DESIGN OF DUAL BANDPASS FILTER USING PARALLEL COUPLED LINES

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MASTERS OF TECHNOLOGY

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

By

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Declaration By The Scholar

I hereby declare that the work reported in the M.Tech dissertation entitled "**DESIGN OF DUAL BANDPASS FILTER USING PARALLEL COUPLED LINES**" submitted at **Jaypee University of Information Technology, Waknaghat India**, is an authentic record of my work carried out under the guidance of **Dr. Salman Raju Talluri**. I have not submitted this work elsewhere for any other degree or diploma.

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Supervisor's Certificate

This is to certify that the work reported in the M.Tech dissertation entitled "**DESIGN OF DUAL-BANDPASS FILTER USING PARALLEL COUPLED LINES**" submitted by **Neelam Kumari** at **Jaypee University of Information Technology, Waknaghat, India,** is a bonafide record of her original work carried out under my supervision. This work has not been submitted elsewhere for any other degree or diploma.

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Date: Neelam Kumari

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Abstract

In this report two techniques are used to design dual bandpass filter. First technique is based on the frequency transformations of prototype lowpass filter to the desired bandpass and band reject filters and arranging them in series and shunt configurations in such away to meet the desired specifications. Different possible combinations have been considered and presented the best possible configuration to validate this new design. Emphasis is given for dual bandpass filter while this can be extended to multi bandpass filters. The design of dual bandpass with different orders is presented in this paper for maximally flat and equal ripple filters.

In second technique the behavior of single port coupled line is analyzed using different configurations. Using single port coupled line different resonant frequency filters is obtained. A conventional four port parallel coupled lines on microstrip has ten canonical forms. Of these ten forms, two port parallel coupled lines are used in the design of bandpass filters. From the frequency characteristics of this single port parallel coupled line in open and short circuit configurations, the design of dual bandpass filter is proposed by connecting this single port network in the shunt configuration for the conventional bandpass filter at the mid points. After this hairpin coupled line filter is analyzed based on different structure and dual bandpass filter is obtained with shunt coupled lines connected in between hairpin lines.

CHAPTER 1

INTRODUCTION

In microwave frequency region, power is considered in terms of electric and magnetic fields that are transformed or directed from one point to other point. The physical structure that guide the electromagnetic fields in particular direction is called as the transmission line. Transmission line can be used at low frequency as well as at high frequency.

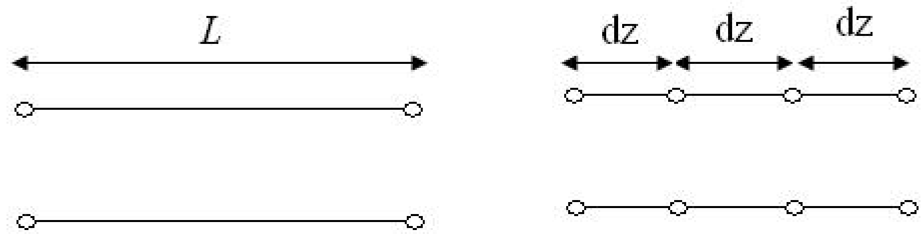


Figure 1.0.1. Design of two wire transmission lines

The simplest transmission line is shown in Figure 1.0.1 is two wire transmission line. To analyze the behavior of the transmission line, it is partitioned into sections. Each section of the transmission line is described by the lumped elements as shown in Figure 1.0.2.

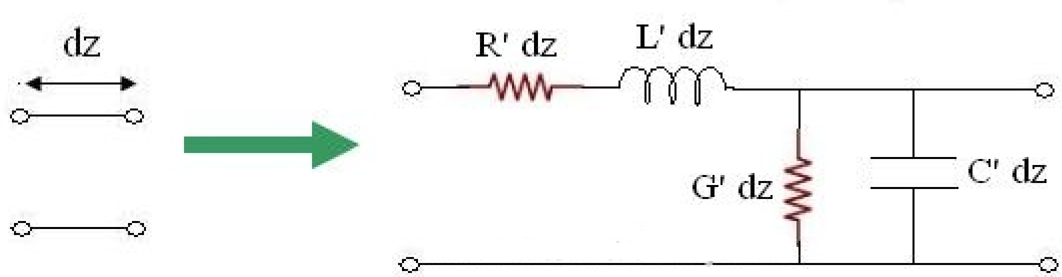


Figure 1.0.2. Equivalent lumped structure of one section of transmission line

The parameters mentioned in the lumped structure are:

R' : Resistance per unit length.

L' : Inductance per unit length.

G' : Conductance per unit length.

C' : Capacitance per unit length.

Other types of transmission lines are coaxial cable, microstrip line and stripline. In this report microstrip transmission line is used. The simple coupled microstrip transmission line [**1**] is shown in Figure 1.0.3. When two transmission lines are placed close so that power can be coupled from one line to the other due to the interaction of the electromagnetic fields. Such lines are called as coupled transmission lines.

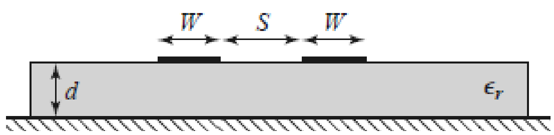


FIGURE 1.0.3. Coupled microstrip transmission line

The coupled line shown in Figure 1.0.3 is symmetrical. Symmetrical means that the two conducting strips have the same width and position relative to ground. A parallel coupled line on microstrip is realized by placing two high impedance transmission lines in close proximity such that the electromagnetic fields on one line can produce similar kind of field distributions on the other line[**1, 2, 3, 4**]. The maximum coupling between the coupled lines occur when the transmission line length is chosen to be quarter wavelength at the operating frequency. A simple coupled line can be utilized in ten canonical forms [**1**]. However the difficulty in providing the short circuit connections to the ground on microstrip, most of the circuits involving coupled lines are realized using one of the forms as simple parallel coupled line with the ends are open circuited. In recent times, with the advancement of printed circuit board technology, a plated through hole can be realized easily and hence the other canonical forms with short circuit can also be used in the design of microstrip circuits. Because of this reason, a simple couple line filter with shorting pins at different locations have been analyzed in order to obtain the frequency response and to use them in the design of filters.

1.1. Literature Review

In [**5**], a method is proposed to suppress second and third harmonic in parallel coupled line filters. Sliding coupling is used in this to improve band-reject characteristics. In this method odd mode length is increased while even mode length is maintained.

In [**6**], corrugated coupled lines for fixed and tunable microstrip bandpass filters is presented. The approach uses a microstrip corrugated coupled line to synthesize a coupling coefficient which maintains a nearly constant absolute bandwidth across the tuning range.

In [**7**], a technique of synthesis of wideband parallel coupled line bandpass filters with controllable non equal-ripple frequency responses is presented. The reflection lobes present in the non equal-ripple filters can be redistributed within the operating passband. The result of this is that the filters have a reduced sensitivity to manufacturing errors and have good tolerance control for maximum in-band reflection loss.

In [**8**], a design technique for distributed dualband passband filter is presented. This technique consists in designing two lumped bandpass filters, which are combined into a single one by means of multi resonant circuits and then it is transformed into an equivalent distributed filter.

In [**9**], improved dual filter structure is presented. The dual resonators consist of shunt open and short circuited stubs. To fulfill the requirements of dual inverters, dualband structure of stepped impedance asymmetric coupled lines and its equivalent circuit is also presented. This type of filter have more freedom of bandwidth ratio and can achieve relatively large practical passband center frequency ratios.

In [**10**], a synthesis method for symmetric dualband microwave filter is presented. This method employs frequency transformation techniques for finding the locations of poles and zeros of a desired filter. This method can be used to design dualband filters with prescribed passbands and attenuation at stopbands directly without the need for any optimization processes.

In [**11**], a reduced length parallel coupled line dualband filter is presented. In this paper coupled lines are cascaded in order to get the dual response. Two ports of coupled lines are short circuited. Coupled lines are shorted and between two coupled lines shorted stub is used and it is connected in parallel.

In [**12**], a design approach for achieving impedance matching and enhancing the isolation of multiplexer is presented. The channel filters consisting the multiplexer utilize the T-shaped short circuited resonators and short circuited parallel coupled lines as inter stage couplings. The embedded open ended stubs of resonators are placed along the main transmission path of each channel that contribute the virtual shorts. This process create the transmission zeros thereby making the matching and isolation improvement possible.

In [**13**], a novel method of spectral formulation is proposed for the coupling integral between a cylindrical wave with arbitrary radial wave number, azimuthal dependence, a slot placed on a plane orthogonal to the wave front. The two fold spatial integral coupling, is transformed into an equivalent one fold spectral integral. The integration path of which is selected to obtain Gaussian decay of the integrand. For this both propagating and evanescent cylindrical modes are considered.

In [**14**], the parallel coupled lines present in conventional hairpin line filter is replaced by inter digital capacitor. To get the optimal physical length, design equations are derived. Using this method size is reduced compare to the conventional hairpin line filter.

In [**15**], a bandpass filter with a wide stopband is presented which is compact. The harmonics passed by the bandpass filter can be suppressed. Because this filter consists of two path coupled lines. To get wide stopband two path coupled lines are employed and are connected at input/output ports separately.

In [**16**], a method of miniaturized short ended parallel coupled lines are used for bandwidth compensation. Using this method fractional bandwidth of the filter is reduced and this method can be applied to any kind of filter made from coupled lines.

In [**17**], a five pole bandpass filter is presented which is compact in size. To calculate the coupling coefficients full wave simulator is used. The proposed structure of bandpass filter is narrow band and have high selectivity.

In [**18**], two transmission zeros, lowpass filter is presented. To generate transmission zeros tap lines are used between stepped impedance hairpin units, when inter-digital structure is introduced in it.

In [**19**], a method is proposed to design a filter which have two transmission poles and five transmission zeros. The mixed electric and magnetic coupling between hairpin units interfere with each other and generate three transmission zeros. To generate additional two transmission zeros stubs are used at the feeding lines.

In [**20**], a method of re-configurable coupled line filter is presented. A re-configurable filter designed from this method can switch between three different bandwidths. This kind of re-configurable filter have insertion loss of 0.57dB.

In [**21**], dual bandpass filter is proposed using asymmetrical coupled lines. Because of the asymmetrical coupled lines dual bandpass filter have common mode suppression ratios. This filter also have dual bandpass characteristics at differential mode of operation.

In [**22**], a method is proposed, in which the bandpass filter contains the wide stopband. The filter design contains the stepped coupled lines and two short circuited stubs. The electrical length of the filter is quarter of wavelength so that the size of the filter is compact.In

In [**23**], triple band bandpass filter is presented with good selectivity. Selectivity is based on modified grounded stepped impedance resonators (SIRs). To obtain dual-band response fundamental and first higher order resonances of the two grounded SIRs are utilized. Bandwidths of the two passbands can be controlled by either increasing/ decreasing the distance between the two grounded vias.

1.2. Objective

The main objective of this report is to design a dualband microwave filter using parallel coupled lines. Initially dual filter is to be analyzed on the basis of lumped design. After this coupled lines are to be designed using two port and single port network. These single port and two port network are to be arranged in such a manner so that dual band filter can be realize.

