Design and Analysis of Microstrip Low Pass and Bandstop Filters

Hussain Bohra, Amrit Ghosh

Abstract**: *In this paper a simple approach of designing the microstrip low pass and bandstop filter is presented. The microstrip stub based low pass filter with 2.4 GHz and attenuation of more than 60 dB at 4 GHz frequency is designed. The bandstop filter is also designed with notch characteristics at 2.4 GHz frequency. The fractional bandwidth of designed filter is estimated to be 30% with 117 dB of attenuation is recorded at notch frequency of 2.4 GHz in SIR based bandstop filter topology. The bandstop filter is implemented using coupled line structure as well as step impedance resonator techniques. The filters are designed on Roger RC40003C substrate. The design and analysis of filter with its layout and EM simulation is accomplished using Agilent ADS software. These filters can be used in front end transceiver systems, antennas, and modern wireless communication systems.***

Keywords: Bandstop Filter, Coupled line structure, Low pass filter, Microstrip, Step Impedance resonator.

I. INTRODUCTION

In modern microwave communication system the filters are most essential devices to reshape the frequency response by eliminating unwanted frequency bands. Presently filter design is carried out utilizing various methods viz. Insertion Loss method in advanced high frequency softwares like ADS, CST studio, HFSS etc. The purpose of utilizing these softwares is to optimize the filter design in accordance of targeted response. The main role of a low pass filter is to pass low frequencies with minimum attenuation and stops higher frequency components based on its cutoff frequency.

Filters can be designed and fabricated by employing either techniques viz. distributed and lumped components. Realization of these filters with lumped components i.e. using inductors and capacitors above 500 MHz or 1GHz is very difficult as their dimensions tend to be equal with signal's wavelength which results in disseminate impacts. While distributed elements are composed of transmission line segments that are transformation equivalent of corresponding inductance and capacitance values.

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Various techniques are available and studied in literature to transform the low-pass /bandstop filters from lumped to its equivalent distributed filter. The distribute filter topology can be attained through microstrip stub implementation, in which the Richard transform is utilized to supplant the lumped elements with the transmission line, and Kuroda's transformation is utilized to isolate the filter components. Microstrip design plays significant role in numerous Radio Frequency or Microwave fields. A lot of challenges faced due emerging technologies such as modern wireless communication which demands good performance, compactness and cheaper cost. Microstrips are fabricated on dielectric substrate with metal strips engraved on top and/or bottom/ground layer using printed circuit board [PCB] technology. Micro strip RF filters are widely employed to transfer microwave-frequency signal in microwave devices transceivers operating in the range of hundreds of MHz to 30 GHz frequency spectrum.

Various existing wireless communication technologies are prone to degrade the performance of communication systems due to interference of signals lying within the bandwidth of interest. Extensive researches have been done in developing single band as well as multiband band-stop filters. They are specifically designed for applications such as modern communication systems. Bandstop filters are employed in microwave or radio frequency (RF) communication system applications to suppress unenviable or undesired frequency components.

Band-stop filter is employed to alleviate specific frequency components in the transceiver of a communication system. The rejection bandwidth of a bandstop filter should be narrow enough to boost up its performance characteristics and to suppress interfering frequency components. For an ideal band-stop filter design, the transition response at lower cut-off frequency along with higher one should be sharp enough to attenuate undesired narrow band of frequencies.

A variety of bandstop filter designs is studied and employed till date. Generally the conventional techniques are widely employed to enhance the operational features of the bandstop filter. These techniques involve transformation of low pass filter into bandstop filter. Later these filters are fabricated using transmission line structures. Various short/ open circuited half wavelength/quarter wavelength structures can be employed to design the resonators coupling line structures. Both low pass filters as well as stop band filters are widely used in transformers, oscillators, mobile phones, cable television, transformers, satellite location systems etc.

In this paper the analysis and design of stub based low pass filter as well as step impedance resonator based band stop filter is accomplished. The design of these filters is carried out using high frequency software Agilent ADS.

The element values of low pass filter prototype viz. equi ripples and maximally flat are employed to specify & finalized filters parameters. The filters are first implemented with lumped components. At high frequencies above 500 MHz the practical implementation of these filters are highly impractical due to its bulkier size. To eradicate this issue the filters are implemented using microstrip transmission lines i.e. distributed components. Richards's transformation and Kuroda's identities are used to transform lumped components into microstrip coupled line structures. Step impedance resonator (SIR) implementation is accomplished by finding the electrical length of short or open stubs and thereby calculating dimensions of transmission line using Linecalc in ADS. Finally optimization and EM simulation is accomplished to achieve desired filter response.

II. LITERATURE SURVEY

A. Low pass filter

Microstrip lowpass filters are key microwave components in various modern wireless communication systems. A lot of research has been done to improve in-band and out-band performances of these filters in recent years. A wide stop band stub-loaded coupled-line hairpin low pass filter with sharp cutoff is proposed in [38]. A compact microstrip LPF with wide stopband rejection is proposed and implemented using patch resonators [27]. A wide band rejection compact low pass filter implemented by transformed radial stubs is presented and fabricated in [13].

