Design of Compact Quad-Band Bandpass Filter Using Crossed Resonators

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Abstract

Crossed resonators are used as quad-mode resonators to design the quad-band bandpass filter in this paper. Due to the quad-mode resonator, compact size is achieved. Four passband frequencies all have wide tunable range. The design procedure and design curves are given. To illustrate the concept, one quad-band filter is designed, fabricated and measured. The four passbands of the proposed filter locate at 1.575, 2.4, 3.5, 5.75 GHz, respectively, with insertion loss less than 2 dB..

1. Introduction

Bandpass filters are important devices in the modern communication industry. Efficient in reducing circuit size and cost, quad-band bandpass filters are highly desired in multi-standard communication systems. Various structures of quad-band bandpass filter were proposed. There are mainly two design methods; one is using two sets of dual-mode resonators [1]-[5], and the other is using quad-mode resonator [6]-[8]. In [1]-[2], the authors used two sets of stepped-impedance resonators (SIRs) to generate four passbands. In [3], asymmetric SIRs were utilized in the design. The filter in [4] consists of two set of stub-loaded resonators (SLRs). In Ref. 5, centrally SIRs and SLRs were both utilized in the design. On the other hand, in [6][7], SLRs were utilized as quad-mode resonators to obtain four passbands. In [8], a two-side open-circuited SIR with short-circuited stubs loaded was proposed as a quad-mode resonator.

Using two sets of dual-mode resonators, resonance frequencies can be conveniently adjusted, but results in large size. By using quad-mode resonators, circuit size can be efficiently reduced. Lack of design freedom, the frequency adjustable ranges in the previous works [6]-[8] were limited, and the bandwidths of four passbands were not easy to control.

Crossed resonators have been used in tri-band bandpass filter design [9]. In this paper, we use crossed resonators as novel quad-mode resonators. This filter, firstly, has a compact size. Secondly, a wide frequency adjustable range is achieved. Thirdly, the external quality factor, the coupling coefficient and the frequencies can be conveniently adjusted.

2. Resonance and Coupling Properties

Figure 1 shows the proposed resonator. The open-circuited stub (Z_2, θ_2) and the short-circuit stub (Z_3, θ_3) are shunted at midpoint of the transmission line. As a symmetric structure, odd- and even-mode analysis can be utilized to obtain the resonance conditions.

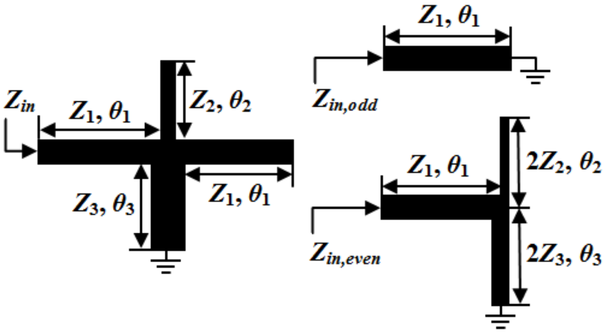

Fig. 1 Layout of the crossed resonator and the odd-/even-mode equivalent circuit.

The input impedance for odd-mode and even-mode can be expressed as

$$Z_{in,odd} = jZ_1 \tan\theta_1 \qquad \text{(odd-mode)} \tag{1}$$

$$Z_{in,even} = Z_1 \frac{1 + jZ_1 Y_L \tan\theta_1}{Z_1 Y_L + j\tan\theta_1} \qquad \text{(even-mode)} \tag{2}$$

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where

$$Y_L = j\left(\frac{\tan\theta_2}{2Z_2} - \frac{1}{2Z_3\tan\theta_3}\right) \tag{3}$$

From (1), the first odd-mode resonance frequency f_{odd1} occurs when θ_1 is quarter-wavelength. The second odd-mode resonant frequency f_{odd2} is $3f_{odd1}$. The even-mode resonance condition is determined by the following equation.

$$2Z_2Z_3\tan\theta_1 + Z_1Z_3\tan\theta_2 - Z_1Z_2\cot\theta_3 = 0 \tag{4}$$

Solutions to (4) correspond to the even-mode resonance frequencies of the crossed resonator. The first three resonant frequencies of the even-mode are denoted as f_{even1}, f_{even2}, f_{even3}. It can be observed from (1) that the open-circuited and short-circuited stubs are irrelevant to the odd-mode frequencies.

To analyze the resonant mode of the crossed resonator, the length and impedance and ratios are defined as:

$$k_1 = \frac{\theta_2}{\theta_1},\ k_2 = \frac{\theta_3}{\theta_1},\ k_3 = \frac{Z_2}{Z_1},\ k_4 = \frac{Z_3}{Z_1} \tag{5}$$

The resonant frequencies of the crossed resonator under different parameters are depicted in Fig. 2. It's shown that under most values of k_2 and k_4, the possible values of f_{even2}/f_{odd1} range from 1.25 to 1.36, which can be approximately viewed as constant.

