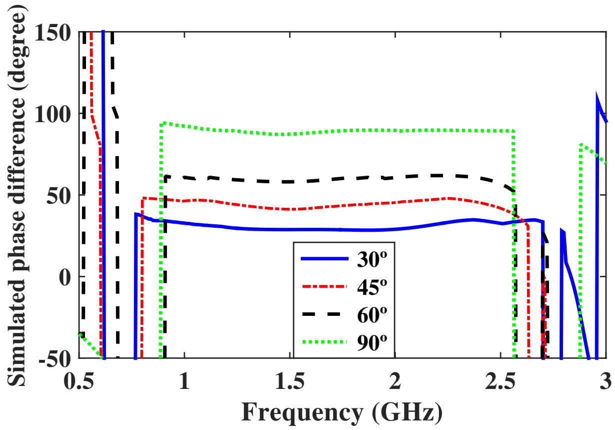

Figure 3.4: Simulated phase difference for all design cases

To validate the working of these design examples, a prototype for the case of 90 ° has been developed on Rogers5880 with substrate thickness 1.575 mm, relative dielectric constant 2.2, and tan as 0.0009, with the copper cladding of 35 μm on both the sides.

. The eventual design also requires slight optimization in the simulation environment for achieving flatter response. The fabricated prototype, with dimensions of 45 mm $\times$ 62 mm, shown in figure 3.5 is measured using Keysight VNA.

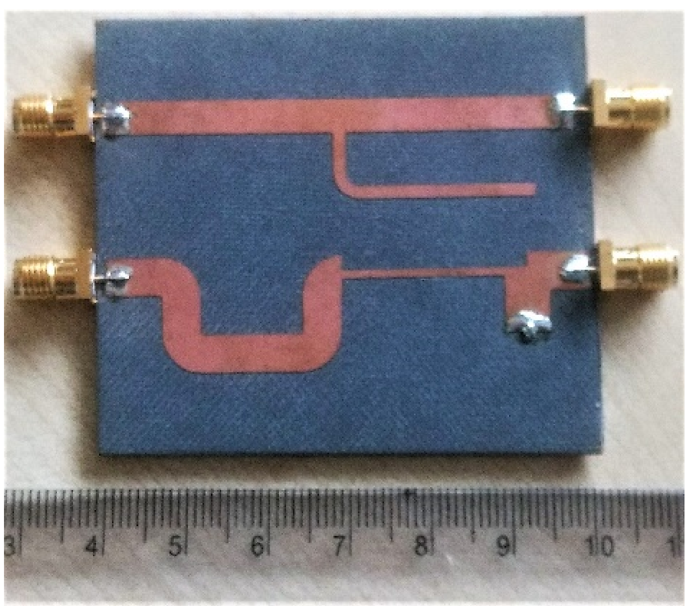

Figure 3.5: The fabricated prototype of phase shifter

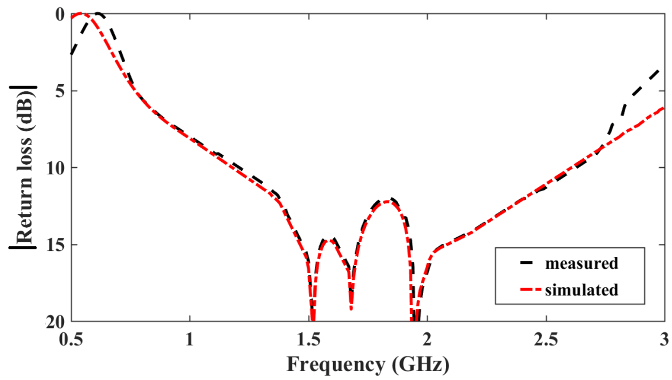

Figure 3.6: EM-simulated and measured return loss

All the measured results are compared with EM simulation results. Both simulated and measured results for return loss are plotted in figure 3.6 and for insertion loss plotted in figure 3.7. These figures confirms very good match between simulated and measured results.

