Quad-Band Bandpass Filter Using Quad-Mode Stub-loaded Resonators

Haiwen Liu, Xiaomei Wang, Yan Wang, Shen Li, Yulong Zhao, and Xuehui Guan

Compact multi-band bandpass filters using quad-mode stub-loaded resonators are proposed in this letter. Firstly, a novel approach about the mode-splitting characteristics of the quadruple-mode resonator is investigated, which can provide dual-band behavior. Secondly, a quad-band filter is proposed and designed by cascading two quadruple-mode resonators; the upper one operates at 1.8/2.4 GHz (GSM- and WiMax-band) and the lower one at 1.57/2.1 GHz (GPS- and WCDMA-band). Finally, the proposed filters have been fabricated. Respectable agreement between simulation and measurement verifies the validity of this design methodology.

Keywords: Quad-band, bandpass filter, BPF, quad-mode, stub-loaded resonators.

I. Introduction

Multi-band bandpass filters (BPFs) have attracted much attention due to their wireless communication applications, such as in wireless local area networks (WLANs), Worldwide Interoperability for Microwave Access (WiMAX), and Wideband Code-Division Multiple Access (WCDMA). The dual-mode BPFs, based on DWG resonators and hexagonal resonators [1], have been presented before, but they can not meet the requirements of multiple passbands at the same time. To meet various application requirements, many methods have been proposed for multi-band BPFs. In general, the reported quad-band BPF design methods can be classified into three typical categories. The first category is to introduce transmission zeroes inside passbands of the dual-band BPF to split both passbands to obtain four frequency responses [2]. The second category is to cascade two or more types of BPF in parallel to form a quad-band filter [3]. The third category is based on the quad-mode resonator [4]. Among these design methods, the third method is simple and only uses a single type of resonator. But, the number of resonators required for a given filter degree is minimum. Hence, the quad-band BPF (based on the quad-mode resonators), which results in a compact configuration with a high degree of design freedom is worthy of study.

In this letter, a microstrip quad-mode stub-loaded resonator is used to design multi-band BPFs. A novel approach to the mode-splitting characteristics of the quadruple-mode resonator is investigated. Note that the dual- or quad-band passbands of the proposed filter can be tuned independently with a high degree of design freedom. Based on this theory, a compact quad-band filter is designed to provide experimental verification and theoretical prediction.

II. Analysis of Quad-Mode Resonator

Figure 1 illustrates the proposed quad-mode resonator from [5], which was originally used for a single wideband filter design. In our work, a novel approach about the mode-splitting characteristics of the quadruple-mode resonator is investigated, which can provide multi-band behaviors. The proposed quad-mode resonator is formed by adding two identical open-circuited stubs, denoted by length L_2 and width w_2, at both sides and another open-circuited stub (L_1, w_1) at the center plane along a high impedance microstrip line with length of ($2L_0$ + $2s$) and width of w_0. Because the proposed quad-mode resonator is a symmetrical structure its operating mechanism can be justified by an even/odd mode analysis [6].

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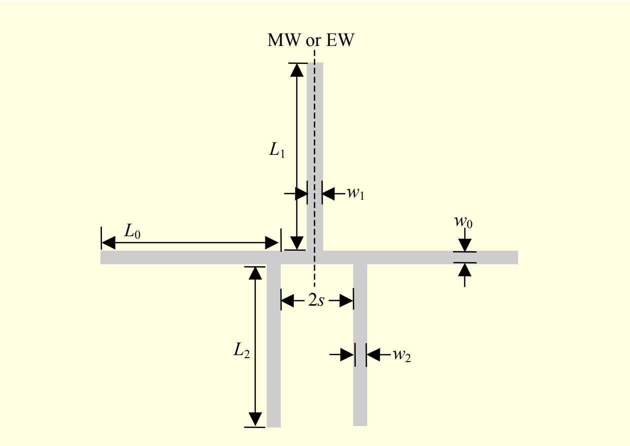

Fig. 1. Structure of proposed quad-mode stub-loaded resonator.

