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Quad-mode dual-band bandpass filter based on a stub-loaded circular resonator

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Abstract

In this paper, a quad-mode dual-band bandpass filter (BPF) only using a stub-loaded circular resonator is presented. The odd- and even-mode resonant frequencies can be easily computed and flexibly controlled by the radius of the circle and the two sets of stubs, as all odd- and even-mode equivalent circuits are half-wavelength resonators (double-ended short-circuited uniform transmission line resonator). Introducing the resonator makes the filter be analyzed and designed easily. To further improve the isolation between the two passbands, a dual-band BPF is designed by introducing the source-load coupling technique; the simulation and test S-parameter curves show that the designed BPF has four controllable transmission zeros. The good agreement of measured data with simulation results verifies the proposed design.

Keywords: Bandpass filter (BPF), Dual-band, Circular resonator, Coupling

1 Introduction

With the development of microwave and millimeter-wave technology, there is an increasing need of the high performance and miniaturization of multi-frequency band filter in communication systems [1].

In [2], a dual-band bandpass filter (BPF) was achieved by a dual-mode circular resonator; however, there were only two transmission poles in each passband. A resonator with a cross slot and unbalanced stubs has been proposed [3] for the design of dual-band BPF. A dual-band BPF [4] makes common-mode rejection be improved by introducing four coupled U-shaped defected ground structures below the resonators, and the differential mode is not significantly affected. In [5], some resonators were used to design dual-band filter, but resonant frequencies were dependent. Unfortunately, the poor in-band performance of the dual-band filter is also an existing disadvantage of the revised method in [2–4]. Meanwhile, these solutions increase the complexity of structure and analytical method in [2–10].

In this letter, a stub-loaded quad-mode circular resonator is presented to design the dual-band bandpass filter. This resonator can generate four independent resonant frequencies. The properties of the presented resonator are analyzed theoretically and simulated by full-wave simulation software.

A passband controllable dual-band BPF can be formed by adding a suitable external coupling structure. To greatly improve the isolation between the two passbands, the source-load coupling is introduced, which increases the transmission zeros between the two passbands. Finally, the dual-band filter with 1.25 GHz and 2.0 GHz is presented, and the measurement results show good performance.

2 Methodology of the proposed resonator

2.1 Analysis of the proposed resonator

The proposed stub-loaded quad-mode circular resonator structure consists of a circular resonator and four short-circuited stubs, which is shown in Fig. 1a. Due to the symmetrical structure of the resonator, the theory of odd and even modes can be used to analyze it [11–13].

As shown in Fig. 1b, it was clear that the equivalent circuits of odd and even mode still have a symmetrical structure feature of the resonator with double-ended short-circuit, and the short-circuited stub shunted at the midpoint of the resonator. Consequently, we can utilize the odd- and even-mode theory to analyze its odd- and even-mode equivalent circuits again. That is the main idea of our proposed method. The analytical results are shown in Fig. 2a and b, respectively.

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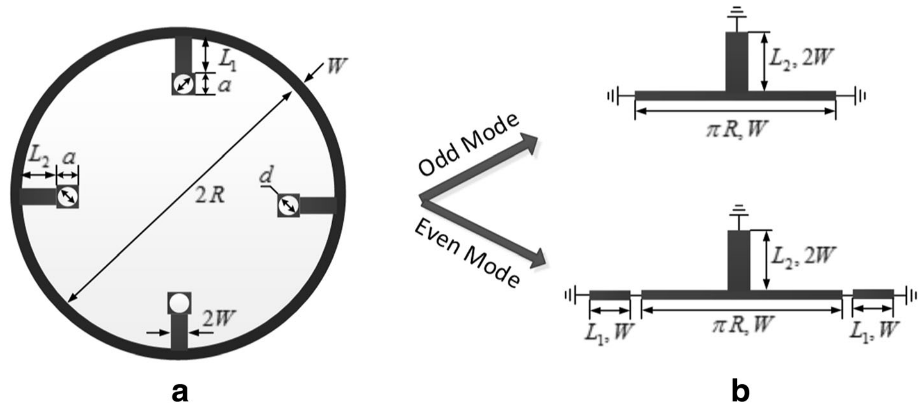

