

NOVEL TWO-WAY FILTER AND DIPLEXER

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requirements for the award of the degree of
Bachelor (Hons) of Electronic and Communications Engineering**

**Faculty of Engineering and Science
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APRIL 2013

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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Specially dedicated to
my beloved parents and friends.

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NOVEL TWO-WAY FILTER AND DIPLEXER

ABSTRACT

Filters and diplexers are microwave devices that are commonly found in communication systems. Due to the many applications, researchers are always coming up with new ideas and better techniques to improve the performance or the functionality of such microwave devices. The beginning chapters of this thesis explain the objectives of this project, the microwave engineering theories involved, research methodologies used and the literature review based on published journals. This thesis is made up of two proposed ideas for a filter and another for a diplexer. The first design is a two-way low-pass and high-pass filter whereby individual low-pass and high-pass filters are merged together to form an independent four-port filter. It has two input ports and two outputs ports. Second proposed idea is a low-pass and bandpass diplexer. Similar to the first idea, the proposed diplexer is also based on the combination of two separate low-pass and bandpass filters. Unlike the designed filter, the diplexer has only one input port. Thus, the input is split according to frequency. Overall, comparison between the simulation and measured results for both designs shows good agreement.

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LIST OF SYMBOLS / ABBREVIATIONS

f	Frequency, Hz
ϵ_r	Dielectric constant
ω_c	Cutoff frequency
Z_o	Characteristic impedance, Ω
Z_C	Impedance of capacitor, Ω
Z_L	Impedance of inductor, Ω
S_{11}	Return loss, dB
S_{21}	Insertion loss, dB
S_{31}	Insertion loss, dB
S_{33}	Return loss, dB
S_{34}	Insertion loss, dB

CHAPTER 1

INTRODUCTION

1.1 Background

Microwave wireless devices and technologies have been widely used in today's modern world. Microwave frequency range is used mostly for broadcasting, wireless communication and military applications. In microwave, the spectrum ranges from 300 MHz to 300 GHz. Waves from 30 GHz to 300GHz are called millimetre waves due to their wavelengths from 1 mm to 10 mm (Hong 2011). The advancement of research in the field of microwave allows the development of microwave devices such as filters, power dividers and directional couplers.

Many microwave applications are created during the time of war. During the World War II, microwave engineering plays a significant role in the development of radar. Radar at that point in time was widely used by many troops to accurately locate enemy battle ships and fighter planes (Das and Das 2001). However, in the modern world, microwave applications are widely used in wireless telecommunication all around the world. Emerging applications in telecommunication requires more development in microwave devices in order to achieve higher performance, more functionalities, smaller size and lower cost (Hong 2011). Table 1.1 tabulates the new and old designations of the microwave bands and their frequencies.

Table 1.1: Microwave bands

New Designation	Frequency (GHz)	Old Designation	Frequency (GHz)
C	0.5-1.0	VHF	0.5-1.0
D	1.0-2.0	L	1.0-2.0
E	2.0-3.0	S	2.0-4.0
F	3.0-4.0	C	4.0-8.0
G	4.0-6.0	X	8.0-12.4
H	6.0-8.0	Ku	12.4-18.0
I	8.0-10.0	K	18.0-26.5
J	10.0-20.0	Ka	26.5-40.0
K	20.0-40.0	v	40.0-75.0
L	40.0-60.0		
M	60.0-100.0		

Obtained from: Microwave Engineering by Annapurna Das and Sisir K. Das (2001)

1.2 Research Aim and Objectives

The main objective of this project is to propose and fabricate a novel two-way filter and a diplexer using a microstrip substrate board. Convenience, functionalities and wide bandwidth, are the few things to bear in mind when it comes to designing the two-way filter and diplexer.

The first proposed idea is to design a two-way low-pass and high-pass filter. It consists of a total of four ports whereby there are two input ports and two output ports. This is basically a new design technique by combining two independent filters into one design. Passive elements such as capacitors and inductors were incorporated into the design. Achieving a wide bandwidth low-pass and high-pass filter is the main objective. The configuration as well as the simulated and measured results of this proposed idea will further be discussed in Chapter 3.

In the second idea of this project, a low-pass and bandpass diplexer has been proposed and designed. Likewise the first idea, two individual filters are combined to form a diplexer. However, unlike the first idea; there is only a single input port and two output ports that are frequency dependent. Chapter 4 further explained and discussed the configuration and the simulated and measured results of this proposed diplexer.

Throughout this project, many reference books and journals were referred to in order to get a better understanding on the theories and design parameters of microwave filters.

1.3 Project Motivation

The motivation of this project is to come up with new methods for filters and diplexer. In order to be inspired by new ways and methods to designing microwave devices, a fair amount of time and effort has been put into researching by referring to reference books and journal publications. Proper research methodologies are learnt and applied throughout this project.

Furthermore, many problem-solving skills have been acquired throughout the process of completing this project. Good and concise writing skills were also gained in the process of thesis writing. The constant motivation and guidance from Dr. Lim Eng Hock makes learning a lot easier. Additionally, an opportunity to publish a paper in any renowned journal publications also adds to the motivation when completing this project.

1.4 Thesis Overview

This thesis begins with Chapter 2 introducing the types of microwave filters, the parameters of filters, the effect of mismatch and the types of filters using LC elements. Recent developments on filters and diplexers were also discussed as literature review. At the end of the chapter, the research methodologies and its three main stages were introduced.

Chapter 3 introduces the first idea of a two-way low-pass and high-pass filter. This chapter further discusses the configuration and simulation and measured results. Furthermore, the process of parametric analysis is performed and the analysing is done by plotting out various graphs for comparison and discussion. In Chapter 4, the proposed idea is a low-pass and bandpass diplexer. Similar to Chapter 3, Chapter 4 goes through the same process of designing, obtaining the simulated and measured results, and analysing the various parameters for discussion. Based on the results obtained, the two proposed designs are concluded to have been a successful design with good agreement between the simulation and experiment results.

Finally, Chapter 5 concludes the achievement of the entire project. Further recommendations for future works are mentioned as well.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

The basic and fundamental theories of microwave filters are being introduced in this chapter. Research has been made through online journal publications and several journal publications are discussed in detail in section 2.3 as literature review. Besides that, the research methodologies used throughout this project are stated at the end of this chapter.

2.2 Microwave Filters

Microwave filters are two-port devices that are dependent on frequency. Depending on the design and function, the main purpose of a filter is to allow transmission of certain frequencies within the passband and eliminate undesired frequencies within the stopband (Pozar 1998). Figure 2.1 illustrates the four basic types of filters that are commonly used.

- Low-pass filter: It passes all frequencies below f_{C2}
- High-pass filter: It passes all frequencies above f_{C1}
- Bandpass filter: It passes all frequencies between f_{C1} and f_{C2}
- Bandstop filter: It blocks all frequencies between f_{C1} and f_{C2}

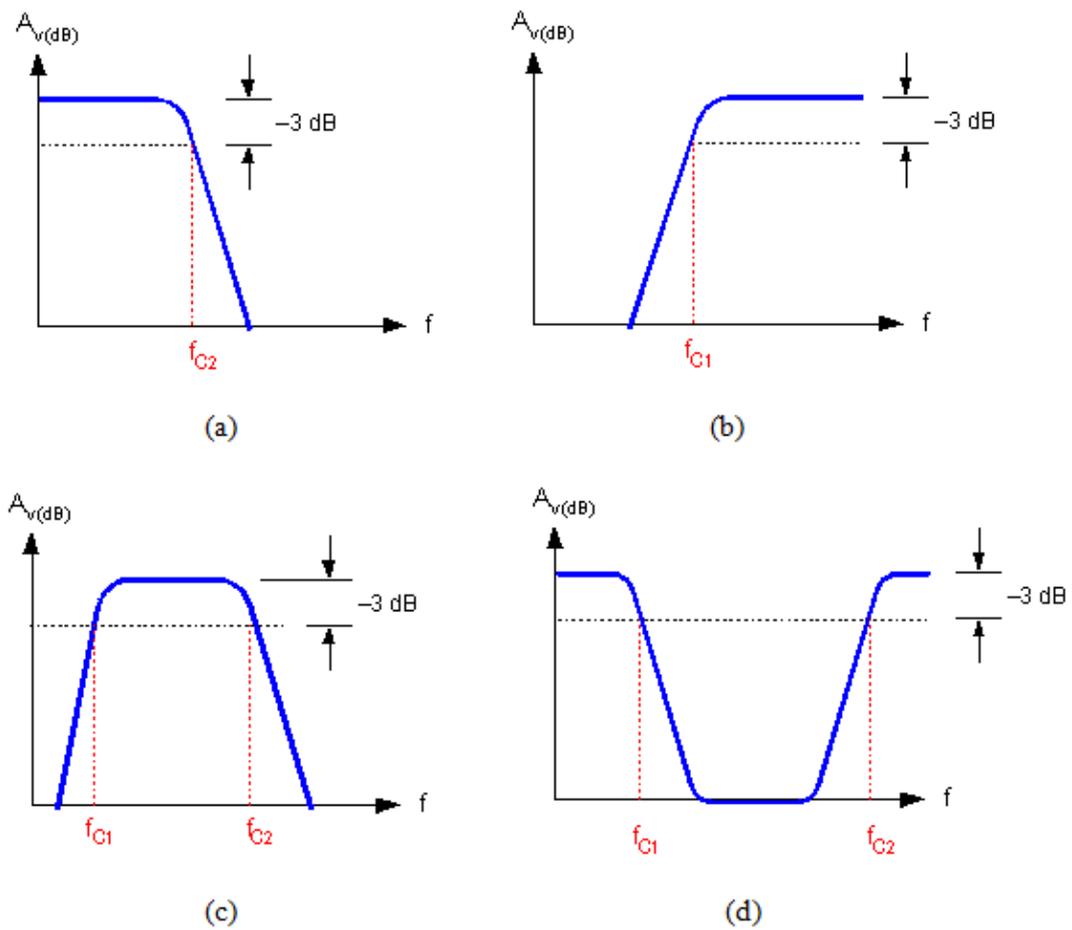


Figure 2.1: Basic types of filters (a) low-pass filter, (b) high-pass filter, (c) bandpass filter, and (d) bandstop filter

2.2.1 Filter Parameters

When it comes to designing a good functioning filter, there are several parameters that need to be considered. These parameters are:

- Operating Bandwidth
- 3-dB cutoff frequency
- Input and output impedances
- Insertion loss
- Return loss
- Group delay

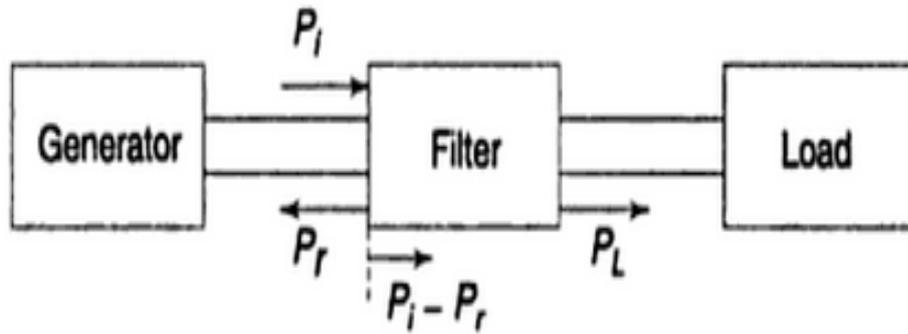


Figure 2.2: Block diagram of a filter between a generator and a load

Figure 2.2 shows a block diagram of a filter in between a generator and a load. P_i is the incident power, P_r is the reflected power and P_L is the power supplied to the load. The amplitude response of a filter determines the characteristics of the filter. From the Amplitude response, the most important parameters are the insertion loss and the return loss (Das and Das 2001).

The insertion loss and return loss of a filter are defined as follow:

Insertion loss, IL

$$= 10 \log \frac{P_i}{P_L} = 10 \log \frac{P_i}{P_i - P_r} = 10 \log \frac{1}{1 - |\Gamma|^2} \quad (dB) \quad (2.1)$$

where $P_L = P_i - P_r$ if the filter is lossless and Γ is the reflection coefficient of voltage, whereby $|\Gamma|^2 = P_r / P_i$.

Return loss, RL

$$= 10 \log \frac{P_i}{P_r} = 10 \log \frac{1}{|\Gamma|^2} \quad (dB) \quad (2.2)$$

where it represents in quantity the amount of impedance matching at the input port.

2.2.2 The Effect of Mismatch

A typical microstrip filter has to be designed with characteristic impedance, Z_0 where the impedance is dependent on the width of the microstrip feed line and the dielectric constant. When both the input and output ports are properly terminated, there will be no reflection at the ports. However, if the ports are mismatched; the filter will experience a reflection of signals at the ports (Das and Das 2001).

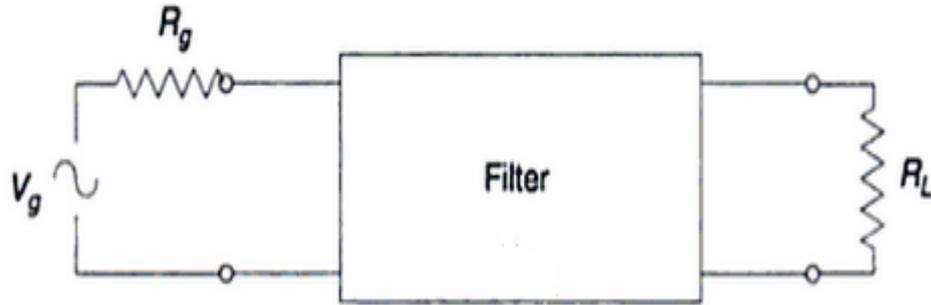


Figure 2.3: A simple filter network with a mismatch termination

The above Figure 2.3 shows a simple filter connected to a voltage generator, V_g with impedance, R_g ; is terminated by a load, R_L . Assuming $R_g = R_L \neq Z_0$. Without the filter, the maximum power delivered to the load is:

$$P_1 = \frac{|V_g|^2}{4R_g} \quad (2.3)$$

When the filter is inserted between the generator and load, the power delivered to the load is:

$$P_2 = \frac{|V_L|^2}{R_L} \quad (2.4)$$

Therefore, the insertion loss of the filter becomes,

$$IL \text{ (dB)} = 10 \log \frac{P_1}{P_2} = 20 \log \left[\frac{1}{2} \sqrt{\left(\frac{R_L}{R_g} \right)} \left| \frac{V_g}{V_L} \right| \right] \quad (2.5)$$

If $R_g = R_L$,

$$IL (dB) = 20 \log \left(\frac{1 V_g}{2 V_L} \right) = \alpha_0 \quad (2.6)$$

If there is no mismatch in the filter, $R_g = R_L = Z_0$ and $V_L = V_g / 2$,

$$IL (dB) = 20 \log \left(\frac{1 V_g}{2 V_L} \right) = 0 \quad (2.7)$$

However, if there is a mismatch of impedance,

$$IL (dB) = 20 \log \sqrt{\left(\frac{R_L}{R_g} \right)} + 20 \log \left(\frac{1 V_g}{2 V_L} \right) = \alpha_0 + 10 \log \left(\frac{R_L}{R_g} \right) \quad (2.8)$$

Therefore, impedance matching is very important when it comes to designing a microwave filter. A mismatch of impedance will result in a reflection of signals at the ports and thus, affects the performance of the filter (Das and Das 2001).

2.2.3 Low-pass and High-pass Filters using LC Elements

Filters can be designed using passive elements such as inductors and capacitors. In this section, the low-pass and high-pass filters in the form of T-network and π -network will be discussed in detail (Pozar 1998).

In a T-network configuration, a low-pass filter is made up of series inductors and shunt capacitor. It allows low frequency signals to pass but blocks high frequency signals (Pozar 1998). The impedances of capacitor and inductor is given by:

$$Z_C = \frac{1}{j\omega C} \quad (2.9)$$

$$Z_L = j\omega L \quad (2.10)$$

where

$$\omega = 2\pi f$$

The cutoff frequency, ω_c is defined as:

$$\omega_c = \frac{2}{\sqrt{LC}} \quad (2.11)$$

The characteristic impedance, Z_0 is defined as:

$$Z_0 = \sqrt{\frac{L}{C}} \quad (2.12)$$

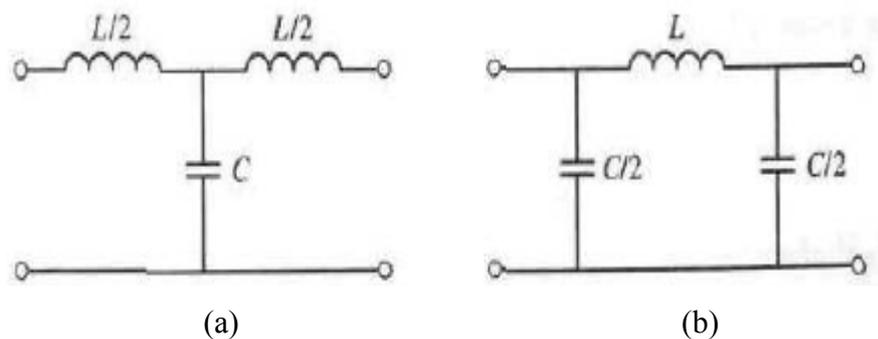


Figure 2.4: Equivalent circuits of a low-pass filter with (a) T-network and (b) π -network

For a T-network high pass filter, it consists of series capacitor and shunt inductor. The high-pass filter allows high frequency signals to pass through while blocking the low frequency signals (Pozar 1998). Similar to the low-pass filter, Z_C and Z_L can be calculated using the previous shown equations.

The cutoff frequency, ω_c is now defined as:

$$\omega_c = \frac{1}{2\sqrt{LC}} \quad (2.13)$$

The characteristic impedance, Z_0 still remains as:

$$Z_0 = \sqrt{\frac{L}{C}} \quad (2.14)$$

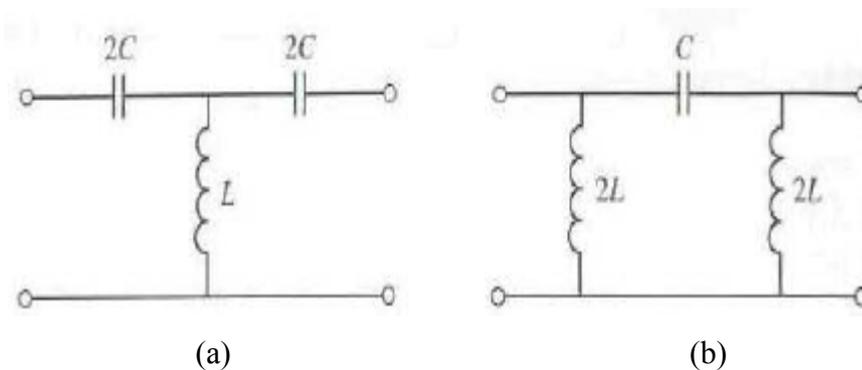


Figure 2.5: Equivalent circuits of a high-pass filter with (a) T-network and (b) π -network

2.3 Recent Developments

In the development of filters and diplexers, researchers have developed various methods to improve the overall performance. Researchers concentrate on improving their designs in aspects such as bandwidth, selectivity, size and isolation. The following show several methods and techniques that were proposed in recent years.

2.3.1 Miniaturized Filters and Diplexers

Microwave devices such as diplexers and filters are becoming more in demand as they are commonly used in microwave and millimeter wave transceivers as channel separators (Zayniyev, Budimir et al. 2008). There are demands for these devices to be low cost, small size and high efficiency. The design procedure of a conventional diplexer involves two steps. First step is the design of microwave filters, whereby the common structures are either bandpass or bandstop (Matthaei and Cristal 1965). Other times, low-pass or high-pass filters are also used in the design (Capstick 1999). The second step is to combine these filters together by using matching networks (Matthaei, Young et al. 1980). In this journal, Damir Zayniyev, Djuradj Budimir and George Zouganelis, proposed a miniaturized microstrip diplexer that has two passbands. The authors managed to reduce the size of the diplexer by combining bandpass filters without the need for a matching network (Zayniyev, Budimir et al. 2008).

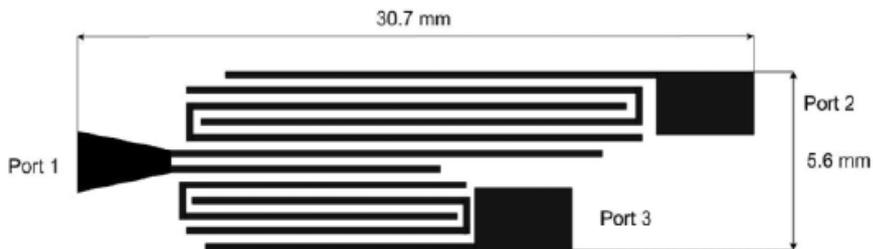


Figure 2.6: Structure of the proposed microstrip diplexer

Finally, a miniaturized diplexer with a size of 5.60 x 30.70 mm was successfully produced as shown in Figure 2.7. Additionally, the diplexer has two passbands with centre frequencies of 2.7 GHz and 3.8 GHz.

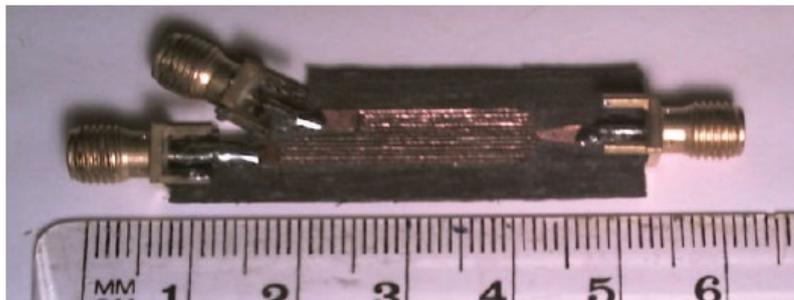


Figure 2.7: Fabricated microstrip diplexer

The below Figure 2.8 and Figure 2.9 shows that the experimental results of the fabricated microstrip have good agreement with the simulated results (Zayniyev, Budimir et al. 2008).

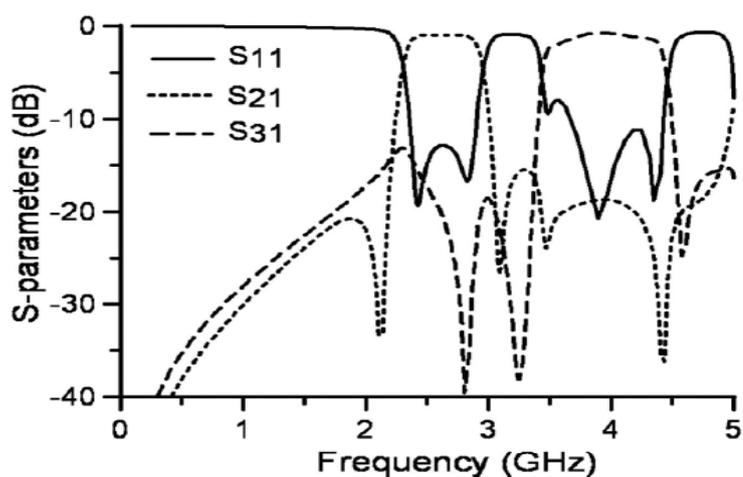


Figure 2.8: Simulated results of the proposed microstrip diplexer

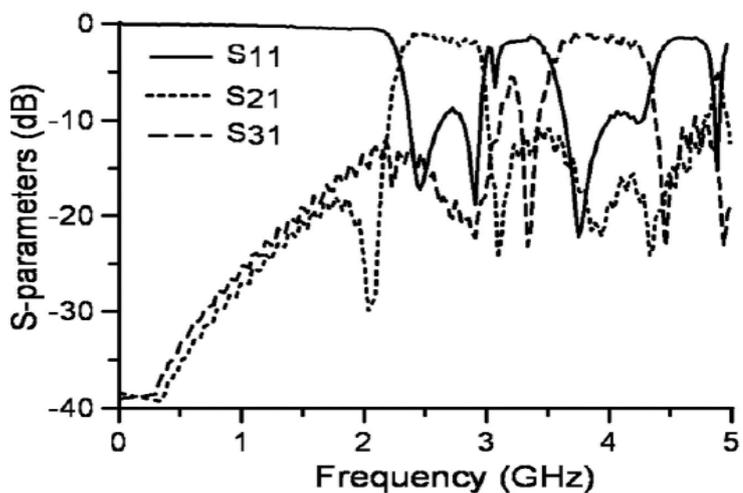


Figure 2.9: Measured results of the proposed microstrip diplexer

2.3.2 High Isolation Diplexer using $\lambda/4$ Resonator Filter

Diplexers have been widely used in communication systems to separate a single input signal into two outputs with different frequencies. However, these diplexers usually experience high insertion loss (Dong and Itoh 2011) or have poor isolation (Xue and Chen 2008). In this letter, F. Cheng, X.Q. Lin, Z.B. Zhu, L.Y. Wang and Y. Fan presented a diplexer that has low loss and high isolation with centre frequencies of 1.8 GHz and 2.4 GHz (F.Cheng, Lin et al. 2012). The proposed diplexer was designed with two filters, each filter having two $\lambda/4$ resonators coupled by the inductive metallized via which works as a K-inverter (F.Cheng, Lin et al. 2012). The authors applied a $\lambda/4$ resonator in the filter design which greatly reduces the size of the diplexer and also provides a wider stopband than the diplexers with a $\lambda/2$ parallel filter or dual-mode filter (W.Q. Xu, Ho et al. 2007). Figure 2.10 shows the layout of the designed microstrip diplexer.

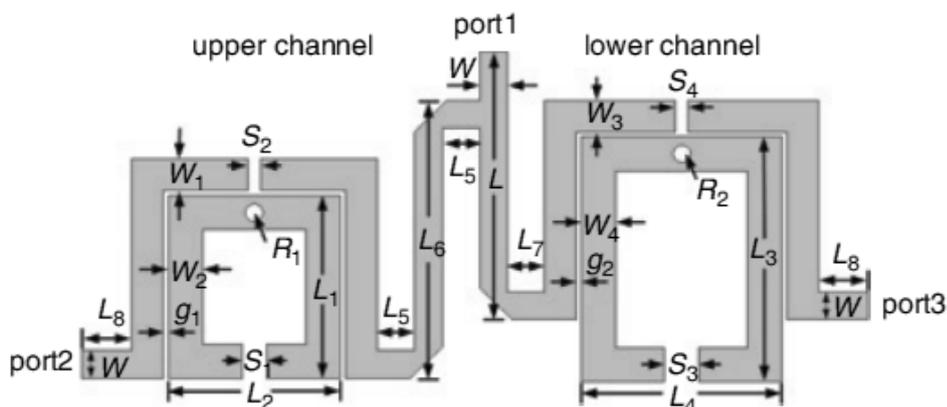


Figure 2.10: Layout of the designed microstrip diplexer

Figure 2.11 shows the simulated responses of both the upper and lower channels of the diplexer. By varying the gaps S_2 and S_4 , the transmission zeros in the upper and lower channels can be shifted. When properly designed, the upper channel's lower transmission zero can be placed at the centre frequency of the lower channel and the lower channel's higher transmission zero can be placed at the centre

frequency of the upper channel. Such characteristic allows the improvement of the isolation between the two channels (F.Cheng, Lin et al. 2012).

