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Research paper

Compact Low Pass Filter Using Sharp Roll-off Ultra-Wide Stopband T-shaped Resonator

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Extended Abstract

Background and Objectives: In this paper, an ultra-wide stopband microstrip low pass filter (LPF) with sharp roll-off and compact size is designed and fabricated. Also, proposed filter is designed, simulated, optimized, fabricated and measured and we can see a good agreement between the simulations and measurement results.
Methods: T-shaped and stepped impedance have been used, because these structures have a very small dimensions. This method provides a suitable cut off frequency.
Results: The cut off frequency at -3dB is 3.1GHz. In the proposed structure, the insertion loss is lower than 0.12dB and the return loss is greater than 15dB. In order to achieve a -20dB attenuation level in the stopband, a modified L-shaped structure is utilized. This filter has an ultra-wide stopband that is expanded from 3.37GHz to 37.5GHz. Also, the suppression level is greater than -20dB. The fabricated LPF has a size about 16.6 × 13.5 mm^2 which is equal to 0.28ƛg × 0.22ƛg, where ƛg is the guided wavelength at 3.1GHz, which is very small.
Conclusion: A microstrip LPF with 3.1GHz cut-off frequency consisting of T-shaped and stepped impedance resonators has been proposed, simulated and fabricated. The transition band (-3 to -40dB) is 0.38GHz, which is a very sharp response. The stopband of the proposed filter is from 3.37 to 37.5 GHz which is equal to 12.1f_c. There was a significant agreement between the simulation and the measured results. With all these features, these filters are widely used in wireless communication systems.

Introduction

In recent years, Low pass filters are one of the most important elements in the design of telecommunication systems. Filters consist of elements such as inductors, capacitors and resistors. One of the main application is the separation of different frequencies. These elements are known as lumped circuits. In high frequency, they lose their behaviors and cause inefficiencies. Microstrip lines are one of the best options for designing lowpass filters. Microstrip lines have advantages such as very small dimensions, low cost, low losses, sharp responses in the transition band and high slope in the stopband. There are various methods for designing microstrip LPF [1, 2]. In the design of the microstrip LPF**,** the simplest structure is T-shaped [3]. One of the mean advantage of this structure is compact size but if the proposed structure is used alone, it always causes problems such as lack of sharp response in the transition band. A Defected ground structure (DGS) is one of the favorite techniques for the design of a microstrip LPF [4]. Using modified T-shaped structure, a new resonator was designed.

Then, with the help of defected ground structure a suitable stopband bandwidth has been provided. Using the defected ground structure (DGS), the size of the filter is increased. Stepped impedance resonators provide a sharp response in the transition band [5]. In the design of microstrip LPF, they play a vital role, but this resonator does not provide an appropriate stopband. With the help of this resonator and its combination with other resonators, the stopband bandwidth problem should be resolved. A compact low pass filter based on a coupled-line hairpin unit has been presented [6].

As can be seen in the proposed structure, it is able to create a desirable stopband by creating a gap in the structure, but this gap reduces the suppression level in the stopband. In passband, the return loss is not acceptable. Another microstrip lowpass filter with lattice-shaped resonators has been designed and fabricated [7]. The purpose of the lattice resonator is to achieve transmission zeros at various frequencies on the stopband.

Then, with the use of U-shaped structure, the basic parameters have been improved. The biggest problem of the proposed filter is the high cut off frequency which reduces the figure of merit. In the design of this filter, a new structure has been used [8]. An octagonal-shaped structure, a new resonator, was designed with small dimensions.

Using the symmetry of the proposed resonator, the parameters such as the return loss and the insertion loss have been greatly improved. A new approach with hexagonal shape resonators and defected ground structure (DGS) has been investigated [9]. In the design process, if more attention was paid to parameters such as wide stopband and insertion loss, an ideal microstrip low pass filter could be made.

