POLITECNICO DI TORINO

Master's Degree in Electronic Engineer
Wireless Systems Design

Master's Degree Thesis

Controllable Phase Shifters for Dynamically Steerable Antennas

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Summary

The following thesis is Steerable Antenna focused on the phase shifter part for GNSS application which working in 1.55 GHz to 1.57 GHz. The purpose of this thesis is to design an Analog Phase Shifter with the capability of phase shifting in 360° and a low return loss ratio. In this thesis, a quadratic hybrid branch line is used as the main part. The key component of the phase shifter is the Varactor Diode which its Capacitor value is varying by changing DC voltage which I used two of it. It works from 0 V to 5 V and its capacitance value is change in 12 different values. To prevent the effects of the DC voltage on the RF signal in the input and output, two Interdigital Capacitors are located on the input and output port. On the other hand, a low pass filter is connected to the quadratic hybrid branch line to block the RF signal path to the DC port. Moreover, for covering more phases, I have used 4 lines with 0°, 90°, 180° and 270° electric length respectively. To pass the signal through each line, two switches are placed at the output of the Analog Phase Shifter and the end of the lines. The substrate is I-Tera with $\epsilon_r = 3.45$ and its thickness is 0.250 mm. Moreover, the conductor is copper with a thickness equal to 18 μm

By this structure, the input RF signal is phased shifting in 48 different degrees (4 lines and each line has 12 phases). The return loss of the Analog Phase Shifter for all the phases is below -15 dB in the frequency range.

The Analog Phase Shifter is a low-cost phase shifter concerning the other types. Also in this thesis, it is tried to reduce the size of the Phase Shifter and decrease radiation loss.

Acknowledgements

First and most of all I want to thank to my love of my life, Tahmineh Javadzadeh, who has supported and encouraged me during this path and without her I couldn't go further even one step.
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Acronyms

IDC
: Interdigital Capacitor

FoM
: Figure of Merit

FET
: Field effective transistor

APS
: Analog Phase Shifter

GNSS
: Global Navigation Satellite System

GPS
: Global Positioning System

IC
: Integrated Circuit

Chapter 1

Introduction

1.1 Introduction

Antennas are the essential parts of any wireless communication. By increasing the demand for Wireless communication, researching antenna part has been grown up. One of the applications of wireless communication is in Navigation Systems. In navigation, antennas should be connected to the satellites to recognize the position of the user. Thus, the antenna should have the ability to change the angle of the beam which is called Beamforming, to increase efficiency, and could find the Satellite to make better connection. Beamforming in the antenna is done by phase shifters. Based on the usage and application, the phase shifters could be Electrical or Mechanical.
The mechanical phase-shifting procedure is to moving an antenna and set it at the desired angle by a mechanical stuff. Moving the mechanical part requires high power and also a large area to provide the mechanical unit. The speed of this change is low, concerning the electrical phase shifter. The mechanical Phase shifter has uncertainty and also a large area for providing movement of an antenna. Moreover, it costs more than an electrical one and low efficiency. Also uses more power than the electrical one. Due to these reasons in many cases, Electrical Phase Shifters is preferred.
Electronic Phase Shifters are two types: Analog Phase Shifters and Digital Phase Shifters.
In the Digital Phase Shifters, phase shifting is done by an IC. Each phase shifter controlled by a controller. Based on the number of bits, the phase shifter can shift the signal for the specific number of degrees (2^n; where n is the number of bits). The main advantage of the digital type is accuracy. On the other hand, their cost is usually higher than the Analog one and also they need a control circuit for controlling the phase shifting. Moreover, the number of phases are limited due to

the number of bits. However, in Analog Phase Shifter it could cover more phases by changing the variable unit in it.
Analog phase shifters can be implemented by using lumped elements or microstrip lines or waveguide phase shifters. The main concept of electronic phase shifting is providing a delay in the signal. This delay in electronics could be provided by lumped elements such as capacitors and inductors or by distributed elements for instance different lengths of the microstrip lines. In the waveguide model, phase shifting is done by inserting posts and surfaces as capacitors and inductors. In this project, the consideration is on distribution type of Analog Phase Shifter.
In the microstrip Analog Phase Shifters, the main part is the microstrip branch-line

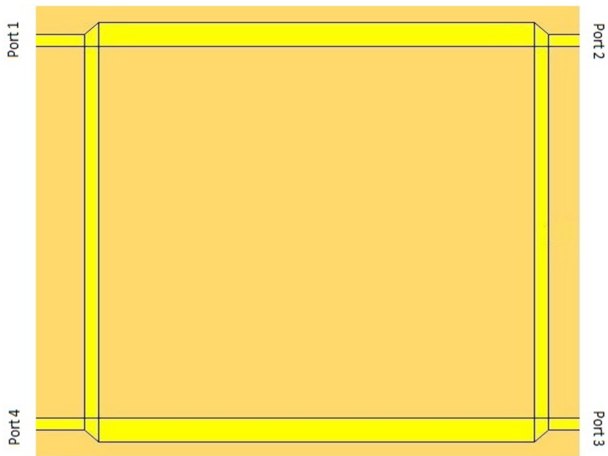


Figure 1.1: Quadrature Hybrid-Branch Microstrip Line

quadrature hybrid which is 4 port component as it is represented in the figure 1.1. Two of them are connected to the input and output(e.g. Port 1 and Port 4, two ports on the left side), and the rest of them use for other components to provide phase shifting(Port 2 and Port 3, two ports in the right side). The phase-shifting approaches are various. For instance, impedance terminating is used in Port 2 and 3, and in port 1 and 4, put impedance matching[1]. The other approach is to use some varactor capacitors and inductors for phase-shifting [2]. In another case, varactor diode connected to series inductor on port 2 and 3 [3]. Also by cascading the varactor diodes by a quarter wavelength line in port 2 and 3 it can be provided full 360° phase shifting[4]. Furthermore, by using two parallel varactor diode in series with another varactor diode provide phase shifting [5]. Moreover, two series quadrature hybrid can be connected with resonated loads [6]. Another approach is that instead of using quadratic hybrid, use rat-race coupled [7].In some cases for designing analog phase shifter consideration is on the Figure of Merit (FoM) [8]. Also, the idea of using FET transistor has been implemented for phase-shifting [9]. In some instances, the Bandwidth of the phase shifter is considered. Therefore, a wideband quadratic hybrid has been designed which is slightly different from the usual one[10].

1.2 GNSS

GNSS is Global Navigation Satellite Systems, is the navigation system which is used satellites to provide geospatial position. After receiving data from a user, it provides geometrical information such as height, latitude, and longitude.
GNSS has different terms concerning different countries which are: GPS for United State, Galileo for European Union, GLONASS for Russia, and BDS for China [11]. All global navigation systems use same frequency and signal L1 and nowadays many applicants can use more then one navigation systems but in the rare systems, they should use just GPS system.
Four more important issues in performance of GNSS are [12]:

- Accuracy
- Integrity
- Continuity
- Availability

Accuracy is important due to the difference of real position, velocity and timing and the information which is received. Integrity is about the capability of the GNSS in prividing service. Continuity is important because GNSS shouldn't have stop or lag. And finally GNSS should always be available for all users

Chapter 2

Design

2.1 Introduction

In this project, I have designed an Analog Phase Shifter in GNSS frequency band and it is working between 1.55 GHz to 1.57 GHz.
My approach is using two varactor diodes to provide phase shifting. Moreover, for decreasing insertion loss and increasing the phase coverage it has been used RF block, DC block, and two switches.
In this Analog Phase Shifter, the varactor diodes are connected to port 2 and port 3. These varactor diodes consist of the variable capacitor, resistor, and inductor. The variation of the capacitance is related to DC voltage. Therefore, in the phase shifter, DC voltage is needed. simultaneously, phase shifters are used for the RF frequency band. Due to the existing RF and DC signal, it should be considered that there is no cross-talking and noise in the input and the output. DC voltage doesn't have to be in the input and output port so Interdigital Capacitor has been used to perform as a DC Block. Also, RF signal is not allowed to be on the DC port. Thus, Low Pass Filter has been designed.
Furthermore, two switches are connected on the output port in series. Between these two switches, 4 lines are designed for providing 0°,90°,180° and 270° delays. The substrate used in this project is I-Tera with dielectric constant ϵ_r=3.45 and the height is 0.250 mm. The conductor is copper with 18μm thickness.
The two DC Blocks and the varactor diodes have been connected to ports 1 & 4 and ports 2 & 3 respectively of the quadratic hybrid 1.1. The LPF's output is located between port 2 and port 3. Two switches are connected to the Output port. In this project, two different models of switches have been used. One of them is NJG1684ME2 for the JRC company and the other one is MASWSS0192 for MACOM company. I had to use one pair of switches in the output and between them, depends on the model of the switches, 2 or 4 lines with different delay lines.

JRC switch has 4 paths and 1 IN/OUT port. Therefore, it can connect 4 different lines to provide 0°, 90°, 180° and 270° delays as it is shown in the figure 3.14.