A stepped impedance hairpin resonator based compact low pass filter with radial stubs is proposed in [11] with wide stopband characteristics. This filter lags to achieve a sharp transition band in this filter response.

The design of lumped filters is presented with the physical interpretation of the terminology and characteristics of radio frequency (RF) filters [40]. It also explained the design of low pass filters used in communication systems to suppress spurious modes in oscillators, mixers etc. Radio Frequency (RF) or microwave filters can be implemented either by lumped configuration or distributed topologies as per requirements and applications in various modern communication systems is presented [7]. To optimize the design of the microwave filters in context to attain compactness, improve performance, sharpness, higher selectivity, lower cost etc. in order to meet emerging applications of wireless communications is presented in [3]. A short circuited microstrip low pass filter at 2 GHz in ADS is presented in [23].

The lumped element filters becomes impractical at high frequencies as its wavelength becomes comparable with the physical size, resulting in the severe losses which degrades the filter's performance is studied in [33]. The comparative study between Chebyshev or equi-ripple filter and the maximally flat response revealed that Chebyshev has superior characteristics than Butterworth response [8].

B. Bandstop Filter

Single band and multi band compact bandstop filters are proposed and fabricated employing T-shaped DMS (defected microstrip structure) with sharp frequency selectivity in [19]. Tri passband filter between (1 to 2.9 GHz) with compact design of band stop filter is proposed by Liu [37].The wideband bandstop filter implemented using SIR (step impedance resonator) embedded with open stubs that attained reasonable insertion loss is proposed in [39].

An open stub T-inverted topology with ultra compact design of band stop filter in presented in [20]. This filter has compact size of 43.4 mm x 34.5 mm attained 900 MHz bandwidth with return loss (>20 dB) at cut-off frequency of 1.80 GHz.

Split ring resonator topology based band stop filter with insertion loss less than 10 dB over 38% of fractional bandwidth at 4 GHz centre frequency is proposed in [14]. The resonator structure is printed on both sides of substrate to attain the ultra-compact filter design.

In a nutshell, the wideband frequency spectrum is widely employed for military applications, radar systems, modern wireless communication systems etc. However, the existing frequency spectrum may interfere with newly launched wideband technology for other emerging communication applications. To alleviate this issue, the microstrip bandstop filter designed with narrow notch characteristics is very effective in removing undesired frequency components from existing radio signal in the passband. Thus the overall performance of these communication systems enhances upto a greater extent.

III. DESIGN AND ANALYSIS OF FILTERS

A. Design of Stub Based Microstrip Lowpass Filter

In this paper a 5^{th} order low-pass filter at 2.4 GHz cut off frequency and 50Ω matched Input-output impedance is proposed. The filter shows equi-ripple characteristics with a sharp rejection of greater than 60 dB at 4 GHz frequency. Roger RO4003C substrate of ε_r = 3.55 with its thickness t=0.017 mm is used for design purpose. We will use transformations viz. Richard's transformation and Kuroda's identities for implementation of this filter in distributed topology.

The procedure of designing proposed filter can be shown as:

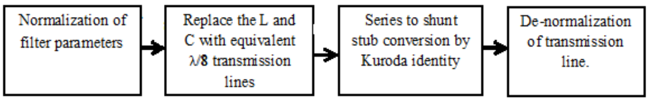

Figure 1. Design flow chart for stub based LPF

Figure 2. shows the equivalent realizations of a low pass filter using normalized elements, where g_{N+1} represents the load resistor while g_n reflects shunt capacitance or series inductance.

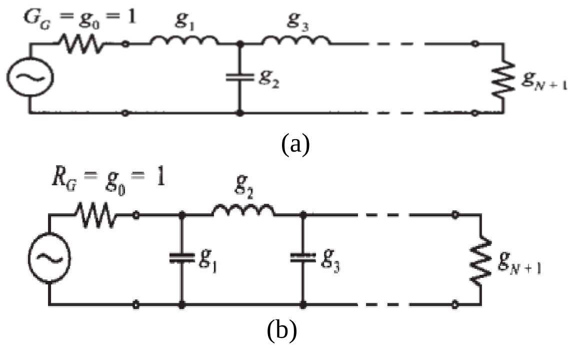

Figure 2. Realization of LPF with normalized elements

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The proposed filter then can be implemented using low pass prototype equivalent (0.5 dB Equi-ripple Low Pass Filter). The cut off frequency and source-load impedance are normalized to unity. The 5th order low pass filter prototype can be shown as:

