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## COMPACT BANDPASS FILTER BASED ON NOVEL HAIRPIN RESONATOR WITH SELF-CONTAINED TRIPLE TRANSMISSION ZEROS

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**Abstract**—A compact coupled-line hairpin resonator is proposed and analyzed for designing a novel bandpass filter (BPF) in this letter. Compared with conventional stepped-impedance and stub-loaded resonator, the proposed resonator can produce three transmission zeros, which can be applied to achieve a wide and highly-attenuated upper stopband. To validate this attractive feature, a microstrip BPF is designed and fabricated with the center frequency at 2.4 GHz and a fractional bandwidth of 6%. Measured frequencies responses show a wider upper stopband up to 6.9 GHz ( $2.9f_0$ ) with insertion loss higher than 20 dB.

### 1. INTRODUCTION

Microstrip bandpass filters (BPFs) have gained popularity due to their easy synthesis, compact size, light weight, low cost, and easy integration with other circuits, whereas wide upper stopband with large insertion loss is always highly desired [1–5]. BPFs can be designed using stepped-impedance resonators (SIRs), where the first harmonic passband of these filters can be effectively pushed up by choosing a large impedance ratio of two distinctive sections [6, 7]. In order to suppress the first two harmonic passband, the work in [8] proposes a so-called Koch fractal shaped resonator, but the constituted filter complicates the fabrication process. In [9], the modified triple- and quad-mode stub-loaded resonators are presented to develop a class of BPFs with compact size and sharpened rejection skirts. But due

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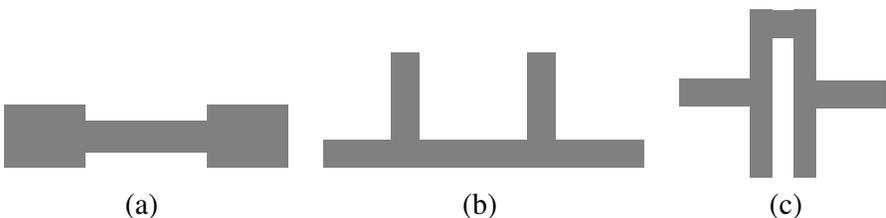
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to uncontrollable high-order resonant modes in these resonators, the implemented filters [9] demonstrate unsatisfactory upper stopband performance.

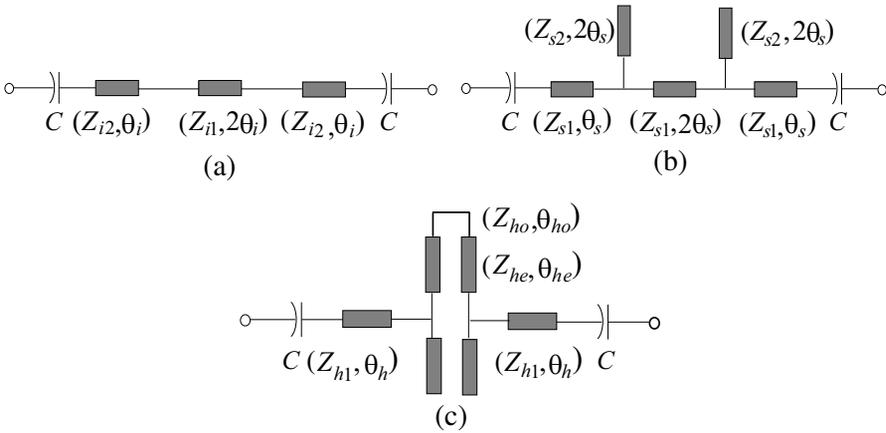
In this letter, a compact BPF based on coupled-line hairpin resonators with self-contained three transmission zeros is proposed. Extensive studies are firstly conducted to provide a physical insight on the emergence of these three transmission zeros from a single resonator. Next, a 3rd-order Chebyshev BPF with wide and highly-attenuated upper stopband is designed and fabricated. Both the simulated and measured results successfully verify the predicted performance of the filter.

