

DESIGN AND IMPLEMENTATION OF BANDPASS FILTER USING PARALLEL COUPLED RESONATOR

A dissertation submitted towards the partial fulfilment of the requirement for the
award of the degree of

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in
Microwave and Optical Communication**

Submitted by
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CERTIFICATE

This is to certify that work which is being presented in the dissertation entitled **Design and Implementation of Bandpass Filter using Parallel Coupled Resonator** is the authentic work of **Shruti Awasthi** under my guidance and supervision in the partial fulfilment of requirement towards the degree of **Master of Technology in Microwave and Optical Communication Engineering**, jointly run by Department of Electronics & Communication Engineering and Department of Applied Physics in Delhi Technological University during the year 2013-2015.

As per the candidate declaration this work has not been submitted elsewhere for the award of any other degree.

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DECLARATION

I hereby declare that all the information in this document has been obtained and presented in accordance with academic rules and ethical conduct. This report is my own, unaided work. I have fully cited and referenced all material and results that are not original to this work. It is being submitted for the degree of Master of Technology in Engineering at the Delhi Technological University. It has not been submitted before for any degree or examination in any other university.

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ABSTRACT

Band-pass filters play a vital role in wireless communication systems. Transmitted and received signals have to be filtered at a certain centre frequency with a specific bandwidth. Band-pass filters are used as frequency selective component in many RF and Microwave applications. There are several applications of a band-pass filter, for instance, at the receiver end it is used to eliminate the image frequency and to bandlimit the received signal. In the transmitter, they are used to reject the spurious signals generated by the local oscillator (LO). This project deals with the analysis, design, simulation, fabrication and testing of parallel coupled band-pass filter. Advanced Design System (ADS) 2011.10 Software is used for mathematical calculations and simulations. The filter is designed at the centre frequency 2.4 GHz using FR-4 as a substrate.

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Chapter 1

INTRODUCTION

1.1 OVERVIEW

In the last few years, a vast growth in wireless communication systems has been observed. The speedy raise in wireless communications, 3G and 4G mobile internet, and ultra-wideband communication has created the requisite for the development of microwave components with more better specifications and good performance. Microwave components like duplexers, microwave filters, dielectric resonant antennas/arrays etc are crucial elements in these systems. A microwave filter is a circuit, a two port network use to adjust the response by allowing transmission at frequencies within passband and attenuating at frequencies in the stopband. Frequency response usually include low pass, high pass, bandpass and bandstop filter. In the case of microwave filters, while designing a filter certain parameters are considered namely selectivity, bandwidth, phase linearity and compactness. Although the discussion in this report is limited to Bandpass Filter.

A bandpass filter allows transmission of frequencies in the passband and attenuates frequencies in the stopband. Bandpass Filters are used in all kinds of instrumentation, Sonar, even medical applications for example cardiograms, EEGs etc.

The scope of this report is designing, simulation and optimization of Bandpass filter using parallel coupled resonator.

1.2 MOTIVATION AND PROBLEM STATEMENT

The motivation for this project come during course study of Microwave and how different types of filters can be possible from lowpass filter prototype. Microstrip is reliable and easy to connect with the other planar device. Microstrip is not so expensive, have higher Quality factor(Q), lighter and more compact than traditional waveguide technology. Parallel coupled microstrip

bandpass filters are widely used in wireless communication and microwave systems. They can be easily fabricated and have simple design procedure. They can also be made compact by folding lengths resulting in hairpin configuration[1-2]which can also provide a wide bandwidth range [3].

1.3 Objectives

- ✓ Understanding ADS Software
- ✓ Basic theory of filter and how to design Band-pass Filter
- ✓ Design and simulate Band-pass Filter at 2.4 GHz
- ✓ Fabricate the designed filter on the FR4 board

1.4 Scope

The scope of this project is to design microstrip parallel coupled bandpass filter using Advanced Design System (ADS), 2011.10 software, with 50Ω termination at the input and output ports of microstrip parallel coupled line and analysis of insertion loss and return loss using Chebyshev characteristic response with passband ripple of 0.1dB. This project will involve simulation and fabrication of microstrip bandpass filter at 2.4 GHz. The design will be fabricated on FR4 board having dielectric constant as 4.2, height = 1.5 mm and thickness of 0.035mm.

1.5 Project Sketch

This report comprises of five chapters. The first chapter briefly discusses the overviews about the project such as introduction, objectives, problem statements and scope of this project. Chapter 2 describes about the various techniques used for designing a bandpass filter . Every facts and information, which found through by any references had been selected. This literature review has been explained about the designing of microstrip bandpass filter. Chapter 3 describes about the microwave filter theory and its application. It includes the theory of microstrip lines and various parameters related to microstrip lines and its application. Chapter 5 discusses about the technique used in designing of microwave bandpass filter. The concept of parallel coupled resonator and

the derivation of the equations to be used in the designing process. Chapter 6, describe about the discussion and project finding such as the result and analysis. The result is presented by calculation. All the initial simulation results of parallel couple microstrip bandpass filter and collected data are documented using the table and discussed it. This is including the graphs that have obtained during the simulation. Finally the conclusion has been made and recommendation for the future works under chapter 7.

Chapter 2

Literature Appraisal

2.1 Introduction

Designing of Microwave Filters has been unrelenting and prolific field for review since the commencement of microwave engineering. Basically, there are four types of filters: lowpass, highpass, bandpass, and bandstop. Microwave Filters are two-port reciprocal, passive, linear device used to manage the response in a system by allowing transmission of desired signal frequencies while eliminating frequencies that lie outside the desired range of frequencies. Filters are used to protect receivers from interference outside their operating range. To satisfy the specifications of modern communication system, designing of microwave and millimeter-wave devices require more accurate results. Presently, microwave systems require sharp performance filters. They are used to combine or separate different frequencies, as in frequency converters or multipliers, or in multiplex communications.

2.2 Bandpass Filter

A Bandpass Filter is a device that allows a signal for a certain range of frequencies, attenuating the signals that fall outside this range as shown in figure 2.1. In a broad-spectrum, the performance of the filter is expressed in terms of insertion loss, return loss, frequency selectivity(Q) and so on. There are two types of bandpass filters i.e wide bandpass and narrow bandpass filters. A wide bandpass filter has figure of merit(Q) less than 10 while the narrow bandpass filters has $Q > 10$. Quality factor is proportional to Selectivity and inversely related to Bandwidth therefore, higher the quality factor more is the selectivity and thus narrower is the Bandwidth(BW).

Bandpass filters has two varieties: passive and active. Passive filters contain component: inductors, resistance and capacitors (L,R and C). Active filters consist of

components, such as operational amplifiers (op amps) and transistors are widely used for RF applications where tuning is required. However for lower frequencies, they provide an effective means to pass only a given band of frequencies. Lumped Bandpass filter proves to

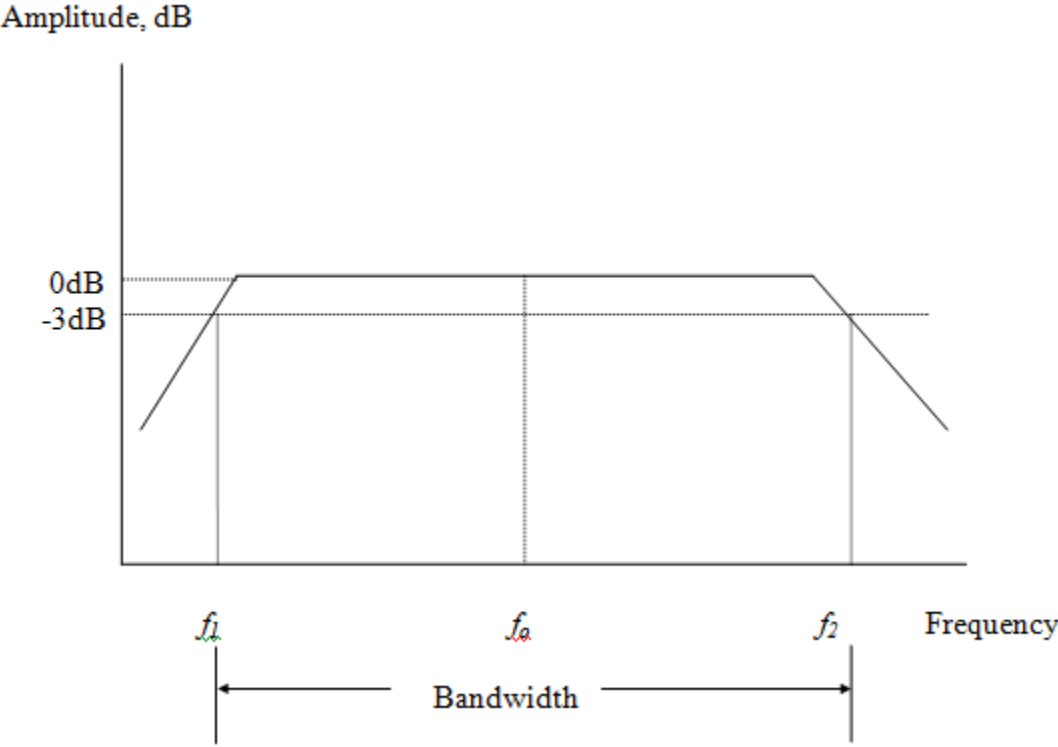


Figure 2.1: Bandpass Filter

be effective only upto 18GHz and also of less practical interest when insertion loss and power handling are of concern therefore distributed filters are used to overcome the advantages of lumped filters. Microwave Bandpass filter can be implemented using microstrip lines and their variations, some of them are mentioned below.

2.3 Designing techniques of Bandpass filter

There are various techniques in which a bandpass filter can be designed. Some of the techniques are represented in a diagram given below:

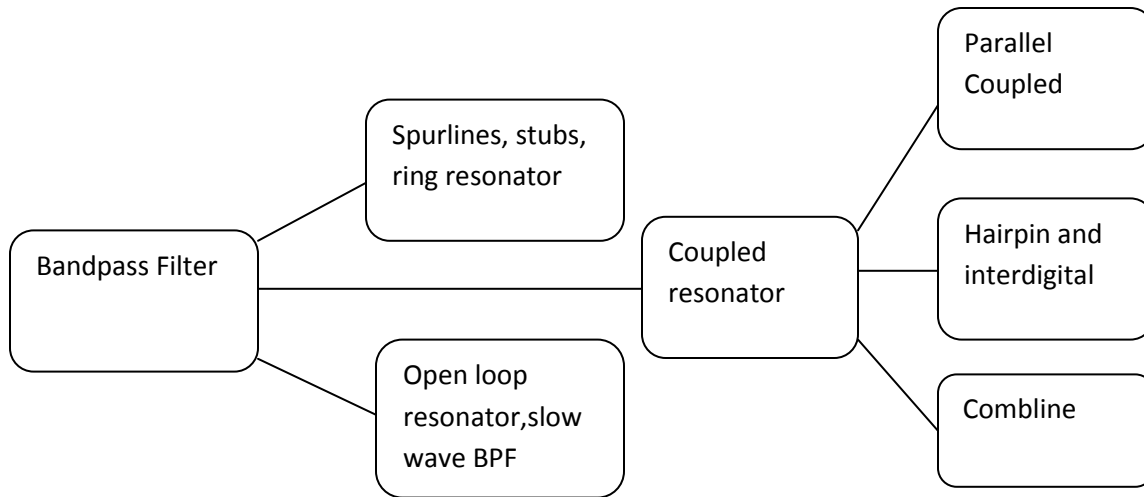


Figure 2.2: BPF designing techniques

Some of the techniques are overviewed below:

1. Ring Resonator: Ring resonator with conventional microstrip feedlines suffers from considerable insertion losses due to the curvature of the ring and loose coupling between the ring and feedlines, therefore a new feedline using linear & tapered microstrip lines is proposed in[4].The main advantage of this technique is insertion loss is increased by more than 7dB as compared to conventional one.

2. Slow wave bandpass filters: Lower insertion loss can be achieved in a new slow-wave bandpass filters by eliminating coupling loss between resonators as presented in[5] designed using stepped impedance hairpin resonators.

3. Slot-line resonator: To produce frequency selectivity, an external coupling is utilized to suppress unwanted harmonics for which a feeding arrangement with T-shaped microstrip to design a bandpass filter(BPF) is proposed[6]

4. Open Loop resonator: To enhance coupling a very compact filter using the combination of floating metallic patches and open-loop resonators has been proposed in [7]. Defected Ground structures has also been proposed for the designing of open loop resonator BPF to improve the bandwidth and to suppress second and third harmonics as mentioned in[8].

Defected ground structure (DGS) provides the advantage of having wide stopband and compact size. To suppress harmonics, a bandpass microstrip filter using coupled-line has been designed as in[9-13].

5. Spur lines : A spur line is formed by etching a portion of a microstrip lines to form an open stub. The open stub suppress the higher order harmonics[14].