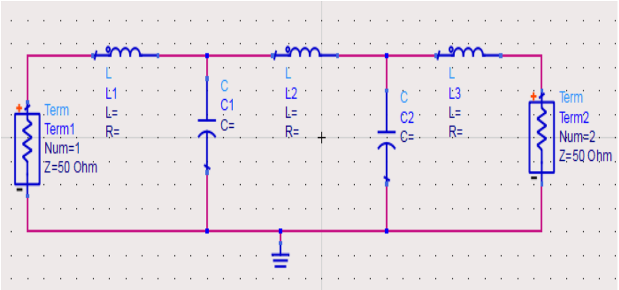

Figure 3. Schematic of 5th order Low pass filter prototype

The series arm inductance and shunt arm capacitance values are tabulated in table 1 (for cut off frequency of 2.4 GHz) using following formulas:

$$L_n = \frac{g_n Z_0}{\omega_c} \text{ and } C_n = \frac{g_n}{Z_0 \omega_c} \quad (1)$$

Table 1: Series L and Shunt C elements values

Values of Elements	L & C values (corresponding)
g1=1.7058	L1=5.43 nH
g2= 1.2296	C2=1.63 pF
g3=2.5408	L3=8.43nH
g4=1.2296	C4=1.63 pF
g5=1.7058	L5= 5.43 nH

Thus using series L and shunt C values from above table 1, the corresponding filter designed in ADS can be shown as:

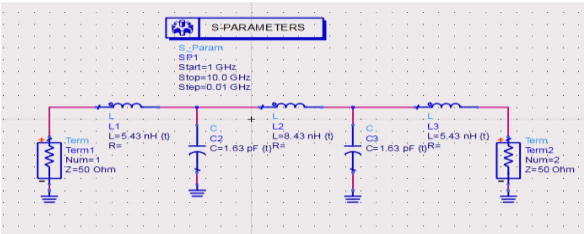

Figure 4. Schematic of 5th order Low pass filter in ADS

The corresponding S-parameter output waveform of LPF implemented using lumped elements can be shown as:

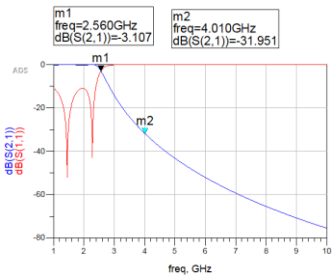

Figure 5. Simulated S11 and S22 parameter of lumped circuit

Lumped based filters are difficult to implement beyond 0.5 GHz frequency due to their comparable physical dimensions with its wavelength. For practical implementation, necessary transformations are to be carried out to obtain equivalent distributed element realizations. So we will undergo micro strip implementation. To accomplish this design, we will follow these transformations [8]:

- Richards Transformation
- Kuroda Identities

(a) Richards Transformation

Richards's transformation is applied to carry out following replacements:

- Shorted stubs are employed in place of lumped inductors.
- Open stubs are employed in place of lumped capacitor.

(b) Kuroda's Identities

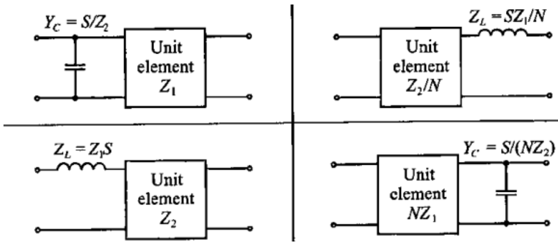

Figure 6. Kuroda's Transformation

The value of N shown above can be calculated by following equation:

$$N = 1 + {}^{Z_2}\!/_{Z_1} \quad (2)$$

The shorted series stub is difficult to realize as compared to open stubs. This problem can be alleviated using another transformation known as Kuroda's identities. For practical implementation of microstrip filters, the unite elements are inserted having quarter wavelength electrical length to carry out necessary conversions into their equivalent open stubs topology.

After applying Richards Transformation and Kuroda Identity, finally the low pass filter needed to undergo denormalization process as shown table 2. Thus for each L and C length and line width are calculated using linecalc in ADS as shown in table 2.

Table 2. Impedance values with their equivalent (W, L) dimensions

Impedance (Ω) by Kuroda Identity	Width (W) in (mm)	Length (L) (mm)
Z1 = 64.9	0.4689	9.71999
Z2= 217.5	0.78111	9.53546
Z3=70.3	0.614679	9.62544
Z4=217.5	0.78111	9.53546
Z5=64.9	0.4689	9.7199

Finally the transformation from prototype to microstrip low pass filter can be shown as:

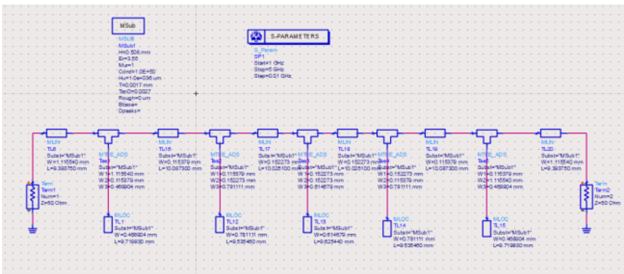

Figure 7. Schematic of Microstrip based 5th order Low Pass Filter

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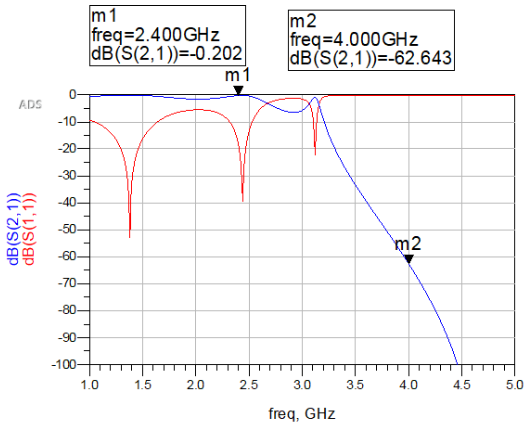