## 2. ANALYSIS ON THE PROPOSED HAIRPIN RESONATOR

As described in Fig. 1(a), the conventional SIR consists of two sections of transmission lines with dissimilar characteristic impedances. It is applied to design a BPF with wide upper stopband in [6]. In [9], a stub-loaded resonator with two parallel uncoupled open-circuited stubs, as shown in Fig. 1(b), is proposed to design two compact BPFs based on a single resonator, which exhibit a triple- or quad-pole passband. By appropriately folding the central connecting line between the two stubs, a novel coupled-line hairpin resonator shown in Fig. 1(c) can be constructed. Compared with the existing stub-loaded resonator shown in Fig. 1(b), the proposed one apparently has a miniaturized size. Furthermore, the proposed resonator shows the emergency of three transmission zeros between the first and second resonant modes. This feature is due to the proper frequency-dispersive coupling between the two sides of the hairpin unit, and the principle of the three transmission zeros has been explicitly explained in [10]. Among the three transmission zeros, the first and the third ones are adjustable by

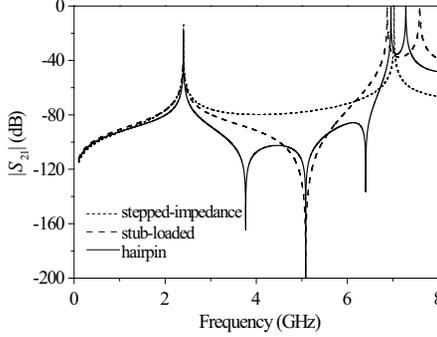


**Figure 1.** (a) Conventional stepped-impedance resonator. (b) Conventional stub-loaded resonator. (c) Proposed coupled-line hairpin resonator.



**Figure 2.** Transmission line models of resonators shown in Fig. 1 with loose coupling. (a) Stepped-impedance resonator. (b) Stub-loaded resonator. (c) Proposed coupled-line hairpin resonator.

changing the coupling strength between the two arms of the hairpin unit, and they can be applied to widen and deepen the upper stopband. To investigate the resonant properties of the three types of resonators, their respective transmission line models shown in Fig. 2 are analyzed in Agilent Advanced System (ADS) on a substrate with a thickness of 1.27 mm and a dielectric constant of 10.8. In Fig. 2, three resonators are loosely-coupled with I/O ports by  $C = 0.01$  pF, here  $(Z_{i1}, Z_{i2}, Z_{s1}, Z_{s2},$  and  $Z_{h1})$  denote characteristic impedance, and  $(\theta_i, \theta_s$  and  $\theta_h)$  indicate electrical length, while  $(Z_{he}$  and  $Z_{ho})$  are the even-/odd-mode characteristic impedance of the proposed resonator, and  $(\theta_{he}$  and  $\theta_{ho})$  are the corresponding electrical length under the even-/odd-mode case. Based on the above analysis, the resonant properties of the three resonators are plotted in Fig. 3 when the frequency ratio of the first spurious and fundamental frequencies  $f_{s1}/f_0$  is set to be 3. It can be seen that there is no transmission zero between the first and second modes when the SIR's electrical length and impedances are  $\theta_i = 65^\circ$  and  $Z_{s1} = 128 \Omega, Z_{s2} = 54 \Omega$ , respectively, thereby the SIR has no harmonic-suppressed effect. Electrical length and impedances for the stub-loaded resonator are chosen to be  $\theta_s = 45^\circ$  and  $Z_{i1} = 80 \Omega, Z_{i2} = 28.5 \Omega$  in Fig. 3. This stub-loaded resonator can generate one transmission zero at 5.2 GHz, whereas for the proposed hairpin resonator ( $\theta_{ho} = \theta_{he} = 90^\circ, Z_{h1} = 80 \Omega, Z_{ho} = 35$ , and  $Z_{he} = 86 \Omega$ ), as discussed in [10], can possess three transmission zeros between the first and second resonant modes under the condition of the impedance



