Wide Stop-Band Microstrip Lowpass Filter with Sharp Roll-off Using Hairpin Resonators

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Abstract **─** A compact microstrip lowpass filter with wide stop-band and sharp roll-off skirt is presented. The structure consists of a combination of modified Hairpin units. The cut-off frequency is 3.1 GHz. The proposed low-pass filter has a very good performance such as extended stop-band bandwidth from 3.36 GHz to 21.5 GHz with the insertion-loss higher than -20.0 dB, sharp roll-off, low insertion-loss, and high return-loss in the pass-band. The filter is designed, fabricated, and tested and the measured results are in good agreement with the EM-simulation results.

Index Terms - Hairpin unit, lowpass filter, microstrip, sharp roll-off, and wide stop-band.

I. INTRODUCTION

Microwave lowpass filters are one of the most important building blocks in modern microwave systems because of their ability to suppress unwanted harmonics and spurious signals. To answer the demands of modern communication systems, LPFs have been studied for many years. Resonators are the basic parts of filters and so different kinds of them such as stepped impedance, pseudo inter-digital and defected ground structures (DGS) have been designed and used to improve the performance of filters. Conventional LPFs suffer from gradual roll-off and narrow stop-band bandwidth [1]. Other disadvantages like high insertion-loss and fabrication complexity are also the problems that make the filters to be far from the ideal form [2]. The main advantages of Hairpin resonators are compact size and ease of fabrication since they were proposed for the first time in 1970's. In [3], a LPF using Hairpin resonator is presented. The filter's structure is simple but it suffers from a gradual roll-off and narrow stop-band bandwidth. In [4], the filter's performance is improved by adding a pair of coupled stepped impedance resonators (SIRs). Compared with the previous structure, this filter has a sharper response but the return-loss has become lower and the stop-band bandwidth is still narrow. In the filters proposed in [5-7], some characteristics like the stop-band bandwidth are enhanced but all those filters suffer from gradual roll-off.

In this paper, the new structure is presented to design a lowpass filter using Hairpin resonators. The simulated and measured results show a sharp roll-off and an extended stop-band bandwidth.

II. NOVEL HAIRPIN UNIT STRUCTURE

Figure 1 shows the structure of the conventional hairpin resonator and its S-parameters simulation results.

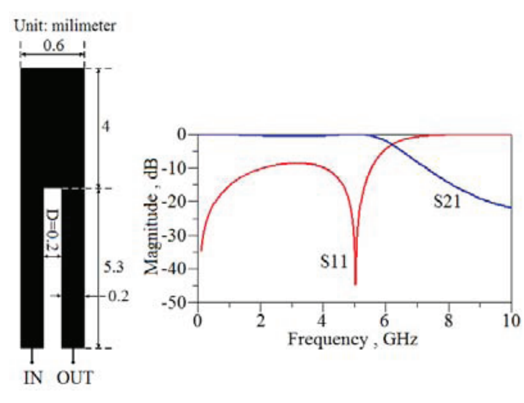

Fig. 1. Conventional hairpin resonator and its S-parameters results.

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As it is clear, the structure is simple and consists of a single transmission line and symmetric parallel coupled lines. This simple structure can be modeled by an LC circuit easily [1] and this is one of the advantages of using hairpin resonators. The equivalent LC circuit of the conventional hairpin unit is shown in Fig. 2.

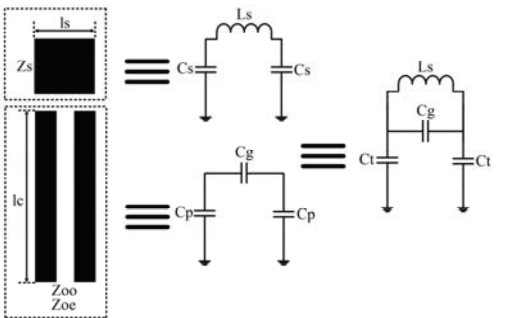


Fig. 2. The equivalent LC circuit of the conventional hairpin unit.