Herein, a novel low pass filter using T-shaped, and stepped impedance structure with ultra-wide stopband and sharp roll off is simulated and fabricated. In the proposed structure, all the parameters such as sharpness, return loss, insertion loss and high attenuation level, are considered. The proposed filter was simulated and optimized using advanced design system (ADS) 2017 and it was fabricated on a RO4003 substrate with 32mm thickness, a relative dielectric constant of 3.38 and a loss tangent of 0.0021.

General Design Process

The general design of a microstrip LPF consists of four parts:

1. Select the appropriate substrate.
2. Design of the main resonator and equivalent LC circuit with desired cut off frequency.
3. Design of the attenuator and equivalent LC circuit with high suppression level.
4. Stub design for improving stopband.

Substrate Layer

In the design, the first step is to determine the appropriate substrate type. This stage plays a vital role as a suitable substrate which can be used to design a compact microstrip LPF.

The suggested substrate is RO4003, and a 32-millimeter thick of this substrate is used to achieve an appropriate return loss and insertion loss.

Fig. 1 depicts the overall structure of the microstrip technology.

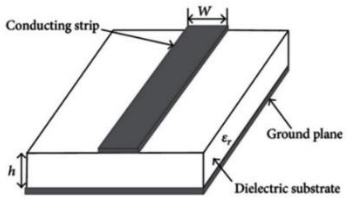


Fig. 1: The overall structure of the microstrip technology.

Microstrip Lines

Microstrip lines play a very important role in telecommunication systems. At high frequencies, microstrip lines can be used instead of lumped circuits, because of their very low losses and very small dimensions. The following models and relationships were used to extract the LC equivalent circuit. The values of the parameters are according to the Eq. 1, Eq. 2. High/low-impedance lossless line terminated at both ends by relatively low impedance lines shown in Fig. 2(a) are considered, which could also be presented by a π-equivalent circuit, as shown in Fig. 2(b).

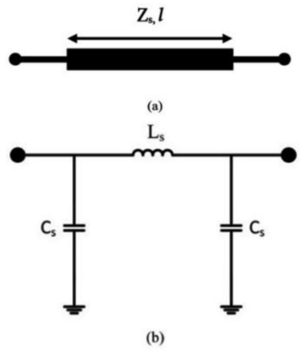


Fig. 2: (a) Layout of a high/low-impedance Lossless line, (b) Equivalent LC circuit of a high/low-impedance Lossless line.

The values of inductors and capacitors can be given as:

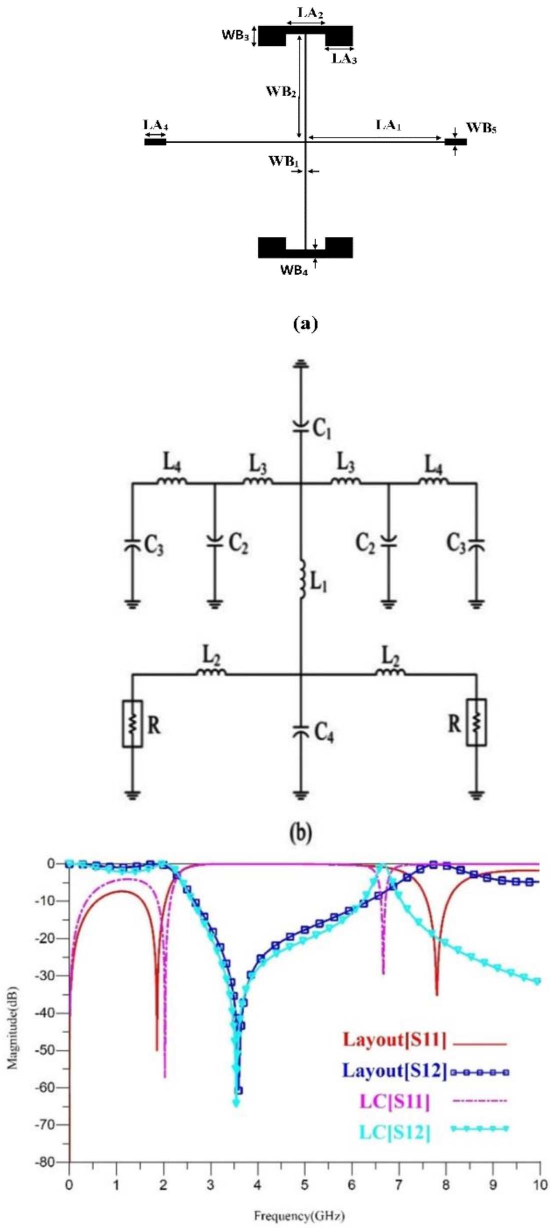
$$L_S = \frac{1}{\omega} \times z_S \times \sin\left(\frac{2\pi}{\lambda_g} l\right) \quad (1)$$