Since coupled resonator provides several merits of low cost, compact size, easy assimilation with various components on a single panel .This project focuses on the parallel coupled resonator and illustrates the designing, simulation and fabrication of BPFs using parallel coupled resonator.

Chapter 3

Filter Theory and Transmission Line

3.1 Introduction

This section provides a general discussion on the microwave filter theory, synthesis method and filter implementation required for designing a bandpass filter.

3.2 Microwave Filter Theory

Microwave filter is used to manage the frequency response by passing frequencies within the passband and attenuation in the stopband. The four types of filters are:

- Low Pass Filter
- High Pass Filter
- Band Stop Filter
- Band Pass Filter

To represent a two-port network at microwave frequencies, scattering parameters(S -parameters) are used. S-parameters which are S_{11} , S_{12} , S_{21} , S_{22} represent reflection coefficients and transmission coefficients of the network under certain “matched” conditions. When port 2 is completely matched then at port 1, S_{11} represents the coefficient of reflection and S_{21} represents the coefficient of transmission. Similarly, when port 1 is completely matched then at port 2, S_{22} represents the coefficient of reflection and S_{12} represents the coefficient of transmission as shown in figure 3.1.

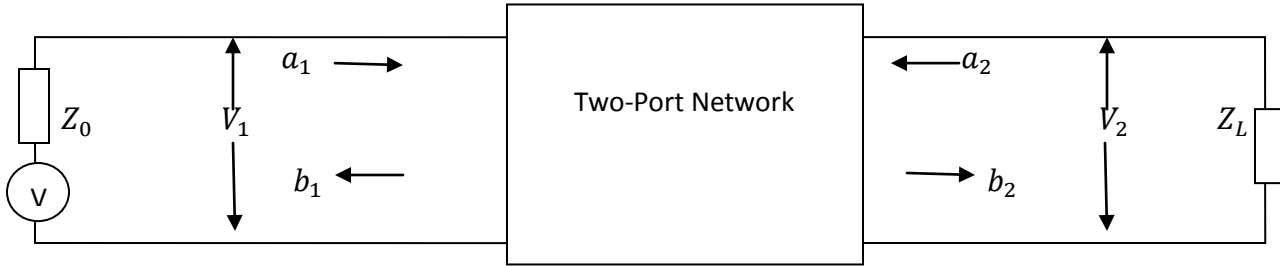


Figure 3.1: Two port network

In the above figure, a_1 denotes the normalized incident wave and b_1 denotes the normalized reflected wave at the port 1, v_1 and i_1 represent voltage and current at port 1. And a_1 , b_1 represent the terminal current and voltage which can be expressed as in Equations 3.1 and 3.2.

$$a_i = v_i + \frac{Z_{o_i}}{2Z_o} \quad 3.1$$

$$b_i = v_i - \frac{Z_{o_i}}{2Z_o} \quad 3.2$$

Here Z_0 is the characteristic impedance and is usually taken as 50Ω for all practical application.

Hence, the scattering parameter in the matrix form can expressed as shown in Equation 3.3

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad 3.3$$

It is to be noted that other two port network parameters like Y and Z parameters are applicable at low frequencies as calculation of these parameters involve short circuiting or open circuiting of ports, but at higher frequencies it is very difficult to open or short circuit any port because an active two port might oscillate if any of its port is short circuited or open circuited, also, it requires a broadband match at higher frequencies. Therefore, a new parameter called S parameter has been defined at RF. The S parameters are defined in the following manner:

S_{11} is input reflection coefficient which is the ratio of reflected wave to incident wave at port1 when port 2 is perfectly matched or can be expressed as,

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} \quad 3.4$$

S_{12} is reverse transmission coefficient which is the ratio of reflected wave at port 1 to the incident wave at port 2 when matching is done at port 1, expressed as,

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} \quad 3.5$$

S_{22} is output reflection coefficient which is the ratio of reflected wave to incident wave at port 2 when port 1 is perfectly matched, expressed as,

$$S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0} \quad 3.6$$

S_{21} is forward transmission coefficient which is the ratio of reflected wave at port 2 to the incident wave at port 1 when matching is done at port 2. It is the Gain of the circuit, expressed as,

$$S_{21} = \left. \frac{b_1}{a_1} \right|_{a_2=0} \quad 3.7$$

The performance of a filter are expressed in terms of the insertion loss (IL), the return loss (RL), Quality Factor(Q), the 3dB bandwidth. Filters should have small insertion loss, a large value of return loss in a passband for proper impedance matching with components that has to be integrated and a high selectivity to prevent any noise from the undesired frequencies.

3.3 Filter Metrics

The order of the filter plays an important role in cost and space parameters. Parameters used for designing a bandpass filter are as follows:

a) Insertion loss: Insertion loss measures loss incurred by insertion of filter between input/output ports which is represented mathematically as,

$$\text{Insertion loss (dB)} = 10 \log_{10} (P_{lr}) \quad 3.8$$

where P_{lr} is the power loss ratio which is the inverse of filter transfer function normalized to zero frequency value of gain. It measures the power reduction due to impedance mismatch. Insertion Losses are less than 3dB within the filter passband irrespective of filter order in Butterworth filter, whereas Insertion losses is sensitive to passband ripples in Chebyshev. Chebyshev insertion loss within passband is less vivid than Butterworth filter.

b) Return Loss: It measures the relative amount of power reflected by an input signal. Mathematically,

$$\text{Return Loss (dB)} = 20 \log \left(\frac{VSWR+1}{VSWR-1} \right) \quad 3.9$$

Where, VSWR is the voltage standing wave ratio related by maximum voltage to minimum voltage. In a perfect transmission line, Return Loss is infinite. In a perfectly reflective circuit it is zero.

c) Bandwidth: The width of the passband expressed as the difference between lower and higher relative 3dB attenuation points.

d) Quality Factor: In Bandpass filter, "loaded Q" is used to define the ratio of center frequency to 3dB bandwidth expressed as

$$\text{Loaded Q} = \frac{\text{Center frequency}}{3 \text{ dB bandwidth}} \quad 3.10$$

3.4 Synthesis Method of Filter Design

There are two methods of filter designing: Insertion loss and the image parameter. In Image parameter method, filter sections are cascaded to provide the desired results. However, the desired frequency response cannot be exactly reproduced. Conversely, the insertion loss method, allows the synthesis of an exact and accurate response. A design by insertion loss initiate from approximate response of the filter as ideal filter construction is not possible. Resolution to the approximation are the Butterworth (flat response), Chebyshev (ripples in the passband), inverse Chebyshev (ripples in the stopband) and elliptic (ripples in the passband and stopband). Butterworth filter is the best approximation, but its magnitude response decreases with increase in frequency , while the magnitude response of the Chebyshev filter fluctuates or show ripples but it has a sharper frequency cut off .An elliptical filter requires lower order and is generally a preferred approximation.

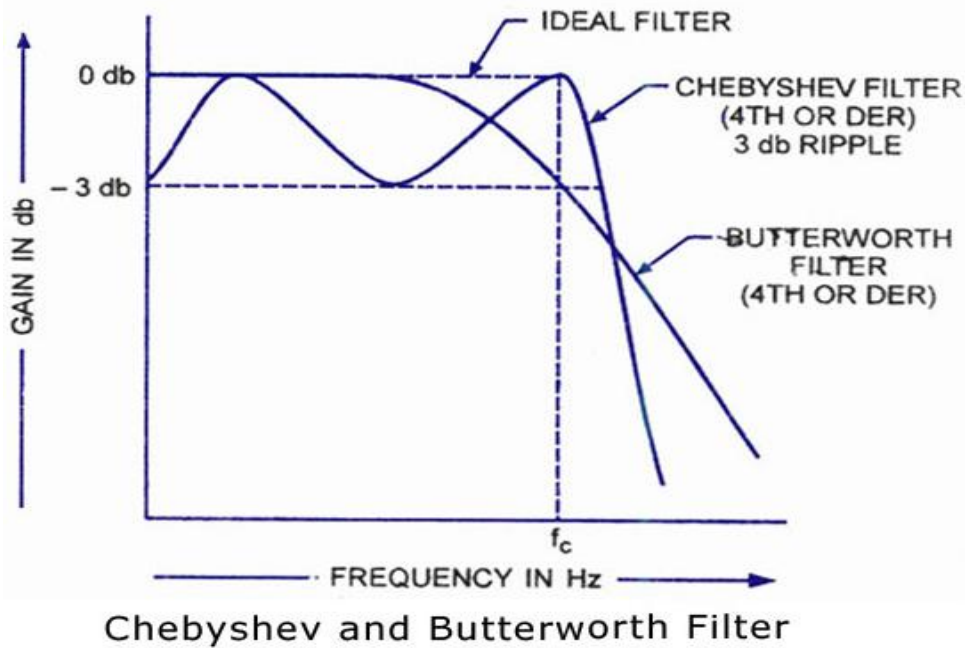


Figure 3.2: Butterworth and the Chebyshev response of a bandpass filter [15]

A lowpass prototype is synthesized by choosing these approximations whose element values are normalized to make the value of resistance and conductance as 1. With the help of frequency scaling, a low pass prototype can be converted to a bandpass filter. A filter designed by using the insertion

loss method gives the circuit which comprises of lumped components. At microwave frequencies, distributed elements are preferred in place of lumped elements. To realize distributed elements, we use transmission line sections and assists the design with Richards' transformation, the Kuroda identities, as well as the impedance and admittance inverters as described in the next section.

3.5 Filter Implementation

In this section, some of methodologies are discussed from which we can improve the filter response. At frequencies greater than 10 GHz, lumped elements are generally difficult to implement, also they provide response up to a limited range. Therefore, Richard's transformation and Kuroda's identities are used to convert the lumped components into transmission line and distinguish the filter components with the help of the transmission line sections, whereas kuroda's four identities convert the series stubs into shunt stubs or shunt stubs into series stubs and can change the impractical impedances into more realizable characteristic impedances.

3.5.1 Richard's Transformation

Richard's transformation is used to design an LC circuit using short and open stub. The transformation provides mapping of w plane to Ω plane represented as :

$$\Omega = \tan \beta l$$

Thus, reactance of an inductor is expressed as :

$$j X_L = j\omega L = jL \tan \beta l \tag{3.11}$$

and the susceptance of capacitor as:

$$j B_C = j\omega C = jC \tan \beta l \tag{3.12}$$

Equation 2.5(a) and 2.5(b) shows that an inductor is substituted with a short circuited stub of length βl with a characteristic impedance of L and capacitor being substituted by an open circuited stub of length βl with a characteristic impedance of $1/C$. The cut off frequency can be obtained by putting Ω equals to 1 which gives length of $\lambda/8$ where λ is the wavelength of the

stub. Since, the lengths of all stubs are same, they are referred as commensurate lines. At frequencies away from the cut off frequency, filter response differ from the desired response..

3.5.2 Kuroda's Identities

In order to obtain more practical microwave filter, redundant transmission lines are used. The four Kuroda's Identities are used to perform this operation by following method:

- By transforming the shunt stubs into series stubs or vice versa
- By altering the impractical characteristic impedances into the characteristic impedance which can be realized more easily.
- By separating transmission line stubs physically

The four identities are given in table 3.1 shown below where each square box denotes a unit element or transmission line of length $\lambda/8$ indicating their characteristic impedance. The short and open circuited stubs represent inductors and capacitors .

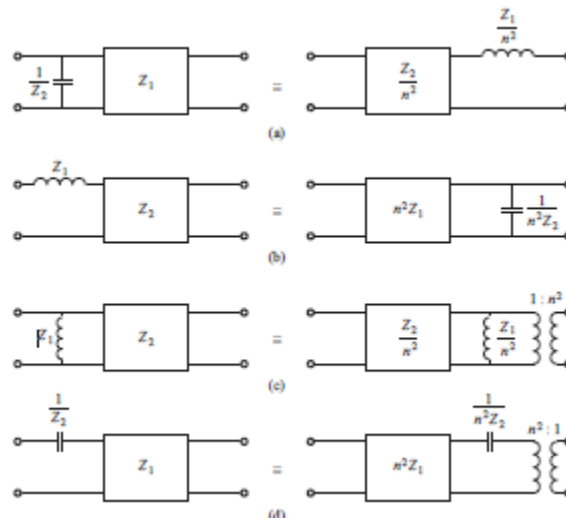


Table 3.1: Kuroda's identities(where $n^2 = 1 + \frac{Z_2}{Z_1}$)[16]

3.5.3 Impedance and Admittance Inverter

Imittance inverter is of two types: admittance inverter and impedance inverter, also known as J inverter and K inverter respectively. In deriving design equations for certain types of band-pass,

it is desirable to convert the low pass filter prototypes which use both inductances and capacitances to equivalent forms which use only inductances or only capacitances. This can be done with the aid of immittance inverter as shown in figure 3.3.