This report is organized in the following manner. In Chapter 2 dual bandpass filter is analyzed based on lumped design. In Chapter 3 coupled lines [**2, 1**] are analyzed using two port and in Chapter 4 coupled lines are analyzed using single port network. In Chapter 5 dual bandpass filter is analyzed for $2.5 - 4.5GHz$ frequency band using parallel coupled lines. In Chapter 6 hairpin-line configuration is used to analyze the behavior of dual bandpass filter. Coupled lines are used because it is easy to fabricate on the microstrip. All the structures are design in CST Microwave Studio [**24**] and results are analyzed in Matlab [**25**].

CHAPTER 2

DUAL BAND FILTER DESIGN BASED ON LUMPED ELEMENTS

To design dual band filter, bandpass and bandstop filters are used. Bandpass and bandstop filter is designed using lowpass prototype filter using filter transformations and frequency scaling [**1, 2**]. After designing both filters, these filters are combined using different connection.

2.1. Basic Design

To design dual bandpass filter, initially bandpass filter and bandstop filter are designed. Bandpass filter and bandstop filter is designed from lowpass prototype filter [**1**]. Third order lowpass prototype filter is used for conversion to bandpass filter and bandstop filter [**1**].

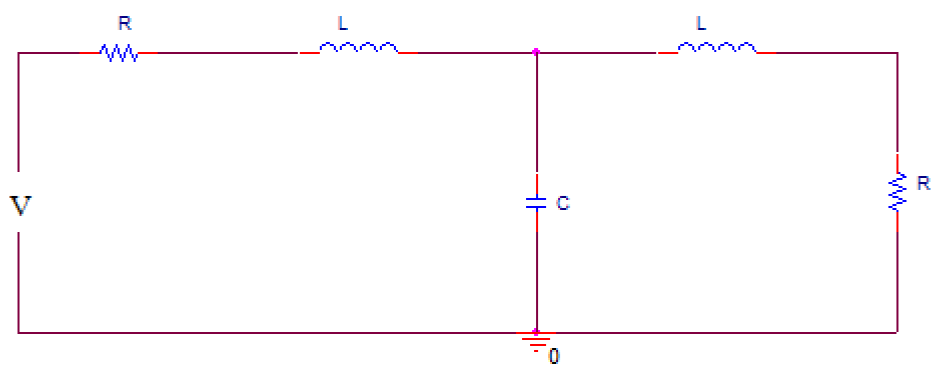
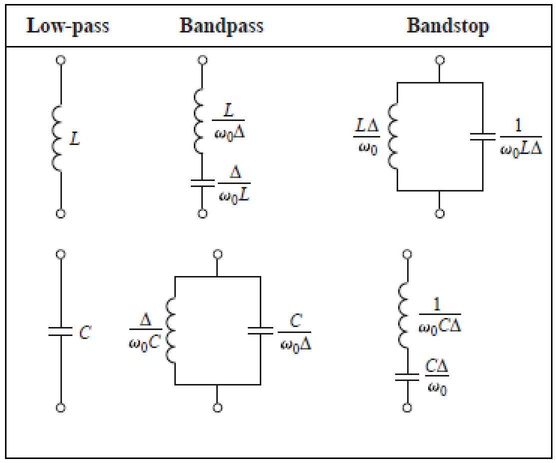


FIGURE 2.1.1. Third order lowpass prototype filter

Figure 2.1.1 shows the third order lowpass filter prototype using lumped elements. There are different arrangements of lumped elements in the design, here first element is series inductor but capacitor can also be used as the first element to design lowpass filter. If capacitor is a first element in the design then it is used in shunt configuration. Table 1 shows the conversion of lowpass filter elements to bandpass and bandstop filter elements.

TABLE 1. Conversion from lowpass prototype filter to bandpass filter and bandstop filter



2.2. Design Equations To Calculate Values Of Inductance(L) And Capacitance(C)

Lowpass prototype filter can be transformed to bandpass filter using frequency transformation defined as:

$$\omega \leftarrow \frac{\omega_0}{\omega_2 - \omega_1}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) = \frac{1}{\Delta}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) \tag{2.2.1}$$

Here ω is the frequency of the lowpass prototype filter.

$$\Delta = \frac{\omega_2 - \omega_1}{\omega_0} \tag{2.2.2}$$

$$\omega_0 = \sqrt{\omega_1 \omega_2} \tag{2.2.3}$$

When series inductor L_n is present in lowpass prototype filter, then it is converted to series combination of inductor and capacitor, and new inductor and capacitor values are given as:

$$L_n^{'} = \frac{L_n}{\Delta \omega_0} \tag{2.2.4}$$

$$C_n^{'} = \frac{\Delta}{L_n \omega_0} \tag{2.2.5}$$

When shunt capacitor C_n is present in lowpass prototype filter, then it is converted to parallel combination of inductor and capacitor and new values are given as:

$$C_n^{'} = \frac{C_n}{\Delta \omega} \tag{2.2.6}$$

$$L_n^{'} = \frac{\Delta}{C_n \omega_0} \tag{2.2.7}$$

To transform lowpass prototype filter to bandstop filter, frequency transformation is given as:

$$\omega \leftarrow -\Delta \left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)^{-1} \tag{2.2.8}$$

Series inductor of lowpass prototype filter is converted to parallel combination of inductor and capacitor. Values of inductor and capacitor are given as:

$$L_n^{'} = \frac{\Delta L_n}{\omega_0} \tag{2.2.9}$$

$$C_n^{'} = \frac{1}{\omega_0 \Delta L_n} \tag{2.2.10}$$

Shunt capacitor present in lowpass prototype filter is converted to series combination of inductor and capacitor, values are given as:

$$C_n^{'} = \frac{\Delta C_n}{\omega_0} \tag{2.2.11}$$

$$L_n^{'} = \frac{1}{\omega_0 \Delta C_n} \tag{2.2.12}$$

TABLE 2. Specifications for designing X band filter using lumped elements

(A) Specifications for X band bandpass Filter

Frequency Range	Center Frequency(ω_0)	Fractional Bandwidth(Δ)
$8GHz - 12GHZ$	$9.79GHz$	0.4082

(B) Specifications for X band bandstop filter

Frequency Range	Center Frequency(ω_0)	Fractional Bandwidth(Δ)
$9.5GHz - 10.5GHZ$	$9.98GHz$	0.1001

Specifications for designing X band is given in Table 2 using these specifications bandpass and bandstop filter is designed.

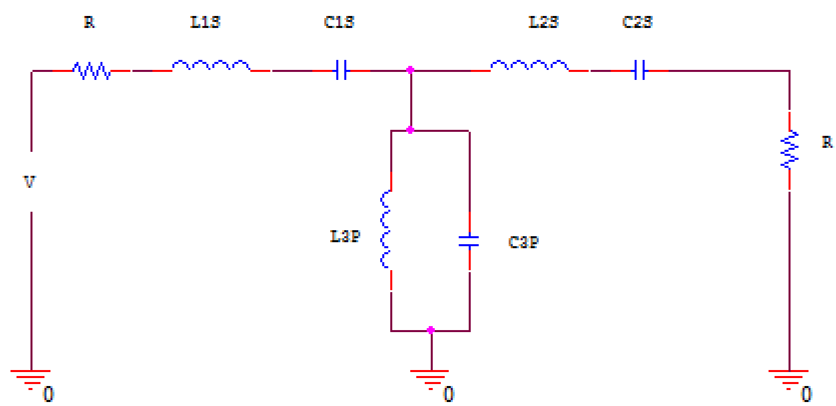


FIGURE 2.2.1. Bandpass filter designed from lowpass prototype filter

Bandpass filter is shown in Figure 2.2.1. Element values are given in Table 3 and using these values bandpass filter is obtained as shown in Figure 2.2.2.

TABLE 3. Inductance and capacitance values for bandpass filter

L1s,L2s (H)	C1s,C2s (F)	L3p (H)	C3p (F)	R (Ω)
1.9894n	0.13263p	0.1657n	1.5915p	50

It is clear from the Figure 2.2.2 that the filter gain is flat from 8GHz to 12GHz which is the desired passband of the filter.

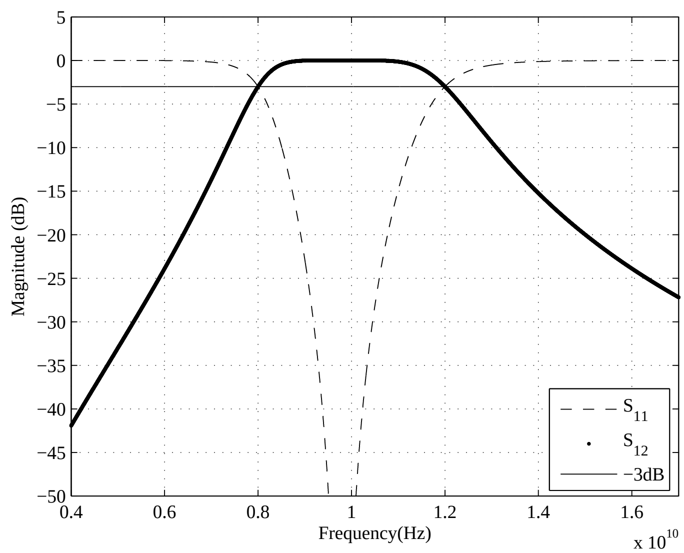


FIGURE 2.2.2. Scattering parameters of bandpass filter

In similar manner bandstop filter is designed using lowpass prototype filter.

$$\omega \leftarrow \frac{\omega_0}{\omega_2-\omega_1}\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)=\frac{1}{\Delta}\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right) \tag{2.2.13}$$

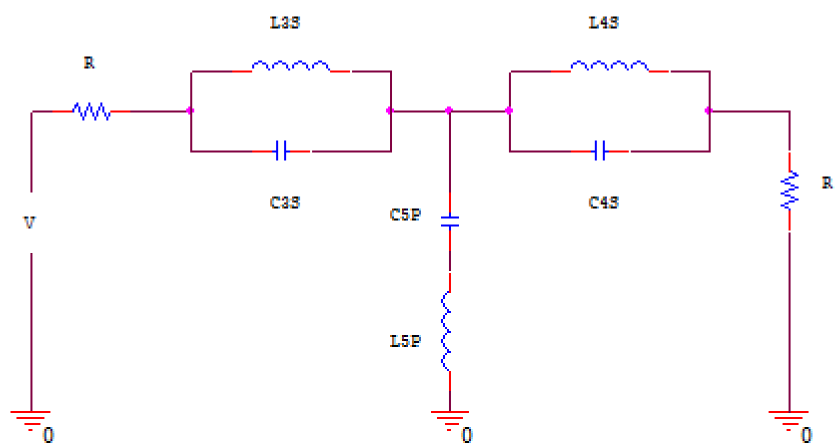


FIGURE 2.2.3. Bandstop filter designed from lowpass prototype filter

TABLE 4. Inductance and capacitance values for bandstop filter

L3s,L4s (H)	C3s,C4s (F)	L5p (H)	C5p (F)	R (Ω)
0.07977n	3.1831p	3.9789n	0.063822p	50

Bandstop filter is shown in Figure 2.2.3. Element values are shown in Table 4 and using these values bandstop filter is simulated and results in bandstop filter with band rejection at 10GHz. This response is shown in Figure 2.2.4.

