

On the Design of Compact Dual Mode Multi-Band Bandpass Filters using Triangular, Circular and Hexagonal Shape Open – Loop Resonators

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Abstract - The design and performance of a band pass filter for UWB communications is presented in this paper. Open loop resonators consisting of parallel arms (stubs) protruding from a 50Ω transmission line create the required rejection bands. The arms height, width and spacing control the bandwidth achieved by the filter. Each pair of arm creates one reject band in the transmission response. Three filters; one with hexagonal shape arms, another with circular shape arms and still another with triangular shape arms are proposed. The triangular shape offers wider pass band along with a narrow stop band response whereas the hexagonal shape exhibits wider stop band and a narrow band pass response. The achieved pass band (experimentally measured) for the filter with triangular arm resonator is from DC to 3.585 GHz, 5.12 GHz to 6.65 GHz and from 7.81 GHz to 8.86 GHz. The corresponding stop bands are from 3.585 - 5.12 GHz, 6.65-7.81 GHz and 8.86 – 10.0 GHz. The filters are expected to be useful in communication devices operating in the UWB frequency range.

Keywords: - Microstrip line, Filters, Multi-band filter, Open Loop Resonators and Communication System

1 Introduction

There is an increasing need for dual-band and multi-band filters to be employed in communication devices operating in the ultra-wideband frequency range like mobile phones and pagers. Such filters are required to be compact in size and have the capability to suppress spurious signals. A number of methods have been proposed in the open literature to achieve the band stop / band pass property in a planar filter. A simple method of achieving dual-band is to put in cascade two narrow band filters having different resonance frequencies [1-2]. However this results in an increase in the overall size of the filter. Another method is to use open stubs which create transmission zeros in the pass band [3-4]. Stepped Impedance Resonators (SIRs) have been utilized to achieve dual-band features by properly adjusting the impedance ratio and the electrical length [5]. Triple-band filters can be formed from the dual-band resonators (DBRs) as suggested by Quendo et al. [6]. Specifically, two tri-band DBRs were needed to be coupled to achieve a second order triple-band filter response with six poles (two poles in each band) and five transmission zeros (single zero between each transmission band and two transmission zeros to the left and to the

right of all pass bands). This cascade topology significantly increased the size of the filter. A design methodology to analyze these kinds of filters using cross-coupled networks represented by coupling matrix was proposed by Mokhtari et al. [7, 8]. However, both the designs presented lacked compactness. In [7], six hairpin resonators were used to achieve a triple-band filter response with six poles (two in each band) and four transmission zeros (two transmission zeros between each two bands). A comparison of the performance of the filters listed in the references is presented in Table – I.

In this paper, three types of printed microstrip band pass filters using open loop resonators are proposed. The arms forming the resonators are triangular and hexagonal in shape respectively. The filter designs are validated experimentally. The results of a detailed parametric study carried out using the 3-D electromagnetic simulator HFSS based on Finite Element Method (FEM) are presented. A comparative study of the triangular and hexagonal shapes is also done. The filters are compact in size, simple to design, easy to fabricate, integrable with MIC and MMIC devices and hence useful for modern UWB communication system.

Table – I
Comparison of the performance of the filters proposed in the references

Ref.	Filter Size / Length	Type	Pass Bands	Pass Band Bandwidth	Pass Band Return Loss	Stop Band Attenuation
2	124.5 mm	Dual Band	2.4 GHz & 5.2 GHz	1 GHz	10 dB	60 dB
3	48 mm	Dual Band	1.5 GHz & 2.0 GHz	5% & 4%	17 dB	45 dB
4	15 x 8 mm ²	Dual Band	2.45 GHz & 5.45 GHz	6% & 12%	15 dB & 10 dB	45 dB
5	31 mm	Dual Band	2.4 GHz & 5.2 GHz	6.5% & 5.6%	20 dB	30 dB
6	50.4 mm	Triple Band	1.4 GHz, 2.3 GHz & 3.4 GHz	100 MHz	30 dB, 10 dB & 40 dB	50 dB
7	--	Triple Band	2.65 GHz, 3 GHz & 3.35 GHz	>50 MHz	15 dB	30 dB
8	--	Dual Band	2.8 GHz & 3.15 GHz	3.5 %	10 dB	20 dB
Proposed (Triangular)	24 x 20 mm ²	Triple Band	DC-3.35 GHz 5.25-6.39 GHz 7.7-8.86 GHz	- 1.14 GHz 1.16 GHz	20 dB	30 dB
Proposed (Circular)	20 x 18 mm ²	Triple Band	DC-2.5 GHz 5.01-5.13 GHz 6.03-6.2 GHz	- 120 MHz 170 MHz	20 dB	30 dB
Proposed (Hexagonal)	20 x 18 mm ²	Triple Band	DC-2.05 GHz 4.1-4.16 GHz 5.05-5.35 GHz	60 MHz 300 MHz	20 dB	20 dB

2 Circuit Geometry

The geometries of the proposed multiband filters are shown in Fig. 1. In all the circuits, a 50 Ω feed line of width ‘W’ mm is printed on a commercially cheap FR4 substrate. The substrate is 1.53 mm in thickness and has a relative dielectric constant $\epsilon_r = 4.4$ and loss tangent $\tan \delta = 0.02$. The transmission line is partitioned at the center and thin metallic strips parallel to each other are arranged so as to protrude from the two sides. The thin strips are bent to form a triangularly shaped open loop resonator in Fig. 1(a). The spacing kept at the top between the strips from the two sides is denoted by C_1 , C_2 and C_3 for the innermost, the middle and the outer pair of arms respectively. The strips have a width of ‘w’ mm and separated from each other by a horizontal spacing of S_x mm and a vertical spacing of S_y mm. Similarly hexagonal and circular shaped open loop resonators are designed and shown in Fig. 1(b) and Fig. 1(c) respectively.

