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LETTER

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Design of triple-band bandpass filter using quad-mode stepped impedance resonator (SIR) with shorted stub

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Abstract: A compact microstrip triple-band bandpass filter (BPF) using an improved quad-mode stepped impedance resonator (SIR) with shorted stub is introduced in this letter. Distinct mode splitting characteristics of the quad-mode SIR are investigated by adopting even- and odd-mode theory. Two pairs of even-odd modes are utilized to design the former two passbands with the help of loop-loop coupling for splitting two identical modes. Then, a tapped side-coupled feed-lines construct an additional passband avoiding occupying extra size. The bandwidth of each passband can be controlled independently. To validate the approach, a triple-band BPF centered at 1.4/2.7/3.57 GHz has been implemented. Good agreement is obtained between simulated and measured results.

Keywords: triple-band filter, quad-mode, stepped impedance resonator

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

In modern wireless communication systems, multiband microwave components are often required. Therefore, multiband filters with compact size, controllable passband bandwidth, and high performance have garnered great attention in recent years. Traditionally, a triple-band bandpass filter (BPF) can be achieved by combining several sets of resonators with common input and output ports [1, 2]. But, these design suffer from big circuit size. Stub-loaded resonators (SLR) [3, 4], multi-mode stepped-impedance resonator (SIRs) [5, 6] and stub-loaded SIRs [7, 8] were proposed to realize the triple-band responses. Nevertheless, the bandwidth of each passband for these structures are difficult to be controlled independently. So, good design flexibility for multiband filter design still remain challenging.

In this article, a compact triple-band BPF using an improved quad-mode SIR and a pair of side-coupled feed-lines are introduced. The proposed quad-mode SIR with short-circuited stub perturbation can generate dual-band response. Its three center frequencies and bandwidths can be allocated conveniently by controlling the corresponding parameters of the resonator properly. Also, source-load coupling between feed lines are adopted to connect this resonator and additional transmission zeros are produced for enhancing selectivity. Finally, the prototype of filter is given and fabricated for verification of the predicted results.

2 Theory and design

A. Analysis of quad-mode SIR

Fig. 1(a) shows the conventional SIR with center loaded shorted-circuit stub. As discussed in [8], bandwidths of the first and third passband are difficult to be controlled independently. To resolve this problem, two square loop structures are

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introduced to replace the low-impedance patch sections of the conventional SIR, as illustrated in Fig. 1(b). Thus, more resonant modes and degrees of design freedom can be obtained. Due to its symmetry in Fig. 1(b), even-odd-mode method is applied to analyze the proposed quad-mode SIR. Under odd-mode excitation, the symmetry plane T-T′ can be modeled as an electric wall, the short-ended stub can be ignored. The odd-mode equivalent circuit is shown in Fig. 2(a). Obviously, it is still symmetrical and the even-odd-mode method is applied once again to analyze the operating mechanism of the first odd-mode equivalent circuit. Fig. 2(c) shows the even- and odd-mode equivalent circuits of the first odd-mode equivalent circuit in Fig. 2(a).

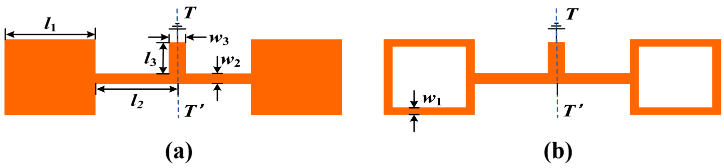

Fig. 1. (a) Schematic view of the conventional SIR with shorted-circuit stub. (b) Proposed quad-mode SIR.

Under even-mode excitation, the symmetry plane T-T′ can be modeled as a magnetic wall, the short-ended stub is bisected and the width is half what it is. The even-mode equivalent circuit is shown in Fig. 2(b). Similarly, it is symmetrical and even-odd-mode analysis is used. Fig. 2(d) shows the even and odd-mode equivalent circuits of the first even-mode equivalent circuit in Fig. 2(a).