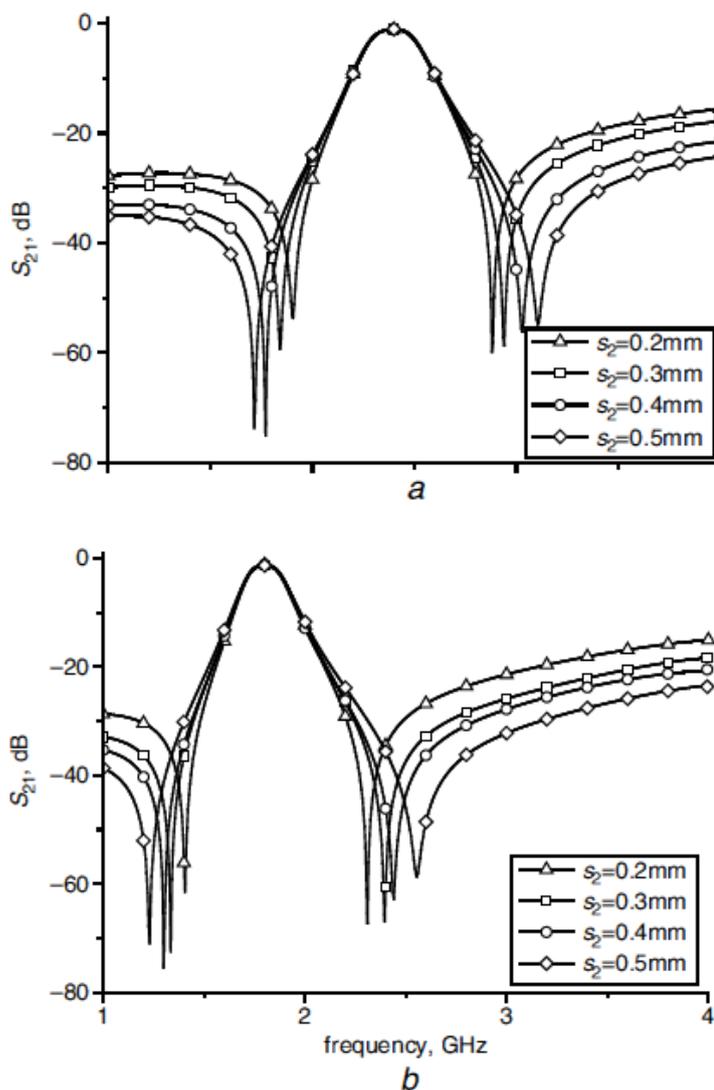


Figure 2.11: Simulated responses of (a) upper channel and (b) lower channel

Based on the results as shown in Figure 2.12, the measured insertion losses at the two centre frequencies of 1.8 GHz and 2.4 GHz are -1.1 dB and -1.18 dB respectively. The diplexer has an isolation of less than -40dB from 1 GHz to 6.62 GHz. Thus, the simulated and the measured results of the diplexer display a good agreement (F.Cheng, Lin et al. 2012).

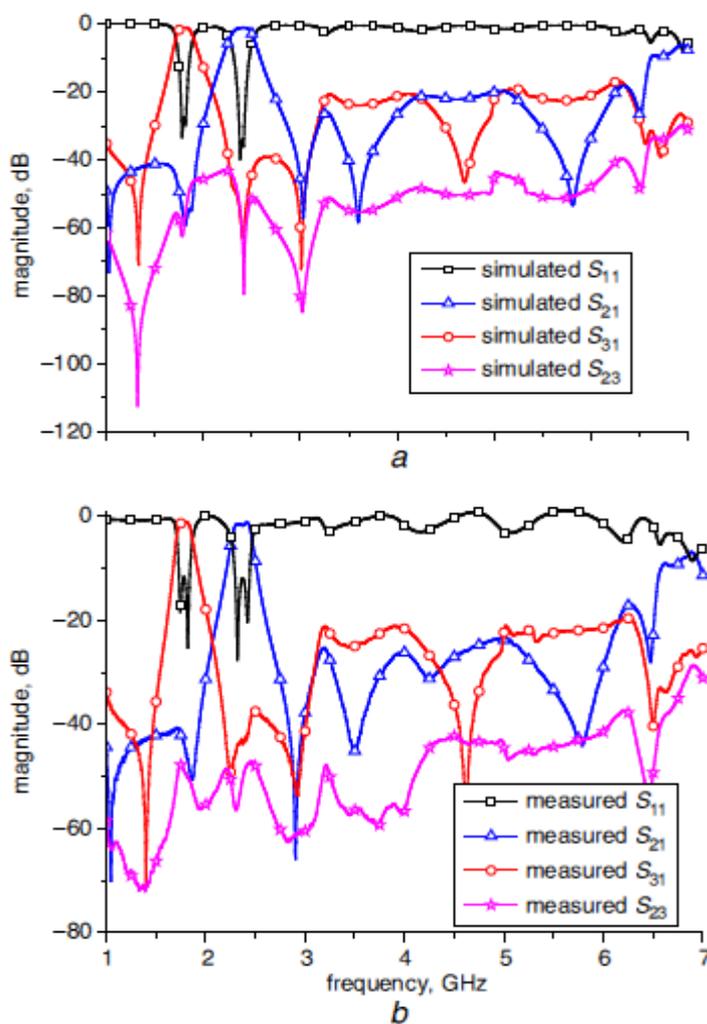


Figure 2.12: The (a) simulated and (b) measured results of the proposed diplexer

2.3.3 High Selectivity Dual-band Bandpass Filter

Many dual-band filters and design methods have been proposed to meet the increasing demands in wireless communication systems. There are basically four main methods (Cheng, Wang et al. 2012). These methods are cascading a broadband filter using a bandstop structure (Tsai and Huse 2004), combining two sets of independent resonators (Deng, Zhao et al. 2010), using a dual-mode resonators

(Wang, Ge et al. 2011) and utilizing stepped impedance resonators (Chu and Chen 2008). In this paper, W. Cheng, X.H Wang, Y. Tuo, Y.F. Bai and X.W. Shi proposed a compact microstrip line dual-band bandpass filter using folded stepped impedance resonators with high selectivity. Figure 2.13 shows the circuit layout of the proposed filter design.

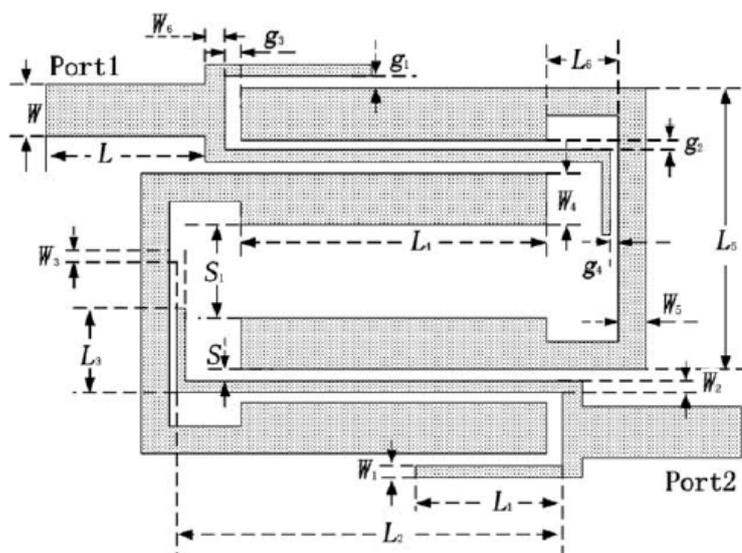


Figure 2.13: Configuration of the proposed filter

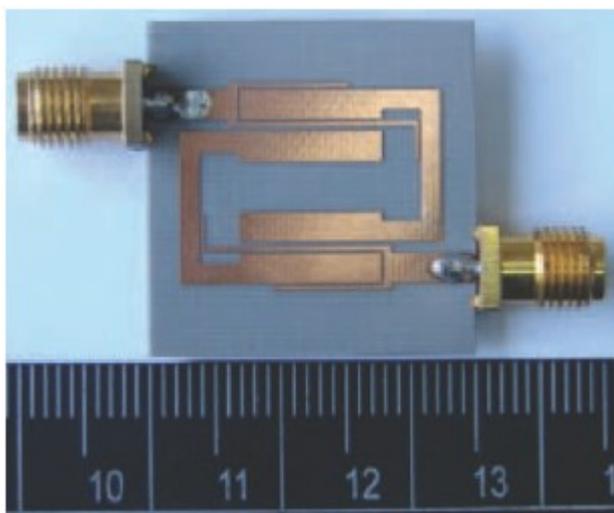


Figure 2.14: Fabricated bandpass filter

With the proposed designs shown in Figure 2.14, a dual-band bandpass filter was obtained. This design consists of two folded stepped impedance resonators and

asymmetric coupling input and output lines. The filter operates at a centre frequency of 2.4 GHz and 5.3 GHz (Cheng, Wang et al. 2012). Figure 2.15 presents the simulated and measured results of the proposed design. A high selectivity filter with five transmission zeros was achieved.

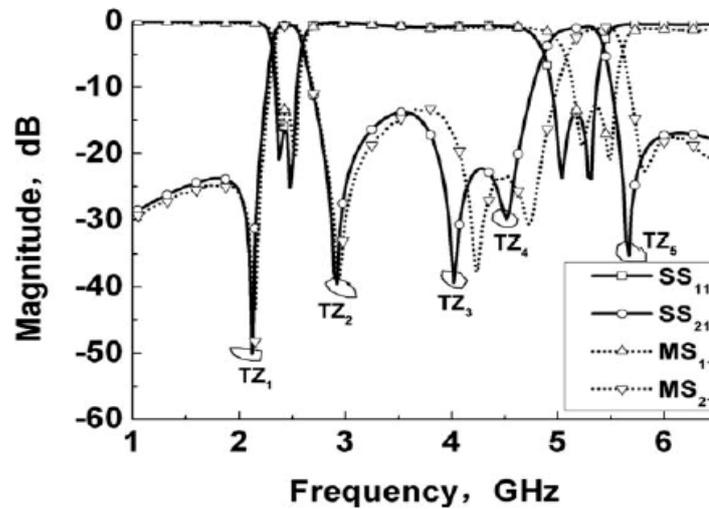


Figure 2.15: Simulated and measured S-parameters of the proposed filters

2.4 Research Methodologies

The process of designing a microwave device is divided into three main stages. These stages are the simulation stage, the fabrication stage and the experiment stage. At each stage, there are specific softwares, tools and equipments that are used in order to produce a successfully functioning design. In the following sections, details of the softwares, tools and equipments used in the three main stages will be introduced.

2.4.1 The Simulation Stage

In this stage, the TX Line and Ansoft HFSS (High Frequency Structure Simulator) softwares were used. Before the designing and simulating process, TX Line was used to calculate out the width of a 50 ohm feed line based on the design specifications. Those specifications that need to be considered are the dielectric constant of substrate and the thickness of the substrate.

Ansoft HFSS is a simulation tool for 3D full-wave electromagnetic (EM) field simulator. It is very effective when it comes to designing high frequency components. Ansoft HFSS uses the Finite Element Method (FEM) with adaptive meshing to solve the simulation process.

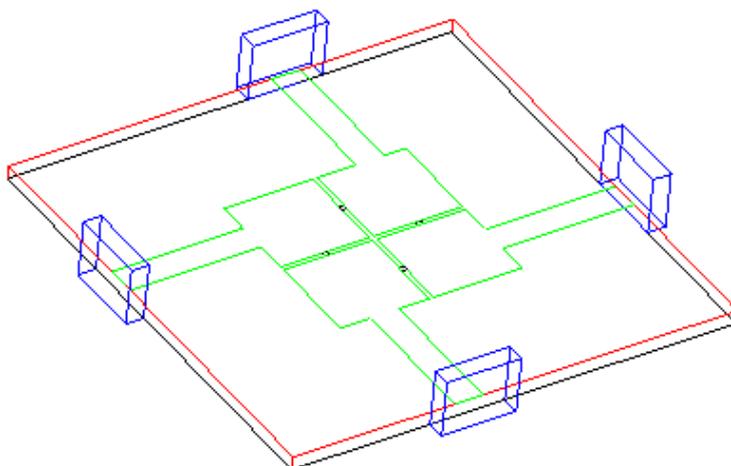


Figure 2.16: 3D drawing using the Ansoft HFSS software

2.4.2 Fabrication Stage

Before proceeding to the fabrication stage, the proposed microwave designs were printed out onto the transparent film before being able to print out on the substrate board. Printing out the designs onto the transparent film requires the CST Design Environment software as the HFSS software does not support the printing function.

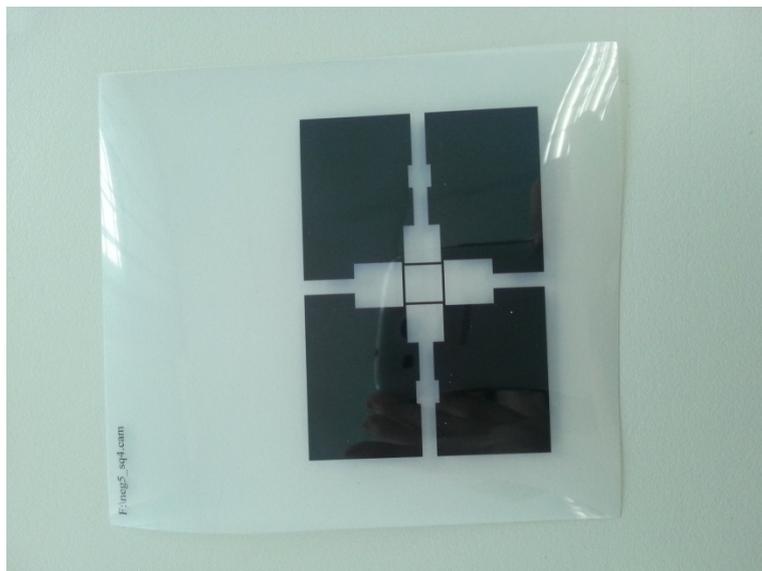


Figure 2.17: Printed transparent film

A laminating machine was used to laminate the substrate board with a layer of photo-resist film. This laminating step only applies to negative board substrate whereas positive board substrate is photo-resist in nature. After the laminating step, UV light exposure machine was used to expose the transparent film onto the board, thus printing the design onto the substrate board.

After washing the board with a film developer solution to remove the photo-resist, etching is done by submerging the printed substrate board into a chemical solution using the etching machine. This is to remove the unwanted copper and thus, leaving only the printed design on the substrate board.

2.4.3 Experiment Stage

During the experiment stage, tools such as the Agilent 85052 D (3.5mm Economy) Calibration Kit and the Rohde & Schwarz Vector Network Analyzer were used to obtain the measured results of the fabricated board. Before any measurement can be performed, the Rohde & Schwarz Vector Network Analyzer is calibrated using the Agilent 85052 D (3.5mm Economy) Calibration Kit. Ensuring all the ports are calibrated in a proper manner will eliminate any losses in the cables and thus, resulting in an accurate measurement.



Figure 2.18: Agilent Calibration Kit



Figure 2.19: Rohde & Schwarz Vector Network Analyzer

Once the calibration is done, the measurement process takes place. Only two ports can take part in the measurement at a time. Ports that are not being measured have to be terminated by the $50\ \Omega$ terminators to ensure accurate results. The measured results from the fabricated board are saved into a USB thumb-drive. A software called Freelance Graphics is used to compare and analyze the simulated and the measured results.

CHAPTER 3

TWO-WAY LOW-PASS AND HIGH-PASS FILTER

3.1 Background

A two-way low-pass and high-pass filter is a combination of two independent filters into one. Each of the filters is self-functioning and thus, does not rely on one another. The low-pass and high-pass filter can only be operated one at a time and not simultaneously. Therefore, it has a total of two input ports and two output ports. The advantage of filters with wide bandwidth is more signals within a range of frequencies are allowed to pass through. This is a very important feature especially in communication system that has a high data rate. Simulation and experiments were performed and results were analysed and discussed in detail.

3.2 Two-way Low-pass and High-pass Filter

A dual-band filter is a two-port device which has a two passbands. Each passband operates at particular frequencies. Unlike dual-band filters, a two-way filter is a combination of two individual filters into one design. In order to achieve this two-way filter, passive elements such as capacitors and inductors were incorporated into the design. The function of a capacitor is to block the signal flow at lower frequencies while an inductor blocks signal flow at higher frequencies. Based on this concept, a four-port two-way filter is proposed.

3.2.1 Configuration

A two-way low-pass and high-pass filter has been successfully designed and fabricated. This proposed design was fabricated on a Duroid RO4003C substrate (with a dielectric constants of $\epsilon_r = 3.38$ and a thickness of 1.524mm). Basically, the proposed design is a four-port filter that consists of both low-pass and high-pass filters. Port 1 functions as the input port for the low-pass filter while Port 2 functions as the output port. For the high-pass filter, Port 3 serves as an input port whereas Port 4 serves as an output port.

Every microstrip feed line in this proposed design have a characteristic impedance of 50Ω . Thus, the width of the feedline was calculated to be fixed at 3.21mm. The proposed filter is designed to be symmetric. The frequency of the device decreases when the length of the travelling path increases. The centre patch of the proposed filter is connected to a pair of inductors and a pair of capacitors. The travelling path with a pair of inductors functions as a low-pass filter while the travelling path with a pair of capacitors functions as a high-pass filter.

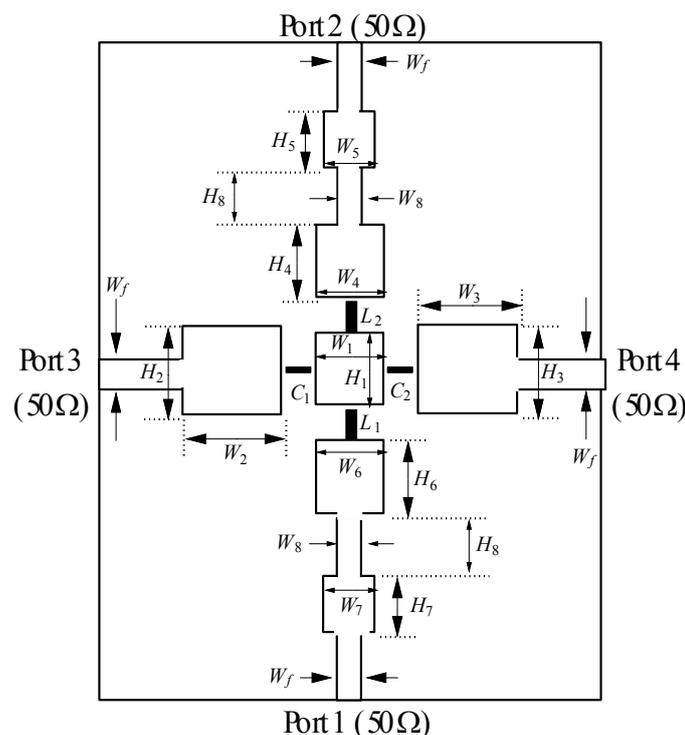


Figure 3.1: Configuration of the proposed two-way filter.

Figure 3.1 illustrates the top view configuration of the proposed two-way filter. Details on the design parameters are tabulated in Table 3.1.

Table 3.1: Parameters values of the proposed filter

Parameters	Values
C_1	0.3 pF
C_2	0.3 pF
L_1	1.3 nH
L_2	1.3 nH
W_f	3.21 mm
W_1	8.0 mm
W_2	10.5 mm
W_3	10.5 mm
W_4	8.0 mm
W_5	5.0 mm
W_6	8.0 mm
W_7	5.0 mm
W_8	3.2 mm
W_9	3.2 mm
H_1	8.0 mm
H_2	9.8 mm
H_3	9.8 mm
H_4	8.23 mm
H_5	5.0 mm
H_6	8.23 mm
H_7	5.0 mm
H_8	8.27 mm
H_9	8.27 mm

3.2.2 Simulation and Experiment Results

The proposed two-way filter was simulated using Ansoft HFSS to obtain the simulated results. The design was fabricated and the experimental results were measured using the Rohde & Schwarz Vector Network Analyzer. In order to examine and compare the simulated and measured results, the amplitude responses of both simulated and measured results were plotted out using the Freelance Graphics software. The fabricated two-way filter is shown in Figure 3.2.

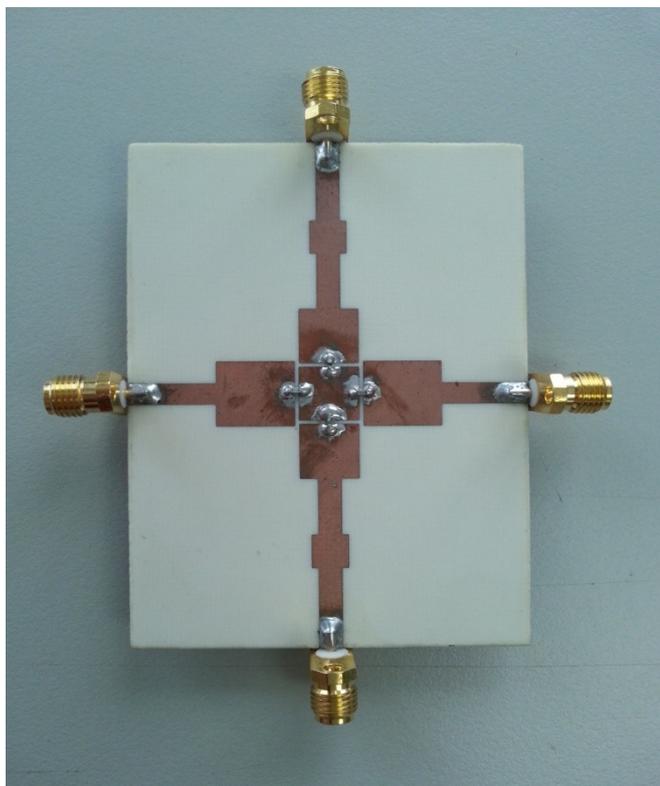


Figure 3.2: Prototype of the proposed two-way filter.

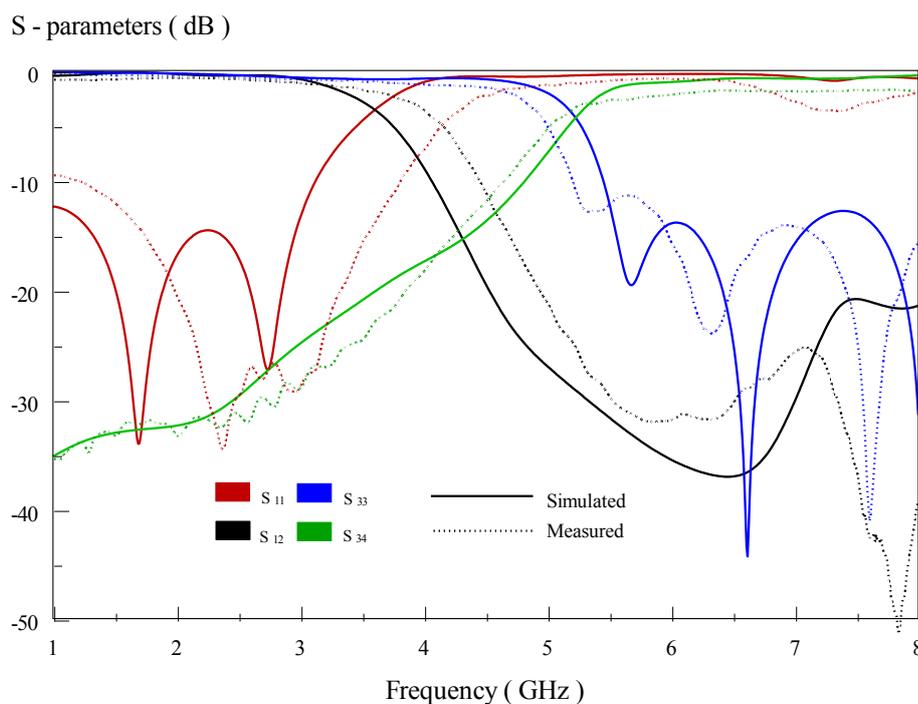


Figure 3.3: Simulated and measured S-parameters of the two-way filter.

Figure 3.3 shows the simulated and measured amplitude responses of the designed filter. The amplitude responses for both the simulation and measurement were fixed within the range of 1 GHz to 8 GHz. In the simulation, the insertion losses for the low-pass and high-pass filters are -0.18 dB and -0.45 dB respectively. The low-pass filter has a 3-dB cutoff frequency of 3.55 GHz whereas the high-pass filter has a 3-dB cutoff frequency of 5.3 GHz. The simulated result shows that the passbands of the low-pass and high-pass filters have a return loss of less than -10 dB within its bandwidth.

The measured insertion losses for the low-pass and high-pass filters are -0.65 dB and -1.72 dB respectively. Measurement from the fabricated design shows that the 3-dB cutoff frequency of the low-pass filter is 4.01 GHz while the high-pass filter has a 3-dB cutoff frequency of 5.05 GHz.

Overall, the simulated and measured results prove to be in reasonable agreement. Measured return loss of the high-pass filter is maintained below -10dB however, the return loss for the low-pass filter in the range of 1.00 GHz to 1.18 GHz

is slightly above -10 dB. This is due to the passive elements in the circuits which have a tolerance of $\pm 5\%$, thus affecting the measured results. Moreover, the soldered ports may cause some losses as well. All these factors will cause discrepancy in cutoff frequency between the simulated and measured results. The low-pass filter has a 3-dB cutoff frequency error of 12.96% whereas the high-pass filter has a 3-dB cutoff frequency error of only 4.72%. Table 3.2 shows the comparison between the simulation and the experiment results of the proposed two-way filter.