**Figure 3.** Frequency responses of three resonator circuits in Fig. 2.

ratio  $R = Z_{ho}/Z_{he} < 0.5$ . In this letter,  $R$  is selected as 0.4, thereby achieving our desired three transmission zeros at 3.8, 5.2 and 6.4 GHz. The three transmission zeros are calculated by

$$S_{21} = \frac{-jY_0\Delta Y_1 \cot(\theta_{eff})}{Y_0^2 \cot^2(\theta_{eff}) - \Delta Y_2 + jY_0 \cot(\theta_{eff})\Delta Y_1} = 0 \quad (1)$$

where

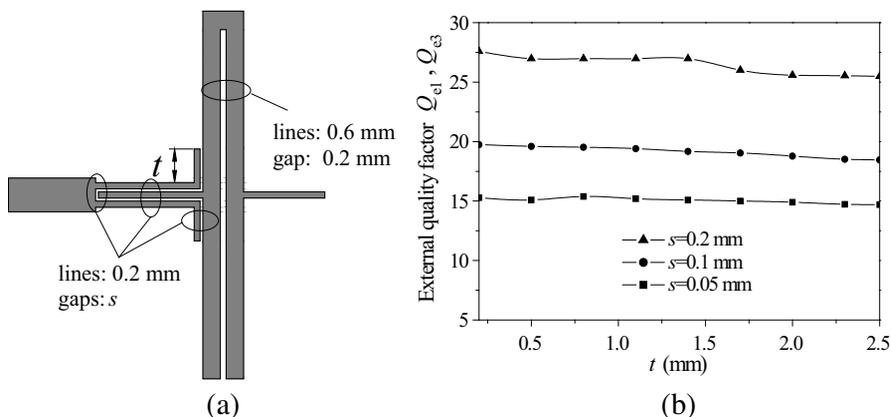
$$\begin{aligned} \Delta Y_1 &= 2Y_{he} + Y_{ho} - Y_{ho} \cot^2(\theta_{eff}) \\ \Delta Y_2 &= 2Y_{he}Y_{ho} (1 - \cot^2(\theta_{eff})) \\ Y_{ho} &= 1/Z_{ho}; \quad Y_{he} = 1/Z_{he} \end{aligned}$$

$\theta_{eff}$  is the arithmetic-averaged electrical length of  $\theta_e$  and  $\theta_o$  for the coupled-line section. Although the stub-loaded resonator can generate a transmission zero, it is apparent that the extra two transmission zeros vastly improve the upper stopband with enhanced attenuation.

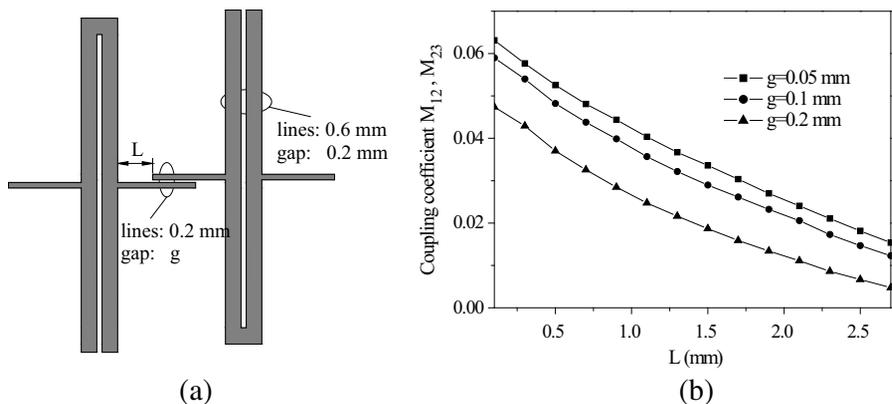
### 3. FILTER DESIGN AND RESULT DISCUSSION

In view of this advantage, a 3rd-order Chebyshev BPF using the proposed resonator is designed with a fractional bandwidth of  $FBW=6.0\%$  at the midband frequency of 2.4 GHz. With a passband ripple of 0.1 dB chosen, the lowpass prototype parameters are  $g_0 = 1.0$ ,  $g_1 = 1.0316$ ,  $g_2 = 1.1474$ ,  $g_3 = 1.0316$  and  $g_4 = 1.0$ . The design parameters can be calculated as follows [11]:  $Q_{e1} = Q_{e3} = 19.7$ ,  $M_{12} = M_{23} = 0.0551$ , where  $Q_{e1}$  and  $Q_{e3}$  are the external quality factors at the input and output ports, and  $M_{12}$  and  $M_{23}$  are the coupling coefficients between two adjacent resonators. Using the ADS Momentum, the external quality factors ( $Q_e$ ) can be extracted from

the calculated phase response of  $S_{11}$  in a single-port excited resonator via fullwave simulation. Fig. 4(b) shows the resulting external quality factors with respect to different lengths of the extended coupling-line at I/O ports when the spaces between the coupling lines and the resonator are selected as 0.05, 0.1, and 0.2 mm, respectively. Thus, the physical dimensions of external coupling structures at I/O ports can be determined. To show the coupling coefficient with respect to the distance between two resonators shown in Fig. 5(a), a set of