As it is shown, the single transmission line can be modeled as a capacitive-inductive π-network and the parallel coupled lines can be modeled as a capacitive π-network. The values of different parameters in the LC circuits are calculated in [1, 8], and they are summarized as follows,

$$Ls = \frac{Z_S \sin(2\beta_S l_S)}{\omega} \text{ (H)} \tag{1}$$

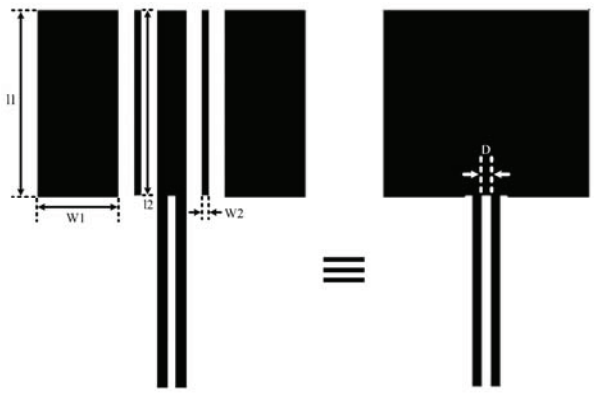
$$Cs = \frac{1-\cos(2\beta_S l_S)}{\omega Z_S \sin(2\beta_S l_S)} \text{ (F)}, \tag{2}$$

$$Cg = \frac{(Z_{oe} - Z_{oo})}{2\omega Z_{oe} Z_{oo} \cot(\beta_C l_C)} \text{ (F)}, \tag{3}$$

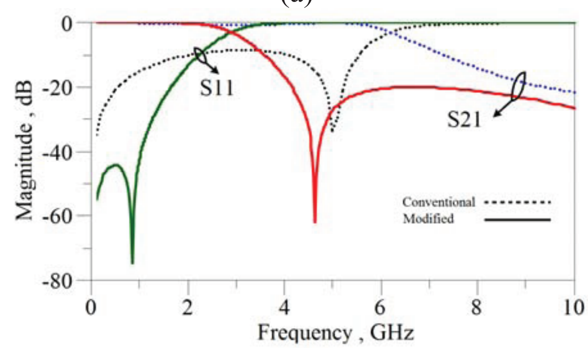
$$Cp = \frac{1}{\omega Z_{oe} \cot(\beta_C l_C)} \text{ (F)}. \tag{4}$$

Z_S is the characteristic impedance of the single transmission line and Z_{OO} and Z_{Oe} are the odd- and the even-modes' impedance of the parallel coupled lines. β_S is the phase constant of the single transmission line and β_C is the phase constant of the coupled lines. In Fig. 2, Ct = Cp + Cs.

In this paper, to enhance the filter's performance and getting close to the ideal form, the structure of the conventional Hairpin resonator is modified by adding two extra stubs, to each side of the top part of the resonator. The new structure is shown in Fig. 3 (a).



(a)



(b)

Fig. 3. (a) Modified hairpin resonator and (b) comparison between the results of the conventional and modified hairpin resonator.

The dimensions in Fig. 3 (a) are: W1 = 1.8, W2 = 0.2, l1 = 4.2, and l2 = 4.1 (all in millimeter). Figure 3 (b) shows a comparison between the simulation results of the modified resonator and the conventional hairpin resonator. As it is obvious in Fig. 3 (b), in comparison with the conventional structure, the modified structure has better performance. For example the return-loss in the pass-band is lower and transmission zeros have moved to lower frequencies and so the resonator has a sharper roll-off.

