Wide Stopband Lowpass Filter with Sharp Roll-off using Multiple Resonators

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Abstract: A compact and wide stopband microstrip lowpass filter with sharp roll-off by cascading multiple resonators on high impedance transmission line is presented. A center resonator and multiple side resonators are loaded symmetrically about a high impedance transmission line. The filter has been designed and fabricated using a low cost glass epoxy material and the experimental result shows a very good agreement with the simulated results. The 3 dB cutoff frequency of the proposed filter is at 2.42 GHz. The measured roll-off rate of the filter is 73 dB/GHz at 20 dB attenuation level. The filter achieves a wide stopband from 2.65 GHz to 11 GHz with a suppression level of 20 dB.

Keywords: Compact lowpass filter; microstrip line; resonator; roll-off rate, high impedance transmission lines.

Introduction

Compact and wide stopband lowpass filters are in great demand for front end circuit of modern RF and wireless communication systems to suppress harmonics and spurious signals. Microstrip filters provides a very good performance characteristics in addition to the compact size, low cost and simple fabrication process. The conventional lowpass filter design using stepped-impedance and open circuited stubs provide only gradual roll-off rate and limited stopband bandwidth with very low suppression level. In order to have a sharp cutoff frequency response and wide stopband, these filters require more inductive and capacitive reactance and that can be achieved by increasing the size of the filter [1]. Harmonic suppression and sharp roll-off rate will be obtained by introducing defective ground structure, which also exhibits slow wave characteristics [2]–[3]. But these filters produce additional radiation due to defects in the ground plane and cannot be fixed on a metal base [4]. Different techniques have been proposed to develop compact microstrip lowpass filters with wide stopband, high suppression level and sharp roll-off rate by cascading multiple resonators [5]–[10]. Even though the compactness was achieved in the filter using stepped impedance hairpin resonator, the response characteristics of filter is not very sharp [5]. Good stopband performance was obtained by multiple resonators and meander transmission line [6]–[7], the filter passband was too narrow and its transition characteristics were poor. Besides, the above mentioned filters are designed using high cost and extremely low loss substrate. Sharp roll-off lowpass filter with wide stopband using stub loaded coupled line hairpin unit fabricated on glass epoxy FR4 was reported in [8], but the filter exhibits periodic fluctuation of more than 15 dB of return loss in the stopband. Compact lowpass filter with sharp roll-off rate at 40 dB attenuation using multiple resonators and high impedance transmission line has been reported in [9], but the filter suffers with low stopband bandwidth and suppression level. Sharp roll-off rate at 20 dB attenuation level can be achieved by the lowpass filter with polygonal patch resonators [10], however, the stopband bandwidth of the filter is not at the required limit.

This paper presents a compact, wide stopband microstrip lowpass filter with sharp roll-off and high suppression level by using multiple polygonal patch resonators. The resonators are designed by loading microstrip patches in series with high impedance short circuited stubs and they are placed symmetrically on a 106 Ω transmission line. The filter is designed and fabricated using low cost glass epoxy FR4 substrate. The measured results of the filter show a very good in and out-off band performances. The filter achieves a wide stopband from 2.65 GHz to 11 GHz and a sharp roll-off of 73 dB/GHz.

The filter design

Lowpass filter with sharp switching characteristics and wide stopband performance for a given number of reactive elements, the filter should generate infinite attenuation at finite frequencies [1]. The proposed filter is designed and developed to execute such performance by using microstrip components with semi-lumped element characteristics. The filter is designed and investigated by cascading multiple resonators on high impedance microstrip line [HIML]. Fig. 1 shows the layout of the proposed lowpass filter. It consists of a center modified polygonal patch resonator (PPR), modified rectangular patch resonator (MRPR) and a square patch resonator (SPR). The resonators are designed with high impedance short circuited stubs and low impedance open circuited capacitive patches and loaded as shunt connected series LC circuits [10]. The lumped