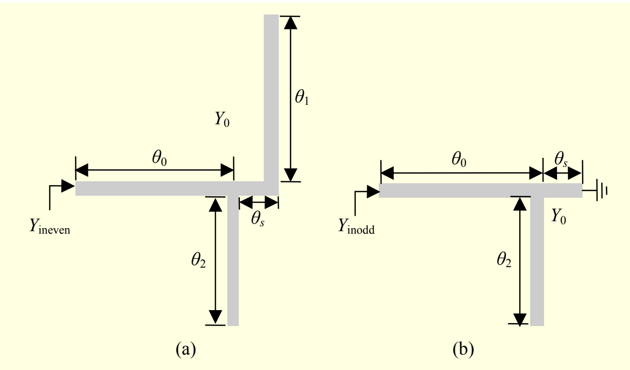

Fig. 2. Equivalent circuits: (a) even mode and (b) odd mode.

Under an even-mode excitation, its equivalent circuit is shown in Fig. 2(a). The characteristic admittance of the widths w_0, $w_1/2$, and w_2 is Y_0, and the electrical lengths of the four sections with lengths L_0, L_1, L_2 and s are θ_0, θ_1, θ_2, and θ_s, respectively. The input admittance Y_{ineven} of the even-mode equivalent circuit is expressed as

$$Y_{\text{ineven}} = jY_0 \frac{\tan\theta_0 + \tan\theta_2 + \tan(\theta_1 + \theta_s)}{1 - \tan\theta_0[\tan\theta_2 + \tan(\theta_1 + \theta_s)]}. \tag{1}$$

Similarly, the input admittance Y_{inodd} of the odd-mode equivalent circuit in Fig. 2(b) can be expressed as

$$Y_{\text{inodd}} = jY_0 \frac{\tan\theta_0 + \tan\theta_2 - \cot\theta_s}{1 - \tan\theta_0\left(\tan\theta_2 - \cot\theta_s\right)}. \tag{2}$$

From the resonant conditions $Y_{\text{ineven}} = 0$ and $Y_{\text{inodd}} = 0$, the resonant frequencies can be expressed as

$$\tan\theta_0 + \tan\theta_2 + \tan(\theta_1 + \theta_s) = 0, \tag{3}$$

$$\tan\theta_0 + \tan\theta_2 - \cot\theta_s = 0. \tag{4}$$

According to (3) and (4), it is found that the even-mode resonant frequencies are determined by L_0, L_1, L_2, and L_s, whereas the odd-mode resonant frequencies can be controlled by tuning L_0, L_2, and L_s. That is to say, the resonator can provide multi-band performances using the above-mentioned physical parameters; thus, it offers a high degree of design freedom.

For demonstration purposes, the resonant characteristics of a resonator with different L_1 and different L_2 are shown in Figs. 3(a) and 3(b), respectively.