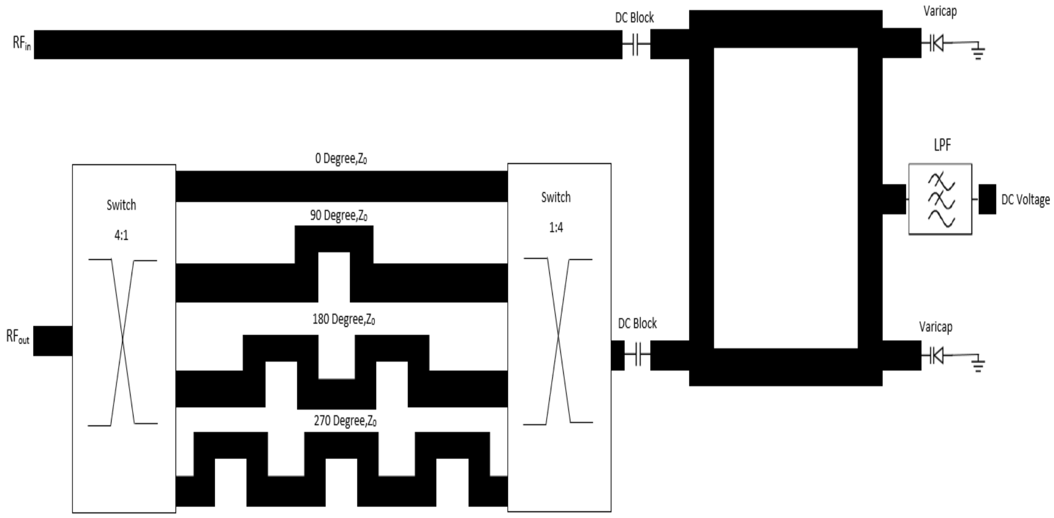


Figure 2.1: Schematic of the Analog Phase Shifter with JRC switches

On the other hand, the MACOM switch has 2 paths and 1 IN/OUT pin. Thus, 2 lines with different delay length can be connected to it which these lines are 0° and 180° represented in the figure 3.17

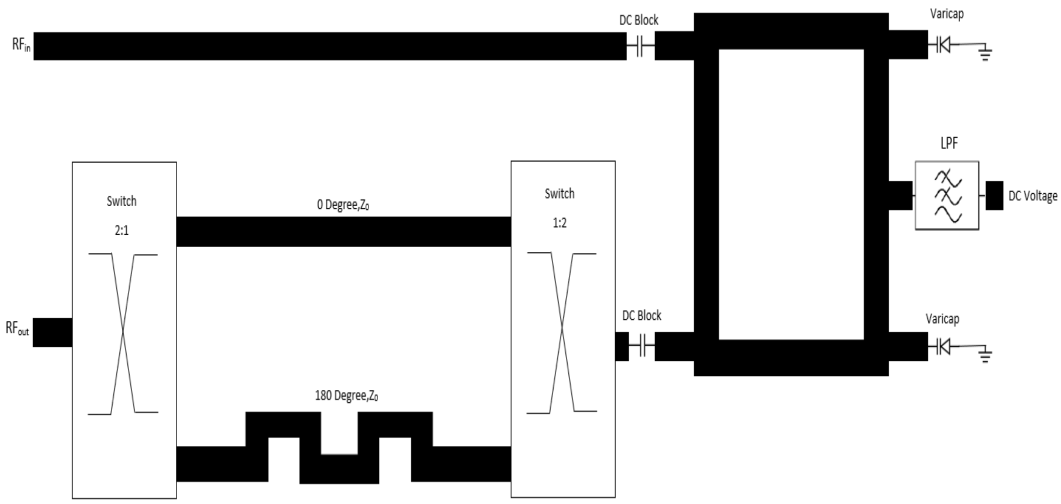


Figure 2.2: Schematic of the Analog Phase Shifter with MACOM switches

Moreover, JRC switch is 2 bit to control the 4 paths (2^2=4). Also, MACOM is

2 bit too but it has 2 paths and the controlling approach is different with respect to JRC one.
In the following sections, each part will be explained in detail.

2.2 Branch-Line Quadrature Hybrid

As it was mentioned in the first chapter, one of the key components of an Analog Phase Shifter is a branch line quadrature hybrid . A Quadrature Hybrid is a kind of 3dB directional couplers which in its output ports have 90° difference. A Quadrature Hybrid can be designed by microstrip or strip lines. By the definition of directional coupler, as it is shown in the figure 2.3, port 4 is isolated. As a result its scattering matrix become as the 2.1 [13] .

$$\left[S\right] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & \jmath & 1 & 0 \\ \jmath & 0 & 0 & 1 \\ 1 & 0 & 0 & \jmath \\ 0 & 1 & j & 0 \end{bmatrix} \tag{2.1}$$

Moreover, a branch line is a symmetric component consists of 4 arms and it is superposition. The characteristic impedance and the impedance of ports can be calculated by analyzing the branch line with even and odd mode analysis.
According to the figure 2.3, the quadrature consists of 4 arms with same length ($\lambda/4$). As it is shown, characteristic impedance of the one pair of arms is $Z_\circ/\sqrt{2}$ and the others are $Z_\circ$.
The other feature of the output powers in the port 2 and 3 is that they have 90

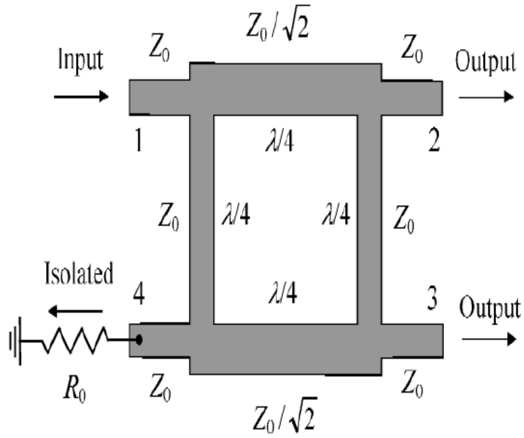


Figure 2.3: Branch Line Quadrature Hybrid with Microstrip

degree phase difference concerning each other.

2.3 Design of Interdigital Capacitor (DC Block)

Following the previous section, the desired frequency is in the range of 1.55 GHz and 1.57 GHz. Also, this Analog Phase Shifter is connected to the DC voltage supply for controlling the varactor diodes. Therefore, the DC voltage could have effects on the RF signal in the input and the output. As a result, a DC Block is connected to filter the DC voltage.
DC Block should be a filter in Band Pass or High Pass type. In many projects to prevent the effects of DC voltage in the input and the output, use capacitors. This capacitor should filter DC voltages. Also in some cases, a capacitor is used in series of input/output ports to avoid the damages of DC voltage such as signal measuring equipment for instance in Oscilloscope.
In general, Capacitor is an Electronic component consists of two metals and a gap between them. The gap can be filled by dielectric or air with respect to the application and desire capacitance value. One of the main usage of a capacitor is DC Block and AC filter and for these applications, the capacitor should be connected in series and shunt respectively.
Moreover, especially in high-frequencies, each to near metals can perform as a Capacitor. Also, as it will be discussed in the next section, open circuit microstrip line with specific length could be capacitor too. It could be justified by using Smith Chart.
Generally, capacitors have many different types for instance lumped capacitor, Monolithic or Interdigital capacitor [5]. Based on the size, cost, capacitance value and frequency they are used in various applications.
In this project, as it was mentioned in the first, the application is DC blocking in frequency range between 1.55 GHz to 1.57 GHz, the Interdigital Capacitor has been used.
An Interdigital Capacitor is a periodic component which is consisted of specific number of fingers and the gaps between them as it is shown in figure 2.4 [14].

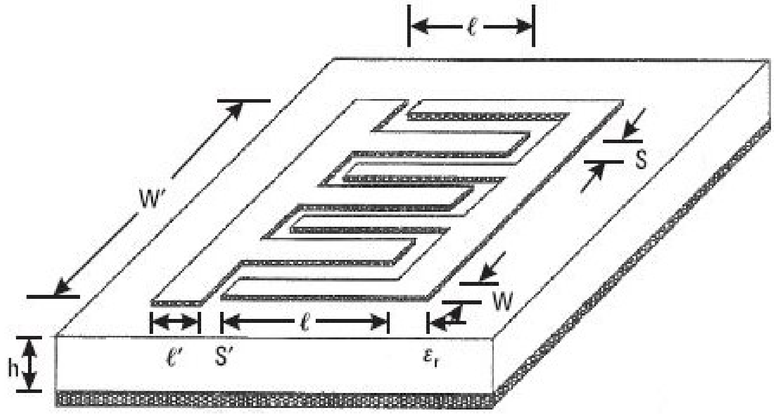


Figure 2.4: Interdigital Capacitor schematic

As it is shown in the figure 2.4, the length and the width of the fingers are W and ℓ respectively. Also the gap between the fingers is S which most of the time is equal to W. These parameters and the number of fingers are main characters of an Interdigital Capacitor.
The equivalent circuit of the IDC consists of Inductors and Capacitors in series and parallels as the figure 2.5 . As it is shown in the figure 2.5, inductors are along the length of fingers and by increasing the length, inductor value will be increased. As it is represented in the figure 2.5, in the equivalent circuit of the IDC, there are some capacitors. The gap between fingers , in S, makes the capacitors. Furthermore, in the S' and between the IDC and ground exist some capacitors too. By increasing the gap (S' or W) or the height of the dielectric (h), Capacitance value will be increased,