Table 3.2: Comparison between the simulation and experiment results

	Low-pass Filter		High-pass Filter	
	HFSS Simulation	Experiment	HFSS Simulation	Experiment
Minimum Insertion loss (dB)	-0.18	-0.65	-0.45	-1.73
3-dB Reference Point (dB)	-3.18	-3.65	-3.45	-4.73
3-dB Cutoff Frequency, f_c (GHz)	3.55	4.01	5.30	5.05
Error of f_c (%)		12.96		4.72

3.2.3 Parametric Analysis

Parametric analysis is done by varying the design parameters shown in Table 3.1. The design parameters were varied by stepping up and stepping down the values. The objective of the parametric analysis is to observe and analyse the effect of varying the design parameters. This process is completed using Ansoft HFSS software.

Parametric Analysis 1

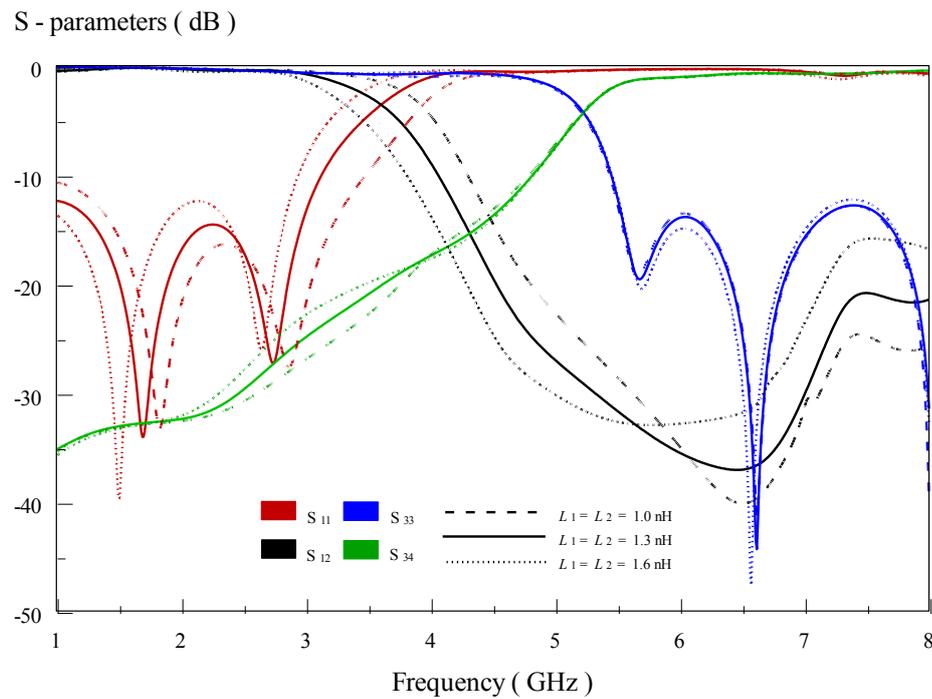


Figure 3.4: The effect of varying parameters L_1 and L_2 on the amplitude response.

The parameters L_1 and L_2 with a value of 1.3 nH were stepped up and stepped down with the following values:

- Step-down value : 1.0 nH
- Step-up value : 1.6 nH

Figure 3.4 shows that changing the parameters L_1 and L_2 only affect the low-pass filter as inductors only play a role in the low-pass filter. The significant changes can be seen at the 3-dB cutoff frequency and the return loss of the low-pass filter. When L_1 and L_2 are fixed at 1.0 nH, the 3-dB cutoff frequency shifts to 3.80 GHz and the return loss shifts to the right. Changing L_1 and L_2 to 1.6 nH causes the 3-dB cutoff frequency to shift to 3.27 GHz and also the return loss to shift to left.

Parametric Analysis 2

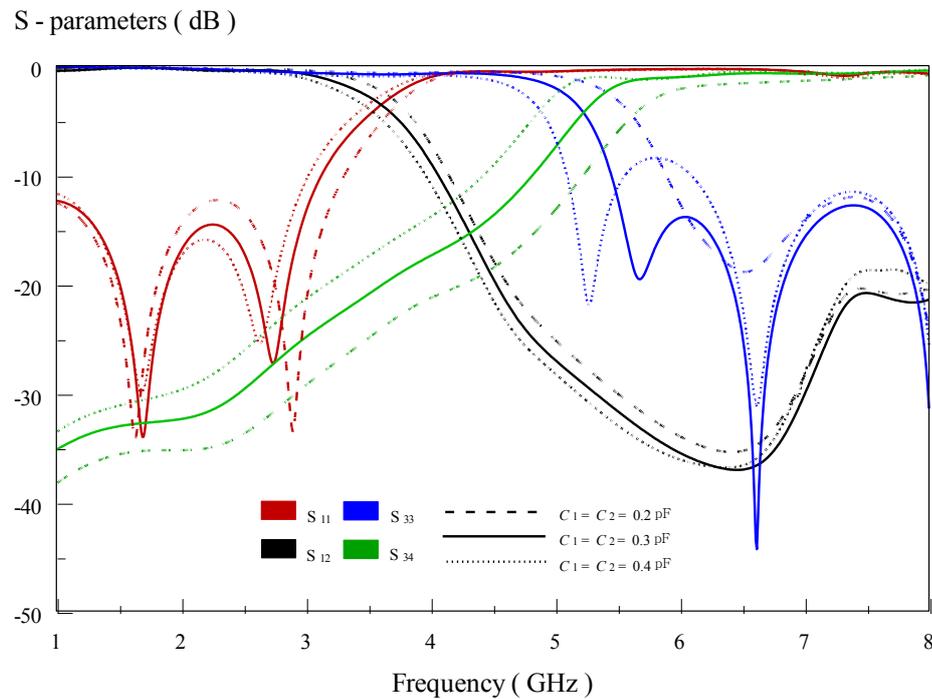


Figure 3.5: The effect of varying parameters C_1 and C_2 on the amplitude response.

The parameters C_1 and C_2 with a value of 0.3 pF were stepped up and stepped down with the following values:

- Step-down value : 0.2 pF
- Step-up value : 0.4 pF

Figure 3.5 shows that varying the parameters C_1 and C_2 significantly affect the amplitude response of the high-pass filter and only cause a small shift in the low-pass filter. The reason for this is because capacitor plays a role in the high-pass filter. When C_1 and C_2 are stepped down to 0.2pF, the 3-dB cutoff frequency of the high-pass filter shifts to 5.74 GHz and the return loss is higher. Moreover, the return loss for the low-pass filter also increases. Stepping up the values of C_1 and C_2 to 0.4 pF causes the 3-dB cutoff frequency of the high-pass filter to shift to 4.93 GHz and a higher return loss is obtained. However, this result has lower return loss at the low-pass filter.

Parametric Analysis 3

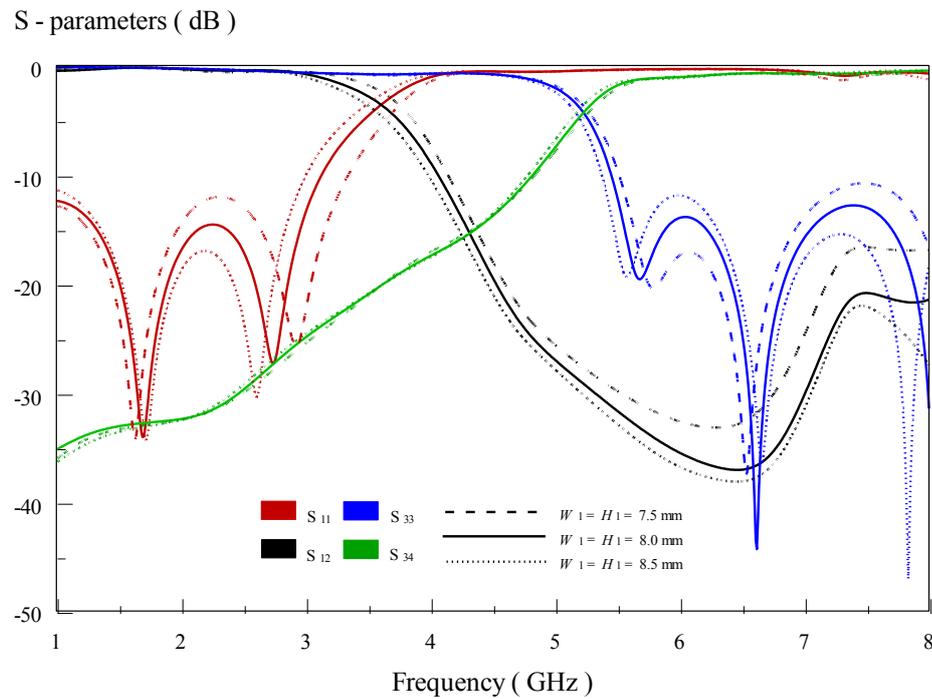


Figure 3.6: The effect of varying parameters W_1 and H_1 on the amplitude response.

The parameters W_1 and H_1 with a value of 8.0 mm were stepped up and stepped down with the following values:

- Step-down value : 7.5 mm
- Step-up value : 8.5 mm

Changing the parameters W_1 and H_1 affect both the low-pass and high-pass filters. The significant effects are in the return loss of both the low-pass and high-pass filters as seen in Figure 3.6. Stepping down W_1 and H_1 to 7.5 mm results in a higher return loss at the low-pass filter. When W_1 and H_1 are increased to 8.5 mm, the return loss of the low-pass filter decreases. Varying W_1 and H_1 also affects the positions of poles of the high-pass filter.

Parametric Analysis 4

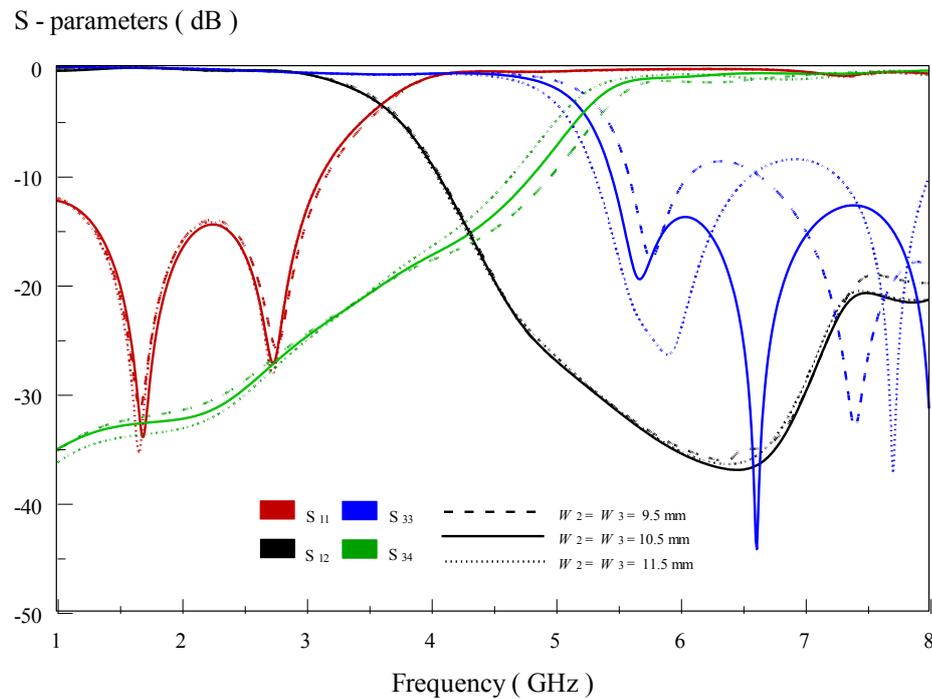


Figure 3.7: The effect of varying parameters W_2 and W_3 on the amplitude response.

The parameters W_2 and W_3 with a value of 10.5 mm were stepped up and stepped down with the following values:

- Step-down value : 9.5 mm
- Step-up value : 11.5 mm

Significant effect on the 3-dB cutoff frequency and return loss of the high-pass filter is shown in Figure 3.19. This is because the parameters W_2 and W_3 are in the travelling path of the high-pass filter. There is impedance mismatch which causes the shifting in the poles of the high-pass filter. Moreover, it increases the return loss of the high-pass filter. Setting W_2 and W_3 to 9.5 mm results in a 3-dB cutoff frequency at 5.45 GHz. Increasing W_2 and W_3 to 11.5 mm causes the 3-dB cutoff frequency to decrease to 5.14 GHz.

Parametric Analysis 5

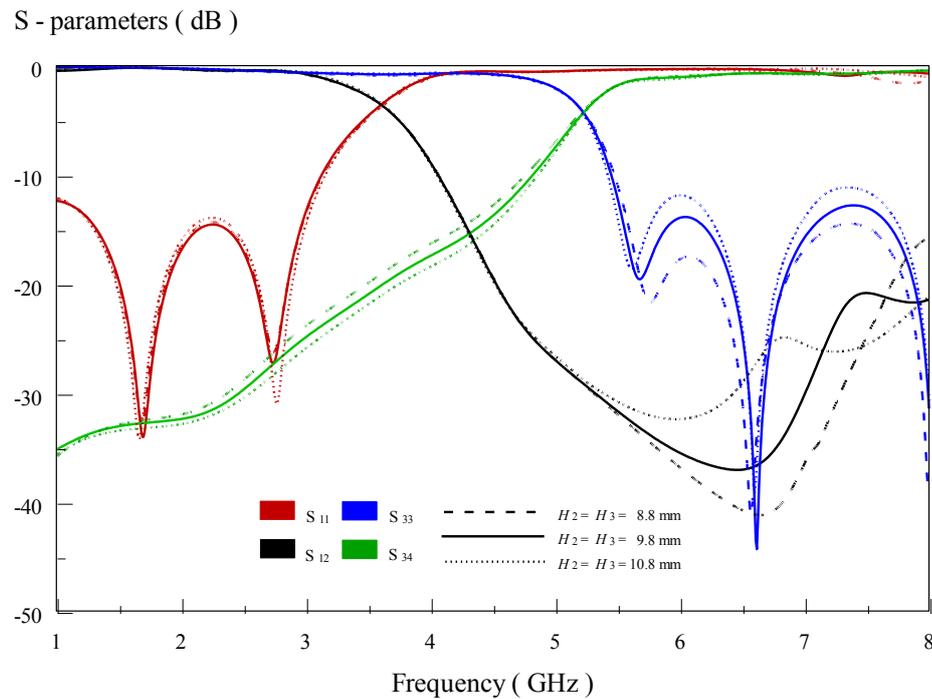


Figure 31.8: The effect of varying parameters H_2 and H_3 on the amplitude response.

The parameters H_2 and H_3 with a value of 9.8 mm were stepped up and stepped down with the following values:

- Step-down value : 8.8 mm
- Step-up value : 10.8 mm

Since parameters H_2 and H_3 are along the travelling path of the high-pass filter, therefore varying the parameters only give effect to the high-pass filter. As shown in Figure 3.8, stepping down and stepping up the parameters vary the return loss by ± 1 dB. However, the 3-dB cutoff frequency of the high-pass filter is maintained.

Parametric Analysis 6

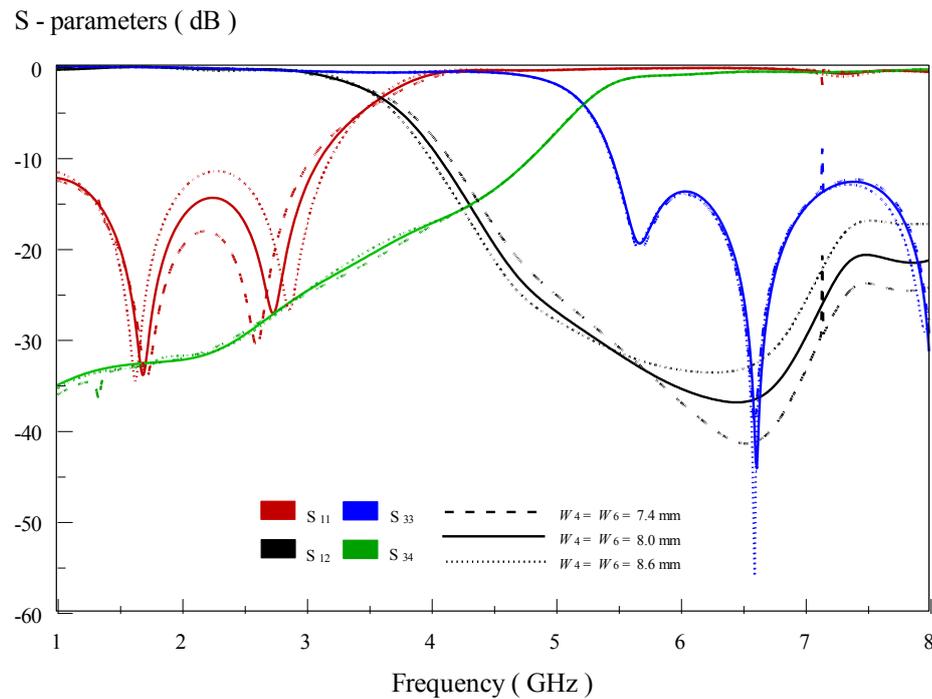


Figure 3.9: The effect of varying parameters W_4 and W_6 on the amplitude response.

The parameters W_4 and W_6 with a value of 8.0 mm were stepped up and stepped down with the following values:

- Step-down value : 7.4 mm
- Step-up value : 8.6 mm

Figure 3.9 shows that varying the parameters W_4 and W_6 do not affect the high-pass filter but only has significant effect on the low-pass filter. The low-pass filter is affected because these parameters are in the travelling path for the low-pass filter. The significant changes are in the return loss while the 3-dB cutoff frequency is not affected. When W_4 and W_6 are fixed at 7.4 mm, the return loss decreases. On the other hand, when W_4 and W_6 are fixed at 8.6 mm, the return loss increases. Additionally, varying the parameters W_4 and W_6 causes the poles at the low-pass filter to experience shift in frequencies.

Parametric Analysis 7

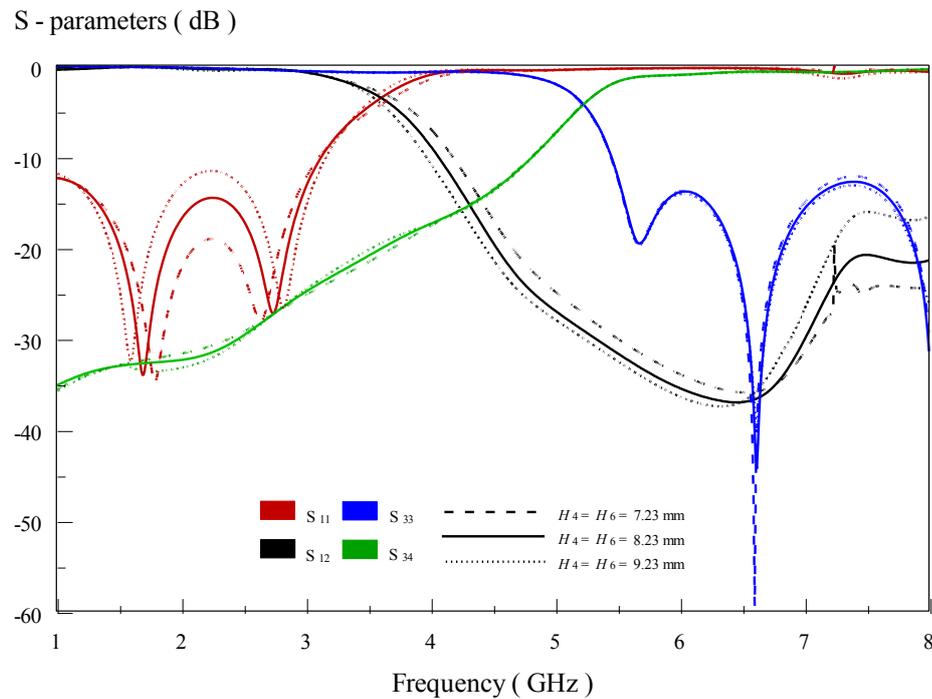


Figure 3.10: The effect of varying parameters H_4 and H_6 on the amplitude response.

The parameters H_4 and H_6 with a value of 8.23 mm were stepped up and stepped down with the following values:

- Step-down value : 7.23 mm
- Step-up value : 9.23 mm

Figure 3.10 shows that changing the parameters H_4 and H_6 only have effect on the low-pass filter. This is because H_4 and H_6 does not lie within the travelling path of the high-pass filter, thus it is not affected by the changes. The return loss of the low-pass filter has some significant changes as the parameters vary. Setting H_4 and H_6 to 7.23 mm causes the low-pass filter to have a lower return loss. As H_4 and H_6 are stepped up to 9.23 mm, the return loss increases at the low-pass filter.

Parametric Analysis 8

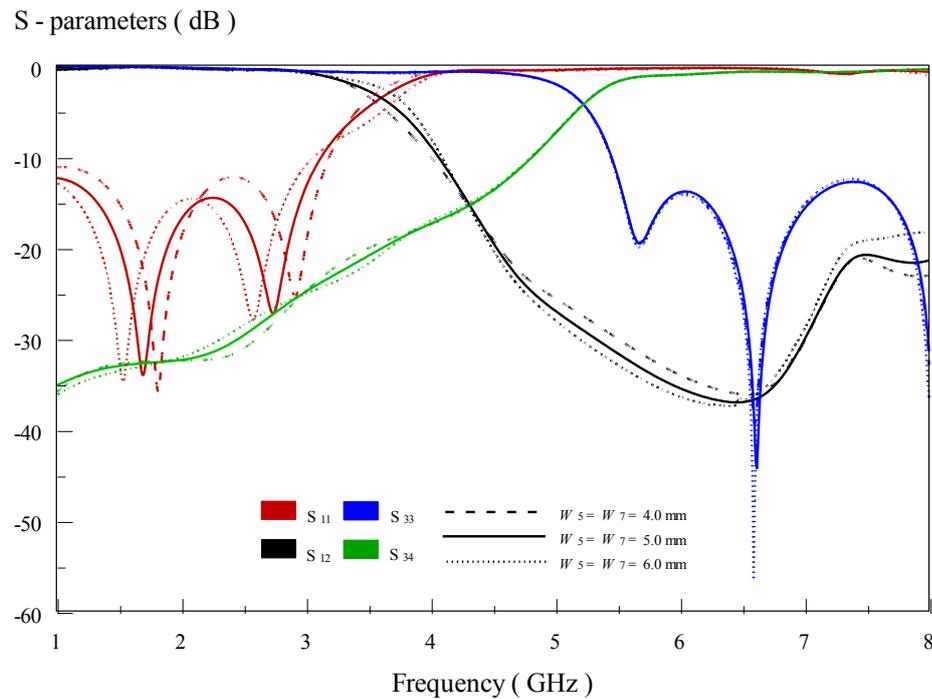


Figure 3.11: The effect of varying parameters W_5 and W_7 on the amplitude response.

The parameters W_5 and W_7 with a value of 5.0 mm were stepped up and stepped down with the following values:

- Step-down value : 4.0 mm
- Step-up value : 6.0 mm

As can be seen in Figure 3.11, the amplitude response of the low-pass filter is affected by the changes in values of the parameters. Clearly, the response for the high-pass filter is not affected as the parameters are not part of the travelling path of the high-pass filter. Basically, the poles of the low-pass filter experience a shift in frequency. Meanwhile, they have minimal effects on the 3-dB cutoff frequency of the low-pass filter as the parameters W_5 and W_7 are varied.

Parametric Analysis 9

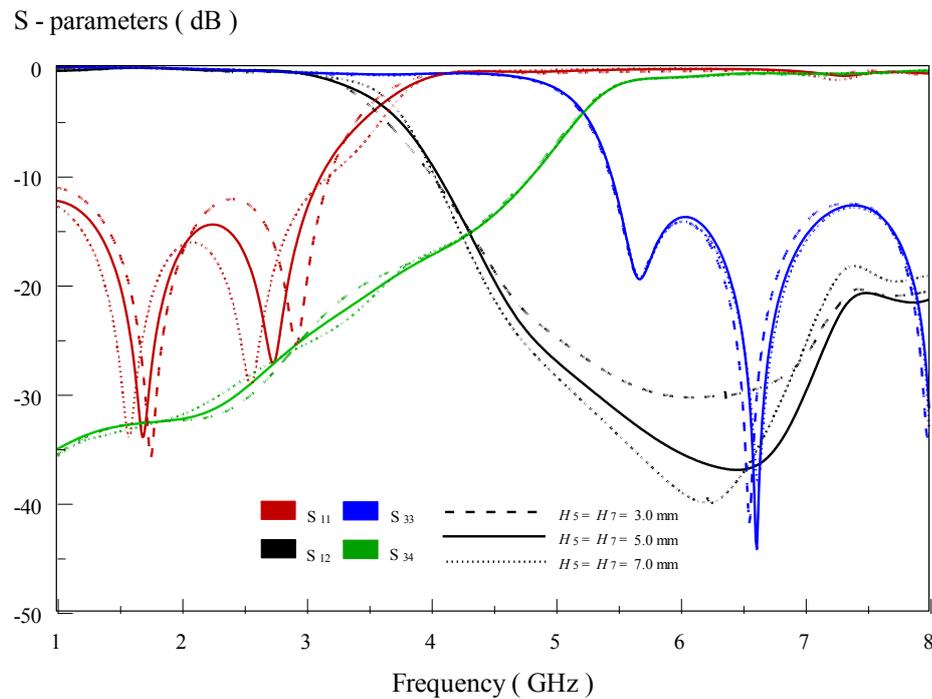


Figure 3.12: The effect of varying parameters H_5 and H_7 on the amplitude response.

The parameters H_5 and H_7 with a value of 5.0 mm were stepped up and stepped down with the following values:

- Step-down value : 3.0 mm
- Step-up value : 7.0 mm

Figure 3.12 shows that changing the parameters H_5 and H_7 only have effect on the low-pass filter not the high-pass one. As H_5 and H_7 do not lie within the travelling path of the high-pass filter, thus it is not affected by the changes. The return loss is affected by ± 1 dB and the poles of the low-pass filter are being shifted as the parameters vary. Reducing H_5 and H_7 to 3.0 mm causes the low-pass filter to have a lower return loss and the shifting of the poles towards the right. When H_5 and H_7 are stepped up to 7.0 mm, the return loss is lower at the low-pass filter and the poles of the filter shift towards the left.