$$C_S = \frac{1}{\omega} \times \frac{1}{Z_S} \times \tan\left(\frac{\pi}{\lambda_g} l\right) \quad (2)$$

where z_s is the characteristic impedance, l is the length of line, and λ_g is the wavelength at the cut_off frequency. Fig. 3 (a-b) shows the structure and equivalent LC circuit.

(a) (b)

Fig. 3: (a) Open-end, (b) Equivalent LC circuit.



(c)

Fig. 4: (a) Configuration of the main resonator, (b) Equivalent LC circuit for the main resonator, (c) Frequency response of the main resonator.

Main Resonator

After determining the substrate type, the design of the main resonator is considered. The main resonator plays a very important role in the determination of the cut off frequency and sharp response in the transition band. Both parameters play a significant role in the figure of merit. As can be seen from Fig.4 (a), T-shaped and stepped impedance structures have been used. These resonators are combined to complement each other and produce ideal parameters.

The result of the combination of resonators has led to a good cut off frequency. The parameters related to these structure are LA_1=7.3, LA_2=2, LA_3=1.4, LA_4=0.95, WB_1=0.1, WB_2=6.2, WB_3=1.1, WB_4=0.5 (all in millimeters).

The LC equivalent was designed by π-equivalent circuit and open-end. The LC equivalent of the main resonator is shown in Fig. 4 (b). The parameters of inductors and capacitors were calculated according to Eq. (1) and Eq. (2). The values of these parameters are presented in Table 1. The results obtained from the LC equivalent circuit and the proposed structures are shown in Fig. 4 (c).

where R is the matching impedance and its value is 50 ohms. With the help of this transformation function and changing the values of the inductor and the capacitor, we can shift the cut-off frequency of transfer function (3). As shown in Eq. (1) and Eq. (2), by varying the length and thickness of the microstrip, it is easy to change the values of the inductors and capacitors.

$$\frac{V_o(s)}{V_i(s)}=\frac{AR}{(R+L_1S)(2A+R+L_1S)} \tag{3}$$

$$A=\frac{B+C+D}{E+F+G+H} \tag{4}$$

$$B=1+2C_2L_2s^2+2C_3L_2s^2+2C_4L_2s^2 \tag{5}$$

$$C=C_3L_3s^2+C_4L_3s^2+C_4L_4s^2+2C_2C_3L_2L_3s^4 \tag{6}$$

$$D=2C_2C_4L_2L_3s^4+2C_2C_4L_2L_4s^4+2C_3C_4L_2L_4s^4$$
$$+C_3C_4L_3L_4s^4+2C_2C_3C_4L_2L_3L_4s^6 \tag{7}$$

$$E=3C_2s+2C_3s+2C_4s+2C_2{}^2L_2s^3 \tag{8}$$

$$F=2C_2C_3L_2s^3+2C_2C_4L_2s^3+3C_2C_3L_3s^3$$
$$+3C_2C_4L_3s^3 \tag{9}$$

$$G=3C_2C_4L_4s^3+2C_3C_4L_4s^3+2C_2{}^2C_3L_2L_3s^5$$
$$+2C_2{}^2C_4L_2L_3s^5 \tag{10}$$

$$H=2C_2{}^2C_4L_2L_4s^5+2C_2C_3C_4L_2L_4s^5+$$
$$3C_2C_3C_4L_3L_4s^5+2C_2{}^2C_3C_4L_2L_3L_4s^7 \tag{11}$$

The transformation function was expressed according to the equivalent LC circuit of the extracted resonator. This is explained below.