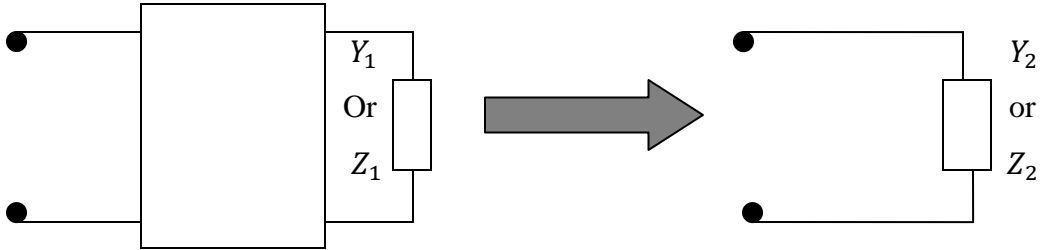


Figure 3.3: Immitance Inverter

An ideal Impedance Inverter is a network in which if one port is terminated in impedance Z_1 , the impedance Z_2 seen looking from the other port is given by:

$$Z_2 = \frac{K^2}{Z_1} \quad 3.13$$

where K is the characteristic impedance of the impedance inverter. An impedance inverter converts an inductance to capacitance and vice versa. The impedance inverter is expressed by the following ABCD matrix i.e

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & \mp jK \\ \pm \frac{1}{jK} & 0 \end{bmatrix} \quad 3.14$$

In the same way, an ideal Admittance inverter is a network in which if one port is terminated in Y_1 admittance then admittance seen from the other port, Y_2 is given by:

$$Y_2 = \frac{J^2}{Y_1} \quad 3.15$$

where J is the characteristic admittance of the admittance inverter. The admittance inverter is expressed by the following ABCD matrix i.e

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & \mp \frac{1}{jJ} \\ \pm jJ & 0 \end{bmatrix} \quad 3.16$$

These inverters are used to make the reciprocal of the load admittance or impedance through which series elements are converted into series elements or vice versa. Quarter wave transformer is used to construct J and K inverter. The impedance and admittance inverter is useful in the designing of bandpass and bandstop filter for the applications which requires narrow bandwidth i.e less than 10%.

There are various methods in which a microstrip bandpass filter can be designed namely, using spurlines, stubs, ring resonator, interdigital filter, parallel coupled line, hairpin etc. From above mentioned technologies, parallel coupled line has been found the most suitable technique for designing a bandpass filter as it offers advantages of simple design procedure, low fabrication cost, compact and high practicality as discussed in chapter 3.

3.6 Applications of Filters

The two major applications of microwave filters are in communication and radar. Some other applications are mentioned below:

- Satellite Communication
- EMS receiver
- Mobile Communication
- Microwave FM multiplexer
- Image frequency rejection application

3.7 Transmission line

Transmission lines are used to carry power from source to load. In this report, microstrip line is used as a transmission line as it is compact, low in cost and can be easily integrated with diodes, transistors etc.

3.7.1 Basic microstrip line

Microstrip line is a type of transmission line, implemented via PCB method which is used to convey microwave signals. It consists of a conducting strip which is isolated from ground by a dielectric layer identified as the substrate.

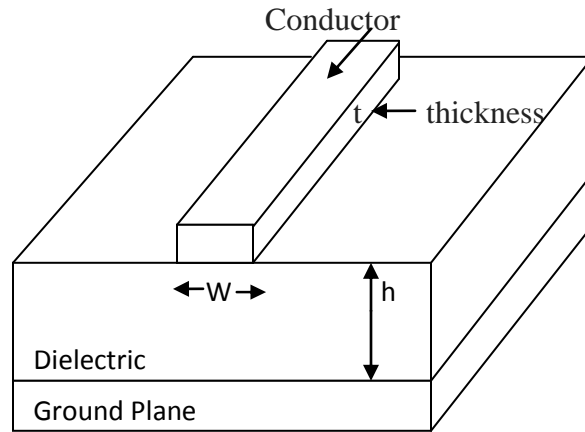


Figure 3.4: The general structure of Microstrip Line

The general structure of microstrip is shown in figure 3.4 as above. The important parameters in microstrip circuit design are the width w and height h , relative permittivity (ϵ_r). The thickness of the top conducting strip t and conductivity s is generally of less importance and often neglected. The conducting strip is usually printed on a microwave substrate material. The field pattern of microstrip line is Quasi-TEM mode as shown in 3.5

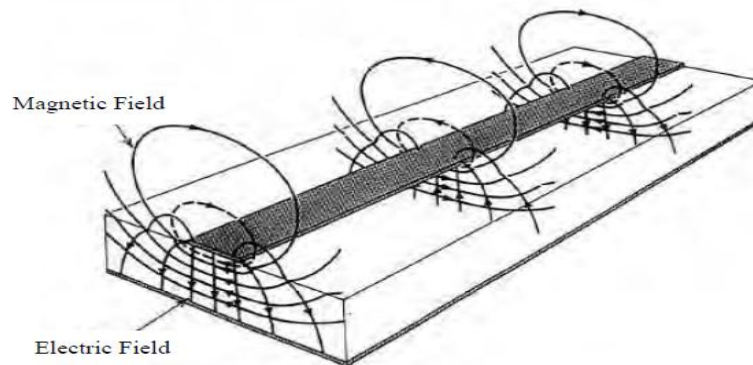


Figure 3.5: Radiation pattern of microstrip lines[17]

The main reason of the quasi-TEM pattern in microstrip line is due to the presence of the dielectric substrate and the surrounding air interface. From the Maxwell's second equation, $\nabla \times E = - dB/dt$, change in the direction of electric field lines at the interface results in the magnetic field. The effective dielectric constant on the microstrip line lie between air and the dielectric as some of the electric energy is stored in the dielectric and some in the air, and because the microstrip structure is not uniform, it will support the quasi-TEM mode.

3.7.2 Substrate material

The choice of substrate used in the microstrip filter is also an important factor. Some of the qualities of the dielectric substrate are as follows:

- i. The dielectric constant
- ii. The dielectric constant is frequency dependent which results in "material dispersion"
- iii. The surface finish and flatness
- iv. The dielectric loss tangent
- v. The cost
- vi. The thermal conductivity
- vii. The surface adhesion properties for the coating of conductor
- viii. The ease of cutting, shaping, and drilling
- ix. The porosity for high vacuum applications

Generally, two types of substrates are used: soft and hard substrates. Soft substrates are flexible, cheap and can be fabricated easily but they have higher thermal expansion coefficients. Some examples of soft substrates are RT Duriod 5870 ($\epsilon_r = 2.3$) and RT Duriod 6010.5 ($\epsilon_r = 10.5$). Hard substrates have better reliability, lower thermal expansion coefficients but are more expensive and non-flexible. Some of the examples of hard substrates are quartz ($\epsilon_r = 3.8$), alumina ($\epsilon_r = 9.7$), sapphire ($\epsilon_r = 11.7$) and Gallium Arsenide GaAs ($\epsilon_r = 12.3$).

3.7.3 Wavelength in Microstrip and length of the Microstrip line

The guided wavelength of the microstrip is given by:

$$\lambda_g = \frac{\lambda}{\sqrt{\epsilon_{re}}} \quad 3.17$$

Where λ is the wavelength in air at the operation frequency f . The guided wavelength can be expressed as below if the frequency is in Gigahertz(GHz):

$$\lambda_g = \frac{300(\text{GHz})}{\sqrt{\epsilon_{re}}} (\text{mm}) \quad 3.18$$

The length of the microstrip line:

$$L = \frac{\lambda_g}{4} \quad 3.19$$

3.7.4 Generation of W/h:

Equations for W/h are expressed in terms of Z_c and ϵ_r , derived by Wheeler and Hammerstad, as mentioned below:

$$\frac{W}{h} = \frac{8e^n}{e^{2n-2}} \quad 3.20$$

Where,

$$n = \frac{\sqrt{\epsilon_r+1}}{2} \cdot \frac{Z_0}{60} + \frac{\epsilon_r+1}{\epsilon_r-1} \left(0.23 + \frac{0.12}{\epsilon_r} \right) \quad 3.21$$

$$\epsilon_{re} = \frac{\epsilon_r-1}{2} + \frac{\epsilon_r-1}{2} \left(1 + 10 \frac{h}{W} \right)^{-ab} \quad 3.22$$

Where,

$$a = 1 + \frac{1}{49} \ln \left[\frac{\left(\frac{W}{h} \right)^4 + \left(\frac{W}{52h} \right)^2}{\left(\frac{W}{h} \right)^4 + 0.432} \right] + \left(\frac{1}{18.7} \right) \ln \left(1 + \left(\frac{1}{18.1h} \right)^3 \right) \quad 3.23$$

$$b = 0.564 \left(\frac{\epsilon_r-0.9}{\epsilon_r+3} \right)^{0.053} \quad 3.24$$

Characteristic impedance of the microstrip line is :

$$Z_c = \frac{1}{c \sqrt{c_a c_d}} \quad 3.25$$

c_a is the capacitance per unit length in air and c_d is the capacitance per unit length with dielectric constant present. c is the velocity of waves in free space $= 2.99 \times 10^8$ m/sec.

3.8 Applications

Microstrips are particularly suitable for those applications where low cost, compactness and light-weight are the main requirement. Some of the applications are as follows:

- i. Satellite communications
- ii. Radar
- iii. Radio altimeter
- iv. Wireless communication

CHAPTER 4

Parallel Coupled Resonator

4.1 INTRODUCTION

This section gives the main concept of parallel coupled resonator and the mathematical calculations required for designing a bandpass filter.

4.2 Coupled Line Theory

The coupled line consists of two transmission line where the lines are closely coupled to each other which can be used for the implementation of filters and directional couplers as shown in figure 4.1. The interaction of electromagnetic field lines represent the amount of power coupled between the lines. Generally, coupled transmission line operates in TEM mode and usually suitable for microstrip structure.

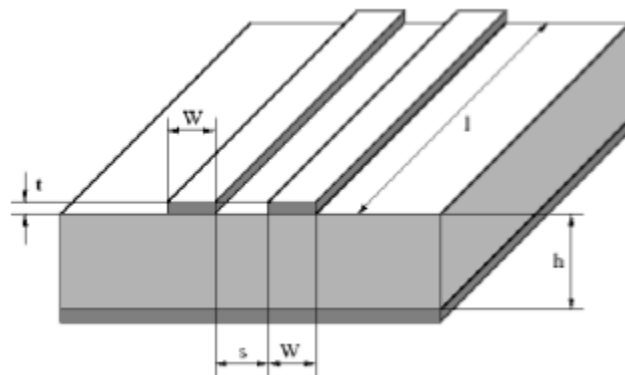


Figure 4.1: Microstrip Coupled Line [16]

There are two types of line: symmetrical (having same dimension) and asymmetrical (having different dimension). In symmetrical configuration, conductors have equal width and there is a constant spacing between them, whereas, in asymmetrical configuration, conductors have different widths but the spacing between them is same. The asymmetrical configuration is also called as uniformly coupled asymmetric line and the symmetric configuration is also known as uniformly coupled symmetric line.

In case of microstrip line, the spacing between the lines can vary depending upon the applications. The coupling will reduce if the spacing between the line is large resulting in the

better the electrical performance. Generally, the circuit or design with larger separation gaps are easier to fabricate as the chances of overlapping in those cases are less but it comes with a disadvantage of providing bandwidth less than 20%. To increase the bandwidth tighter coupling is required which can create fabrication related issues.

Next section will discuss the properties of quarter-wave coupled line which can be used to design a parallel coupled bandpass filter.