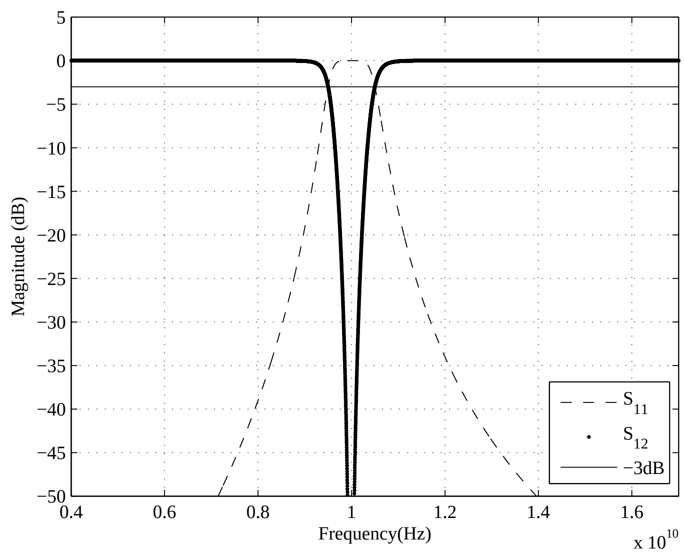


FIGURE 2.2.4. Scattering parameters of bandstop filter

2.3. Dual band Filter Design Based On Lumped Elements

Dual band filter is designed using above mentioned filter i.e. bandpass filter & bandstop filter [**9**]. Dual band filter can be designed using numerous methods [**8, 10**] using bandpass filter & bandstop filter. These methods are:

(1) Cascade connection of bandpass and bandstop filter.
(2) Series connection of bandpass and bandstop filter.
(3) Parallel connection of bandpass and bandstop filter.

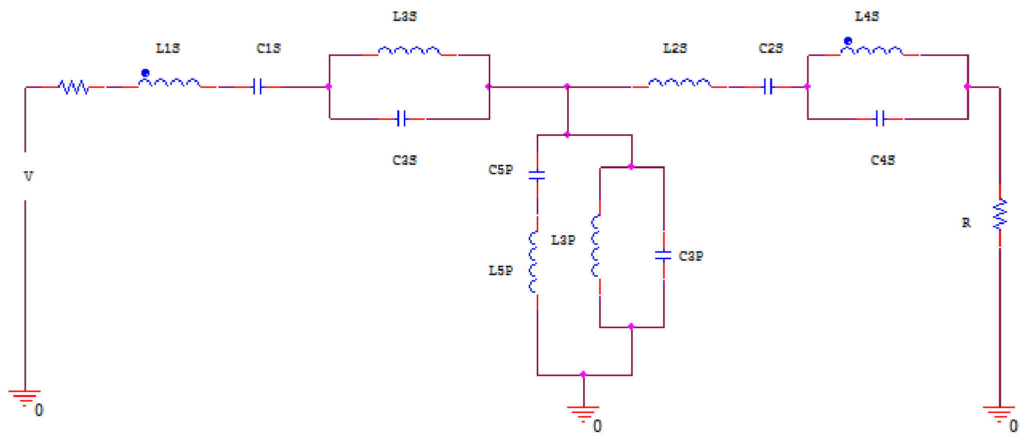


FIGURE 2.3.1. Third order dual band filter

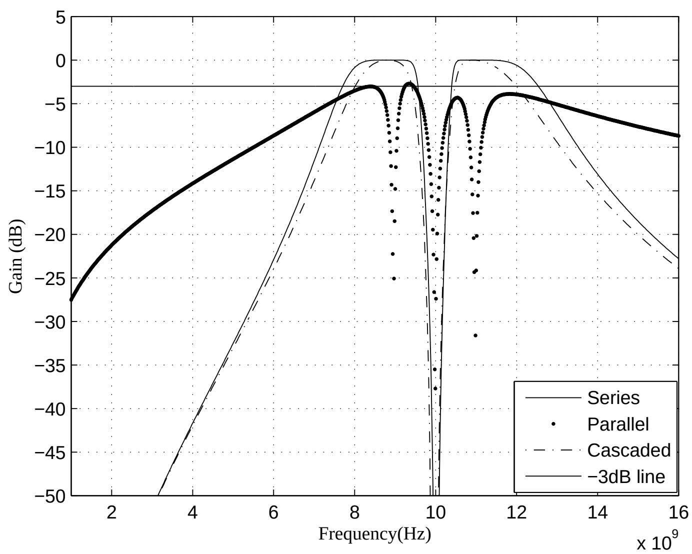


FIGURE 2.3.2. Comparison of three designs

The traces shown in Figure 2.3.2 is in accordance with different design methods. From the graph it is concluded that the series connection of bandpass filter and bandstop filter gives the better performance compared to other two designs (cascaded connection of bandpass filter and bandstop filter, parallel connection of bandpass filter and bandstop filter). Although the response corresponding to the cascade connection of bandpass filter and bandstop filter is reasonably good but it does not give that much flat gain as given by series connection of bandpass filter and bandstop filter.

Figure 2.3.1 shows the series connection of bandpass and bandstop filter. After choosing the series connection of bandpass filter and bandstop filter for designing the dual band filter, different order filters are designed using this design and results are compared.

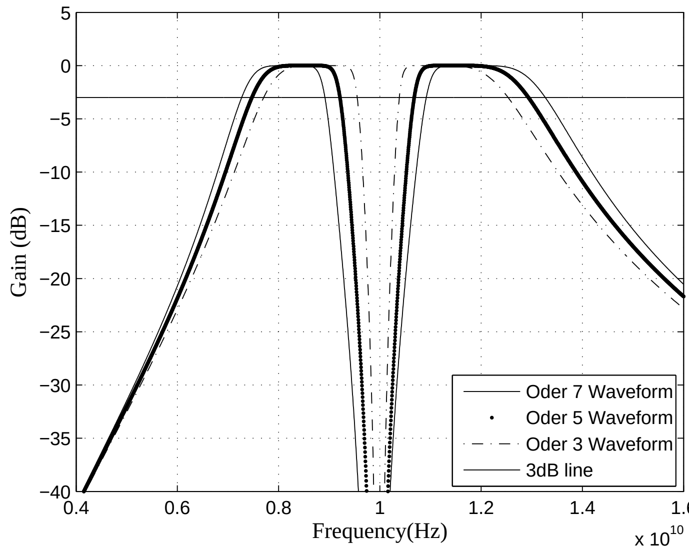


FIGURE 2.3.3. Comparison of different order filters

From the Figure 2.3.4 it is clear that the third order filter gives flat gain in passband but it roll-off very slow. As the order of the filter is increased the gain in passband becomes more flat and it roll-off sharply compares to lower order filter.

For the same design (series connection of bandpass filter and bandstop filter), third order dual band filter results are compared by changing the fractional bandwidth (Δ) of bandstop filter while keeping the fractional bandwidth (Δ) of bandpass filter constant.

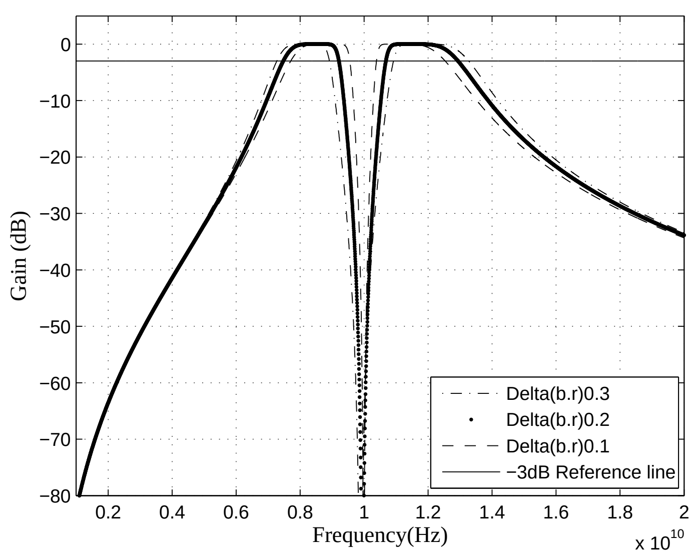


FIGURE 2.3.4. Comparison of different bandstop fractional bandwidth

From the Figure 2.3.4 it is cleared that if the fractional bandwidth of bandstop filter is increased, the passband is shifted accordingly but the roll-off remains same. Delta(b.r) mentioned in the Figure 2.3.4 is fractional bandwidth of band reject filter.

$$\omega \leftarrow \frac{\omega_0}{\omega_2-\omega_1}\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)=\frac{1}{\Delta}\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right) \quad (2.3.1)$$

Figure 2.3.5 is the third order maximally-flat dual band filter. It is shown in Figure 2.3.5, the gain in passband of maximally-flat filter is flat but the roll-off is slow. This filter is used where flat passband gain is required but the roll-off is not of much importance.

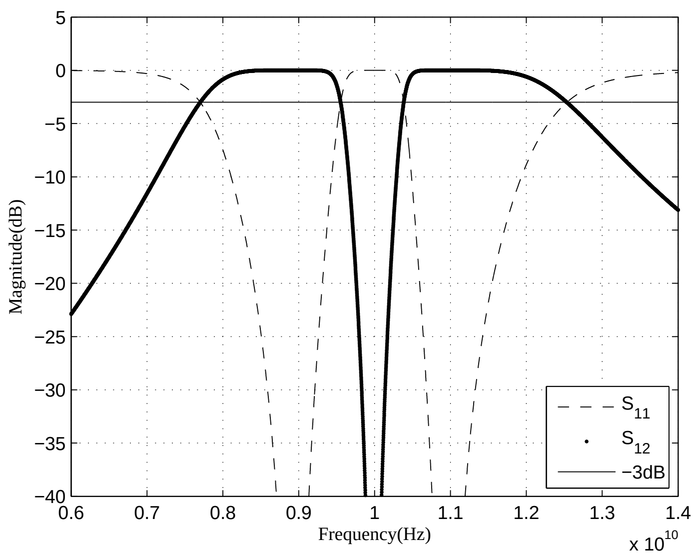


FIGURE 2.3.5. Third order maximally-flat dual band filter

As it is a dual band filter, so it passes frequency ranging from 8GHz - 9.5GHz and 10.5GHz - 12GHz. From the Figure 2.3.5 it is cleared that the gain in the required range i.e. from 8GHz - 9.5GHz and 10.5GHz - 12GHz is flat, but the roll-off is not very sharp.