Table 1: Calculated inductors and capacitors

Parameter	L_1	L_2	L_3	L_4
Value	3.4nH	8.6nH	0.5nH	0.5nH
Parameter	C_1	C_2	C_3	C_4
Value	0.14pF	0.08pF	0.13pF	0.35pF

Attenuator Design

As shown in Fig. 4 (c), frequency response of the proposed resonator is just like a frequency response of a low pass filter. These resonators produced a transmission zero at 3.59GHz with -60.72dB attenuation level. However, in the other frequencies, the suppression level is not enough. To solve this problem, a symmetrically modified L-shaped structure has been used.

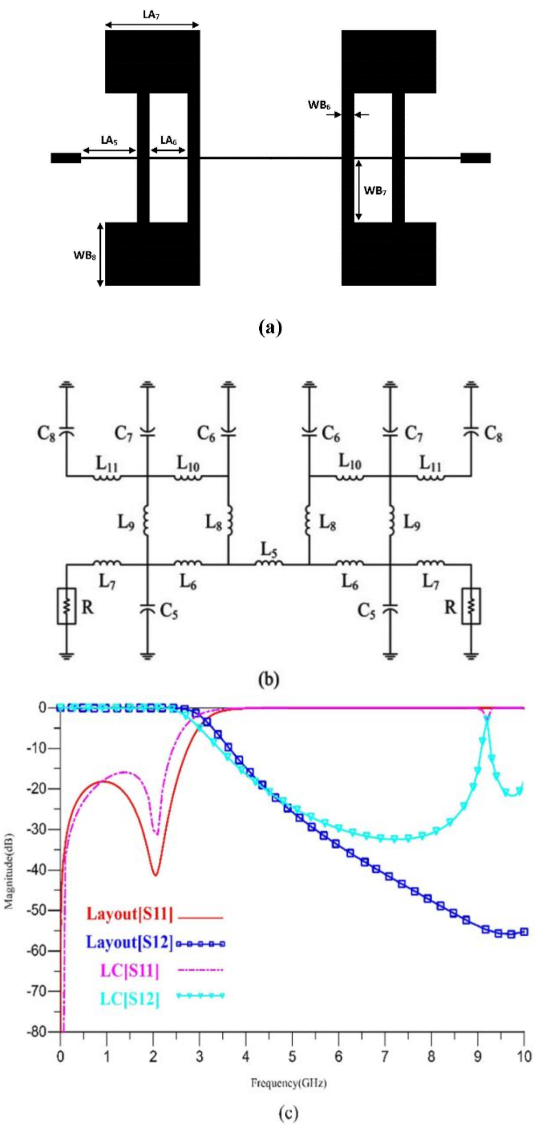


Fig. 5: (a) Structure of the proposed attenuator, (b) LC equivalent of the proposed attenuator, (c) Frequency response of the attenuator.

Table 2: Calculated inductors and capacitors

Parameter	L_5	L_6	L_7	L_8
Value	3.0375nH	1.7415nH	2.02nH	0.12nH
Parameter	L_9	L_{10}	L_{11}	
Value	1.5nH	1.1445nH	0.7nH	
Parameter	C_5	C_6	C_7	C_8
Value	1.8405pF	0.21pF	0.18pF	0.06pF

The calculated dimensions for the attenuator are LA_5=2.05, LA_6=1.5, LA_7=3.75, WB_6=0.5, WB_7=2.5, WB_8=2.5 (all in millimeters). The proposed attenuator is shown in Fig. 5 (a). Also the LC equivalent circuit is shown in Fig. 5 (b). The frequency response of the proposed resonator and LC equivalent is shown in Fig. 5 (c). Table 2 shows the values of the inductors and capacitors. As can be seen in Fig. 5 (c), the level of suppression in the stopband is very high.