Figure 8. Simulated S11 and S21 parameters for Microstrip LPF

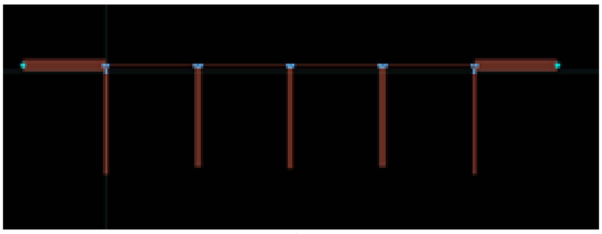

Figure 9. Layout of Microstrip LPF

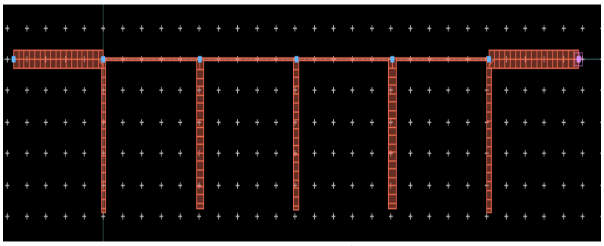

Figure 10. EM Layout of Microstrip LPF

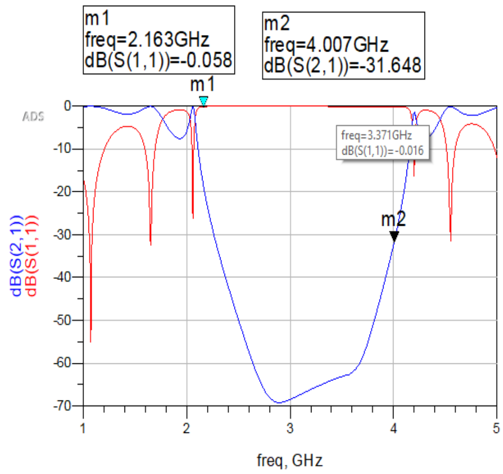

Figure 11. EM Simulation Result of stub loaded LPF

Full wave EM analysis on ADS is carried out to generate more accurate results. The Momentum layout and 3-D preview of the designed circuit are illustrated in Figure (10) and (12) respectively.

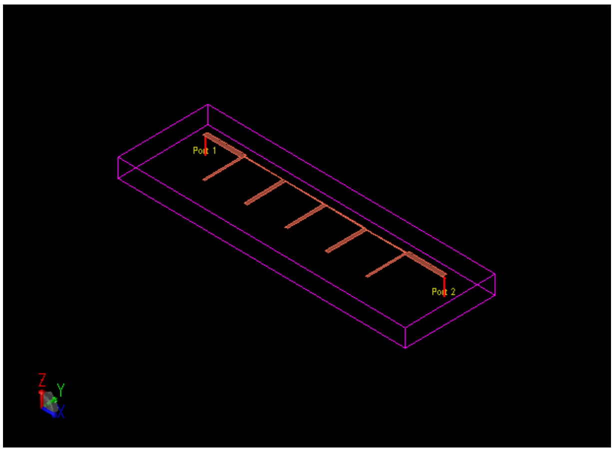

Figure 12. A 3 D preview of Momentum Layout of LPF

B. Design of Coupled Line Based Bandstop Filter

To design coupled line band stop filter (BSF) at 30% of fractional bandwidth, f_c=2.4 GHz, insertion loss (>40 dB) and matched impedance of 50 ohm, we will be using ADS and its various features as shown in figure 13.

To design 5th order bandstop filter using Roger RO4003C substrate with ε_r = 3.55 (dielectric constant), h =0.508 mm (thickness), Z_0 = 50 Ω (characteristic impedance), etc. are selected. The low pass prototype maximally flat filter needs to be transformed to bandstop configuration with lumped elements as shown in figure 13.

