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Compact Microstrip Low-Pass Filter with wide stopband using symmetrical U-shaped resonator

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Abstract: This paper peresents a novel Microstrip Low-Pass Filter (LPF) using a simple symmetrical U-shaped resonator. In this work, a 5.45 GHz LPF is developed. The experimental results show that in comparison with other LPFs, it has a wide stopband with high attenuation in the stopband and acceptable sharp frequency response. The insertion-loss is less than 0.1 dB and the rejection band over −20 dB covers 6.05 GHz to 37.35 GHz. The measured and simulated results are in good agreement.

Keywords: Low-Pass Filter (LPF), U-shaped structure, wide stopband

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Compact-size microstrip low-pass filters (LPFs) are highly demanded in many communication systems to suppress harmonics and spurious signals [1]. Though raising the filter's order can improve its performance, this enlarges the overall size and increases insertion loss [2]. In order to achieve a sharp cut-off frequency response, more sections are needed, but increasing sections will also increase the loss in the passband and circuit size [3]. A number of ways to improve the performance of LPFs are proposed. In [1] an elliptic-function low-pass filter using defected ground structure is proposed that has small size and a sharp roll off, but it doesn't have a low insertion-loss and its stopband with -20 dB is narrow. A LPF using stepped impedance hairpin units is proposed in [2], that presents sharp roll off and wide stopband; but it results, large size and high insertion-loss in stopband. In [4] a miniaturized microstrip low-pass filter is proposed that has a small area, and has a wide stopband with -17 dB; but it has a narrow stopband with -20 dB and doesn't have a sharp roll off. Two filters with tapered dual-plane electromagnetic bandgap structures are proposed in [5] that present sharp roll off; but these structures have, low return loss in the passband, very large size and narrow stopband. In [6] using front coupled tapered, filter presents low insertion-loss in stop-band and has a very small size but its stopband with -20 dB is very short in comparison to the proposed filter. In this paper, novel microstrip low-pass filter with symmetrical U-shaped stepped impedance resonator with a simple structure is proposed and implemented. The proposed filter has low insertion loss, wide stopband and high suppression in the stopband. As compared to the previous works, the proposed structure achieves simple shape and better performance with a significant increment in the stopband.

2 Design and study of the proposed filter structure

Fig. 1 (a) shows the layout of the proposed U-shaped resonator. Fig. 1 (b) shows LC equivalent circuit of the proposed resonator which is simplified using symmetrical properties. In the equivalent circuit L_4 and L_5 represent inductances of the transmission line between input and output ports. L_t is inductance of the stubs with width of W_r. L_1 and L_3 are inductances of the stubs with the length of d_r and L_2 is inductance of the ending rectangles with width of W_r. C_t is the coupling capacitance between the rectangular loads, C_{g1} and C_{g2} are the capacitances of different parts of the filter with respect to ground. Using symmetrical properties, we know that $L'_t = L_t/2$, $L'_1 = L_1/2$, $L_s = L_4 = L_5$ and $C'_t = 2C_t$, $C'_{g1} = 2C_{g1}$, $C'_{g2} = 2C_{g2}$. In comparison to the width of W_r, the width of the W_s is so small. Because of this fact, the inductance of this line (L_2) is dispensable, so the ABCD matrix of the proposed resonator is given by:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & L_s S \\ 0 & 1 \end{pmatrix} \begin{pmatrix} T \end{pmatrix} \begin{pmatrix} 1 & L_s S \\ 0 & 1 \end{pmatrix} \tag{1}$$

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where the impedance matrix (Z) of the T network is given by:

$$\begin{pmatrix} (L_1' + L_t)S + S^{-1}(\frac{1}{C_{g1}} + \frac{1}{C_t}) & L_1'S \\ L_1'S & (L_1' + L_t)S + S^{-1}(\frac{1}{C_{g2}} + \frac{1}{C_t}) \end{pmatrix} \quad (2)$$

Finally, equation (1) is rewritten in the form of :

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 2L_sS \\ 0 & 1 \end{pmatrix} \begin{pmatrix} L_{tot}S + C_{tot}S^{-1} & det[Z] \\ 0 & L_{tot}S + C_{tot}S^{-1} \end{pmatrix} (\frac{-1}{L_1'S}) \quad (3)$$

where: $det[Z] = ([(L_1' + L_t)S + S^{-1}(\frac{1}{C_{g1}} + \frac{1}{C_t})]^2 - (L_1'S)^2)$; $L_{tot} = L_1' + L_t$; $C_{tot} = \frac{1}{C_{g1}} + \frac{1}{C_t}$.