In the transition band, the desired sharpness is not achieved. The main resonator and the attenuator are combined to resolve the problems. The structure of the attenuator with the main resonator is shown in Fig. 6 (a), also the frequency response of the proposed attenuator with the main resonator is illustrated in Fig. 6 (b).

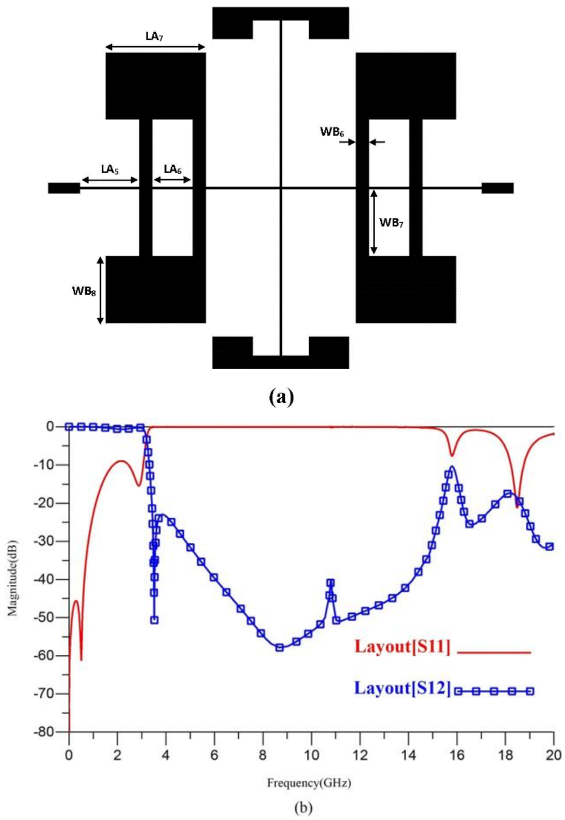


Fig. 6: (a) Structure of the attenuator with the main resonator, (b) Frequency response of the attenuator with the main resonator.

Transmission zeros are produced at frequencies of 3.51, 8.68 and 19.54 GHz with values of -50.65, -57.88 and -31.55 dB, respectively. The performance of the proposed attenuator is very suitable.

Final Filter

As mentioned above, stub design is at the final stage. For improving the stopband, a rectangular shape has been used.