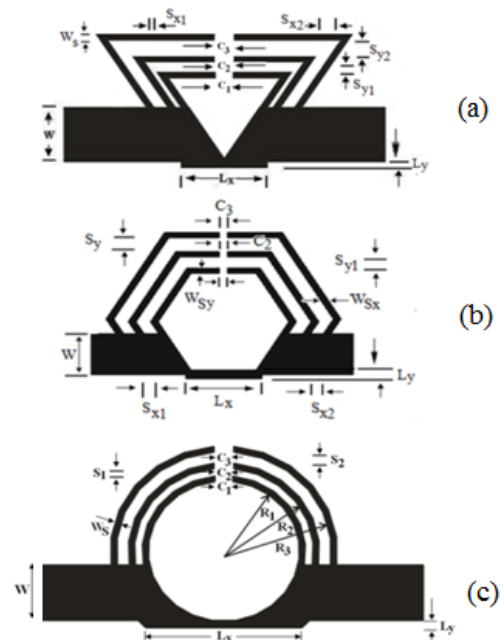


Fig.1, Geometry of the (a) Triangular, (b) Hexagonal and (c) Circular Shape Open Loop Resonator Filters

Table 1 Dimensions of the Proposed Filters (All values in mm)

Description	Parameter	Triangular Resonator	Hexagonal Resonator	Description	Parameter	Circular Resonator
Feed Line Width	W	3.0	3.0	Feed Line Width	W	3.0
Arm Width (along X axis)	W_{sx}	0.3	0.5	Arm Width	W_s	0.3
Arm Width (along Y axis)	W_{sy}	0.25	0.433			
Side Length of the Arm	Inner	5.8	4.35	Radius of the Circle formed by the Arms	R_1	3.95
	Middle	8.05	5.75		R_2	4.65
	Outer	11.52	7.15		R_3	5.55
Arm Spacing (along X axis)	S_{x1}	0.46	0.9	Arm Spacing	S_1	0.4
	S_{x2}	0.58	1.0		S_2	0.6
Arm Spacing (along Y axis)	S_{y1}	0.4	0.78			
	S_{y2}	1.25	0.98			
Gap Width	C_1	0.9	1.2	Gap Width	C_1	0.9
	C_2	1.0	1.2		C_2	1.0
	C_3	1.0	1.2		C_3	1.0
Shorting Stub Width	L_x	3.5	4.8	Shorting Stub Width	L_x	7.8
	L_y	0.25	0.3		L_y	0.4

3 Experimental Results

The multi-armed triangular, circular and hexagonal shape open loop resonator filters were initially designed on Ansoft HFSS and then fabricated with the optimized dimensions. The photographs of the prototypes are shown in Figure 2. The simulated and experimental results of each of the designs are discussed next followed by a brief analysis of the behavior.

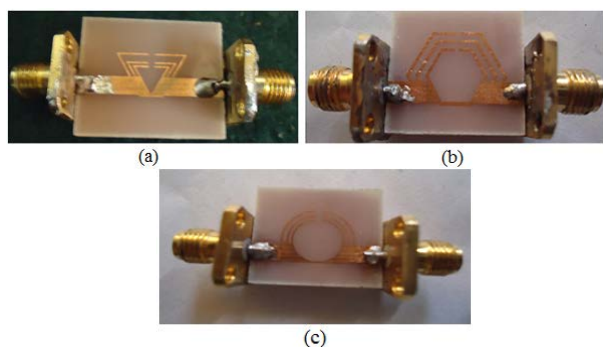


Fig. 2, Photographs of the fabricated (a) Triangular (b) hexagonal (c) Circular shape filters

3.1 Triangular – Shaped Arms

The simulated (CST and HFSS) and experimentally measured results for the triangular shape open arm resonator filter are shown in Fig. 3. It is seen from the results that the transmission response is characterized by a low pass region and two band pass regions or alternatively by three stop bands. In

case of the measured response, the low pass region is from DC to 3.35 GHz and the two band pass regions are from 5.25 GHz to 6.39 GHz and 7.70 GHz to 8.86 GHz. The region of transmission rejection is from 3.98 GHz to 5.06 GHz, 6.67 GHz to 7.68 GHz and 8.86 GHz to 10.0 GHz. It is further seen that the return loss is better than 12 dB in the pass band. The stop band rejection levels are better than 30 dB with a sharp fall in 0.7 GHz implying high selectivity. The insertion loss is less than 0.5 dB in the low pass band, around 1.5 dB in the second pass band and 2.5 dB in the third pass band. Compared to the measured results, the simulated results show a slight variation which may be due to fabrication tolerances, uncertainty in the dielectric constant and thickness of the substrate, lower quality of the SMA connector used and soldering effects. Other reason may be the asymmetric response of the filter. A comparison of the filter response when employing a single triangular shape open loop resonator and two resonators can be made by observing Fig. 4. It is observed that as the number of arms of the open loop resonator increases, the center frequency of the low pass, band pass and stop band regions shifts towards the lower frequency side and the bandwidth becomes narrower. It is also seen that as the number of pass bands increase, the insertion loss increases. Moreover, the insertion loss is found to be more at higher frequencies because of the lossy nature of the FR4 substrate.