Fig. 1 a The stub-loaded quad-mode circular resonator. **b** The odd- and even-mode equivalent circuit

It can be seen from Fig. 2 that the four equivalent circuits are all double-ended short-circuited resonators in the form of a uniform transmission line. The frequencies corresponding to the four resonant modes are denoted by f_1, f_2, f_3, and f_4, respectively. According to the odd- and even-mode theory, the resonant frequencies can be derived as

$$f_1 = \frac{(2n-1)c}{2 \times \left(\frac{1}{2}\pi R\right)\sqrt{\varepsilon_{\text{eff}}}} \tag{1}$$

$$f_2 = \frac{(2n-1)c}{2 \times \left(\frac{1}{2}\pi R + L_2\right)\sqrt{\varepsilon_{\text{eff}}}} \tag{2}$$

$$f_3 = \frac{(2n-1)c}{2 \times \left(\frac{1}{2}\pi R + L_1\right)\sqrt{\varepsilon_{\text{eff}}}} \tag{3}$$

$$f_4 = \frac{(2n-1)c}{2 \times \left(\frac{1}{2}\pi R + L_1 + L_2\right)\sqrt{\varepsilon_{\text{eff}}}} \tag{4}$$

In the case of $L_2 \geq L_1$, there is a relationship existing among the four frequencies: $f_4 < f_2 < f_3 < f_1$. It is not hard to find, stub L_1 exists only in f_3 and f_4 and L_2 exists in f_2 and f_4. All the resonant frequencies will reduce as the radius R increases. By changing the length of the stub L_1, only f_3 and f_4 can be affected. Similarly, f_2 and f_4 are only affected by the length of the stub L_2. In order to verify the above theoretical conclusions, full-wave simulation is

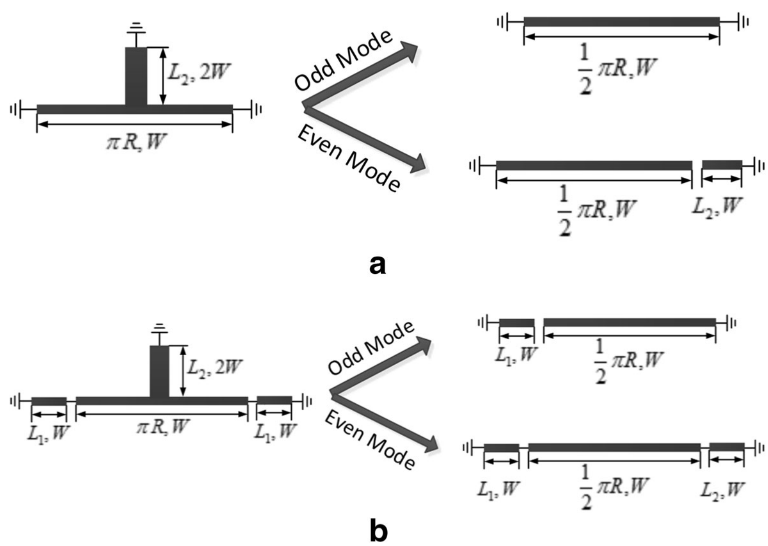

Fig. 2 a The odd- and even-mode equivalent circuits of the odd-mode equivalent circuit. **b** The odd- and even-mode equivalent circuits of the even-mode equivalent circuit