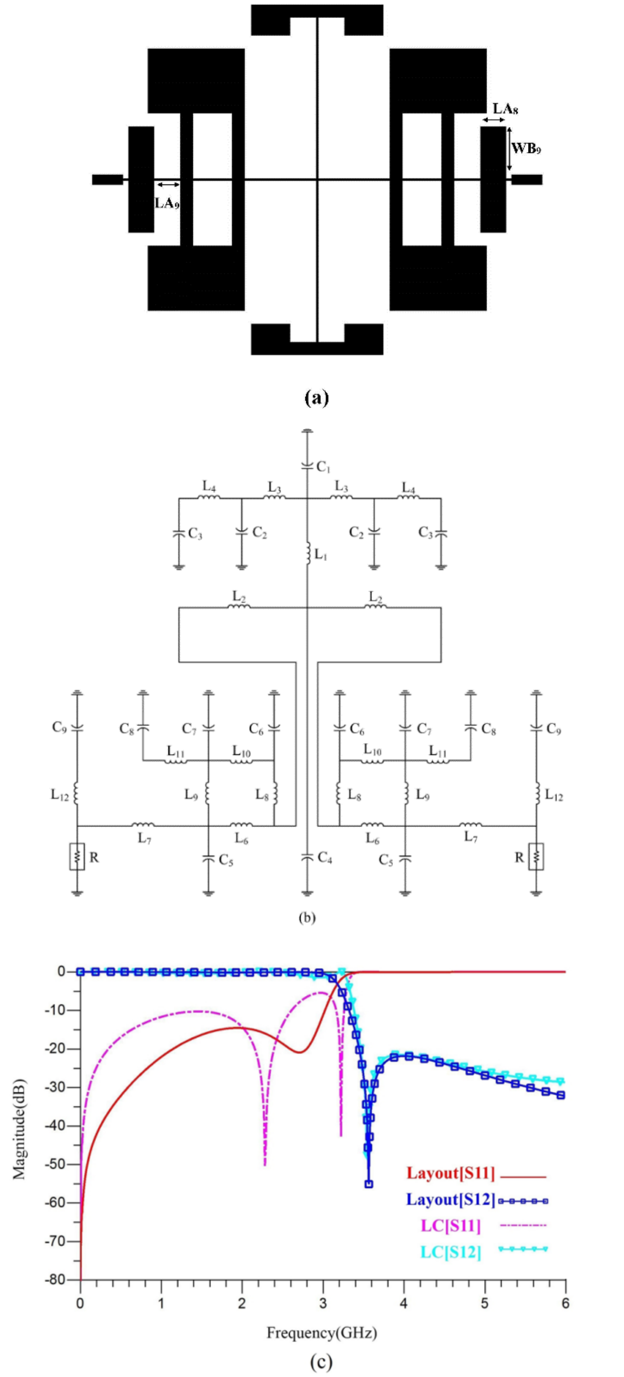


Fig. 7: (a) Structure of the stub with the main resonator and attenuator, (b) LC equivalent of the stub with the main resonator and attenuator, (c) Frequency response of the stub with the main resonator and attenuator.

The parameters of the stubs in Fig. 7 are as follows: LA_8=1.1, LA_9=0.75, WB_9=2.05 (all in millimeters). The final structure of the proposed filter is shown in Fig. 7 (a), also the LC equivalent circuit of the final structure is shown in Fig. 7 (b). The final frequency response of the proposed filter and LC equivalent is illustrated in Fig. 7 (c). Table 3 shows the values of the inductors and capacitors.

Table 3: Calculated inductors and capacitors

Parameter	L_{12}	C_9
Value	0.1nH	0.03pF

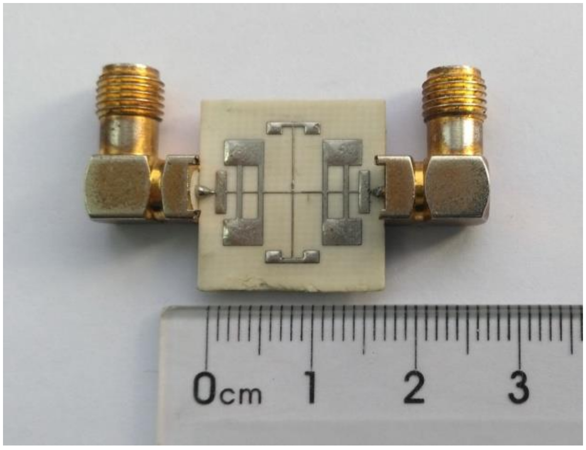


Fig. 8: Photograph of the proposed filter.

Fig. 8 shows the photograph of the fabricated filter. Moreover, the measured and simulation results are shown in Fig. 9. All parameters are considered and their values are very suitable. As shown in Fig. 9, close agreement between the simulated and measured results can be seen.

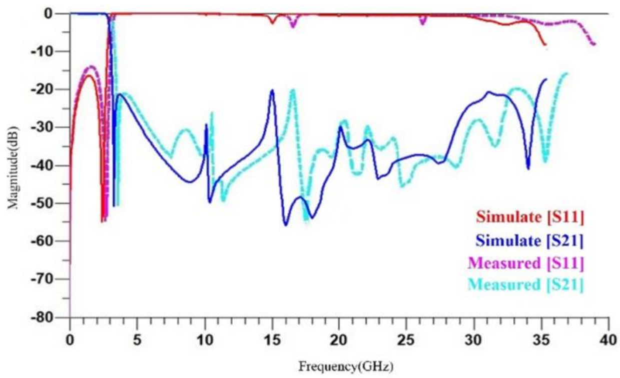


Fig. 9: Frequency response of the proposed filter.