Figure 2.3.6 is the third order equal-ripple dual band filter. Equal-ripple bandpass filter contains ripples but the roll-off is very sharp. This filter is used where flat passband gain is not required but the roll-off is of much importance. From the Figure 2.3.6 it is cleared that the roll-off of third order filter is 52dB.

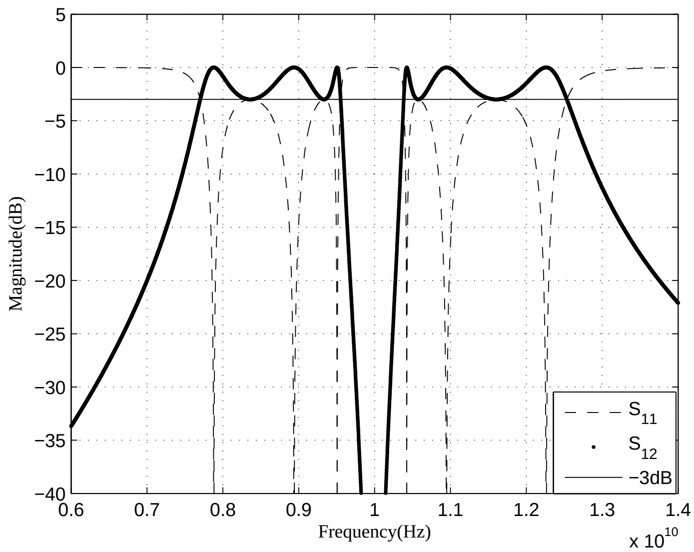


FIGURE 2.3.6. Third order equal-ripple dual band filter

Figure 2.3.7 is the triple band filter, which is designed for the frequency range 4GHz-12GHz. In this figure three passbands and two stopbands are present.

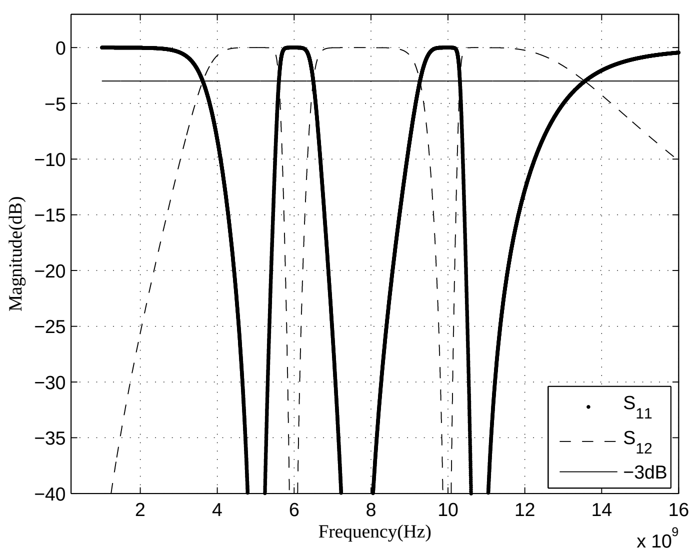


FIGURE 2.3.7. Third order Triple-band filter

From all these results it is concluded that dual bandpass filter is obtained from series combination of bandpass and bandstop filter and using same technique triple order filter is also obtained.

CHAPTER 3

ANALYSIS OF PARALLEL COUPLED LINES AS TWO PORT NETWORK

At microwave frequencies there are some limitations using lumped elements.These limitations are:

(1) Lumped element inductors and capacitors are generally available only for a limited range of values and can be difficult to implement at microwave frequencies.
(2) At microwave frequencies the distances between filter components is not negligible.

To avoid these problems distributed elements are used. Distributed element used here is the parallel coupled lines.

3.1. Design Of Coupled Line Bandpass Filters

A simple coupled line bandpass filter can be made by taking two parallel lines. As there are two parallel lines so there will be four ports. A two port network can be formed from a coupled line section by terminating two of the four ports with either open or short circuits, or by connecting two ends.

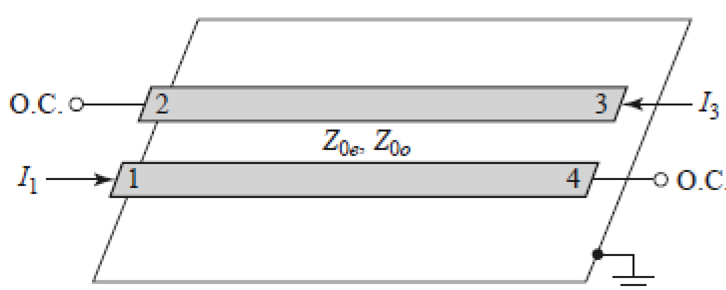


FIGURE 3.1.1. Two port coupled line design

Z parameters of the Figure 3.1.1 are given as:-

$$Z_{11} = Z_{22} = Z_{33} = Z_{44} = \frac{-j}{Z_0}(Z_{0e} + Z_{0o})cot\theta \tag{3.1.1}$$

$$Z_{12} = Z_{21} = Z_{34} = Z_{43} = \frac{-j}{Z_0}(Z_{0e} - Z_{0o})cot\theta \tag{3.1.2}$$

$$Z_{13} = Z_{31} = Z_{42} = Z_{24} = \frac{-j}{Z_0}(Z_{0e} - Z_{0o})csc\theta \tag{3.1.3}$$

$$Z_{14} = Z_{41} = Z_{23} = Z_{32} = \frac{-j}{Z_0}(Z_{0e} + Z_{0o})csc\theta \tag{3.1.4}$$

The coupled line design shown in Figure 3.1.1 is the simplest coupled line design to fabricate on the microstrip. Impedance matrix of the Figure 3.1.1 is given as:-

$$V_1 = Z_{11}I_1 + Z_{13}I_2 \tag{3.1.5}$$

$$V_2 = Z_{31}I_1 + Z_{33}I_2 \tag{3.1.6}$$

Image impedance of the above equations is given as:-

$$Z_i = \sqrt{Z_{11}^2 - \frac{Z_{11}Z_{13}^2}{Z_{33}}} \tag{3.1.7}$$

$$Z_i = \sqrt{(Z_{0e} - Z_{0o})^2 csc^2\theta - (Z_{0e} + Z_{0o})^2 cot^2\theta} \tag{3.1.8}$$

When the coupled line section is $\lambda/4$ long ($\theta = \frac{\pi}{2}$), then image impedance is given as:-

$$Z_i = \frac{1}{2}(Z_{0e} - Z_{0o}) \tag{3.1.9}$$

Propagation constant is given as:-

$$cos\beta = \sqrt{\frac{Z_{11}Z_{33}}{Z_{13}^2}} = \frac{Z_{11}}{Z_{13}} = \frac{(Z_{0e} + Z_{0o})}{(Z_{0e} - Z_{0o})}cos\theta \tag{3.1.10}$$

To design equations for coupled line, firstly approximate the Figure 3.1.1 to its equivalent circuit. Initially image impedance and propagation constant are calculated for equivalent circuit and showing that they are approximately equal to those of the coupled line section for $\theta = \frac{\pi}{2}$, which will correspond to the center frequency of the bandpass response.

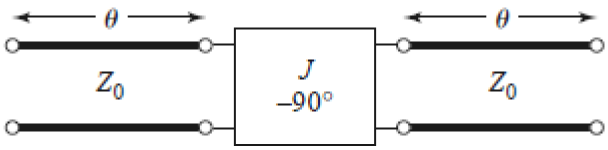


FIGURE 3.1.2. Equivalent circuit of coupled line

Figure 3.1.2 shows the equivalent circuit of coupled line. Here θ is the electrical length and $Z_0$is the characteristic impedance of the circuit. Here J is the admittance inverter which is used to transform series connected elements to shunt connected elements, or vice versa.

The $ABCD$ parameters of the equivalent structure are given as:-

$$[ABCD] = \begin{bmatrix} cos\theta & jZ_0 sin\theta \\ \frac{jsin\theta}{Z_0} & cos\theta \end{bmatrix} \begin{bmatrix} 0 & -\frac{j}{J} \\ -jJ & 0 \end{bmatrix} \begin{bmatrix} cos\theta & jZ_0 sin\theta \\ \frac{jsin\theta}{Z_0} & cos\theta \end{bmatrix}$$

$$[ABCD] = \begin{bmatrix} (JZ_0 + \frac{1}{JZ_0}) sin\theta cos\theta & j(JZ_0^2 sin^2\theta - \frac{cos^2\theta}{J}) \\ j(\frac{sin^2\theta}{JZ_0^2} - Jcos^2\theta) & (JZ_0 + \frac{1}{JZ_0}) sin\theta cos\theta \end{bmatrix} \tag{3.1.11}$$

The image impedance of the equivalent circuit is given as:-

$$Z_i = \sqrt{\frac{B}{C}} = \sqrt{\frac{(JZ_0 + \frac{1}{JZ_0}) sin\theta cos\theta}{j(\frac{sin^2\theta}{JZ_0^2} - Jcos^2\theta)}} \tag{3.1.12}$$

$$Z_i = JZ_0^2 \tag{3.1.13}$$

Propagation constant is given as:-

$$cos\beta = A = (JZ_0 + \frac{1}{JZ_0}) sin\theta cos\theta \tag{3.1.14}$$

Which reduces to the following value at the center frequency $\theta = \frac{\pi}{2}$, from equation (3.2.12) and (3.2.13)

$$JZ_0^2 = \frac{1}{2}(Z_{0e} - Z_{0o}) \tag{3.1.15}$$

$$\frac{(Z_{0e} + Z_{0o})}{(Z_{0e} - Z_{0o})} = JZ_0 + \frac{1}{JZ_0} \tag{3.1.16}$$

assume $sin\theta$ =1 for θ near $\frac{\pi}{2}$. The even- and odd-mode line impedances are:-

$$Z_{0e} = Z_0[JZ_0 + (JZ_0)^2 + 1] \tag{3.1.17}$$

$$Z_{0o} = Z_0[-JZ_0 + (JZ_0)^2 + 1] \tag{3.1.18}$$

The design equations for a bandpass filter with N + 1 coupled line sections are given below:-

$$JZ_1 = \sqrt{\frac{\pi\Delta}{2g_1}} \tag{3.1.19}$$

$$JZ_n = \frac{\pi\Delta}{2\sqrt{g_n g_{n-1}}} \tag{3.1.20}$$

where $n = 2, 3, ..., N - 1$

$$JZ_{N+1} = \sqrt{\frac{\pi\Delta}{2g_N g_{N+1}}} \tag{3.1.21}$$

3.2. Parallel Coupled Line As Two Port Network

A simple parallel coupled line as shown in Figure 3.2.1 has been extensively used in the filter design. This simple structure acts a bandpass filter provided the length is taken as quarter wavelength at the operating frequency. For the simulations purpose, this filter is designed for the S band (2.5GHz - 4.5GHz) with center frequency of 3.5GHz. As per the procedure [**1**] , the final layout is obtained as shown in Figure 3.2.1 with the specifications as tabulated in Table 1. Here the feeding line impedance has been taken as 50Ω and the high impedance of the parallel coupled line has been taken as 75Ω. The properties of the microstrip substrate material RT-duroid 5880 are also given in the same table. The

TABLE 1. Specifications of parallel coupled line filter designed at at 3.5 GHz

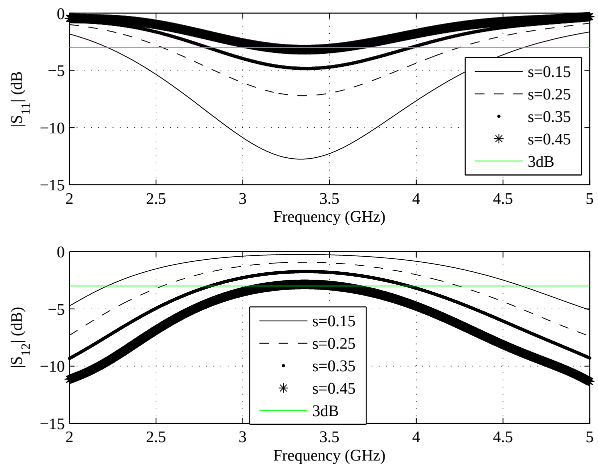
Parameters	Values	Description
$w(mm)$	0.3	width of coupled line
$s(mm)$	0.15	spacing between coupled line
$l(mm)$	16	length of coupled line
$lf(mm)$	5	length of feeding line
$wf(mm)$	1.2	width of feeding line
$t_c(mm)$	0.035	thickness of conductor
$h(mm)$	0.508	height of substrate
ε_r	2.2	dielectric constant

FIGURE 3.2.1. Layout of two port parallel coupled line filter.

