Mohsen Hayati, Saeedeh Lotfi*, Hesam Siahkamari, Tomas Blecha, Richard Linhart and Mohammad (Behdad) Jamshidi

A compact simple microstrip lowpass filter based on elliptical analyzed resonator

<https://doi.org/10.1515/freq-2021-0157>

Received June 30, 2021; accepted November 10, 2021;

published online November 29, 2021

Abstract: In this article, a compact microstrip lowpass filter (LPF) using elliptical shaped resonators with ultra-wide stopband is rendered. In this respect, LC equal structures of the elliptical shaped resonators are calculated based on the formula of circumference. In addition, to calculate transmission zeros of the presented elliptical shaped resonator, the LC equal structure and its output to input ratio are employed. The proposed LPF has a -3 dB cut-off frequency at 1.50 GHz and the stopband bandwidth of the designed filter is about $13f_c$, which refers to its ultra-wide stopband. The occupied circuit size of the presented filter is $0.151\lambda_g \times 0.044\lambda_g$ (λ_g is the guided wavelength at 1.50 GHz). The designed filter is fabricated on RT/Duroid 5880 substrate. The results of the fabricated and designed filter have clearly demonstrated that not only has the proposed LPF shown a suitable agreement between measured and simulated S -parameters, but also an appropriate stopband bandwidth.

Keywords: elliptical shaped resonator; LC equal structure; lowpass filter (LPF); output to input ratio; transmission zero; ultra-wide stopband.

1 Introduction

Compact microstrip LPFs with ultra-wide stopband are extremely desirable for wireless and mobile communication

systems to suppress unwanted high frequency harmonics. These systems need the LPF circuits with high performance. Therefore, LPFs with good frequency features are very noticeable in many communication systems [1, 2]. Several studies have been done to implement and analyze LPFs and microwave circuits with high performance [3–31]. One method, which is used in LPFs implementation, is Defected Ground Structure (DGS) to obtain high stopband suppression and size reduction [3, 4]. Another method is using stub-loaded resonators such as a compact LPF with a wide stopband, which is presented in [5]. Using coupled rhombic stubs, a compact and highly selective LPF with a wide stopband is presented in [6]. Authors in [7] applied hexangular shaped resonators for designing a LPF with high performance. Another LPF with compact size and sharp roll-off using modified Complementary Split-Ring Resonator (CSRR) was presented in [8]. A compact harmonic suppressed microstrip structure is presented in [9], which consists of stepped impedance lines and symmetric modified semi-circular patches. The dual-plane structure is another method that is used to design compact LPFs as mentioned in [10]. Another type of LPF is presented in [11], which is called multi stub LPF, in this structure the open stubs are used instead of impedance lines. A compact microstrip LPF with ultra-wide stopband is designed in [12], which uses an analyzed triangular shaped resonator in its design. Using a lattice-shaped resonator, a compact LPF with flat group delay with a wide rejection band and sharp roll-off is presented in [13]. Another LPF with sharp roll-off and ultra-wide stopband using circular sectors and cross-coupled structures is designed in [14]. A very applicable procedure for designing a lowpass filter is presented in [15], which some polygonal structures are embedded in its design and its analysis has been done based on transfer function evaluation. In [16], using LPF design, a dual-wideband bandpass filter with a wide upper stopband is presented, which uses a short stepped-impedance stub-loaded resonator in its LPF design. Another LPF with compact and ultra-wide stopband is designed in [17], which uses a narrow width microstrip line with high impedance and three multimode resonators in its structure. Using fractal structures and hairpin units are other methods to design the LPFs, such as [18–20]. Authors in [21] applied non-uniform radial stubs resonators to design another compact microstrip

***Corresponding author: Saeedeh Lotfi**, Department of Materials and Technology, University of West Bohemia in Pilsen, Plzen, Czech Republic, E-mail: lotfi@fel.zcu.cz.