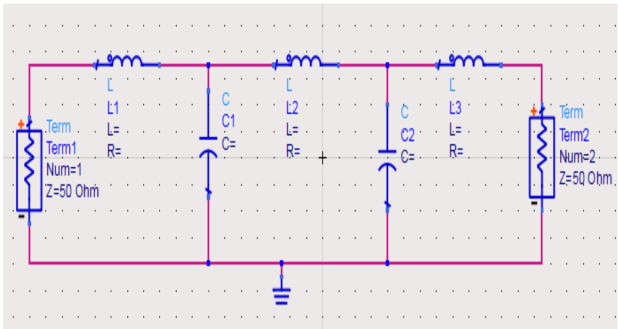

Figure 13. Low pass filter (Lumped configuration)

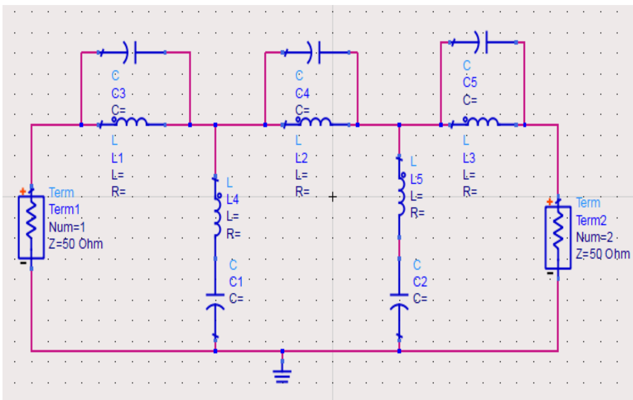

Figure 14. Prototype of Band stop filter using ADS

Now we will calculate the inductor and capacitor values in above lumped circuit diagram using the element values of 0.5 dB equi-ripple prototype LPF as:

$R_0 = g_0 = 1$, $L1 = g_1$= 1.7058, $C2 = g_2$= 1.2296, $L3 = g_3$= 2.5408, $C4 = g_4$= 1.2296, $L5 = g_5$= 1.7058, $R_L = g_6 = 1$

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Prototype filter transformations tabulated as shown below.

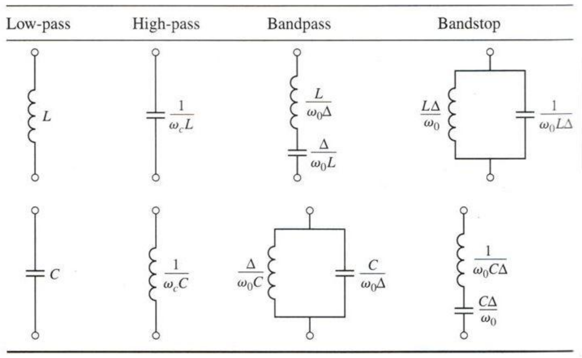

Figure 15. Prototype filter transformations

We can find the FBW (fractional bandwidth) using following equation:

$$\Delta = \frac{\omega_2-\omega_1}{\omega_0} = 0.3 \tag{3}$$

The scaling of impedances can be determined by following relations:

$$L' = R_0\, L,\ C' = C\ /R_0,\ \mathrm{Rs} = R_0,\ R_L = R_0 \tag{4}$$

where $R_0 = 50 \neq 1$

Conversion from series L (inductor) of LPF equivalent to parallel combination of LC can be given as:

$$L'_n = \frac{\Delta L_n}{\omega_0} \quad \text{and} \quad C'_n = \frac{1}{\Delta\omega_0\, L_n} \tag{5}$$

Combined with the impedance-scaled:

$$L'_n = \frac{\Delta R_0 L_n}{\omega_0} \quad \text{and} \quad C'_n = \frac{1}{\Delta\omega_0\, R_0\, L_n} \tag{6}$$

Conversion from shunt C (capacitor) of LPF equivalent to series combination of LC can be given as:

$$C'_n = \frac{\Delta C_n}{\omega_0} \quad \text{and} \quad L'_n = \frac{1}{\omega_0\, \Delta C_n} \tag{7}$$

Combined with the impedance-scaled:

$$C'_n = \frac{\Delta C_n}{\omega_0 R_0} \quad \text{and} \quad L'_n = \frac{R_0}{\omega_0 \Delta C_n} \tag{8}$$

The corresponding L & C values for parallel and series combinations determined from above mentioned formulas can be tabulated as:

Table 3: Impedance-scaled and frequency-transformed element values

Parallel L-C Connection			
Components	Value (nH)	Components	Values (pF)
L1	0.615	C1	7.128
L2	2.2686	C2	15.568
L3	0.6027	C3	7.2
Series L-C Connection			
L4	7.3081	C4	0.6
L5	6.9666	C5	0.6

Using ADS simulation software, the schematic of bandstop filter can be drawn as:

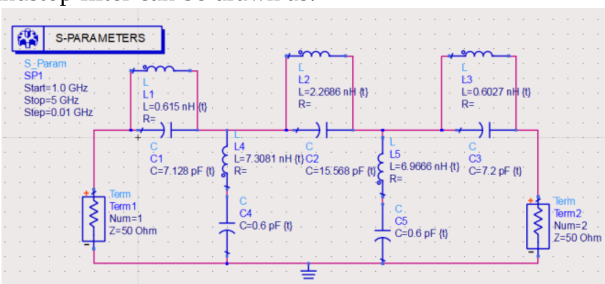

Figure 16. Schematic of 5th order Bandstop filter in ADS

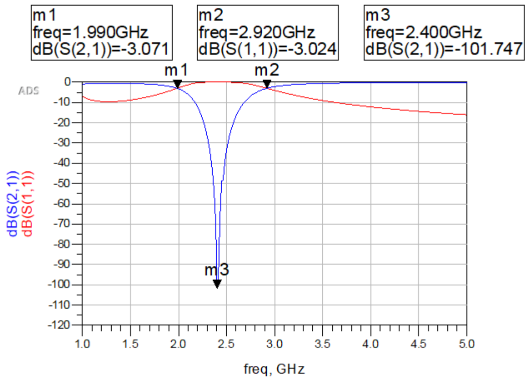

Figure 17. Simulated S parameter of 5th order Bandstop filter

The coupling line method to design the bandstop filter at the same center frequency of 2.4 GHz can be implemented as:

$$Z_{0e} = Z_0[1 + JZ_0 + (JZ_0)^2] \quad \text{and}$$
$$Z_{0O} = Z_0[1 - JZ_0 + (JZ_0)^2] \tag{9}$$

where Z_{0e} is even-mode and Z_{0O} is odd-mode impedance.

The coupled line segments can be linked in series for designing sharp notched filters. Propagation constant and various image impedance parameters will be evaluated. JZ_0 represents the admittance inverter and turns ratio $N = JZ_0$ are determined with following relations as:

$$Z_0 J_1 = \sqrt{\frac{\pi\Delta}{2g_1}} \tag{10}$$

$$Z_0 J_n = \frac{\pi\Delta}{2\sqrt{g_{n-1}\, g_n}} \quad \text{for } n = 2,3,4,\ldots\ldots..N. \tag{11}$$

$$Z_0 J_{N+1} = \sqrt{\frac{\pi\Delta}{2g_N g_{N+1}}} \tag{12}$$

where Z_0 is the characteristic impedance and $\Delta = (\omega_2 - \omega_1)/\omega_0$ is the fractional bandwidth.

Thus, the proposed coupled line bandstop filter implementation can be initiated by determining the element values from maximally flat low pass filter prototype. Then by using above equation (9), we can calculate Z_{0e} and Z_{0o} values and Z_0J_n can be found from equations (10) to (12). Now W (width) and L (length) can be computed in Linecalc of ADS software and tabulated as:

Table 4. Even and Odd mode impedances

n	gn	Z_0J_n	$Z_{oe}(\Omega)$	$Z_{0o}(\Omega)$
1	1.7085	0.5255	90.08	37.53
2	1.2296	0.3252	71.55	39.028
3	2.5408	0.2665	66.876	40.226
4	1.2296	0.2665	66.876	40.226
5	1.7085	0.3252	71.55	39.028
6	1	0.5255	90.08	37.53

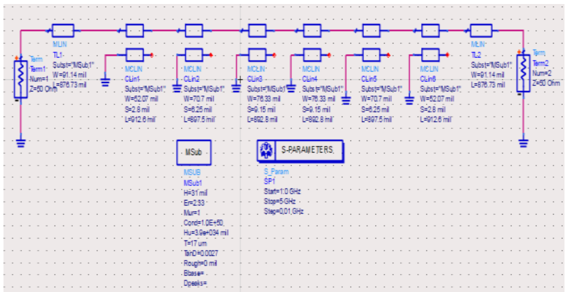

Figure 18. Coupled line structure of 5th order bandstop filter

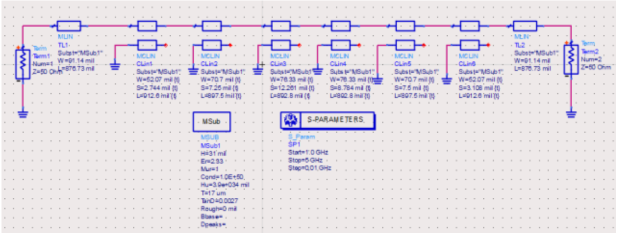

Figure 19. Tuned Coupled line structure of 5th order Bandstop filter in ADS

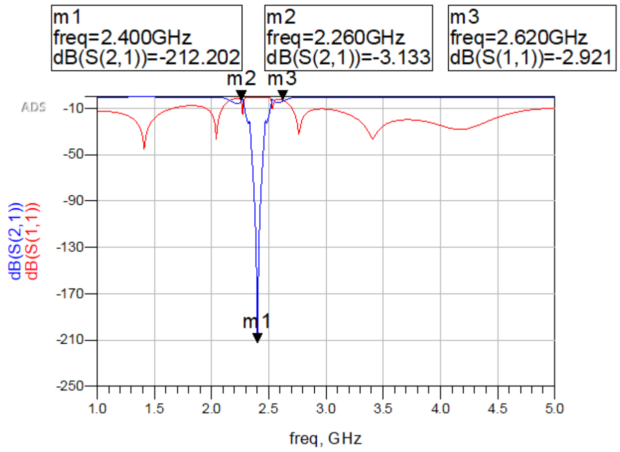

Figure 20. Simulation of S11 and S21 of coupled line bandstop filter

(2) Designing BSF by SIR technique

At first, using maximally flat LPF prototype, the LPF will be transformed into its equivalent bandstop filter topology. Stepped impedance resonator (SIR) technique will be employed to design 5th order BSF at $f_c = 2.4$ GHz with 117 dB of insertion loss. The input-output impedances are matched to 50 ohm.