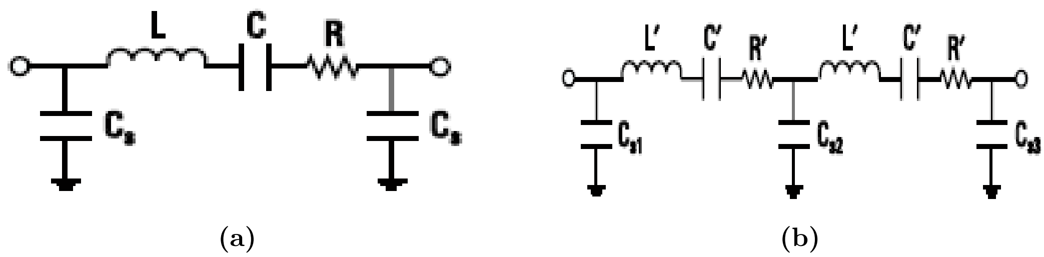


Figure 2.5: Equivalent Lumped Element model of IDC,(a) Low frequency (b) High frequency

The equivalent capacitor of the IDC could be approximate with the parallel of interior and exterior capacitors. Based on this assumption the equivalent capacitor is:

$$C = \frac{\epsilon_r + 1}{W'} \ell[(N-3)A_1 - A_2] \tag{2.2}$$

In the equation 2.2, C is the capacitance per unit length along W′.In the equation 2.2, N represents the number of fingers and ϵ_r is the dielectric constant of the substrate. The dimensions of the W′ and ℓ in the figure 2.4 are in the micron.
As it was mentioned before, an IDC consists of interior capacitors which are A_1 and exterior capacitors A_2 in the equation 2.3. As it is obtained from the equation 2.3, by increasing the thickness of the dielectric, the capacitance will be increased.If the substrate height h is finite, its effects on the equivalent capacitance, should be considered. Moreover, to reduce an error in the IDC, consider S=W. The values of A_1 and A_2 are capacitance along the length of the fingers in micron (ℓ) and they are obtained by approximation curve fitting data in [15]. These expressions are provided in follow:

$$A_1 = 4.409 \tanh[0.55(\frac{h}{W})^{0.45}] \times 10^{-6} (pF/\mu m) \tag{2.3a}$$

$$A_2 = 9.92 \tanh[0.52(\frac{h}{W})^{0.5}] \times 10^{-6} (pF/\mu m) \tag{2.3b}$$

The IDC's series resistor is obtained by:

$$R = \frac{4}{3} \frac{\ell}{WN} R_s \tag{2.4}$$

Where the R_s is sheet resistivity in ohm per square of the capacitor's conductor.
The metal thickness affects on the Quality factor of the IDC which is obtained by:

$$Q_c = \frac{1}{\omega CR} = \frac{3WN}{\omega C 4 \ell R_s} \tag{2.5}$$

Furthermore, two other parameters can be calculated by the equations which are series capacitance C_s and inductance L. They are calculated when S/h≪1. Under this assumption, by microstrip transmission line theory, L and C_s are calculated. Based on this assumption magnetic line field loop around the cross section of W' but not along the fingers. Moreover, C_s will be assumed that is microstrip total shunt capacitor over 2. The equation will be discussed in the followed.

$$L = \frac{Z_0 \sqrt{\epsilon_{re}}}{c} \ell \tag{2.6a}$$

$$C_s = \frac{1}{2} \frac{\sqrt{\epsilon_{re}}}{Z_0 c} \ell \tag{2.6b}$$

In the equation 2.6, $Z_\circ$ and ϵ_{re} should be obtained by W' and h of the microstrip and c=3 $\times$ 10^{10} cm/s is the light speed in the space.
The total series capacitance of an IDC is calculated

$$C = \frac{\epsilon_{re} \times 10^{-3}}{18\pi} \frac{K(k)}{K'(k)} (N-1)\ell(pF) \tag{2.7}$$

where ℓ is in micron and W is microstrip width. Also ϵ_{re} is effective dielectric constant and N referred to the Number of fingers.
The first kind K(k) and its complement K′(k) elliptic integral is

$$\frac{K(k)}{K'(k)} = \begin{cases} \frac{1}{\pi} ln(2\frac{1+\sqrt{k}}{1-\sqrt{k}}) & \text{for} \quad 0.707 \leq k \leq 1 \\ \frac{\pi}{ln(2\frac{1+\sqrt{k}}{1-\sqrt{k}})} & \text{for} \quad 0 \leq k \leq 0.707 \end{cases} \tag{2.8}$$

Also

$$k = \tan^2 (\frac{a\pi}{4b}), a = W/2, b = (W+S)/2, k' = \sqrt{1-k^2} \tag{2.9}$$

furthermore, there is a curve to help how to obtain the IDC's parameter which is called designed curves.
One of the main critical points in designing an IDC is to consider the discontinuity

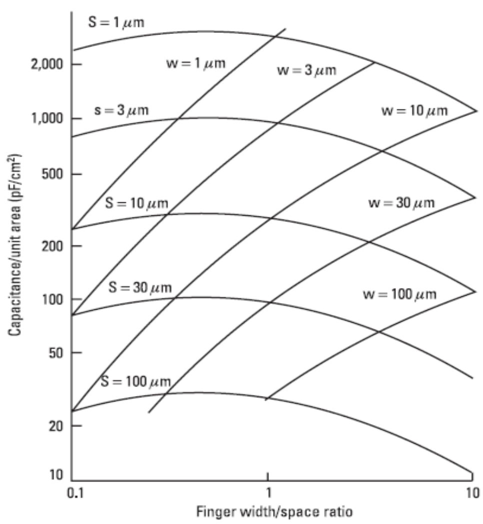


Figure 2.6: Design Curve

between the feeding line and the IDC. Due to this issue, the number of fingers and also the gap between the fingers and width of fingers shouldn't cause significant discontinuity. Otherwise, the equations don't work properly and also the bandwidth will be reduced.

2.4 Design of Filter (RF Block)

A filter is a component which is used to block undesired signals and pass desired one. Filters are two types: passive filters and active filters. Passive filters consist of inductors and capacitors and active filters including resistor too.
Based on the frequencies passed through filters they divided into: Low Pass Filters, Band Pass Filters, Band Stop Filters, High Pass Filters, and All-Pass Filters.
The main parameter of any filter is the transform matrix of the filters [16]. By the Transform function, it is possible to determine all features of the filter.

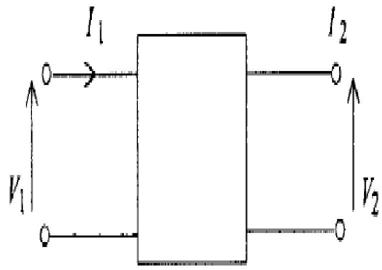


Figure 2.7: Two Port Network[16]

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{2.10}$$

According to the equation 2.10 transform matrix is:

$$\begin{bmatrix} T \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{2.11}$$

And the relation between ABCD and Scattering parameters are:

$$S_{11} = \frac{A - D + B - C}{A + B + C + D} \tag{2.12a}$$

$$S_{22} = \frac{D - A + B - C}{A + B + C + D} \tag{2.12b}$$

$$S_{21} = \frac{2}{A + B + C + D} \tag{2.12c}$$

Thus

$$|S_{21}(j\omega)|^2 = \frac{4}{|A+B+C+D|^2} \tag{2.13}$$

By using 2.13 and 2.12, the behaviour of desired filter can be obtained.
Moreover, by cascading the different components to each other the transformation matrix become 2.14

$$\begin{bmatrix}T\end{bmatrix} = \begin{bmatrix}T_1\end{bmatrix}\begin{bmatrix}T_2\end{bmatrix} .... \tag{2.14}$$

The transfer function of the simple two port series elements as it is shown in the figure 2.8 is :

$$\begin{bmatrix}T\end{bmatrix} = \begin{bmatrix}1 & Z \\ 0 & 1\end{bmatrix} \tag{2.15}$$

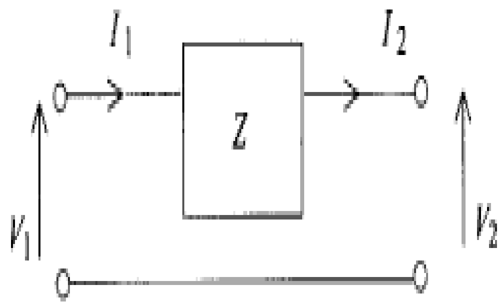


Figure 2.8: Series Circuit Element

On the other hand, for the shunt two-port element shown in the figure 2.9 the transform function is:

$$\begin{bmatrix}T\end{bmatrix} = \begin{bmatrix}1 & 0 \\ Y & 1\end{bmatrix} \tag{2.16}$$

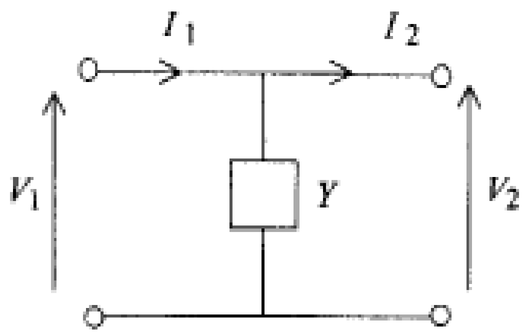


Figure 2.9: Shunt Circuit Element

For distributed elements, Transfer function is change to 2.17

$$\begin{bmatrix}T\end{bmatrix} = \begin{bmatrix}\cosh(\gamma l) & Z_o \sinh(\gamma l) \\ Y_o \sinh(\gamma l) & \cosh(\gamma l)\end{bmatrix} \tag{2.17}$$