Modeling microstrip structures with LC circuits is very important. However, it is usually very hard to model microstrip circuits with lumped-elements but it has many advantages. An LC model can help the designers describe the behavioral characteristics of a microstrip structure better and perform analysis easier and faster. It is especially very useful for optimizing the values of different parts because as it is mentioned, the analysis of an LC circuit in comparison with microstrip structures is very fast. In addition, in some circuits both lumped-elements and microstrip structures exist and to analyze such circuits, it is useful to model the microstrip structures with LC circuits.

The equivalent LC circuit for the proposed resonator is shown in Fig. 4 (a), where their values are: L1 = 1.13 nH, L2 = 1.7 nH, C1 = 0.2 pF, C2 = 0.36 pF, C3 = 1 pF, C4 = 0.1 pF. The values of LC parameters are calculated from the basic equations of hairpin unit and transmission lines i.e., equations (1) to (4), and then the values are optimized to improve the accuracy of the response. Figure 4 (b) shows the comparison between the simulation results of the layout and the LC model of the proposed resonator. As it is obvious, there is a very good agreement between the circuit and the EM simulation results.

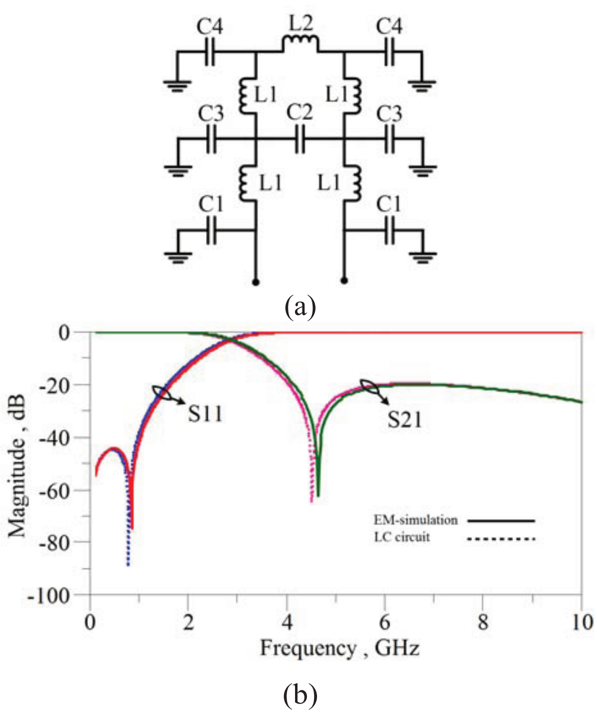


Fig. 4. (a) The equivalent LC circuit for the proposed resonator and (b) the comparison between the results of the LC circuit and EM simulation.

In hairpin resonators, the distance between the parallel lines is a very important parameter because any changes in the amount of this distance, will highly affect the response characteristics of the resonator and so it is important to study the effects of changing the value of this parameter on the response. This parameter is shown in Fig. 3 (a) as D.

Figure 5 (a) shows the simulation results of the proposed resonator for different values of D. As it is shown in this figure, by decreasing the value of D from 0.25 mm to 0.15 mm, the filter will have a sharper roll-off skirt. Because by decreasing the value of D, the coupling capacitance between the parallel lines will increase, which leads the transmission zeros to move to lower frequencies and so the roll-off will be sharper.

The coupling capacitance between the parallel lines is shown as C2 in Fig. 4 (a). In Fig. 5 (b), the effect of changing the value of C2 is presented and as it is expected, by increasing the value of C2, the transmission zeros will move to lower frequencies. And it confirms what was claimed before about D.