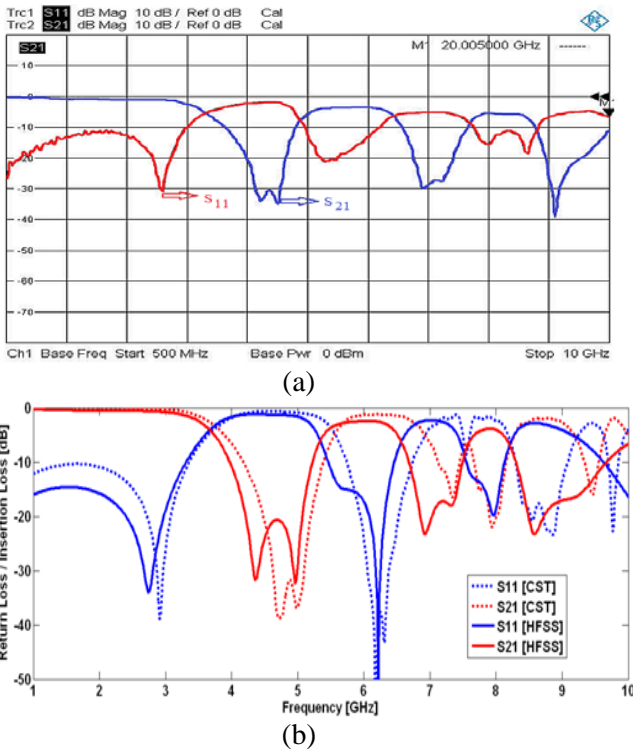


Fig. 3, (a) Measured and (b) Simulated Insertion / Return Loss for Triangular Resonator Filter(3 Arms)

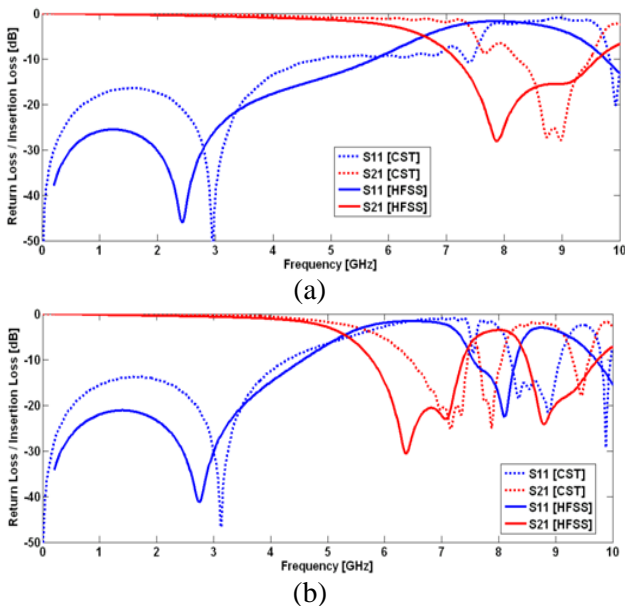


Fig. 4, Simulated Insertion / Return Loss of Triangular Resonator Filter (a) 1 Arms (b) 2 Arms

3.2 Hexagonal – Shaped Arms

The experimental and simulated return loss and insertion loss of the filter with hexagonal shaped arms for the open loop resonator are shown in Figure 5. This triple armed hexagonal shape filter exhibits one low pass, two pass bands and three rejection bands. The experimental results indicating the low pass band from DC to 2.50 GHz, two pass bands from 5.01 GHz to 5.13 GHz and 6.03 GHz to

6.20 GHz. The stop bands are observed from frequency 3.35 GHz to 4.90 GHz, 5.15 GHz to 5.89 GHz and 6.20 GHz to 6.71 GHz. The experimental and simulated results are in close agreement.

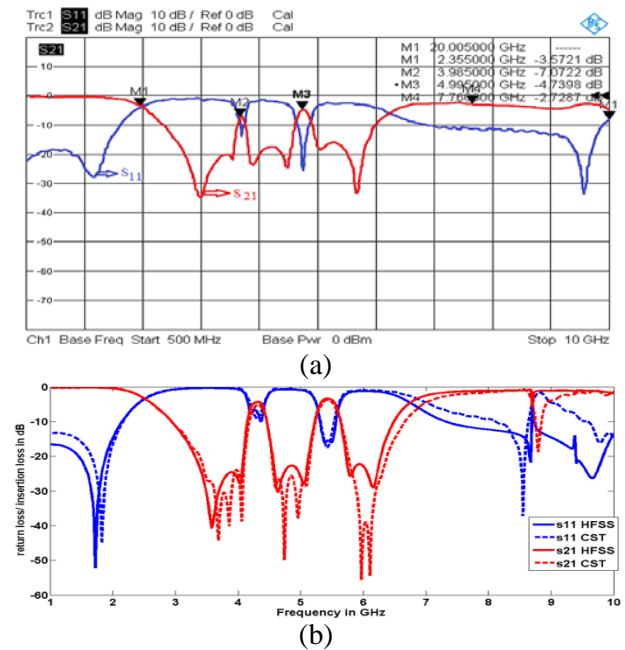


Fig. 5, (a) Measured and (b) Simulated Insertion / Return Loss for Hexagonal Filter (3 Arms)

3.3 Circular – Shaped Arms

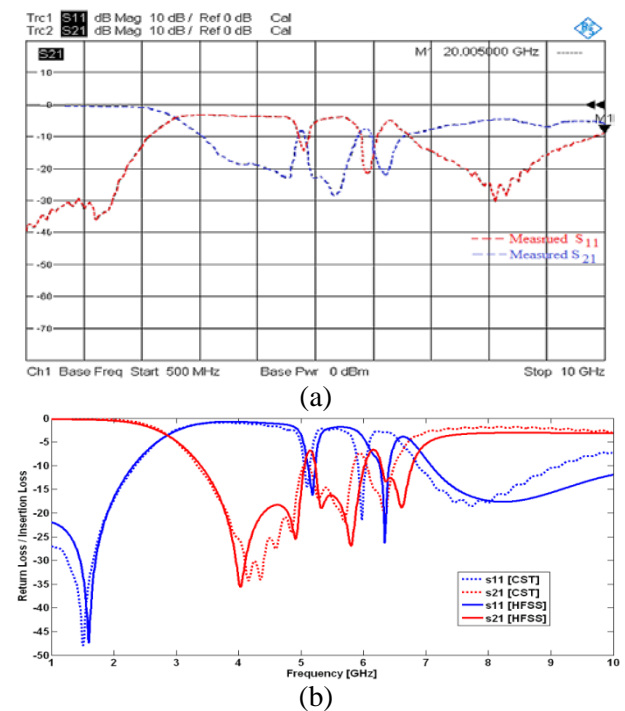


Fig. 6, (a) Measured and (b) Simulated Insertion / Return Loss for Circular Resonator Filter (3 Arms)