Parametric Analysis 10

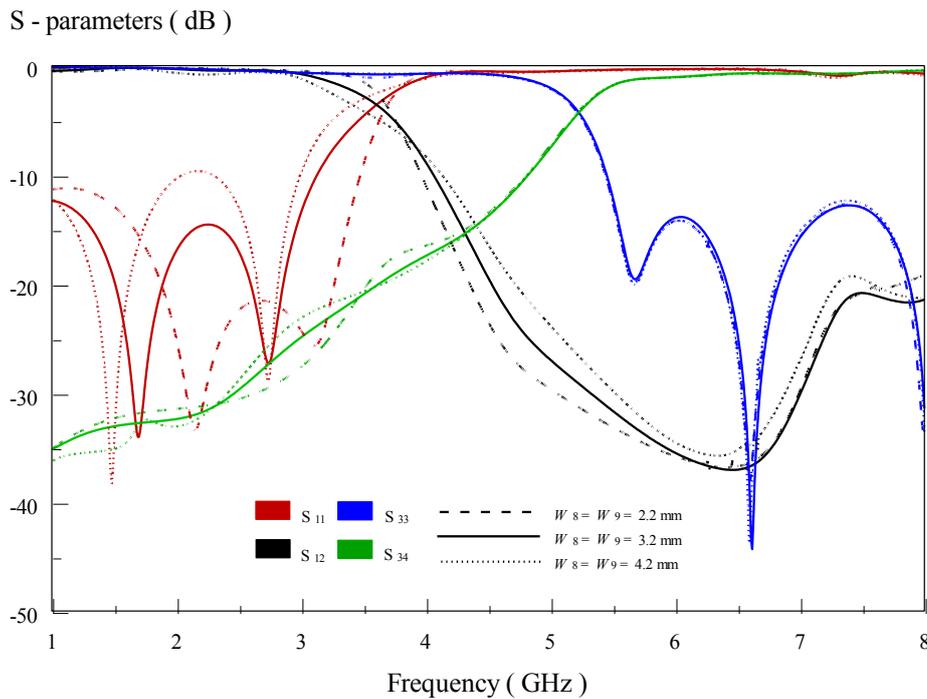


Figure 3.13: The effect of varying parameters W_8 and W_9 on the amplitude response.

The parameters W_8 and W_9 with a value of 3.2 mm were stepped up and stepped down with the following values:

- Step-down value : 2.2 mm
- Step-up value : 4.2 mm

Figure 3.13 shows that varying the parameters W_8 and W_9 have no effect on the high-pass filter. However, W_8 and W_9 have significant effect on the low-pass filter as it is part of the travelling path. There are significant changes in the return loss and the shifting of the poles. On the other hand, the changes have very minimal effect on the 3-dB cutoff frequency. As W_8 and W_9 are decreased to 2.2 mm, the return loss becomes lower and wider gap between the poles increases the bandwidth of the filter. However, stepping up W_8 and W_9 to 4.2 mm results in higher return loss and the shifting of the first pole towards a lower frequency.

Parametric Analysis 11

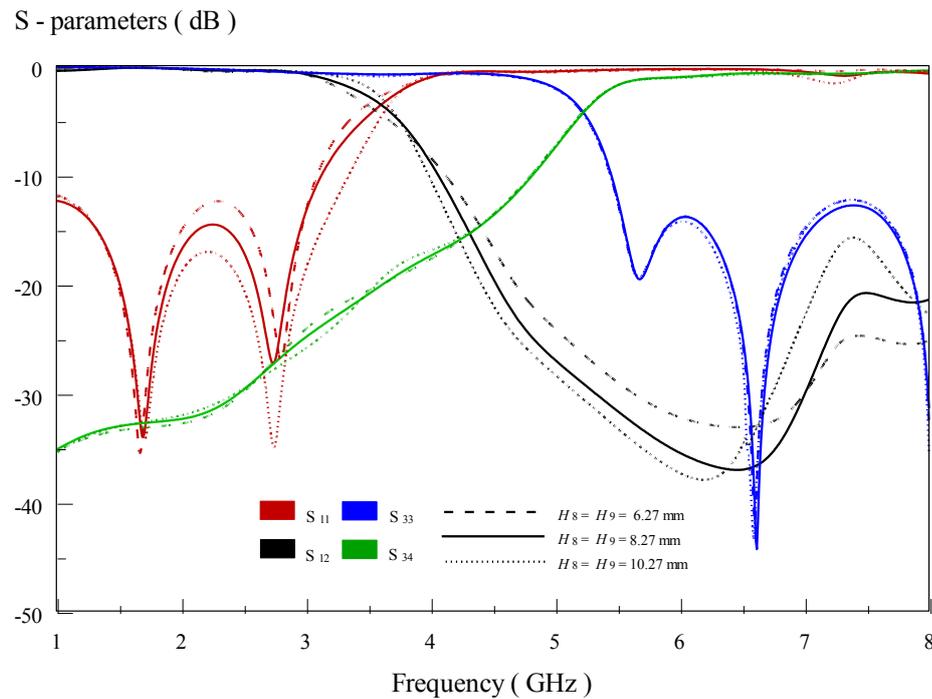


Figure 3.14: The effect of varying parameters H_8 and H_9 on the amplitude response.

The parameters H_8 and H_9 with a value of 8.27 mm were stepped up and stepped down with the following values:

- Step-down value : 6.27 mm
- Step-up value : 10.27 mm

Figure 3.14 shows that changing the parameters H_8 and H_9 only give effect on the low-pass filter and not the high-pass filter. Since H_8 and H_9 do not lie within the travelling path of the high-pass filter, thus it is not affected by the changes. The return loss is affected by ± 1 dB as the parameters vary. The low-pass filter has a higher return loss when H_8 and H_9 are decreased to 6.27 mm. When H_8 and H_9 are increased to 10.27 mm, the return loss becomes lower at the low-pass filter. Varying H_8 and H_9 also slightly shift the 3-dB cutoff frequency of the low-pass filter.

Parametric Analysis 12

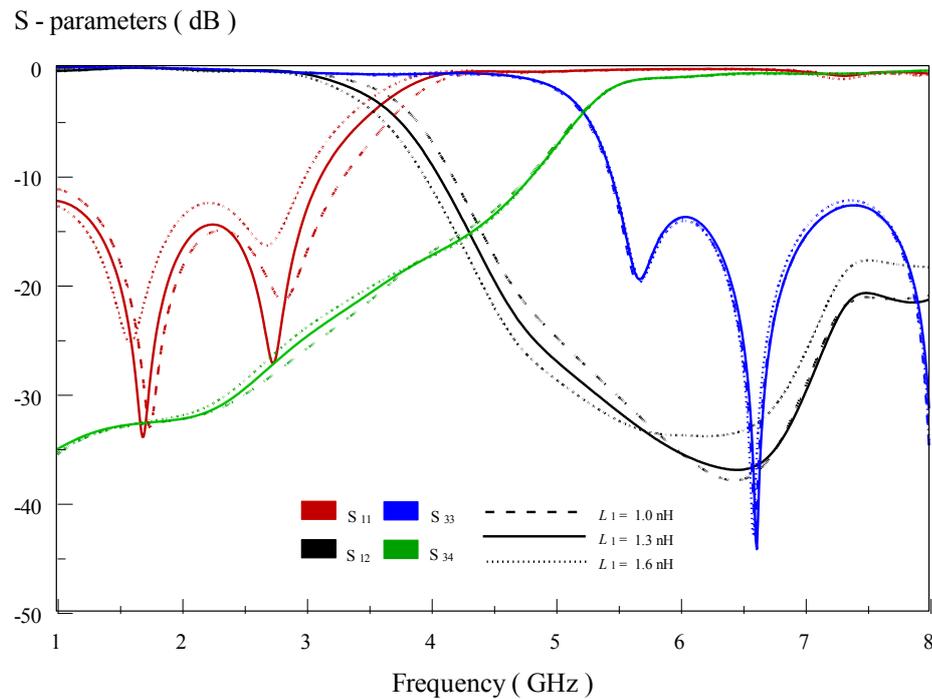


Figure 3.15: The effect of varying parameter L_1 on the amplitude response.

The parameter L_1 with a value of 1.3 nH were stepped up and stepped down with the following values:

- Step-down value : 1.0 nH
- Step-up value : 1.6 nH

The parameter L_1 is along the travelling path of the low-pass filter. Thus, by varying its value; only the amplitude response of the low-pass filter is affected as shown in Figure 3.15. The changes mainly affect the return loss and the 3-dB cutoff frequency. Stepping down L_1 to 1.0 nH results in slight shift of poles and the 3-dB cutoff frequency shifts up to 3.71 GHz. The return loss increases as L_1 is increased to 1.6 nH. Moreover, the 3-dB cutoff frequency shifts to 3.42 GHz.

Parametric Analysis 13

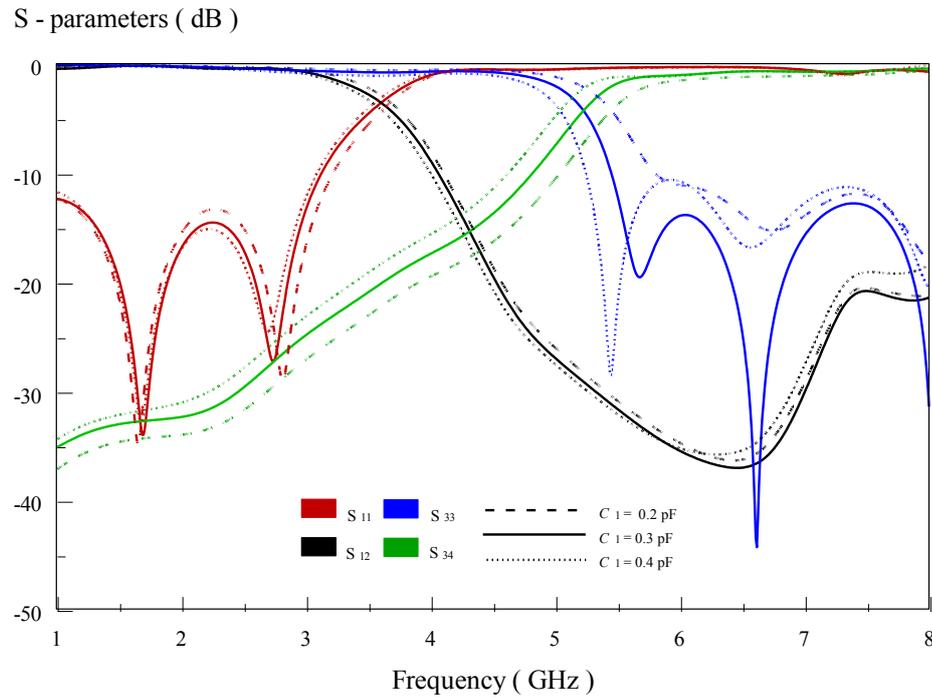


Figure 3.16: The effect of varying parameter C_1 on the amplitude response.

The parameter C_1 with a value of 0.3 pF was stepped up and stepped down with the following values:

- Step-down value : 0.2 pF
- Step-up value : 0.4 pF

As shown in Figure 3.16, both amplitude response of the low-pass and high-pass filters are affected by any changes made to the value of C_1 . However, varying C_1 majorly affects the high-pass filter compared to the low-pass filter because it lies directly in the travelling path of the high-pass filter. The 3-dB cutoff frequency of the high-pass filter is 5.52 GHz when C_1 is set to 0.2 pF. When C_1 has a value of 0.4 pF, the 3-dB cutoff frequency decreases to 5.11 GHz. Stepping up and stepping down the value of C_1 causes the matching S_{33} to increase. Minor changes can be seen at the low-pass filter.

Parametric Analysis 14

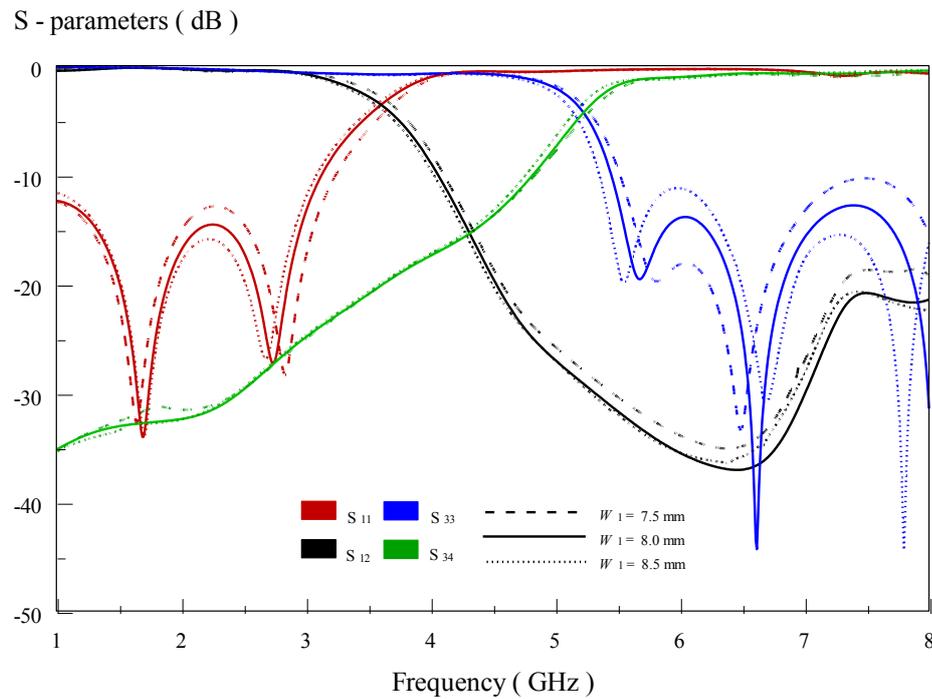


Figure 3.17: The effect of varying parameter W_1 on the amplitude response.

The parameter W_1 with a value of 8.0 mm were stepped up and stepped down with the following values:

- Step-down value : 7.5 mm
- Step-up value : 8.5 mm

Varying the value of parameter W_1 only gives significant effect to the return losses of both the low-pass and high-pass filters as shown in Figure 3.17. As the value of W_1 varies by ± 0.5 mm, the return loss of the low-pass filter varies by ± 1 dB. Similarly, the changes in W_1 also bring drastic effect to the return loss of the high-pass filter. The return loss varies at approximately ± 2 dB from the optimal value. Moreover, there are frequency shifts at the poles of the high-pass filter.

Parametric Analysis 15

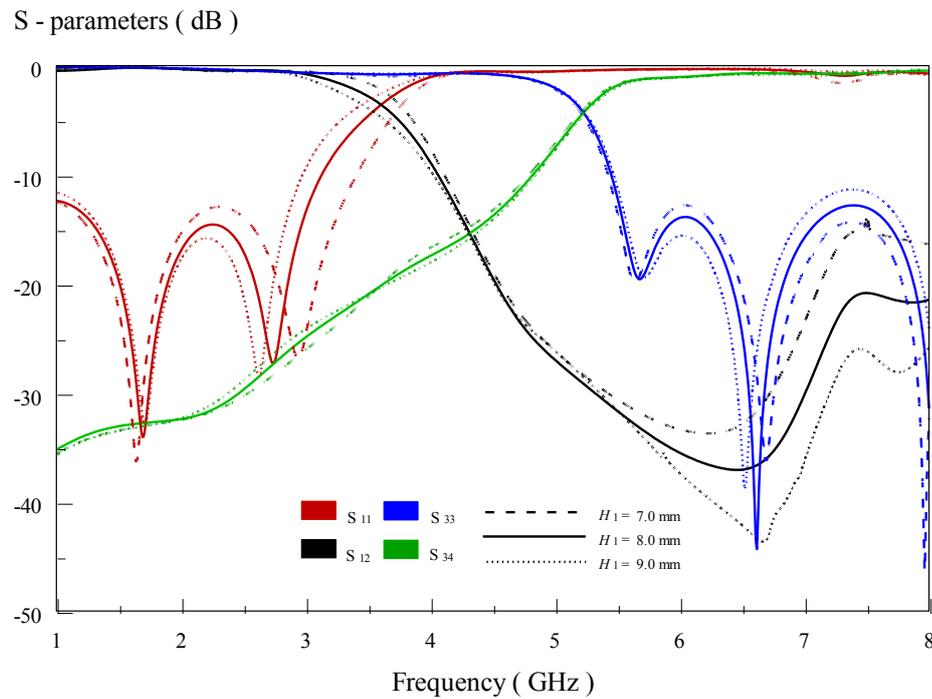


Figure 3.18: The effect of varying parameter H_1 on the amplitude response

The parameter H_1 with a value of 8.0 mm was stepped up and stepped down with the following values:

- Step-down value : 7.0 mm
- Step-up value : 9.0 mm

Figure 3.18 shows that changing the parameter H_1 affect both the low-pass and high-pass filters. Major effect from stepping up and stepping down the parameter value can be seen at the return loss of both filters. As the value of H_1 is being increased and decreased, both the responses of S_{11} and S_{33} vary by ± 1 dB. There is also slight shift in the 3-dB cutoff frequency of the low-pass filter.

Parametric Analysis 16

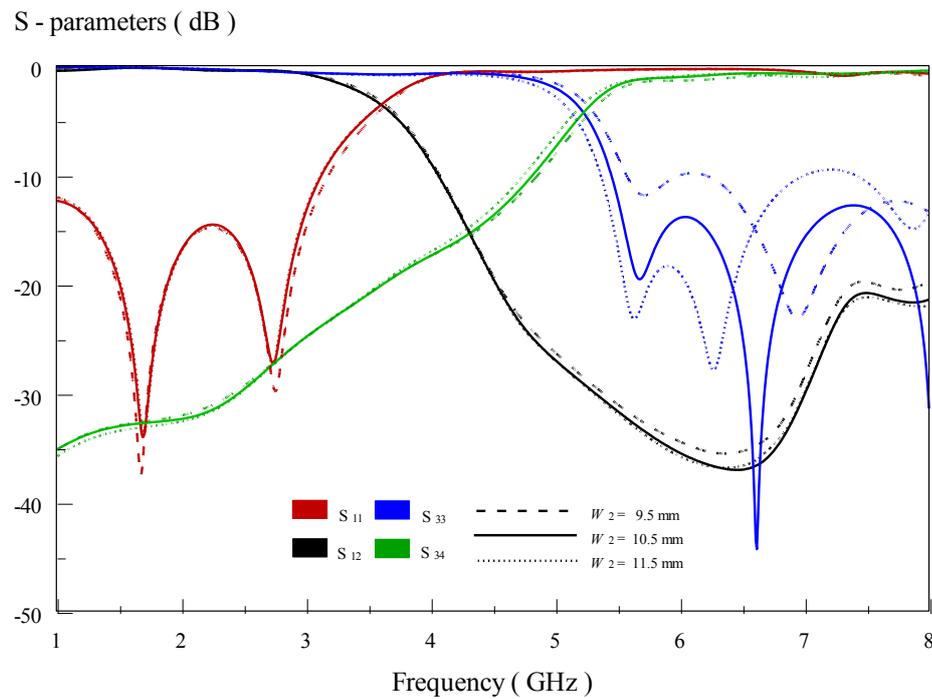


Figure 3.19: The effect of varying parameter W_2 on the amplitude response.

The parameter W_2 with a value of 10.5 mm was stepped up and stepped down with the following values:

- Step-down value : 9.5 mm
- Step-up value : 11.5 mm

Significant effect on the return loss of the high-pass filter is shown in Figure 3.19. This is because the parameter W_2 is in the travelling path of the high-pass filter. The low-pass filter is not affected by the varying parameter. The effect from the varying parameter is caused by impedance mismatch at S_{33} . Moreover, the poles of the high-pass filter are shifted to different frequencies. The other S-parameters are maintained.

Parametric Analysis 17

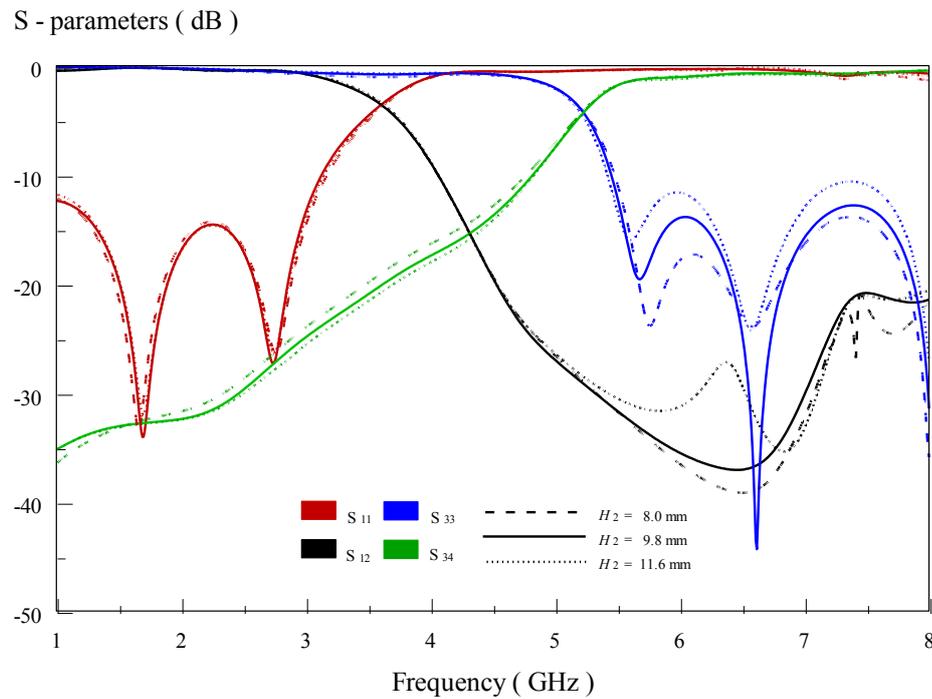


Figure 3.20: The effect of varying parameter H_2 on the amplitude response.

The parameter H_2 with a value of 9.8 mm was stepped up and stepped down with the following values:

- Step-down value : 8.0 mm
- Step-up value : 11.6 mm

Changing the parameter H_2 has no effect on the low-pass filter as it is not part of the filter's travelling path. However, the affect of the changes can be seen at the return loss of the high-pass filter as shown in Figure 3.20. This is caused by the impedance mismatch. When the value of H_2 is decreased to 8.0 mm, the return loss is slightly reduced. The return loss of the high-pass filter increases when the parameter H_2 increases.

Parametric Analysis 18

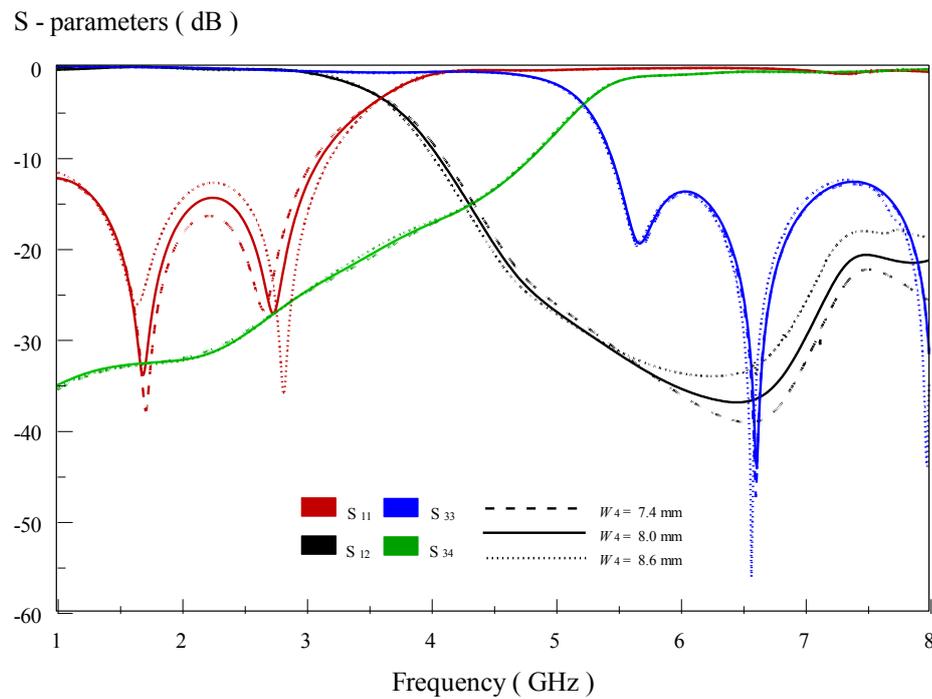


Figure 3.21: The effect of varying parameter W_4 on the amplitude response.

The parameter W_4 with a value of 8.0 mm was stepped up and stepped down with the following values:

- Step-down value : 7.4 mm
- Step-up value : 8.6 mm

Figure 3.21 shows the effect of varying parameter W_4 on the S-parameters. Since this parameter lies along the travelling path of the low-pass filter, thus only the response of the low-pass filter is affected. Stepping up and stepping down the value of W_4 affects the return loss of the low-pass filter by ± 1 dB. Reducing W_4 to 7.4 mm decreases the return loss. On the other hand, increasing W_4 to 8.6 mm causes the return loss to increase as well.

Parametric Analysis 19

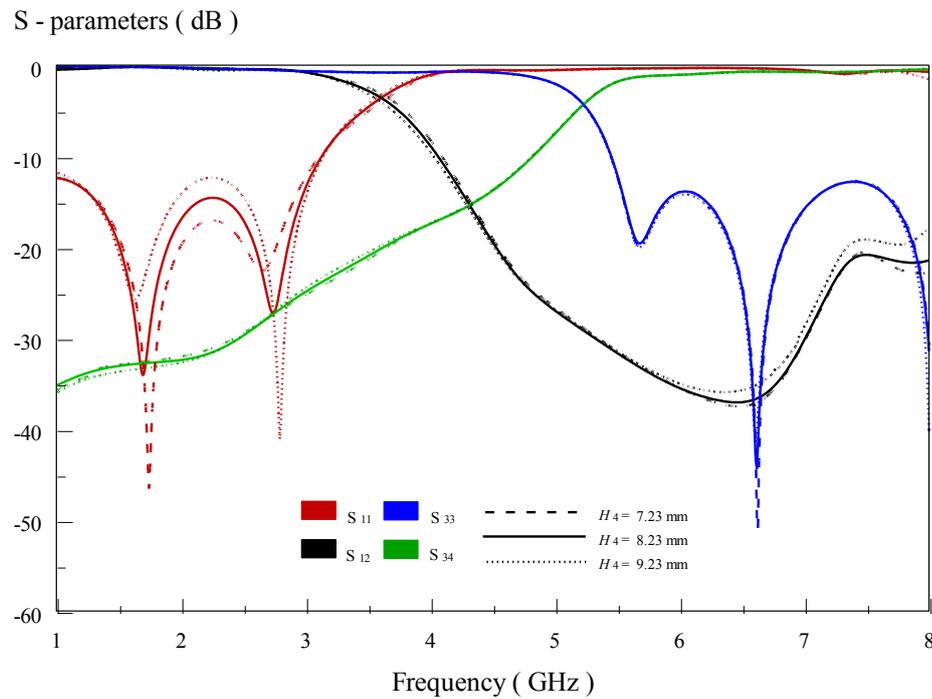


Figure 3.22: The effect of varying parameter H_4 on the amplitude response.

