Sharp Response Microstrip LPF using Folded Stepped Impedance Open Stubs

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Abstract. *A novel microstrip lowpass filter with high selectivity and wide stopband is proposed that comprises two lateral folded open stubs and a central mirrored semi-circle ended suppressing cell. The proposed filter has cut-off frequency of 2.28 GHz and is very compact. The stop-band width with attenuation level more than -20 dB is equal to 5.47* f_c *and the transition band is only 0.14 GHz. This filter is designed, fabricated and measured and the simulated and measured results are in good agreement.*

Keywords

Low pass filter, microstrip technology, folded open stub, sharp response, wide stopband.

1. Introduction

Suppression of harmonics and selection of right frequency band are of great importance in modern communication systems according to the numerous applications in close frequency bands that are potential sources of noise for their neighbors. Consequently, using high performance filters is inevitable to solve this problem and this has been a motivation for researchers to put the stress in this area.

As a part of these efforts numerous methods and structures have been devised so far to present lowpass characteristics with improved parameters. In [1], combination of stepped impedance hairpin resonator and split ring resonator defected ground structure is used to achieve sharp cut-off frequency and compact size but the stopband is not very wide. Embedding an interdigital structure between the two low-impedance sections of a stepped impedance hairpin unit and then tap-connecting resonators of different dimensions is proposed in [2] to improve the stopband width and has gained considerable success.

Open complementary split ring resonator [3] and uniplanar double spiral resonators [4] are exploited to achieve deeper and wider stopband but this improvement has cost large size. Fractal shapes are used in [5] to improve the passband performance but the resulting filter has a narrow stopband and slow transition. Koch-shaped electromagnetic structure is exploited in [6] to reduce the physical size and improve the stopband width but the cut-off response is gradual. In [7], symmetrically loaded resonant patches and meander transmission line are used together in the same structure to achieve ultra-wide stopband with the cost of gradual cut-off. A new arrangement of radial stubs is proposed in [8] and exemplary wide stopband is resulted although according to the numerous resonators, the passband performance is not very good and the filter is relatively complicated. A simple stub-loaded hairpin unit with sharp roll-off is also proposed in [9] that has a wide stopband.

In this work, folded stepped impedance open stubs are used to present sharp response and compact size. The resonator structure is studied by extracting its LC model and effect of dimensions variation on the response is investigated.

2. Proposed Filter Design and Implementation

Stepped impedance open stubs are very useful components in designing lowpass filters according to their capability in generating transmission zeros with instant attenuation at the resonance frequency. This feature makes the designer able to create a filter by connecting some elements with different dimensions in series form to make the stopband wider. The main problem of this method is that the open stubs become very long when creating smaller transmission zeroes. Thus, optimization methods are required to decrease the size.

Before going through optimization steps, the primary resonator has to be designed. The resonator design starts from a basic LC structure [10] that is shown together with its response in Fig. 1a and 1b, respectively. The value of the LC elements for this resonator are $L_1 = L_2 = 3.6$ nH, $L_3 = 4$ nH, $C_b = 1$ pF.

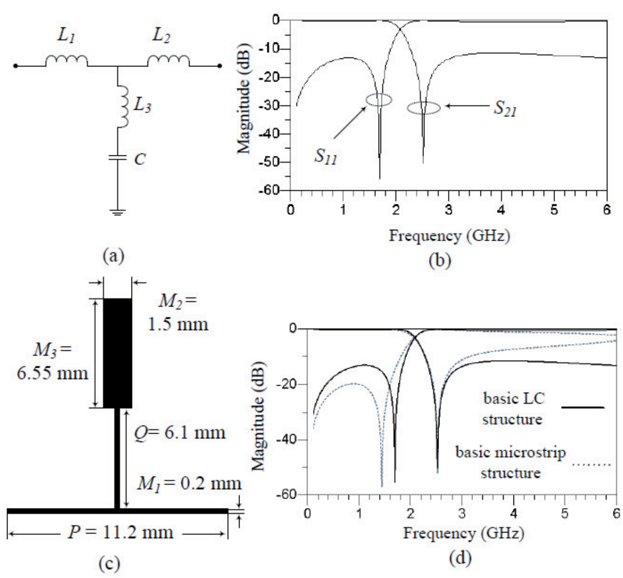

Fig. 1. (a) Basic LC structure. (b) Simulation results of the basic LC structure. (c) Basic microstrip structure. (d) Simulated results of the basic LC and microstrip structure.

