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Design and Analysis of a Compact and Harmonic Suppressed Microstrip Lowpass Filter

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Abstract

A new compact and harmonic suppressed microstrip Lowpass Filter (LPF) is designed to generate a sharp skirt transition band with wide rejection area. In this structure, some triangular and square-shaped structures are used. The suggested LPF with 3 dB cut-off frequency at 1.64 GHz has been designed, fabricated and tested to show the validity of the proposed LPF structure. LC equal model is extracted, then using the LC equal model, the output to input ratio of the filter is calculated. Exact equations for the main Transmission Zero (T_z) which placed after transition band, is computed and analyzed based on LC equal model and output to input ratio. The proposed LPF stopband is expanded from 1.89 GHz up to 15 GHz with suppression level more than 20 dB. Also, its Figure of Merit (FOM) is calculated about 22000.

1. Introduction

Microwave filters have outstanding role in RF and wireless communication systems. These systems need the LPF circuits with high performance. The most interesting idea for anyone involved in electronic circuit design is to have the ability to develop LPFs with sharp roll-off, small size and ultra-wide stopband rejection. Many devices such as mixers or oscillators require LPFs to suppress harmful signals. Therefore, LPFs with good frequency performance are in high demand in many communication systems, [1-2]. Based on mentioned desirable performances, an extensive investigation have been done and several LPFs and consequently high frequency circuits have been proposed and published in recent years, [3-20]. For example, using high and low impedance structures, a microstrip LPF with sharp response and wide stopband has been suggested in [3]. Based on utilizing hairpin structures, another-

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LPF with wide rejection band has been designed in [4]. Applying radial stub loaded structure, a compact microstrip LPF with ultra-wide rejection band, is suggested in [5]. Another LPF is presented in [6], which is used triangular and two 120 degree radial patches resonators to reach a compact size and good harmonics suppression. Using T-shaped structure and open stubs, a compact microstrip LPF with wide stopband has been suggested in [7]. In [8], a compact LPF with wide rejection band is designed, which is used coupled rhombic stubs structure. Utilizing stepped impedance units, another compact LPFs with wide rejection bands are designed in [9-10]. Dual-plane structure is another method which is used to design compact LPFs as mentioned in [11]. Another approach to design a microstrip LPF is discussed in [12], which is used elliptical and radial structures. Utilizing rhombus-shaped resonators, another LPF with simple structure is suggested in [13]. Using a symmetrical modified T-shaped and flag-shaped structures, another LPF with small circuit size and excellent harmonics suppression is presented in [14]. Using triangular-shaped resonator another compact and ultra-wide LPF is developed in [15], which is used output to input ratio for determining transmission zeroes. Researchers have recently developed high frequency circuits using microstrip structures, to suppress unwanted harmonics and reduce the circuits' size; [16-20].

In this paper, a novel LPF with ultra-wide rejection band and small size is discussed. The proposed LPF has a simple structure that makes its study easier. The simulation and measurement results of proposed filter are acceptable and confirms the proper performance of the filter in compared with the previous structures. With all the features and benefits mentioned above, the presented LPF can be utilized for telecommunication and microwave usage. The main aspect of using triangular and square structures is to achieve wide rejection band from 1.89 GHz to 15 GHz with large attenuation level for more than 25 dB. In the following, the first issue is study of the resonators and LPF design, which is reported in section 2 and 3 using Advanced Design System (ADS) software and mathematical computing the Matematica V.9 software. Also, the simulation responses and measurement results of final filter are proposed in section 4.