4.2.1 Properties of Quarter-Wave Coupled Line Section

A quarter wavelength line is a transmission line whose electrical length is an odd multiple of quarter wavelength. The characteristic impedance is related to input and load impedance by the following equation:

$$Z_s = Z_0^2 \cdot Z_L$$

where:

Z_s is the impedance at the input

Z_0^2 is the characteristic impedance of the transmission line

Z_L is the impedance at the load

If the quarter wave line is open circuited and the frequency of input signal less than the resonant frequency of LC circuit is employed, the electrical length(βl) decreases below the half wavelength making the input impedance as capacitive, thus, open circuited quarter wave line acts as a parallel resonant circuit. Similarly, if applied frequency is greater than resonant frequency is applied to a short circuited quarter wave line, the input impedance behaves as an inductor and the short circuited quarter wave line behaves as a series LC circuit. The relation between quarter wave line termination and LC circuit is given in table 4.1 below:

Quarter Wave Line Termination	$f < f_0$	$f = f_0$	$f > f_0$	LC circuit
Open circuit	Z_s is capacitive, electrical length $< \lambda/2$	Z_s is zero, electrical length $= \lambda/2$	Z_s is inductive, electrical length $< \lambda/2$	Series LC
Short circuit	Z_s is inductive, electrical length $< \lambda/2$	Z_s is infinite, electrical length $= \lambda/2$	Z_s is capacitive, electrical length $> \lambda/2$	Parallel LC

Table 4.1: The relation between quarter wave line termination and LC circuit

4.3 Equivalent structure of filter composed of Parallel Coupled Resonator

Coupled lines are used as filter elements, they behaves as resonators and therefore, can have short-circuit or open-circuit terminations. Coupled lines are generally used in planar structures, where they can be easily implemented. Parallel-coupled lines is a popular technique for printed boards suitable for the implementation of open circuited lines. The design consists of an array of $\lambda/2$ resonators oriented parallelly, but coupling occurs to only $\lambda/4$ to each of the adjacent resonators. Wider fractional bandwidths are possible in this filter than with the help of capacitive gap filter, but they do suffer from spurious response at frequency twice the central frequency

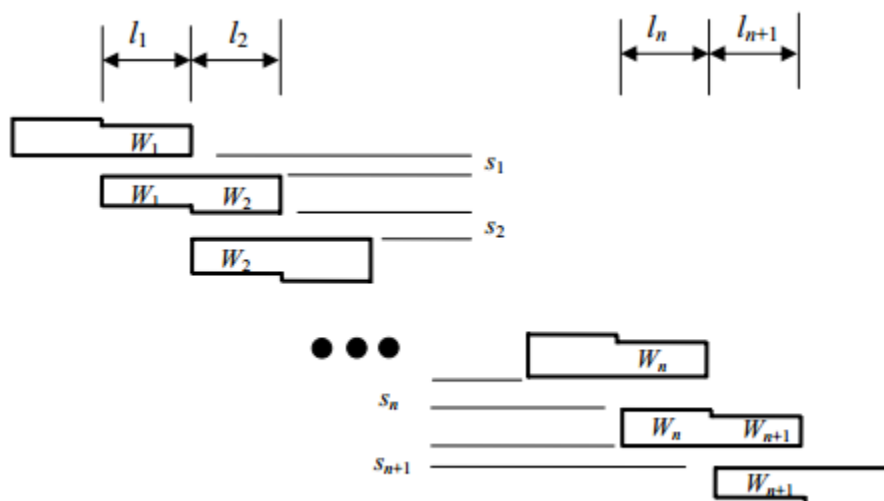


Figure 4.2: Parallel coupled line[2]

Parallel Coupled lines support two modes of excitation : Even mode and odd mode.

a) Even mode: In even mode, both the coupled lines in microstrip possesses same potential leads to a magnetic wall at the symmetry boundary as demonstrated in figure 4.3

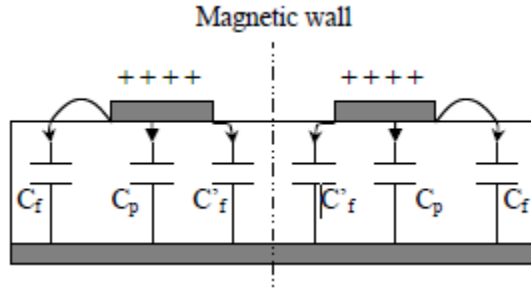


Figure 4.3: Even Mode excitation of Microstrip Coupled Lines

$$\text{Even mode capacitance : } C_e = C_p + C_f + C_f' \quad 4.1$$

where C_p is the capacitance between the microstrip line and the ground plate given by:

$$C_p = \epsilon_r \epsilon_0 \frac{W}{h} \quad 4.2$$

C_f is the fringe capacitance and C_f' is the modified fringe capacitance given by :

$$C_f = \frac{\sqrt{\epsilon_r}}{C.Z_c} C_p \quad 4.3$$

$$C_f' = \frac{C_f}{1 + A \frac{h}{z} + \tanh \frac{8s}{hs}} \quad 4.4$$

Where $A = \exp [-0.1 \exp (2.33 - 2.53 \frac{W}{h})]$

The even mode characteristic impedance can also be expressed as:

$$Z_c^e = c \sqrt{C_e C_e^a}^{-1} \quad 4.5$$

Where, c is the speed of light, C_e^a is the even mode capacitance with air as dielectric. The effective dielectric constant for even mode is expressed as:

$$\epsilon_{re}^e = \frac{C_e}{C_e^a} \quad 4.6$$

b) Odd mode : In odd mode excitation, the coupled line have the opposite potential which results into a electric wall at the symmetry boundary as demonstrated in figure 4.4.

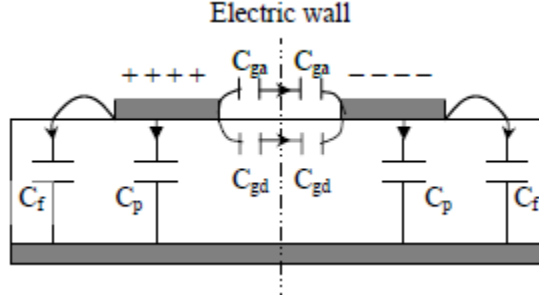


Figure 4.4: odd mode excitation of coupled line

The odd mode capacitance is given by:

$$C_o = C_p + C_f + C_{gd} + C_{ga} \quad 4.7$$

C_{gd} and C_{ga} represent fringe capacitance over the dielectric and between the two microstrip lines over the air expressed as:

$$C_{ga} = \epsilon_o \frac{K(k')}{K(k)} \quad 4.8$$

Where , $k = \frac{\frac{s}{h}}{\frac{s}{h} + \frac{2w}{h}}$; $k' = \sqrt{1 - k^2}$

The even mode characteristic impedance can also be expressed as:

$$Z_c^o = c\sqrt{C_o C_o^a}^{-1} \quad 4.9$$

Where, c is the speed of light, C_o^a is the odd mode capacitance with air as dielectric. The effective dielectric constant for odd mode is expressed as:

$$\epsilon_{re}^o = \frac{C_o}{C_o^a}$$

4.10

4.4. Calculation of Even and odd mode characteristic impedance

This section describes the mathematical calculation for finding the even and odd mode characteristic impedance to be used in designing of parallel coupled microstrip bandpass filter. A network representation with cascaded two-port subnetworks and 50Ω input and output terminations is shown in Fig.4.5(a). The next step is to replace each coupled-line section with its equivalent circuit using J inverter. The resultant circuit contains J -inverters and half wavelength ($\lambda/2$) resonators as shown in fig. 4.5(b).

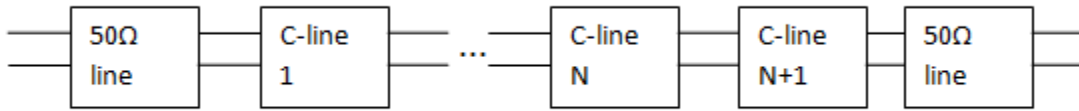


Figure 4.5(a): Network representation with cascaded sub networks and 50Ω terminations

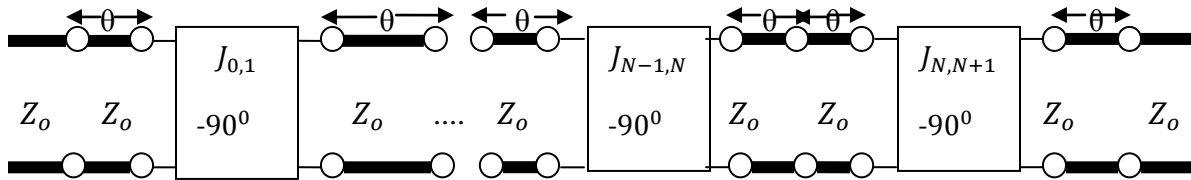


Figure 4.5(b): Equivalent circuit using J inverter.

A single coupled-line section as shown in from Fig. 4.6 can be approximately illustrated by its equivalent circuit demonstrated in Fig. 4.7. It is done by calculating the $ABCD$ matrix of the coupled-line section and showing that it is equal to the $ABCD$ matrix of its equivalent circuit for $\theta=\pi/2$

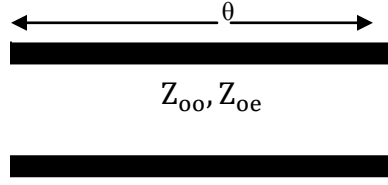


Figure 4.6 Single Coupled line section

4.4.1 The ABCD Matrix of Single Coupled Line Section

z-parameters for a section depicted in Fig. 4.6 are

$$\begin{bmatrix} Z_{11} & Z_{14} \\ Z_{41} & Z_{44} \end{bmatrix} = \begin{bmatrix} \frac{-j}{2}(Z_{oo} + Z_{oe})\cot\theta & \frac{-j}{2}(Z_{oo} + Z_{oe})\csc\theta \\ \frac{-j}{2}(Z_{oo} + Z_{oe})\csc\theta & \frac{-j}{2}(Z_{oo} + Z_{oe})\cot\theta \end{bmatrix} \quad 4.11$$

where Z_{oo} and Z_{oe} are the odd and even impedance respectively. From the above Z matrix, ABCD matrix can be computed as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \frac{Z_{oe}+Z_{oo}}{Z_{oe}-Z_{oo}} \cdot \cos\theta & \frac{(Z_{oe}+Z_{oo})^2 \cdot \cos^2\theta - (Z_{oe}-Z_{oo})^2}{2j \cdot (Z_{oe}-Z_{oo}) \cdot \sin\theta} \\ 2 \frac{j}{Z_{oe}-Z_{oo}} \sin\theta & \frac{Z_{oe}+Z_{oo}}{Z_{oe}-Z_{oo}} \cdot \cos\theta \end{bmatrix} \quad 4.12$$

4.4.2. The ABCD Matrix of the Resultant Circuit

The ABCD matrix of the equivalent circuit for a coupled line as presented in figure 3.4 can be computed by using ABCD matrix of transmission line of electrical length, θ and ABCD matrix obtained using J inverter as given below:

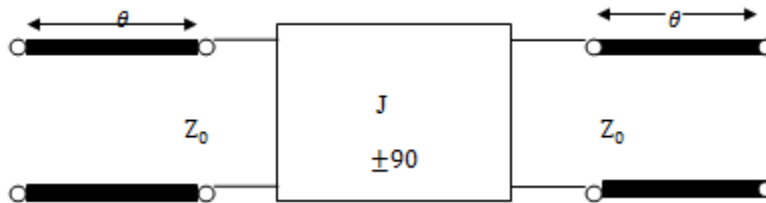


Figure 4.7: Equivalent circuit of the coupled line section

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = ABCD_{\theta} \cdot ABCD_J \cdot ABCD_{\theta} =$$

$$\begin{bmatrix} \left(J \cdot Z_0 + \frac{1}{J \cdot Z_0} \right) \cdot \sin\theta \cdot \cos\theta & j \cdot \left(J \cdot Z_0^2 \cdot \sin^2\theta - \frac{1}{J} \cdot \cos^2\theta \right) \\ j \cdot \left(\frac{1}{J \cdot Z_0^2} \cdot \sin^2\theta - J \cdot \cos^2\theta \right) & \left(J \cdot Z_0 + \frac{1}{J \cdot Z_0} \right) \cdot \sin\theta \cdot \cos\theta \end{bmatrix} \quad 4.13$$

4.4.3. Even- and Odd-mode Characteristic Impedances

Even and odd mode impedances can be obtained by equating equation 4.8 and 4.9 which gives two sets of equations as shown below:

$$\frac{Z_{oe} + Z_{oo}}{Z_{oe} - Z_{oo}} = \left(J \cdot Z_0 + \frac{1}{J \cdot Z_0} \right) \cdot \sin\theta \quad 4.14$$

$$2 \frac{j}{Z_{oe} - Z_{oo}} \sin\theta = j \cdot \left(\frac{1}{J \cdot Z_0^2} \cdot \sin^2\theta - J \cdot \cos^2\theta \right) \quad 4.15$$

By solving equations (4.10) and (4.11) at $\theta = \pi/2$, the even and odd mode impedances obtained are as follows:

$$Z_{oe} = \left(1 + J \cdot Z_0 + J^2 \cdot Z_0^2 \right) \text{ ----- even mode impedance} \quad 4.16$$

$$Z_{oo} = \left(1 - J \cdot Z_0 + J^2 \cdot Z_0^2 \right) \text{ ----- odd mode impedance} \quad 4.17$$

For conversion from lowpass to bandpass using J inverter, following equations are used:

$$J_{01} / Y_0 = \sqrt{\pi \text{FBW} / 2g_0g_1} \quad 4.18$$

$$J_{N,N+1} / Y_0 = \sqrt{\pi \text{FBW} / 2g_Ng_{N+1}} \quad 4.19$$

$$J_{j,j+1} / Y_0 = \frac{\pi \text{FBW}}{2\sqrt{g_jg_{j+1}}} \quad , \text{ for } j=1 \text{ to } N-1 \quad 4.20$$

Where FBW is the fractional bandwidth and g_0, g_1, \dots, g_N are the element values of lowpass prototype. The fractional bandwidth of bandpass filter is expressed as $\frac{w_2 - w_1}{w_0}$, w_0 is the resonant frequency and $w_2 - w_1$ is the Bandwidth. J_0, J_1, \dots, J_N are the characteristic impedance of J inverter and Y_0 is the characteristic impedance of the termination.