The experimental and simulated return loss and insertion loss of the filter with circular shaped arms

for the open loop resonator are shown in Figure 6. This triple armed circular shape filter exhibits one low pass, two pass bands and three rejection bands. The experimental results indicating the low pass band from DC to 2.05 GHz, two pass bands from 4.10 GHz to 4.16 GHz and 5.05 GHz to 5.35 GHz.

The stop bands are observed from frequency 2.85 GHz to 4.03 GHz, 4.26 GHz to 5.00 GHz and 5.40 GHz to 6.20 GHz. Again, the experimental and simulated results are found to be in close agreement.

Table 2 Simulated and Measured Stop / Pass Bands for the three Designs

Filter with Triangular Shape Arms for the Open Loop Resonator							
	Low Pass (GHz)	Stop Band (GHz)	Pass Band (GHz)	Stop Band (GHz)	Pass Band (GHz)	Stop Band (GHz)	Pass Band (GHz)
1-Arm	DC – 5.80	7.15 – 9.60	9.70 –				
2-Arms	DC – 4.60	5.80 – 7.30	7.50 – 8.30	8.50 – 9.70	9.70 –		
3-Arms	DC – 3.30	4.00 – 5.20	5.40 – 6.50	6.70 – 7.50	7.55 – 8.20	8.30 – 9.70	9.70 –
3-Arms (Meas.)	DC – 3.35	3.98 – 5.06	5.25 – 6.39	6.67 – 7.68	7.70 – 8.86	8.86 – 10.0	
Filter with Circular Shape Arms for the Open Loop Resonator							
	Low Pass (GHz)	Stop Band (GHz)	Pass Band (GHz)	Stop Band (GHz)	Pass Band (GHz)	Stop Band (GHz)	Pass Band (GHz)
1-Arm	DC – 2.70	4.60 – 6.60	7.10 –				
2-Arms	DC – 2.60	4.00 – 5.90	6.00 – 6.18	6.23 – 6.75	7.00 –		
3-Arms	DC – 2.30	3.40 – 5.00	5.10 – 5.25	5.25 – 6.00	6.26 – 6.28	6.28 – 6.78	7.10 –
3-Arms (Meas.)	DC – 2.50	3.35 – 4.90	5.01 – 5.13	5.15 – 5.89	6.03 – 6.20	6.20 – 6.71	
Filter with Hexagonal Shape Arms for the Open Loop Resonator							
	Low Pass (GHz)	Stop Band (GHz)	Pass Band (GHz)	Stop Band (GHz)	Pass Band (GHz)	Stop Band (GHz)	Pass Band (GHz)
1-Arm	DC – 2.90	4.75 – 6.55	7.25 –				
2-Arms	DC – 2.60	3.70 – 5.20	5.30 – 5.50	5.63 – 6.52	7.00 –		
3-Arms	DC – 2.10	2.90 – 4.05	4.10 – 4.15	4.35 – 5.15	5.20 – 5.45	5.55 – 6.45	7.30 –
3-Arms (Meas.)	DC – 2.05	2.85 – 4.03	4.10 – 4.16	4.26 – 5.00	5.05 – 5.35	5.40 – 6.20	

Table 3 Simulated and Calculated Resonances

Shape of the Resonator	Arm Length in mm (From Base to Tip)			Calculated resonance frequencies using $f = \lambda_{\text{eff}} / 4l$ (in GHz)			Center frequency of Stop Band (Simulated) (in GHz)		
	Outer most	Middle	Inner most	f_3	f_2	f_1	First Stop Band	Second Stop Band	Third Stop Band
Hexagonal	11.77	8.92	7.34	3.50	4.62	5.61	3.47	4.75	6.00
Triangular	10.21	6.74	4.92	4.04	6.11	8.38	4.60	7.10	9.00
Circular	9.20	7.80	6.74	4.48	5.28	6.11	4.20	5.62	6.53

3.4 Calculated Resonances

Each arm of the open loop resonator introduces a transmission zero and can be said to resonate at $\lambda/4$. The calculated resonances and the center of the simulated stop bands are shown in Table 3.

In the above formula

$$\lambda_{eff} = \frac{\lambda}{\sqrt{\epsilon_{r,eff}}} \text{ and } \epsilon_{r,eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + \frac{12h}{w} \right]^{-1}$$

With $\epsilon_r = 4.4$, $h = 1.58$ mm and $w = 3$ mm, we get $\epsilon_{r,eff} = 3.33$ and $\sqrt{\epsilon_{r,eff}} = 1.82$

3.5 Current Distribution

The arms of the open loop resonator act as stubs resonating at quarter wavelengths and creating the desired transmission zeros. A plot of the current distribution for the filter with hexagonal shape arms is given in Fig. 7. Similarly plot of current distribution for circular and triangular resonators are given in Fig. 8 and Fig. 9 respectively. From these figures, the absence of current on the right hand side of the transmission line can be clearly observed for the stop bands.