In the lossless line $\alpha = 0$, so $\gamma = j\beta$. where:

$$\gamma = \alpha + j\beta \tag{2.18}$$

In the lossless line $\alpha = 0$, so:

$$\gamma = j\beta \tag{2.19}$$

Moreover, in the 2.19:

$$\beta = \frac{\lambda}{2\pi} \tag{2.20}$$

The wave velocity is v :

$$v = f\lambda \tag{2.21}$$

so,

$$\beta = \frac{\omega}{v} \tag{2.22}$$

then,

$$\beta l = \frac{\omega l}{v} = a\omega \tag{2.23}$$

where

$$a = \frac{\omega}{v} \tag{2.24}$$

As a result transform function become:

$$\begin{bmatrix} T \end{bmatrix} = \begin{bmatrix} \cosh(a\omega) & Z_o \sinh(a\omega) \\ Y_o \sinh(a\omega) & \cosh(a\omega) \end{bmatrix} \tag{2.25}$$

Another fundamental parameter of the filters is the Degree of the filter. The degree is the number of inductors and capacitors which are used in the filters.
In Designing filters, there is some common prototype and approach such as Butterworth, Chebyshev and elliptic filters which have specific features and complexity for various applications. These features are insertion loss, rolling off, and so on.
In Handbooks for any types of filter, for desired frequency, have been provided many tables. One of these books is [13] that is used for designing filters in this project.
The filters can be designed with lumped elements and distributed elements. Also for very high frequencies, it could be designed with waveguides. In this project, the distributed one is considered.
For designing any filters, the first step is to recognize the type of our filter, for instance, the low pass filter. Then if there is any limitation for Loss, we should choose the proper degree of the filter. After that based on the cut-off frequency, the values for the LC prototype should be chosen. It could be done by using the tables in the Handbooks.
By extracting the values of inductors and capacitor, with equation 2.26 we can find the correct values of the components.

$$L'_k = \frac{R_0 L_k}{\omega_c} \tag{2.26a}$$

$$C'_k = \frac{C_k}{R_0 \omega_c} \tag{2.26b}$$

According to the figure 2.10, the short circuit and open circuit have represented the inductor and capacitor respectively. This transformation is called Richard transformation [16] The distribution filter has two types: the normal one and the stepped impedance. In this project, the former one has been considered. In this type g values extracted from the Handbooks and the Z=g$\times$ Z_0 represent the

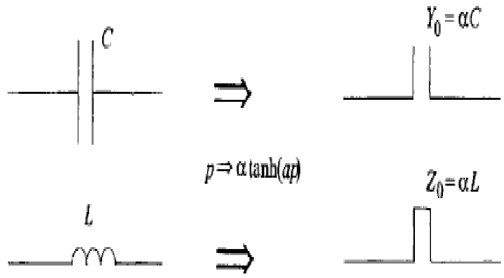


Figure 2.10: Richard transformation

impedance of the line. The length of the microstrip lines should be $\lambda/8$. With this information, the designing progress is started.

2.5 Varactor Diode

A diode is the first semiconductor component. A simple type of diodes is made of a p-n junction. The main characteristic of the diode is ideally zero-ohm resistant in one direction and infinite resistance in the other directions.
Based on the p and n materials and also a combination of them with metals, the diodes are used in different applications. Some common types of diodes are Diode, LED (Light Emitted Diode), Photodiode, Schottky, Varicap to varactor diode, Zener diode.
In this project, Varicap or Varactor diode has been used. The key feature of this diode is that its total capacitor varying by changing the voltage in reverse bias. The internal structure of varicap diode is shown in figure 2.11 [17].

As it is mentioned in figure 2.11, same as the other diodes, it has a p-n junction. By increasing voltage, the depletion layer between p and n is increased and by decreasing voltage, it decreased. Changing the size of the depletion layer cause changes in the total capacitance parameter of the diode as it is presented in the figure 2.12.

Varactor is used in VCO (Voltage Control Oscillator), frequency multiplier, and parametric amplifier. VCO is used in PLL (Phased Locked Loop) and transmission and modulation like FM modulation.
The figure 2.5 indicates the equivalent circuit of the varactor diode [18].

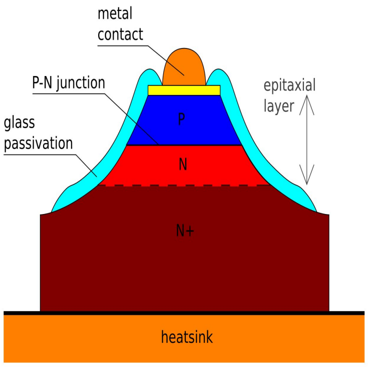


Figure 2.11: Internal Structure of Varactor Diode

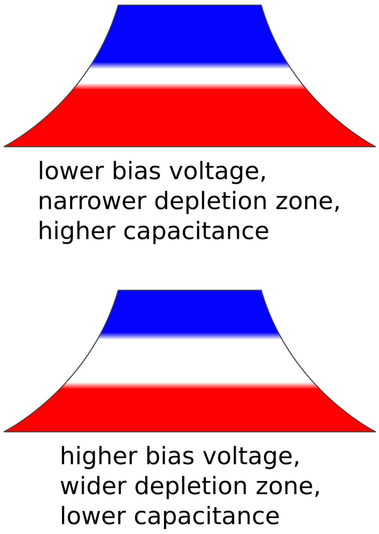
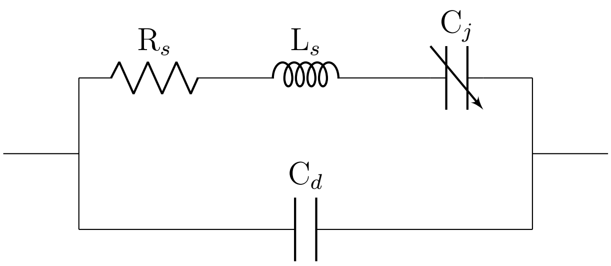


Figure 2.12: Affect of voltage on Depletion layer



2.6 Switches

2.6.1 JRC switch

As it was mentioned in chapter 1, JRC switch has 4 paths and 1 In/Out pin and it is a 2-bit component. For controlling the paths, control pins should be on and off as table 2.1 These two control pins are VCTL1 and VCTL2. This switch is the

VCTL1	VCTL2	Path
L	L	$P_{in/out}$-P1
H	L	$P_{in/out}$-P2
L	H	$P_{in/out}$-P3
H	H	$P_{in/out}$-P4

Table 2.1: Truth Table of JRC

GaAs SO4T switch MMIC component. It is suitable to work up to 2.7 GHz and support high power signals. It can be used in CDMA, LTE, Antenna purpose for band switching, and so on.

2.6.2 MACOM Switch

This project also used from MACOM switch instead of JRC switch to compare them with each other.
MACOM switch which is used here is MASWSS0192 with 2 paths and 1 In/Out port. This switch is the GaAs PHEMT MMIC SPDT switch. It is suited to use in the frequency range of DC to 3 GHz. The truth table of this switch is as 2.2 In this table, RFC is In/Out port, and RF1 and RF2 are the path 1 and path 2 respectively. Also, Control V1 and Control V2 are control pins.

Control V1	Control V2	RFC-RF1	RFC-RF2
1	0	ON	OFF
0	1	OFF	ON

Table 2.2: Truth Table of MACOM

Chapter 3

Simulation

3.1 Branch-Line Quadrature Hybrid

Initially, the Quadrature designed as main part of the Analog Phase Shifter. The characteristic impedance ($Z_\circ$) is equal to 50 Ω. Therefore, $Z_\circ/\sqrt{2}$ is 35 Ω. The width of the former and the latter are equal to 0.5 mm and 1 mm respectively. As it is shown in the figure 2.3, the length of all arm based on our center frequency (f=1.56 GHz) and the dielectric constant (ϵ_r=3.45) should be equal to 3.1.

$$l_{35\Omega} = l_{50\Omega} = \frac{\lambda}{4\sqrt{3.45}} \tag{3.1}$$

In the figure 3.1 the designed Quadrature Hybrid is represented. The isolated port is loaded with 50 Ω impedance.

The lengths are a bit longer than the 3.1. Loss of the dielectric and the conductor

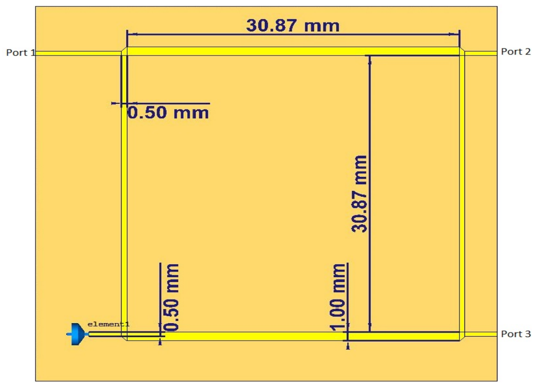


Figure 3.1: Designed Branch Line Quadrature Hybrid

cause the difference between the simulation and calculation values.