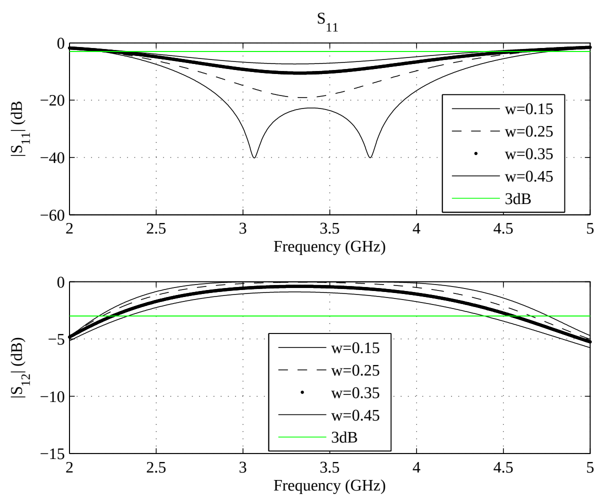
simulations are carried out for this structure using a 3D-Electromagnetic simulator [**24**] in order to observe the frequency response.

A simple parametric study has been performed on this structure by changing the spacing between the conductors by keeping the width and length of lines constant. Similarly, by keeping the space and length constant, width has been varied. Finally, the length has been varied for fixed values of space and width. Figure 3.2.2a represents the scattering parameters of the structure with different values of spacing for a width of w=0.3mm and length of l=16mm. Similarly, Figure 3.2.2b represents the response for different widths with spacing s=0.15mm and with length l=16mm. And lastly, Figure 3.2.2c represents the parametric study of the coupled line by fixing width and spacing constant for different lengths. Bandwidths have been obtained for all these structures and tabulated in Table 2.

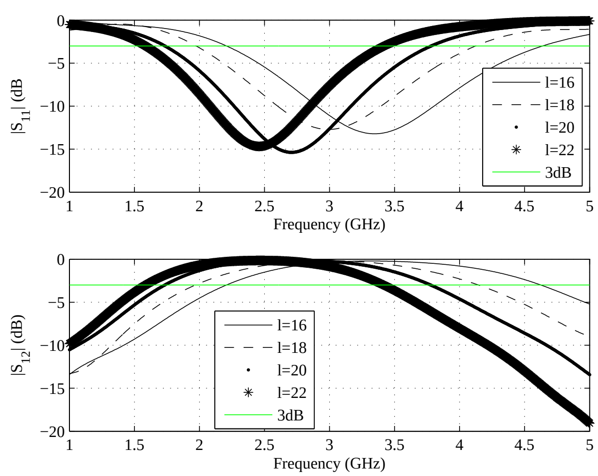
From this table, it is concluded that as the spacing between the coupled lines is increased, the bandwidth of the filter decreases and the response of the filter becomes narrower. When the width of coupled line is increased, the bandwidth again decreases and with the increase in the length of the line, the response shifts towards lower frequencies and bandwidth of the filter decreases. Hence, by adjusting these three parameters, it is possible to control the resonant frequency, bandwidth and the roll off of the filter.



(A) Spacing is varied for w=0.3mm and l=16mm.



(B) Width is varied for s=0.15mm and l=16mm.



(C) Length is varied for w=0.3mm and s=0.15mm

FIGURE 3.2.2. Parametric study results on parallel coupled line filter.

TABLE 2. Bandwidth calculation for various parameters

$w(mm)$	0.15	0.25	0.35	0.45
$f1(GHz)$	2.171	2.207	2.249	2.33
$f2(GHz)$	4.754	4.655	4.541	4.3667
$B.W(f2-f1)(GHz)$	2.583	2.448	2.292	2.0367
$s(mm)$	0.15	0.25	0.35	0.45
$f1(GHz)$	2.216	2.522	2.795	3.179
$f2(GHz)$	4.601	4.238	3.947	3.536
$B.W(f2-f1)(GHz)$	2.385	1.716	1.152	0.357
$l(mm)$	16	18	20	22
$f1(GHz)$	2.208	1.988	1.736	1.596
$f2(GHz)$	4.628	4.144	3.772	3.42
$B.W(f2-f1)(GHz)$	2.42	2.156	2.036	1.824

3.3. Design Of Third Order Parallel Coupled Line Bandpass Filter

In this section a standard procedure of designing bandpass filter from the third order lowpass prototype filter and the values taken in the prototype are corresponds to equal ripple filter [**1, 2, 26, 27, 28**] has been considered and the final layout has been shown in Figure 3.3.1. This bandpass filter is designed at a center frequency of 3.5GHz with a passband from 2.5GHz to 4.5GHz. Using above mentioned equations, design parameters for third order coupled line bandpass filter are calculated.

TABLE 3. Design properties of Rogers RT5880

$t_c(mm)$	$h(mm)$	$l(mm)line\_length$	$lf(mm)feeding\_length$	$w_n(mm)$
0.035	0.508	13.7	5	0.75

TABLE 4. Design parameters for third order coupled line bandpass filter

n	JZ_n	JZ_{0e}	JZ_{0o}	$w_n(mm)$	$s_n(mm)$
1	0.7128	111.04	39.76	0.26	.09
2	0.6125	99.39	38.13	0.3	0.1
3	0.6125	99.39	38.13	0.3	0.1
4	0.7128	111.04	39.76	0.26	0.09

FIGURE 3.3.1. Third order coupled line bandpass filter.

With the design Parameters given in Table 3,4 .

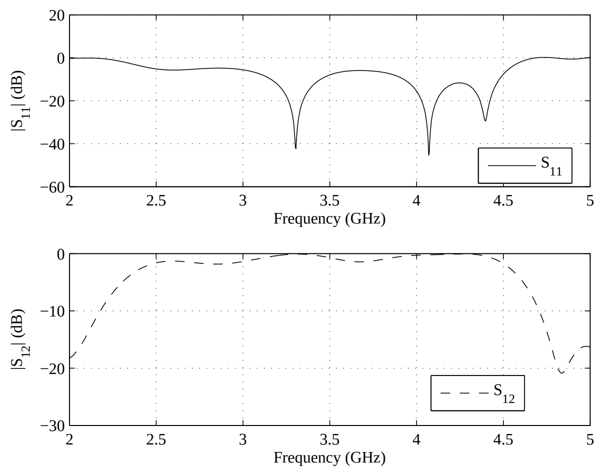


FIGURE 3.3.2. Scattering parameters of third order coupled line bandpass filter.

The scattering parameters of the bandpass filter is shown in Figure 3.3.2. Which gives the bandpass response for the desired band 2.5 - 4.5GHz with center frequency 3.5GHz and hence the S_{21} response appears to be oscillatory in nature but within the 3dB over the desired frequency band. From the layout of the higher order bandpass filter, it can be easily converted into dual bandpass filter by connecting the band rejection branches in the shunt configuration at the mid points of the parallel coupled lines and this has been explored in the next section by connecting the shunt branches on one side and on both the sides separately.

CHAPTER 4

ANALYSIS OF PARALLEL COUPLED LINES AS SINGLE PORT NETWORK

Conventional parallel coupled lines are designed and only one port is connected at one end of the line. This coupled line is called single port coupled line.

4.1. Single Port Coupled Line

Single port parallel coupled line is designed using either short circuiting the end or keeping the ends of the line open circuited. Single port parallel coupled line is shown in Figure 4.1.1.

(A) Coupled line with open circuit ends

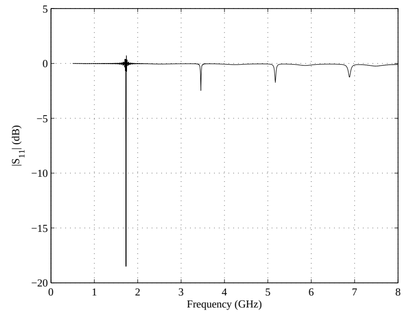
(B) Coupled line with right bottom end short circuited

(C) Coupled line with right top end short circuited

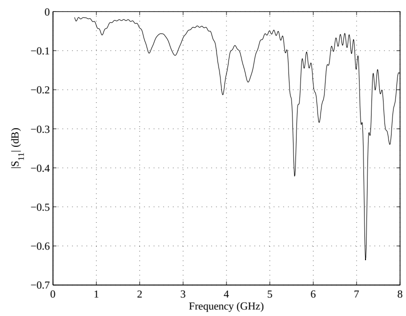
(D) Coupled line with left bottom end short circuited

FIGURE 4.1.1. Single port coupled line design

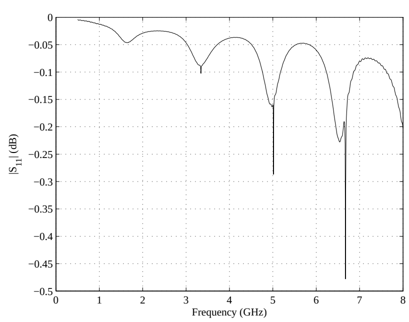
In Figure 4.1.1 four designs of single port parallel coupled line is proposed and simulations are carried out on these designs and S parameters are calculated. From all the simulation result it is concluded that all the designs behave as bandstop filter with very narrow peak. All the structures are designed at 0.8GHz to check that whether the structure behave as dual band filter or not.