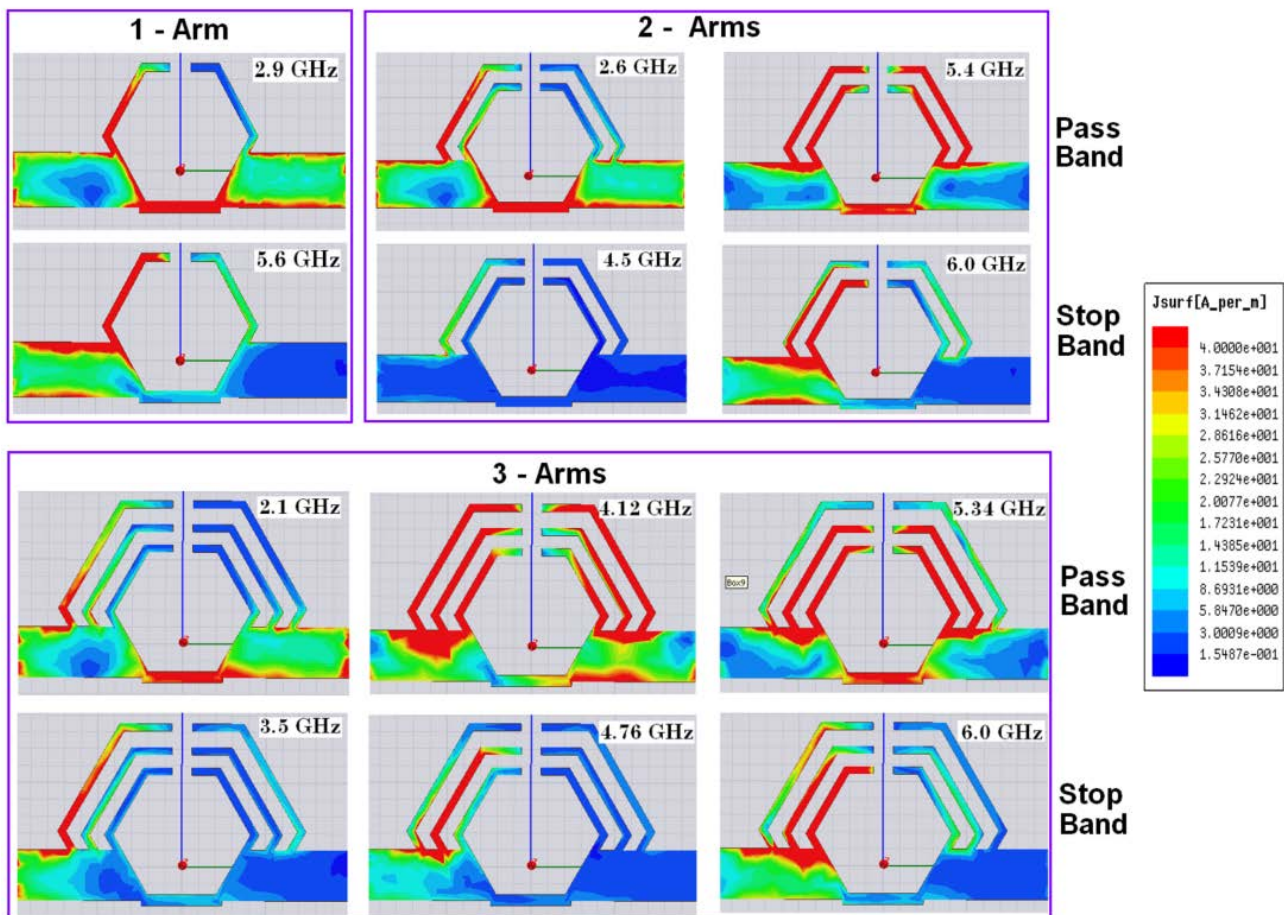


Fig. 7, Current distribution at Resonance Frequencies for the One Arm, Two Arm and Three Arm Hexagonal Resonator Filter

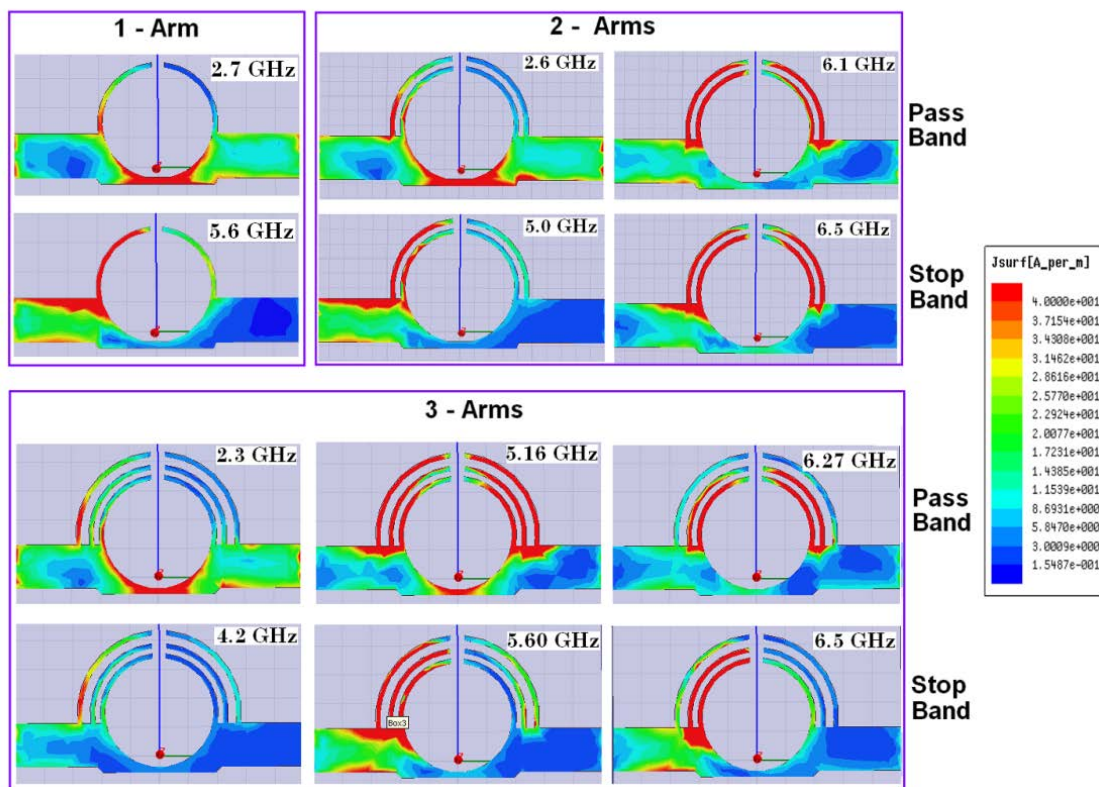


Fig. 8, Current distribution at Resonance Frequencies for the One Arm, Two Arm and Three Arm Circular Resonator Filter