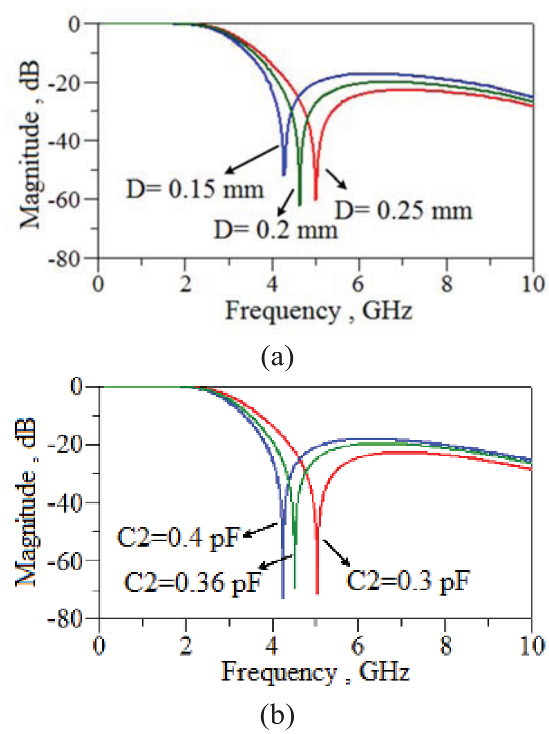


Fig. 5. The proposed resonator simulation results (a) as a function of D in microstrip structure and (b) as a function of C2 in the equivalent LC circuit.

As it is obvious in Fig. 5 (a), by decreasing the value of D, the insertion-loss in the stop-band will decrease and so a proper value for D should be chosen to achieve the best performance for the filter. Finally, the value of D = 0.2 mm is chosen. The value of the cut-off frequency can be changed by changing some dimensions of the structure, but it should be considered that any changes in the dimensions of the resonator, will affect the response and the performance of the structure. A good method to change the cut-off frequency without changing the performance of the LPF is to change all the dimensions with the same scale. Figure 6 shows the response of the proposed resonator for different scale factors.

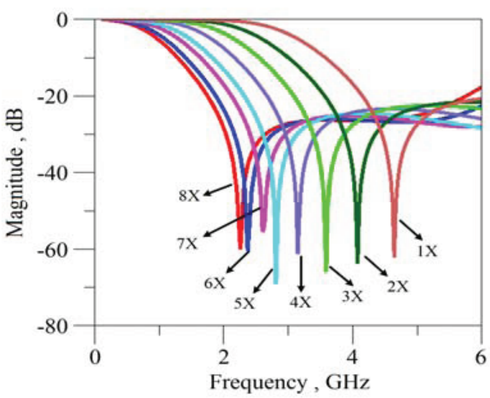


Fig. 6. The response of the proposed resonator for different scale factors.

It is seen in Fig. 6, as the dimensions of the proposed resonator become larger, the cut-off frequency will become smaller, while the response curves have almost the same shapes (that shows the same performance in the structures). Figure 7 shows a relationship between the value of the cut-off frequency and the scaling factor.

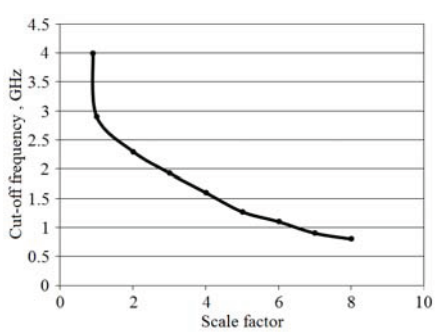
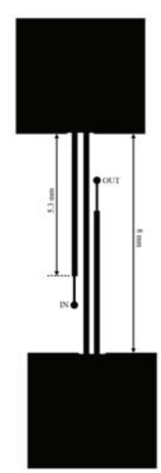


Fig. 7. The values of the cut-off frequency for different scaling factors.

Figure 7 is very useful to determine the dimensions of the structure to obtain a certain value for the cut-off frequency. According to Fig. 7, to increase the value of the cut-off frequency, it is needed to decrease the size of the structure and to decrease the value of cut-off frequency, the size of the structure should be increased. In Fig. 7, the response curve is an exponential type and so the change in the size of the resonator to increase the value of cut-off frequency will be very small, but to decrease the value of cut-off frequency there will be a bigger change in the size of the structure. Therfore, this method is more efficient especially when it is needed to increase the value of the cut-off frequency.