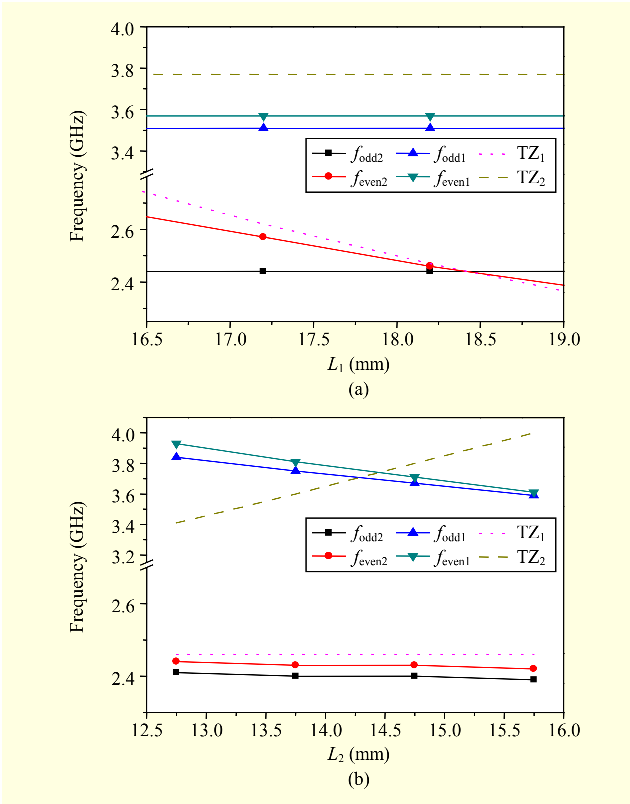

Fig. 3. Resonant characteristics of a resonator: (a) different L_1 and (b) different L_2.

In Fig. 3(a), by changing the length L_1 of the center-loaded open stub, the resonator frequency f_{even2} can be shifted within a wide range, whereas the other resonator frequencies f_{even1}, f_{odd1}, and f_{odd2} remain stationary. In addition, the location of one transmission zero, TZ_1, clearly moves toward the lower frequency as L_2 increases.

Figure 3(b) shows the resonant characteristics of the proposed resonator for cases of different length L_2. It is observed that the stub length L_2 brings the resonator frequencies f_{odd1} and f_{even1} closer together, whereas the other two resonant frequencies remain almost unchanged. At the same time, the location of TZ_1 is almost unchanged, and the location of TZ_2 is greatly improved. Thus, the resonant frequency f_{even2} and transmission zero TZ_1 can be allocated in a desired location by reasonably choosing the length L_1 and the resonant frequencies f_{even1} and f_{odd1}. The transmission zero TZ_2 can be

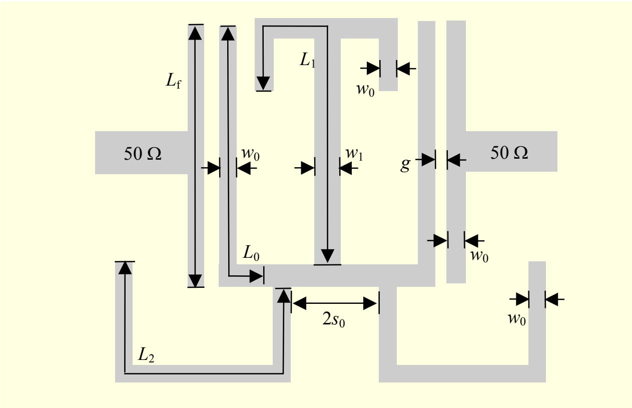

Fig. 4. Configuration of designed dual-band BPF.

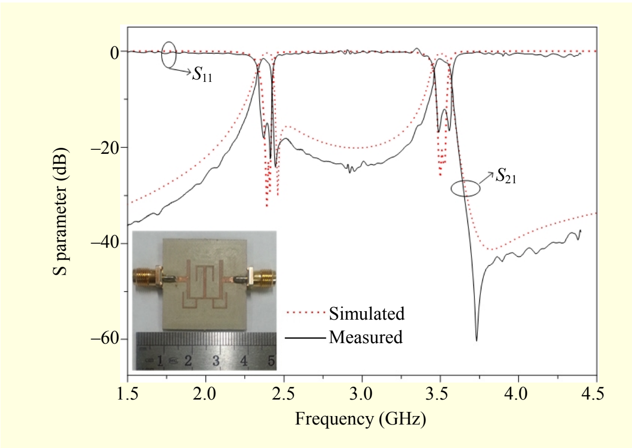

Fig. 5. Results of designed dual-band BPF and its photograph.

adjusted within the desired passband by changing the parameter L_2. Furthermore, the bandwidths of the first passband can be adjusted by the length L_1, while the bandwidth of the second passband can be changed by adjusting the length L_2; therefore, a dual-band BPF is generated with the help of the quad-mode resonator.