The Scattering parameters of the Quadrature are depicted in the figure 3.2 . As

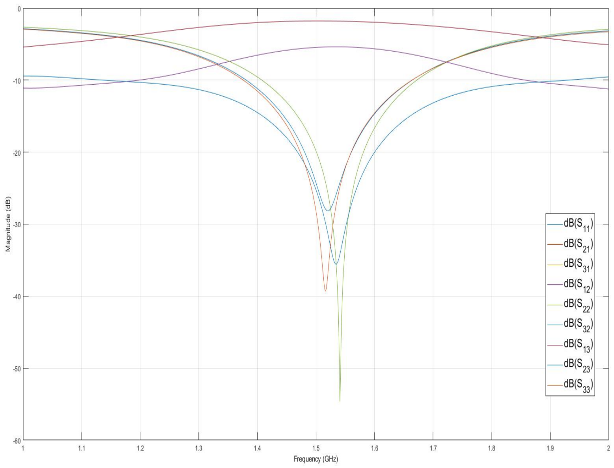


Figure 3.2: Scattering Parameters of the Quadrature Hybrid

the figure 3.2 represents that the difference between S_{21} and S_{31} is 3 dB

3.2 Interdigital Capacitor

In our Analog Phase Shifter, DC and RF signals are used simultaneously. To prevent the effect of the DC signal in the output and the output, the IDC is used at both input and output ports.
The IDC which has been designed is shown in figure 3.3

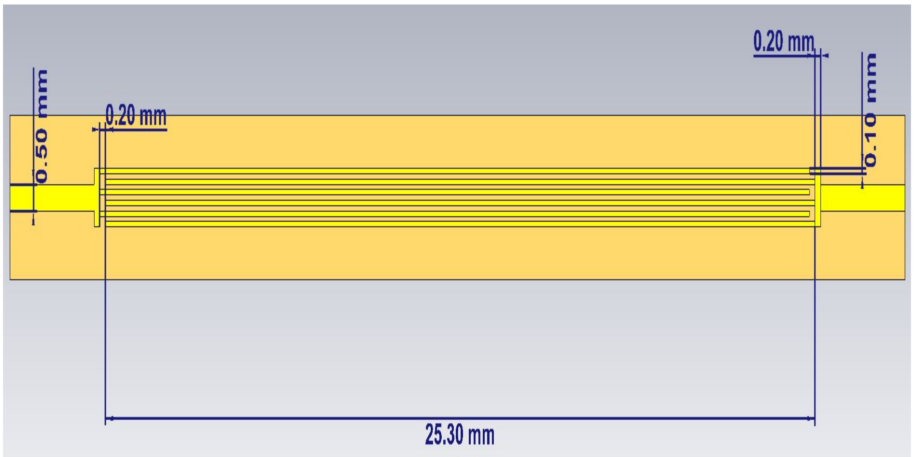


Figure 3.3: Interdigital Capacitor

As it is shown in the figure 3.3, and also by considering the discontinuity between the feeding line and the IDC, as it was mentioned before, the IDC consists of 6 fingers. Also, I had designed it with 4 fingers too but after connecting the other parts of the system and changing the voltage of Varactor Diode it didn't have satisfying S_{11} and by the voltage its S_{11} was changed so much. Therefore, N=6 has been chosen due to its stability. For the N>6 , due to the discontinuity, the bandwidth will be reduced.

Based on the equations 2.2 and 2.2 the length of the Interdigital Capacitor was supposed to be 40 mm. However, in the equation, the dielectric and the conductor losses and also effects of the different parts of a component are not noticed. By considering all these effects, in the simulation, finger length was decreased and equal to 25.30 mm.

The next step was choosing the finger width and gap between the fingers. In designing an IDC, usually, the finger width and gap between them are assumed equal to reduce the error of equations. As it was mentioned before, to prevent discontinuity the width of the finger and gap between the fingers have been chosen 0.1 mm.

Also ℓ' is equal to 0.2 mm. The desired cut-off frequency is less than 1.5 GHz. So the Capacitance is 3.15 pF. Based on this value and According to the equation 2.2 and with $\epsilon_r = 3.45$ and h=0.250 mm, the length of fingers is 25.30 mm. On the other hand, by optimizing the dimensions, S' value in the figure 2.4 should be 0.2 mm to block the DC voltage better.

The sheet resistance of the copper is R_s=0.5mΩ/sq. With the IDC's dimensions and the R_s value, the series resistance of the IDC according to 2.4 is equal to 28.1mΩ. By having R and C, series resistance, and equivalent capacitor, the Quality factor Q_s based on 2.5 in the center frequency f=1.56 GHz is 1136.

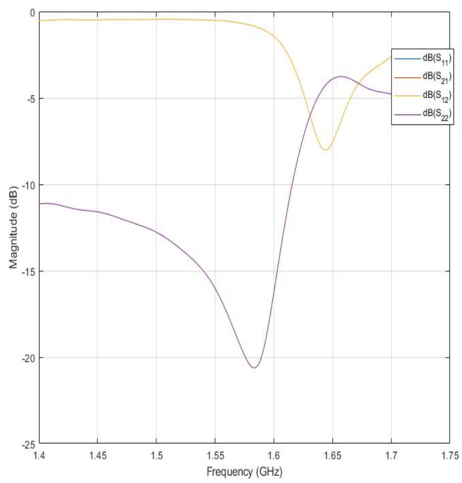
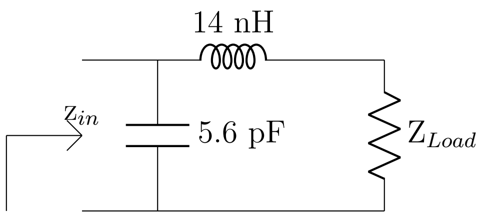


Figure 3.4: $|S_{11}(j\omega)|$ & $|S_{21}(j\omega)|$ of the IDC

According to the figure 3.4, the Bandwidth of the IDC is more than 200 MHz. The length of the fingers shifts the S_{11}. By increasing the length, the graph moves to the left. Furthermore, to have better results the other dimensions should be properly selected. But finger length play a key roll in resonance frequency.

3.3 Filter

The filter used in this project is Butterworth LC prototype low pass filter with degree 2. The cut-off frequency is 800 MHz and has been implemented with distributed elements.
in the 3.3 the schematic of the filter is shown.



The load of the filter is 50 Ω. Therefore input impedance is obtained by the following equations.

$$Z_L = j\omega L \tag{3.2a}$$

$$Z_C = 1/j\omega C \tag{3.2b}$$

$$Z_{in}(j\omega) = Z_c||(Z_L + Z_{Load}) = \frac{j\omega L + Z_{Load}}{-\omega^2 LC + j\omega C Z_{Load} + 1} \tag{3.2c}$$

By computing Z_{in}, with characteristic impedance $Z_\circ$, the Scattering parameters can be obtained

$$S_{11} = \frac{Z_{in} - Z_\circ}{Z_{in} + Z_\circ} \tag{3.3a}$$

$$S_{11}(j\omega) = \frac{\omega^2 LC + j\omega(L - CZ_{Load}Z_\circ) - Z_\circ}{-\omega^2 LC + j\omega(L + \omega CZ_{Load}Z_\circ) + Z_\circ} \tag{3.3b}$$

In the Lossless systems the relation between S_{11} and S_{21} is

$$|S_{11}|^2 + |S_{21}|^2 = 1 \tag{3.4}$$

According to the [13] the values for the capacitor and the inductor are g_1=g_2=1.4142. Then based on cut-off frequency, these values should be scaled to exact values with respect to 2.26 which for capacitor and inductor are 5.6 pF and 14 nH respectively. Based on these values and the equations 3.2c,3.3b and 3.4, the plot of Scattering parameters represents in the figure 3.5.

The cut off frequency is 800 MHz. Therefor, the wavelength is equal to 375 mm.

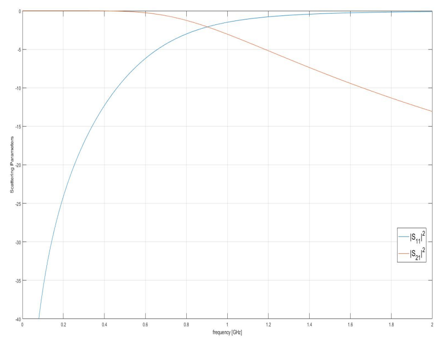


Figure 3.5: Low Pass Filter Degree 2 & f_c=800 MHz with lumped elements

The dielectric constant of the substrate is ϵ_r=3.45 so the effective wave length is:

$$\lambda_{eff} = \frac{\lambda}{\sqrt{\epsilon_r}} \tag{3.5}$$

Based on the 3.5, effective wavelength is equal to 201.9 mm. The 1/8 of the wavelength is 25.2 mm.

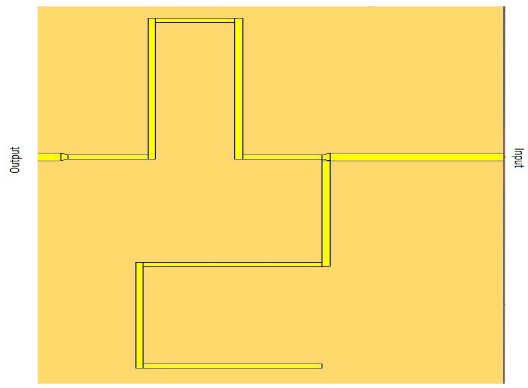


Figure 3.6: Low Pass Filter Degree 2 & f_c=800 MHz

Due to limitations in length and reducing the size of the filter, I have bent the lines. As it is shown in the circuit 3.3, the stub is referred to as capacitor and the short circuit line is referred to as inductor.
In the figure 3.7, represents the $|S_{11}(j\omega)|$ & $|S_{21}(j\omega)|$. The cut-off frequency is almost 800 MHz

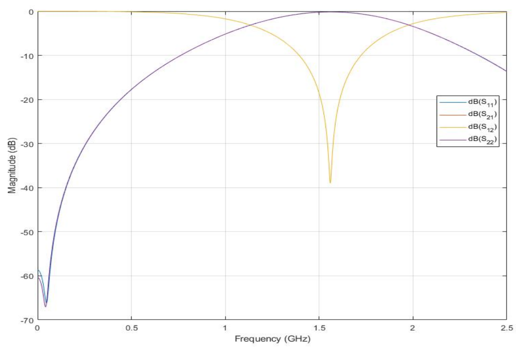


Figure 3.7: S parameters of the filter

The difference between the figure 3.5 and the figure 3.6 is that the former is plotted with lumped element and the latter is for a distributed element which is periodic element 2.25. Also distributed filter is periodic with $\lambda/2$