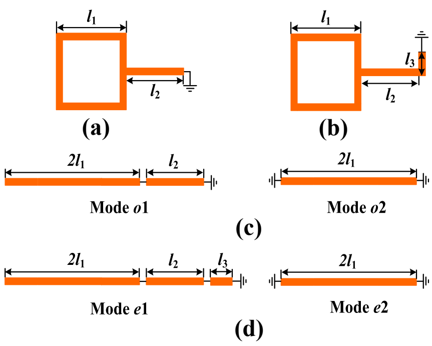

Fig. 2. (a) Odd-mode equivalent circuit of quad-mode resonator. (b) Even-mode equivalent circuit of quad-mode resonator. (c) Even- and odd-mode equivalent circuit of Fig. 2(a). (d) Even- and odd-mode equivalent circuit of Fig. 2(b).

Based on the above analysis, four modes, indicated as mode o_1, o_2, e_1, and e_2, are obtained from Figs. 2(c) and 2(d). Obviously, o_1 and e_1 mode equivalent circuits are $\lambda/4$ uniform impedance resonators (UIRs), o_2 and e_2 mode equivalent circuits are $\lambda/2$ UIRs. The fundamental frequencies of the four modes are named as f_{e1}, f_{e2}, f_{o1} and f_{o2} with the relationship $f_{e1} < f_{o1} < f_{e2} = f_{o2}$. They can be deduced as follows:

$$f_{o1} = \frac{c}{4(2l_1 + l_2)\sqrt{\varepsilon_{eff}}} \qquad f_{o2} = \frac{c}{8l_1\sqrt{\varepsilon_{eff}}} \tag{1}$$

$$f_{o1} = \frac{c}{4(2l_1 + l_2 + l_3)\sqrt{\varepsilon_{eff}}} \qquad f_{o2} = \frac{c}{8l_1\sqrt{\varepsilon_{eff}}} \tag{2}$$

where c is the speed of the light in free space, and ε_{eff} is the effective dielectric constant of substrate.

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It can be concluded that (i) the stub l_1 exists in modes o_1, o_2, e_1, and e_2, (ii) the stub l_2 is in mode o_1 and e_1, and (iii) the stub l_3 only exists in modes e_1. So, the mode frequencies can be tuned by changing the lengths of corresponding stubs. Fig. 3(a), 3(b), 3(c) and 3(d) describe the resonant frequencies against w_1, l_1, l_2 and l_3.

As shown in Fig. 3(a), f_{o1} and f_{e1} are decreasing while f_{o2} and f_{e2} increase when w_1 enlarges. In Fig. 3(b), the four resonant frequencies f_{e1}, f_{e2}, f_{o1} and f_{o2} go down when l_1 increases. In Fig. 3(c), f_{e1} and f_{o1} are changed by the variation of l_2, whereas f_{o2} and f_{o2} keep a constant. From Fig. 3(d), it can be observed that l_3 only relates to f_{e1} and, has no influence on other three modes. Therefore, more degrees of freedom for controllable passbands design can be realized.

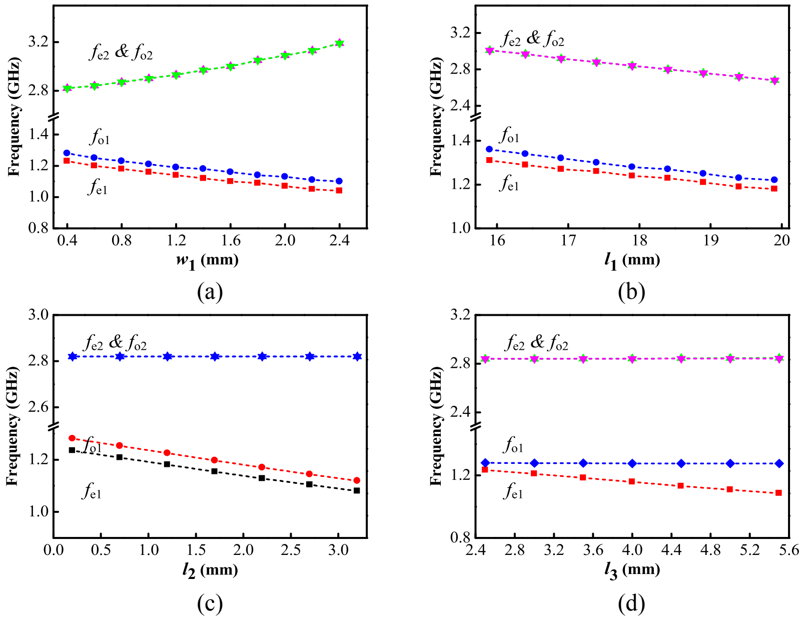

Fig. 3. Resonant frequencies under different (a) w_1, (b) l_1, (c) l_2 and (d) l_3.