III. FILTER DESIGN

By using the proposed resonator, a new LPF with wide stop-band bandwidth and sharp roll-off is designed in this paper. In the first step, to improve the performance, a combination of two modified Hairpin units is used. One way to obtain a good performance and also a small size, is arranging the resonators in cascade model. So as it is shown in Fig. 8 (a), the coupled resonators have one common leg, which means: the output leg for the first resonator is as the input leg for the second one. The length of the legs also should be optimized to obtain the best possible performance. Figure 8 (b) shows the simulation results of the structure.



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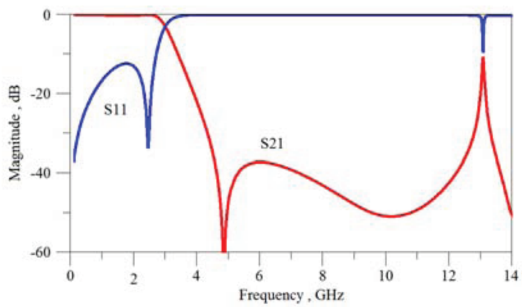
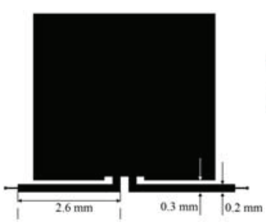


(b)

Fig. 8. The combination of two modified Hairpin resonators (a) layout and (b) simulation results.

As it is observed in Fig. 8 (b), the new structure has better response characteristics. The roll-off skirt is sharper and the stop-band bandwidth is wider but the return-loss in the pass-band is becoming low. In the next step, to extend the stop-band bandwidth, another modified Hairpin unit is designed. This unit and its simulation results are shown in Fig. 9.



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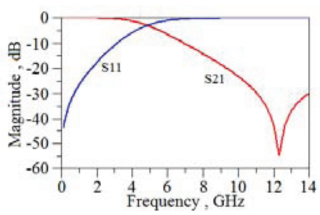
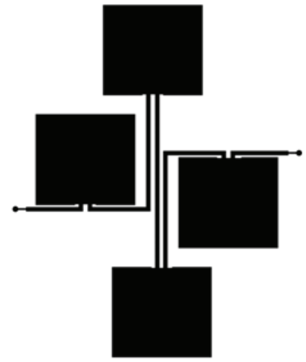


(b)

Fig. 9. The second modified Hairpin unit (a) the structure and (b) simulation results.

In Fig. 9, the structure is achieved by bending the parallel lines at 90 degrees. As a result, the coupling capacitances between them will be removed and there will be new coupling capacitances between the lines and the top parts of the resonator. All these changes will highly affect the response characteristics of the structure and make the zero of S21 moves to higher frequencies and so the response characteristics of the resonator will be like what is shown in this figure.

By adding this new unit to the previous structure, a new combination is achieved. Figure 10 (a) shows this new structure and the simulation results are shown in Fig. 10 (b). The final structure is shown in Fig. 11.



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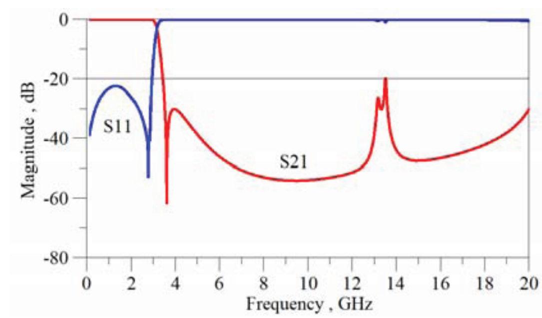


(b)

Fig. 10. The new structure (a) layout and (b) simulation results.