The parameter H_4 with a value of 8.23 mm was stepped up and stepped down with the following values:

- Step-down value : 7.23 mm
- Step-up value : 9.23 mm

The parameter H_4 lies along the travelling path of the low-pass filter. Therefore, only the response of the low-pass filter is affected by the changes. The response of the high-pass filter is maintained. The return loss of the low-pass filter varies by ± 1 dB as H_4 is being varied to 7.23 mm and 9.23 mm. Figure 3.22 shows that as H_4 increases, S_{11} decreases. The higher the value of the return loss, the more reflection occurs at the ports.

Parametric Analysis 20

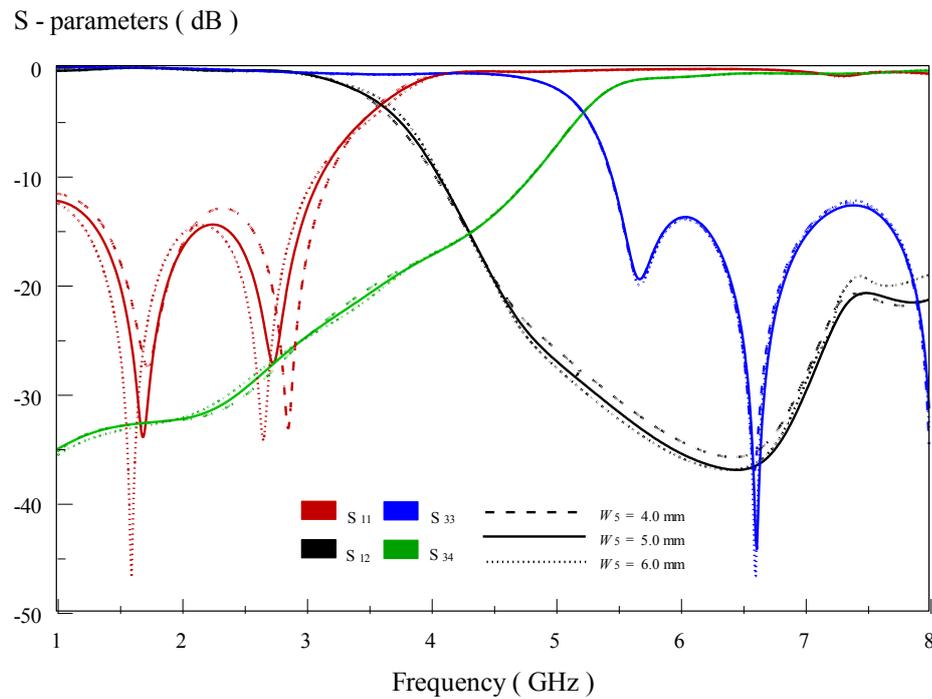


Figure 3.23: The effect of varying parameter W_5 on the amplitude response.

The parameter W_5 with a value of 5.0 mm was stepped up and stepped down with the following values:

- Step-down value : 4.0 mm
- Step-up value : 6.0 mm

As shown in Figure 3.23, changing the value of W_5 only has effect on the low-pass filter since it is a part of the travelling path for the filter. The S_{11} of the low-pass filter is affected due to the impedance mismatch. Varying the value of parameter W_5 by ± 1 mm, causes a shift in the poles of the filter. The poles are at lower frequencies as W_5 increases to 6.0 mm. When W_5 is fixed at 4.0 mm, the poles of the low-pass filter tend to have slightly higher frequencies.

Parametric Analysis 21

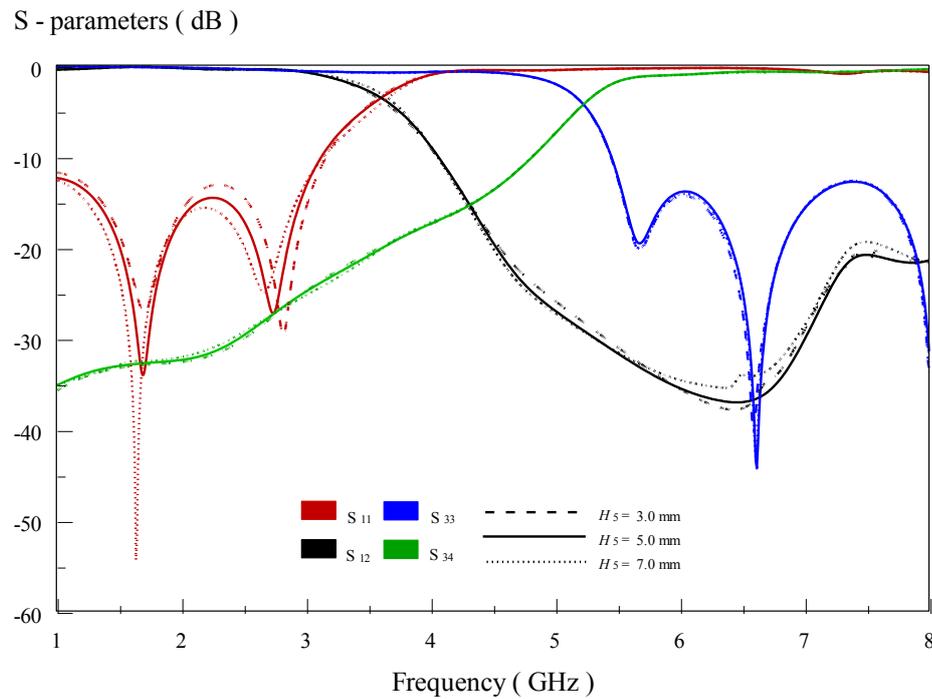


Figure 3.24: The effect of varying parameter H_5 on the amplitude response.

The parameter H_5 with a value of 5.0 mm was stepped up and stepped down with the following values:

- Step-down value : 3.0 mm
- Step-up value : 7.0 mm

Figure 3.24 shows the effect of parameter H_5 on the amplitude response of the two-way filter. The changes have no effect on the high-pass filter but that is not the case for the low-pass filter. Stepping down and stepping up the value of H_5 only results in a ± 1 dB change to the return loss of the low-pass filter. There are no changes on the rest of the S-parameters.

3.3 Discussion

Basically, a two-way low-pass and high-pass filter is to allow signals of lower and higher frequencies to pass through and block undesired signals that are not within the range of the passbands. The experimental results as shown in Section 3.2.2 concluded that the measured 3-dB cutoff frequencies for the low-pass and high-pass filters are 4.01 GHz and 5.05 GHz, respectively. Thus, only signals below 4.01 GHz and signals above 5.05 GHz are allowed to be transmitted across the filters.

Passive elements were used in order to separate out the filters, enabling them to function independently. Furthermore, passive elements are used to reduce the size of the design. Inductors with value of 1.3 nH were used at the low-pass filter whereas 0.3 pF capacitors were used at the high-pass filter. The values of the inductors and capacitors were determined based on circuit theory as shown in the equations below:

$$Z_C = \frac{1}{j\omega C} \quad Z_L = j\omega L \quad (3.1)$$

where $\omega = 2\pi f$

These equations were used to calculate the impedances where Z_C is the impedance for capacitors and Z_L and is the impedance for inductors. From the equations above, the impedance, Z_C increases as the frequency decreases. However, impedance, Z_L increases with frequency. Thus, capacitor is suitable for blocking signals with low frequencies and inductor blocks signals at higher frequencies.

As shown previously in Figure 3.3, the two-way filter has a total of four poles within the range of 1GHz to 8 GHz. The low-pass and high-pass filters, each has two poles within its passband. The poles at the low-pass filter are located at 1.69 GHz and 2.75 GHz. As for the high-pass filter, the two poles can be seen at 5.67 GHz and 6.62 GHz. Having two or more poles within the passband of a filter shows that the particular filter has a wide bandwidth. The electric fields at different poles of the filter were captured and analysed in detail.

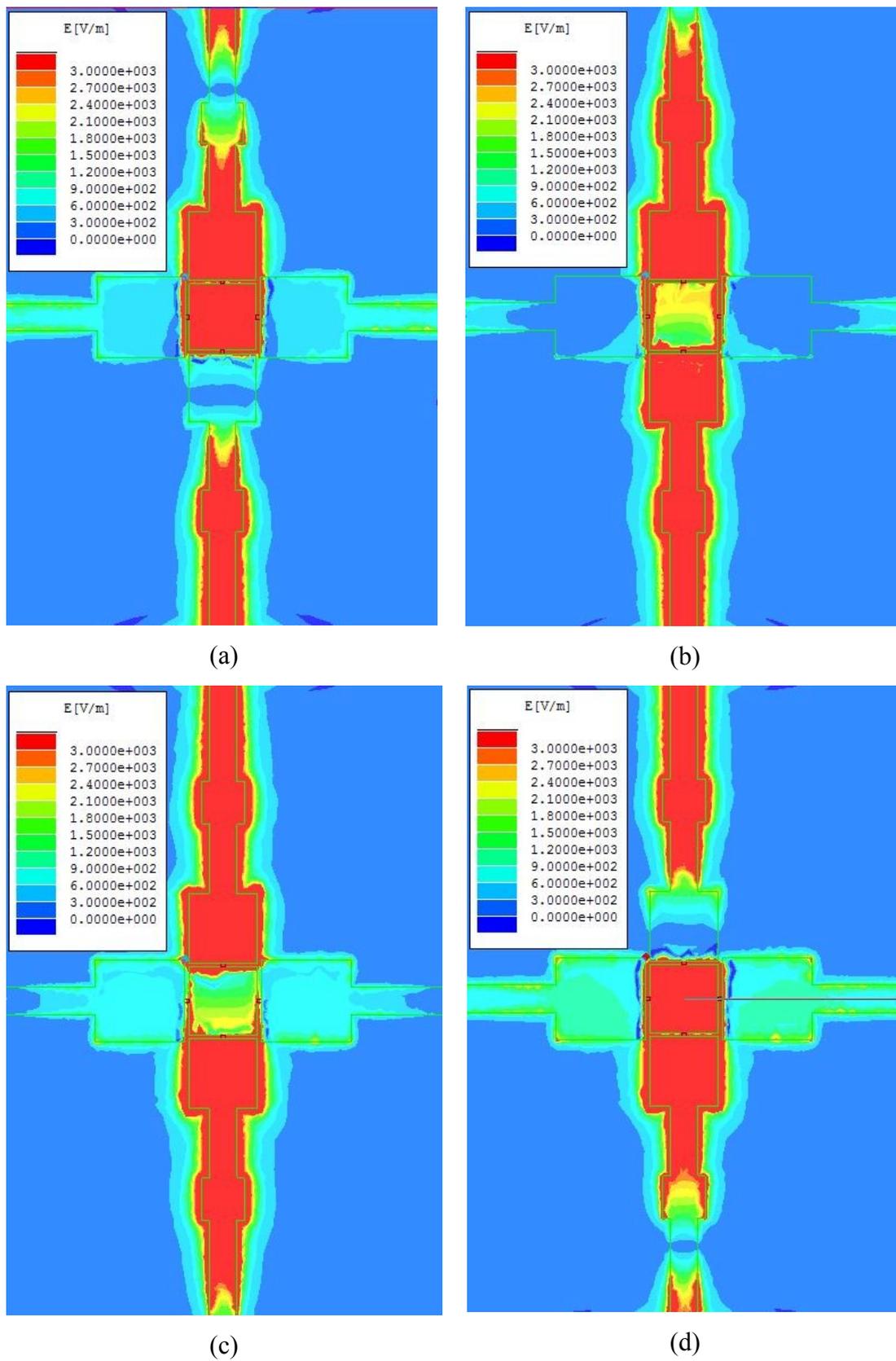


Figure 3.25: The electric field of the low-pass filter at 1.69 GHz with phases of (a) 0°, (b) 40°, (c) 80° and (d) 120°.

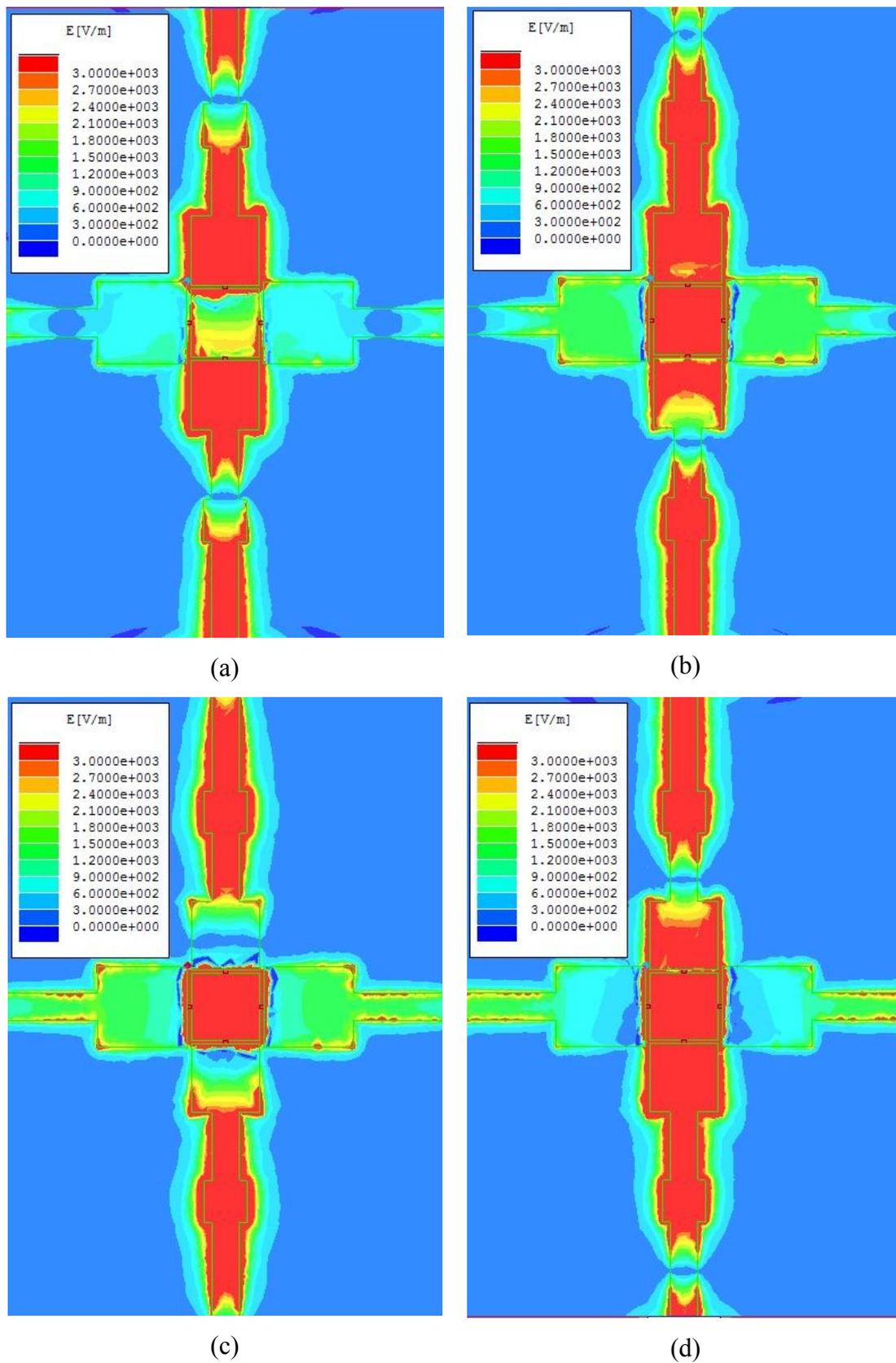


Figure 3.26: The electric field of the low-pass filter at 2.75 GHz with phases of (a) 0° , (b) 40° , (c) 80° and (d) 120° .

The electric fields of the low-pass filter at 1.69 GHz with different phases can be observed in Figure 3.25. The electric fields were captured at different input phases to illustrate that the fields are in the form of travelling wave. The fields can be seen travelling from Port 1 to Port 2 as the phase varies from 0° to 120° . Similarly, Figure 3.26 shows the travelling electric field of the low-pass filter at 2.75 GHz as the phase varies.

Furthermore, the intensity of the electric field at the input port is similar to the output port as signals are able to flow through the low impedance 1.3 nH inductors. Therefore, most of the input signals are being transmitted over to the output port and thus, causing the filter to have very low return loss at the input port. Figure 3.25 and Figure 3.26 further show that almost no signal can be transmitted to Port 3 and Port 4. This is due to the presence of the 0.3 pF capacitors. Previous equations have proven that the capacitors have high impedance at low frequencies and thus, most of the signals are blocked.

Figure 3.27 and Figure 3.28 illustrate the captured electric fields of the high-pass filter at 5.67 GHz and 6.62 GHz respectively. Similar to the low-pass filter, the electric fields in both figures are travelling wave and this is proven when the fields are captured at phases from 0° to 120° . The electric fields are obviously travelling from Port 3 to Port 4.

Most of the input signals from Port 3 are being transmitted to Port 4 as the 0.3 pF capacitors have low impedance when operating at high frequencies. There is also no reflection of signal back to the input port. This can be clearly seen as the electric fields at the input and output ports are of the same intensity. On the other hand, there are no signals propagating towards Port 1 and Port 2 due to the attached 1.3 nH inductors at the centre patch. Inductors operating at high frequencies will have high impedance which prevents signals from flowing through. This is proven in the earlier equations.

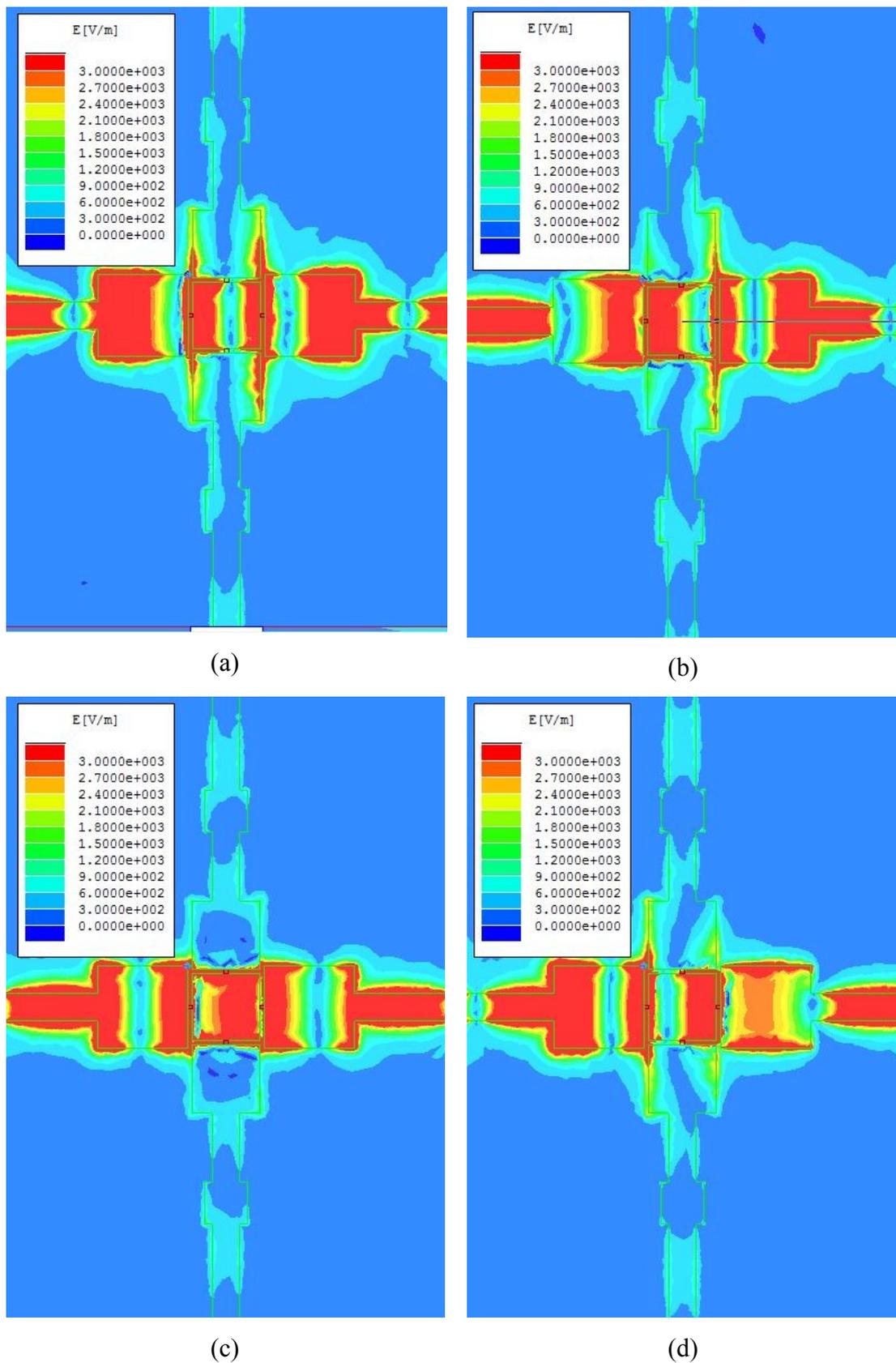


Figure 3.27: The electric field of the high-pass filter at 5.67 GHz with phases of (a) 0° , (b) 40° , (c) 80° and (d) 120° .

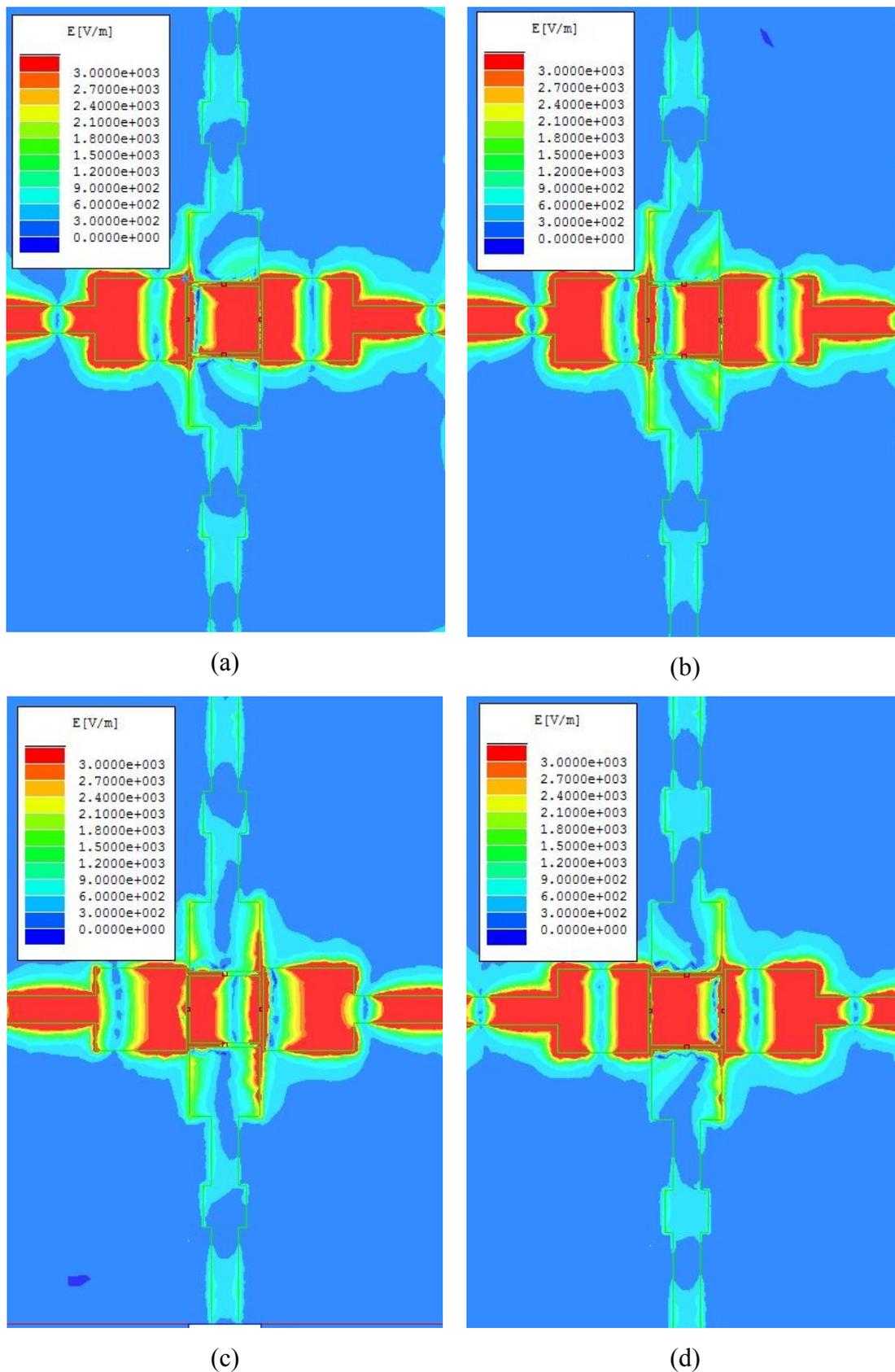


Figure 3.28: The electric field of the high-pass filter at 6.62 GHz with phases of (a) 0°, (b) 40°, (c) 80° and (d) 120°.