Chapter 5

Designing and Simulation

5.1 INTRODUCTION

This chapter deals with the designing of the parallel coupled microstrip bandpass filter at 2.4 GHz. The simulation is done using ADS 2011 software followed by optimization and tuning to get desired response and then fabricated on FR-4 substrate.

5.2 Design methodology

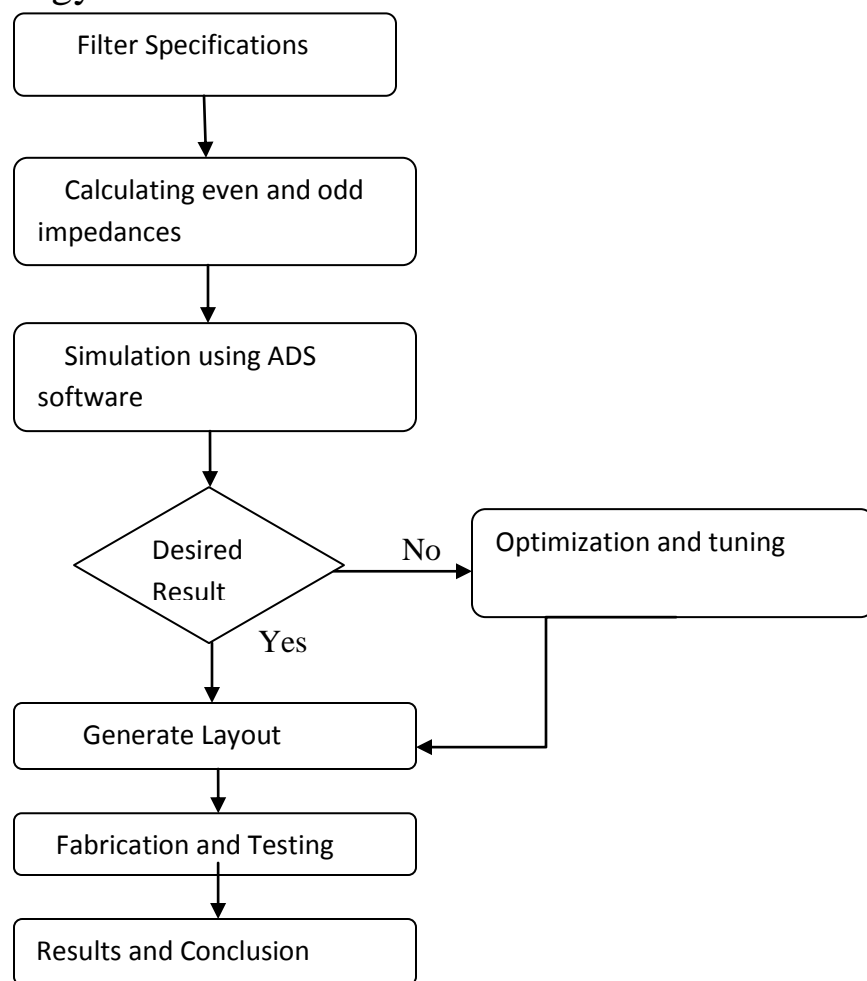


Figure 5.1: Flowchart representing the Design methodology

5.2 Filter Specification

The parallel coupled microstrip bandpass filter designed has the following specifications:

Filter Type	Chebyshev
Centre frequency	2.4GHz
Bandwidth	0.24GHz
Ripple	0.1 dB
The order of the filter	6
Source impedance	50Ω
Load impedance	50Ω
Return loss	>16 dB
Insertion loss	<1 dB
Implementation	Microstrip(FR-4)
Relative permittivity of substrate(ϵ_r)	4.2
Height of substrate(h)	1.5 mm

Table 5.1: Filter specifications

5.3 Filter Design

5.3.1 Calculation of even-odd impedances

The first step in the designing process starts with computing the low pass prototype values. The element values with ripple 0.1 dB can be found out from the table below:

Order	C1	L2	C3	L4	C5	L6	C7	L8
2	0.8431	0.6220	.07378					
3	1.0316	1.1474	1.0316					
4	1.1088	1.3062	1.7704	0.8181	0.7378			
5	1.1468	1.3712	1.9750	1.3712	1.1468			
6	1.1681	1.4040	2.0562	1.5171	1.9029	0.8618	.07378	

Table 5.2: Low pass filter elemental values for 0.1dB ripple

When attenuation(L_{AS}) is greater or equal to 40dB and passband ripple is 0.1dB for chebyshev response, return loss is found to be -16.42dB from equation(5.1) and the order of the filter can be determined from equation(5.2) which is found to be 5.45 or approximately 6.

$$L_{Ar} = -10 \log(1 - 10^{0.1L_r}) \text{ dB} \quad 5.1$$

where, L_r is the ripple.

$$n \geq \frac{\cosh^{-1} \sqrt{\frac{10^{0.1L_{AS}-1}}{10^{0.1L_r-1}}}}{\cosh^{-1} \Omega} \quad 5.2$$

From above equation, the filter order is found to be 6, taking element values from table 5.2, it can be summarized the element value for order 6 as:

$$g_0 = g_6 = 1, g_1 = g_5 = 1.1468, g_2 = g_4 = 1.3712 \text{ and } g_3 = 1.9750$$

Using equations as derived in chapter 4, the even and odd characteristic impedance can be calculated and are registered in the table given below:

For instance, even and odd impedance for coupled line 1 and 6 is calculated in the following method:

$$Z_0 J_{0,1} = \sqrt{\frac{22/7 \times 10}{2 \times 1 \times 1.1468}} = 0.3701 = Z_0 J_{5,6}$$

$$\text{For odd mode characteristic impedance, } Z_{0o} = 50[1 - 0.3701 + 0.3701^2] = 38.3437 \Omega$$

$$\text{For even mode characteristic impedance, } Z_{0e} = 50[1 + 0.3701 + 0.3701^2] = 75.3537 \Omega$$

Even and odd impedance for coupled 2 and 5

$$Z_0 J_{1,2} = \frac{22/7 \times 10}{2} \sqrt{\frac{1}{1.1468 \times 1.3712}} = 0.1253 = Z_0 J_{4,5}$$

$$\text{For odd mode characteristic impedance, } Z_{0o} = 50[1 - 0.1253 + 0.1253^2] = 44.5214 \Omega$$

For even mode characteristic impedance, $Z_{0e} = 50[1+0.1253+0.1253^2] = 57.0477\Omega$

Even and odd impedance for coupled 3 and 4,

$$Z_0 J_{2,3} = \frac{22/7 \times 10}{2} \sqrt{\frac{1}{1.3712 \times 1.9750}} = 0.0955 = Z_0 J_{3,4}$$

For odd mode characteristic impedance, $Z_{0o} = 50[1-0.0955 +0.0955^2] = 45.6829 \Omega$

For even mode characteristic impedance, $Z_{0e} = 50[1+0.0955+0.0955^2] = 55.2282\Omega$

J Inverter	$Z_0 J_{N,N+1}$	Odd impedance(Z_{0o})	Even impedance (Z_{0e})
0,1	0.3701	38.3437	75.3537
1,2	0.1253	44.5214	57.0477
2,3	0.0955	45.6829	55.2282
3,4	0.0955	45.6829	55.2282
4,5	0.1253	44.5214	57.0477
5,6	0.3701	38.3437	75.3537

Table 5.3: Odd and even characteristic impedances of coupled lines

Using ADS 2011 software, from the table 5.3, the width (W), spacing(S) between the coupled lines and the length of each coupled lines are calculated using lincalc tool in ADS as tabulated in the table 5.4:

Coupled line	Width(mm)	Spacing(mm)	Length (mm)
1 & 6	2.120290	0.338760	18.050600
2 & 5	2.804530	1.587790	17.533600
3 & 4	2.850420	2.094830	17.488000

Table 5.4: Dimensions of Parallel Coupled Lines

These dimensions are then put into schematic along with the simulation tool and the substrate specifications. The schematic of the design along with the dimensions for each coupled line is given in figure 5.2 and upon simulation, the results so obtained are in figure 5.3.

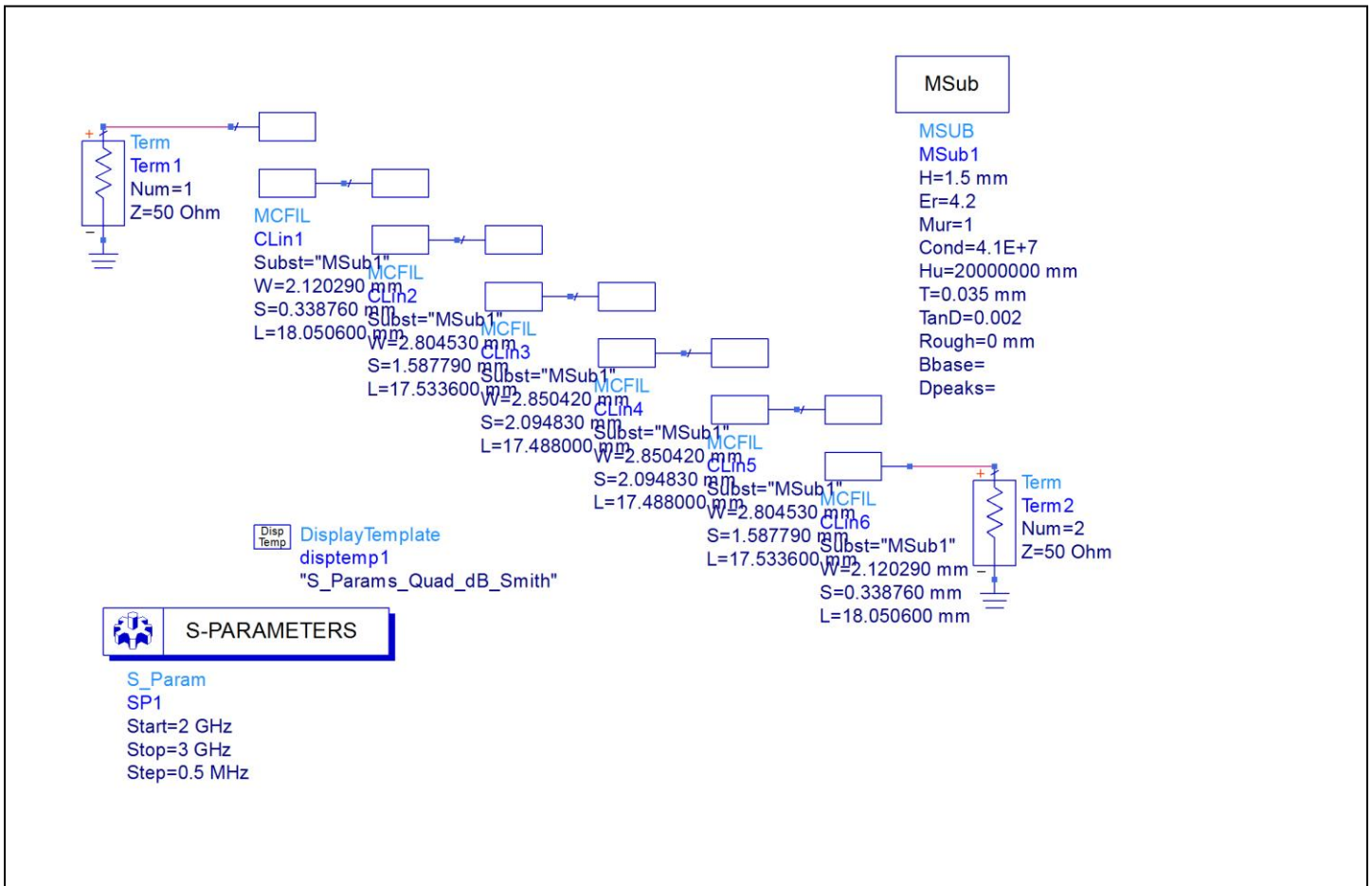


Figure 5.2: Schematic diagram of parallel coupled bandpass filter

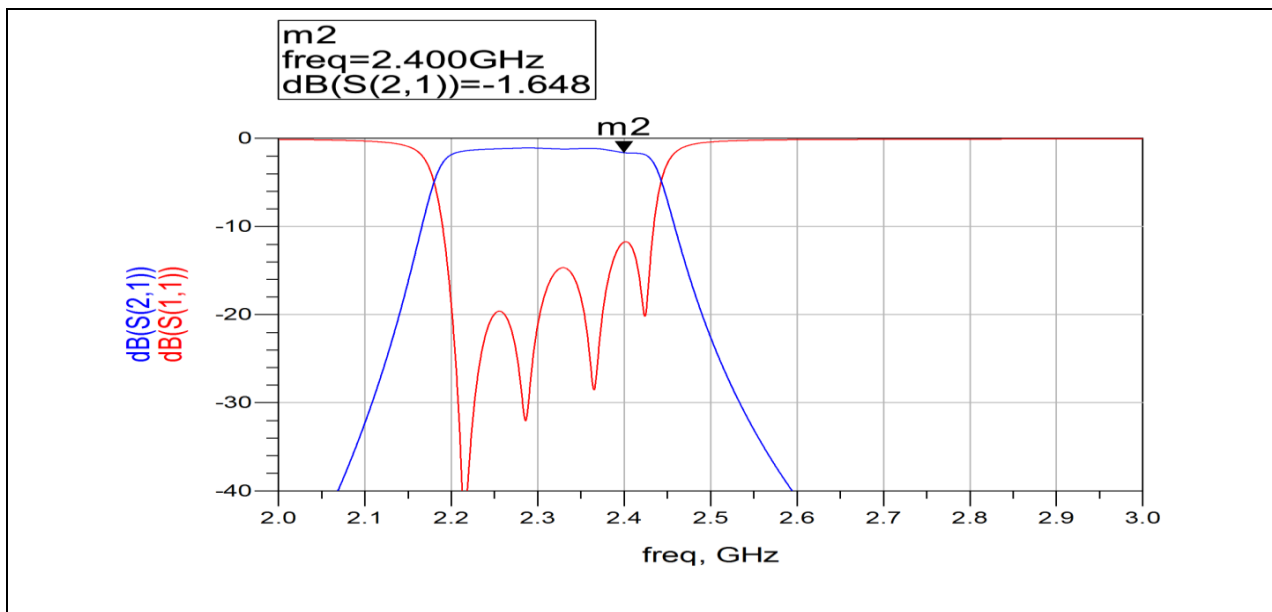


Figure 5.3: Results obtained from the schematic diagram

From above figure, it is evident that the response is not at 2.4 GHz which is the requirement, and also the insertion loss at 2.4GHz is found to be greater than 1dB, therefore, to get the desired response optimization is done.