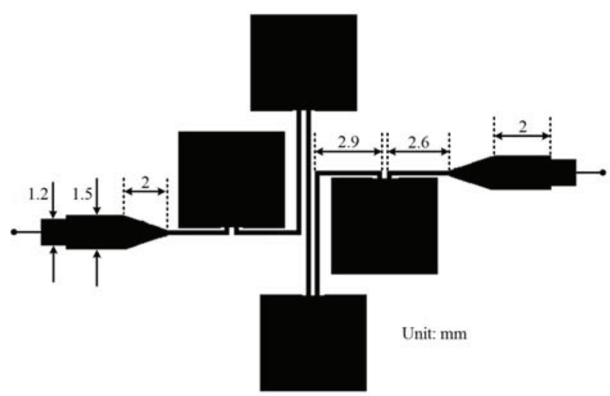
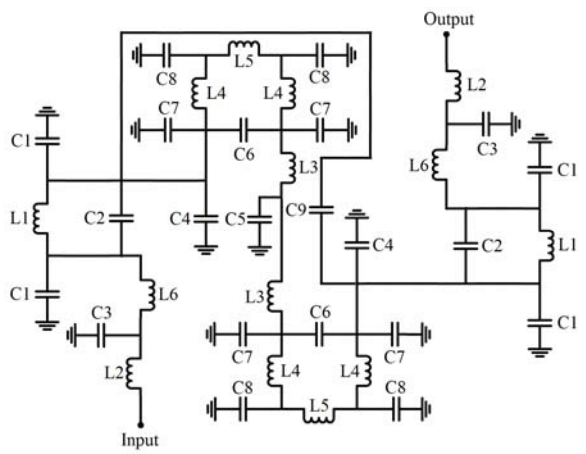


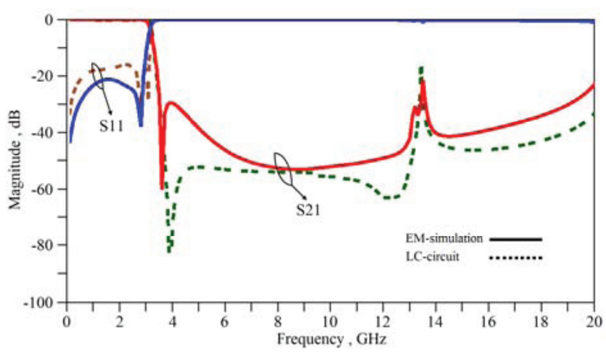
Fig. 11. The proposed lowpass filter.

As it is clear in Fig. 10 (b), there is a pole for S21 in the frequency of 13.5 GHz. The value of S21 in that frequency is lower than -20 dB. To increase this value to more than -20 dB, which extend the stop-band bandwidth (for the insertion-loss higher than -20 dB), it is needed to add some other parts to the structure. These parts are added to the feeding lines, which can be seen in Fig. 11. The parts with 1.5 mm wide are used for that reason. The parts with 1.2 mm wide are used to have better impedance matching for 50 ohm ports.

Using the same method for the proposed resonator, the LC circuit model of the proposed lowpass filter is shown in Fig. 12 (a). In this figure the values of the elements are: C1 = 0.1 pF, C2 = 1 pF, C3 = 0.3 pF, C4 = 0.2 pF, C5 = 0.38 pF, C6 = 0.36 pF, C7 = 1 pF, C8 = 0.1 pF, C9 = 0.02 pF, L1 = 1.7 nH, L2 = 0.3 nH, L3 = 0.84 nH, L4 = 0.59 nH, L5 = 1.7 nH, L6 = 0.3 nH. Figure 12 (b) shows a comparison between the LC circuit model and EM-simulation results of the proposed filter.