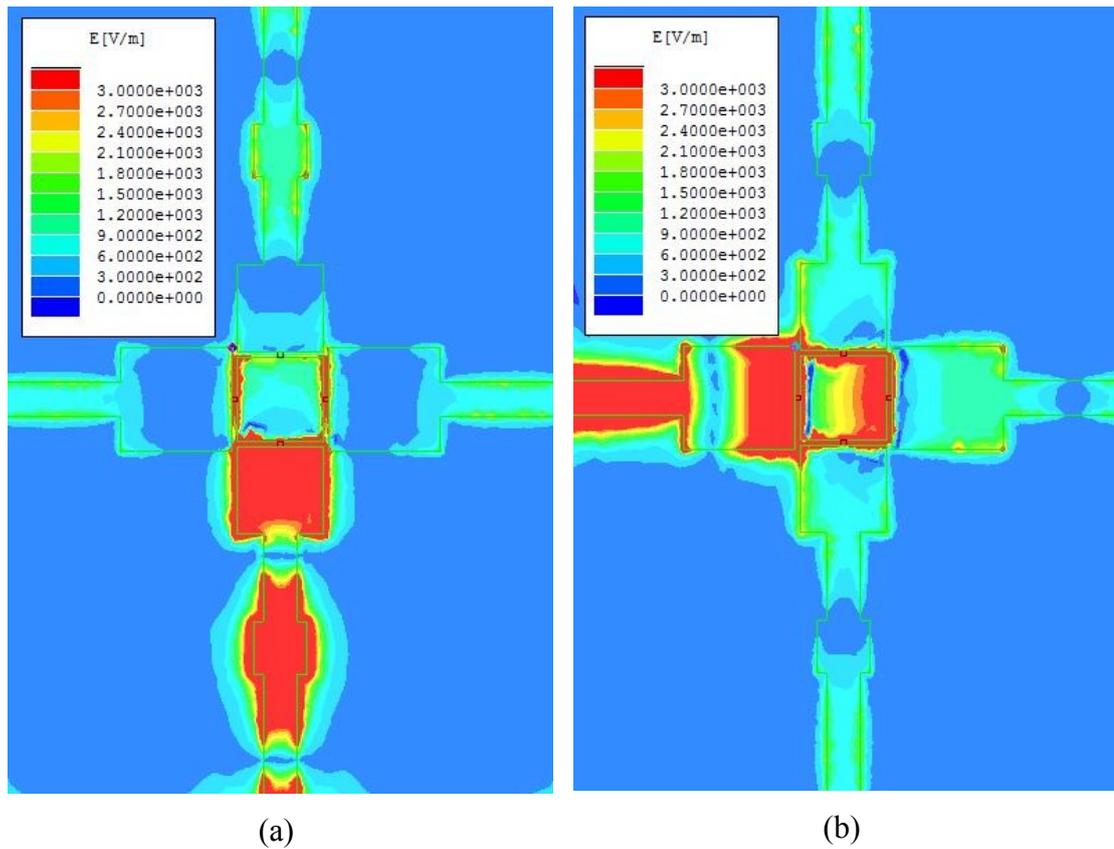


Figure 3.29: The electric field at 4.3 GHz in the (a) low-pass filter and (b) high-pass filter.

The electric fields of the two-way low-pass and high-pass filter at 4.3 GHz were captured as shown in Figure 3.29. Since 4.3 GHz lies at the stopband of the two filters, therefore the input signals from Port 1 and Port 3 are not being transmitted to their respective output ports. Moreover, most of the signals are reflected back to the input ports, thus causing the return loss to be close to 0dB.

CHAPTER 4

LOW-PASS AND BANDPASS DIPLEXER

4.1 Background

A low-pass and bandpass diplexer basically is a three-port passive device which is a combination of a low-pass filter and a bandpass filter. These filters operate simultaneously. It is used to split the input signals according to frequencies that are within the passbands of the low-pass and bandpass filters. Diplexers are proven to be useful in a communication system that shares a common input or channel such as the duplex communication system over a single channel. Similar to Chapter 3, simulation and experiments were performed. Results were analysed and discussed in detail.

4.2 Low-pass and Bandpass Diplexer

A low-pass and bandpass filters are combined into a design to produce a low-pass and bandpass diplexer. Therefore, two passbands can be obtained whereby each of the passband operates at certain frequencies. Passive elements such as capacitors and inductors were used when it comes to designing the proposed diplexer. The purpose of a capacitor is to stop signal from flowing at lower frequencies while an inductor prevents signal from flowing at higher frequencies. Based on this theory, a three-port low-pass and bandpass diplexer was proposed.

4.2.1 Configuration

The proposed design of a low-pass and bandpass diplexer was designed and fabricated on a Duroid RO4003C substrate (with a dielectric constants of $\epsilon_r = 3.38$ and a thickness of 1.524mm). In the design, the Port 1 is the input port whereas the Port 2 and Port 3 are the output ports. Port 2 is the output port for signals which are below the 3-dB cutoff frequency of 2.05 GHz whereas Port 3 is the output port for for the bandpass signals within the range of 4.07 GHz to 4.65 GHz.

All microstrip feed lines are fixed to have a characteristic impedance of 50Ω . Based on calculation, this is achieved by designing each feed line to have a width of 3.21mm. As the length of the travelling path decreases, the frequency of the device increases. Therefore, the shorter travelling path which functions as a bandpass filter, is connected by capacitors. On the other hand, the longer travelling path that serves as a low-pass filter is connected by inductors.

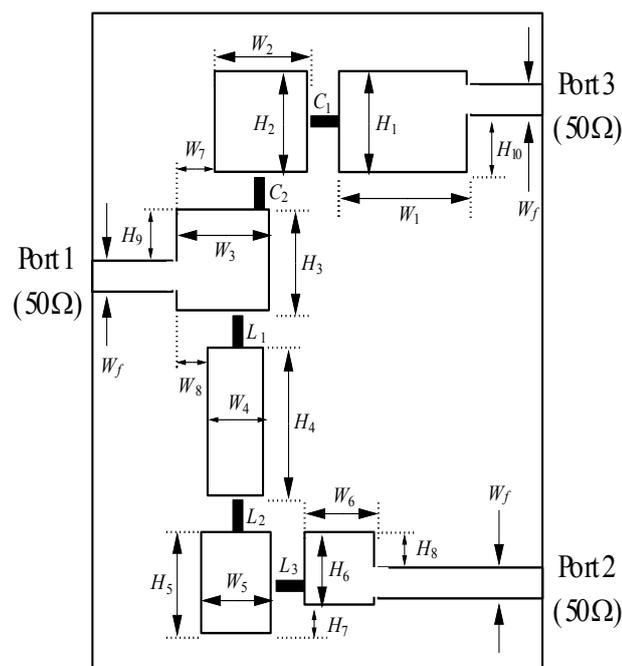


Figure 4.1: Configuration of the proposed low-pass and bandpass diplexer.

Figure 4.1 illustrates the top view configuration of the proposed diplexer. Details on the design parameters are tabulated in Table 4.1.

Table 4.1: Parameters values of the diplexer

Parameters	Values
C_1	0.9 pF
C_2	0.9 pF
L_1	3.0 nH
L_2	3.0 nH
L_3	3.0 nH
W_f	3.21 mm
W_1	12.5 mm
W_2	10.0 mm
W_3	10.0 mm
W_4	7.5 mm
W_5	8.0 mm
W_6	7.5 mm
W_7	3.5 mm
W_8	2.25 mm
H_1	10.0 mm
H_2	10.0 mm
H_3	10.0 mm
H_4	15.5 mm
H_5	10.0 mm
H_6	7.0 mm
H_7	3.0 mm
H_8	3.395 mm
H_9	4.395 mm
H_{10}	5.395 mm

4.2.2 Simulation and Experiment Results

The proposed design of the low-pass and bandpass diplexer was simulated using Ansoft HFSS to obtain the simulated results. The design was fabricated and the experimental results were measured using Rohde & Schwarz Vector Network Analyzer. In order to examine and compare the simulated results with the measured results, the amplitude responses of both simulated and measured results were plotted out using the Freelance Graphics software. The fabricated diplexer is shown in Figure 4.2.

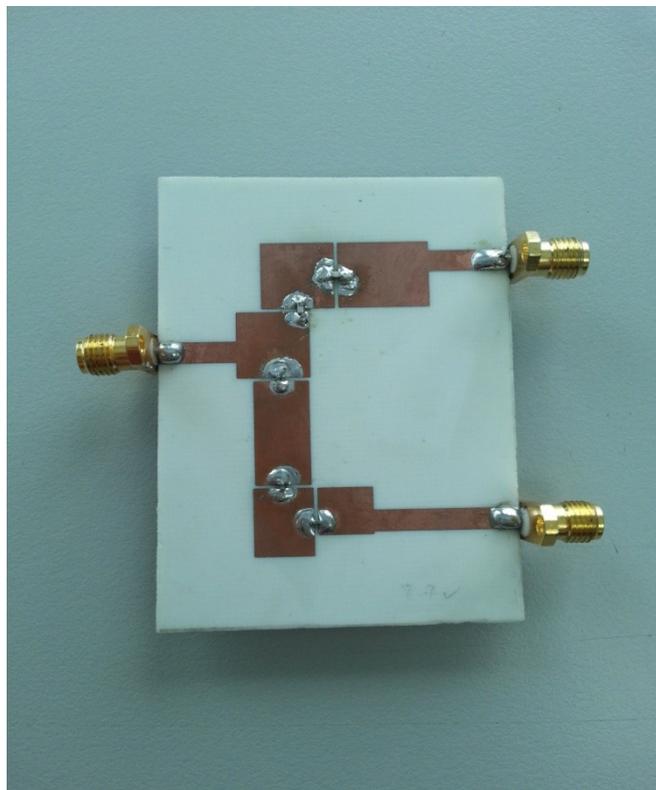


Figure 4.2: The fabricated low-pass and bandpass diplexer.

The following formulas were used to calculate the centre frequency, operating bandwidth and fractional bandwidth of the proposed diplexer:

Centre Frequency,

$$= \frac{\text{Lower Frequency, } f_L + \text{Higher Frequency, } f_H}{2} \quad (4.1)$$

Operating bandwidth,

$$= \text{Higher Frequency, } f_H - \text{Lower Frequency, } f_L \quad (4.2)$$

Fractional Bandwidth,

$$= \frac{\text{Higher Frequency, } f_H - \text{Lower Frequency, } f_L}{\text{Centre Frequency, } f_0} \times 100\% \quad (4.3)$$

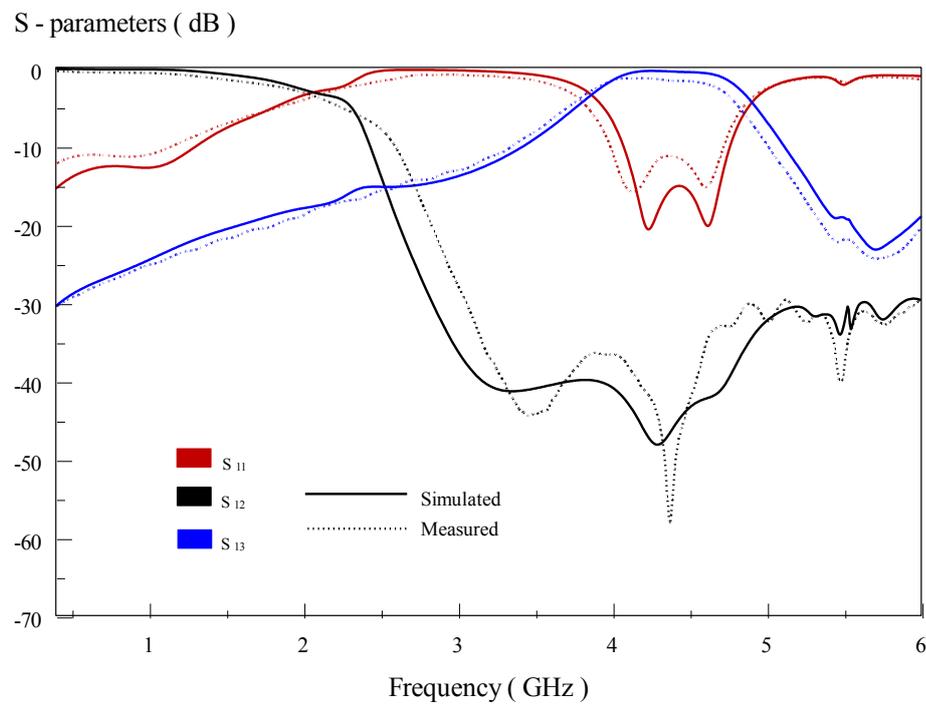


Figure 4.3: Simulated and measured S-parameters of the diplexer.

Figure 4.3 shows the simulated and measured amplitude responses of the proposed low-pass and bandpass diplexer. The amplitude responses for both the simulation and measurement were fixed within the range of 400 MHz to 6 GHz. In the simulation, the insertion losses for the low-pass and bandpass filters are -0.12 dB and -0.43 dB respectively. The low-pass filter has a 3-dB cutoff frequency of 2.05 GHz whereas the bandpass filter has a centre frequency of 4.415 GHz. The bandpass filter is capable of operating within the range from 4.07 GHz to 4.76 GHz, which is a bandwidth of 690 MHz. Additionally, both the low-pass and bandpass filter have a return loss of less than -10 dB within its bandwidth.

From the experiment, the measured insertion losses for the low-pass and bandpass filter are -0.44 dB and -1.37 dB respectively. Measurement from the fabricated design shows that the 3-dB cutoff frequency of the low-pass filter is at 2.03 GHz while the bandpass filter has a centre frequency of 4.35 GHz. The operating passband of the bandpass filter is from 3.99 GHz to 4.71 GHz, which comes to a total bandwidth of 720 MHz. Furthermore, the measured return loss of both filters are below -10dB as required.

Overall, the simulated and measured results are said to be in good agreement. There are some minor shifts in the bandwidth of the low-pass filter and bandpass filter. This is from the effect of the passive elements in the design which have a tolerance of $\pm 5\%$, thus affecting the results during experiment. Moreover, the soldered ports may introduce some losses. The low-pass filter has a 3-dB cutoff frequency error of only 0.98% while the bandpass filter has a centre frequency error of only 1.47%. Table 4.2 shows the comparison between the simulation and the experimental results of the proposed diplexer.

Table 4.2: Comparison between the simulation and experimental results

	Low-pass Filter		Bandpass Filter	
	HFSS Simulation	Experiment	HFSS Simulation	Experiment
Minimum Insertion loss (dB)	-0.12	-0.44	-0.43	-1.37
3-dB Reference Point (dB)	-3.12	-3.44	-	-
3-dB Cutoff Frequency, f_c (GHz)	2.05	2.03	-	-
Error of f_c (%)		0.98		-
f_L (GHz) / f_H (GHz)		-	4.07 / 4.76	3.99 / 4.71
Centre Frquency, f_0 (GHz)		-	4.415	4.35
Fractional Bandwidth (%)		-	15.63	16.55
Error of f_0 (%)		-		1.47

4.2.3 Parametric Analysis

Parametric analysis is performed by varying the design parameters shown in Table 4.1. All design parameters were varied by stepping up and stepping down the values. The objective of the parametric analysis is to observe and analyse how changing of the parameters affect the results. This process is completed using Ansoft HFSS software.

Parametric Analysis 1

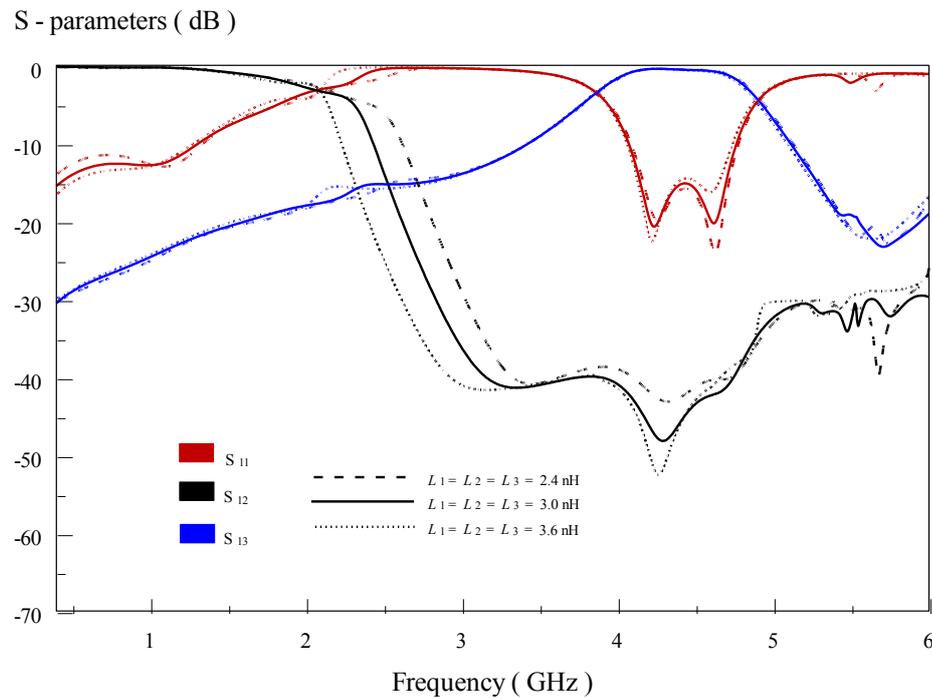


Figure 4.4: The effect of varying parameters L_1 , L_2 and L_3 on the amplitude response.

The parameters L_1 , L_2 and L_3 with a value of 3.0 nH were stepped up and stepped down with the following values:

- Step- down value : 2.4 nH
- Step-up value : 3.6 nH

Figure 4.4 shows that changing the parameters L_1 , L_2 and L_3 significantly affect the low-pass filter as inductors only play a role in the low-pass filter. The significant changes can be seen on the roll-off of the low-pass filter. When L_1 , L_2 and L_3 are fixed at 2.4 nH, the roll-off shifts to higher frequency. Changing L_1 , L_2 and L_3 to 3.6 nH causes the roll-off to shift to lower frequency. Varying L_1 , L_2 and L_3 has slight effect on the return loss in both the low-pass and bandpass filters.

Parametric Analysis 2

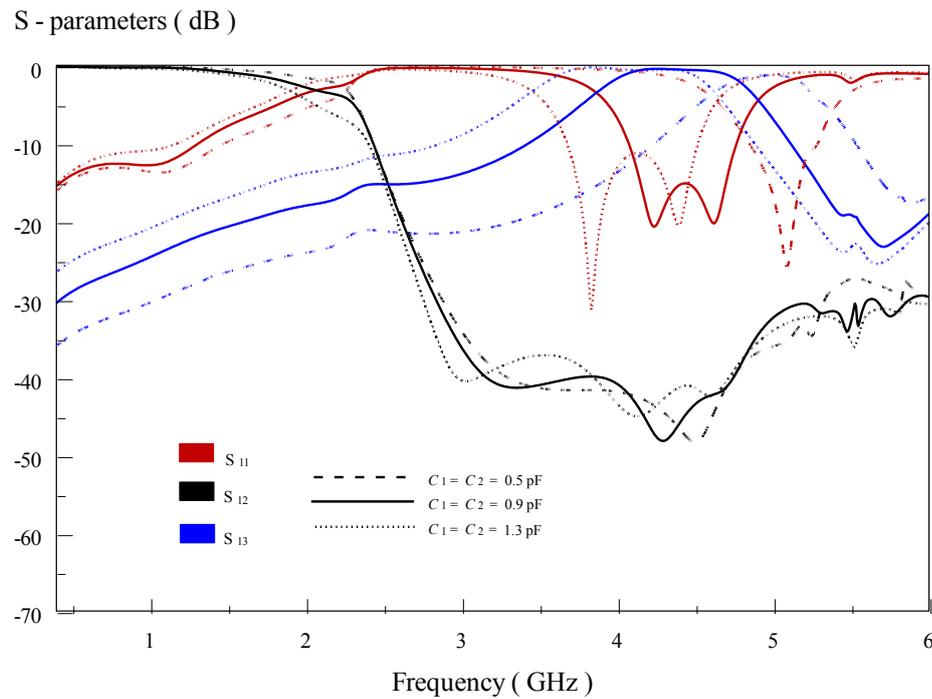


Figure 4.5: The effect of varying parameters C_1 and C_2 on the amplitude response.

The parameters C_1 and C_2 with a value of 0.9 nH were stepped up and stepped down with the following values:

- Step- down value : 0.5 pF
- Step-up value : 1.3 pF

Figure 4.5 shows that varying the parameters C_1 and C_2 drastically affect the amplitude response of the bandpass filter while the amplitude response of the low-pass filter is slightly affected. The reason for this is because the capacitors play a significant role in the high-pass filter. When C_1 and C_2 are stepped down to 0.5 pF, the S_{11} of the bandpass filter has only one pole and thus, a narrower bandwidth is obtained. Stepping up the values of C_1 and C_2 to 1.3 pF causes the poles of the bandpass filter to shift towards lower frequencies and also increases the bandwidth of the filter.

Parametric Analysis 3

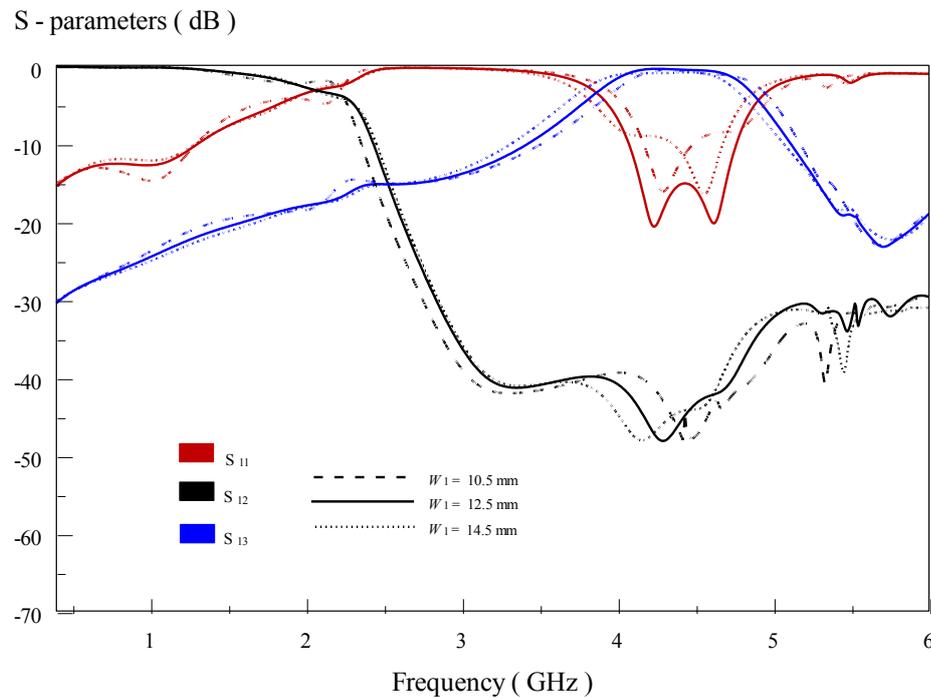


Figure 4.6: The effect of varying parameter W_1 on the amplitude response.

The parameters W_1 with a value of 12.5 mm was stepped up and stepped down with the following values:

- Step- down value : 10.5 mm
- Step-up value : 14.5 mm

As the parameter W_1 is being varied, the amplitude response of the bandpass filter is affected. This is because W_1 lies in the travelling path of the bandpass filter. Stepping down W_1 to 10.5 mm causes the return loss of the bandpass filter to increase and the passband to shift to the right. When W_1 increases to 14.5 mm, the return loss of the bandpass filter increases. Moreover, the passband of the bandpass filter is being shifted to the left. There are minor effects on the low-pass filter as W_1 varies.

Parametric Analysis 4

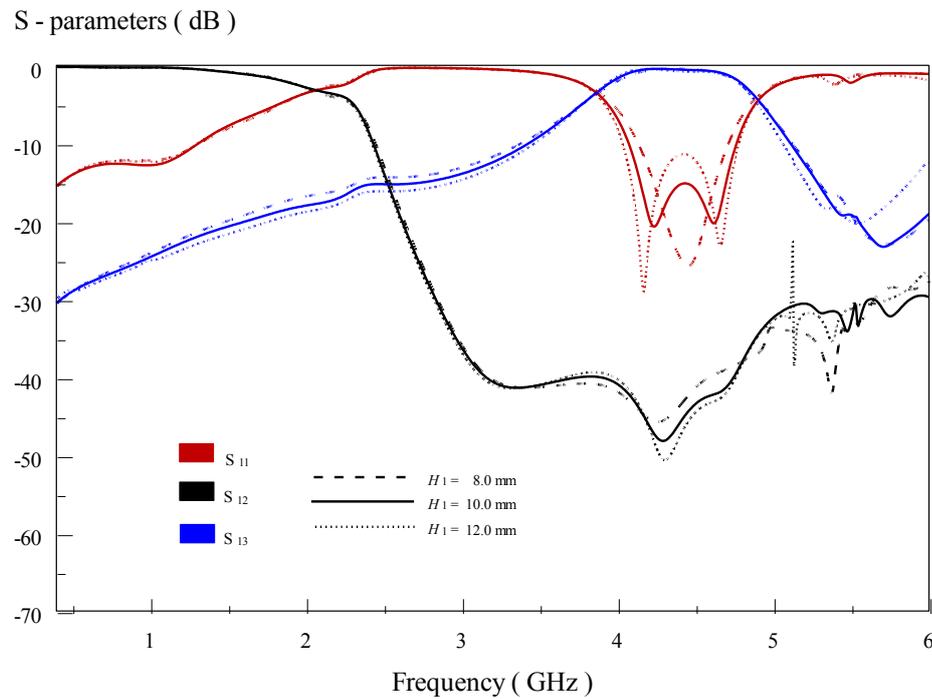


Figure 4.7: The effect of varying parameter H_1 on the amplitude response.

The parameters H_1 with a value of 10.0 mm was stepped up and stepped down with the following values:

- Step- down value : 8.0 mm
- Step-up value : 12.0 mm

Since H_1 lies within the travelling path of the bandpass filter, therefore the low-pass filter is not affected by the changes. Figure 4.7 shows that varying the parameter H_1 only affect the return loss of the bandpass filter while the insertion loss is maintained. Decreasing H_1 to 8.0 mm causes the two poles of the bandpass filter to combine. On the other hand, fixing H_1 at 12.0 mm causes the poles to shift and a higher return loss is obtained.