The filter can be designed according to the following procedure. Firstly, as a quarter-wavelength resonator, θ_1 can be determined by f_{odd1}. Secondly, k_1 and k_3 can be found in Fig. 2(b) using the given f_{even2}. Since k_2 and k_4 barely affect f_{even2}, $k_2 = 0.41$ and $k_4 = 0.63$ are arbitrarily chosen in Fig. 2(b). It can also be observed that k_1 and k_3 have less effect on f_{even2}. Finally, substituting the acquired parameters into equation (4) and solve it can obtain k_2 and k_4. Fig. 2(c) shows the solutions when $k_1 = 0.7$ and $k_3 = 1.65$.

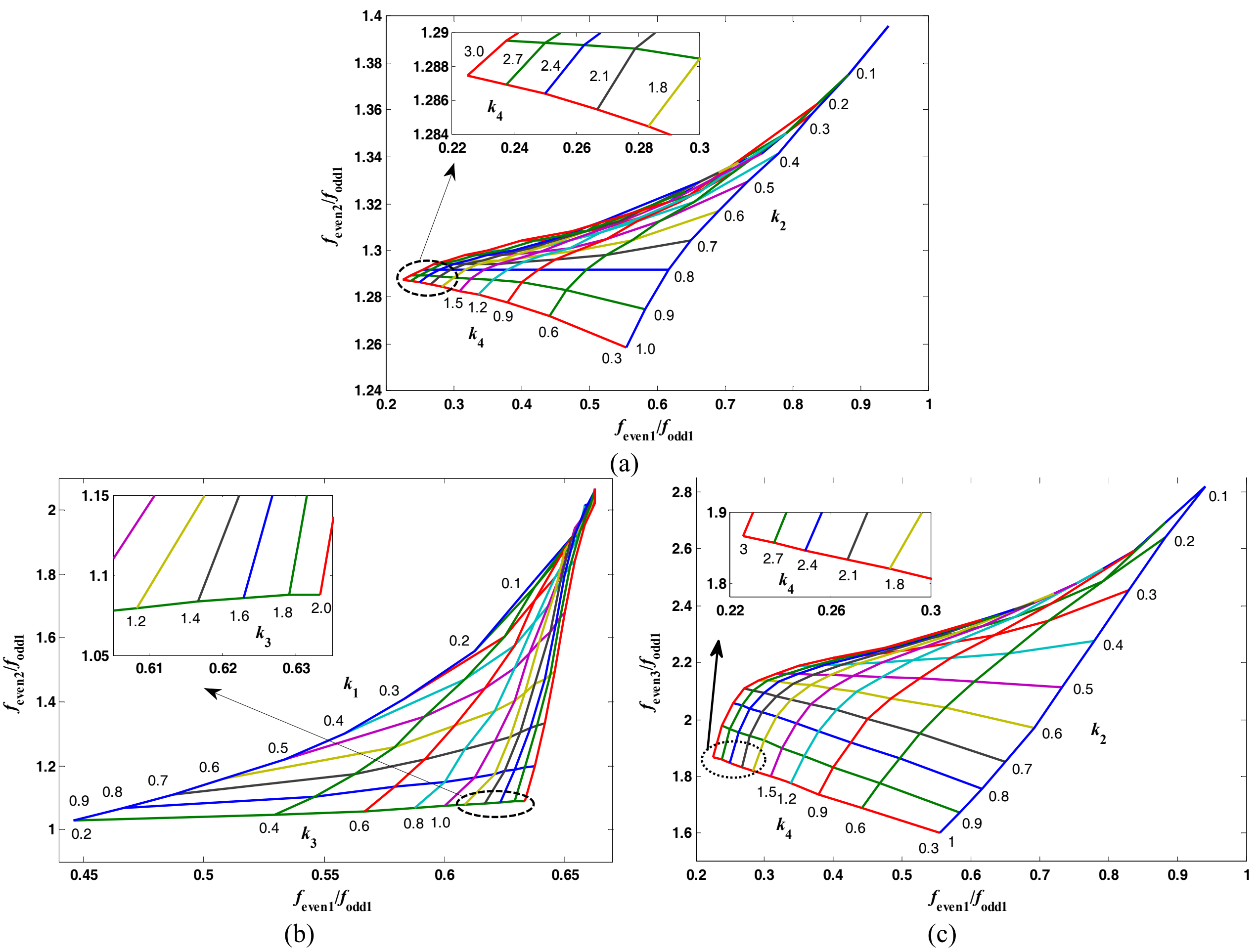


Fig. 2. (a) Frequency ratio values under different parameters. (a) f_{even2}/f_{odd1} and f_{even1}/f_{odd1} under k_2 and k_4. (b) f_{even2}/f_{odd1} and f_{even1}/f_{odd1} under k_1 and k_3. (c) f_{even3}/f_{odd1} and f_{even1}/f_{odd1} under k_2 and k_4.