Assume that: $det[Z] >> L_s$; $Z_{tot} = (L_1' + L_t)S + S^{-1}(\frac{1}{C_{g1}} + \frac{1}{C_t}) >> L_s$ and $C_{g1} = C_{g2}$. Therefore:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} Z_{tot} & det[Z] \\ 0 & Z_{tot} \end{pmatrix} (\frac{-1}{L_1'S}) \quad (4)$$

Equation (4) shows that the transition matrix depend on L_1' and Z_{tot} where each one depend on length d_r and width W_r.

This resonator creates one transmission zero, i.e. TZ_1 at about 15.44 GHZ with −52 dB attenuation, which is shown in Fig. 1 (c). It can provide a stop-band from 12.1 GHz to 18.4 GHZ, with one transmission zero. However it's not ideal and roll-off is not acceptable. As seen in Fig. 1 (d), by increasing the length of d_r from 2.5 mm to 6.25 mm, because of increasing inductance of L_1, the transmission zero gets smaller in about 9 GHz and roll-off gets better. Then we changed the length of W_r from 1.75 mm to 3.5 mm, because of increasing inductances of L_1' and L_t, the transmission zero gets smaller in about 11 GHz with better attenuation about −55 dB, as it is shown in Fig. 1 (e). With respect to these discussion, we decided to cascade two U-shaped resonator to design a new resonator with better performance by adding a new transmission zero, i.e. TZ_2, which is near another transmission zero. Fig. 1 (f) and Fig. 1 (g) shows the proposed cascaded U-shaped resonator and its simulated s-parameters respectively.

It provides better wide rejection band from 7.8 GHz to 18.2 GHz. But for improving the filter performance such as roll off, we proposed a symmetric cascaded U-shaped resonator. The symmetric cascaded U-shaped resonator consists of four U-shaped resonators and a single open stub impedance that is shown in Fig. 2 (a) and its simulated s-parameters is shown in Fig. 2 (b). As it is seen, it resonates at 5.45 GHz and provides wide stopband from 6.1 GHz to 22.1 GHz with sharpness of 0.58 GHz from −3 dB to −20 dB. Using a symmetric cascaded U-shaped resonator with symmetrical open stubs impedance units, a low-pass filter with high performance is obtained as shown in Fig. 2 (c). The open stub impedance units causes a significant attenuation in the high frequencies and provide a wide stopband. Each stub add a pole to the filter, to suppress harmonics in the high frequencies.