Parametric Analysis 5

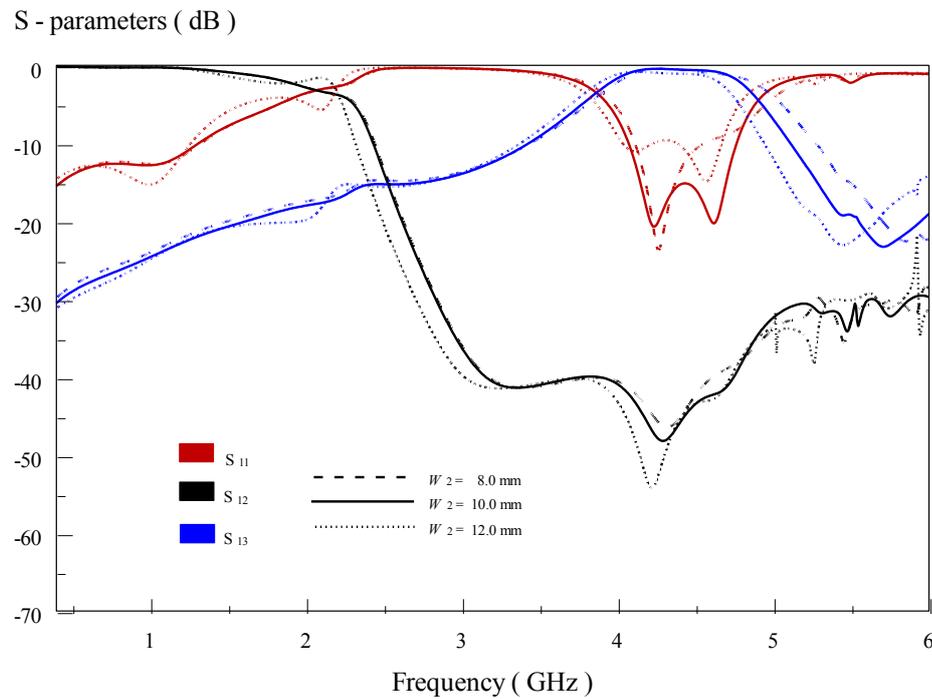


Figure 4.8: The effect of varying parameter W_2 on the amplitude response.

The parameter W_2 with a value of 10.0 mm was stepped up and stepped down with the following values:

- Step- down value : 8.0 mm
- Step-up value : 12.0 mm

Figure 4.8 shows that changing the parameter W_2 have significant effect on the amplitude response of the bandpass filter. This is because W_2 is part of the travelling path of the bandpass filter. Decreasing and increasing the value of W_2 , results in an increased in the return loss by +2 dB at the bandpass filter. The roll-off at S_{13} experiences some frequency shifts as well. Moreover, the return loss of the low-pass filter is slightly affected.

Parametric Analysis 6

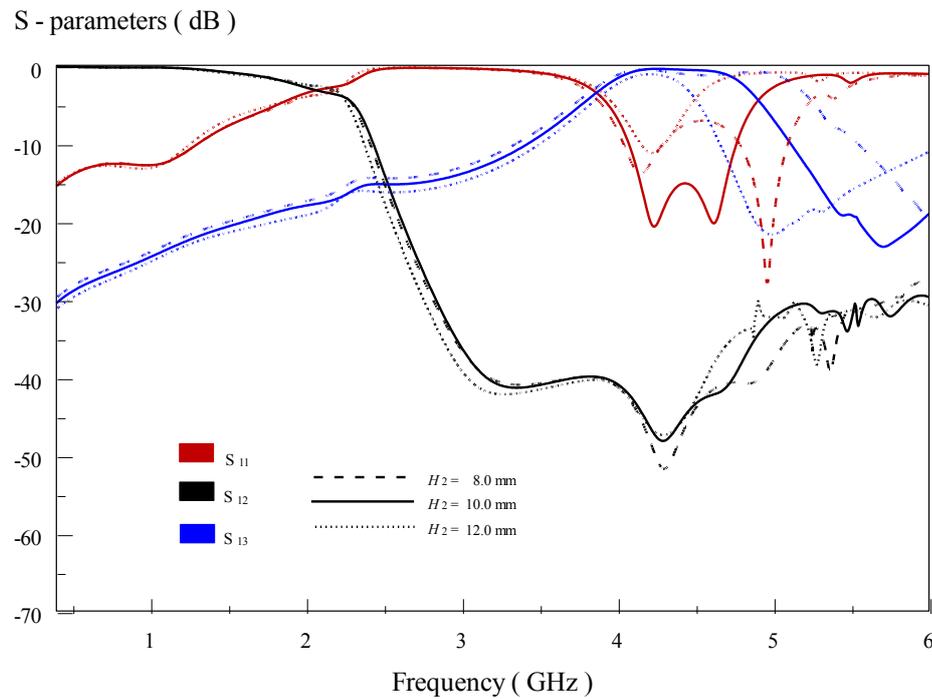


Figure 4.9: The effect of varying parameter H_2 on the amplitude response.

The parameter H_2 with a value of 10.0 mm was stepped up and stepped down with the following values:

- Step- down value : 8.0 mm
- Step-up value : 12.0 mm

Figure 4.9 shows that varying the parameter H_2 affect only the amplitude response of the bandpass filter. H_2 is a part of the travelling path of the bandpass filter and therefore affects the bandpass filter only. The low-pass filter is not affected at all by the changes. Changing H_2 to 8.0 mm causes the return loss of the bandpass filter to increase. It also widens the bandwidth of the bandpass filter. On the other hand, increasing H_2 to 12.0 mm results in a single pole at the S_{11} of the bandpass filter and a narrower bandwidth is obtained.

Parametric Analysis 7

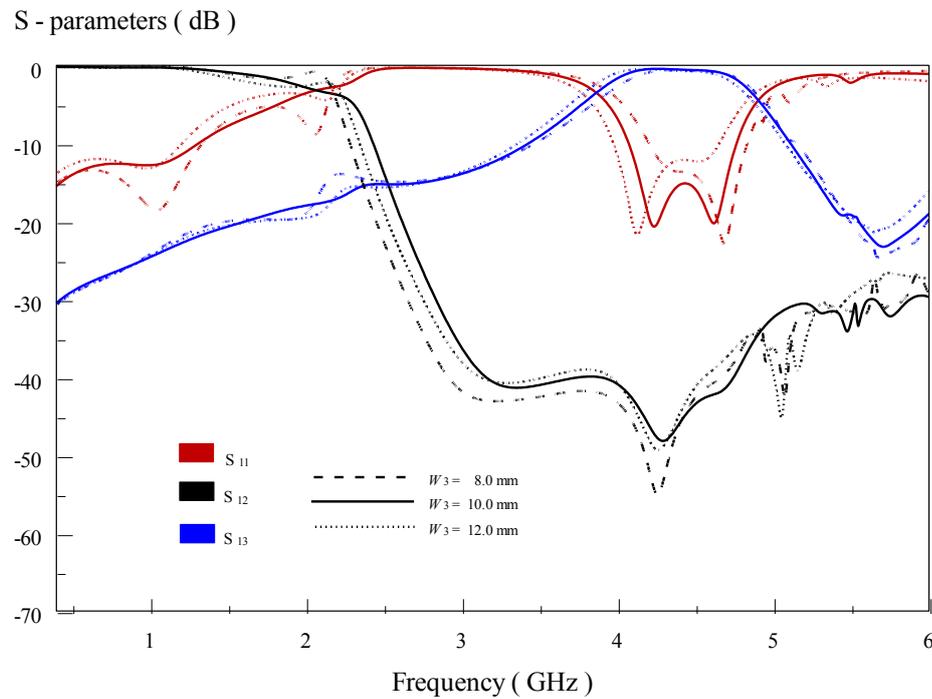


Figure 4.10: The effect of varying parameter W_3 on the amplitude response.

The parameter W_3 with a value of 10.0 mm was stepped up and stepped down with the following values:

- Step- down value : 8.0 mm
- Step-up value : 12.0 mm

Since W_3 is a crucial part of the microstrip patch that is connecting the two filters together by an inductor and a capacitor, changing the parameter W_3 has effects on both the low-pass and bandpass filters. Decreasing W_3 to 8.0 mm causes the S_{11} at the low-pass filter to split into two poles and the return loss of the bandpass filter to increase. Setting W_3 to 12.0 mm results in poor impedance matching at the low-pass and bandpass filters.

Parametric Analysis 8

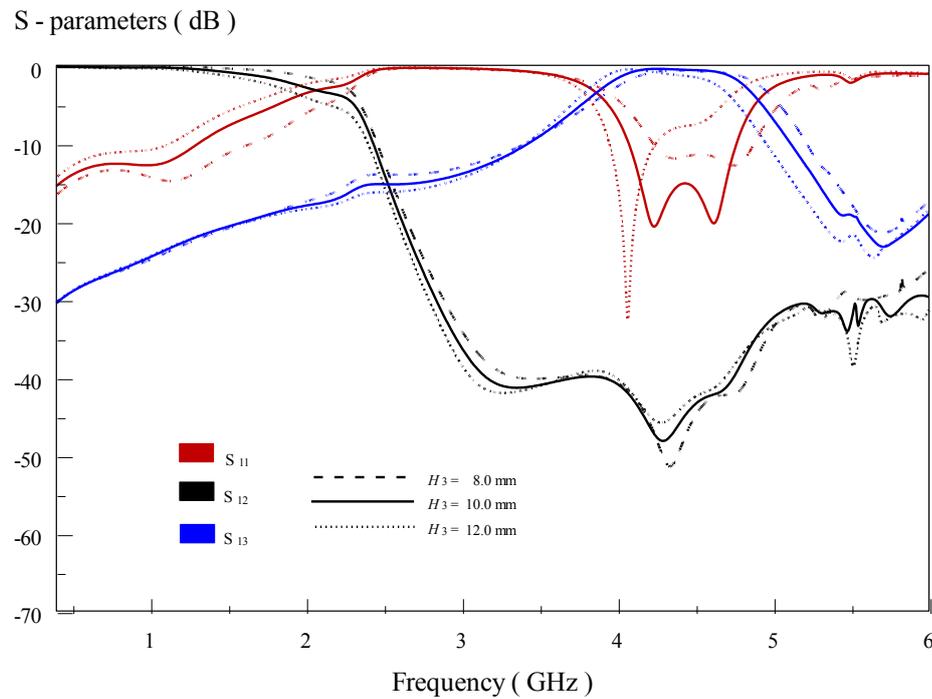


Figure 4.11: The effect of varying parameter H_3 on the amplitude response.

The parameter H_3 with a value of 10.0 mm was stepped up and stepped down with the following values:

- Step- down value : 8.0 mm
- Step-up value : 12.0 mm

Significant effect on the amplitude response of the low-pass and bandpass filters can be observed in Figure 4.11. Since H_3 is part of the microstrip patch that is attached to both filters through passive elements, therefore changing it affects both filters. Stepping down H_3 to 8.0 mm affects the impedance matching at the low-pass and bandpass filters. It also shifts the 3-dB cutoff frequency of the low-pass filter to 2.28 GHz and widens the bandwidth of the bandpass filter. The return losses of both filters are affected when H_3 increases to 12.0 mm. Moreover, the 3-dB cutoff frequency of the low-pass filter shifts to 1.87 GHz and a narrower bandwidth is obtained at the bandpass filter.

Parametric Analysis 9

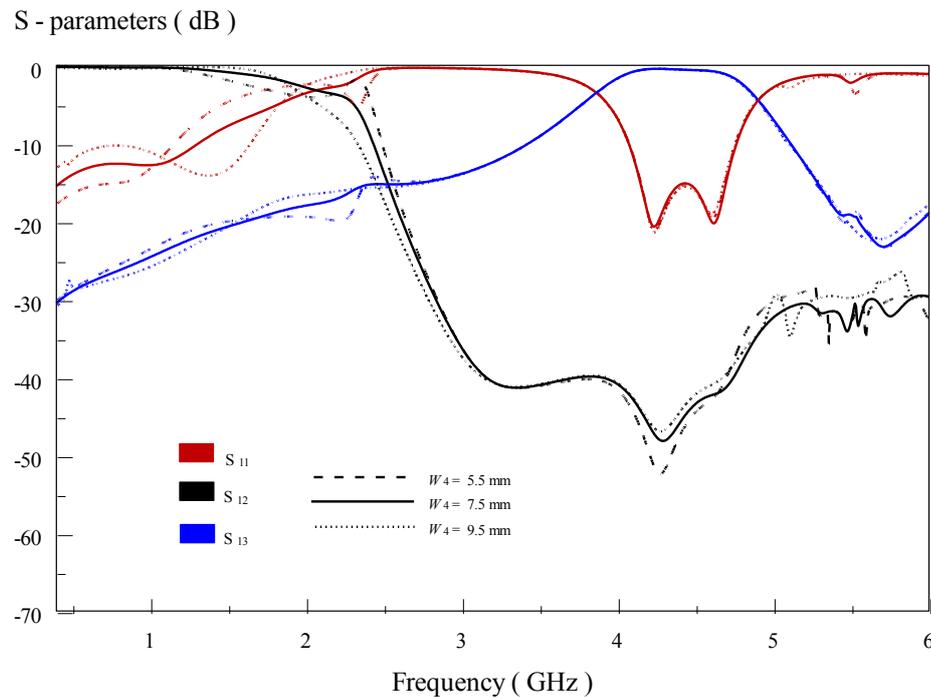


Figure 4.12: The effect of varying parameter W_4 on the amplitude response.

The parameter W_4 with a value of 7.5 mm was stepped up and stepped down with the following values:

- Step- down value : 5.5 mm
- Step-up value : 9.5 mm

Figure 4.12 shows that altering the parameter W_4 only has significant effect on the low-pass filter. This is because W_4 lies in the travelling path of the low-pass filter. When W_4 is reduced to 5.5 mm, the impedance matching becomes poor. Similarly, increasing W_4 to 12.0 mm also affects the impedance matching. The return loss at the low-pass filter is affected by ± 1 dB. Additionally, there are slight shift in the 3-dB cutoff frequency as the value of W_4 is being stepped down and stepped up.

Parametric Analysis 10

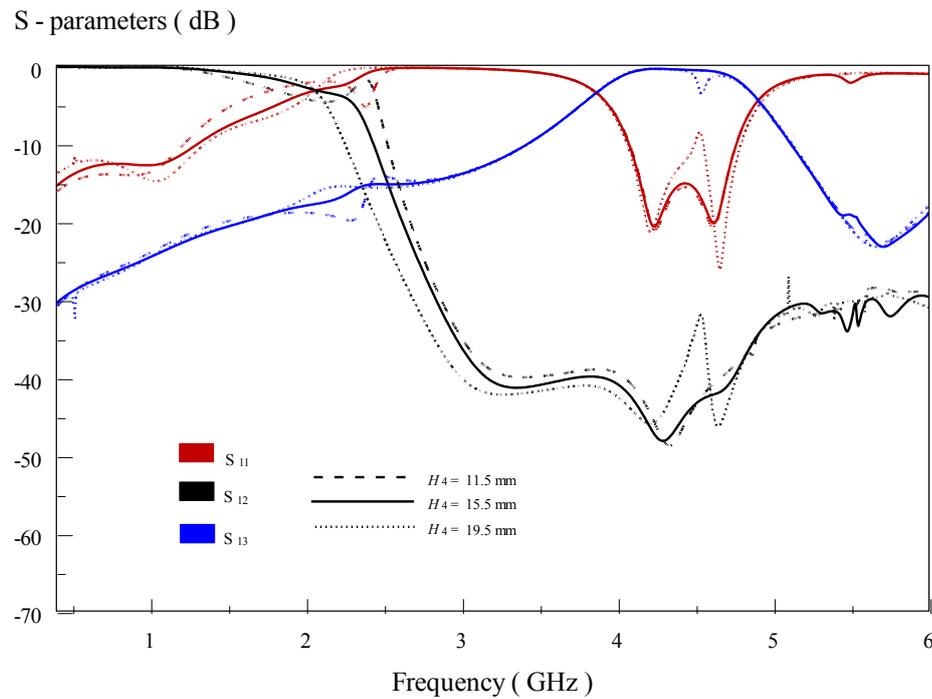


Figure 4.13: The effect of varying parameter H_4 on the amplitude response.

The parameter H_4 with a value of 15.5 mm was stepped up and stepped down with the following values:

- Step- down value : 11.5 mm
- Step-up value : 19.5 mm

Figure 4.13 shows that varying the parameter H_4 has major effect on the low-pass filter. The bandpass filter is not affected much by the varying parameter of H_4 as it is not in the travelling path of the bandpass filter. As H_4 decreases to 11.5 mm, there is a shift in the 3-dB cutoff frequency due to the poor impedance matching at S_{11} . The impedance matching is also affected when H_4 increases to 19.5 mm and thus, causing the 3-dB cutoff frequency to shift. Moreover, there is an unexpected change in the return loss at the bandpass filter.

Parametric Analysis 11

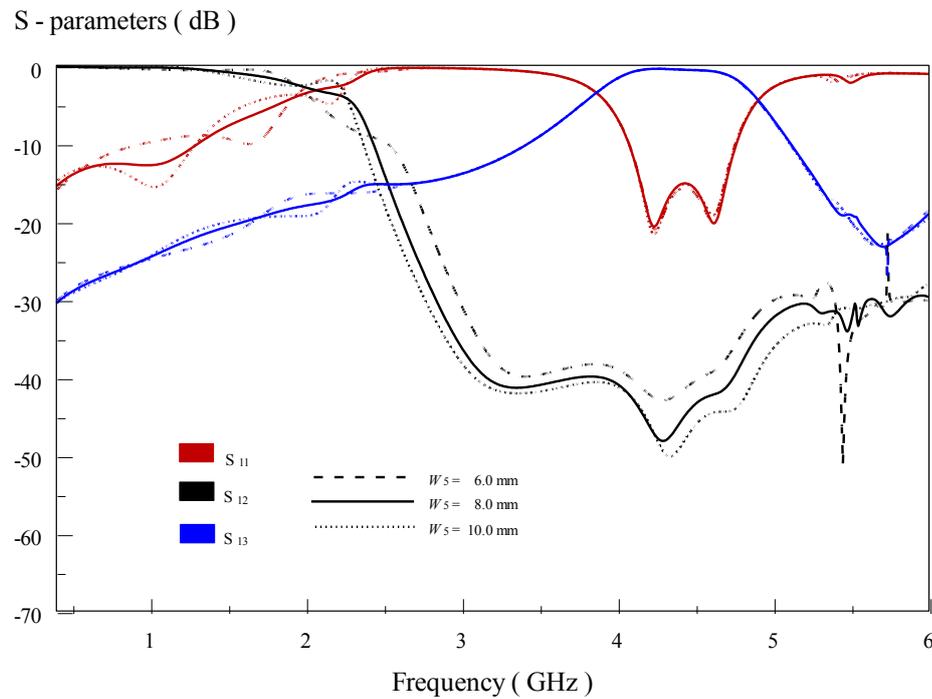


Figure 4.14: The effect of varying parameter W_5 on the amplitude response

The parameter W_5 with a value of 8.0 mm was stepped up and stepped down with the following values:

- Step- down value : 6.0 mm
- Step-up value : 10.0 mm

Figure 4.14 shows that changing the parameter W_5 only gives significant effect on the low-pass filter. This is because W_5 lies in the travelling path of the low-pass filter. Decreasing W_5 is to 6.0 mm worsens the matching at S_{11} . Similarly, increasing W_5 to 10.0 mm also affects the impedance matching. The figure also shows that varying the parameter of W_5 causes the 3-dB cutoff frequency to shift.

Parametric Analysis 12

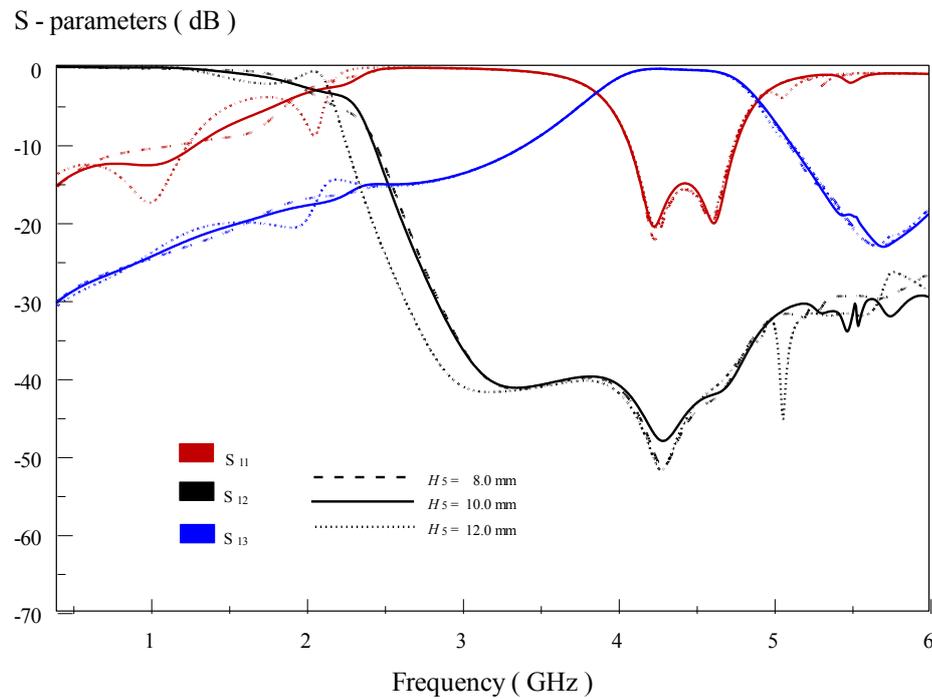


Figure 4.15: The effect of varying parameter H_5 on the amplitude response.

The parameter H_5 with a value of 10.0 mm was stepped up and stepped down with the following values:

- Step- down value : 8.0 mm
- Step-up value : 12.0 mm

Varying the parameter H_5 only affects the amplitude response of the low-pass filter, as H_5 is part of the travelling path of the low-pass filter. Stepping down or stepping up the value of H_5 clearly affects the return loss of the low-pass filter by ± 1 dB. Moreover, the 3-dB cutoff frequency of the filter also experiences a shift in frequency. Figure 4.15 shows that varying the parameter H_5 gives no effect on the amplitude response of the band-pass filter.

Parametric Analysis 13

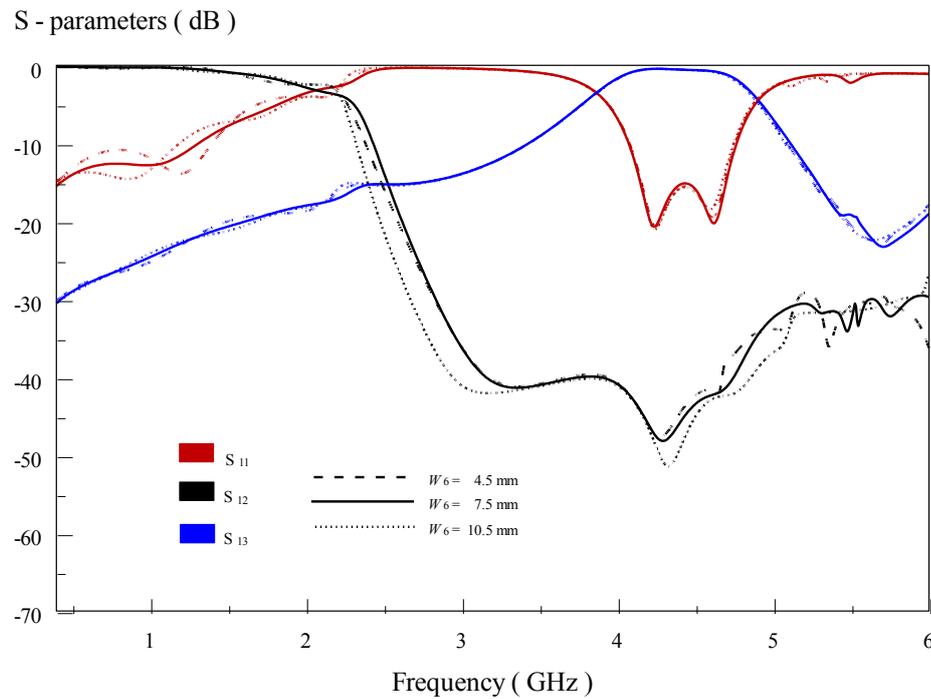


Figure 4.16: The effect of varying parameter W_6 on the amplitude response.

The parameter W_6 with a value of 7.5 mm was stepped up and stepped down with the following values:

- Step- down value : 4.5 mm
- Step-up value : 10.5 mm

Figure 4.16 shows that changing the parameter W_6 only gives effect on the low-pass filter. The bandpass filter is not affected by the changes because W_5 does not form part of the travelling path in the bandpass filter. As W_6 being stepped down and stepped up to different values, the return loss at the low-pass filter is clearly affected by the changes. Poor impedance matching is unwanted as it will result in poorer performance of the filter.

Parametric Analysis 14

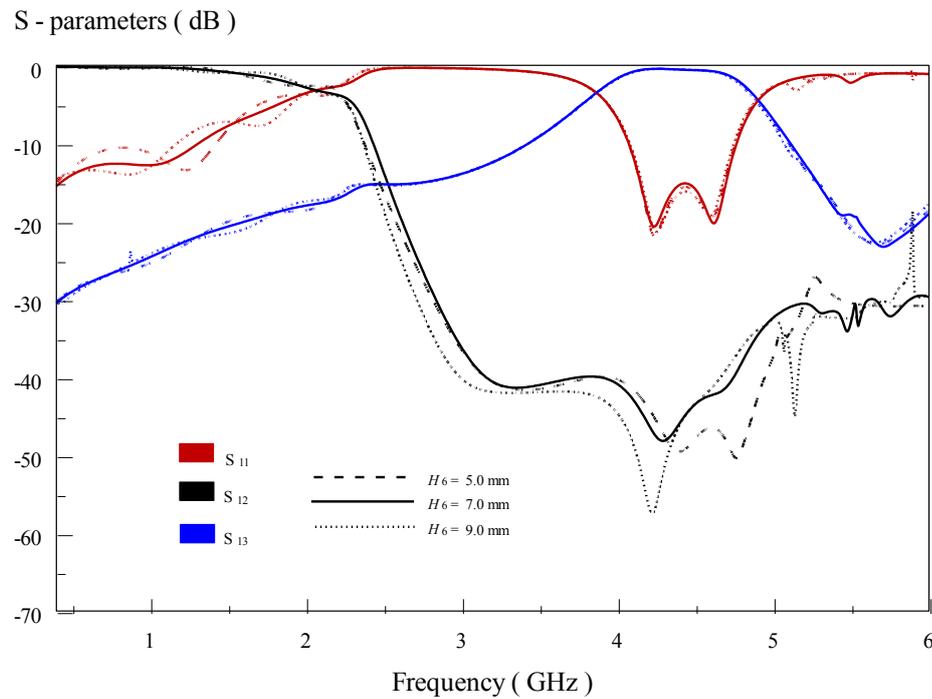


Figure 4.17: The effect of varying parameter H_6 on the amplitude response.