2. Main Resonator

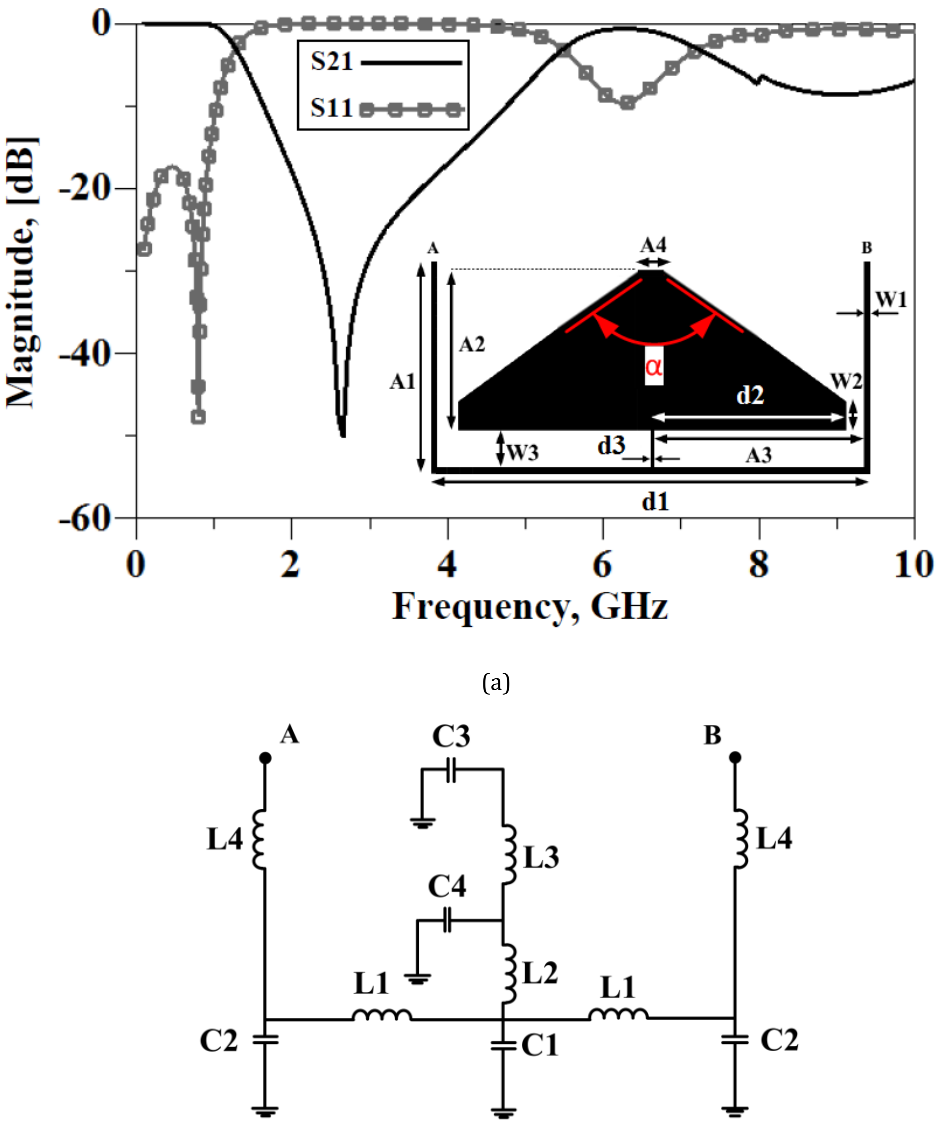
The configuration of the base resonator is illustrated in Figure 1 (a). This resonator is composed of triangular and square structures which are in series. The LC equal model of the main resonator is presented in the Figure 1 (b). Also, its frequency responses are demonstrated in Figure 1 (a). The calculated value for LC equal model are summarized in Table. 1.

L1, L4 denotes the inductance of the transmission line. C2, C1, C4 and L2, L3 are capacitance and inductance of high impedance lossless line and C3 is the summation of the equal capacitances of open-end structure and high-impedance lines. The method of calculating the value of this parameters is discussed in [2, 15]. The equations of inductances and capacitances in square structure are pend in Eq. 1 and Eq. 2, also a comprehensive method for computing inductances and capacitances of triangular structure is discussed in [15]. Here we use that equations to computing the amounts of inductances and capacitances for the base resonator. The dimensions of the proposed resonator which is mentioned in Figure 1 (a) are listed as bellows:

W1=0.2, d1=14.7, A1=6.9, A2=5.2, A3=7.1, A4=1, d2=6.4, W2=1, d3=0.1, W3=1.2 (All in millimeter)

$$Ls = \frac{1}{\omega} \times z_s \times \sin(\frac{2\pi}{\lambda_g} L) \quad (1)$$

$$Cs = \frac{1}{\omega} \times \frac{1}{Z_s} \times \tan(\frac{\pi}{\lambda_g} L) \quad (2)$$



(a)

(b)

Figure 1. Base resonator, (a) Layout and frequency responses, (b) LC equal model.

Table. 1. Calculated value for LC equal model, (Units of C and L are pF, nH, respectively).

Element	L1	L2	L3	L4	C1	C2	C3
Value	4.15	0.87	0.37	3.9	0.33	0.31	2.04

As seen, the base resonator has a transmission zero at around 2.6 GHz, this transmission zero is very important since it can determine the sharpness and the cut-off frequency location. The output to input ratio can be expressed as a deduction, as mentioned in Eq. (3). Its numerator and denominator determine the zero and pole, respectively. Resonators behavior with the help of zeros and poles in the output to input ratio can be analyzed. In this paper by using LC circuit and output to input ratio the transmission zero is calculated in Eq. (4). The output to input ratio is extracted from LC circuit. (Note: r=50Ω)

$$\frac{vo}{vi} = (ar)\Big/\frac{((r + \mathrm{L1}s + \mathrm{L4}s + \mathrm{C2L1}rs^2 + \mathrm{C2L1L4}s^3)}{(2a + r + \mathrm{L1}s + \mathrm{L4}s + 2a\mathrm{C2}rs + 2a\mathrm{C2L4}s^2 + \mathrm{C2L1}rs^2 + \mathrm{C2L1L4}s^3))} \quad (3)$$

$$a = \frac{1 + s^2(C4L2 + C3(L2 + L3 + C4L2L3s^2))}{s(C1 + C3 + C4 + (C1(C3 + C4)L2 + C3(C1 + C4)L3)s^2 + C1C3C4L2L3s^4)}$$

$$T_Z = \frac{\sqrt{-\frac{1}{\mathrm{C2L2}}-\frac{1}{\mathrm{C2L4}}-\frac{1}{\mathrm{C3L4}}-\frac{\sqrt{-4\mathrm{C2C3L2L4}+(\mathrm{C2L2}+\mathrm{C3L2}+\mathrm{C3L4})^2}}{\mathrm{C2C3L2L4}}}}{2\pi\sqrt{2}} \quad (4)$$

The Electromagnetic Momentum (EM) and circuit simulation responses of the base resonator are in good accordance as demonstrated in Figure 2.

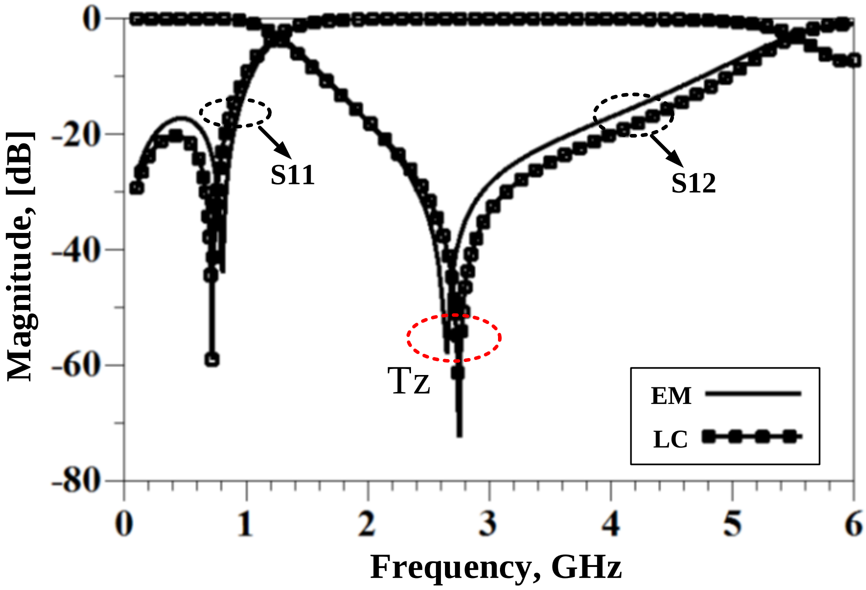


Figure 2. EM and LC simulation responses of base resonator.