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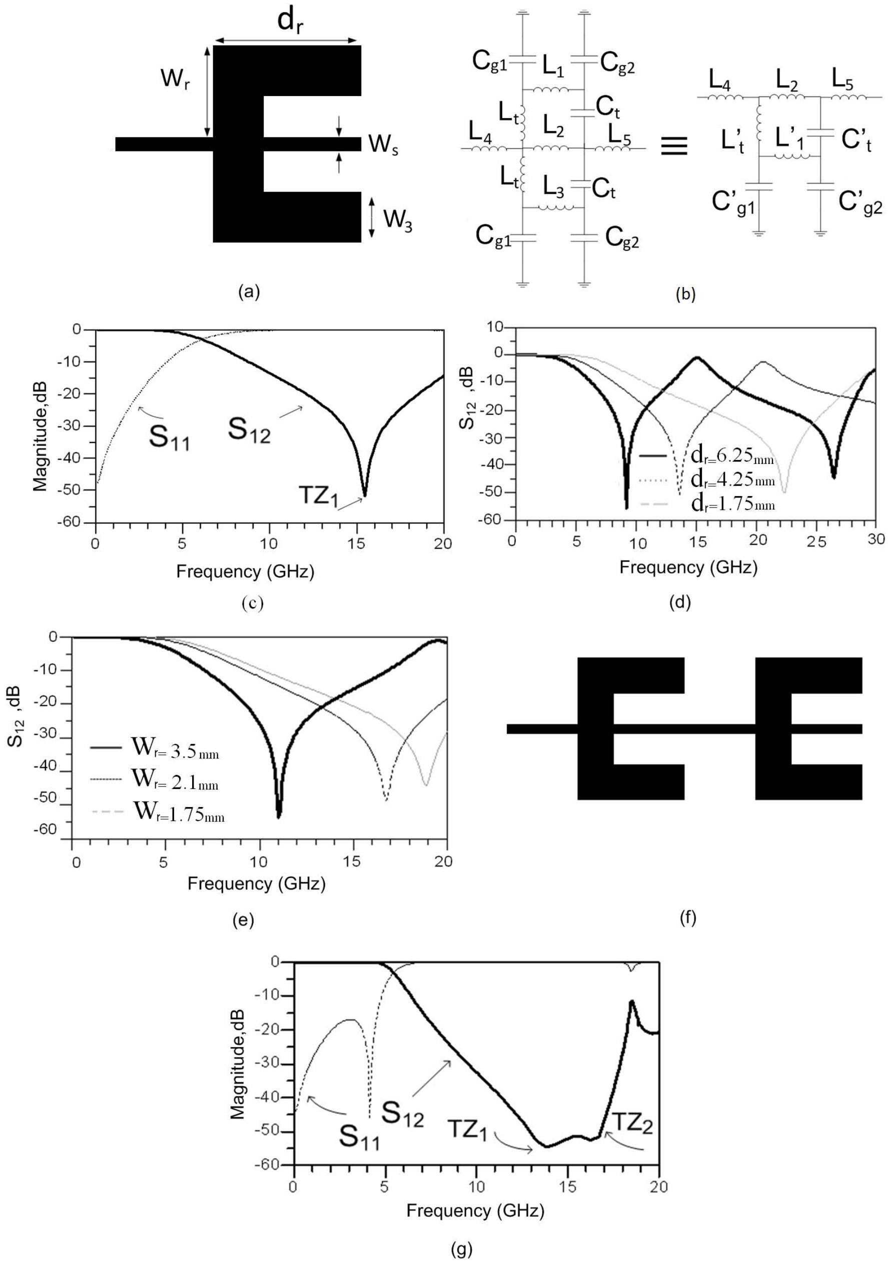

Fig. 1. (a) Structure of the Proposed U-shaped resonator (b)LC Equivalent circuit of the Proposed U-shaped resonator (c) simulated results of the Proposed U-shaped resonator (d) Simulated s-parameters of the proposed resonator as a function of d_r (e) Simulated s-parameters of the proposed resonator as a function of W_r (f) Structure of the Proposed Cascaded U-shaped resonator (g) Simulated s-parameters of the Proposed Cascaded U-shaped resonator

3 Simulation and measurement

A prototype low-pass filter has been fabricated on RT/Duriod 5880 substrate with dielectric constant(ϵ_r), thickness(h) and loss tangent of 2.22, 15 mil and 0.0009 respectively; as shown in Fig. 2 (d), and measured by a HP8757A

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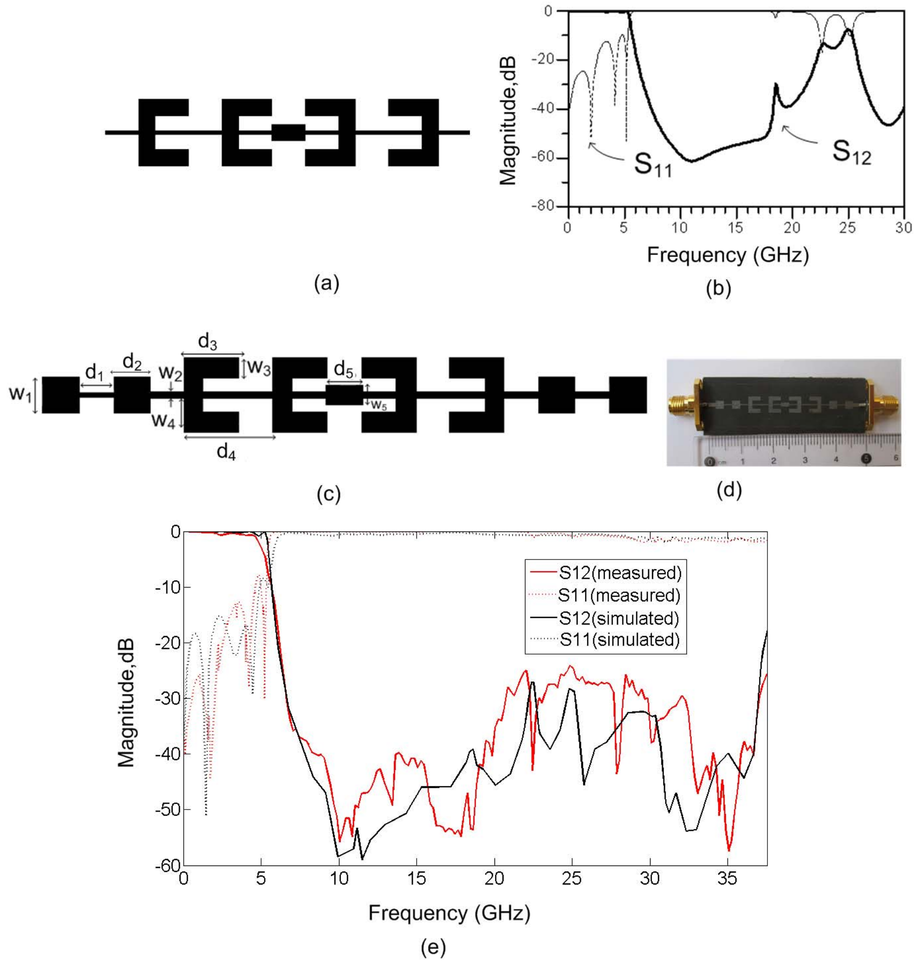