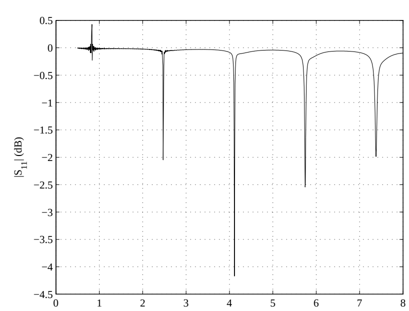
(A) Simulation result of open circuit ends



(B) Simulation result of right bottom end



(C) Simulation result of right top end

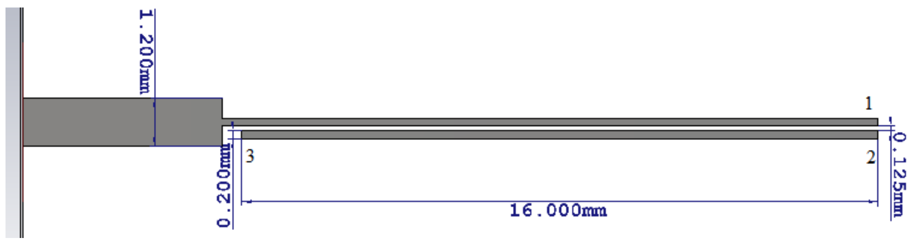


(D) Simulation result of left bottom end

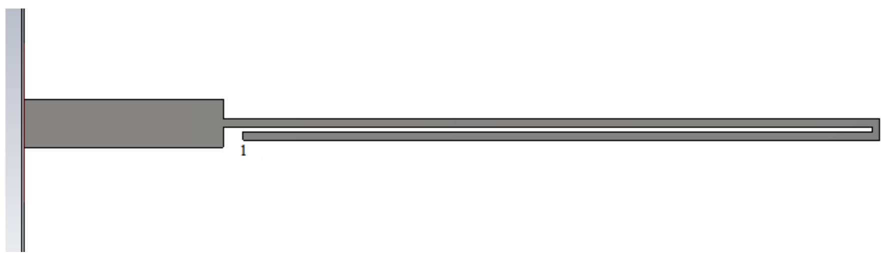
FIGURE 4.1.2. Single port coupled line design simulation results

But it is clear from the result that all the designs follow the nature of dual band. But the repetition factor of every filter is different so 4.1.2a and 4.1.2d are used for the analysis.

Two types of coupled lines are used namely one with the short circuit and other with the open circuit. This microstrip coupled line structure is placed on the material RT-duroid 5880. These coupled lines are designed for 2.5GHz to 4.5GHz frequency range, with center frequency at 3.5GHz.



(A) Single port coupled line



(B) Single port coupled line with right extremes ends short circuited

FIGURE 4.1.3. Different configurations of single port coupled lines

Different combinations of coupled lines are considered. These different combinations are considered using different cases for Figure 4.1.3. Figure 4.1.3a is described using four cases. These cases are defined below as:

Case A - when no shorting pin is connected to the coupled line.

Case B - when shorting pin is connected at point 1.

Case C - when shorting pin is connected at point 2.

Case D - when shorting pin is connected at point 3.

In Figure 4.1.3b coupled line ends with point 1 and 2 are short circuited. So two cases are considered for this coupled line, these cases are defined below as:

Case E - when shorting pin is connected at point 3.

Case F - when point 3 kept open circuited.

Figure 4.1.4 is the result of Figure 4.1.3a with different combinations of connections, mentioned above. Here impedance parameters are used to analyze the result, because single port is used in the coupled line and scattering parameters does not give the clear information about the result. Imaginary part of the impedance is used here because it

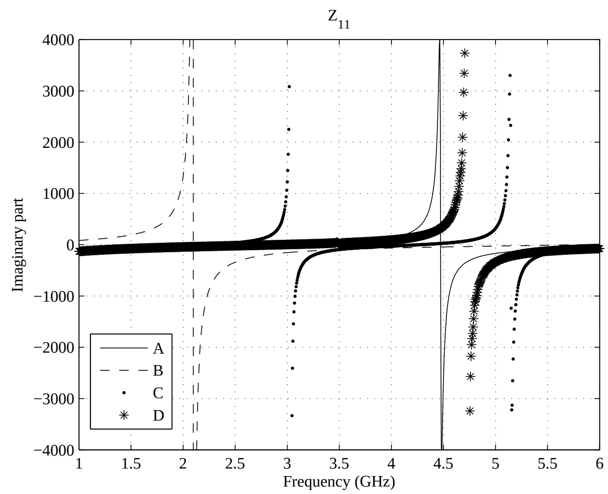


FIGURE 4.1.4. Impedance parameters

tells about the resonance. For case A, resonance occurs at the end of the frequency range (2.5GHZ - 4.5GHz). For case B, resonance occurs before the desired frequency range (2GHz). For case C, resonance occurs before the center frequency. For case D, resonance occurs after the desired frequency range.

Figure 4.1.5 is the result of Figure 4.1.3b and it is clear from the result that for case E, resonance occurs after the center frequency. For case F, resonance occurs before center frequency same as for case C.

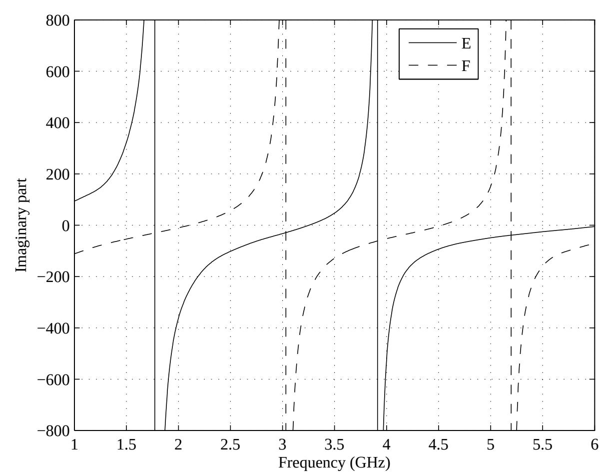
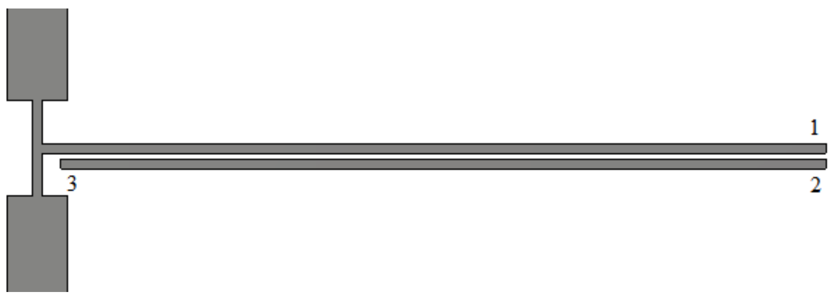


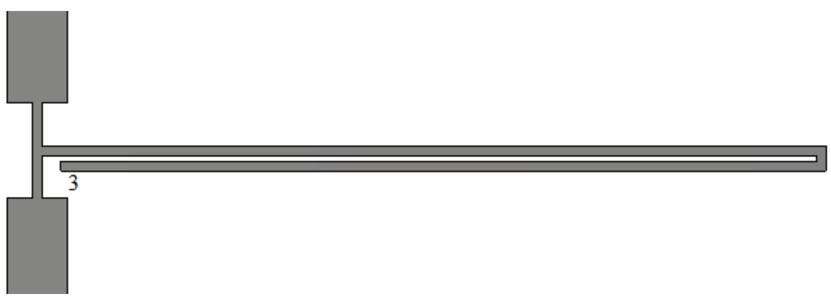
FIGURE 4.1.5. Impedance parameters

4.2. Single Port Parallel Coupled Line Connected In Shunt To Two Port Network

Figure 4.2.1 contains two different structures of the coupled lines connected in parallel to the two port network. Figure 4.2.1a contributes to four cases as described for the Figure 4.1.3a and Figure 4.2.1b contributes to two cases as described for Figure 4.1.3b.



(A) Single port coupled line connected in shunt to two port network



(B) Single port coupled line with right extremes ends short circuited and connected in shunt to two port network

FIGURE 4.2.1. Different configurations of single port coupled lines connected in shunt

Figure 4.2.2 shows the scattering parameters of Figure 4.2.1a and from the result it is clear that for case A coupled line behave as bandstop filter with center frequency 3.5 GHz.

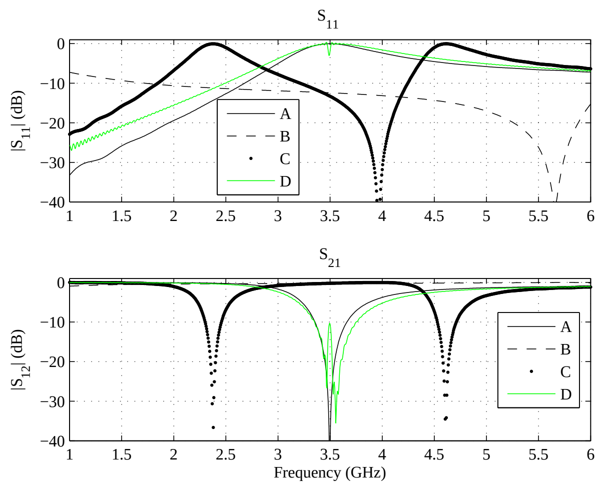


FIGURE 4.2.2. Scattering parameters

For case B coupled line behave as wide bandpass filter and for case C coupled line behave as bandpass filter with frequency range 2.5GHz to 4.5 GHz, which is the frequency range for the designing of coupled lines. For case D coupled lines behave as bandstop filter, but with some distortion at center frequency.

Figure 4.2.3 is the result of Figure 4.2.1b and from the result it is clear that for case E coupled line behave as bandstop filter. Response of this bandstop filter is much sharp compared to the case A, described for Figure 4.2.1a. For case F coupled line response is bandpass filter same as for case C described for Figure 4.2.1a.

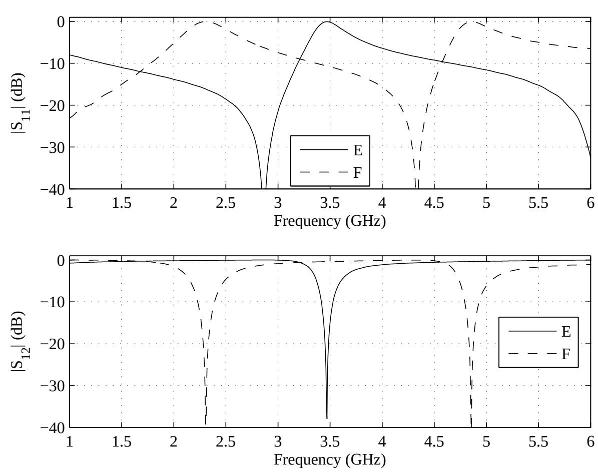


FIGURE 4.2.3. Scattering parameters

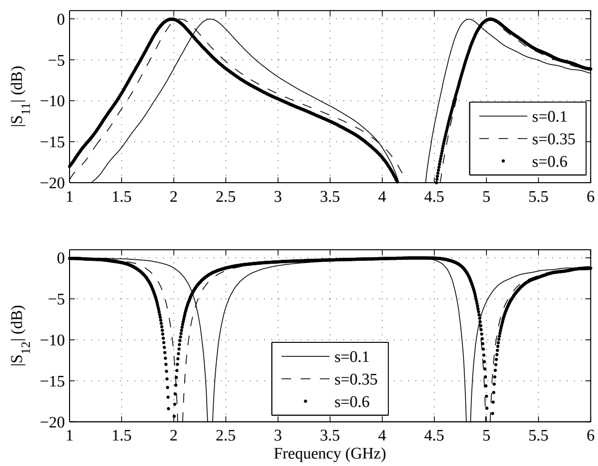


FIGURE 4.2.4. Single port coupled line with short circuit end connected in shunt to the two port network with different spacing

Figure 4.2.4 is the result of Figure 4.2.1b for case F. This result is analyzed for different spacing between coupled lines. From the scattering parameters it is clear that as the spacing between the lines is increased the fractional bandwidth is increased.