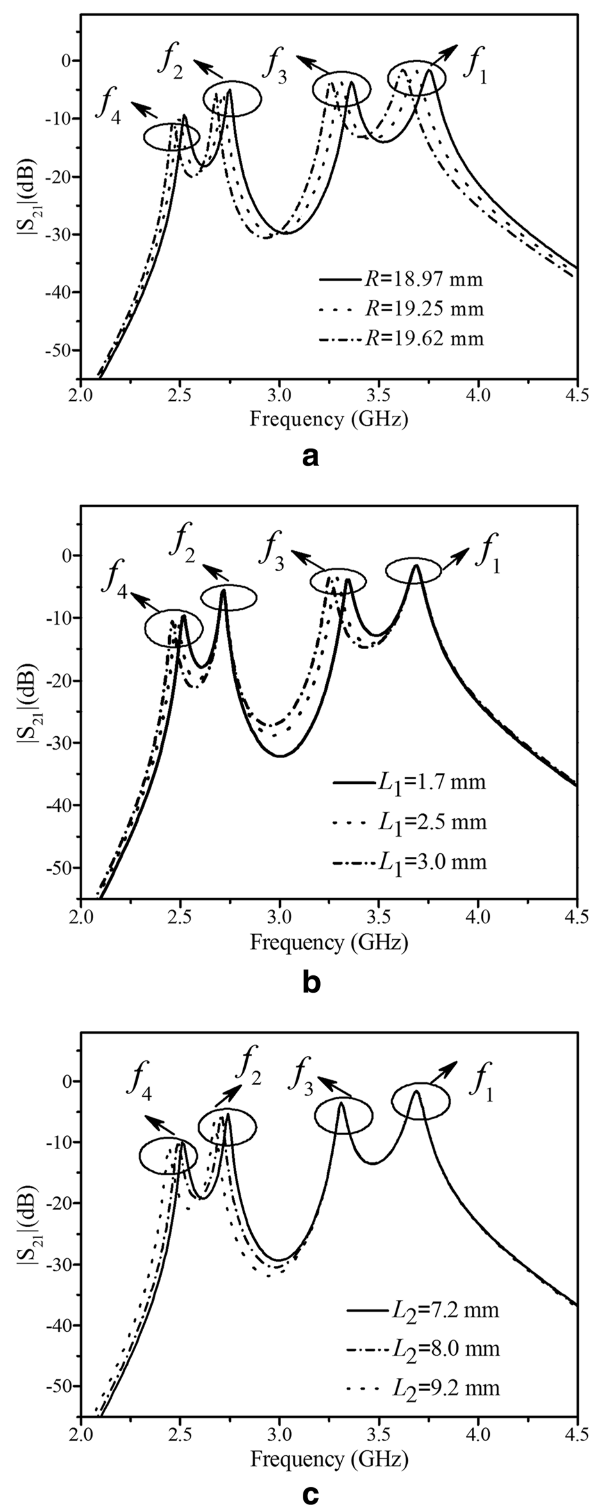

Fig. 3 The effects of structural parameters on the resonant frequency. **a** The *R* radius of the circle. **b** The length of the stub L_1. **c** The length of the stub L_2

carried out, and the simulation results shown in Fig. 3 coincide with the theoretical analysis.

2.2 The source-load coupling technique

According to the above analysis, the four resonant frequencies can be divided into two groups in accordance with their values, the first group including f_2 and f_4 forms the first passband and the second group including f_1 and f_3 forms the second passband. In the basis of the resonator, a dual-band BPF can be designed by adding the arc-shaped parallel coupling feeder. That way we can control the center frequencies and relative bandwidths of the dual-band by adjusting the values of each resonant frequencies and the strength of coupling. In order to further improve the performance of the filter and enhance the isolation between the two passbands, the source-load coupling technique is introduced.

As shown in Fig. 4 (for simplicity, get arc-shaped feeder structure straightened out), both ends of the