3.4 Analog Phase Shifter with Varactor Diode

As it was mentioned in the chapter 1, in this Analog Phase Shifter, for phase shifting varactor diode has been used. This varactor diode is SMVA1248-079LF:

Hyperabrupt Junction Tuning Varactor produced by Skyworks company. This diode is used for Voltage Control Oscillator(VCO) and with low voltage tuning. Figure 3.8 represents the spice model of our diode [**19**]. The diode is working in

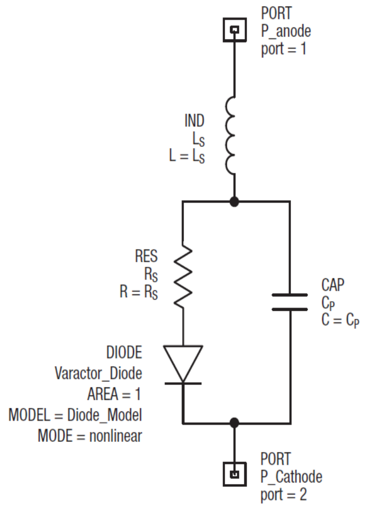


Figure 3.8: Spice model of varactor diode

the range of 0 to 8 V. By changing the voltage the total capacitor of the diode is changed based on the table 3.1 The diodes are connected to port 2 and port 3 of the quadrature branch line as it is shown in figure 3.9. According to figure 1.1,

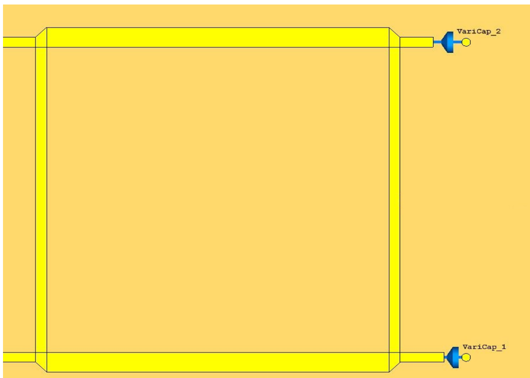


Figure 3.9: Quadrature branch line with varactor diodes

port 1 and 4 are input and output respectively. In this project, the DC voltage increases up to 5V. By increasing voltage, the total capacitor is decreased and it is causes phase shifting in the signal.
The difference between phases of the Input signal and output signal is depends

V_R (V)	C_T (pF)
0	22.62
0.5	16.32
1	12.33
1.5	9.12
2	6.27
2.5	3.93
3	2.57
3.5	1.95
4	1.71
4.5	1.59
5	1.49
5.5	1.44
6	1.40
6.5	1.36
7	1.33
7.5	1.31
8	1.30

Table 3.1: Capacitance vs. Reverse Voltage

on the reflection coefficients of the port 2 and port 3 which are connected to the varactor diodes. As a result the reflection coefficient of port 2 and port 3 is as the equation 3.6 . In this equation the characteristic impedance of the quadrature hybrid is $Z_\circ$. Also instead of varactor diode, equivalent total capacitor varied by voltage, is used [5].

$$\Gamma_2(V) = \Gamma_3(V) = \frac{1/\jmath\omega C(V) - Z_\circ}{1/\jmath\omega C(V) + Z_\circ} = \frac{1 - \jmath\omega C(V) Z_\circ}{1 + \jmath\omega C(V) Z_\circ} \tag{3.6}$$

Also the relation between reflection coefficient and transmission coefficient is 3.7 .

$$T = 1 + \Gamma \tag{3.7}$$

As a results, the transmission coefficient become as 3.8 .

$$T_2(V) = T_3(V) = \frac{2}{1 + \jmath\omega C(V) Z_\circ} = 2\frac{1 - \jmath\omega C(V) Z_\circ}{1 + \omega^2 C(v)^2 Z_\circ^2} = S_{21} \tag{3.8}$$

Therefore, the phase of the output signal is 3.9 .

$$\angle S_{21} = \frac{\pi}{2} - 2\arctan(\omega C(V) Z_\circ) \tag{3.9}$$

In the equation 3.9, $\pi/2$ referred to the arm of quadrature which is equal to $\lambda/4$. Also due to two transmission coefficient, 2 coefficient is added.
The effects of changing voltage of the varactor diode on the output signal phase is 3.10 . After that, by adding IDCs and Low Pass Filter to the figure 3.9, the

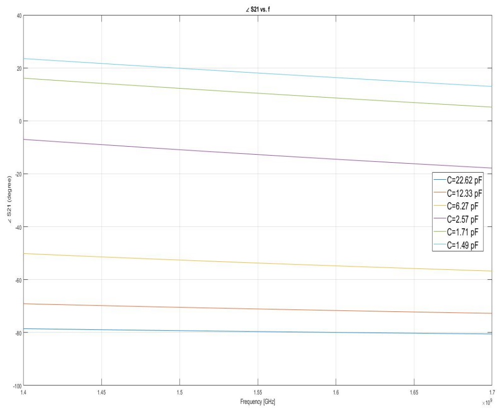


Figure 3.10: Variation of the output signal phase by changing the varactor diode's voltage

first part of the Analog Phase shifter has been completed. After connecting the whole component, by increasing the DC voltage, as was mentioned before, the total capacitor of the diode changed and it affects the scattering parameters as it is represented in the figures 3.12. As it is obtained from the figure 3.12 (c), by changing the voltage, the phase of the signal is change and it causes phase shifting. After Connecting all parts, with previous dimensions of the Low Pass

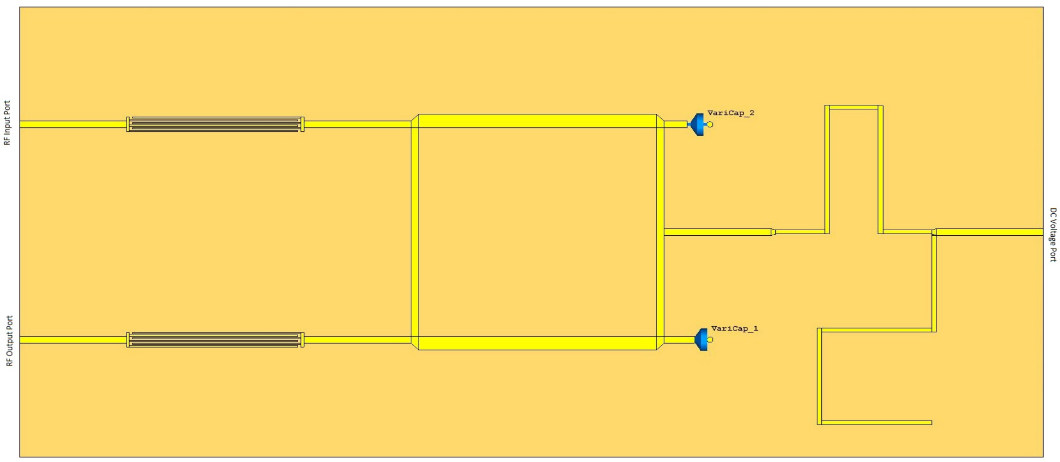


Figure 3.11: Analog Phase Shifter with Varactor Diodes

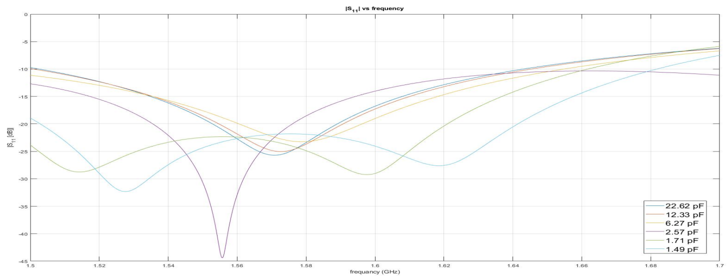
Filter, Interdigital Capacitor, and Quadratic Hybrid Branch Line, the Analog Phase Shifter didn't work in desired frequency properly and they needed to change.
First of all, to set S_{31}'s minimum on the desired Bandwidth (1.55 GHz to 1.57 GHz), I increased the length of the inductor and capacitor and it became 26.9 mm. In the next step, I decided to optimize the S_{11} with respect to finger lengths of the Interdigital Capacitor and arms of the Quadratic Hybrid branch line. After optimizing, as it is depicted in the figure 3.11, they have been 11 mm and 15.57 mm respectively. The arms in the fabricating become 15.6 mm to limitation of manufacturing.
As it is obtained from the graph 3.12a, the Bandwidth of the phase shifter is from 1.5 GHz to 1.56 GHz for all voltages from 0 to 5 V and in our desired Bandwidth it is below -15dB.
The graph 3.12b is shown that at the most voltages from 0 to 5 V, the $|S_{21}|$ is -1 dB and for 3 V it become -4 dB.
In the graph 3.12c, the variation of the phase is represented. In the graphs 3.16 this variation specifically is shown.