CHAPTER 5

REALIZATION OF DUAL-BANDPASS FILTER USING PARALLEL COUPLED LINES

Initially in the communication system separate transmitters and receivers are used to transmit and receive different frequencies. As communication system contains number of component, filter is one part of the communication system which is used at the front end of the transceiver. With the advancement in the communication technology, a single transceiver operating at multiple frequency bands are used, so this leads to the designing of dual band [**29, 30, 31, 32, 33, 34, 35, 36**] filter at microwave frequencies.

5.1. Different Order Parallel Coupled Lines With Single And Double Shunt Coupled line

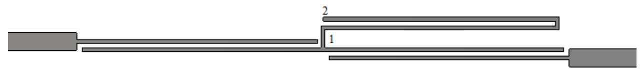
To design the dual bandpass filter, a conventional parallel coupled line bandpass filter is designed and it is loaded in shunt by the single port parallel coupled line structure at the mid point as shown in Figure 5.1.1.

This single sided loading has been considered for different order filter in order to observe the response for higher orders. Since the loading can be done on upper side and lower side of the conventional parallel coupled lines, double sided loading also considered for different orders. Along with this there are combinations of open circuit and shorts circuits for the shunt connected ports and different possible layouts as shown in Table 1 are simulated.

The scattering parameters for all structures in Figure 5.1.1 are analyzed using [**25**]. Figure 5.2.1 represents the scattering parameters for the single sided loading of the conventional parallel coupled line filter while Figure 5.2.2 are for double sided loading.

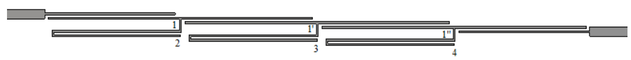
5.2. Results

From Figure 5.2.1a, it is observed that there is some improvement in the roll off for case L in comparison with the conventional parallel coupled line (Case N), while maintaining the

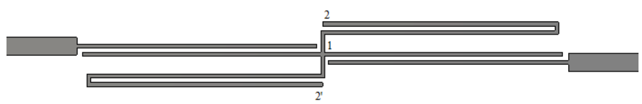


(A) First order parallel coupled line filter.

(B) Second order parallel coupled line filter.

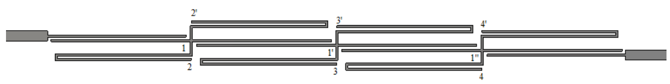


(C) Third order parallel coupled line filter



(D) First order.

(E) Second order.

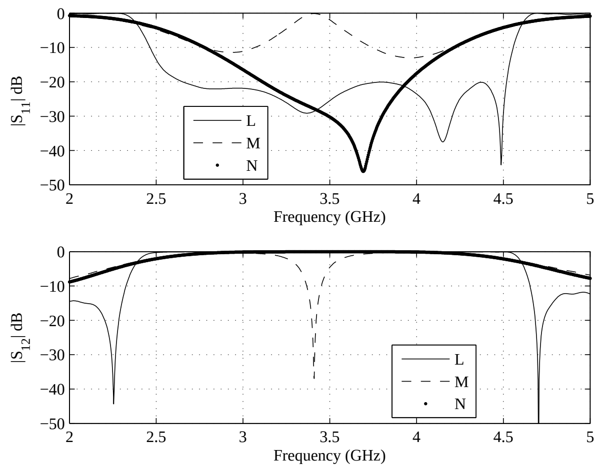


(F) Third order.

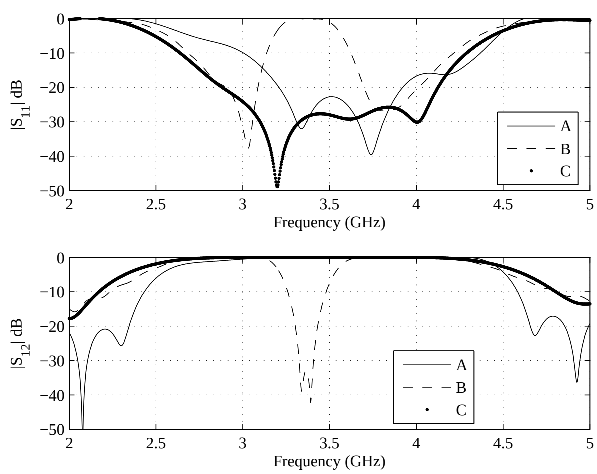
FIGURE 5.1.1. Single sided and double sided loading of parallel coupled line for different orders.

passband at constant value while case M results in band reject filter. From Figure 5.2.1b, case A results in the bandpass filter. Case B results in band reject filter. But the problem with this band reject filter is that the roll off is not sharp. Case C results in bandpass filter with slow roll off compared to the case A. From Figure 5.2.1c similar type of observations can be made. From these figures, it is clear that connecting the open circuited single port in the middle of the parallel coupled line is improving the bandpass nature while short circuited single port is providing the dual-bandpass filter nature.

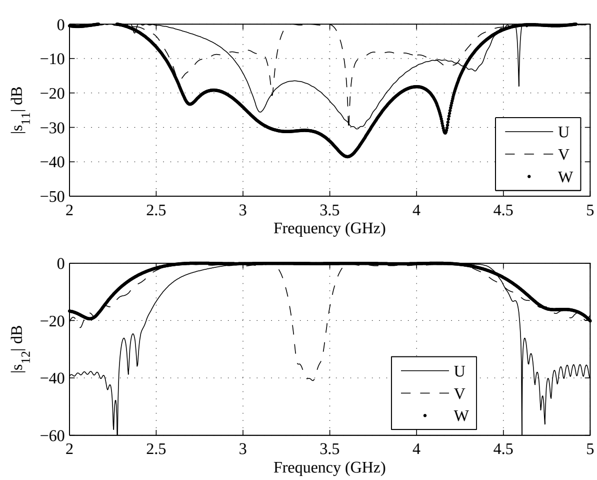
Figure 5.2.2a shows that case I, results in bandpass filter with sharp roll off. Case J gives the band reject filter. Case K results in dual band filter. Figure 5.2.2b shows that for case



(A) First order.

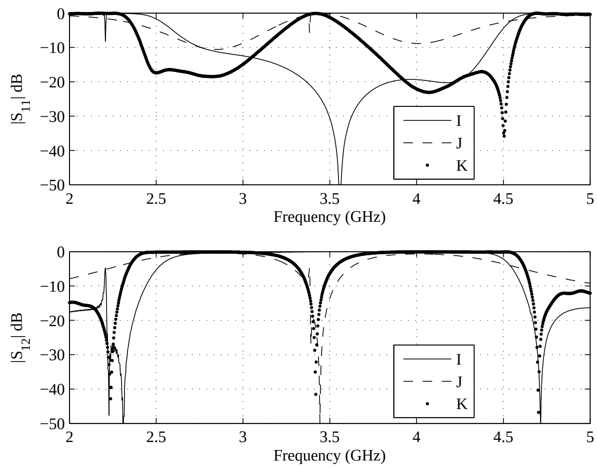


(B) Second order

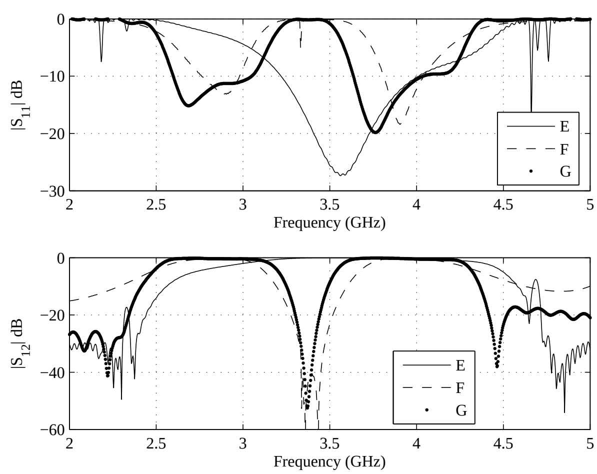


(C) Third order

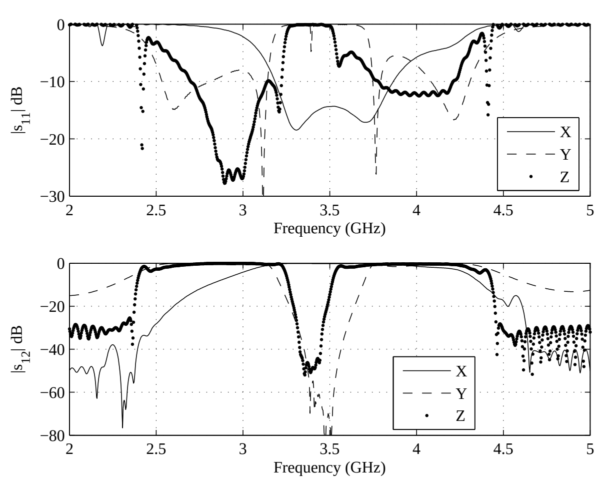
FIGURE 5.2.1. Scattering parameters of single shunt connected parallel coupled line filters for three orders.



(A) First order.



(B) Second order.



(C) Third order.

FIGURE 5.2.2. Scattering parameters of double sided shunt connected parallel coupled lines filters.

TABLE 1. Different cases

1	case L	point 2 is O.C.
2	case M	point 2 is S.C.
3	case N	with no shunt branch.
4	case A	point 2 and point 3 is O.C.
5	case B	when point 2 and point 3 is S.C.
6	case C	no shunt connections at 1 and 1'.
7	case U	point 2, point 3, point 4 are O.C.
8	case V	point 2, point 3, point 4 are S.C.
9	case W	no coupled line is connected at point 1, 1', 1".
10	case I	point 2 and point 2' are O.C.
11	case J	point 2 and point 2' are S.C.
12	case K	point 2 is O.C and point 2' is S.C.
13	case E	point 2, 2' and point 3, 3' is O.C.
14	case F	point 2, 2' and point 3, 3' is O.C.
15	case G	point 2, 3' are O.C, point 2', 3 are S.C.
16	case X	point 2, 2', point 3, 3', point 4,4' are O.C.
17	case Y	point 2, 2', point 3, 3', point 4,4' are S.C.
18	case Z	point 2, 3', 4 are O.C, point 2', 3, 4' are S.C.