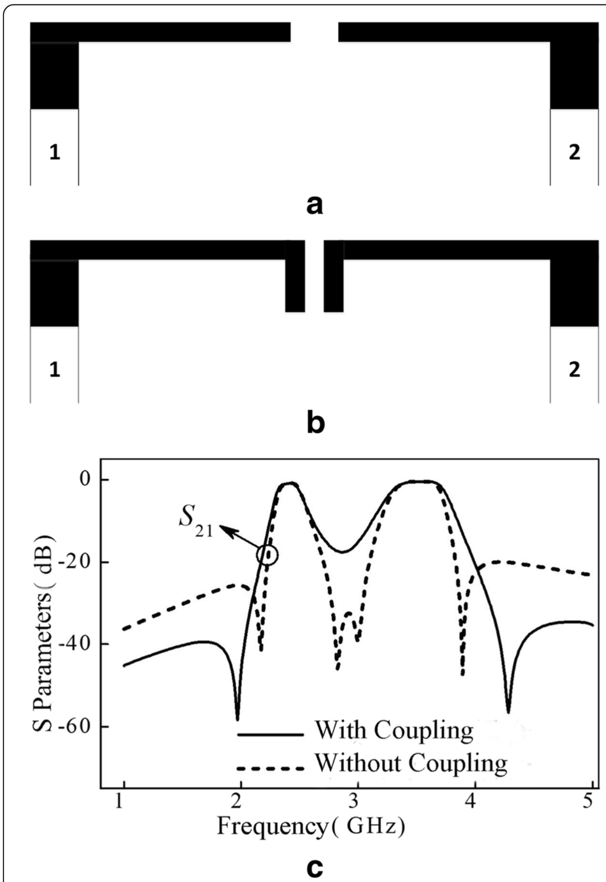

Fig. 4 Source-load coupling. **a** The structure characteristic without the source-load coupling technique. **b** The structure characteristic with the source-load coupling technique. **c** The comparison of S parameters between with and without source-load coupling

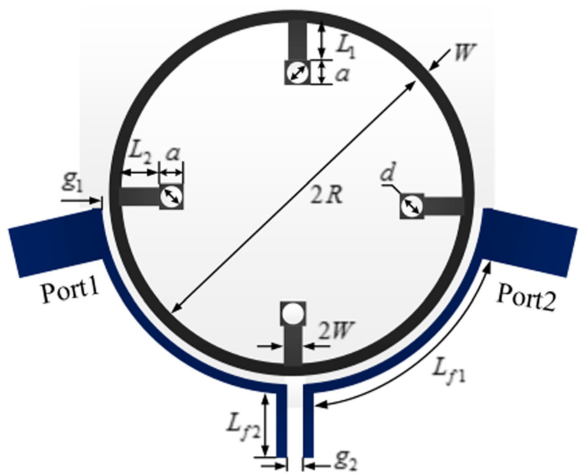

Fig. 5 Filter configuration

feeder that is close to each other are extended and then bent down. Source-load coupling technique refers to the introduction of a certain resonant coupling structure between the two ports so that some signals at the source end are directly coupled to the load through the coupling structure, while the other part is coupled to the load through the resonator. When the amplitude is equal and the phase difference is 180°, the transmission zeros can be generated as shown in Fig. 4c. The position of transmission zeros can be flexibly controlled by controlling the resonant frequency and coupling size of the coupling structure. Such a way makes the design of the resonator and feeders become more convenient.

3 Results and discussion

3.1 Structure of the dual-band BPF

Based on the proposed structure and the analysis of the resonant characteristics above, a dual-band BPF in other frequency is designed. The design parameters of the filter are as follows: The center frequencies of the two passbands are 1.25 GHz and 2 GHz, respectively. The insertion losses are less than 1.5 dB, and the return losses are greater than 15 dB. The first passband has a relative bandwidth of 7 to 12%, and the second is from 10 to 15%.

According to the above performance indicators and the material of existing dielectric substrates, the F4BMX dielectric substrates with a dielectric constant of 2.65 and a thickness of 1 mm were selected. The specific design ideas are as follows:

Firstly, according to Formula (1), the radius R of the ring is calculated preliminarily so that the resonant frequency of the ring is near the central frequency of the second passband. Then, the radius R is optimized by eigen-mode solution through HFSS.

Secondly, adding branch L_1 to the model and optimizing its length makes the coupling of resonant frequencies f_1 and f_3 reach the required strength.

Thirdly, the resonant frequencies f_2 and f_4 of the ring resonator are located near the central frequency of the first passband by adding a branch L_2 and optimizing its length in the model.

Fourth, by optimizing the length of the feeder L_{f1} and the distance between L_{f1} and the resonator g_1, the external coupling strength can meet the requirements of their respective passband bandwidth.

