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Design, Simulation and Fabrication of a Microstrip Bandpass Filter

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Abstract: This paper presents the design technique, simulation, fabrication and comparison between measured and simulated results of a parallel coupled microstrip BPF. The filter is designed and optimized at 2.44 GHz with a FBW of 3.42%. The first step in designing of this filter is approximated calculation of its lumped component prototype. Admittance inverter is used to transform the lumped component circuit into an equivalent form using microwave structures. After getting the required specifications, the filter structure is realized using parallel coupled technique. Simulation is done using ADS software. Next, optimization is done to achieve low insertion loss and a selective skirt. The simulated filter is fabricated on FR-4 substrate. Comparison between the simulated and measured results shows that they are approximately equal.
Keywords: Advanced Design System (ADS), Flame retardant 4 (FR-4), Bandpass Filter (BPF), Fractional Bandwidth (FBW)

1. INTRODUCTION

The microwave filter is a two port network which is used to control the frequency response at a specific point in a communication system by providing transmission at frequencies within the passband and attenuation in the stopband of a filter. Around the years preceding World War II, microwave filter theory and practice began by pioneers such as Mason, Sykes, Darlington, Fano, Lawson and Richards. Today, most microwave filter designs are done with sophisticated computer-aided design (CAD) packages based on the insertion loss method. The image parameter method may yield a usable filter response for some applications, but there is no methodical way of improving the design. The insertion loss method, however, allows a high degree of control over the passband and stopband amplitude and phase characteristics, with a systematic way to synthesize a desired response[1],[2].

1.1 Bandpass Filter

A bandpass filter only passes the frequencies within a certain desired band and attenuates others signals whose frequencies are either below a lower cutoff frequency or above an upper cut-off frequency. The range of frequencies that a bandpass filter allows to pass through is referred as passband. A typical bandpass filter can be obtained by combining a low-pass filter and a high-pass filter or applying conventional low pass to bandpass transformation.

The ideal bandpass filter has a flat passband where no gain or attenuation is there and all frequencies outside the passband are completely rejected. In general condition, there is no ideal band pass filter. Thus, it can be said that the filters do not attenuate all frequencies outside the desired frequency range. This phenomenon is known as filter roll off and is usually expressed in dB of attenuation per octave or decade of frequency. The resonant series and parallel LC circuits are combined to form a band-pass filter as shown in Fig.1below. In this circuit, the resonant series LC circuits are used to allow only the desired frequency range to pass while the resonant parallel LC circuit is used to attenuate frequencies outside the passband by shunting them towards the ground.

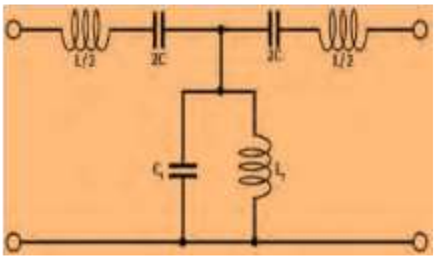


Fig.1 Example of a bandpass filter

Lumped components come with parasitics. For example, an inductor has parasitic resistance and parasitic capacitance. As high frequency is approached (around 1 GHz), parasitics start affecting the frequency response of the filter. It is also very difficult to model a lumped component. Thus, lumped component bandpass filter circuit is converted to microstrip transmission line structure using various methods such as richard's transformation, kuroda's identities, immitance inverters and so on[3].
Nowadays, a microstrip transmission line or strip line is being made as a filter due to its behavior as a good resonator. Micro strip lines give better compromise in terms of size and performance than lumped element filters. The microstrip transmission lines consist of a conductive strip of width (W) and thickness (t) and a wider ground plane, separated by a dielectric layer (ε) of thickness (h) as shown in Fig. 2 below.