3.5 Analog Phase Shifter with Switches

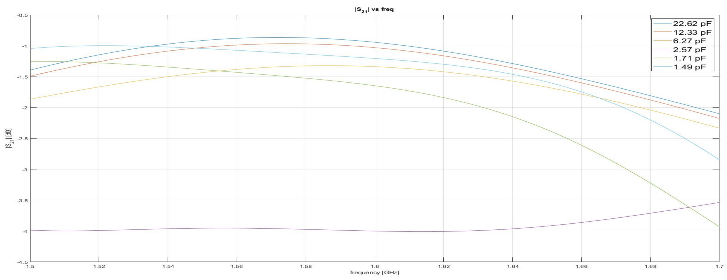
In the last step, the switches connected to the output of the previous part as it is shown in the figure 3.14 and 3.17 which are for JRC and MACOM respectively.
The Impedance of bot types is 50 Ω so the impedance graph of both of them is the same as it is represented in the figure 3.13. Also, the Radiation loss for both of them is -33.82 dB. As the figure 3.13 is depicted, all impedance are almost 50 Ω. They are a bit higher because due to limitation in the fabrication of the board, minimum accuracy is 0.1 mm. so between 0.5 mm and 0.6 mm of the line with the former has been chosen.
In the following, the operation of the Analog Phase Shifter with these types of switches will be discussed separately.

3.5.1 JRC

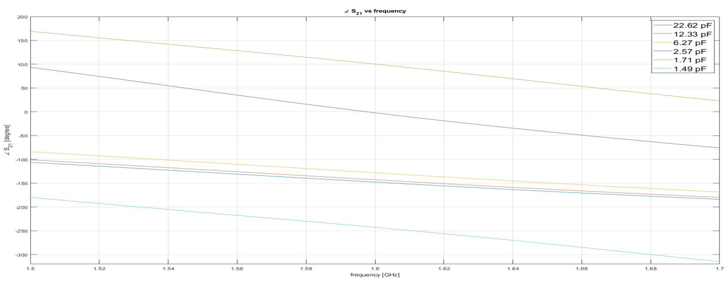
After connecting the first switch in the output, 4 lines with different Electrical lengths were connected to it which were 0°, 90°, 180° and 270°. These lines went through the other JRC switch's paths. The figure 3.14 depicts the schematic of the whole system with switches.
The pins of the JRC switch are 0.3 mm and the width of the microstrip line with 50Ω impedance is 0.5 mm. Therefore, for connecting them, tapered lines have been used.
As it is shown in the figure 3.14, the line between two tapered lines is supposed to be 0°, 90°, 180° and 270° lines. After connecting all these components to the



(a)



(b)



(c)

Figure 3.12: Variation of the Varactor Diode on S parameter,(a) $|S_{11}|$ (b) $|S_{21}|$ (c) $\angle S_{21}$

previous parts of Analog Phase Shifter, the Scattering parameters were obtained which are provided in the figure 3.18.

As the figure 3.15a represents, the $|S_{11}|$ is not change with respect to the situation without switches. Also $|S_{21}|$ isn't affected by them too as it is depicted in the figure 3.15b.

Moreover, the figure 3.15c shows the variation of the output signal phase with respect to the Capacitor values of the varactor diode. As it is obtained from the graph 3.15c, the variation of the phase between the different lines are almost

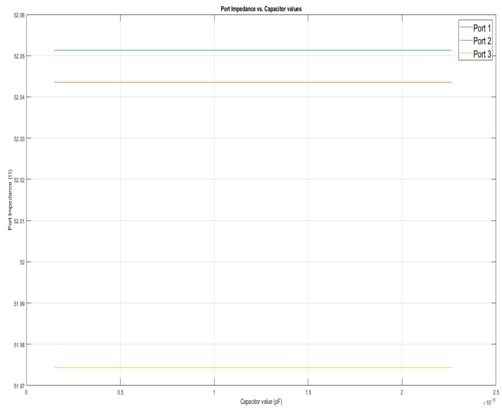


Figure 3.13: Impedance of the ports

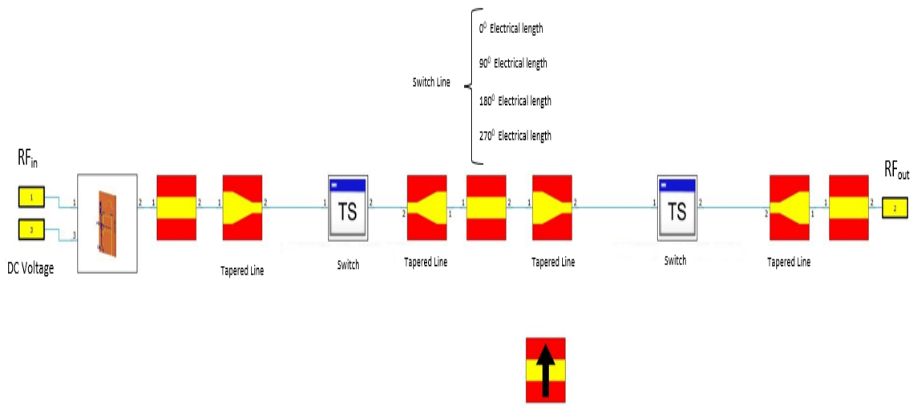
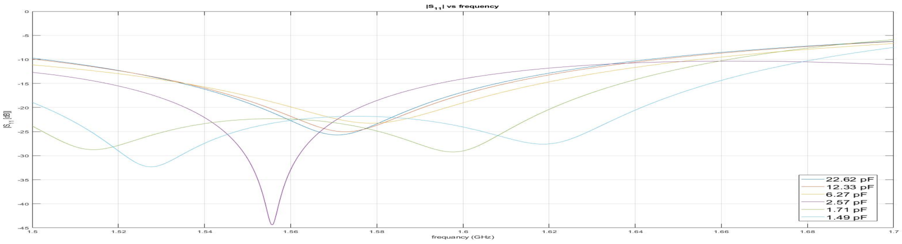
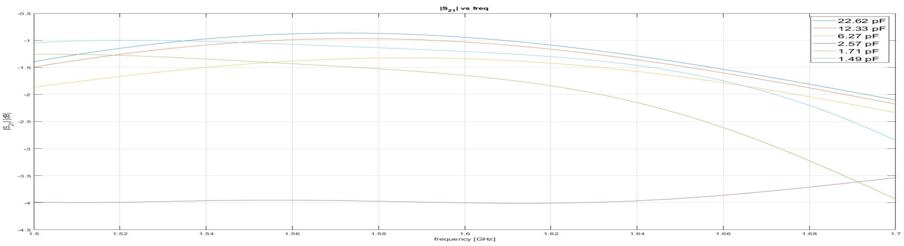


Figure 3.14: Schematic of the Analog Phase Shifter with JRC switch

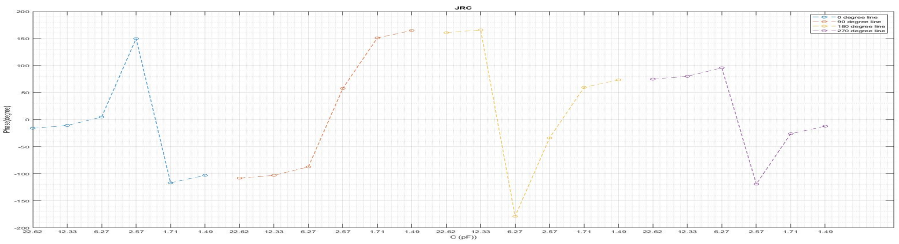
continuously and it means that the phase of the line with the Capacitor value 1.49 pF is almost the same as the phase of that line plus a 90-degree electrical length with the Capacitor value of 22.62 pF.
Based on the graph 3.16 by increasing DC voltage, the phase-shifting moves toward positive degrees, and also by increasing the frequencies the graphs shift down. The dimensions of Analog phase shifter with the JRC switches are provided in the table 3.3. As it was mentioned before the dimensions were changed a bit after connecting all components together. The reason is that after connecting the different parts to each other, the input and output impedance have been changed. Moreover, some discontinuity between components and their behaviour in different frequencies are the other reasons.



(a)



(b)



(c)

Figure 3.15: Scattering Parameters of the APS with JRC,(a) $|S_{11}|$ (b) $|S_{21}|$ (c) $\angle S_{21}$

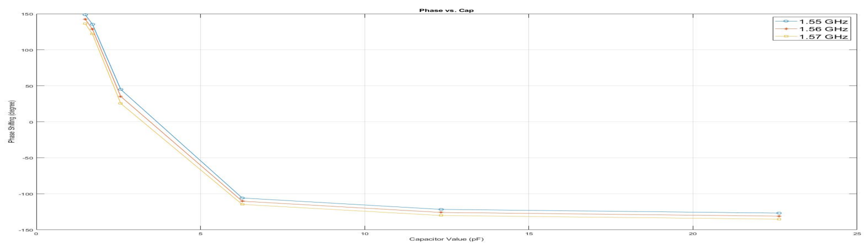


Figure 3.16: Phase Shifting with respect to capacitor value of Varicap in 3 different frequencies with JRC switch

dimensions [mm]							
IDC		Quadrature Hybrid		Filter		Switches	
ℓ'	0.2	$l_{35\Omega}$	15.57	l_L	28.8	$l_{Tapered-line}$ (larger part)	3
ℓ	25.3	$l_{50\Omega}$	15.57	l_C	28.8	$l_{Tapered-line}$ (Smaller part)	3
W	0.1	$W_{35\Omega}$	1	W_L	0.3	$W_{Taperedline}$ (larger part)	0.5
S	0.1	$W_{50\Omega}$	0.5	W_C	0.3	$W_{Taperedline}$ (Smaller part)	0.3
S′	0.2					l_{0°	4
W′	1.1					l_{90°	33.6
						l_{180°	63.1
						l_{270°	91.5

Table 3.2: Dimensions of the Analog Phase Shifter with JRC switch

As it is known, the 90°, 180° and 270° were supposed to be $\lambda/4$,$\lambda/2$ and $3\lambda/4$. However again due to the losses in the substrate and conductor and other effects, they are a bit different with the calculation.