As mentioned, the suggested structure can provide a transmission zero at 2.5 GHz. The location of transmission zero in designing a LPF with wide rejection band and sharp skirt transition band is really important. The location of transmission zero is adjusted by Eq. (4). The equation shows which parameters are important to change the place of transmission zero; one of those important parameters is L4. Figure 3 shows the effects of L4 changes on the location of the T_Z.

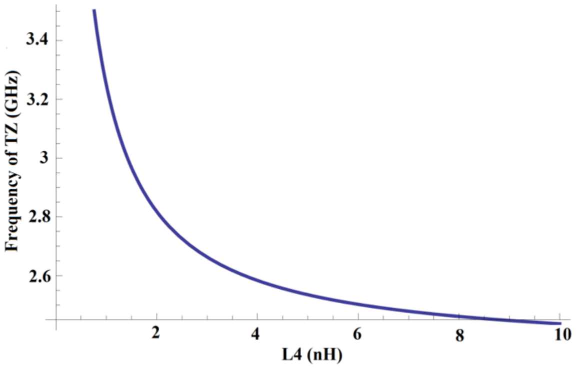
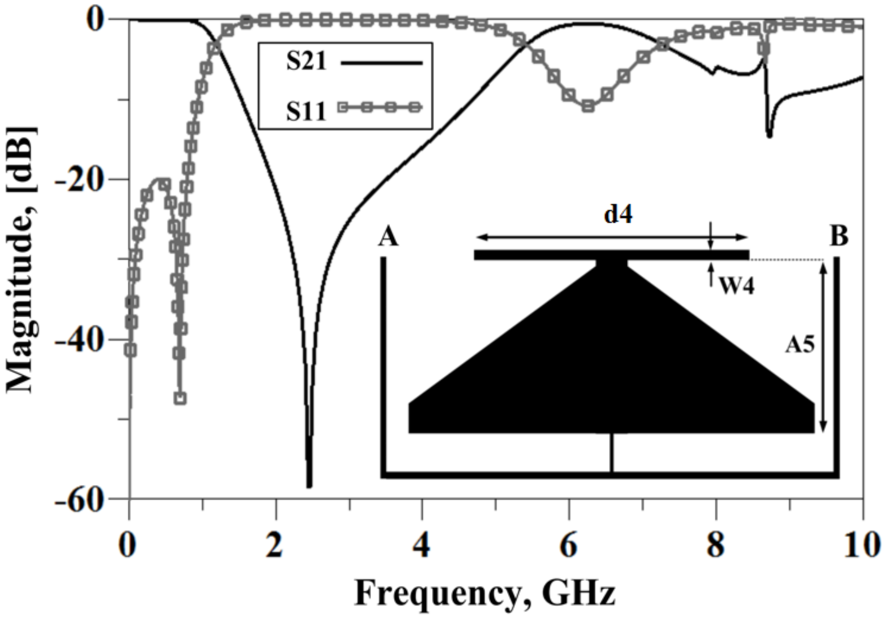
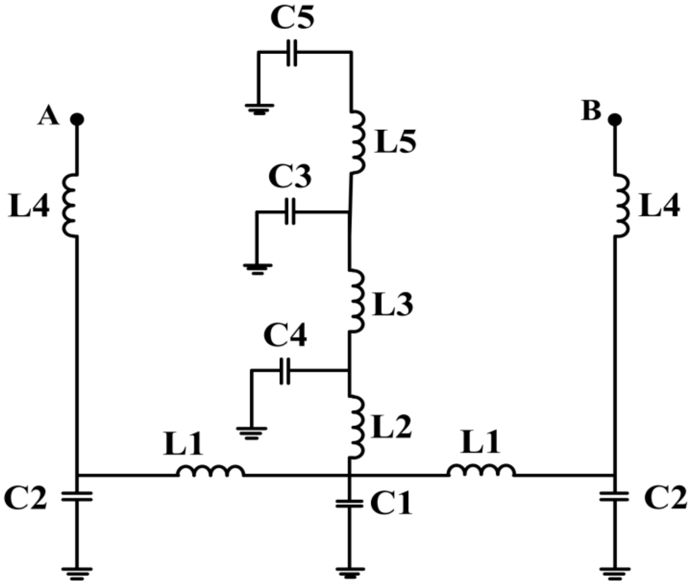