B. Triple-band filter design

In this section, a triple-band BPF is designed, whose layout are shown in Fig. 4. This filter is composed of the improved quad-mode SIR and tapped side-coupled feed-lines. To realize dual-band BPF response using quad-mode SIR, two identical resonance frequencies f_{e2} and f_{o2} are designed to split. Two loops of the resonator are folded inward to introduce loop-loop coupling, which can be tuned freely by changing the gap d_1 and the length l_4. Fig. 5 shows a comparison of S_{21} with and without the loop-loop coupling. It can be observed that f_{e2} and f_{o2} are separated from each other under loop-loop coupling. Then, f_{e1} and f_{o1} form the first passband, f_{e2} and f_{o2} form the second passband with the excitation of the feed-lines.

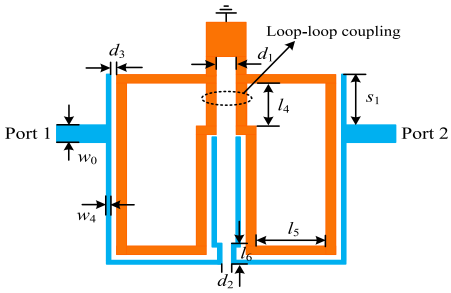

Fig. 4. Configuration of the proposed triple-band filter (left).

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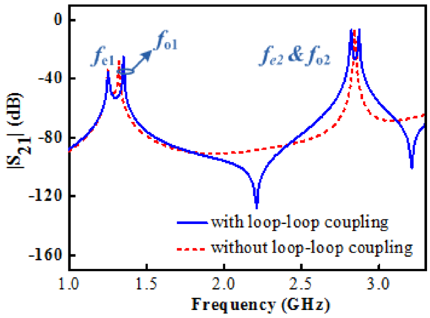

Fig. 5. A comparison of simulated S_{21} with and without loop-loop coupling (right).

Fig. 6 shows the simulated S_{21} of the tapped side-coupled feed-lines structure. As shown in the picture, the tapped side-coupled feed-lines not only provides excitation for first two passbands, but also creates the third passband. It can be equivalent to a $\lambda/2$ uniform impedance resonator (UIR) with taper feed. Also, the feed-lines are bent, which contribute to tuning the external Q-factors of the first two passbands and bandwidth of the third passband (l_6). And Fig. 7 shows that bandwidth of the first, second and third passband can be tuned by the stub length l_3, the gap d_1 and the length l_6 individually, respectively.

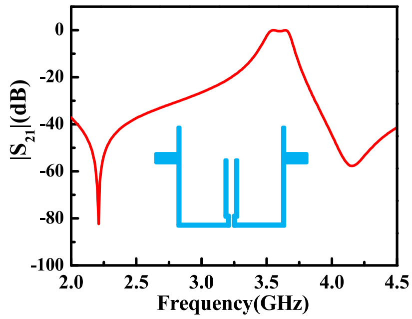

Fig. 6. Simulated S_{21} of 3_{rd} passband generated by tapped side-coupled feed-lines