3.5.2 MACOM

The MACOM switch is opposite JRC one and the switch line length affects the S_{11}. It means that by increasing the length of the switch line from 0 degrees to 90 degree, the S_{11} moved out of desired range, and then from 90 degree to 180 degree again it became suitable for our proper frequency range.
The schematic of the Analog Phase Shifter with MACOM switches provided in the figure 3.17 .

The scattering parameters of the Analog Phase Shifter with switch line equal to 0 degree is the same as the line with 180 degree length. The figure 3.18a shows that in the desired frequency range, $|S_{11}|$ is below -15dB. Also, $|S_{21}|$ in all capacitor values are almost -1dB except one of them which is -4 dB. The series plot of the phase represents in the phase variation, phase of the 0 degree line and 180 degree line are along with each other which is different with JRC switch 3.15b. In the JRC, the lines with 90 degree difference were along.
In the figure 3.19 variation of the phase in some specific frequencies are represented.

As it was described in the previous subsection 3.5.1 the dimensions are different considering to individual components.
The main difference as it was discussed before is that MACOM switch just has two path. Furthermore, by connecting 90° line to one of them, S_{11} was changed and become undesirable. Therefore 180° line has been used instead of it. Same is the subsection 3.5.1 this length is a bit different with calculated value.

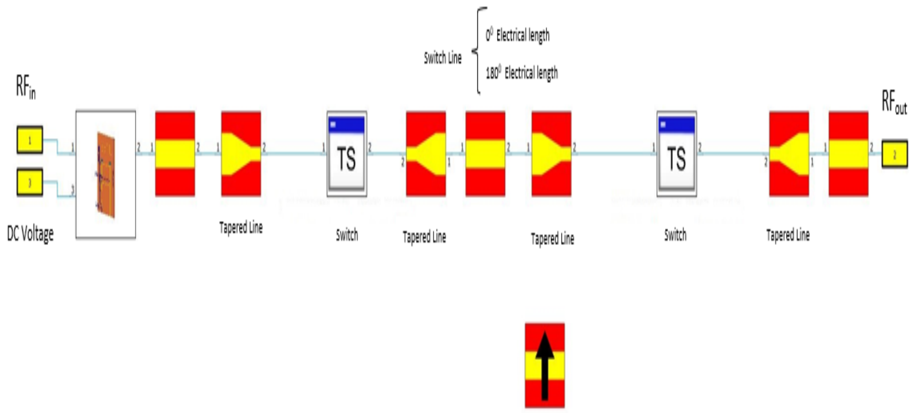
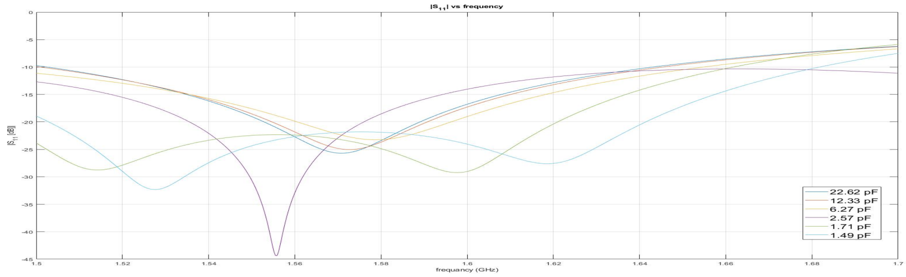


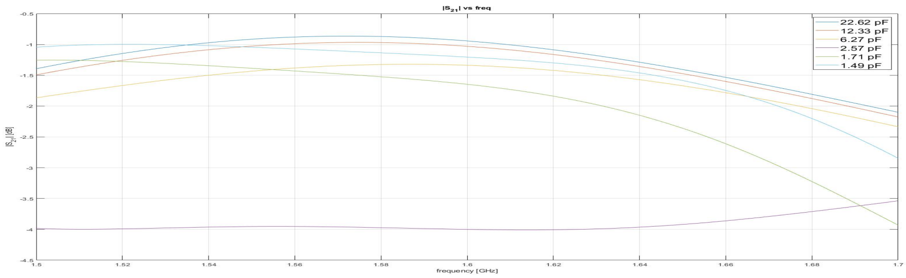
Figure 3.17: Schematic of the Analog Phase Shifter with MACOM switch

dimensions [mm]							
IDC		Quadrature Hybrid		Filter		Switches	
ℓ'	0.2	$l_{35\Omega}$	15.57	l_L	28.8	$l_{Tapered-line}$ (larger part)	3
ℓ	25.3	$l_{50\Omega}$	15.57	l_C	28.8	$l_{Tapered-line}$ (Smaller part)	3
W	0.1	$W_{35\Omega}$	1	W_L	0.3	$W_{Taperedline}$ (larger part)	0.5
S	0.1	$W_{50\Omega}$	0.5	W_C	0.3	$W_{Taperedline}$ (Smaller part)	0.3
S'	0.2					l_{0°	4
W'	1.1					l_{180°	61.48

Table 3.3: Dimensions of the Analog Phase Shifter with MACOM switch



(a)



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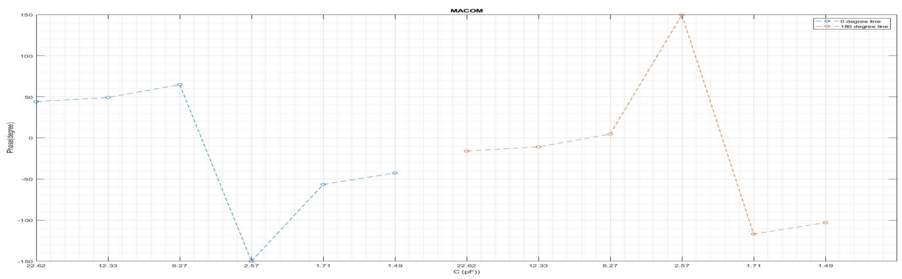
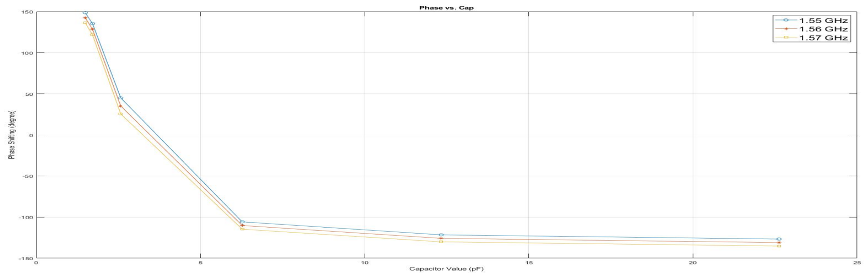
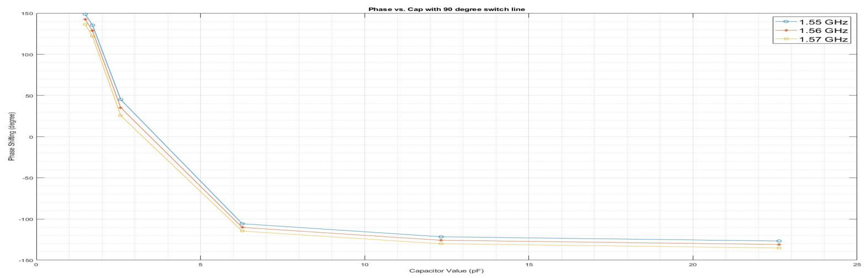


(c)

Figure 3.18: Scattering Parameters of the APS with MACOM,(a) $|S_{11}|$ (b) $|S_{21}|$ (c) $\angle S_{21}$



(a)



(b)

Figure 3.19: Variation of $\angle S_{21}$ with MACOM in different frequencies,(a) 0 degree line (b) 90 degree line

Chapter 4

Future Work

4.1 Phased Array Antenna

Following the previous chapters, the next step which I have decided to do is designing an Antenna in 1.55 GHz to 1.57 GHz and connect to the phase shifter and after that make a Phased Array Antenna.
The antenna which is supposed to designed is microstrip patch antenna and I will try to design it in two ways: first Microstrip Patch and then by T shape antenna. The desired Microstrip patch antenna in this frequency is a bit large. The length of the antenna should be half of the wave length and in this case $\lambda/2$ is equal to 50 mm. Also, the width of the Antenna should be larger than the length and it adjust the impedance.
On the other hand T shape antenna as it is used in the cellphones is better idea due to the size. But it has its own disadvantages for instance about gain and directivity.
Also for tilting the beam of the Antenna I have planned to connect an Embedded system to control the voltage of the varactor diode and pins of switches. I am supposed to use an ARM microcontroller and program it. Then I will design and synthesize an Electronic board for the ARM.
After all, I am going to connect the Electronic circuit and Analog Phase Shifter, and Antenna to each other. Then try to program the ARM to cover all degrees in the environment. The Phased Array Antenna is supposed to be a planar array. The Phased array antenna was supposed to sweep the environment and manually adjust in the specific direction.

4.2 Optimization

In the next step, I have decided to make the Phased Array Antenna practical. One of the main usages of the Antenna is in GPS and Navigation. As a result, I will work on an optimizing Algorithm for this purpose with Python and MATLAB. The optimization should be based on the location of the user

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