Figure 3. Location of Transmission Zero (T_Z) based on L4 changes.

In the following, a narrow square structure added to the proposed base resonator. This structure is illustrated in Figure 4 (a). Its dimensions are as listed as bellows: W4= 0.3, d4= 8.8, A5= 5.4 (All in millimeter). The frequency response and the LC equal model of this structure are shown in Figure 4 (a) and (b), respectively.



(a)



(b)

Figure 4. Main resonator, (a) Layout and EM frequency responses, (b) LC equal model.

The amounts of C3, C5 and L5 are equal to 1.28 pF, 1.2 pF and 0.02 nH, respectively. This raises the question of which variations will be made after adding the square patch. It can be seen from the Figure 4 (a), that cut-off frequency will be decreased and the sharpness of frequency response will be better. Zero transmission is shifted to the left. The EM and LC equal model simulation responses of the main resonator are in acceptable accordance as can be seen in Figure 5.

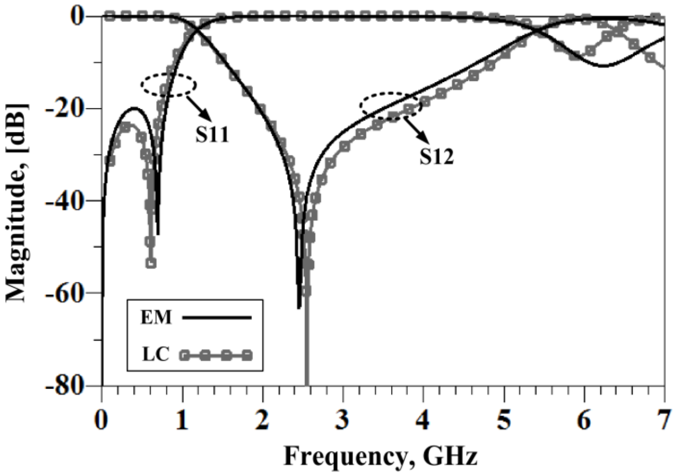
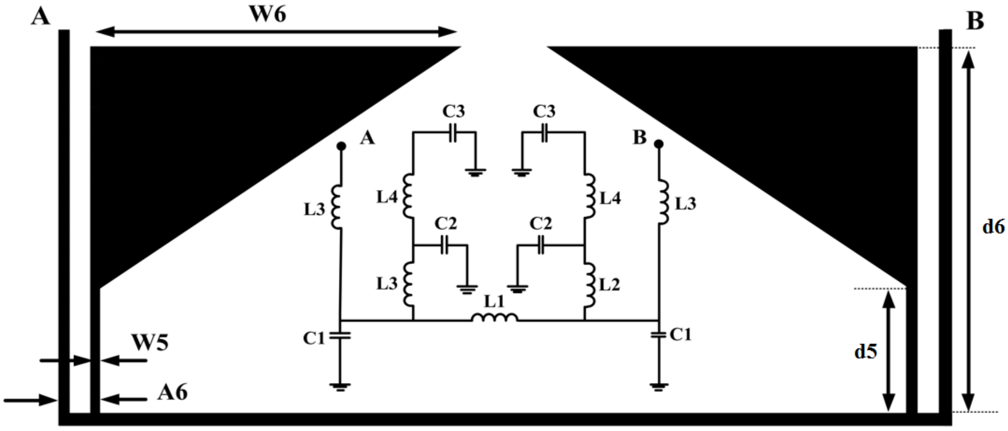


Figure 5. EM and LC simulation responses of main resonator.