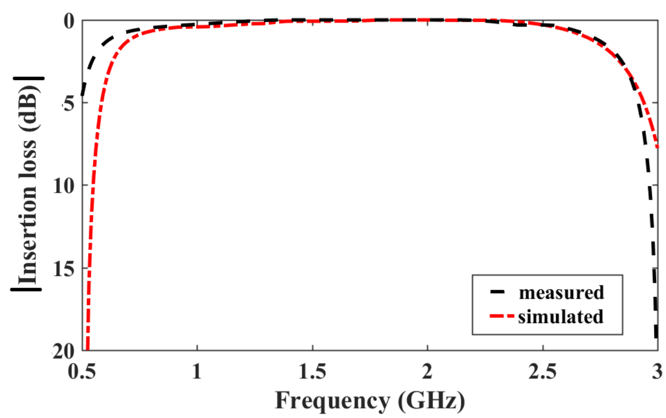

Figure 3.7: EM-simulated and measured insertion loss

The simulated and measured results for 90 ° phase shifter are provided in Fig. 3.8 which confirm very good return 90 ° phase difference for 106 % bandwidth (0.7 GHz to 2.6 GHz) for a phase ripple of 3 °. The measured results from the prototyped phase shifter are compared in next chapter with the state-of-the-art designs. It is apparent that the proposed phase shifter performs better over a larger bandwidth with small phase ripple and insertions loss.

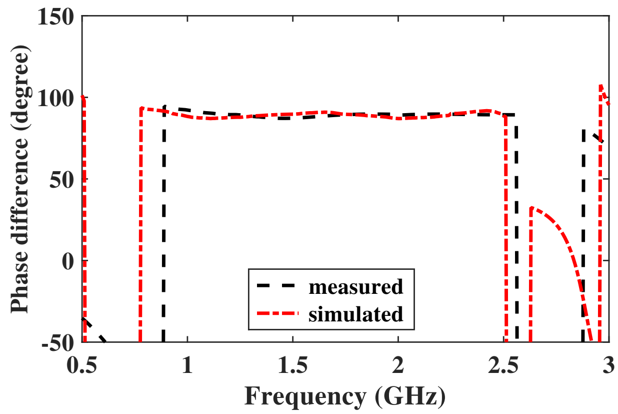

Figure 3.8: EM-simulated and measured phase difference

3.5 Conclusions

In this chapter, a unique wideband phase shifter is proposed. The design has a very simple architecture and can be analyzed easily. First the design was supported with mathematical modelling. After obtaining the electrical parameter values of the transmission line using mathematical modelling, the design was verified using Advanced Design System (ADS). A number of case studies have been presented to demonstrate the key concept behind the proposed technique. A prototype has been developed for the validation of the design procedure and it has been shown that a wideband performance with 106 % bandwidth considering 3 ° phase ripples can be obtained. A comparison with the state-of-the-art shows the advantages of the proposed technique.

Chapter 4

Comparison with State of Art

In this chapter, the proposed works are compared with the state of art designs.
As explained in previous chapters, a tri band coupler operating at three arbitrary frequencies and wideband phase shifter has been designed in Keysight ADS and fabricated prototype is measured with VNA. After measurement, the obtained results are compared with the various state of art designs and it is found that the proposed design has better performance.

Proposed designs of tri-band coupler and wideband phase shifter are compared with the state-of-art techniques keeping in perspective the various performance parameter of a design such as efficiency of design, circuit size, bandwidth, insertion loss (IL), return loss (RL) and complexity of design. The comparison of tri band coupler and wideband phase shifter are provided in Table 4.1 and 4.2 respectively.