The next step is to convert the designed resonance circuit to a microstrip structure. This work is performed by converting every LC component to its equivalent microstrip line [10] using (1) and (2) where l is the length of a microstrip line when the line width is considered constant. In these equations, C and L are the capacitance and inductance respectively; Z_c is the characteristics impedance and v_p represents the phase velocity.

$$l = CZ_c v_p , \quad (1)$$

$$l = \frac{Lv_p}{Z_c} . \quad (2)$$

To calculate the values of v_p and Z_c, equations (3-7) can be used where w is width of the microstrip line, h and ε_r represent thickness and permittivity of the substrate, respectively, ε_{re} is the effective permittivity, the parameter η is a constant equal to $120\pi\ \Omega$ and c represents the light speed.

$$v_p = \frac{c}{\sqrt{\varepsilon_{re}}} \quad (3)$$

For $w/h \le 1$:

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left\{\left[1 + 12\frac{h}{w}\right]^{-0.5} + 0.04\left[1 - \frac{w}{h}\right]^2\right\}, \quad (4)$$

$$Z_c = \frac{\eta}{2\pi\sqrt{\varepsilon_{re}}}\ln\left[8\frac{h}{w} + 0.25\frac{w}{h}\right] . \quad (5)$$

For $w/h \ge 1$:

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-0.5} , \quad (6)$$

$$Z_c = \frac{\eta}{\sqrt{\varepsilon_{re}}}\left\{\frac{w}{h} + 1.393 + 0.677\ln\left[\frac{w}{h} + 1.444\right]\right\}^{-1} . \quad (7)$$

For lines with $w = 0.2$ mm and $w = 1.5$ mm, the calculated values are ($\varepsilon_{re} = 2.52$, $Z_c = 113.99\ \Omega$) and ($\varepsilon_{re} = 2.5$, $Z_c = 44.58\ \Omega$), respectively. According to these results and equations (1) and (2), the converted structure is shown in Fig. 1c. Simulated results of the basic LC and microstrip structure are depicted in Fig. 1d.

It can be observed that there is a reasonable agreement between the simulated s-parameters for the LC and microstrip circuits that verifies the success of the conversion. The next step is to optimize the designed basic microstrip structure to decrease its overall area.

To solve the problem, folding the open stub is proposed in this work. The layout and simulated response of the proposed stepped impedance folded stub are shown in Fig. 2a and 2b, respectively. Dimensions of the layout are: $W = 0.3$ mm, $W_1 = 1.6$ mm, $W_2 = 1.5$ mm, $W_3 = 0.2$ mm, $W_4 = 0.2$ mm, $L_1 = 5.6$ mm, $S = 0.4$ mm and $H = 5.2$ mm. It can be observed that a transmission zero is generated at 2.66 GHz with attenuation level of -52.14 dB.

To study different parts of the resonator, its LC model is extracted that is shown in Fig. 2c. In this circuit, L_t and L_s are inductances of the central transmission line and folded stub, respectively while C_t and C_s represent the capacitances of these parts with respect to ground. Circuit simulated results with $L_s = 3.8$ nH, $C_s = 0.954$ pF, $C_t = 0.093$ pF and $L_t = 1.41$ nH is shown in Fig. 2d together with the EM simulated results. Good agreement between these two curves verifies the validity of the extracted LC model and values of its elements.