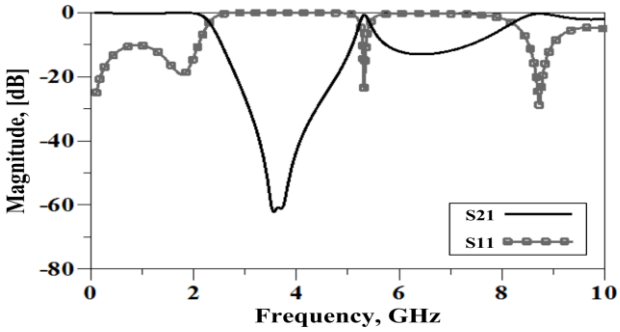
3. Lowpass Filter Design

We will deal with the question of "how to make a wide stopband". The truth of the matter is that other triangular resonators should be added to the main structure, which is demonstrated in Figure 6 (a), [15]. The simulation responses of the proposed triangular structures are shown in Figure 6 (b).

From the Figure 6 (b) it seems that, a transmission zero is generated in 3.7 GHz. By way of illustration can be seen that, eliminating of some harmonics could be done by the transmission zero. Another way of looking at this matter is to calculate the LC equal model, which is illustrated in Figure 6 (a). The dimensions of the proposed triangular structures are listed as follows: W5= 0.15, d5=2.2, W6=6, d6=6.4, A6=0.6. (All in millimeter).



(a)



(b)

Figure 6. Triangular structures, (a) Layout and LC model, (b) EM frequency responses.

The C1, C2, C3 and L1, L2, L3, L4 are equal to 0.6, 0.63, 0.48 pF and 7.33, 4.08, 4.09, 0.59 nH, respectively. The EM and LC simulation responses of triangular structures are in good accordance as can be seen in Figure 7. The equations of output to input ratio and transmission zero (T_{z1}) are penned in Eq. (5) and Eq. (6), respectively. (r=50Ω)

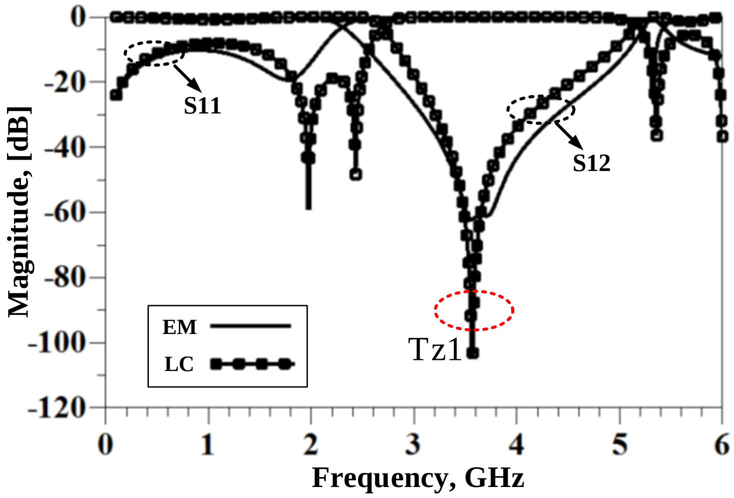


Figure 7. EM and LC simulation responses of triangular structures.