Based on the above discussion, we designed and implemented a compact dual-band filter using the proposed quad-mode resonator shown in Fig. 4. The proposed filter consists of a quad-mode resonator and a pair of 50 Ω T-shape feed lines. It is meandered to realize compactness of the structure. The coupled-line structure is employed to design the input/output coupling structure, which enhances degrees of freedom. The filter was designed, analyzed, and simulated by a commercial simulator — namely, Sonnet — and fabricated on a substrate with a relative dielectric constant of 3.5 and a thickness of 0.76 mm. The dimensions of the filter are optimized as follows: L_f = 10.7, L_0 = 14.75, L_1 = 18.3, L_2 = 14.05, w_0 = 0.5, w_1 = 0.6, g = 0.2, and s_0 = 2.1 (all in millimeters).

Simulated and measured frequency responses of the designed dual-band BPF are shown in Fig. 5. The two passbands of the filter are centered at 2.4 GHz (WLAN-band) and 3.5 GHz (WiMax-band) with fractional bandwidths of 3.8% and 3.1%, respectively. Maximum insertion loss within the passband is less than 1.0 dB, which would be mainly attributed to the conductor and dielectric loss. The configuration also displays extra transmission zeroes at 2.46 GHz and 3.83 GHz, which are caused by virtual ground due to stubs L_1 and L_2.

III. Quad-Band BPF Design and Results

Following the above analysis, a quad-band bandpass response can be achieved by cascading two quad-mode stub-loaded resonators in parallel to form a quad-band performance. As shown in Fig. 6, the I/O feed lines are located between the upper quad-mode resonator (in pink) and the lower quad-mode resonator (in blue) so that the resonant frequencies of the two resonators can be adjusted independently. That is, there is no mutual coupling between the two resonators. And the coupling between the external circuit and the quad-mode resonators (external Q) can be characterized by the equation in [7]. To reduce the overall circuit area, the quad-mode resonators are modified with inward-folded and outward-folded curve stubs, respectively.

The schematic view of the proposed quad-band BPF is shown in Fig. 6. The upper and lower quad-mode stub-loaded resonators are chosen and designed to operate at 1.8/2.4 GHz

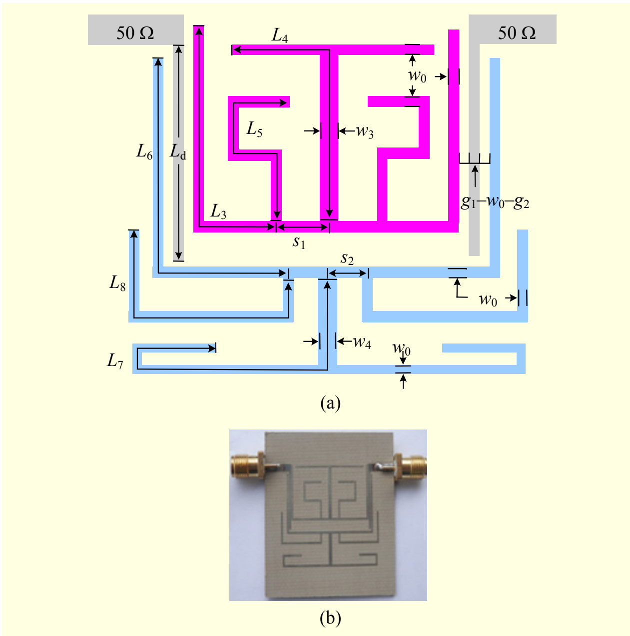

Fig. 6. Proposed quad-band BPF: (a) configuration and (b) photograph.