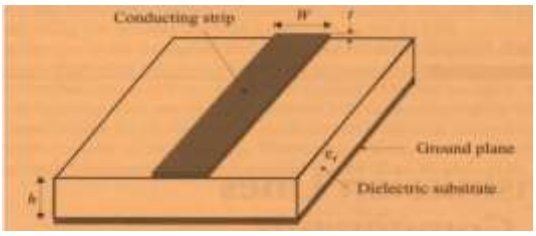


Fig.2 General microstrip structure

1.2 Microstrip

A microstrip line filter type includes stub impedance, step impedance and coupled line filter. Parallel coupled transmission-line filter in microstrip and stripline technology are very common for implementation of bandpass and band-stop filters with required bandwidth up to a 20 % of central frequency. Due to their relatively weak coupling, this type of filter has narrow fractional bandwidth but instead has desired advantages such as low-cost fabrication, easy integration and simple designing procedure[4]. Designing equations for the coupled line parameters such as space-gap between lines and line widths and lengths, can be found in classical microwave books. This way, following a well-defined systematic procedure, the required microstrip filter parameters can be easily derived for Butterworth and Chebyshev prototypes. The same can be done by using ADS software too.

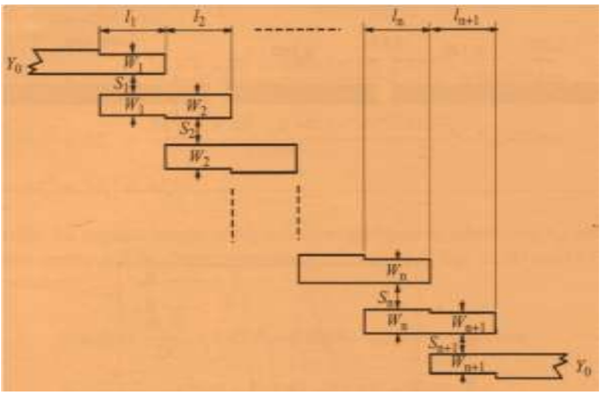


Fig.3 General structure of microstrip parallel coupled line filter

In the figure above, the width, gap, length and impedance are labeled as (W), (S), (l), and (Y0) consequently. The coupling gaps correspond to the admittance inverters in the low-pass prototype circuit(Fig.4). Even- and odd- mode characteristic impedances of parallel-coupled half-wave resonators are computed using admittance inverters. These even- and odd-mode impedances are then used to compute physical dimensions of the filter.

1.3 ADS Software

ADS is used as the simulation software. Advanced Design System (ADS) is an electronic design automation software system produced by AGILENT EEs, a unit of Agilent Technologies. It provides an integrated design environment to designers of RF electronic products such as mobile phones, pagers, wireless networks, satellite communications, radar systems, and high speed data links. Agilent ADS supports every step of the design process—schematic capture, layout, frequency-domain and time-domain circuit simulation, and electromagnetic field simulation—allowing the engineer to fully characterize and optimize an RF design without changing tools.

1.3 FR-4 PCB

Fabrication of the filter is done on FR-4 printed circuit board. FR-4, an abbreviation for Flame Retardant 4, is a type of material used for making a printed circuit board (PCB). It describes the board itself with no copper covering. The FR-4 used in PCBs is typically UV stabilized with a tetra functional epoxy resin system. It is typically a yellowish color. FR-4 manufactured strictly as an insulator (without copper cladding) is typically a dysfunctional epoxy resin system and a greenish color. FR-4 is preferred over cheaper alternatives such as synthetic resin bonded paper (SRBP) due to several mechanical and electrical properties; it is less loss at high frequencies, absorbs less moisture, has greater strength and stiffness and is highly flame resistant compared to its less costly counterpart. Fr-4 is widely used to build high-end consumer, industrial, and military electronic equipment. It is also ultra-high vacuum (UHV) compatible[5].