Figure 3 shows the layout of the quad-band filter using pseudo-interdigital coupling structure. The filter is designed on a substrate with dielectric constant ε_r=2.55, loss tangent δ=0.0029, and thickness h=0.8 mm for validation. The passband frequencies are selected to be 1.575, 2.4, 3.5 and 5.75 GHz. Q_{e1}, Q_{e2}, Q_{e3} and Q_{e4} denote the external quality factors of the first, second, third and fourth passbands respectively. Values of external quality factors under different L_1, L_2, and L_3 are shown in Fig. 4. More design data can be acquired by adjusting W_3, W_4.

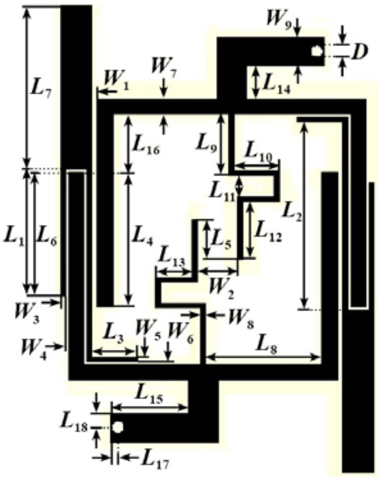


Fig. 3. Layout of the quad-band bandpass filter.

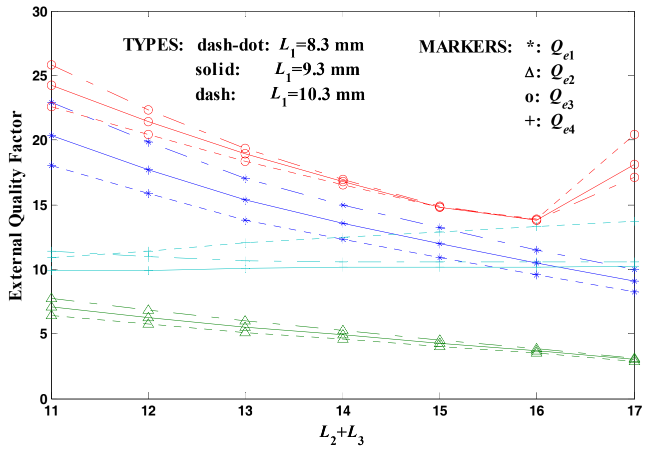
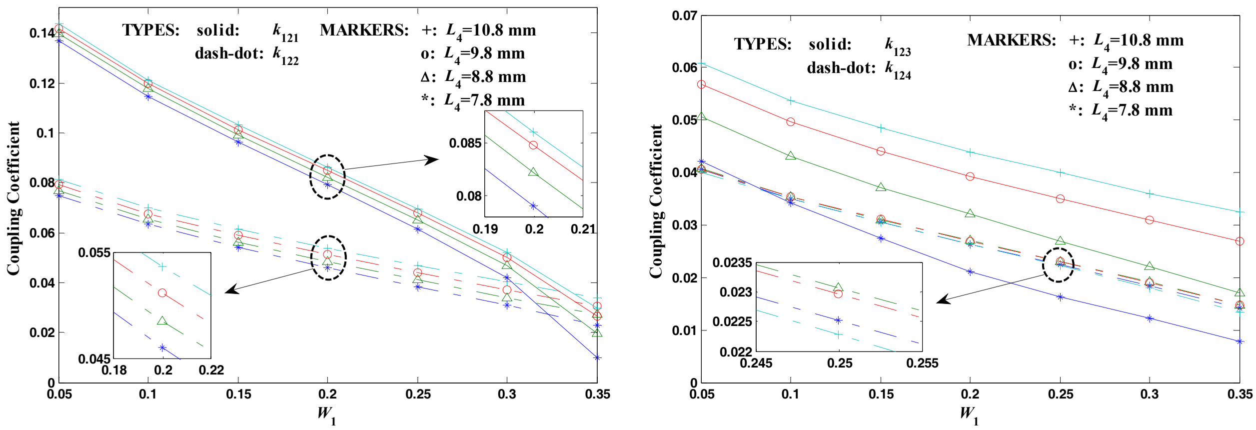


Fig. 4. External quality factors under different L_1, L_2, and L_3.