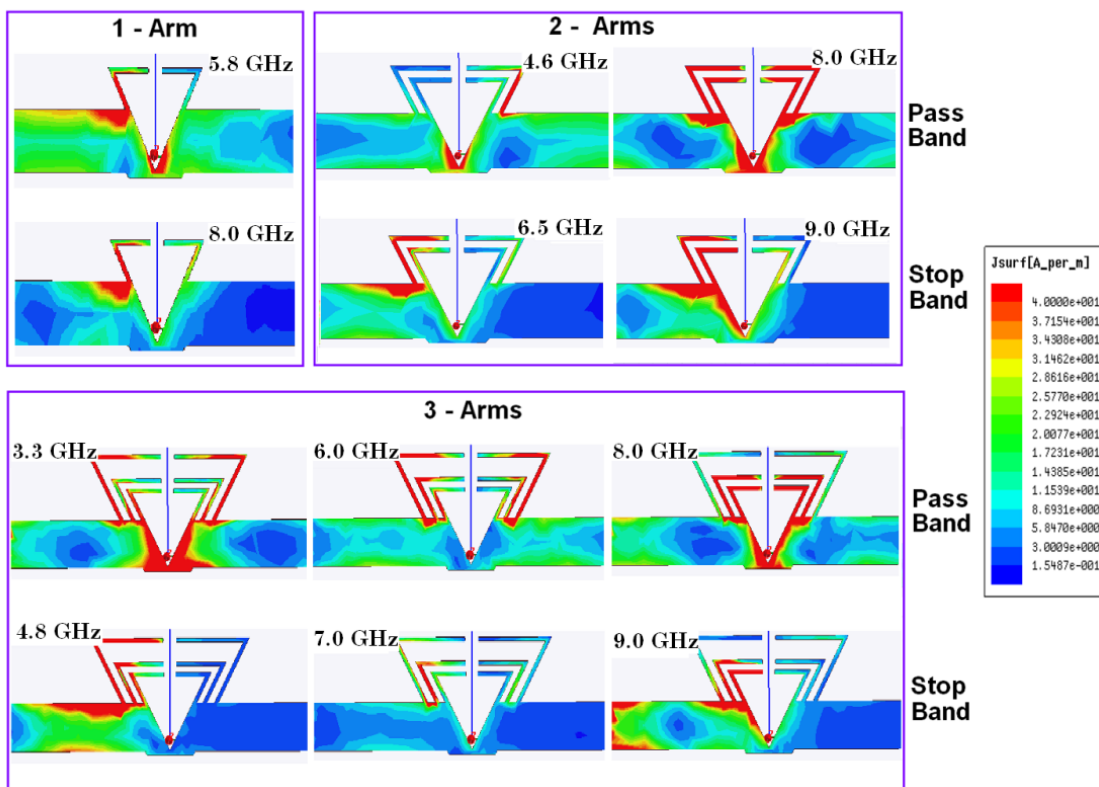


Fig. 9, Current distribution at Resonance Frequencies for the One Arm, Two Arm and Three Arm Triangular Resonator Filter

4 Parametric Study

To investigate the capability of the proposed structures, a detailed parametric study is carried out on the triple-armed triangular shape open loop resonator filter using commercial software HFSS. The structure is designed on FR4 substrate of thickness 1.53 mm and relative dielectric constant of 4.3. The width of all the arms is kept constant during the study.

4.1 Effect of Varying the Open Loop Resonators Length and their Spacing

First, the side length of the open loop resonator arms is varied keeping all other dimensions constant. As expected, the center frequency of the pass band shows a critical dependence on this dimension as shown in Fig. 10. As the length of the arm varies, the center frequency of the band pass changes as shown in the figure. The simulation is carried out with the length of the middle arm taking the values of 5.75, 7.75 and 9.75 mm.

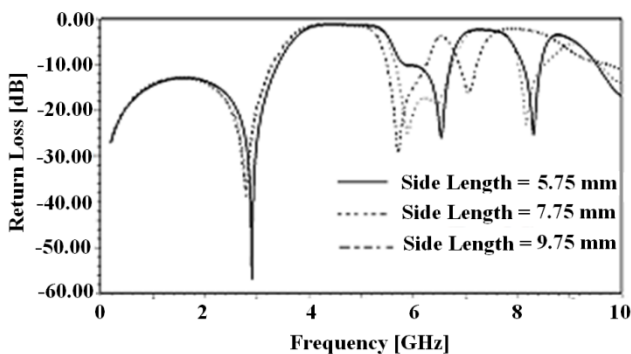


Fig. 10, Effect of the side length (Middle arm) of triangular shape open loop resonators

4.2 Effect of Varying the Open Loop Gap Width

The effect of varying the gaps (C_1 , C_2 and C_3) between the ends of the resonator arms was investigated to ascertain the capability of controlling each reject band almost separately. The gap between the outer-most arms C_3 was assigned three values; 0.9 mm, 1.0 mm and 1.1 mm for the parametric study and the results shown in Fig. 11. It is seen that the effect is more on the higher frequency reject band. Next, the gap distance between the inner most arms C_1 was varied. This gap distance basically affects the lower frequency reject band as shown in Fig. 12. Hence, it can be said that the effect of changing the open loop gap widths between each arm gives the capability of controlling each reject band.