2. DESIGN FLOW

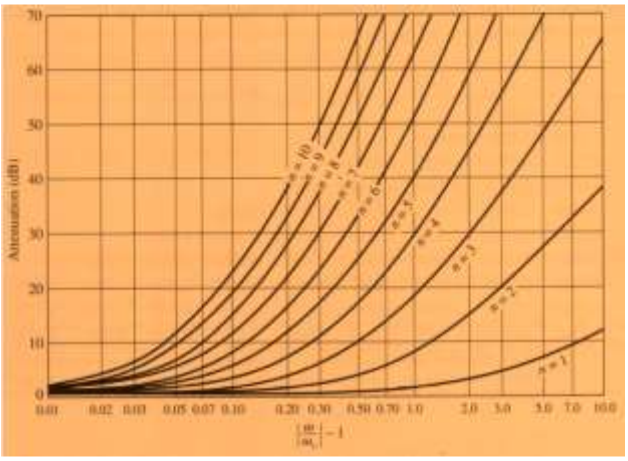
A chebyshev filter is designed to operate between 2.40-2.48 GHz with the center frequency of 2.44 GHz[6]. Passband ripple is taken as 0.5 dB. Insertion loss and return loss are required to be ≤ 1 dB and > 15 dB respectively.

The first step in designing a filter is to find its order. The fractional bandwidth and normalized frequency are found by the formulae given below[7].

$$\text{Fractional Bandwidth (FBW)} = \frac{\omega 2 - \omega 1}{\omega o} = 0.0342$$

$$\text{Normalized Frequency} = \left| \frac{\omega}{\omega 1} \right| - 1 = 0.42$$

Here, ω1 and ω2 are the edge frequencies and ωo is the center frequency. Then the order of the filter is found out by the attenuation $v_{s.}$ normalized frequency graph for 0.5 dB ripple as shown in the graph given below.



Graph 1. Attenuation $v_{s.}$ normalized frequency graph for 0.5 dB

The order of the filter is n=5 at minimum attenuation=20dB and normalized frequency=0.42. The element values for fifth order filter are determined from Table 1.

Table 1. Table of Element values for 0.5dB ripple low pass filter prototype

					0.5 dB Ripple						
N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}
1	0.6986	1.0000									
2	1.4029	0.7071	1.9841								
3	1.5963	1.0967	1.5963	1.0000							
4	1.6703	1.1926	2.3661	0.8419	1.9841						
5	1.7058	1.2296	2.5408	1.2296	1.7058	1.0000					
6	1.7254	1.2479	2.6064	1.3137	2.4758	0.8696	1.9841				
7	1.7372	1.2583	2.6381	1.3444	2.6381	1.2583	1.7372	1.0000			
8	1.7451	1.2647	2.6564	1.3590	2.6964	1.3389	2.5093	0.8796	1.9841		
9	1.7504	1.2690	2.6678	1.3673	2.7239	1.3673	2.6678	1.2690	1.7504	1.0000	
10	1.7543	1.2721	2.6754	1.3725	2.7392	1.3806	2.7231	1.3485	2.5239	0.8842	1.9841

The element values obtained are: g1 =g5 =1.7058, g2 =g4=1.2296, g3=2.5408. The low-pass prototype elements values obtained can be represented as shown in Figure 4.

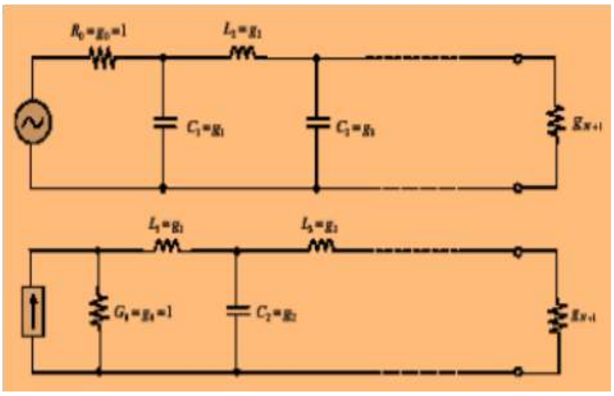


Fig. 4 Low pass filter prototype

The low-pass filter consists of series and parallel branch. J-inverter is used to convert low-pass filter to bandpass filter with only shunt branch as shown in figure 5.