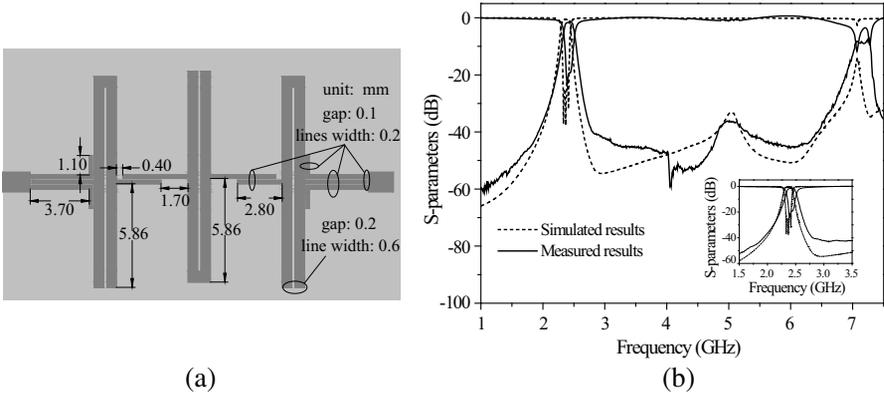
**Figure 4.** (a) Layout of I/O structure. (b) Variation of external quality factors with different lengths of extended coupling-line,  $t$ .



**Figure 5.** (a) Coupling aperture between two adjacent resonators. (b) Variation of coupling coefficients with different distance between the two resonators.

results is plotted in Fig. 5(b) when the two ports are very weakly coupled to the resonators, from which we can roughly estimate the required structure between adjacent resonators and the optimal size of the coupling aperture.

In order to demonstrate the performance of the proposed filter, the filter circuit is synthesized and optimally designed, and its relevant layout with detailed dimensions is depicted in Fig. 6(a). Fig. 6(b) describes the simulated and measured results. It can be observed that the stopband is now expanded up to 6.9 GHz with insertion loss larger than 20.0 dB, where the maximum in-band return loss is 19.0 dB and the minimum insertion loss is 1.3 dB. The measured 3-dB fractional bandwidth is about 5.8%. Simulated results exhibit almost agreeable with measured results over a wide frequency range from 1.0 to 7.5 GHz. Slight discrepancy of insertion loss near 5.0 GHz is mainly caused by



**Figure 6.** Optimally designed filter. (a) Dimensional layout. (b) Simulated and measured results.

**Table 1.** Comparison with other reported bandpass filters.

	Circuit size ( $\lambda_0 \times \lambda_0$ )	Insertion loss (dB)	Return loss (dB)	Stop-band with insertion loss larger than 20.0 dB
Ref. [9] (Quad-mode)	$0.19 \times 0.12$	0.7	18.0	$1.5f_0$
Ref. [12]	$0.48 \times 0.04$	1.4	28.0	$3.0 f_0$
This work	$0.17 \times 0.09$	1.3	19.0	$2.9f_0$

unexpected tolerance in fabrication [5]. In final, Table 1 is provided to compare our proposed filter with those previous works, where  $\lambda_0$  is the free space wavelength at the central frequency  $f_0$ .

#### 4. CONCLUSION

In this letter, a compact coupled-line hairpin resonator has been proposed and used for designing a novel harmonic-suppressed BPF. It is demonstrated that the presented resonator with three transmission zeros not only can widen the upper stopband, but also can enhance its rejection level as desired. The measured frequency responses of the fabricated BPF successfully justify our proposed technique.

#### ACKNOWLEDGMENT

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