Table 4.1: Comparison of proposed coupler with state of art technique

Ref	All Arbitrary Frequencies	Phase Difference (°)	Equal Power Division	Design Technique	Design Complexity
[16]	Yes	NA	Yes	Triple Band Resonator	***
[36]	No	90	Yes	Coupled line and DGS	***
[37]	No	NA	No	Resonators and microstrip stubs	**
[38]	Yes	90	No	Compensation Technique with folded microstrip stubs	**
[39]	No	90	Yes	Stepped Impedance Resonator	***
[17]	No	NA	No	Microstrip line	*
Proposed Coupler	Yes	90	Yes	Microstrip line	*

Table 4.2: Comparison of proposed phase shifter with state of art technique

Ref	Band-width (%)	Phase ripple (°)	Insertion Loss	Design Technique	Design Complexity
[25]	70	5.0	1.0	Coupled line and DGS	***
[30]	82	6.4	0.6	Microstrip line	*
[40]	80	4.0	2.5	Coupled line	**
[31]	67	2.1	2.5	Microstrip line	**
[23]	116	10	0.5	Lumped Components	*
Proposed Phase Shifter	106	3.0	1.0	Microstrip line	*

Chapter 5

Conclusion and Future Works

5.1 Conclusion

In this thesis work, a modified architecture of tri band branch line coupler and wideband phase shifter has been presented. The proposed architecture of tri band coupler operating at three arbitrary frequencies is capable to provide a phase shift of 90 ° and equal power division between through and coupled port. To validate the reported design procedure, a branch line coupler working at 1.8 GHz, 2.4 GHz and 3.5 GHz is prototyped.

In second part of this thesis, a unique structure for wideband phase shifter with stub loaded transmission line has been presented. A number of case studies have also been presented to demonstrate the proposed design technique. A prototype has been developed for the validation of the design procedure and the proposed wideband phase shifter is able to provide a bandwidth of 106 % considering only 3 ° phase ripples.

Both designs were fabricated using Rogers5880 with substrate thickness of 1.575mm and dielectric constant of 2.2. After simulation in ADS, All simulations of the proposed designs were carried out using Keysight ADS simulator and the fabricated design PCB has been practically tested using Vector Network Analyzer (VNA). The EM simulation and measurements results matches well and thus they validates the theory used in proposed designs.

5.2 Future Work

Slow wave structure can be used for reducing the size of circuits especially it reduces the physical length of the transmission line. The periodic shunt loading of these structures reduces the phase velocity and therefore increases the effective electrical length of the transmission line. This same concept can be used in miniaturizing the physical size of design and size reduction can be achieved by increasing the transmission line slow-wave factor. Slow wave factor (SWF) can be defined as the ratio of wavelength of free space wave to the wavelength of guided wave. SWF can be increased by using a high dielectric constant material in substrate as it gives smaller wavelength.

The tri band coupler design can be extended to quad band, multi band or broadband operating frequencies with wider bandwidth. Similarly, the wideband phase shifter can be further extended to multi-band operating frequency with wider bandwidth. Any new design technique can also be introduced to achieve better performance as compared to this work.

Bibliography

[1] "D. m. pozar, microwave engineering, 3rd ed., new delhi: J. wiley sons,2010."

[2] E. C. Desk, "Electronic warfare and radar systems engineering handbook," 1997.

[3] S. Y. Kim and G. M. Rebeiz, "A 4-bit passive phase shifter for automotive radar applications in 0.13 μm cmos," in *Compound Semiconductor Integrated Circuit Symposium, 2009. CISC 2009. Annual IEEE.* IEEE, 2009, pp. 1–4.

[4] F. Ellinger, R. Vogt, and W. Bachtold, "A high yield ultra small passive vector modulator based phase shifter for smart antenna combining at c-band," in *Microwave Conference, 2000 Asia-Pacific.* IEEE, 2000, pp. 794–798.

[5] J.-W. Lee and S.-Y. Kim, "60 ghz switched-line-type phase shifter using body-floating switches in 0.13 μm cmos technology," *Electronics letters*, vol. 48, no. 7, pp. 376–378, 2012.