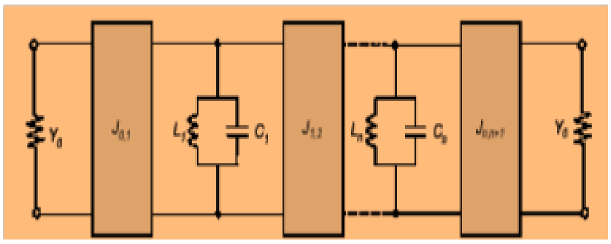


Fig. 5 Bandpass filter prototype

Using the equations given below, J-inverter performs the low pass to bandpass conversion.

$$\frac{J_{01}}{Y_0} = \sqrt{\frac{\pi FBW}{2 g_0 g_1}}$$

$$\frac{J_{j,j+1}}{Y_0} = \frac{\pi FBW}{2\sqrt{g_j g_{j+1}}}$$

---------j=1 to n-1

Where FBW is the fractional bandwidth of the bandpass filter, Jj, j+1 are the characteristic admittances of the J-inverters and Y_0 the characteristic admittance of the terminating lines. To realize the J-inverters, even- and odd-mode characteristic impedances of coupled lines are determined by using the relations given below.

$$(Z_{0e})_{j,j+1} = \frac{1}{Y_0}\left[1 + \frac{J_{j,j+1}}{Y_0} + \left(\frac{J_{j,j+1}}{Y_0}\right)^2\right]$$

$$(Z_{0o})_{j,j+1} = \frac{1}{Y_0}\left[1 - \frac{J_{j,j+1}}{Y_0} + \left(\frac{J_{j,j+1}}{Y_0}\right)^2\right]$$

-------j=0 to n

The calculated results are tabulated below.

Table 2. Parallel coupled filer parameters

Stages of filter	Admittance inverters $J_{j,j+1}/Y_0$	Even mode impedance (Z_{0e})	Odd mode impedance(Z_{0o})
1	0.17746	60.4476	42.7016
2	0.03709	51.923	48.214
3	0.03039	51.5656	48.5266
4	0.03039	51.5656	48.5266
5	0.03709	51.923	48.214

By using the LineCalc tool in Advanced Design System (ADS), Agilent Technologies version 2013 software, the dimensions of width, spacing and length of each stage are calculated by using even and odd characteristic impedance. The characteristic impedance Z_0 is typically assumed as 50 Ohms. The standard FR-4 board requirements are-

Table 3 FR-4 Specifications

Conductor thickness	0.035mm
Height	1.6mm
ε_R	4.8
tanδ	0.002
conductor conductivity	5.8e7

Next, optimization is done. All parameters and goals have to be set up properly. After that, the optimization and tuning process carried on for the best results and performance. The finalized dimensions of width, gap and length of each stage are shown in Table 4 below.

Table 4 Geometrical parameters of the coupled lines

Line description	Width(mm)	Length(mm)	Spacing(mm)
50Ω-line1	2.61	4.1137	-
Coupled line1	2.61	11.704	0.35261
Coupled line2	2.61	19.3057	3.558
Coupled line3	2.61	11.727	0.473
Coupled line4	2.61	11.41799	0.11089
Coupled line5	2.61	19.255	0.498
50Ω-line2	2.61	4.35312	-

3. IMPLEMENTATION IN ADS

As a final step, the coupled line filter is designed in the ADS simulation software environment. It accepts filter parameters and produces physical dimensions of the filter layout and a simulation of the filter response.