5.3.2 Optimization and Tuning

Optimization in ADS occurs in 3 steps :

- a. Optimization Goals are set
- b. Optimization controller is placed and type of optimizer and number of iterations are chosen.
- c. Select component values to be optimized.

As shown in figure 5.4, two goals are used to define the required insertion losses and return losses and also center frequency. Three variables (VAR) are used for putting W1, S1, and L1 for coupled line one and since, the structure is symmetrical $W1=W6, S1=S6, L1=L6$ and similarly, other two variables are defined. The centre frequency is found to be 2.4 GHz and the insertion loss is about 1dB.

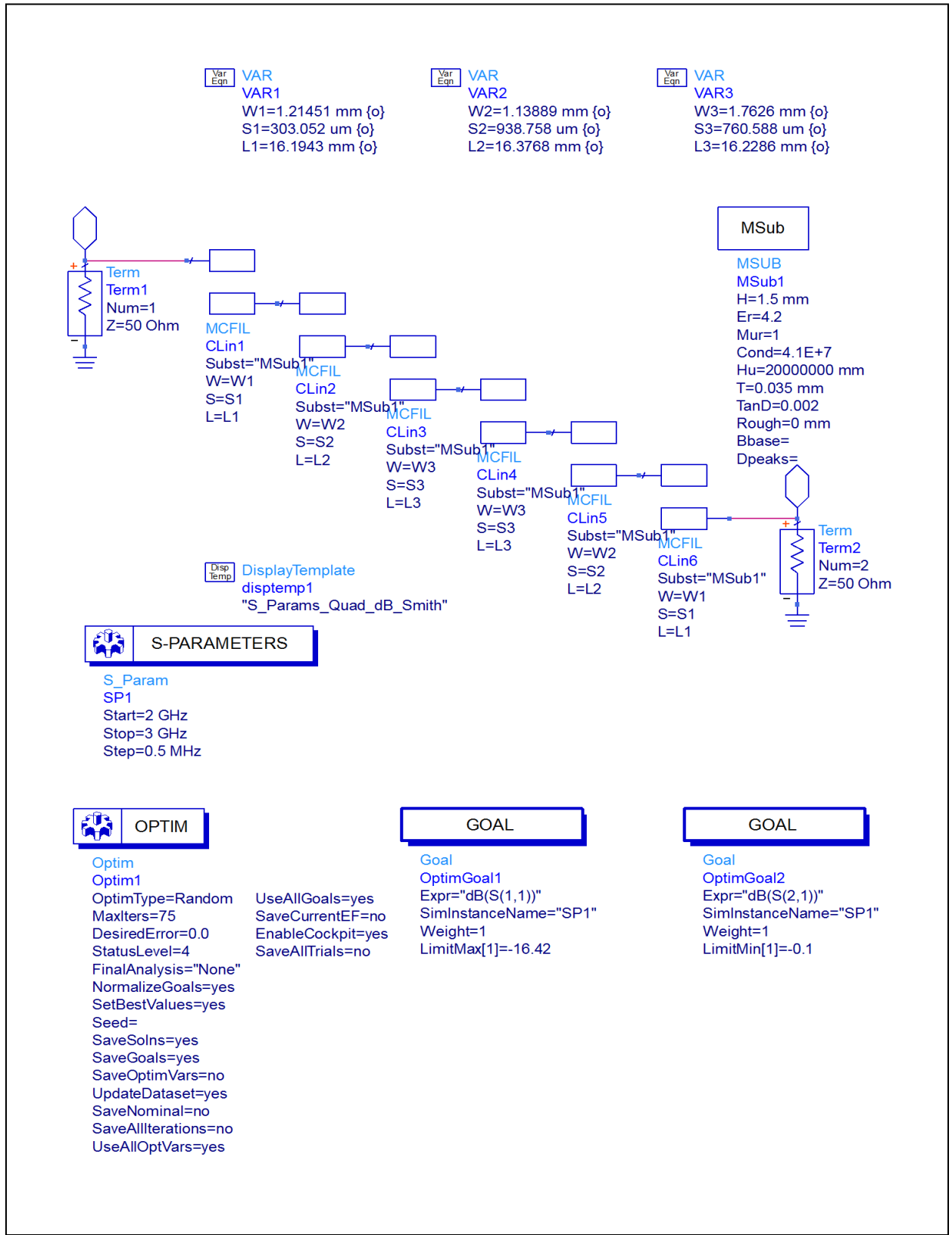


Figure 5.4: Schematic diagram for optimization

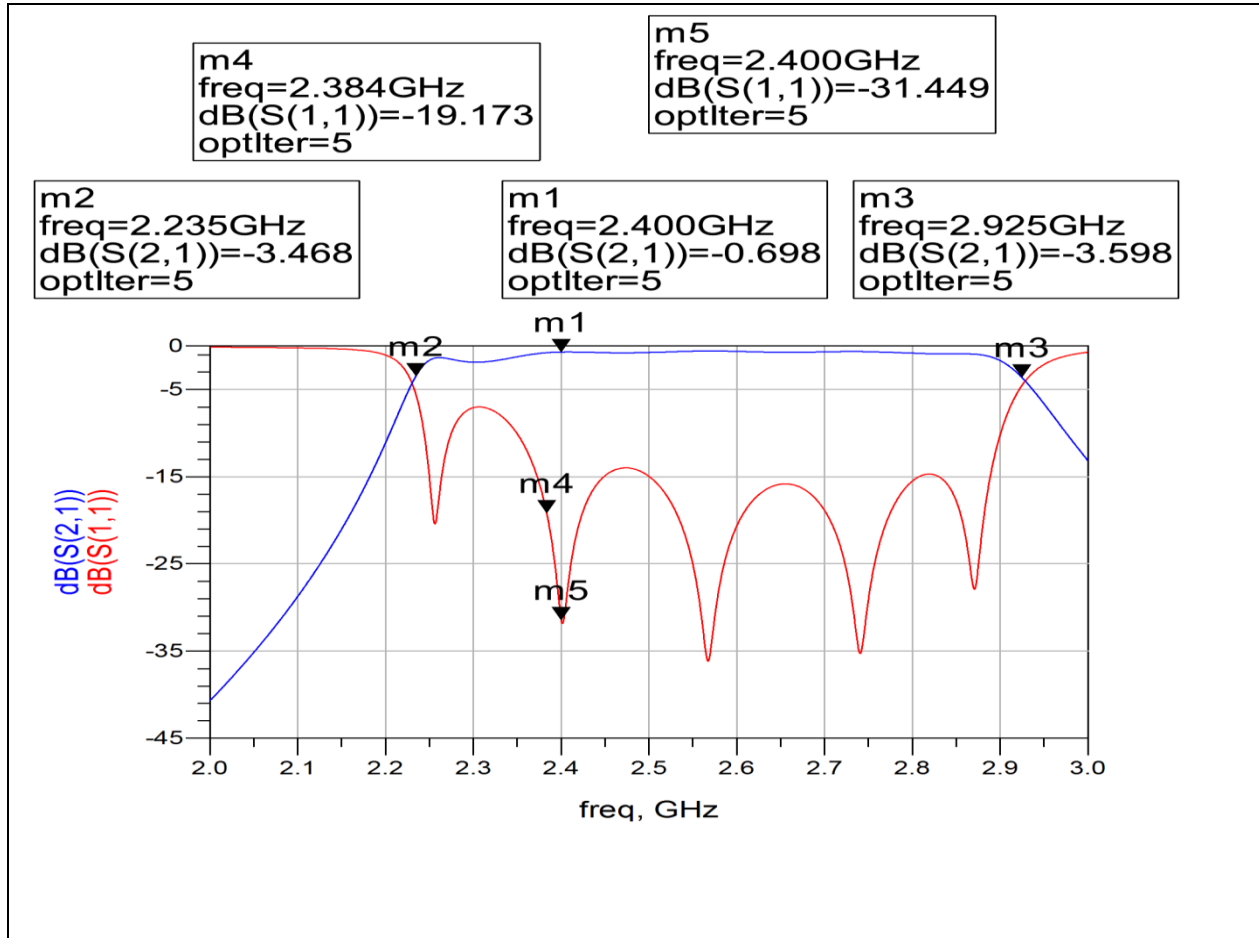


Figure 5.5: Results obtained after optimization

From above figures in 5.4 and 5.5, the response is at 2.4 GHz and also the insertion loss is less than 1dB which is 0.698dB and return loss obtained is found to be 19.173dB at frequency 2.38GHz. The dimensions of the coupled lines obtained after optimization are registered in a tabular form as mentioned below:

Coupled line	Width(mm)	Spacing(μm)	Length (mm)
1 & 6	1.21451	303.052	16.1943
2 & 5	1.13889	938.758	16.3768
3 & 4	1.7626	760.588	16.2286

Table 5.5: Dimensions of the coupled lines after optimization

But on generating the layout for this design after optimization, the insertion loss is again found to be greater than 1dB as shown in figure 5.6.

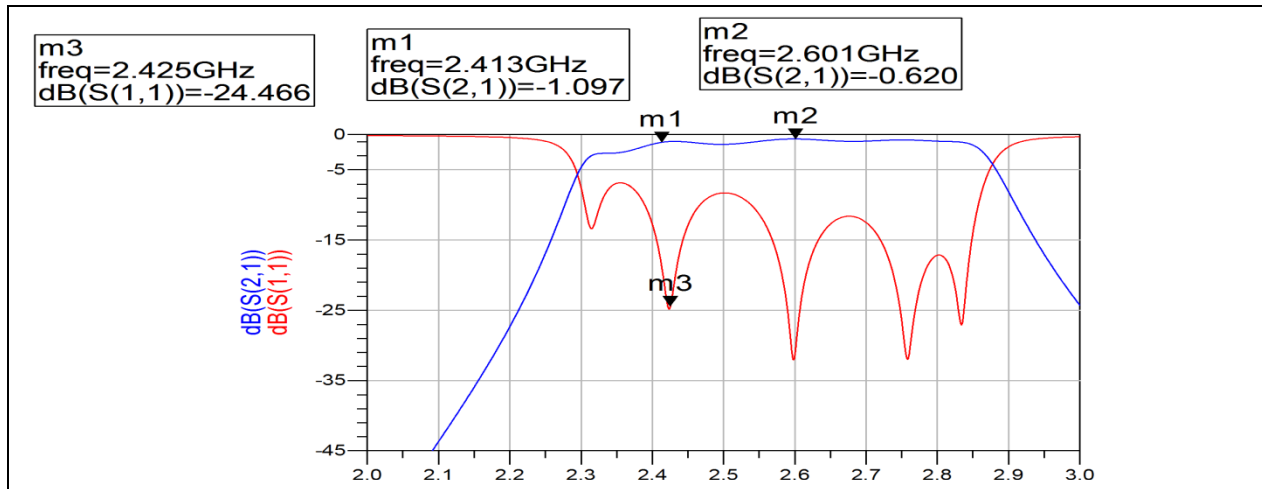


Figure 5.6: Layout result after optimization

To make the insertion loss as per the requirement, a slight tuning is done at coupled line 1. Tuning is a method by which the component values can be changed and the impact of the change can be seen on circuit performance. It is a manual method of achieving the desired performance for a circuit which works better in certain cases. The schematic after tuning is shown in figure along with the results obtained after tuning as in figure 5.7 and 5.8 respectively.