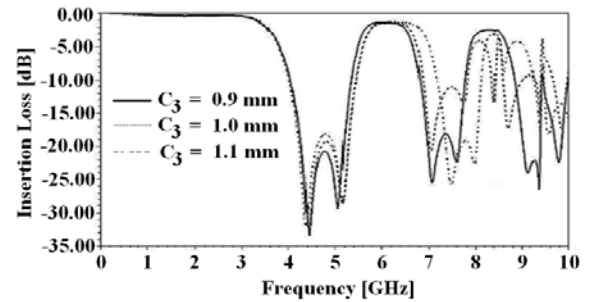


Fig. 11, Simulated results by varying the open loop gap C_3

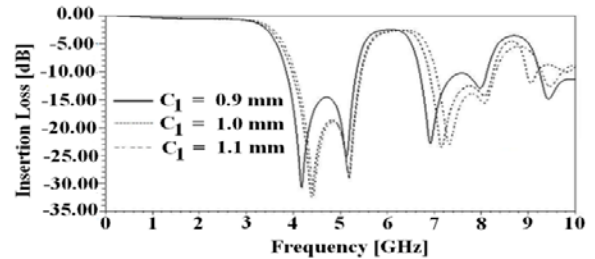


Fig. 12, Simulated results by varying the open loop gap C_1

4.3 Effect of Varying the Spacing between the Open Loop Resonator Arms

The spacing between the resonator arms is given in terms of the vertical separation (S_y) and the horizontal separation (S_x). The effect of varying S_x and S_y on the return loss is shown in Fig. 13 and Fig. 14 respectively. Other dimensions are kept constant. As expected, the center frequency of the pass band is seen to be critically dependent on S_y as shown in Fig. 14. As the gap varies from 1.25 mm to 0.85 mm, the center frequency shifts towards the higher frequency side as shown in the figure. The amount of shift in the center frequency is small as compared to that obtained by a change in the length of the open loop resonator. Similarly, as S_x is changed from 0.58 mm to 0.48 mm, the center frequency shifts towards higher frequency side as shown in Figure 14. In both the cases, the shift in the frequency is due to a change in the coupling between the open loop arms. It can be concluded that the bandwidth of the transmission band can be controlled by changing the resonator arm length and the spacing S simultaneously (Fig. 15).

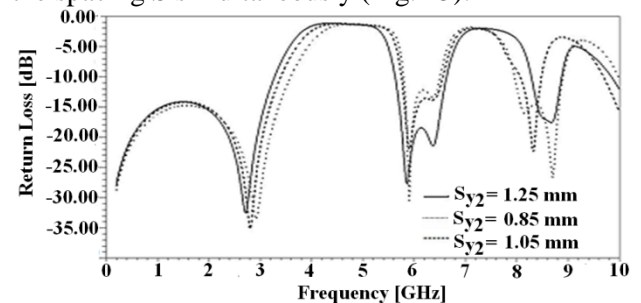


Fig. 13, Effect of the vertical spacing between the second and third triangular arms (S_{y2})

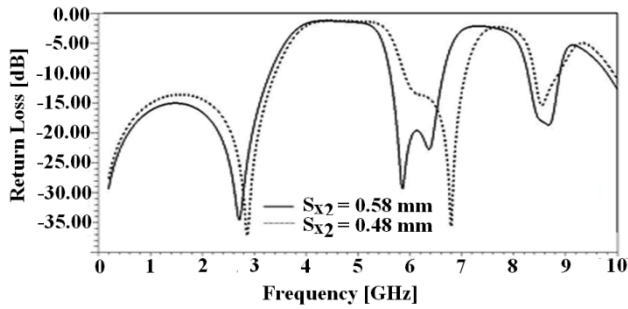


Fig. 14, Effect of the horizontal spacing between the second and third triangular arms (S_{x2})

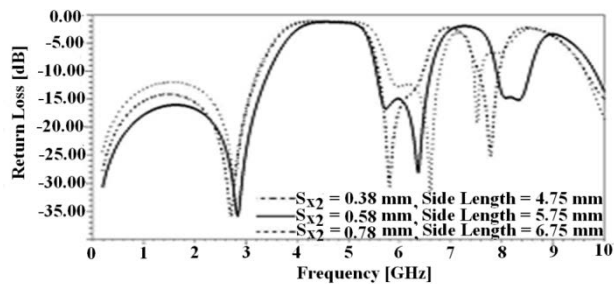


Fig. 15, Effect on the bandwidth by changing arm length and horizontal spacing between the arms of the open loop resonator.

4.4 Effect of the Triangular, Hexagonal and Circular Cuts

The proposed filter has its multi arm open loop resonators directly coupled with the input and output feed line as shown in Fig. 1. First, the filter was analyzed and optimized with the triple triangular open loop arms directly connected to the 50 Ω input and output line. The simulated result with and without the triangular cut is shown in Figure 16. It is observed that the return loss is hardly -10 dB in the first two pass bands without the triangular cut. There is a need to improve the return loss. To improve the return loss, a small triangle is slotted in the feed line and optimized. The simulated result of the final proposed filter is shown in the figure with a solid black line. It is observed with the return loss is improved in all the three pass bands better than -20 dB. Similarly the effect of hexagonal and circular cuts are shown in Fig. 17 and Fig. 18 respectively.