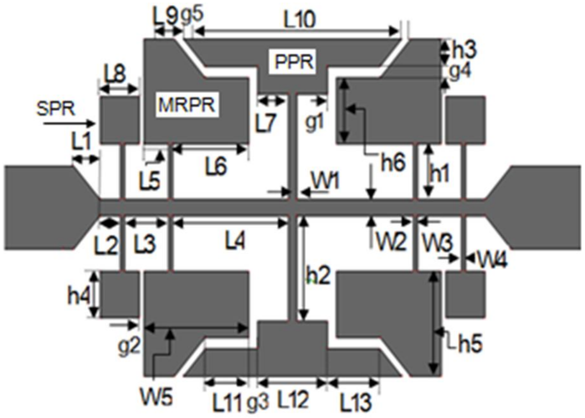


Figure 1.The layout of the proposed filter

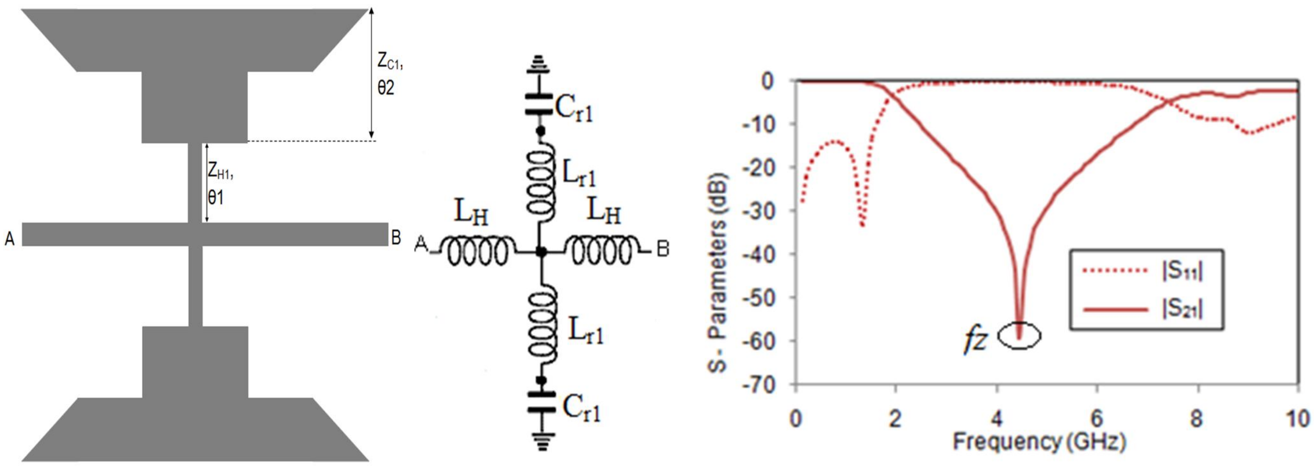
element values of high impedance inductance, L and capacitance, C can be determined by the methods demonstrated in [11]. As shown in Fig. 1, the shape and size of MRPR is fully compatible with that of PPR to provide the tight coupling between the capacitive patch elements of the resonators, which makes the structure more compact.

Design of center polygonal patch resonator (PPR)

Fig. 2(a) shows the layout and equivalent circuit of the proposed center polygonal patch resonator, where the L_H corresponds to the series inductance of the central microstrip line with respect to the junction and L_{r1}-C_{r1} combination in the parallel arm corresponds to the inductance and capacitance associated with the narrow connecting stub and the polygonal patch respectively. As demonstrated in Fig. 2(b), the PPR exhibits a sharp transmission zero with approximately 60 dB attenuation level at fz = 4.44 GHz.

Design of modified rectangular patch resonator (MRPR)

Fig. 3(a) demonstrates the layout of unit cell model of modified rectangular patch resonator (MRPR). It is also designed with high inductive impedance Z_{H2} and low capacitive impedance Z_{C2} with electrical length θ1 and θ2 respectively. As demonstrated in Fig. 3(b), the L-C equivalent circuit of the proposed MRPR is similar to that of PPR. The inductance L_{r2} and capacitance C_{r2} of these elements are also computed by the methods demonstrated in [11] with appropriate parameters. The dimensions and the shape of the MRPR are designed to make the whole structure compact to provide better approximation of lumped capacitance [1]. Fig. 3(c) shows the response characteristics of MRPR with its transmission zero depend on L_{r2} and C_{r2}.



(a) (b)

Figure 2. Layout, L-C equivalent circuit and simulated S- parameter characteristics of proposed PPR