In the next step, effect of dimensions variation on the resonator response as well as the value of the circuit elements is studied. H, W_3 and W_2 are selected for this purpose according to their significant impacts. Changes of the resonator response as a function of its effective dimensions is shown in Fig. 3a, b and c. Variation of the values of the LC model is also presented in Tab. 1a, b and c.

Results indicate that increasing the value of H causes the transmission zero to get smaller that is mostly because of increased value of L_s. This is while; by increasing the value of W_3 only the return loss in the passband varies according to the smaller L_t. W_2 variations has a similar impact to H on the cut-off frequency but this variation is made by the increased C_s.

In the above-mentioned study, the variation of the dimension S that is a consequence of changing H is neglected because small values of S only create a humble coupling capacitance between the stub and the central transmission line and has no observable role on the overall response in the frequency range of interest. The circuit simulation of the resonator verifies that the above mentioned capacitance can be ignored.

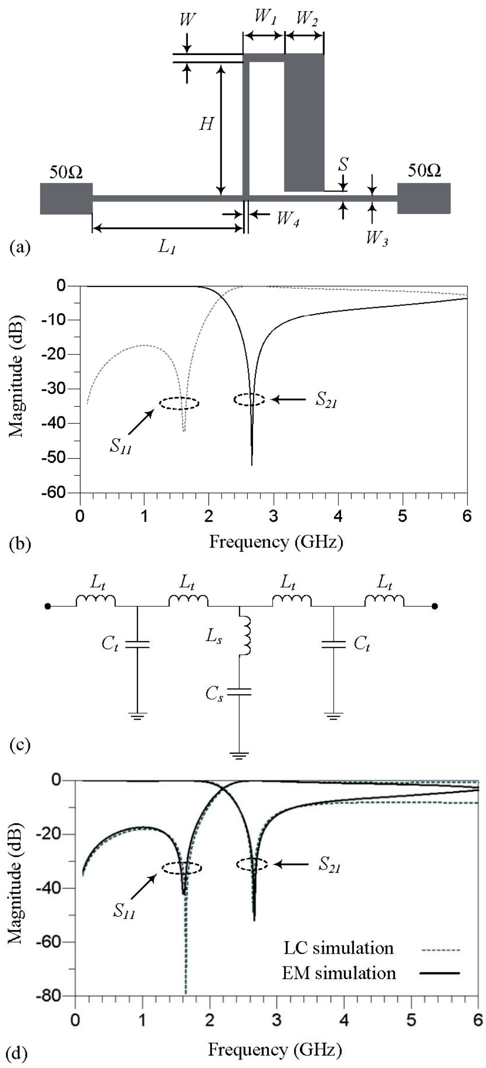

Fig. 2. (a) Layout of the proposed resonator. (b) EM simulation results of the proposed resonator. (c) LC model of the proposed resonator. (d) EM and circuit simulation results of the proposed resonator.

(a)

	H = 5.2 mm	H = 6.2 mm	H = 7.2 mm
L_s (nH)	3.8	4.45	4.97
C_s (pF)	0.95	0.97	0.99
L_t (nH)	1.41	1.41	1.41
C_t (pF)	0.09	0.09	0.09

(b)

	W_3 = 0.2 mm	W_3 = 0.4 mm	W_3 = 0.6 mm
L_s (nH)	3.8	3.8	3.8
C_s (pF)	0.95	0.95	0.95
L_t (nH)	1.41	1	0.75
C_t (pF)	0.09	0.11	0.15

(c)

	W_2 = 1.5 mm	W_2 = 2 mm	W_2 = 2.5 mm
L_s (nH)	3.8	3.8	3.8
C_s (pF)	0.95	1.21	1.36
L_t (nH)	1.41	1.41	1.41
C_t (pF)	0.09	0.09	0.09

Tab. 1. Variation of the LC values with changing the resonator dimensions (a). Variation of H. (b) Variation of W_3. (c) Variation of W_2.

For further investigation, a scale factor is defined as a factor that can be multiplied by all of the dimensions of a resonator simultaneously to achieve a similar structure with different response characteristics and physical size. Effect of dimensions scaling on the resonator response based on the defined factor is then presented as depicted in Fig. 3d.