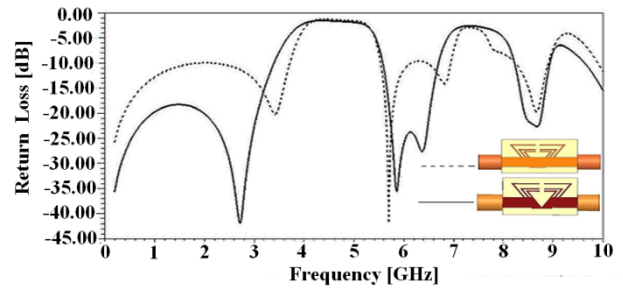


Fig. 16, Reflection Coefficient (dB) with and without triangle cut in feed

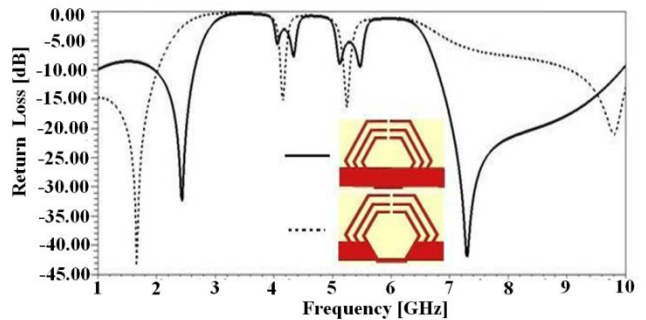


Fig. 17, Reflection Coefficient (dB) with and without hexagonal cut in feed

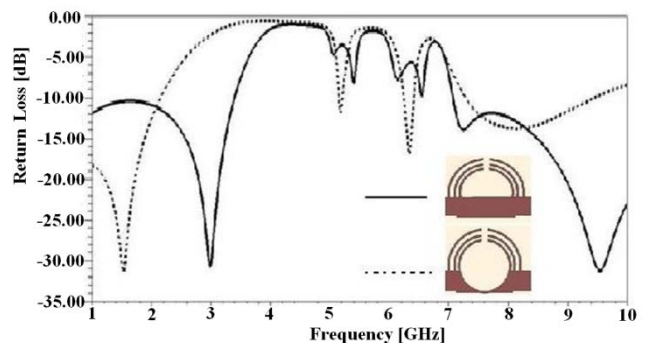


Fig. 18, Reflection Coefficient (dB) with and without Circular cut in feed

5 DESIGN FLOWCHART

A general flowchart of the filter design process is presented in Fig. 19. The process starts with choosing specifications for the filter based on the desired application. These specifications will be in the form of the number and location of the pass bands. Next, choice is made of a suitable substrate. The design part starts with the 50 ohm microstrip line and addition of stubs to create transmission zeros at various frequencies. The circuit is then simulated and optimized on EM solver, fabricated with the optimized dimensions and performance measured for the fabricated prototype. The process stops when the measured performance matches with the design specifications.

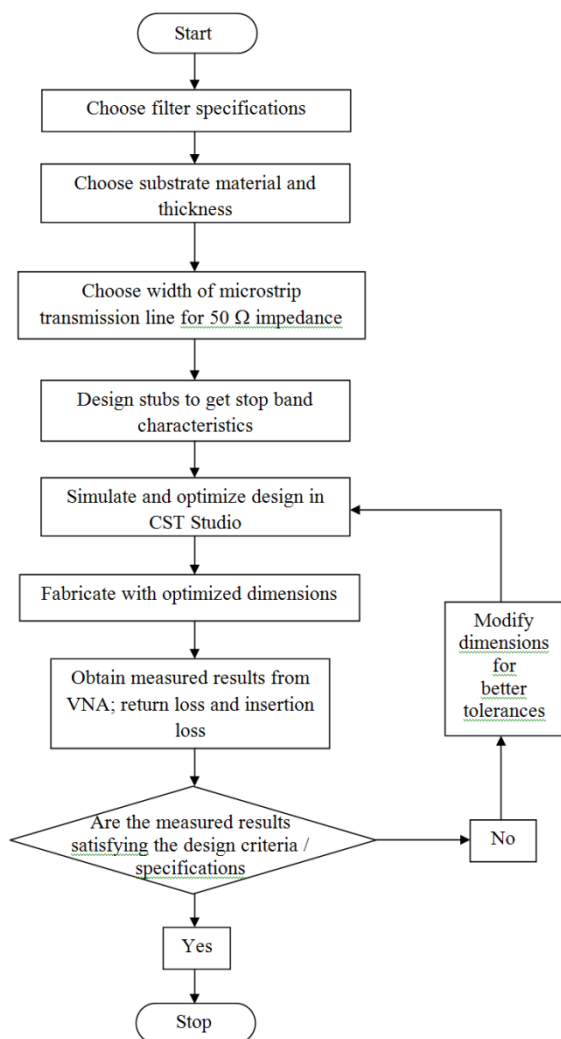


Fig. 19. Flowchart of the filter design process

6. CONCLUSIONS

In this article, filters with triangular, circular and hexagonal shape open loop resonators have been proposed and implemented experimentally. The filters with three arms for the open loop resonator exhibit one low pass region, two pass bands and three stop bands. The triangular shape filter offers wider pass bands in comparison to the hexagonal and circular shape open loop resonator filter. Hexagonal shape filter provides wider stop bands in comparison to the triangular shape filter. The number of pass bands and stop bands depend upon the number of arms open loop resonators pair arms. The detail parametric study of triangular shape filter has been carried out using HFSS software. The experimental and simulated results are found to be in close agreement. All the filters are compact in size, simple to design, lightweight, easy to fabricate and integrate with other devices. Such type of multipurpose filters can be used for multi standard wireless communication systems.

7 Acknowledgement

Authors are grateful to the Vice Chancellor, DIAT (Deemed University), Pune, India for encouraging this work. Author is also thankful to the colleagues of the Department of Electronics Engg. for timely support and cooperation.

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