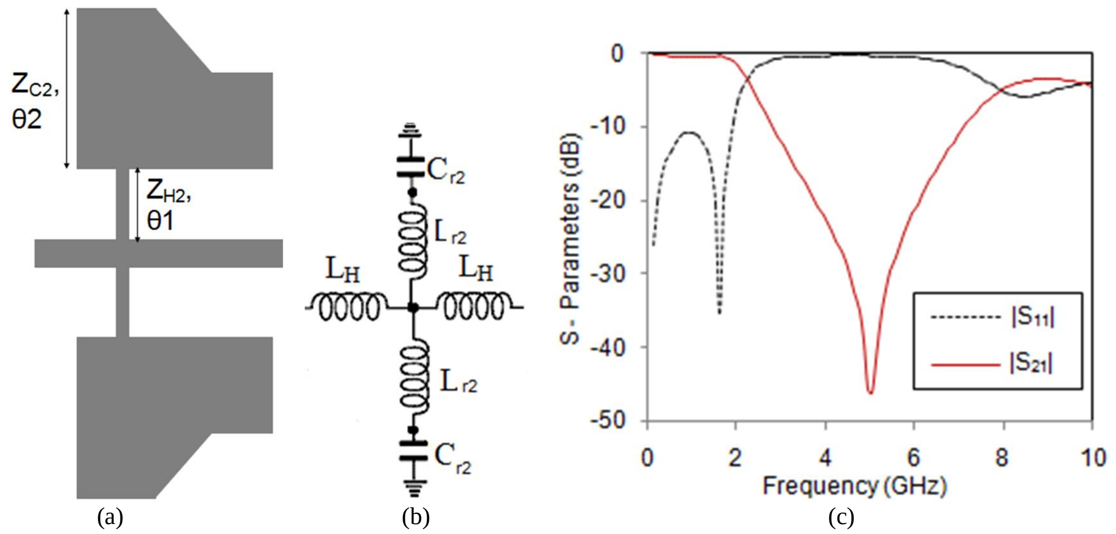


Figure 3. Layout, LC equivalent circuit and response characteristics of MRPR

Compact Elliptic Function Lowpass Filter Design using PPR and MRPR

Observing the frequency response of individual resonators shown in Fig. 2(b) and Fig. 3(c), the attenuation level of each resonator increases after cutoff frequency and reaches its maximum level at transmission zero frequency, *fz* and starts decreasing just after the resonance. By suitably combining both resonators as PPR as center resonator and MRPR as side resonators, we can transform the resonator characteristics to an elliptic function lowpass filter characteristics with sharp roll-off rate and wide stopband bandwidth. Fig. 4 demonstrates the transmission characteristics of the filter as a function of resonators. As shown in the characteristics, the filter with PPR shows single transmission zero located at 4.38 GHz, far from its cutoff frequency 1.96 GHz by 2.42 GHz, whereas the filter with MRPR shows first transmission zero at 4.26 GHz with its cutoff frequency 2.36 GHz by 1.9 GHz. Moreover the MRPR consists of two sets of resonant components, so that the filter with MRPR shows better roll-off and stopband performance than the filter with PPR.

As illustrated in Fig. 4, the first transmission zero generated by the filter with PPR and MRPR is at 2.7 GHz, which is very near to its cutoff frequency 2.4 GHz by 0.3 GHz that improves the roll-off rate as well as the stopband performance. The sharp skirt very close to the *fc* is achieved due to the simultaneous effect of series and parallel resonance caused by the patch resonators and high impedance central microstrip line. Moreover, the series and parallel combination short out transmission at their resonant frequencies and thus gives three finite attenuation poles together with wide stopband performance. Cascading separate resonators also increases the effective reactance, which makes the structure a slow-wave transmission line. The structural dimensions of the filter have been optimized using simulation software Ansoft HFSS and Zeland IE3D.

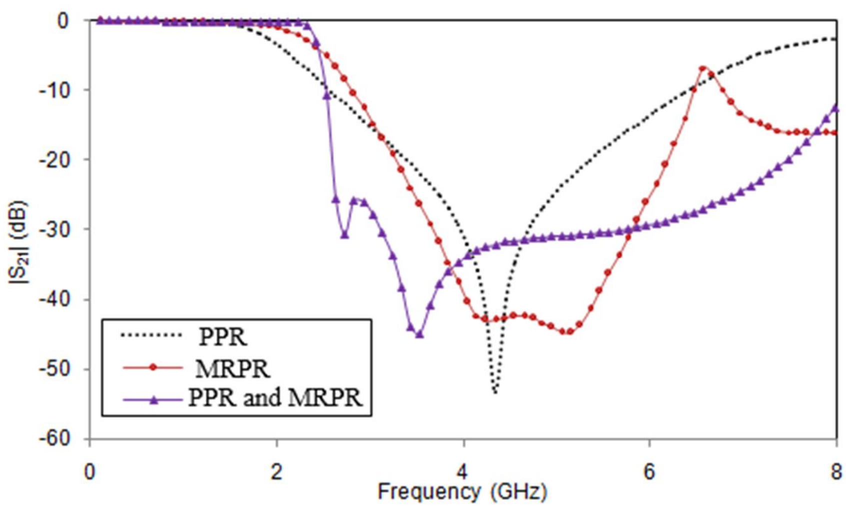
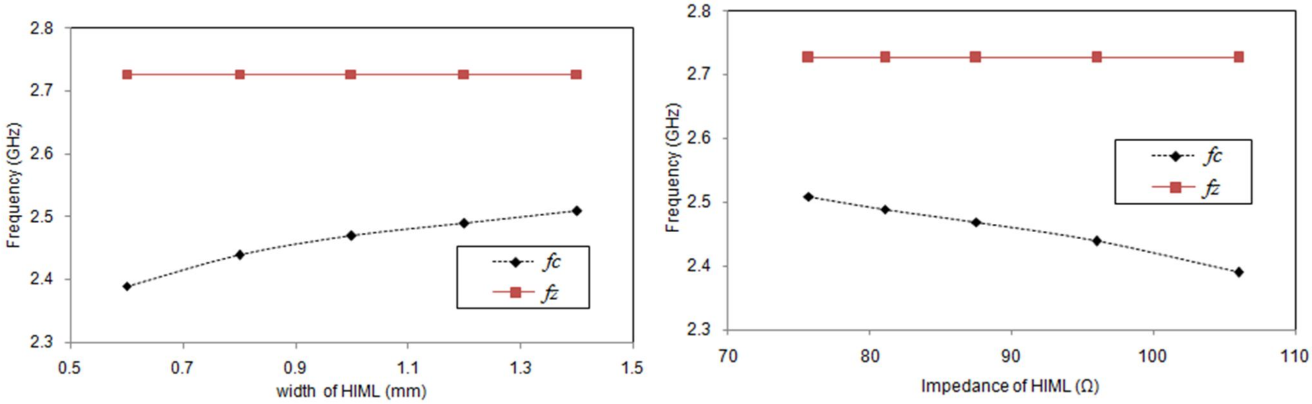