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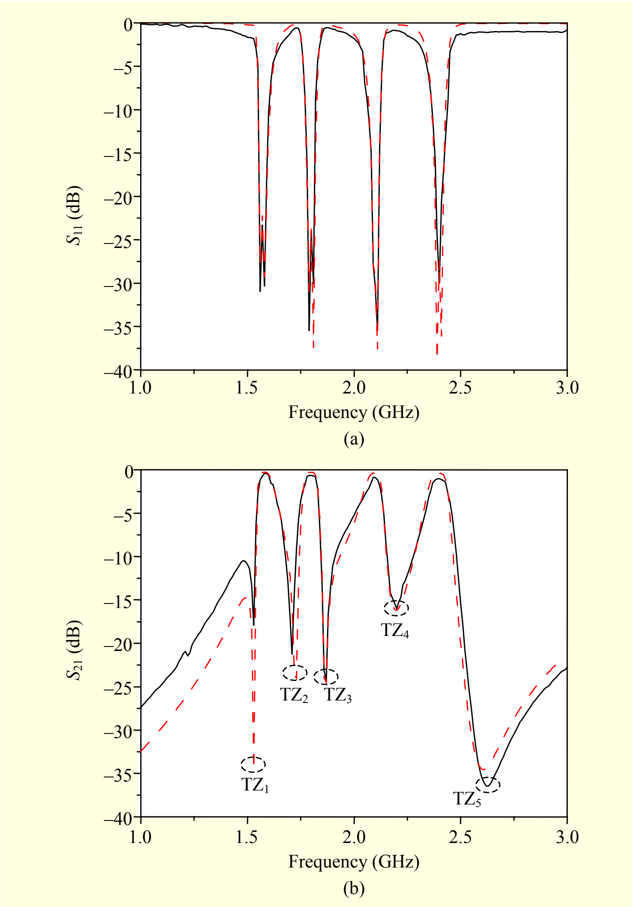

Fig. 7. Simulated (red dash line) and measured (black solid line) frequency responses of fabricated filter: (a) S_{11} and (b) S_{21}.

and 1.57/2.1 GHz, respectively. According to the design equations (3) and (4) in section II, the physical dimensions of the filter are chosen and optimized as follows: L_d = 14.15, L_3 = 21.75, L_4 = 22.4, L_5 = 19.5, L_6 = 24.15, L_7 = 29.7, L_8 = 21.25, w_0 = 0.5, w_3 = w_4 =1, s_1 = s_2 = 2.55, and g_1 = g_2 = 0.2 (all in millimeters). The proposed filter is fabricated on the same substrate as mentioned above. The proposed fabricated filter occupies only about 28.5 mm × 24.75 mm (about 0.15 λ_0 × 0.13 λ_0, where λ_0 is the guided wavelength in the free space at the central frequency of the first passband).

A comparison of the simulated and measured frequency responses are shown in Fig. 7. Results show that the designed quad-band filter is centered at 1.57 GHz (GPS-band), 1.8 GHz (GSM-band), 2.1 GHz (WCDMA-band) and 2.4 GHz (WiMax-band) with a 3 dB fractional bandwidth of 5.9%, 4.4%, 4.4%, and 4.6%, respectively. The measured maximum insertion loss among the passbands is less than 0.9 dB. Note that the upper quad-mode resonator produces four resonant modes at 1.79 GHz, 1.81 GHz, 2.39 GHz, and 2.41 GHz and that the lower one exhibits four resonant modes at 1.56 GHz, 1.585 GHz, 2.095 GHz, and 2.11 GHz. In addition, the transmission zero TZ_2 at 1.73 GHz, generated by the transversal interference between the two signal paths from one port to another, is shown in Fig. 7. The four transmission zeroes (TZ_1, TZ_3, TZ_4, and TZ_5 at 1.53 GHz, 1.86 GHz, 2.2 GHz, and 2.61 GHz, respectively) are due to open stubs, explained in section II, which greatly improve the selectivity and stopband suppression. Respectable agreement between the simulated and measured results demonstrates the proposed structure.

IV. Conclusion

A compact quad-band BPF using two quad-mode resonators was introduced in this letter. With the help of even- and odd-mode analysis, the synthesis method was developed to explain quad-mode characteristics that can provide dual-band behavior with a high degree of design freedom. Furthermore, a quad-band BPF implemented by cascading two quad-mode resonators was designed and fabricated, from which several resonant modes and transmission zeroes were created to greatly improve selectivity and stopband suppression. For a system integrating multi-band applications, this design could be applied to filter signals among multiple commercial bands.

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