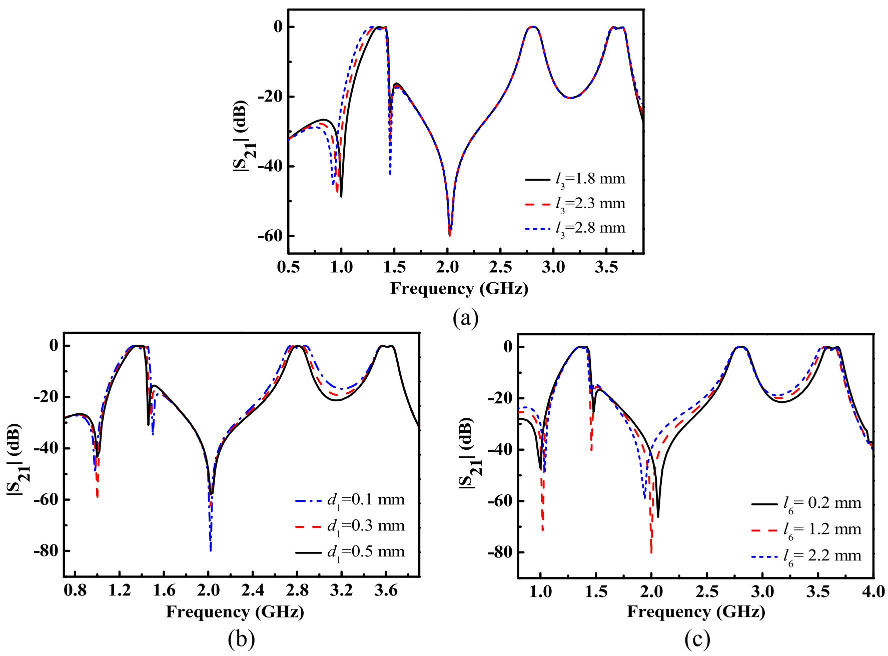

Fig. 7. Simulated $|S_{21}|$ for different (a) l_3, (b) d_1 and (c) l_6.

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3 Experimental results and discussion

To verify the above analysis, a triple-band BPF working at 1.4, 2.7, and 3.57 GHz was designed and fabricated on the substrate with a relative dielectric of 3.5 and thickness of 0.8 mm. The dimension are as follows: $l_1 = 17.15$ mm, $l_2 = 0.6$ mm, $l_3 = 1.8$ mm, $l_4 = 7.1$ mm, $l_5 = 8.2$ mm, $l_6 = 0.7$ mm, $w_0 = 1.8$ mm, $w_1 = 0.4$ mm, $w_2 = 0.7$ mm, $w_3 = 1.8$ mm, $w_4 = 0.2$ mm, $d_1 = 0.4$ mm, $d_2 = 0.2$ mm, $d_3 = 0.2$ mm, $s_1 = 10.8$ mm. The circuit size of the proposed filter occupies only $0.096\,\lambda g * 0.131\,\lambda g$.

The simulated and measured results are compared in Fig. 8. Measured three passbands are centered at 1.4, 2.7, and 3.75 GHz, there 3 dB fractional bandwidths are 13.1%, 5.6% and 4.6%, respectively. In addition, the filter has four transmission zeros where located at 0.96, 1.48, 2.02, and 4.1 GHz, which improve the selectivity of the filter greatly. The transmission zeros T_{Z1} and T_{Z2} are due to source-load coupling [9, 10]. T_{Z3} is produced by the hook-shape feedlines. T_{Z4} is created by the coupling between the feedlines and the resonator [11].

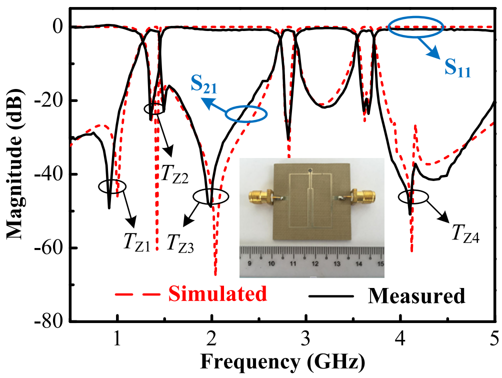

Fig. 8. Simulated (dashed line) and measured (solid line) frequency responses of the designed filter and photograph of the fabricated filter.

4 Conclusion

In this article, an improved quad-mode SIR with short stub is presented. Based on the proposed resonator and side-coupled feed-lines, a compact triple-band BPF operating at 1.4, 2.7, and 3.57 GHz is designed and fabricated. Its center frequency and bandwidth of each passband can be tuned freely by changing the corresponding parameters. The properties of the proposed quad-mode SIR are verified by simulation and experiment. This compact triple-band filter is suitable for multi-band and multi-service applications in wireless communication systems.

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