Figure 4. Simulated transmission characteristics as a function of resonators



(a) (b)

Figure 5. The effect of width of HIML w_2 and characteristic impedance Z_C on 3 dB cutoff frequency, *fc* and first transmission zero frequency, f_Z of the filter, (a) effect of width of HIML w_2, (b) effect of characteristic impedance Z_C

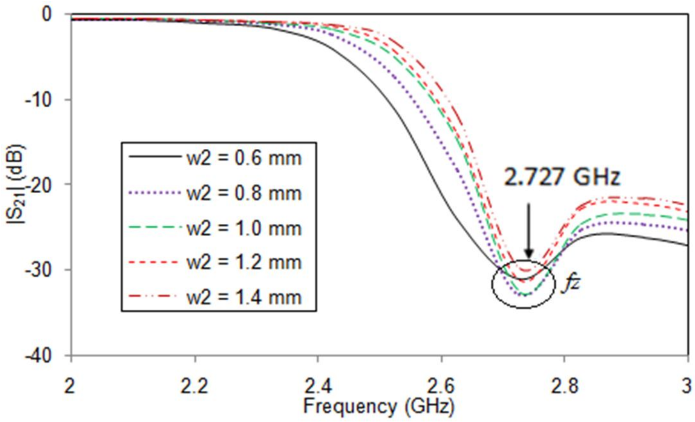


Figure 6. Simulated $|S_{21}|$ characteristics of the compact filter as a function of width, w*2* of HIML

Parametric Analysis

Since many variables are involved in the filter design, a detailed full-wave EM model parametric analysis has been conducted to optimize the dimensions of the filter. As all the individual circuit elements contribute to the performance of the filter, we can tune either the cutoff frequency or the transmission zero frequency by changing dimensions of individual components. Several degrees of freedom exist for adjusting the response of the filter. The exact dimensions are adjusted to optimize the performance of the filter.

Width of High Impedance Transmission Line, (w2)

Figs. 5(a) and 5(b) demonstrate the effect of width w_2 and characteristic impedance Z_C of high impedance microstrip line (HIML) on 3 dB cutoff frequency *fc* and first transmission zero frequency f_Z of the filter. As the inductance of HIML is directly related to its impedance, *fc* increases as w_2 increases from 0.6 mm to 1.4 mm. Since the value of *fz* is depends exactly on the resonator parameters, f_Z remains constant throughout the variation of w_2. However the characteristic impedance Z_C of HIML follows an inverse relationship with the width w_2 of HIML. As Z_C varies from 75 Ω to 110 Ω, the filter passband increases as Z_C whereas f_Z remains constant at 2.727 GHz as shown in Fig. 6.

Compact Elliptic Function lowpass Filter Design using modified PPR

One of the important characteristics of lowpass filter is the sharp transition from passband to stopband, and is defined in terms of roll-off rate ξ as in (1) as:

$$\xi = \frac{\alpha_{\max} - \alpha_{\min}}{f_s - f_c} \text{ dB/GHz}, \tag{1}$$

where is 20 dB attenuation point, is the 3 dB attenuation point, *fs* is 20 dB stopband frequency and *fc* is the 3dB cutoff frequency.