As seen, position of the near-band zero and cut-off frequency of the resonator get smaller as the scale factor gets larger. Fig. 3 can be used to design optimized filters with different cut-off frequencies.

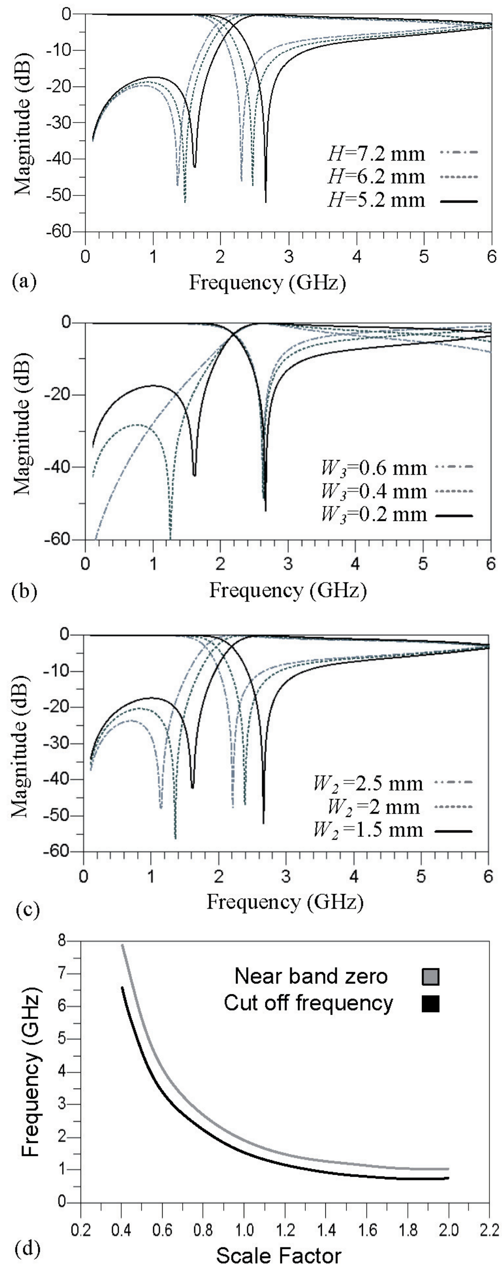

Fig. 3. Variation of the resonator response as a function of: (a) H, (b) W_3, (c) W_2. (d) Location variation of the near-band transmission zero and the cut-off frequency as a function of Scale Factor.

To do this, the corresponding scale factor of the desired cut-off frequency should be first found in Fig. 3d and then used to reach a resonator. Keeping in mind the effects of the dimensions variations in Fig. 3a, 3b and 3c, the resonator response can be optimized using H, W_3 and W_1.

After these studies, a mirrored semi-circle ended suppressing cell is designed to improve the stopband of the resonator. Layout and simulated response of this structure are shown in Fig. 4a and 4b, respectively. Dimensions of the proposed suppressing cell are: $R = 2$ mm, $L_2 = 12$ mm, $W_5 = 3$ mm, $W_6 = 4$ mm, $W_7 = 0.2$ mm, and $S_1 = 0.8$ mm.