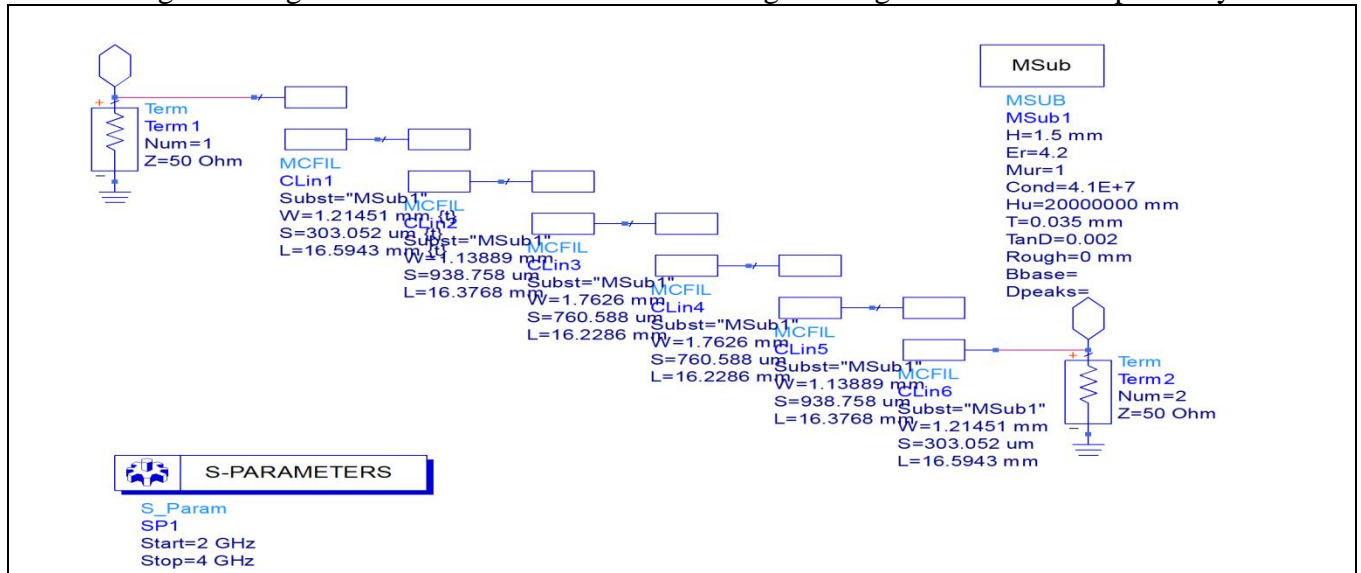


Figure 5.7: Schematic diagram after tuning

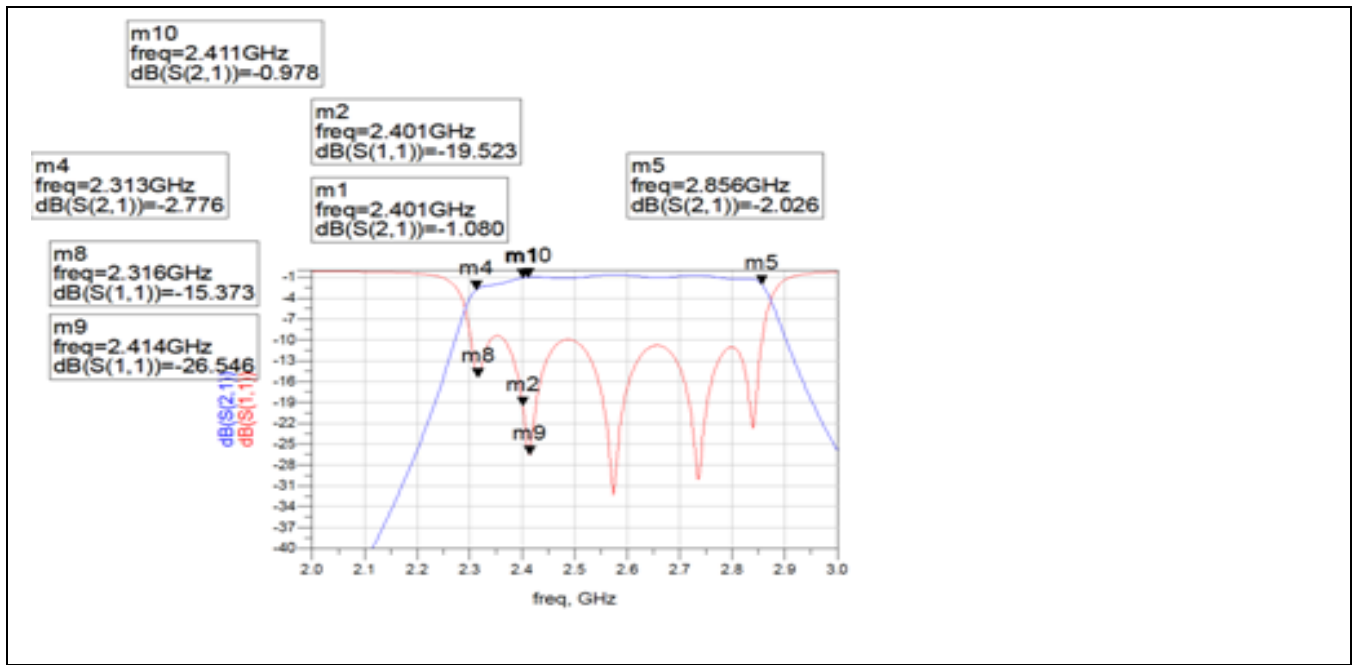


Figure 5.8: Results after tuning

Dimensions of the coupled lines after tuning are recorded in a tabular form as shown below:

Coupled line	Width(mm)	Spacing(μm)	Length (mm)
1 & 6	1.21451	303.052	16.5943
2 & 5	1.13889	938.758	16.3768
3 & 4	1.7626	760.588	16.2286

Table 5.6: Dimensions of the coupled lines after tuning

After tuning the insertion loss is found to be 1.080dB at 2.4GHz but at 2.41GHz its value is 0.978 which is less than 1 dB. Also, the return loss is found to be greater than 16.42dB. After getting the desired results, 50 Ω transmission lines are connected at the input and output port as shown in figure in figure 5.9. The final dimensions of the coupled lines along with the dimensions of transmission lines are mentioned in the table below:

Coupled line	Width(mm)	Spacing(μm)	Length (mm)
1 & 6	1.21451	303.052	16.5943
2 & 5	1.13889	938.758	16.3768
3 & 4	1.7626	760.588	16.2286
50 Ω line	2.92880	-	17.411900
50 Ω line	2.92880		17.411900

Table 5.7: Dimensions of coupled lines and 50 Ω line

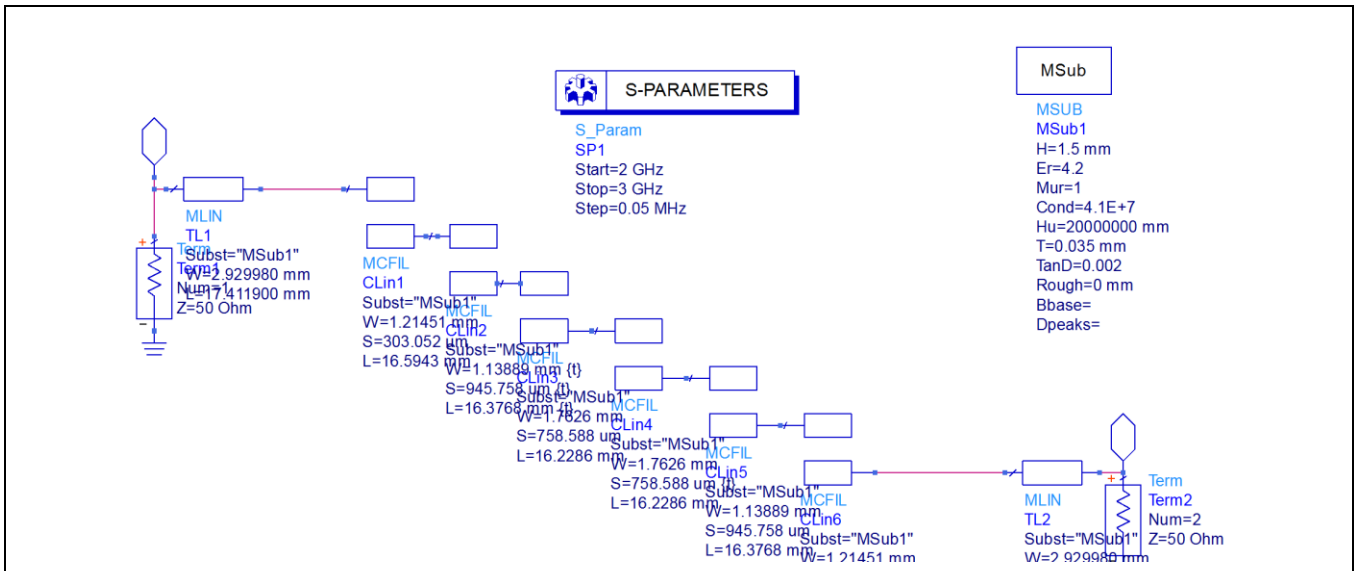


Figure 5.9: Schematic diagram of the final design

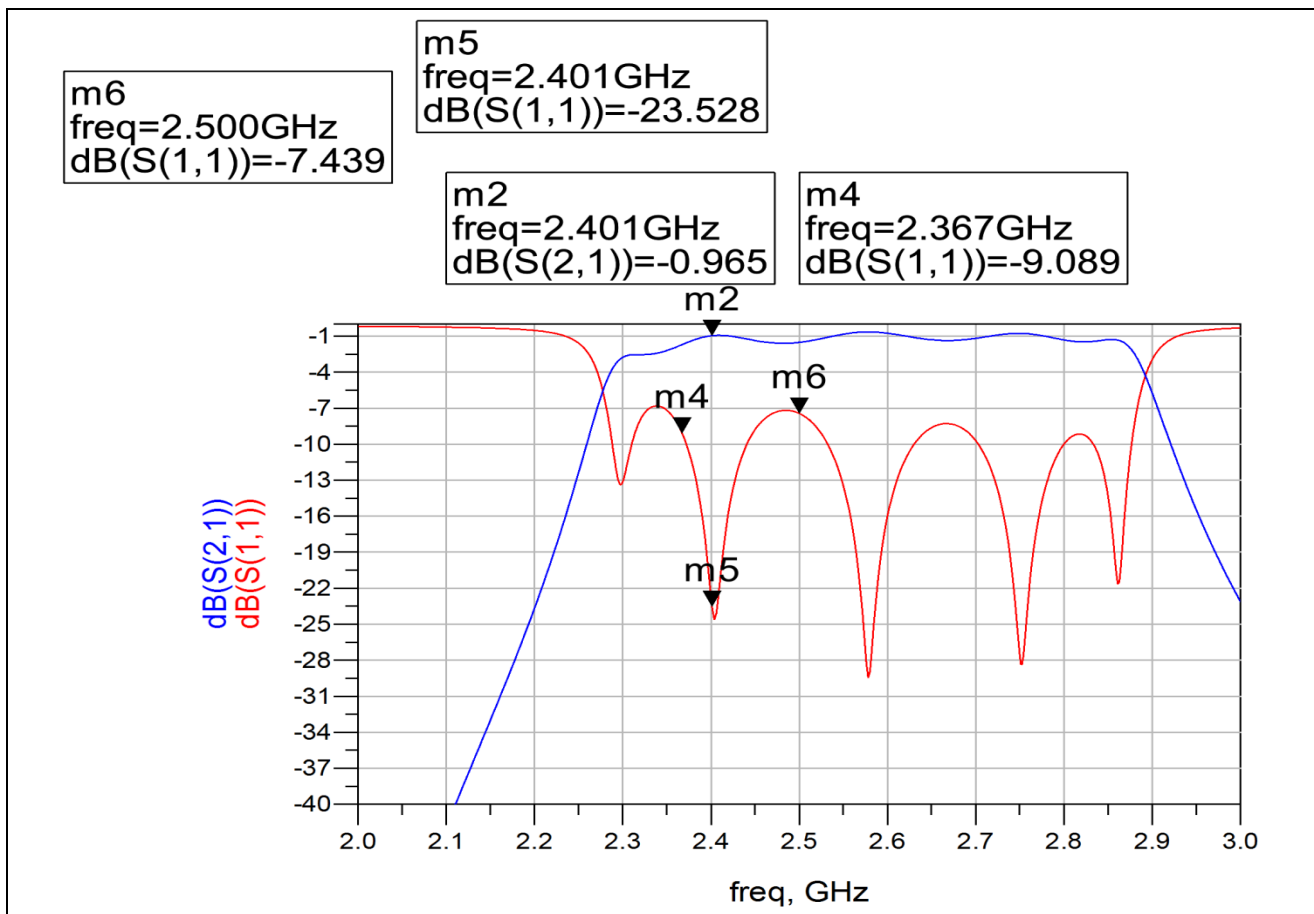


Figure 5.10: Results of the final design

5.3.3 Substrate definition

A substrate in EM simulation describes the medium where a circuit exists. To demonstrate the proposed design methodology, the microwave bandpass filter is simulated using microstrip line build on a FR-4 substrate having thickness of 1.5 mm and dielectric constant of $\epsilon = 4.2$. The figure 5.11 shows substrate for microstrip in Agilent ADS software.