Fig. 2. (a) The structure of the symmetric cascaded U-shaped resonator (b) Simulated s-parameters of the symmetric cascaded U-shaped resonator (c) Layout of the proposed low-pass filter (d) photograph of the proposed filter (e) Simulated and measured S-parameters of the proposed lowpass filter

network analyzer. The structure parameters of the LPF are: $W_1 = d_1 = d_2 = d_5 = 2.5\,\text{mm}$, $W_2 = 0.32\,\text{mm}$, $W_3 = W_5 = 1.25\,\text{mm}$, $W_4 = 2.18\,\text{mm}$, $d_3 = 3.75\,\text{mm}$, $d_4 = 6.25\,\text{mm}$. Simulation was done using ADS software. Fig. 2 (e) shows the simulated and measured results. The performance of the proposed filter is compared with other works in Table I. In this table, f_c, SBW and RL are $-3\,\text{dB}$ cut-off frequency, stobband width and return loss respectively. The ralative stopband width (RSB)is given by:

$$RSB = \frac{stopband\ bandwidth}{stopband\ centre\ frequency} \tag{5}$$

As seen from the table, the proposed filter has good performance and also a high RSB among the quoted filters. The size of the filter is only $221\,\text{mm}^2$, that is eight times smaller than [5] and three times smaller than [2], and has the 23% reduction in size with [1] and 18% reduction in size with [4]. Another factor that is important about low-pass filters is the ratio of the stopband

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Table I. Comparison of this work with other filters

ref.	f_c (GHz)	(SBW)/f_c	RSB	RL(dB)	Size(mm^2)
This Work	5.45	5.74	1.49	15	221
[1]	2.4	2.21	1.05	17	283.86
[2]	1	4.12	1.34	20	638.4
[4]	1.5	0.94	0.64	10	269
[5]	6	1.08	0.7	8	1820
[6]	4.16	3	1.2	10.98	83.68

width to the cut off frequency, which the proposed filter has a significant advantage in comparision to other LPFs, that is about six times more than the value of the filter [4], five times more than [5], 259% better than [1], 191% better than [6] and 139% better than [2]. Sharpness of cutoff frequency from −3 dB to −20 dB is about 0.58 GHz that is just 10% of the bandwidth, which is quite sharp and better than [4, 5]. Also, in the proposed filter, from DC to 80% of passband width, the insertion-loss is below 0.1 dB and return-loss is 15 dB.

4 Conclusion

A novel compact low-pass filter with a wide stopband and low insertion-loss in stopband, using a symmetric cascaded U-shaped resonator is presented. This filter has a simple structure that is easy to fabricate. Simulated and measured results of the proposed filter are acceptable and validate the performance of the proposed structure as compared to other works, where the rejection band over −20 dB is from 6.05 GHz to 37.35 GHz. With the above described features, the proposed LPF could be applied to microwave communication purposes.

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