(a)

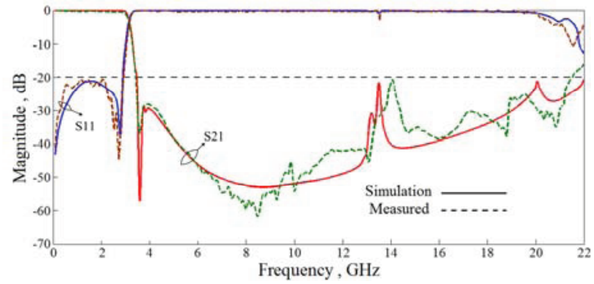


(b)

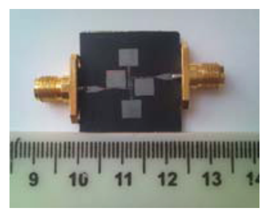
Fig. 12. (a) The equivalent LC circuit of the proposed filter and (b) the results.

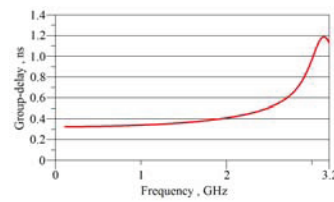
This filter is designed on (RT/Duroid 5880) substrate with 2.22 dielectric constant, 15 mil heights, and 0.0009 loss tangents. The designed filter is fabricated using microelectronic technology and measured by the use of an Agilent network analyzer N5230A.

The simulated and measured results are shown in Fig. 13 (a) and the photograph of the filter is shown in Fig. 13 (b) and also the group-delay of the proposed filter is shown in Fig. 13 (c). As it is clear in Fig. 13 (a), the EM simulation results are in good agreement with the measured results.



(a)





(b) (c)

Fig. 13. Proposed low-pass filter (a) the simulation and measurement results, (b) photograph, and (c) group-delay.

IV. RESULTS

Measured results show very good performance for the proposed filter. The insertion-loss from DC to 2.8 GHz is lower than -0.45 dB and the return-loss is higher than -20.7 dB. The transition from -3 dB to -20 dB is 0.26 GHz, which is equal to 65.38 dB/GHz that shows a sharp roll-off skirt and overall size of the fabricated filter is about 16.4 mm × 20 mm (0.246 λ_g × 0.3 λ_g). The group delay in the pass-band is from 0.3 ns to 1.18 ns.

Table I shows the comparison between the proposed filter and some other LPFs. As it is obvious, in comparison with the proposed filters in [2-13], this new filter has a very good performance. In Table I, all the stop-band bandwidths are calculated for the insertion-loss higher than -20 dB and as it is clear, compared with the other filters, the proposed filter has the sharpest roll-off skirt and also it has other advantages like: wide stop-band bandwidth and very good insertion-loss and return-loss in the pass-band.

Table I. Comparison between the proposed low-pass filter and some other filters.

Ref	Fc (GHZ)	R-O (dB/GHz)	I-L (dB)	R-L (dB)	S-B (up to Fc)
2	3	18.9	1.4	24	4.7
4	1.5	18.8	0.5	10	2.13
5	2.5	24.2	0.45	14	3.44
6	1	48.5	0.4	20	4.1
7	0.5	56.6	0.5	16.3	7.6
8	2.4	34	1.2	5	low
9	4.16	19	0.1	20.18	2.48
10	1.67	24.28	0.5	12	2.63
11	2	18.9	0.6	12	5.32
12	2.95	16.19	0.1	20	5.42
13	2.75	48.5	0.5	17.5	1.7
This	3.1	65.38	0.45	20.7	5.85

R-O = roll-off, I-L = Insertion-loss, R-L = return-loss, and S-B = stop-band.

V. CONCLUSION

A compact low-pass filter with wide stop-band bandwidth and sharp roll-off is designed and fabricated. The simulated and measured results are in good agreement with each other. The filter has the cut-off frequency of 3.1 GHz, wide stop-band bandwidth (from 3.36 GHz to 21.5 GHz with the attenuation level above -20 dB), low insertion-loss, and high return-loss in the passband. The filter with these features can answer the demands of modern communication systems.

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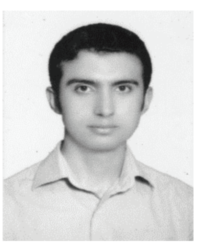

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