Basically roll-off rate is a measure of the switching characteristics of the filter from passband to stopband, and is inversely proportional to the difference between the 3 dB cutoff frequency *fc* and specified attenuation frequency *fs*. The roll-off rate can be improved by shifting the attenuation frequency close to the *fc*, so as to maintain the difference in frequencies to a minimum level. Efforts to enhance the roll-off rate of the filter with patch resonators are continuously being extended to minimize the difference between these two frequencies. Since the filter characteristics after *fc* depend very much on the resonator parameters, the attenuation level frequency, *fs* can be decreased to a great extent by modifying the center resonator as well as the position of high impedance stub of side resonators.

One of the methods to improve the roll-off rate of the filter is by modifying the dimensions of center resonator, thereby enhancing the inductance and capacitance associated with stub and patch of PPR without changing the dimensions of MRPR. By increasing the height of stub and decreasing the height of patch, we can modify the roll-off rate to a great extend without modifying the overall filter dimensions. Fig. 7 illustrates the layout of compact lowpass filter with modified PPR.

Height of high impedance stub of PPR, (h2)

Figs. 8(a) and 8(b) show the transmission and reflection characteristics of the filter as a function of height of high impedance stub of PPR, (h2) respectively. As shown in Fig, 8, as *h2* increases, the attenuation level of transmission zero just after cutoff and the stopband suppression level are increases. Moreover, as shown in Fig. 9, the reflection characteristics in the passband are also enhanced by increasing *h2*. The optimized value of *h2* = 3.9 mm.

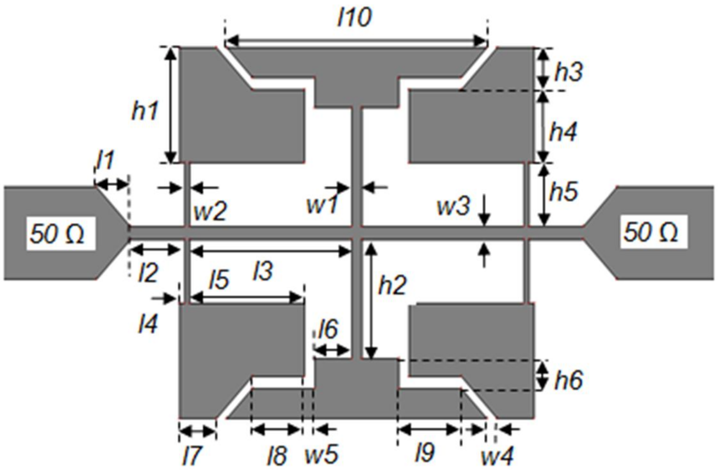


Figure7. Layout of compact lowpass filter modified PPR

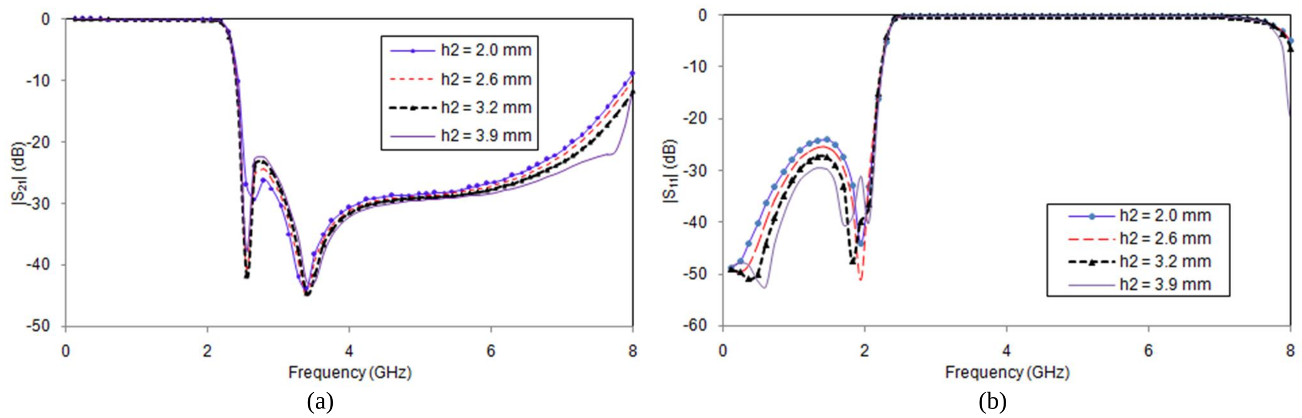


Figure. 8 Characteristics of filter as a function of stub height of PPR, *h2, (a)* Transmission characteristics, (b) Reflection characteristics