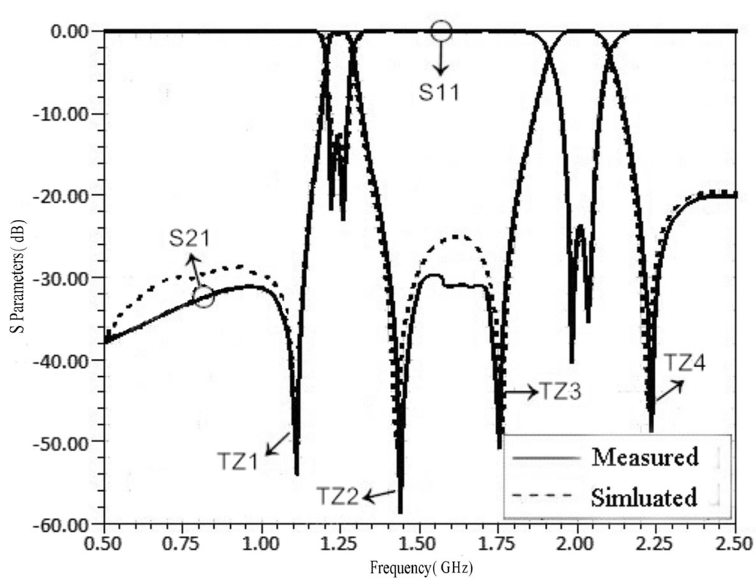

Fig. 6 Frequency responses of the filter with four transmission zeros

Table 1 Comparison with some prior dual-band BPF

	Center frequency (GHz)	Return loss (dB)	Insertion loss (dB)	3-dB relative bandwidth (%)	Transmission zeros
Filter in [2]	2.4/5.8	20/25	1.4/3.2	12/–	2
Filter in [3]	2.4/5.16	≥ 12	0.6/1.4	13.7/6.3	2
Filter in [5]	1.7/2.15	15/18	3.5/4.8	6.35/4.6	4
Filter in this paper	1.25/2.0	18/27	0.8/0.5	7.8/10.6	4

Finally, according to the theory of source-load coupling, the length of L_{f2} is optimized, and the location of transmission zeros is determined.

The configuration of structure is shown in Fig. 5. The dimensions are determined as follows: $R = 32.98$ mm, $L_1 = 2.59$ mm, $L_2 = 26.5$ mm, $W = 0.5$ mm, $g_1 = 0.35$ mm, $g_2 = 0.7$ mm, $d = 1.4$ mm, $L_{f1} = 27.14$ mm, and $L_{f2} = 3.2$ mm. The short-circuited effect is achieved with a metalized via of 1 mm diameter at the end of the short-circuited stub.

3.2 Simulated and measured results of the dual-band BPF

Figure 6 shows the simulated and measured results. The center frequencies of the two passbands are 1.25 GHz and 2 GHz, respectively. The insertion losses of the lower and upper passbands are only 0.4 dB and 0.5 dB, respectively. The measured return losses of the lower and upper passbands are 18 dB and 27 dB, respectively. These meet the needs of design targets. The error between simulation and measurement results is very small, and there is a good agreement between them. Some of these deviations may be due to machining errors and SMA connectors.

3.3 Comparison between the existing filters and the proposed filter

The comparison with the existing filters is summarized in Table 1. It can be observed that the developed filter offers many advantages in this letter, such as better performance in the return losses and passbands, lower insertion losses, independently controlling bandwidths, and simple structure. It is conducive to the realization of the filter miniaturization. But the filter still has many shortcomings in design, and better performance filters will definitely be realized in the future.

4 Conclusion

In this letter, a stub-loaded circular resonator is proposed. Because all odd- and even-mode equivalent circuits have the same structure, the resonant frequencies can be easily obtained and flexibly controlled. To further improve the selectivity of the filter, a dual-band BPF is designed by introducing the source-load coupling technique so that the BPF has four controllable transmission zeros. The measured results agree well with simulated ones, and the filter has high performance.

Abbreviation

BPF: Bandpass filter

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Availability of data and materials

Not applicable.

Authors' contributions

ML is the main writer of this paper. He proposed the main idea, deduced the performance of BPF, completed the simulation, and analyzed the result. PR and TX assisted ML in designing the architecture of the resonator and measuring the performance of BPF. ZX gave some important suggestions for the design of the filter. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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