The parameter H_6 with a value of 7.0 mm was stepped up and stepped down with the following values:

- Step- down value : 5.0 mm
- Step-up value : 9.0 mm

Figure 4.17 shows that varying the parameter H_6 only affects the amplitude response of the low-pass filter while the amplitude response of the bandpass filter is maintained. This is because H_6 lies in the travelling path of the low-pass filter. Varying the values of H_6 , has effect on the return loss of the low-pass filter. There are additional poles within the passband of the low-pass filter. Additionally, the roll-off of the low pass filter experience a shift in frequency as the parameter H_6 varies.

Parametric Analysis 15

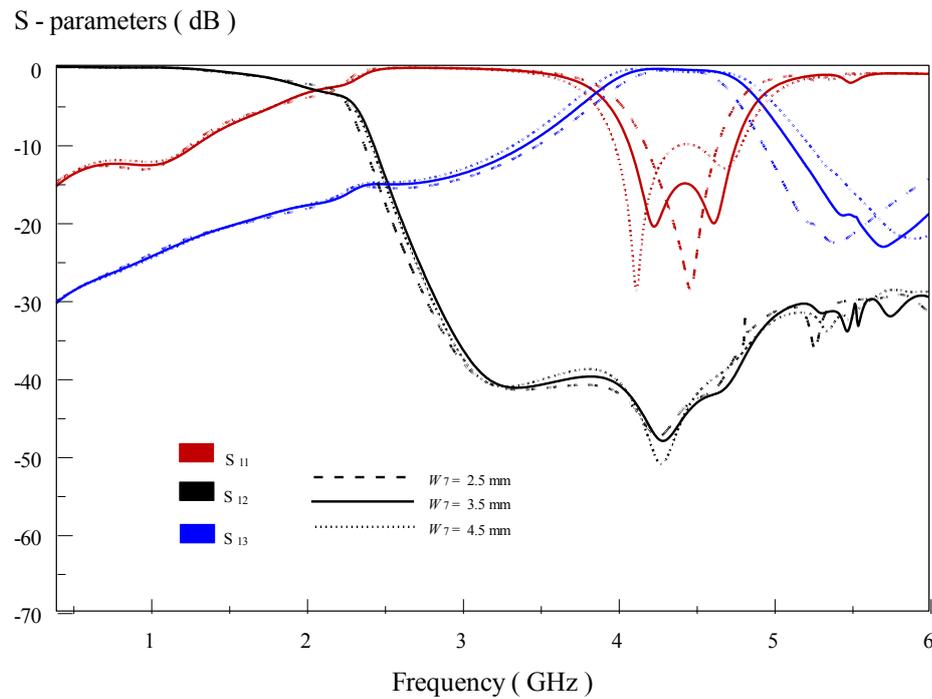


Figure 4.18: The effect of varying parameter W_7 on the amplitude response.

The parameter W_7 with a value of 3.5 mm was stepped up and stepped down with the following values:

- Step- down value : 2.5 mm
- Step-up value : 4.5 mm

Figure 4.18 shows that changing the parameter W_7 has significantly affect the amplitude response of the bandpass filter. The low-pass filter is not affected by the changes because W_7 is not part of the travelling path of the low-pass filter. When W_7 decreases to 2.5 mm, the poles of the filter combined into a single pole and thus, reducing the bandwidth. As W_7 increases to 4.5 mm, the return loss becomes poorer due to impedance mismatch. On the other hand, the bandwidth of the filter widens when W_7 is at 4.5 mm.

4.3 Discussion

Basically, a low-pass and bandpass diplexer divides a single input signal into two output signals with different frequencies. These frequencies have to be within the passbands of the low-pass and bandpass filters. The experimental results as shown in Section 4.2.2 conclude that the measured 3-dB cutoff frequency for the low-pass is 2.03 GHz and the measured operating bandwidth is within the range of 3.99 GHz to 4.71 GHz. Thus, only frequencies below 2.03 GHz and frequencies between 3.99 GHz to 4.71 GHz are allowed to be transmitted across the proposed diplexer.

Passive elements were incorporated into this design in order to separate out the filters. Additionally, the passive elements help in reducing the size of the design. Inductors with value of 3.0 nH were used at the low-pass filter whereas 0.9 pF capacitors were used at the bandpass filter. The values of the inductors and capacitors were determined based on circuit theory as shown in the equations below:

$$Z_C = \frac{1}{j\omega C} \quad Z_L = j\omega L \quad (4.4)$$

where $\omega = 2\pi f$

These equations were used to calculate the impedances where Z_C is the impedance for capacitors and Z_L and is the impedance for inductors. From the equations above, the impedance, Z_C increases as the frequency decreases. However, impedance, Z_L increases with frequency. Thus, capacitor is able to block signals with low frequencies and inductor is capable of blocking signals with higher frequencies.

As shown previously in Figure 4.3, the proposed diplexer has a total of three poles within the range of 1GHz to 8 GHz. The low-pass and bandpass filters each have one pole and two poles respectively, within its passband. The pole at the low-pass filter is located at 1.07 GHz. As for the bandpass filter, the two poles are located at 4.23 GHz and 4.62 GHz. The electric fields at different poles of the diplexer were captured and analysed in detail.

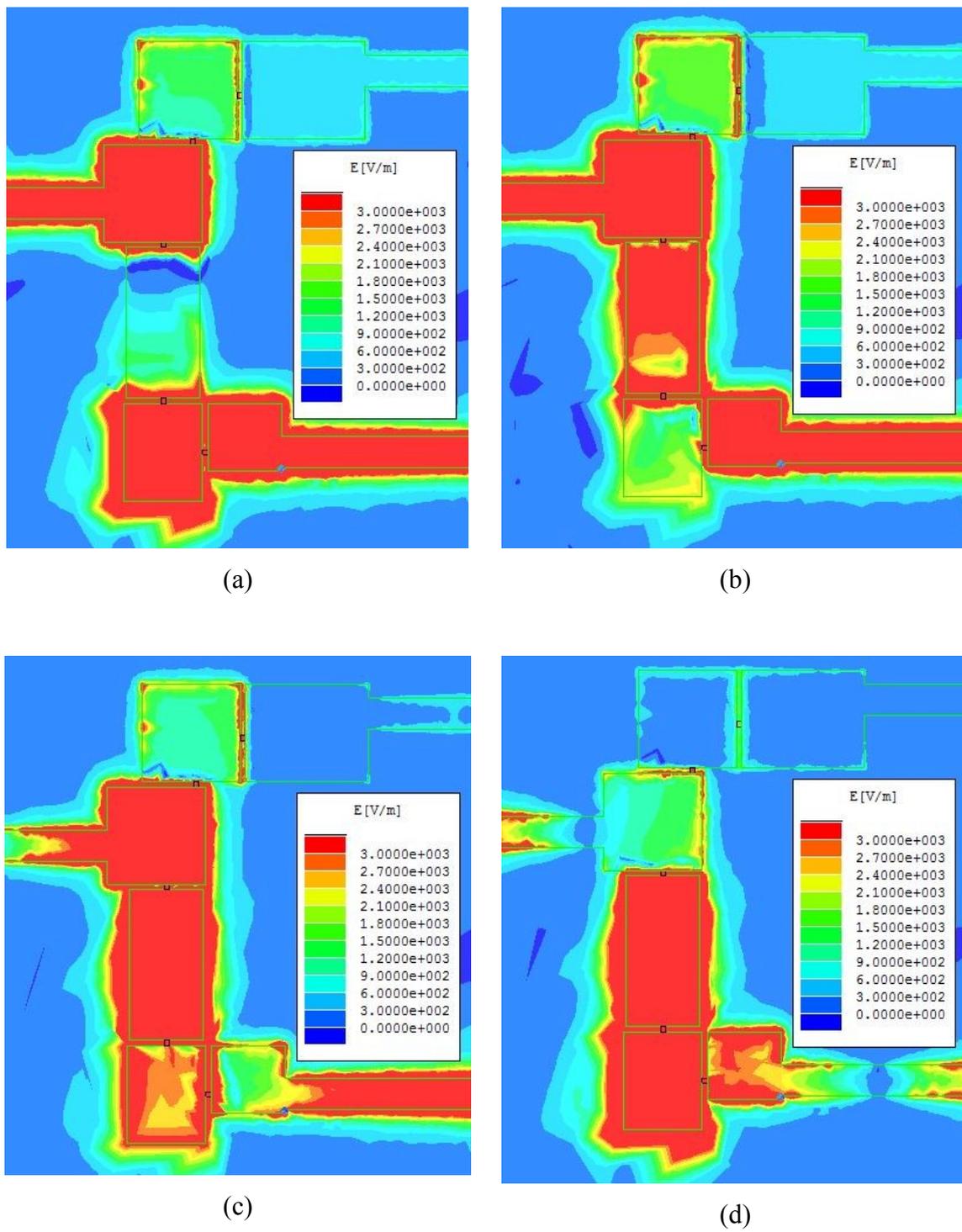


Figure 4.19: The electric field of the low-pass filter at 1.07 GHz with phases of (a) 0°, (b) 40°, (c) 80° and (d) 120°

The electric fields of the low-pass filter at 1.07 GHz with different phases can be observed in Figure 4.19. The electric fields were captured at different input phases to illustrate that the fields are in the form of travelling wave. The fields can be seen travelling from Port 1 to Port 2 as the phase varies from 0° to 120° .

Furthermore, the electric fields at the input port have the same intensity as the electric fields at the output ports. This proves that most signals are able to flow through the low impedance 3.0 nH inductors and thus, causing the filter to have low reflection at the input port. Figure 4.19 further shows that no signal can be transmitted over to Port 3. This is due to the presence of the 0.9 pF capacitors. Previous equations have proven that the capacitors have high impedance at low frequencies and thus, most of the signals are blocked.

Figure 4.20 and Figure 4.21 illustrate the captured electric fields of the bandpass filter at 4.23 GHz and 4.62 GHz respectively. Similarly to the low-pass filter, the electric fields in both figures are travelling wave and are proven when the fields are captured at phases from 0° to 120° . The electric fields are obviously travelling from Port 3 to Port 4.

Most of the input signals from Port 3 are being transmitted over to Port 4 as the 0.9 pF capacitors have low impedance when operating at high frequencies. There is also no reflection of signal back to the input port. This can be clearly seen as the strength of the electric field at the input and output ports are of the same intensity. On the other hand, there are no signals propagating towards Port 2 due to the presence of the 3.0 nH inductor. Inductors operating at high frequencies will have high impedance which prevents signals from flowing through. This is proven in the earlier equations.

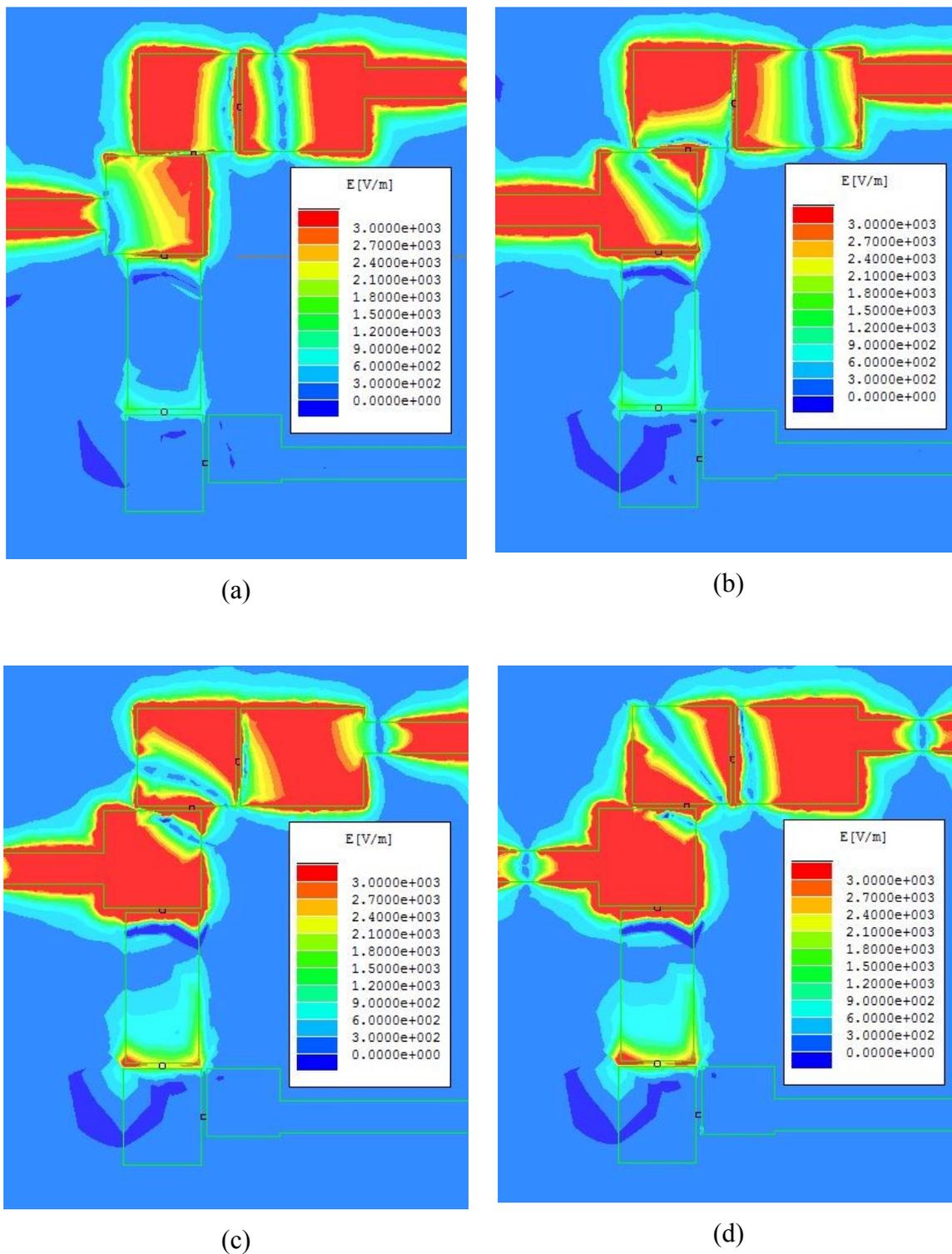


Figure 4.20: The electric field of the bandpass filter at 4.23 GHz with phases of (a) 0°, (b) 40°, (c) 80° and (d) 120°

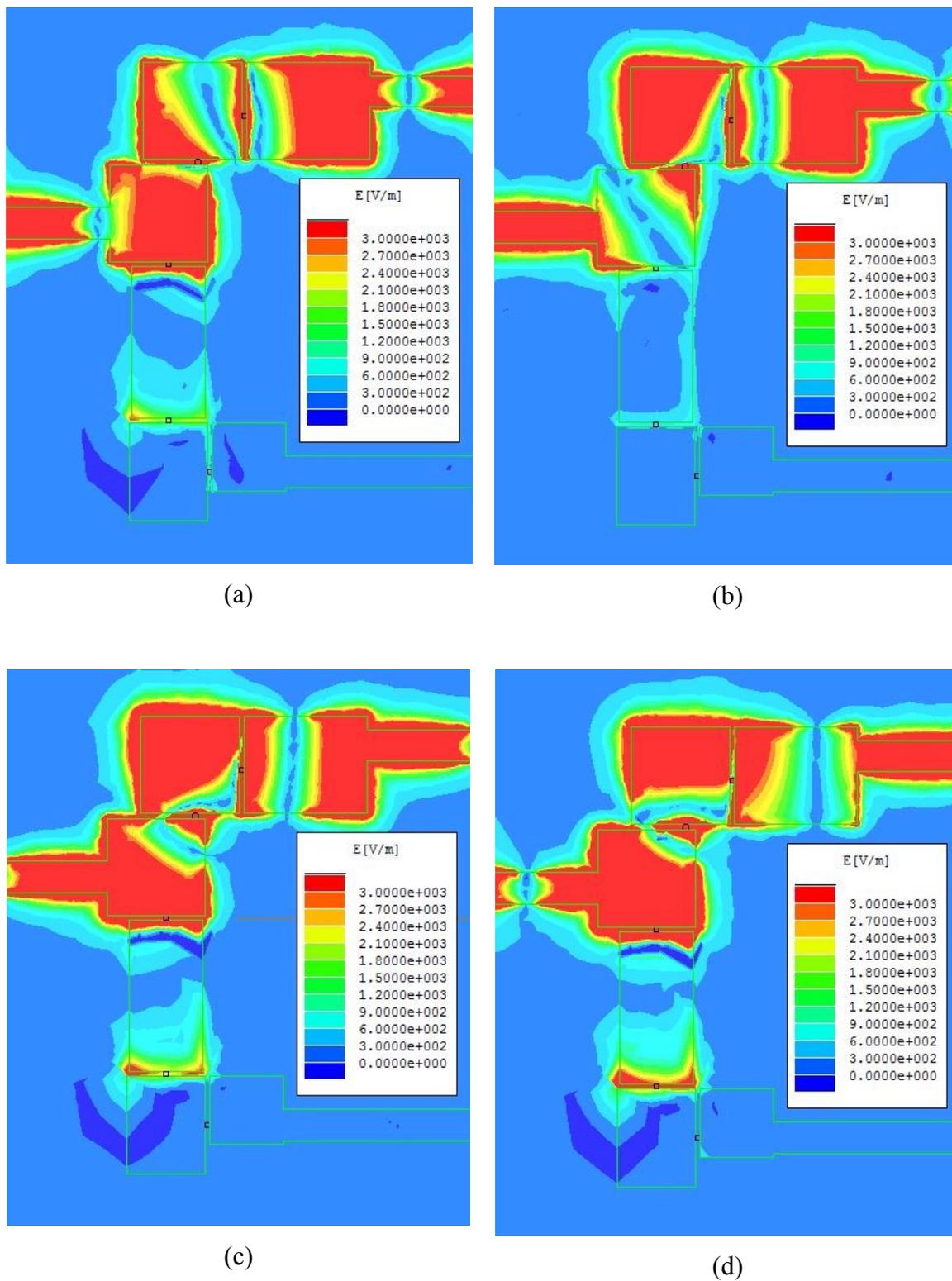


Figure 4.21: The electric field of the low-pass filter at 4.62 GHz with phases of (a) 0° , (b) 40° , (c) 80° and (d) 120°

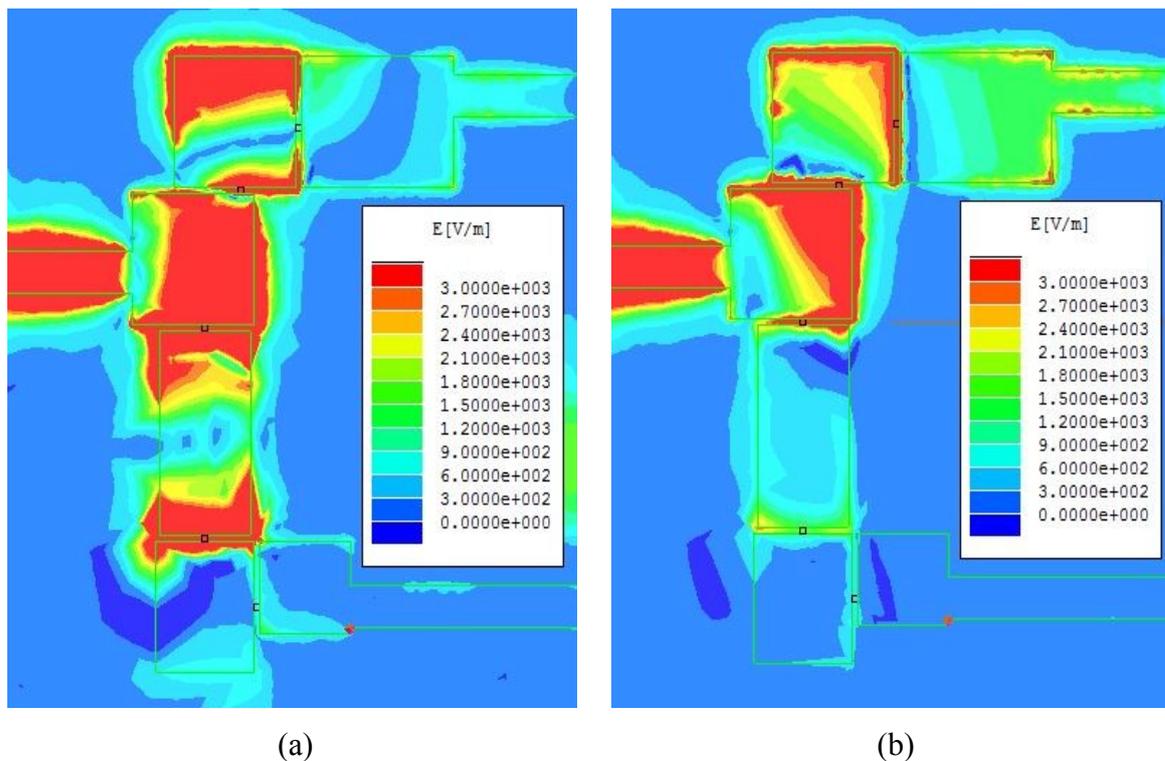


Figure 4.22: The electric field at 3.0 GHz in the (a) low-pass filter and (b) bandpass filter

The electric fields of the proposed diplexer at 4.3 GHz were captured as shown in Figure 4.22. Since 3.0 GHz lies at the stopband, therefore no input signals from Port 1 are being transmitted over to Port 2 and Port 3. Moreover, most of the signals are reflected back to the input port, thus causing the return loss to be close to 0dB.

CHAPTER 5

FUTURE WORK AND RECOMMENDATIONS

5.1 Achievements

A novel two-way low-pass and high-pass filter has been successfully designed as explained in Chapter 3. Based on the configuration shown in section 3.2.1, the proposed two-way filter is a four-port device made up of an independent low-pass and high-pass filter. The proposed two-way filter was fabricated onto a Duroid RO4003C substrate with feed line width of 3.21 mm. The simulation and experimental results are compared as shown in section 3.2.2. From the comparison, it can be concluded that the results obtained from the simulation and experiment are in reasonable agreement with each other. Observation from the results also shows that both the low-pass and high-pass filters have two poles within their passbands. Therefore, a wide bandwidth two-way filter was successfully achieved.

A low-pass and bandpass diplexer was proposed as the second idea for this project. As shown in section 4.2.1, the proposed diplexer is a combination of a low-pass filter and a bandpass filter that are both connected by a single input port. The proposed diplexer was fabricated onto a Duroid RO4003C substrate with feed line width of 3.21 mm. Section 4.2.2 shows the comparison between the simulation and experimental results. The comparison concludes that the simulation and experimental results are in good agreement. Further analysis shows that the percentage error between the simulation and experiment results for the low-pass and bandpass filters,

are 0.98% and 1.47 % respectively. Thus, a successful low-pass and bandpass filter was designed.

5.2 Future Work

Based on the results of the proposed designs of the two-way filter and diplexer, there are room for further improvements. Both the filter and the diplexer can be improved to have steeper roll-off. The steeper the slope, the closer the frequency is cut to the ideal cutoff value; and thus achieving higher selectivity. A smoother roll-off slope is also desired. Furthermore, the configuration of the low-pass and bandpass diplexer can be altered to produce broader bandwidth. A broader bandwidth allows the passband to cater a wider range of frequencies. Designs with wider bandwidth will result in more modes or poles at the passband. Additionally, different designing techniques can be used to prevent losses in the microstrip circuit. Having these losses will affect the insertion loss as well as causing the S-parameters to experience frequency shifting.

5.3 Conclusion

Overall, the objectives of this project have been met. The process of completing this final year project has been fruitful as this is a chance to learn the insight on how to apply microwave engineering theories onto a real-life task project. Design considerations, fabrication techniques, and experiment procedures; are very important in order to ensure a successful project. Analysing skills are also gained throughout the experiment stage, especially when it comes to comparing and interpreting the simulation and experimental results. At the end, two successful products are produced for the completion of this final year project. All results obtained from the simulation and experiments are in good agreement.

REFERENCES

- Capstick, M. H., 1999. Microstrip Lowpass-bandpass Diplexer Topology. *Electronic Letters*, 35.
- Cheng, W., X. H. Wang, et al., 2012. High-selectivity Dual-band Bandpass Filter using Folded Stepped Impedance Resonators and Asymmetric Coupling Lines. *Microwave and Optical Technology Letters*, 54(8).
- Chu, Q. X. and F. C. Chen, 2008. A Compact Dual-band Bandpass Filter using Meandering Stepped Impedance Resonators. *IEEE Microwave and Wireless Components Letters*, 18.
- Das, A. and S. K. Das, 2001. *Microwave Engineering*. Singapore, McGraw-Hill.
- Deng, H. W., L. Zhao, et al., 2010) A Dual-band BPF with DSIR and TSIR. *Electronic Letters*, 46.
- Dong, Y. D. and T. Itoh, 2011. Substrate Integrated Waveguide Loaded by Complementary Split-ring Resonators for Miniaturized Diplexer Design. *IEEE Microwave and Wireless Components Letters*, 21(1).
- F.Cheng, X. Q. Lin, et al., 2012. High Isolation Diplexer Using Quarter-wavelength Resonator Filter. *Electronic Letters*, 48(6).
- Hong, J.-S., 2011. *Microstrip Filters For RF/Microwave Applications*. New York, John Wiley & Sons Inc.

Matthaei, G. L. and E. G. Cristal, 1965. Multiplexer Channel-separating Units Using Interdigital and Parallel-coupled Filters. *IEEE Transaction on Microwave Theory and Techniques*, 13.

Matthaei, G. L., L. Young, et al., 1980. *Microwave Filters Impedance-matching Networks and Coupling Structures*. Massachusetts, Artech House, Inc.

Pozar, D. M., 1998. *Microwave Engineering*. New York, John Wiley & Sons Inc.

Tsai, L. C. and C. W. Huse, 2004. Dual-band Bandpass Filter using Equal Length Coupled-serial-shunted Lines and Z-transform Techniques. *IEEE Transaction on Microwave Theory and Techniques*, 52.

W.Q. Xu, M. H. Ho, et al., 2007. UMTS Diplexer Design Using Dual-mode Stripline Ring Resonators. *Electronic Letters*, 43(13).

Wang, J., L. Ge, et al., 2011. Compact Microstrip Dual-mode Dual-band Bandpass Filter with Wide Stopband. *Electronic Letters*, 47.

Xue, Q. and J. X. Chen, 2008. Compact Diplexer Based on Double-sided Parallel-strip Line. *Electronic Letters*, 44(2).

Zayniyev, D., D. Budimir, et al., 2008. Miniaturized Microstrip Filters and Diplexers For Wireless Communication Systems. *Microwave and Optical Technology Letters*, 50(10).