Simulation and Measurements Results of Compact Lowpass Filter with Modified PPR

The filter dimensions are optimized with the simulation software Zeland IE3D. The optimized filter dimensions are: *l1* = 1.3 mm, *l2* = 2.1 mm, l3 = 6.2 mm, *l4* = 0.4 mm, *l5* = 4.4 mm, *l6* = 1.4 mm, *l7* = 1.4 mm, *l8* = 2 mm, *l9* = 2.4 mm, *l10* = 10 mm, *h1* = 3.8 mm, *h2* = 3.9 mm, *h3* = 1.4 mm, *h4* = 2.4 mm, *h5* = 2.1 mm, *h6* = 1 mm, *w1* = 0.4 mm, *w2* = 0.2 mm, *w3* = *w4* = *w5*

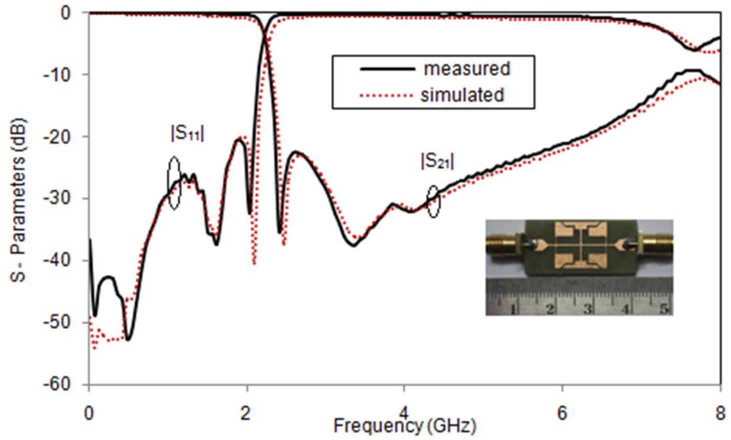


Figure 9. Measured and simulated results of compact lowpass filter with modified PPR

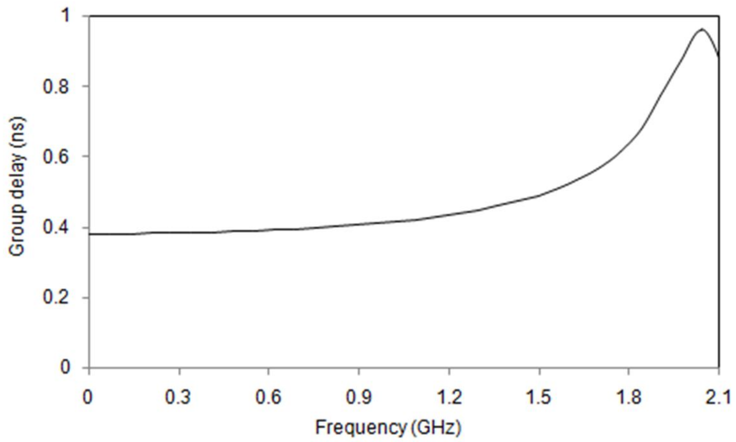


Figure10. Measured group delay characteristics of the compact lowpass filter with modified PPR

= 0.4 mm. As shown in Fig. 9, the measurements results are in good agreement with the simulated results. The measured results show that the filter has an insertion loss less than 0.4 dB in the passband at 1.5 GHz and the 3 dB cutoff frequency is at 2.21 GHz. The filter achieves a wide stopband from 2.38 GHz to 6.7 GHz with a suppression level better than 18 dB in the upper end of the stopband. The return loss is better than 19.5 dB in the passband and close to 1.4 dB at 6.7 GHz. As shown in Fig. 10, the filter achieves almost constant group delay in the lower frequencies in the passband and gradually increases as the frequency approaches the cutoff frequency.

Wide stopband lowpass filter with lowpass filter with sharp roll-off using multiple resonators

Fig. 11 compares the performance enhancement of the filters with and without SPRs. The lowpass filter structure with modified PPR and MRPR achieves a roll-off of 94 dB/GHz and a wide stopband with the suppression level better than 18 dB from 2.38 GHz to 6.7 GHz [10]. The stopband bandwidth and the suppression level can be enhanced by introducing a set of SPR near the feed line without any change in the length of the transmission line. As illustrated in Fig. 11, the filter with modified PPR and MRPR generates a transmission pole, Tp at 7.86 GHz and that can be suppressed by the presence of SPR together with PPR and MRPR. Moreover, the filter with three proposed resonators exhibits a wide stopband of 8.4 GHz with a suppression level better than 20 dB. The tapered feed line provides better impedance matching between 50 Ω feed line and 106 Ω impedance transmission line.