<https://orcid.org/0000-0003-4110-7202>

Mohsen Hayati, Department of Electrical Engineering, Razi University, Kermanshah, Iran

Hesam Siahkamari and Richard Linhart, Department of Electronics and Information Technology, University of West Bohemia in Pilsen, Plzen, Czech Republic

Tomas Blecha, Department of Materials and Technology, University of West Bohemia in Pilsen, Plzen, Czech Republic

Mohammad (Behdad) Jamshidi, Research and Innovation Center for Electrical Engineering (RICE), University of West Bohemia in Pilsen, Plzen, Czech Republic

LPF with a wide stopband. A new method to enhance the LPFs performances is using neural network analysis, in [22], another LPF is designed and fabricated using multiple open stubs and stepped impedance resonators, which its features have been improved utilizing the mentioned method. Another lowpass filter with a sharp rejection band using coupled T-shaped, elliptical and radial resonators is presented in [23]. Using four high-low impedance patches and four radial stub structures, a lowpass filter with efficient performances is designed in [24], which has a high relative stopband bandwidth. Based on inductor-capacitor equivalent circuit analysis and using some series resonators with meandered lines, another LPF is designed in [25]. Another method to design and analyze the filters and other microstrip devices is using even and odd mode technique, [26, 27]. Recently, LPFs are used to develop other microwave devices for example [28–31].

In this paper, a microstrip LPF with considerable features, such as ultra-wide stopband, compact size and simple design with a return loss better than 29 dB is presented. The proposed LPF with –3 dB cut-off frequency at 1.50 GHz is designed using elliptical resonators. In addition to the good features of the suggested design, a new formula is presented to calculate the LC equivalent structure of the elliptical structures based on its geometric circumference, which is a new technique to calculate the LC elements.

2 Filter design

The filter design consists of creating some elliptical resonators and computing their output to input ratios (transfer functions), to analyze their behavior. The elliptical resonators are selected due to their suitable frequency responses, and by applying these types of resonators in different sizes a filter with sharp transition band and wide stopband can be designed. Also, based on its circumference a new formula for calculating LC equivalent circuit can be computed and rendered.

2.1 First elliptical resonator (FER)

The topology and the LC equivalent structure of the first elliptical resonator are shown in Figure 1(a) and (b), respectively. Also, the Electro Magnetic (EM) and LC frequency responses of the FER are illustrated in Figure 1(c), up to 10 GHz. The first transmission zero of this structure occurs at 9.30 GHz with an attenuation level better than 48 dB, which is suitable to design a wide stopband LPFs.

Dimensions of this resonator are (All in millimeters): $L_1 = 5.7$, $L_2 = 0.51$, $W_1 = 8.56$, $W_2 = 2$, $W_3 = 0.1$.

The values of capacitances (C_x) and inductances (L_x) are computed using open ends and high-low impedance lossless lines formulas, [1]. Equations (1) and (2) express these formulas, where Z_s is the characteristic impedance of the lines and λ_g in Eqs. (1) and (2) is calculated by the width of lines [1] (Note: λ_g is the calculated guided wavelength at 1.50 GHz).

$$L_x = \frac{1}{\omega} \times Z_s \times \sin\left(\frac{2\pi}{\lambda_g} L\right) \quad (1)$$

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

To achieve the LC equivalent structure of the proposed elliptical resonators, new computed formulas (Eqs. (3) and (4)) are obtained as:

$$W_{\text{new}} = \begin{cases} \frac{1}{4} \left(\pi \sqrt{\frac{W^2 + L^2}{2}} \right) + \frac{2L}{W} \left(\frac{W}{L} - 1.12 \right) & \text{for } \left(\frac{W}{L} > 1.12 \right) \\ \frac{1}{4} \left(\pi \sqrt{\frac{W^2 + L^2}{2}} \right) + \frac{3L}{W} \left(\frac{W}{L} - 1.12 \right) & \text{for } \left(\frac{W}{L} < 1.12 \right) \end{cases} \quad (3)$$