L_4, W_1 and L_5, W_2 affect the coupling coefficients. k_{121}, k_{122}, k_{123} and k_{124} denote the coupling coefficients of the first, second, third and fourth passbands respectively. As Fig. 2 illuminates, L_4, W_1 affect all the k_{121}, k_{122}, k_{123} and k_{124} (as shown in Fig. 5), and L_5, W_2 mainly affect k_{123} and k_{124} (as shown in Fig. 6).

To meet the bandwidths requirement, designer can adjust L_4 and W_1 to obtain proper k_{121} and k_{122}. Then adjust L_5 and W_2 to obtain proper k_{123} and k_{124} while k_{121} and k_{122} will keep fixed.



(a) (b)

Fig. 5. Coupling coefficients under different L_4 and W_1. (a) k_{121} and k_{122}. (b) k_{123} and k_{124}.

3. Experimental results

A filter is fabricated on a substrate with ε_r=2.55 and h=0.8 mm for validation. The passband frequencies are selected to be 1.575, 2.4, 3.5 and 5.75 GHz. The optimize parameters in Figure 4 are: L_1=8.3 mm, L_2=12.3 mm, L_3=3 mm, L_4=8.8 mm, L_5=2.6 mm, L_6=8.1 mm, L_7=10.65 mm, L_8=7.6 mm, L_9=4 mm, L_{10}=2.95 mm, L_{11}=1.4 mm, L_{12}=3.8 mm, L_{13}=2.4 mm, L_{14}=2.15 mm, L_{15}=5.1 mm, L_{16}=3.8 mm, L_{17}=0.5 mm, L_{18}=0.95 mm, W_1=0.35 mm, W_2=2.65 mm, W_3=W_5=W_8=0.3 mm, W_4=W_6=0.2 mm, W_7=1 mm, W_9=1.9 mm, D=0.8 mm. Figure 7 shows the simulated and measured results. The measured minimum insertion losses for the four passbands are 0.97, 0.63, 1.85 and 1.55 dB, while the return losses are 20, 21, 18 and 18 dB, respectively. The measured 3 dB bandwidths are found to be 1.54 to 1.68 GHz, 2.29 to 2.65 GHz, 3.45 to 3.53 GHz, 5.66 to 5.91 GHz, respectively. The total size is 20.35 mm × 26.5 mm, which is only approximate $0.156\lambda_g$ by $0.203\lambda_g$, where λ_g is the guided wavelength on the substrate at the first passband frequency.

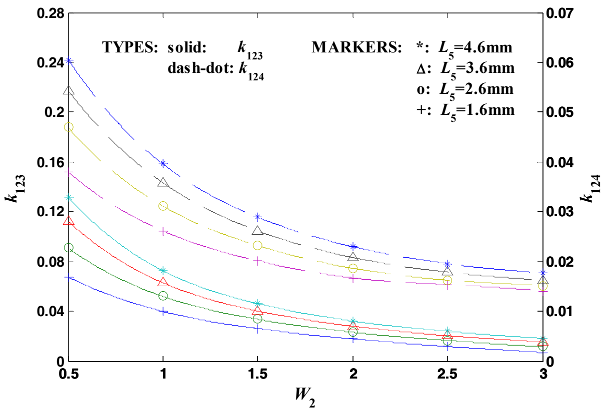


Fig. 6. Coupling coefficients under different L_5 and W_2.

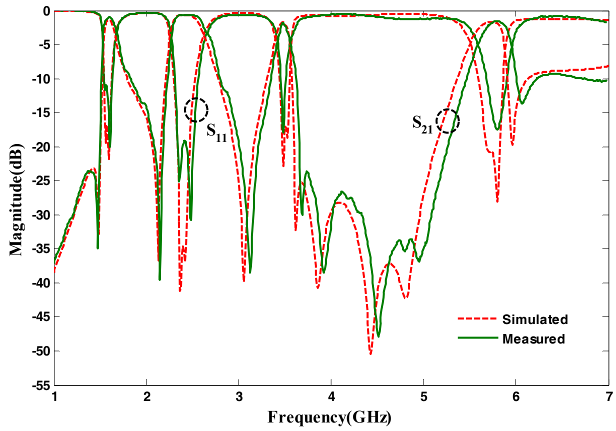


Fig. 7. Simulated and measured results of the filter.

4. Conclusion

This paper present a quad-band bandpass filter based on crossed resonator. The filter has a compact size and a wide frequency adjustable range. Besides, the frequencies and bandwidths can be easily tuned. We believe that this filter can have an extensive use in modern wireless communication systems.

5. Acknowledgments

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6. References

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