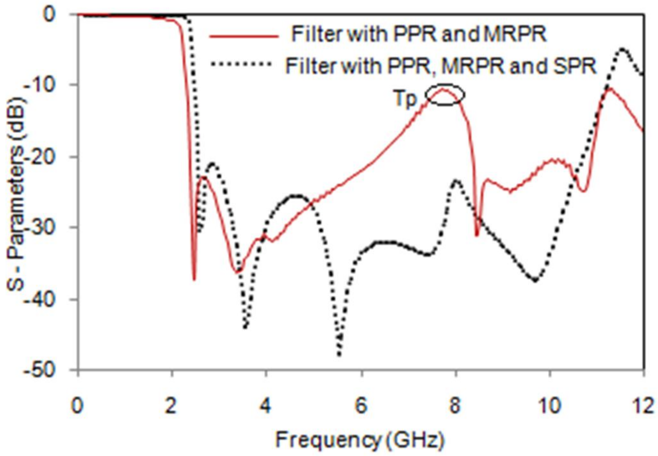


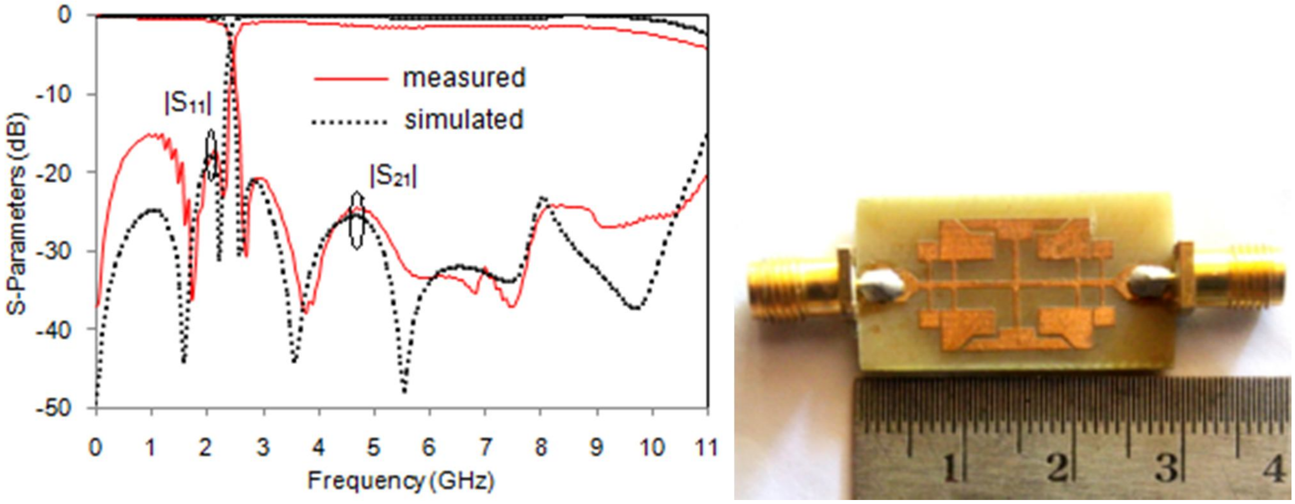
Figure11. The simulated S-Parameter characteristics of proposed lowpass filter with and without SPRs

Simulated and Experimental Results

The proposed filter is designed and developed using 1.6 mm thick glass epoxy lossy FR4 material with permittivity 4.4 and a loss tangent of 0.02. Simulation was accomplished with electromagnetic simulation software Zeland IE3D and the measurement was carried out using R&S ZVL 13 Vector Network Analyzer. Fig. 1 shows the layout of the proposed filter.

The optimized structural dimensions in millimeters are: L1 = 1.2, L2 = 0.8, L3 = 1.8, L4 = 5.6, L5 = 0.8, L6 = 3.8, L7 = 1.4, L8 = 1.8, L9 = 1.4, L10 = 5, L11 = 2, L12 = 3.2, L13 = 1.4, W1 = 0.4, W2 = 0.6, W3 = 0.2, W4 = 0.2, W5 = 4.8, h1 = 2, h2 = 3.9, h3 = 1, h4 = 1.8, h5 = 3.8, h6 = 2.4, g1 = 0.4, g2 = 0.2 and g3 = g4 = g5 = 0.4. As shown in Fig. 12(a), a very good agreement is obtained with the experimental and simulated results of the proposed filter. The cutoff frequency of the filter is at 2.42 GHz.