$$L_{\text{new}} = L \quad (4)$$

Equation (3) is obtained based on the geometric circumference of the elliptical shaped structure. The elliptical resonator is formed using half of an elliptical shaped patch. The W_{new} in Eq. (3) is approximately equal to 1/2 of a semi circumference of an elliptical shaped patch. Therefore, the circumference of an elliptical shaped cell have to be multiplied by 1/4, but the 1/4 of the elliptical circumference has a small error in comparison with EM simulation. To decrease this error, a new formula is computed, based on linearization of error. So, if W/L becomes equal to 1.12, the error will be equal to approximately zero. Therefore, $3L/W$ and $2L/W$ in the first and second lines of Eq. (3) are calculated for decreasing the error. The length (L) and width (W) in Eqs. (1) and (2) are replaced with L_{new} and W_{new} which are given in Eqs. (3) and (4) for achieving the values of the LC equivalent structure of the elliptical resonators. Then, using open ends formulas [1], inductances and capacitances are computed. Calculated values for the LC equivalent structure of the FER are as follows. These amounts are shown by C_{fi} (pF) and L_{fi} (nH), parameters (Note: the “ f ” index is related to FER design and $i = 1, 2, \dots$).

$$C_{f1} = 0.33, C_{f2} = 0.97, C_{f3} = 0.58, L_{f1} = L_{f2} = 7.09, L_{f3} = 0.08, L_{f4} = 0.39.$$

Figure 1: First elliptical resonator, (a) layout configuration, (b) LC circuit, (c) EM and LC simulation, (d) LC equivalent elements.

L_{f1} , L_{f2} , L_{f3} and L_{f4} (Eq. (1)) and C_{f1} (Eq. (2)) are denoted to the inductances and capacitance of high impedance lossless lines. C_{f2} is the summation of the capacitances of the resonator and high impedance lossless line (Eqs. (2)–(4)). C_{f3} denotes the capacitances of the resonator and its open-end effect (formulas of gap [1], Eqs. (3) and (4)). L_{f3} (Eqs. (3) and (4)) refers to the inductance of the investigated resonator. These LC equivalent elements are assigned and shown in Figure 1(d).

The output to input ratio of the investigated elliptical resonator is calculated in Eq. (5). The locations of transmission zeros can be determined by the output to input ratio. The designed structure can generate a deep transmission zero at 9.30 GHz, which is calculated in Eq. (6). It is shown in Figure 1(c) by T_{z1} .

For example, T_{z1} can be changed by L_{f3} and C_{f2} based on Eq. (6), where other inductances and capacitances values

are fixed. If C_{f2} is assumed as 0.94, 0.97 and 1.13 pF, and L_{f3} is assumed as 0.35, 0.38 and 0.42 nH, then T_{z1} will be 10.55, 9.30 and 8.39 GHz, respectively. These calculated parameters are summarized in Table 1. For having mentioned transmission zeros, L_1 can be calculated about 5, 5.7 and 6.4 mm, respectively, based on Eqs. (1) and (2).

$$\frac{v_o}{v_i} = \frac{50a}{(50 + L_{f1}S)(50 + 2a + L_{f1}S)} \quad (5)$$

where: ($S = j\omega$)

$$a = \frac{(1 + (C_{f2}L_{f2} + C_{f3}(L_{f2} + L_{f3}))S^2 + C_{f2}C_{f3}L_{f2}L_{f3}S^4)}{(S(C_{f1} + C_{f2} + C_{f3} + (C_{f1}(C_{f2} + C_{f3}))L_{f2} + (C_{f1} + C_{f2})C_{f3}L_{f3})C_{f1}C_{f2}C_{f3}L_{f2}L_{f3}S^4))}$$

$$T_{z1} = \frac{\sqrt{\frac{1}{C_{f2}L_{f2}} + \frac{1}{C_{f2}L_{f3}} + \frac{1}{C_{f3}L_{f3}} - \frac{\sqrt{-4C_{f2}C_{f3}L_{f2}L_{f3} + (C_{f2}L_{f2} + C_{f3}L_{f2} + C_{f3}L_{f3})^2}}{C_{f2}C_{f3}L_{f2}L_{f3}}}}{2\pi\sqrt{2}} \quad (6)$$

Table 1: Different calculated amounts for T_{Z1-FER} .

$T_{Z1-FER} = 10.55 \text{ GHz}$		$T_{Z1-FER} = 9.30 \text{ GHz}$		$T_{Z1-FER} = 8.39 \text{ GHz}$	
C_{f2}	0.94 pF	C_{f2}	0.97 pF	C_{f2}	1.13 pF
L_{f3}	0.35 nH	L_{f3}	0.38 nH	L_{f3}	0.42 nH

Figure 2: Second elliptical resonator (a) layout configuration, (b) LC equal structure, (c) EM and LC simulation.