[6] J. Reed and G. Wheeler, "A method of analysis of symmetrical four-port networks," *IRE Transactions on Microwave Theory and Techniques*, vol. 4, no. 4, pp. 246–252, 1956.

[7] W. A. Arriola, J. Y. Lee, and I. S. Kim, "Wideband 3 db branch line coupler based on λ /4 open circuited coupled lines," *IEEE microwave and wireless components letters*, vol. 21, no. 9, pp. 486–488, 2011.

[8] S. Lee and Y. Lee, "Wideband branch-line couplers with single-section quarter-wave transformers for arbitrary coupling levels," *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 1, pp. 19–21, 2012.

[9] C.-W. Tang, C.-T. Tseng, and K.-C. Hsu, “Design of wide passband microstrip branch-line couplers with multiple sections,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 4, no. 7, pp. 1222–1227, 2014.

[10] K.-K. M. Cheng and S. Yeung, “A novel dual-band 3-db branch-line coupler design with controllable bandwidths,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 10, pp. 3055–3061, 2012.

[11] H. Zhang and K. J. Chen, “A stub tapped branch-line coupler for dual-band operations,” *IEEE Microwave and Wireless Components Letters*, vol. 17, no. 2, pp. 106–108, 2007.

[12] J. Shao, *Dual-band microwave components and their applications.* University of North Texas, 2011.

[13] T. Moyra, S. K. Parui, and S. Das, “Design of t-split power dividers using dumbbell shared dgs,” , no. 8, pp. 7–7, 2012.

[14] T. Moyra, A. Roy, S. K. Parui, and S. Das, “Design of 10 db branch line coupler by using dgs,” in *Communications, Devices and Intelligent Systems (CODIS), 2012 International Conference on.* IEEE, 2012, pp. 516–519.

[15] G. P. Riblet, “A directional coupler with very flat coupling,” *IEEE transactions on Microwave Theory and Techniques*, vol. 26, no. 2, pp. 70–74, 1978.

[16] C.-Y. Liou, M.-S. Wu, J.-C. Yeh, Y.-Z. Chueh, and S.-G. Mao, “A novel triple-band microstrip branch-line coupler with arbitrary operating frequencies,” *IEEE Microwave and Wireless Components Letters*, vol. 19, no. 11, pp. 683–685, 2009.

[17] S. Tanigawa, K. Hayashi, T. Fuji, T. Kawai, and I. Ohta, “Tri-band/broadband matching techniques for 3-db branch-line couplers,” in *Microwave Conference, 2007. European.* IEEE, 2007, pp. 560–563.

[18] A. Asoodeh and M. Atarodi, “A 6-bit active digital phase shifter,” *IEICE Electronics Express*, vol. 8, no. 3, pp. 121–128, 2011.

[19] B. Schiek and J. Kohler, “A method for broad-band matching of microstrip differential phase shifters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 25, no. 8, pp. 666–671, 1977.

[20] F. Ellinger, R. Vogt, and W. Bachtold, "A high yield ultra small passive vector modulator based phase shifter for smart antenna combining at c-band," in *Microwave Conference, 2000 Asia-Pacific*. IEEE, 2000, pp. 794–798.

[21] C.-W. Wang, H.-S. Wu, and C.-K. C. Tzuang, "Cmos passive phase shifter with group-delay deviation of 6.3 ps at k-band," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 7, pp. 1778–1786, 2011.

[22] B. Schiffman, "A new class of broad-band microwave 90-degree phase shifters," vol. 6, no. 2. IEEE, 1958, pp. 232–237.

[23] H. Liu, L. Zhang, J. Pan, Y. Guo, and X. Dai, "Design of a wideband phase shifter using loaded element," in *2016 Progress in Electromagnetic Research Symposium (PIERS)*, Aug 2016, pp. 2153–2155.