E, result is bandpass filter and for case F result is band reject filter with better rejection at the center frequency. Case G results in dual band filter. This is further extended to the higher order filter and Figure 5.2.2c shows the results for third order filter with double sided loading. In this figure, case X result in bandpass filter and case Y results in band reject filter while case Z results in dual band filter in the similar manner of the previous loading.

From all these simulations, the following conclusions can be made.

(1) A simple two port parallel coupled line can be converted into a single port by connecting the two edges on same side and the remaining port can be either short circuited or open circuited in order to use it the design of dual-bandpass filter.
(2) If the single port is connected in shunt with open circuit at the other end, it improves the roll off of the filter while in short circuit configuration, it rejects the center frequency by making the possibility to use it in dual bandpass filter design.
(3) It is also observed that the double sided loading is giving better results in the case dual-bandpass filter with one shunt loading in open circuit and other shunt loading in short circuit case.

CHAPTER 6

HAIRPIN COUPLED LINE FILTER

Hairpin coupled line filters are obtained by simply folding the parallel coupled lines in U shape.

6.1. Simple Hairpin Coupled Line Filter

The simple hairpin parallel coupled line filter is shown in Figure 6.1.1. This filter is designed for frequency band of 2.5GHz - 4.5GHz.

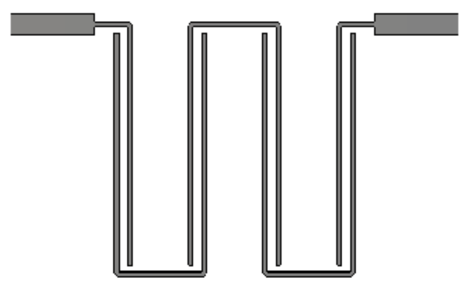


FIGURE 6.1.1. Simple hairpin coupled line filter

The response of the simple hairpin coupled line filter is shown in Figure 6.1.2 and it behaves like a bandpass filter with center frequency of 3.5GHz.

6.2. Hairpin Coupled Line Filter With Shunt Coupled Line

In simple hairpin coupled line, shunt coupled lines are connected at point 1. This structural configuration is used in many ways but only three of these configuration are discussed here. The different cases are mentioned in Table 1

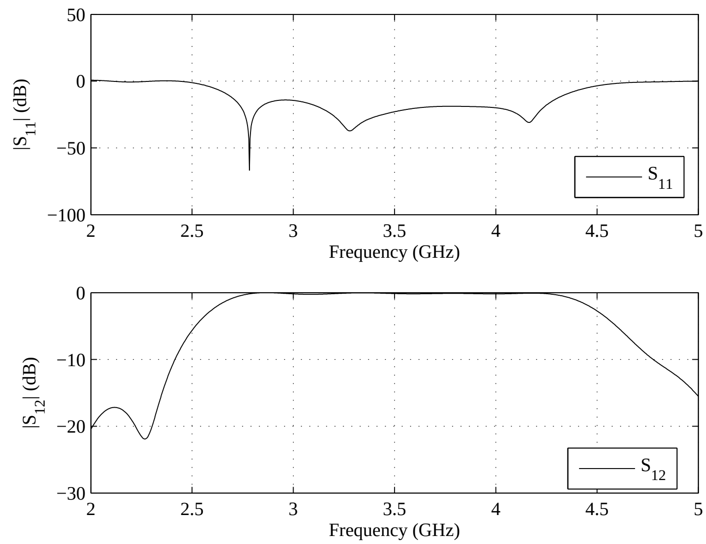


FIGURE 6.1.2. Variation of reflection and insertion loss for simple hairpin coupled line filter

TABLE 1. Different cases for hairpin coupled line structure

1	Case L	point 3,2 are open circuited
2	Case M	point 3,2 are short circuited
3	Case N	point 3 is open circuited and point 2 is short circuited

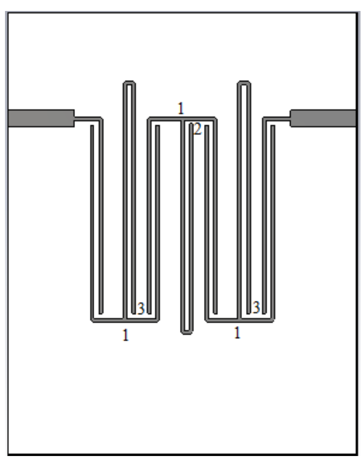


FIGURE 6.2.1. Hairpin coupled line filter with shunt connected coupled line

Case L results in bandpass filter, this bandpass response is more flat compare to the simple hairpin coupled bandpass filter. Case M results in bandstop filter and Case N results in dualband bandpass filter.

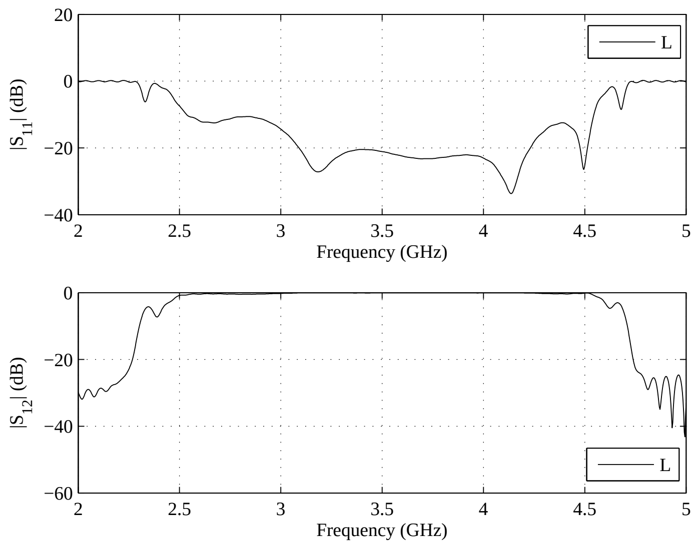


FIGURE 6.2.2. Variation of reflection loss and insertion loss for all shunt open circuited coupled line

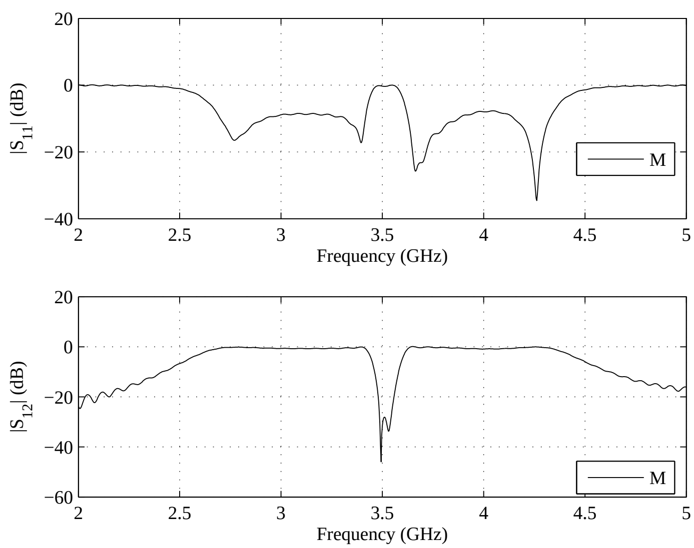


FIGURE 6.2.3. Variation of reflection loss and insertion loss for all shunt short circuited coupled line

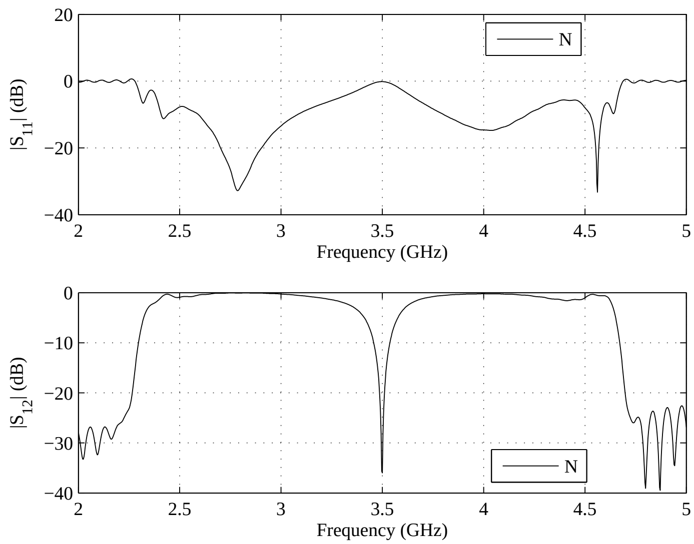


FIGURE 6.2.4. Variation of reflection loss and insertion loss for two shunt open circuited and one open circuited coupled line

Conclusion

To design dual bandpass filter, initially bandpass and bandstop filter are designed from lowpass prototype filter using filter transformations and filter scaling. It consists of combining individual bandpass filter and bandstop filter into one using different connections (series connection, parallel connection, cascade connection of bandpass and bandstop filters). Simulation are carried out on Butterworth filter using these different connections and results are compared. From the results it is concluded that series connection of bandpass and bandstop filter gives more flat response. After this simulation series connection is used for different order filters and the results are compared. From the simulation results it is concluded that as the order of the filter increases the response of the filter approaches to ideal filter. After designing dualband filter this series connection of bandpass and bandstop filter is used to design triple band filter. Although this is lumped design of dual bandpass filter, it is possible to explore this technique for designing of multi band filter.

Lumped elements cannot be used at the high frequencies so distributed elements are used. Coupled lines are used as distributed elements. Coupled lines are analyzed with two ports and single port using different configurations. When coupled lines are designed as two port network and simulations are carried out on this design, then it is concluded that this design behave as a bandpass filter. After analyzing coupled lines as two port network, single port coupled lines are designed using different combinations. After analyzing single port coupled lines, it is concluded that different resonant frequencies can be obtained from different combinations at the desired frequency range. After this single port lines are connected in shunt to the two port network and left bottom end of coupled line is short circuited, then it is analyzed that it results in bandstop filter. When this left bottom end is open circuited, then it results in bandpass filter.

After analyzing two port and single port coupled lines separately, these coupled lines are connected together in such a manner that bandpass, bandstop and dual bandpass response can be obtained. After this hairpin coupled line filter is used because it makes the structure compact and dual bandpass behavior of the filter is analyzed.

Publications

(1) Neelam Kumari, Salman Raju Talluri (2017). ”A Novel Method Of Designing Bandpass and Bandstop Filter Using Single Port Coupled Line”*, Proceedings of the International Conference on Microwaves Antenna Propagation & Remote Sensing (ICMARS-2017), ICRS*, [12th : Jodhpur : 15-17 February, 2017], pp.198-200.

(2) Neelam Kumari, Salman Raju Talluri, ”A Simple Novel Method Of Designing Dual-band And Multi-bandpass Filters”, *International Journal of Advances in Microwave Technology.* (Under Review)

(3) Neelam Kumari, Salman Raju Talluri, ”Novel Method to Design Dual-Bandpass Filter Using Parallel Coupled Lines”, *IETE Jornal Of Research.* (Under Review)

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