2.2 Second elliptical resonator (SER)

As discussed, the first transmission zero and pole of the FER are occur at 9.30 GHz and 1.21 GHz, respectively, but this transmission zero and transmission pole are not near to each other, so the transition band is not sharp in this configuration. To improve the sharpness of the transition band, the SER is designed as seen in Figure 2(a). The LC equivalent structure of the SER is shown in Figure 2(b). The results of the EM and LC simulations are shown in Figure 2(c), up to 10 GHz.

The configuration of the SER generates a transmission zero at 1.97 GHz with the attenuation level better than 48 dB. The structure has a transmission pole at 1.08 GHz, too. So the transmission pole and zero are happen approximately near to each other; therefore, these double and smaller elliptical shaped structures helps to move the first LPF's transmission zero to the lower frequencies and leads to an increase in sharpness of the final LPF's transition band.

SER's dimensions are (All in millimeters): $L_3 = 5.45$, $L_4 = 6.4$, $L_5 = 2$, $L_6 = 0.19$, $L_7 = 2.54$, $L_8 = 16.7$, $W_4 = 4.17$, $W_5 = 0.1$, $W_6 = 2.44$, $W_7 = 1.63$. The LC equal values of the SER are shown by C_{si} (pF) and L_{si} (nH), parameters ($i = 1, 2, 3 \dots$);

$$L_{s1} = 1.7, L_{s2} = 7.11, L_{s3} = 4.23, L_{s4} = 1.39, L_{s5} = 0.52, \\ C_{s1} = 0.27, C_{s2} = 0.11, C_{s3} = 0.45, C_{s4} = 0.60.$$

The output to input ratio of the LC equivalent structure for the SER, as shown in Figure 2(b), is calculated in Eq. (7). Using this ratio leads to determine the transmission zero locations (Note: $r = 50 \Omega$).

$$\frac{v_o}{v_i} = \frac{a^2 r}{(a + r + L_{s1}S)(2ar + 2aL_{s1}S + aL_{s2}S + L_{s2}rS + L_{s1}L_{s2}S^2)} \quad (7)$$

where:

$$a = \frac{(1 + S^2(C_{s4}(L_{s3} + L_{s4} + L_{s5}) + C_{s3}(L_{s3} + L_{s4}))(1 + C_{s4}L_{s5}S^2) + C_{s2}L_{s3}(1 + (C_{s3}L_{s4} + C_{s4}(L_{s4} + L_{s5}))S^2 + C_{s3}C_{s4}L_{s4}L_{s5}S^4))}{(S(C_{s1} + C_{s2} + C_{s3} + C_{s4} + (C_{s2}(C_{s3} + C_{s4})L_{s4} + (C_{s2} + C_{s3})C_{s4}L_{s5} + C_{s1}(C_{s2}L_{s3} + (C_{s3} + C_{s4})(L_{s3} + L_{s4}) + C_{s4}L_{s5}))S^2 + C_{s1}C_{s2}(C_{s3} + C_{s4})L_{s3}L_{s4} + C_{s4}(C_{s1}(C_{s2} + C_{s3})L_{s3} + (C_{s1} + C_{s2})C_{s3}L_{s4})L_{s5}S^4 + C_{s1}C_{s2}C_{s3}C_{s4}L_{s3}L_{s4}L_{s5}S^6))}$$

3 Prototype lowpass filter

The simulation results of the FER and SER are shown in Figure 3(a), up to 20 GHz. As seen, the FER generates three transmission zeros and the SER can create two transmission zeros, too. In order to design a prototype LPF with a sharp transition band and wide stopband bandwidth,

Figure 3: Frequency responses, (a) first and second elliptical resonators, (b) layout structure and frequency response of prototype LPF.

both first and second elliptical resonators are combined and a prototype LPF with five main transmission zeros plus some coupling effects is formed. This designed structure, and its simulation results are shown in Figure 3(b), while the transmission zeros are assigned by T_{zmi} ($i = 1, 2, \dots, 5$). As seen in Figure 3(b), this configuration has not a good suppression level in the stopband.