Calculation

As shown in Table 4, the performance of this filter is compared with the others similar structures in the literature. In Table 1, the roll-off rate is given by:

$$\varepsilon = \frac{\alpha_{max} - \alpha_{min}}{f_s - f_c} \tag{12}$$

where α_{max} and α_{min} are the -40 and -3dB attenuation points, respectively. f_c is the -3dB cut-off frequency and f_s is the -40dB stopband frequency. The relative stopband bandwidth (RSB) is defined as:

$$RSB = \frac{\text{Stopband bandwidth}}{\text{Stopband in center frequency}} \quad (13)$$

The suppression factor (SF) is based on the rejection level in the stopband bandwidth. For example, when three is a 20dB suppression, thus the corresponding SF is 2. A higher suppression means a greater SF.

$$SF = \frac{\text{Rejection level in the stopband}}{10} \quad (14)$$

The normalized circuit size (NCS) is defined as:

$$NCS = \frac{\text{Physical Size (Length×Width)}}{\lambda_g^{\ 2}} \quad (15)$$

where ƛg is the guided wavelength and is calculated by:

$$\lambda_g = \frac{300}{f_C\sqrt{\varepsilon_{re}}} \quad (16)$$

The architecture factor (AF) is the complexity factor of the circuit. It is 1 for 2D designs and 2 for 3D designs.

Conclusion

A microstrip LPF with 3.1GHz cut-off frequency consisting of T-shaped and stepped impedance resonators has been proposed, simulated and fabricated. The transition band (-3 to -40dB) is 0.38GHz, which is a very sharp response. The stopband of the proposed filter is from 3.37 to 37.5 GHz which is equal to $12.1f_c$. There was a significant agreement between the simulation and the measured results. With all these features, these filters are widely used in wireless communication systems.

Table 4: Comparison of different filters with the proposed filter

Ref.	F_C(GHz)	ζ	NCS(λg^2)	SF	RSB
3	1.11	58.6	0.12 × 0.07	2	1.54
4	2.45	56.7	0.11×0.11	2	1.63
5	2.28	94	0.24×0.16	2.3	1.26
6	2	43.9	0.1×0.15	1	1.63
7	4.34	100	0.67×0.11	2	1.58
8	2.8	48.5	0.14×0.15	2	1.61
9	2.45	100	0.24×0.12	2	1.49
10	3.09	46	0.22×0.13	2	1.37
11	0.5	95	0.21×0.1	2	1.4
12	3.14	70	0.25×0.17	1	1.4
13	1.2	17	0.1×0.09	1.5	1.38
14	5.55	84	0.31×0.27	1.5	0.67
15	2.2	58.6	0.15×0.37	2	1.73
This work	3.1	97	0.28×0.22	2	1.67

Author Contributions

F. Yousefi Moghadam has simulated the microstrip low pass filter with the desired specifications such as suitable cut-off frequency, suitable sharpness, suitable stop band, etc. in the Advanced Design System(ADS) software. B. Afzali has extracted the equivalent circuit and calculated transformation function of the main resonator. F. Nadi has been involved in writing and translating the article. R. Zallbeygi has been involved in writing and translating the article.

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Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

Abbreviations

LPF	Low Pass Filter
dB	Decibel
DGS	Defected Ground Structure
fc	Cut-off frequency
Eq.	Equation
Fig	Figure
RSB	Relative Stopband Bandwidth
SF	Suppression Factor
NCS	Normalized Circuit Size
AF	Architecture Factor
ADS	Advanced Design System

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