To determine the lumped component circuit of low-pass filter, we will use the following relations:

$$L = \frac{Z_0 g}{\omega_c} \quad \text{and} \quad C = \frac{g}{Z_0 \omega_c} \qquad (13)$$

The lumped component values from equation (13) can tabulated as:

Table 5: Lumped components of maximally flat LPF

n	Component	Values
1	L1	2.05 nH
2	C2	1.54 pF
3	L3	6.63 nH
4	C4	1.54 pF
5	L5	2.05 nH

Now the transformation to lumped bandstop filter from its low pass equivalent filter can be achieved by using components values (L & C) from aforementioned table 5 and by using following formulas:

- For LC circuit in parallel configuration:

$$L_1 = \frac{g_1 \Delta Z_0}{\omega_0} \quad \text{and} \quad C_1 = \frac{1}{\omega_0 g_1 \Delta Z_0} \qquad (14)$$

- For LC circuit in series configuration:

$$L_2 = \frac{Z_0}{\omega_0 g_2 \Delta} \quad \text{and} \quad C_2 = \frac{g_2\,\Delta}{\omega_0 Z_0} \qquad (15)$$

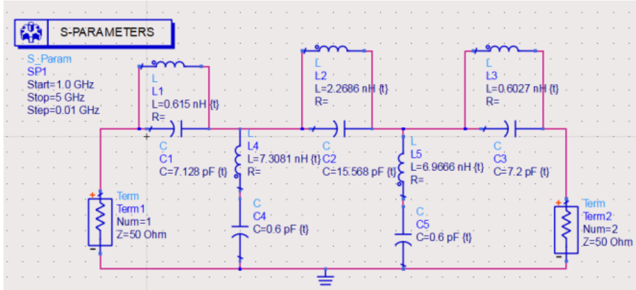

Figure 21. Lumped components 5th order bandstop filter at 2.4 GHz

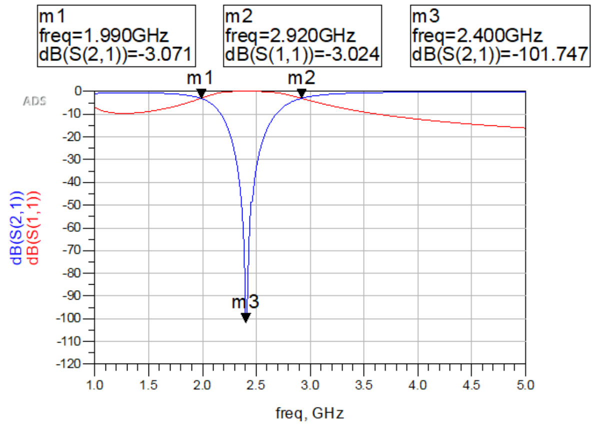

Figure 22. Simulated S-Parameters S11 & S21 for 5th order bandstop filter

At fractional bandwidth $\Delta = 30\% = 0.3$, the theoretical bandwidth is $2.4 \times 0.3 = 0.74$ GHz while simulated results gives bandwidth $2.92 - 1.99 = 0.93$ GHz. The simulated bandwidth based on filter design is nearly approaching towards theoretical values. Microstrip line has a characteristics impedance of $Z_0 = 50$ with its electrical length $\beta l = 90^0$.

Using ADS, the lumped components of 5th order bandstop filter can be transformed to its equivalent microstrip transmission line. Before carrying out this transformation, the lumped components based bandstop filter is modified with all shunted series LC resonator for ease of fabrication shown as:

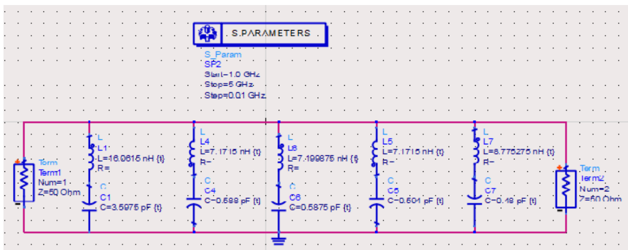

Figure 23. Lumped bandstop filter from parallel LC to shunt LC series connection

The dimension values (W, L) of the lumped components viz. capacitor and inductor will be computed for the purpose of transformation to transmission lines topology. The transformation is based the following principle:

- Inductor: It will be substituted with shorted stub keeping its length equal to βl and characteristic impedance L.
- Capacitor: It will be substituted with open stub keeping its same as inductor while impedance equals to 1/C.

Assuming $\beta l < 45^0$, the low and high impedance values can be given as;

$$Z_l = 15\,\Omega \quad \text{and} \quad Z_h = 150\,\Omega \tag{16}$$

The electrical length of capacitor and inductor can be computed with the help of the scaling equations as:

$$\beta l = \frac{LR_0}{Z_h} \quad \text{and} \quad \beta l = \frac{CZ_l}{R_0} \tag{17}$$

where Z_h, Z_l and R_0 are high characteristics impedance, low characteristics impedance and filter impedance respectively. Whereas L & C corresponds to normalized element values taken from the low-pass prototype filter.