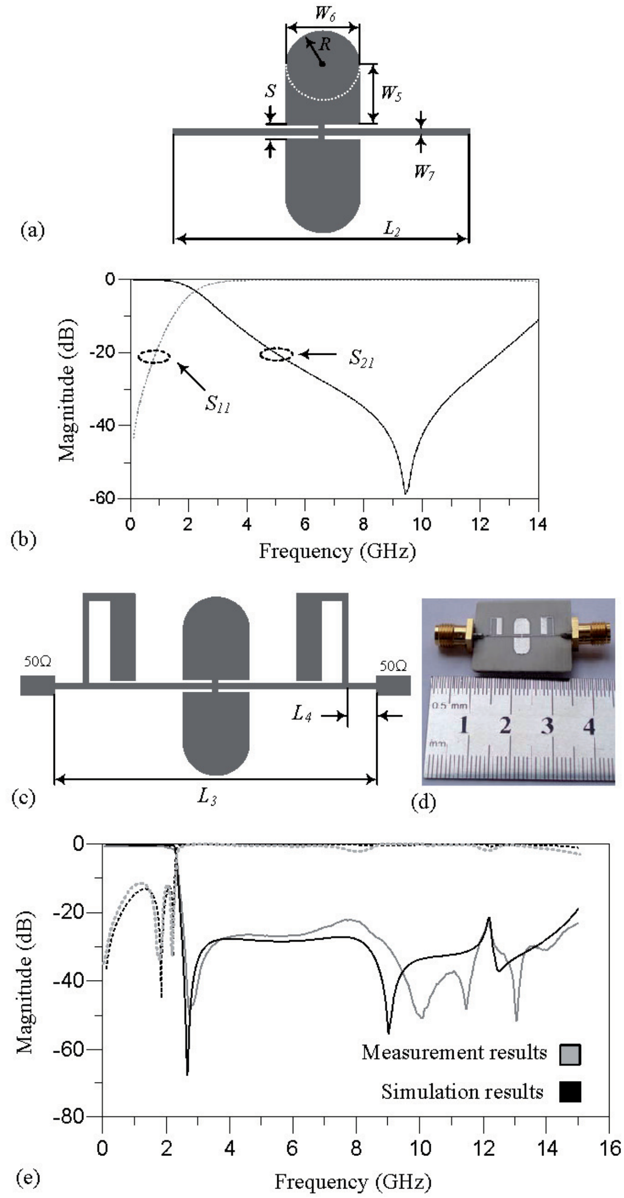

Fig. 4. (a) Layout of the proposed suppressing cell. (b) Simulation results of the proposed suppressing cell. (c) Layout of the proposed filter. (d) Photograph of the fabricated filter. (e) Simulation and measurement results of the proposed filter.

As seen from the simulated results, the transmission zero at 9.43 GHz with -58.78 dB attenuation level generates a wide rejection area that guarantees a wide stopband filter. To use this suppressing cell with the introduced scaling method, it can also be scaled with the same factor as the resonator.

By connecting two units of the proposed folded resonator at the both sides of the suppressing cell, the final filter is created that is shown in Fig. 4c with dimensions: $L_3 = 19.8$ mm and $L_4 = 1.9$ mm. The values of the dimensions L_3 and L_4 are obtained through optimization. Variation of these dimensions mostly affects the return loss in the passband. For example by setting $L_4 = 1.9$ mm, the value of return loss is equal to 10.75 dB with $L_3 = 21.88$ mm and 8.71 dB with $L_3 = 23.8$ mm.

This filter is fabricated on RO4003 substrate with dielectric constant equal to 3.38 and thickness of 20 mil and its photograph is shown in Fig. 4d. The EM-simulation and measured results of the proposed filter that are in good agreement, are shown in Fig. 4e. This filter has cut-off frequency of 2.28 GHz and the transition band from -3 to -20 dB is only 0.14 GHz that is improved in comparison with [2-7] and [9]. The insertion loss in the passband is less than 0.37 dB from DC to 2.22 GHz and the return loss in this frequency range is more than 12.3 dB. Stopband of the proposed filter with attenuation level higher than -20 dB is from 2.42 to 14.9 GHz that is equal to $5.47f_c$. The proposed filter has physical size of only 11 mm × 19.8 mm that is very compact.

3. Conclusion

A compact structure with high selectivity, compact size and wide stopband was designed, fabricated and measured. Simulation and measurement results are in good agreement. This filter is composed of two folded stepped impedance open stubs and a mirrored semi-circle ended suppressing cell. To study the structure of the proposed resonator, its LC equivalent circuit was extracted and investigated in detail.

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