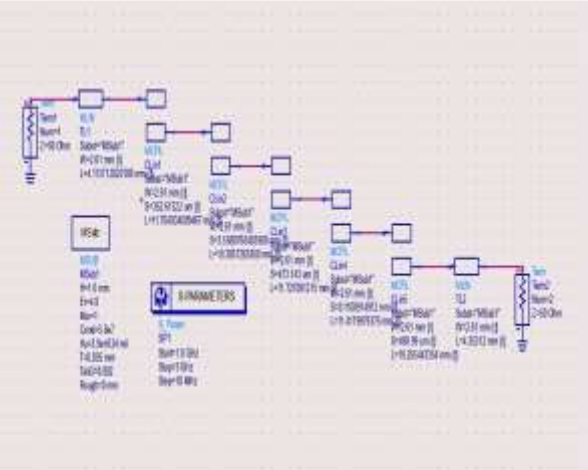


Fig. 6 Schematic of parallel coupled bandpass filter

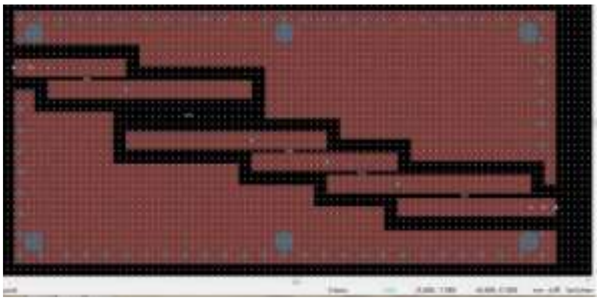


Fig. 7 PCB Layout of parallel coupled bandpass filter

3.1 Simulation

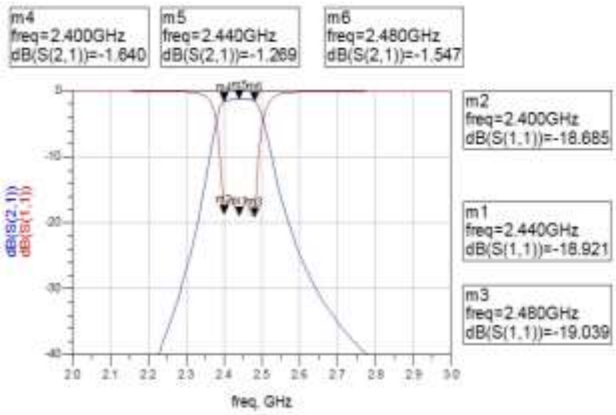


Fig. 8 Simulation result of parallel coupled band pass filter for S (1, 1) and S (2, 1)

Table 5 Simulation results

Parameter	Lower Frequency(ω1) 2.40 GHz	Upper Frequency(ω2) 2.48 GHz	Center Frequency(ω_0) 2.44 GHz
S(1,1)	-18.685 dB	-19.039 dB	-18.685 dB
S(2,1)	-1.640 dB	-1.547 dB	-1.269 dB

The calculated bandwidth was 80MHz.The Simulated bandwidth is less than the calculated bandwidth. The specified insertion loss was supposed to be less than or equal to 1dB but the simulated insertion loss is between 1 to 2 dB. The simulated passband ripple is less than 1dB as per the specifications. The return loss is greater than 15dB as required.

4. FABRICATION

Filter PCB is fabricated using FR-4 board. Filter lay out was generated in ADS tool in Gerber format. It can be noticed from Fig 8 that many plated through holes are made all around the filter to nullify the parasitic effects. Mounting holes are also through drilled and through hole plated at appropriate distances to provide good grounding. Finally the Filter PCB is mounted inside a mechanical housing which is fabricated using Aluminum strips/blocks. Finally the whole housing was CCC plated for better electrical performance SMA connectors are mounted on to the housing in such a way that the center pin of the SMA connector directly land on to the 50 Ohms line for Input/out connectivity.

Fig. 8 Fabricated microstrip parallel coupled line band pass filter

5. TESTING

Performance of the Filter is tested using R&S Scalar Network Analyzer ZLV13, which is 13 GHz network Analyzer[8]. Fig 9 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

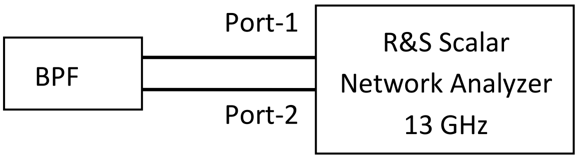


Fig. 9 Test set up for testing micro strip parallel coupled line band pass filter

Table 6 Tested results

Parameter	Lower Frequency(ω1) 2.40 GHz	Upper Frequency(ω2) 2.48 GHz	Center Frequency(ω_0) 2.44 GHz
S(1,1)	-16.5dB	-16 .1dB	-17.3 dB
S(2,1)	-3.0 dB	-3.1dB	-2.7dB

6. CONCLUSION

It can be seen from the test results that insertion loss figures are slightly more (1.5 dB) than 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.

7. REFERENCES

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