$$\frac{vo}{vi}=\frac{b^2r}{(b+r+L3s)(2br+bL1s+2bL3s+L1rs+L1L3s^2)} \qquad (5)$$

Where:

$$b=\frac{1+(C2L2+C3(L2+L4))s^2+C2C3L2L4s^4}{s(C1+C2+C3+(C1(C2+C3)L2+(C1+C2)C3L4)s^2+C1C2C3L2L4s^4)}$$

$$T_{z1}=\frac{\sqrt{-\frac{1}{C2L2}-\frac{1}{C2L4}-\frac{1}{C3L4}-\frac{\sqrt{-4C2C3L2L4+(C2L2+C3L2+C3L4)^2}}{C2C3L2L4}}}{2\pi\sqrt{2}} \qquad (6)$$

An addition it is quite right to add the proposed triangular shaped structures in the last part, to main resonator. Therefore, a prototype LPF is formed. The structure and frequency responses of the prototype LPF is presented in Figure 8.

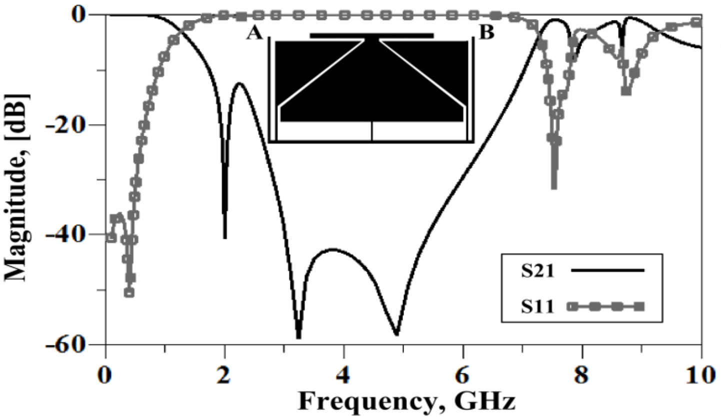


Figure 8. Configuration and frequency responses of prototype LPF.

As can be seen in the Figure 8, there are some unwanted harmonics in the range of 7 GHz to 9 GHz. They are related to the some transmissions zero which are produced due to the coupling between the resonators.

To eliminate the mentioned harmonics, another suppressing cells are considered and its frequency responses are demonstrated in Figure 9, [15]. The values of the designed cells are mentioned as follows: d7=3.5, W7=6.5, W8= 1.2, d8=3.9, A7=3.3. (All in millimeter). The structure of the final microstrip LPF and its frequency responses are presented in Figure 10.

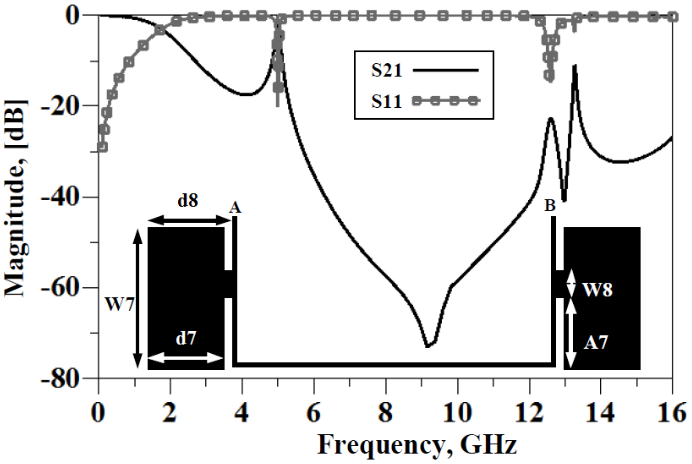


Figure 9. Layout and frequency results of suppressing cells.