The measured roll-off rate of the filter is 73 dB/GHz at 20 dB attenuation level and stopband bandwidth is from 2.65 GHz to 11 GHz with a suppression level of 20 dB. The measured insertion loss of the filter is less than 0.5 dB in the passband at 2 GHz. The maximum return loss in the passband of the filter is 15 dB and in stopband is -1.5 dB at 9 GHz. The filter has a compact size of about 17.6 mm x 12.2 mm, which corresponds to the normalized circuit size of where λg is the guided wavelength at 2.42 GHz. Fig. 12(b) shows the photograph of the proposed filter. Table 1 demonstrates the comparison results of the proposed work with similar works reported in the literature. In this table, ξ is the roll-off rate defined at 20 dB attenuation level, SBW is the stopband bandwidth, SSL is the stopband suppression level and fc is the 3dB cutoff frequency. As shown in Table I, the proposed compact lowpass filter exhibits wide stopband with sharp roll-off rate among the quoted filters.



(a) (b)

Figure 12. The measured and simulated results and photograph of the proposed filter, (a) measured and simulated results, (b) photograph

Table 4.3 Performance comparison of proposed filter with SI-PPR and similar published work in the literature

Ref	ξ (dB/GHz)	SBW (GHz)	SSL (dB)	Dielectric material	*fc* GHz
[5]	18	2.0 - 15.0	10	RT/duroid 5880	1.5
[6]	18	1.57 -12.64	15	Rogers RO4003	0.85
[7]	20	2.0 -14.60	17	RT/duroid 5870	1.3
[8]	63	0.8 - 4.60	20	FR4	0.53
[9]	42	5.58-11.8	15	FR4	5.55
[10]	94	2.38-6.7	18	FR4	2.21
This work	73	2.65-11	20	FR4	2.42

Conclusion

A compact wide stopband lowpass filter with high suppression level and sharp roll-off rate designed and demonstrated. Both simulations and measurement results have been presented and good agreement between them is achieved. The filter achieves very good electrical characteristics together with low cost and ease of fabrication that make it suitable in modern practical communication systems.

References

[1] J. S. Hong and M. J. Lancaster, "Microstrip Filters for RF/ Microwave Applications," John Wiley, New York, 2001.
[2] M. K. Mandal, P. Mondal, S. Sanyal and A. Chakrabarty, Low insertion-loss sharp-rejection and compact microstrip low-pass filters, IEEE Microw Wireless Compon Lett, vol.16, 2006, pp. 600–602.
[3] C. J. Wang and C. H. Lin, "Compact lowpass filter with sharp transition knee by utilizing a quasi-π-slot resonator and open stubs," IET Microwaves Antennas & Propagation, vol. 4, no. 4, April 2010, pp. 512 – 517.
[4] Z. Du, K. Gong, J. S. Fu, B. Gao, and Z. Feng, "Influence of a metallic enclosure on the -parameters of microstrip photonic bandgap structures," IEEE Trans. on Electromagnetic Compatibility, vol. 44, no. 2, 2002, pp. 324–328.
[5] M. H. Yang and J. Xu, "Design of compact broad-stopband lowpass filters using modified stepped impedance hairpin resonators," Electronics Lett., vol. 44, no. 20, 2008, pp. 1198–1200.
[6] H. Cui, J. Wang and G. Zhang, "Design of microstrip low pass filter with compact size and ultra-wide stopband," Electronics Lett., vol. 48, no. 14, 2012, pp. 856 – 857.
[7] L. Ge, J. P. Wang and Y-X Guo, "Compact microstrip lowpass filter with ultra-wide stopband," Electronics Lett., vol. 46, no. 10, 2010, pp. 689 – 691.
[8] V. K. Velidi and S. Sanyal, "Sharp Roll-Off Lowpass Filter With Wide Stopband using Stub-Loaded Coupled-Line Hairpin Unit," IEEE Microw. and wireless Compon. Lett. vol. 21, no. 6, 2011, pp. 301–303.
[9] P. M. Raphika, P. Abdulla, P. M. Jasmine, "Compact lowpass filter with a sharp roll-off using patch resonators," Microw. and Opt. Tech. Lett., Vol. 56, no. 11, 2014, pp. 2534-2536.
[10] Raphika P. M., Abdulla P., Jasmine P. M., "Compact Microstrip Lowpass Filter with Sharp Roll-off and Wide Stopband by Cascading Multiple Resonators," Proceedings of Asia Pacific Microwave Conference, Japan 2014, pp. 1229-1231.
[11] Ma. K and K. S. Yeo, New ultra-wide stopband low-pass filter using transformed radial stubs, IEEE Trans on Microw Theory and Tech, vol. 59, no. 3, 2011, 604–611.