Figure 4: Proposed LPF (a) LC equal structure, (b) layout structure, (c) simulation results up to 10 GHz.

To increase the level of suppression in “a, b and c” points, two attenuator cells are located in series with the prototype LPF. Eventually, the final LPF with -3 dB cut-off frequency at 1.50 GHz is designed. The total equivalent LC circuit is shown in Figure 4(a). As seen in Figure 4(b), the complementary dimensions of the proposed LPF are (All in millimeters): $L_9 = 1.34$, $L_{10} = 4.5$, $L_{11} = 0.2$, $L_{12} = 7.35$, $W_8 = 1$. Also, the LPF LC equal values are (Units: C_{ti} , pF; L_{ti} , nH, $i = 1, 2, 3 \dots$);

$L_{t1} = 0.89$, $L_{t2} = 0.13$, $L_{t3} = 4.86$, $L_{t4} = 4.23$, $L_{t5} = 1.39$, $L_{t6} = 0.52$, $L_{t7} = 0.08$, $L_{t8} = 0.39$, $L_{t9} = 1.12$, $C_{t1} = 0.2$, $C_{t2} = 0.19$, $C_{t3} = 0.23$, $C_{t4} = 0.11$, $C_{t5} = 0.45$, $C_{t6} = 0.41$, $C_{t7} = 0.97$, $C_{t8} = 0.85$, $C_{t9} = 0.18$ (The values of the inductances and capacitances are calculated using Eqs. (1)–(4)). The results of the EM and LC simulations are shown in Figure 4(b), up to 10 GHz.

Table 2: Substrate details.

Relative dielectric constant	Loss tangent	Thickness (mils)
2.2	0.0009	15

4 Simulation and experimental results

The proposed LPF is designed and fabricated on an RT/Duroid 5880 substrate. The substrate details are mentioned in Table 2.

The photograph and S-parameters of the fabricated and simulated LPF are shown in Figure 5(a) and (b), respectively. The measured results are obtained by the Agilent Network Analyser N5230A. The proposed LPF’s cut-off frequency is 1.50 GHz, the stopband bandwidth is expanded from 1.84 up to 21.39 GHz with 20 dB attenuation level, and this stopband region is about $13f_c$. In the pass-band region, a suppression level of 29.7 dB is obtained. The size of the LPF circuit is only about 22×6.45 mm². The designed filter has a high Figure of Merit (FOM) equal to

Figure 5: LPF performance (a) photograph (b) EM and measured simulation up to 25 GHz.

Table 3: Comparison of LPFs performance.

Ref.	RO (ξ)	RSB	SF	NCS (λ_g^2)	AF	FOM
[3]	48.5	1.49	2.5	0.160×0.080	1	14,062
[4]	36	0.96	1.2	0.350×0.200	1	600
[6]	57.8	1.61	3.5	0.120×0.100	1	27,142
[7]	84.7	1.51	2	0.143×0.156	1	11,625
[8]	188.8	0.92	2	0.200×0.180	1	9681
[9]	25.3	1.34	2	0.186×0.101	1	3626
[11]	74	1.74	2.4	0.090×0.136	1	25,274
[13]	100	1.58	2	0.670×0.110	1	4288
[14]	104	1.80	2.5	0.189×0.121	1	22,510
[20]	52.8	1.52	2	0.081×0.113	1	17,638
This work	84	1.69	2	0.151×0.044	1	42,759

RO means roll-off rate or selectivity according to 3 and 40 dB suppressing points [19]. RSB, relative stopband bandwidth; SF, suppression factor; NCS, normalized circuit size; AF, architecture factor; FOM, figure of merit.

42,759. For comparison, Table 3 shows a summary of key LPF performance metrics [12], for current designs.

5 Conclusions

In this paper, a simple and compact microstrip LPF with an ultra-wide stopband based on elliptical resonators is designed, fabricated and measured. The presented LPF has a -3 dB cut-off frequency at 1.50 GHz. The proposed filter has many desirable features, each of which depicts proper characteristics for a LPF theoretically and practically, such as compact size, return loss better than 29 dB, and ultra-wide stopband from 1.84 GHz to 21.39 GHz. With all these good features, the proposed LPF is recommended for modern communications systems.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: None declared.

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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