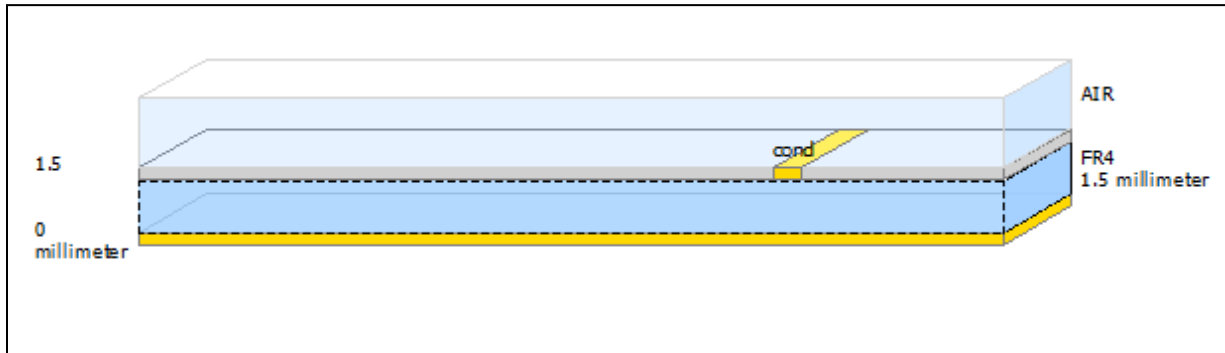


Figure 5.11: Substrate definition in ADS

5.3.4 Layout of Bandpass filter in ADS

Based on the schematic diagram (section 5.2.1) the layout for differentiator is generated in Agilent ADS. For characterization of designed differentiator meshing is performed and analysis is done in Momentum Microwave.

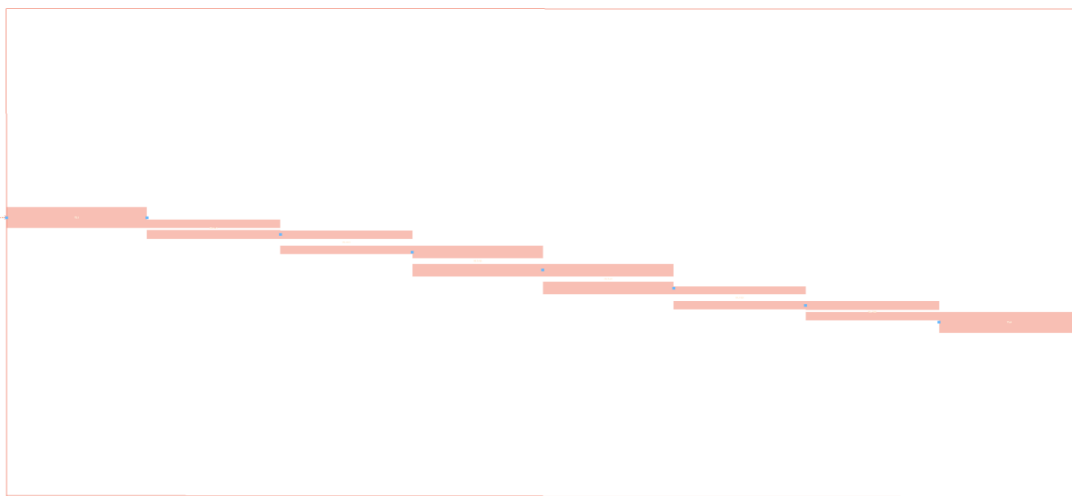


Figure 5.12: Layout of the designed Bandpass filter

Momentum Microwave simulation is used to produce S-parameter for layout-based designs. Momentum is based on Maxwell's equations which includes information about substrate and space wave radiation effects. This simulation includes these physical effects:

- Quasi-static capacitance
- Quasi-static inductance
- conductor loss
- substrate loss
- Dielectric loss
- Skin effect loss

The Momentum mode generate rectangular and triangular cells in the mesh to generate a set of S-parameters for a circuit.

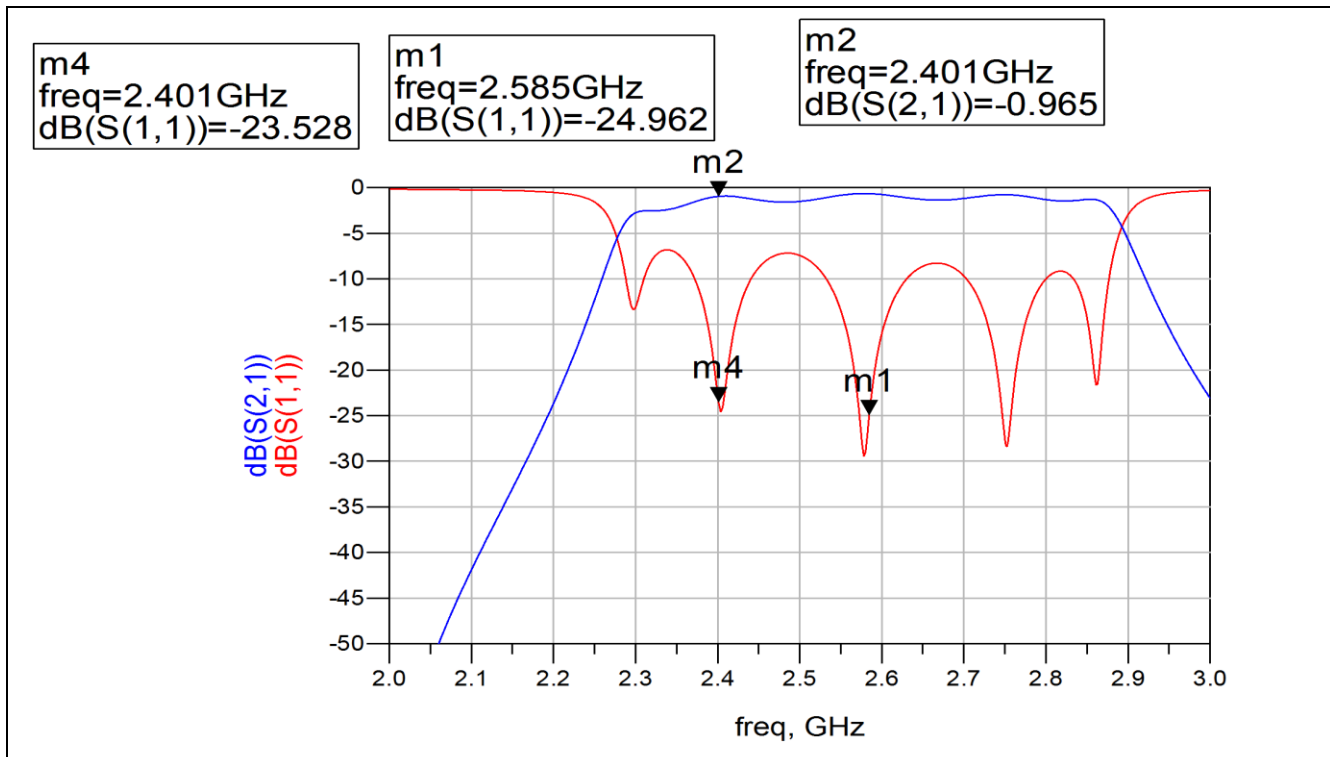


Figure 5.13: Layout Result

The final design meets the required specification of having insertion loss about 1 dB and return loss as 23.528dB (>16dB) and provides the 3dB bandwidth of approx 600MHz.

Chapter 6

6.1 Stimulated Results

A sixth order microstrip bandpass filter using parallel coupled lines with 10% fractional bandwidth and 0.24GHz bandwidth has been implemented. The substrate used is FR-4 with a dielectric constant of 4.2 and thickness 0.035 mm. The simulated results are shown in figure 5.10 with the layout results in figure 5.13 which shows the insertion loss of about 1 dB and return loss greater than 16dB. The bandpass filter fabricated is shown in figure 6.1.



Figure 6.1 :Fabricated Bandpass Filter

6.2 Measured Results

Performance of the Filter is tested using R&S Scalar Network Analyzer ZLV13, which is 13 GHz network Analyzer. Figure 6.2 shows the test set up. Transmission measurements were carried out using S12/S21 set up and Reflection/Return Loss measurements were carried out with S11 and S22 set up. The fabricated bandpass filter is tested using Network Analyzer as shown in figure 6.3.

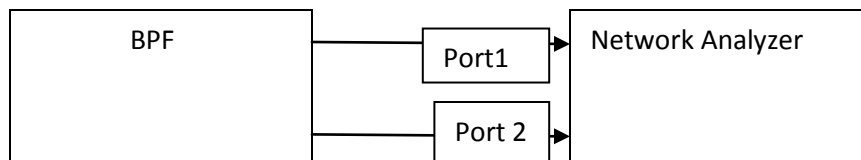


Figure 6.2: Test Set up

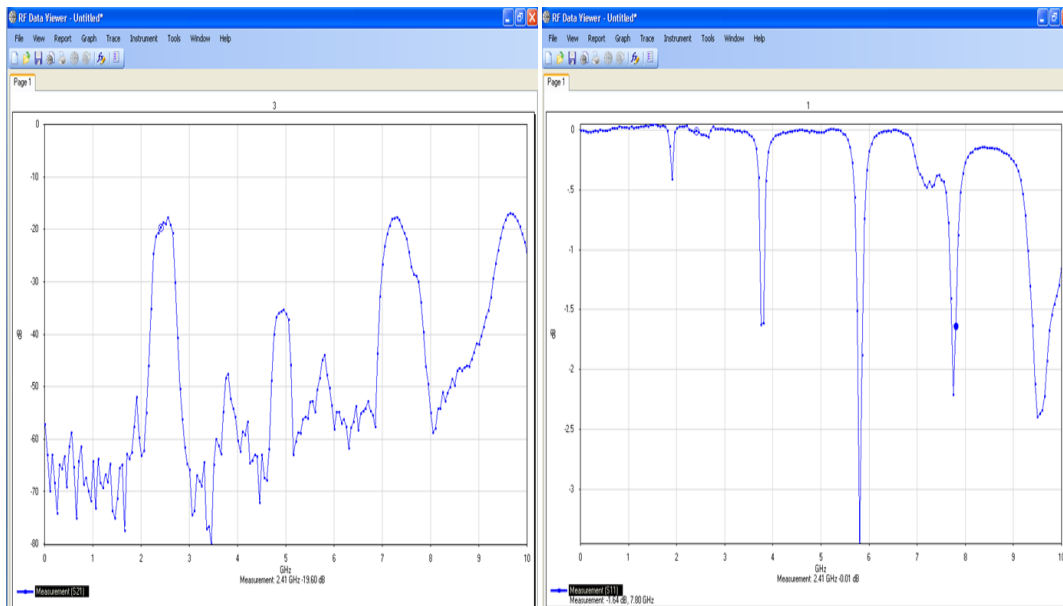


Figure 6.2: Testing Results

It can be seen from the test results that insertion loss figures are not exactly matching the simulated test results. This may be due to Fabrication anomalies/mistakes. FR4 material losses and dielectric unevenness's may also be the reasons for higher insertion loss. It is definitely possible to achieve better results using Teflon Board instead of FR4.

Chapter 7

Conclusions

7.1 Conclusion

A bandpass filter is designed at 2.4GHz using microstrip parallel coupled resonator. It is found that Parallel coupled resonators BPFs are small in size and can be easily fabricated due to absence of short circuits. However, the response of the parallel coupled resonator is sensitive to width and spacing between the lines which may also cause parallel coupled lines to suffer from second harmonic spurious response which can be overcome by using substrate suspension, stepped impedance resonator, stubs etc. As a result, if the implementation process during PCB processing can be controlled, a good bandpass filter can be realized.

7.2 Future work

1. Selectivity of the parallel coupled resonator BPFs can be improved without increasing the filter order by using stub adding techniques.
2. More compactness in the designing of BPFs can be achieved by introducing lumped capacitors to the coupled line sections.
3. Suppression of the second spurious response in microstrip bandpass filter designed by parallel coupled resonator technique can be obtained by uniting stepped impedance lines and open loop resonators.

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