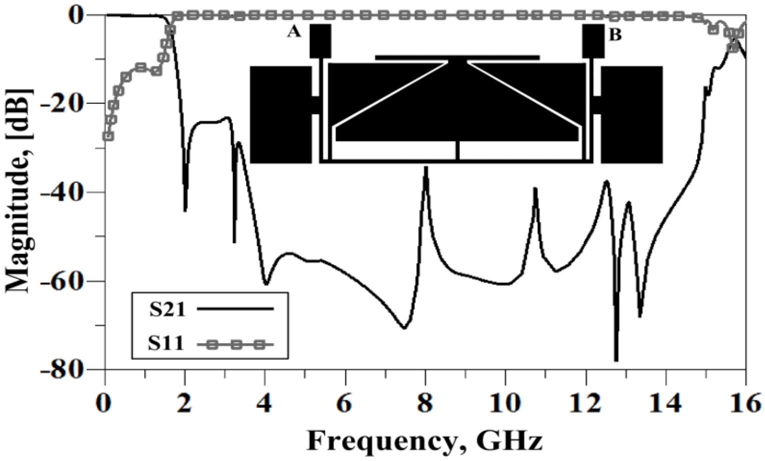
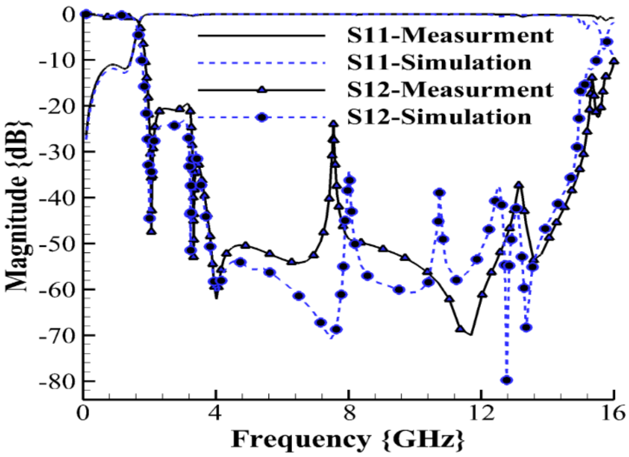


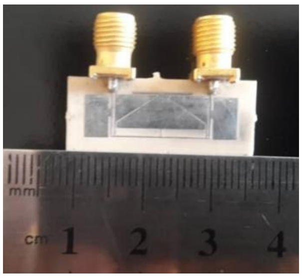
Figure 10. Layout and frequency response of proposed LPF.

4. Simulation and measurement results

The simulation and measurement results of the mentioned compact LPF are presented in Figure 11 (a). The photograph of the designed LPF with the details description of the used substrate is displayed in Figure 11 (b). The measurement result is obtained using an Agilent E8361C vector network analyzer. The performance of the discussed LPF is mentioned in Table. 2 with other reported LPFs for evaluation. It can be observed the proposed LPF provides good performances in stopband rejection and passband insertion loss.



(a)



(b)

Figure 11. (a) Simulation and measurement results of LPF. (b) Photograph of the designed LPF, (Substrate: RT/Duoriod 5880, Thickness: 20 mil, Dielectric constant: 3.38, Loss tangent: 0.0021)

Table. 2. Performance evaluation among reported LPFs and presented one.

Ref	*fc*	ξ	RSB	SF	NCS	FOM
[7]	2.68	43	1.5	2	0.15 × 0.14	6142
[8]	1.60	52.8	1.52	2	0.08×0.11	17638
[9]	1.60	52.8	1.52	2	0.08 × 0.11	18240
[10]	1.45	29	1.54	1.4	0.07 × 0.10	8932
[11]	2.45	56.7	1.63	2	0.11×0.11	6928
This Work	1.64	68	1.55	2.3	0.06 × 0.19	21264

†Note [21]: ξ: roll-off rate according to 3 and 40 dB attenuation points. RSB: the Relative Stopband Bandwidth, SF: Suppression Factor, NCS: Normalized Circuit Size, FOM=$\frac{RO\times RSB\times SF}{NCS\times AF}$

5. Conclusion

In this paper, a novel wide rejection band LPF with cut-off frequency at 1.64 GHz, has been presented and investigated. The suggested LPF provides a low insertion loss of 0.25 dB. It has been shown that the simulations responses achieved by circuit model and full-wave EM were in excellent accordance with the measurements. The discussed LPF can be broadly used to reject higher order harmonics and spurious response in wideband microstrip systems. Based on all these good details, the suggested LPF is suitable for embedded in modern RF and microwave wireless communication systems.

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