[24] W. Steenaart, "The synthesis of coupled transmission line all-pass networks in cascades of 1 to n," *IEEE Transactions on Microwave Theory and Techniques*, vol. 11, no. 1, pp. 23–29, 1963.

[25] Y.-X. Guo, Z.-Y. Zhang, and L. C. Ong, "Improved wide-band schiffman phase shifter," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 3, pp. 1196–1200, 2006.

[26] W. J. Brown and J. P. Starski, "A broad-band differential phase shifter of novel design," in *Microwave Symposium Digest, 1999 IEEE MTT-S International*, vol. 3. IEEE, 1999, pp. 1319–1322.

[27] V. P. Meschanov, I. V. Metelnikova, V. Tupikin, and G. G. Chumaevskaya, "A new structure of microwave ultrawide-band differential phase shifter," *IEEE transactions on microwave theory and techniques*, vol. 42, no. 5, pp. 762–765, 1994.

[28] R. V. Garver, "Broad-band diode phase shifters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 20, no. 5, pp. 314–323, 1972.

[29] G. D. Lynes, "Ultra broadband phase shifters," in *Microwave Symposium, 1973 IEEE G-MTT International*. IEEE, 1973, pp. 104–106.

[30] S. Y. Zheng, W. S. Chan, and K. F. Man, "Broadband phase shifter using loaded transmission line," *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 9, pp. 498–500, 2010.

[31] X. Tang and K. Mouthaan, "Phase-shifter design using phase-slope alignment with grounded shunt $\lambda/4$ stubs," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 6, pp. 1573–1583, 2010.

[32] E. Menzel, B. Schiek, and A. Gronefeld, "Broadband phase shifters using rc-allpass-networks and active balun circuits," in *Microwave Conference, 1988. 18th European.* IEEE, 1988, pp. 397–402.

[33] S. Zheng, S. H. Yeung, W. S. Chan, K. F. Man, and S. H. Leung, "Improved broadband dumb-bell-shaped phase shifter using multi-section stubs," *Electronics letters*, vol. 44, no. 7, pp. 478–480, 2008.

[34] Q. Liu, Y. Liu, Y. Wu, J.-Y. Shen, S. Li, C. Yu, and M. Su, "Generalized impedance-transforming dual-band branch-line couplers for arbitrary coupling levels," *Progress In Electromagnetics Research B*, vol. 53, pp. 399–415, 2013.

[35] M. Maktoomi, M. Maktoomi, A. Yadav, M. Hashmi, and F. Ghannouchi, "Dual-frequency admittance property of two sections transmission-line and application," in *Circuits and Systems (MWSCAS), 2016 IEEE 59th International Midwest Symposium on.* IEEE, 2016, pp. 1–4.

[36] H. Ren, J. Shao, M. Zhou, B. Arigong, J. Ding, and H. Zhang, "Design of tri-band branch-line couplers using novel tri-band transmission lines," in *Texas Symposium on Wireless and Microwave Circuits and Systems*, April 2014, pp. 1–4.

[37] Z. Wang, J.-S. Jang, and C.-W. Park, "Tri-band rat-race coupler using resonators," in *Microwave Technology & Computational Electromagnetics (ICMTCE), 2011 IEEE International Conference on.* IEEE, 2011, pp. 186–189.

[38] F. Lin, Q. X. Chu, and Z. Lin, "A novel tri-band branch-line coupler with three controllable operating frequencies," *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 12, pp. 666–668, Dec 2010.

[39] F. Shirkani, A. Mallahzadeh, and N. Daryasafar, "Article: A novel tri-band branch-line coupler using stepped-impedance resonator," *International Journal of Computer Applications*, vol. 45, no. 14, pp. 10–12, May 2012, full text available.

[40] M. Sorn, R. Lech, and J. Mazur, "Simulation and experiment of a compact wide-band 90 *circ* differential phase shifter," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 3, pp. 494–501, 2012.