The corresponding (W, L) for L and C values from above circuit diagram can be tabulated as:

Table 6. Transmission line dimensions

Component Values (nH)	Transmission line specifications		Component Values (pF)	Transmission line specifications	
	W (mm)	L (mm)		W (mm)	L (mm)
L1=16.0861 5	0.2	15.26 3	C1= 0.265	10.9692	0.80776 8
L4= 7.1715	0.2	9.379 5	C4= 0.588	10.9692	1.7843
L6= 7.1998	0.2	9.407 6	C6 = 0.588	10.9692	1.7828
L5= 7.1715	0.2	9.379 5	C5= 0.594	10.9692	1.8
L7= 8.775	0.2	10.85 4	C7= 0.48	10.9692	1.4594

The layout of the bandstop filter using SIR after carrying out necessary conversions for L and C values in terms of microstrip transmission lines can be shown as:

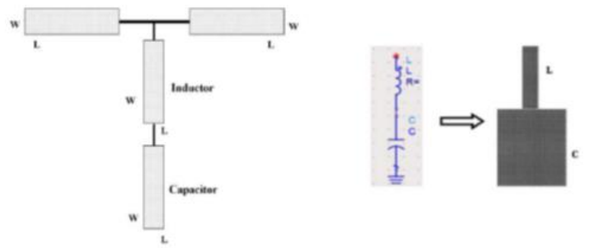

Figure 24. Lumped to SIR transformation

The SIR implementation of proposed BSF at f_c = 2.4 GHz using ADS can be represented with figure 25. The MLIN dimensions that is connecting the series combination of LC circuit is calculated as W=2.3144 mm, L=22.2655 mm.

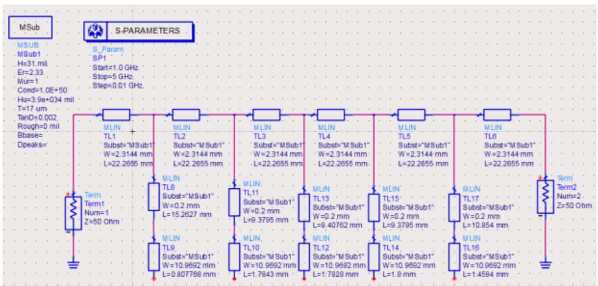

Figure 25. SIR Implementation of 5th order bandstop filter

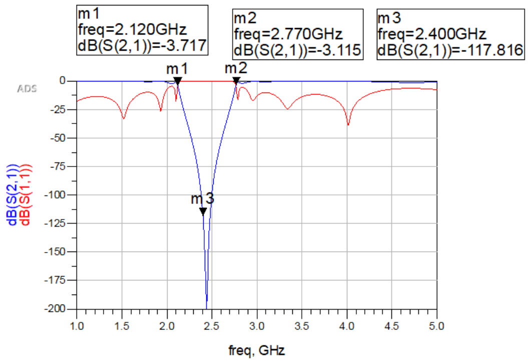

Figure 26. Simulated S11 and S21 parameters for SIR bandstop filter

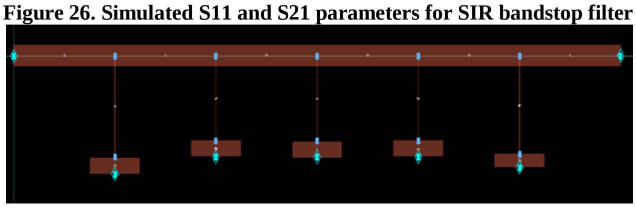

Figure 27. Layout of SIR based bandstop filter

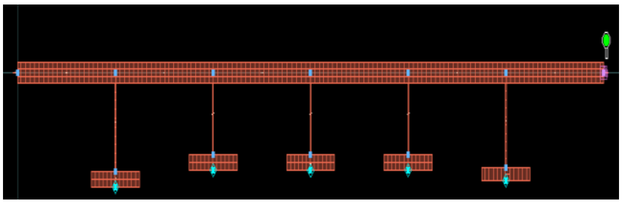

Figure 28. EM simulation layout of SIR based bandstop filter

IV. CONCLUSION

The microstrip low pass and bandstop filter are analyzed and designed using ADS software in this paper. The stub based low pass filter at f_c=2.4 GHz is designed with attenuation of more than 60 dB at 4 GHz frequency. The bandstop filter is also designed with notch characteristics at 2.4 GHz frequency. The fractional bandwidth of proposed filter is estimated as 30%. The design of bandstop filter is carried out using coupled line structure as well as step impedance resonator techniques. More than 117 dB attenuation is recorded at notch frequency of 2.4 GHz in SIR based bandstop filter. The design results revealed that SIR based filter is more compact and easily implemented compared to its coupled line structure equivalent. EM simulation is processed in ADS for optimization of the obtained results. The designed filters can be used in various existing wireless communication systems due to its compactness and sharp response.

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