Miniaturized Tri-band Bandpass Filter Using Modified Triple-mode Resonators With Multiple Transmission Zeros

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Abstract—**A compact microstrip tri-band bandpass filter (BPF) using the modified triple-mode resonators to reduce the size is presented. The center frequencies of the first and the third passband can be conveniently controlled by tuning the dimensions of the short stub and square ring, whereas the second passband frequency is fixed. Moreover, the filter has been implemented with multi-transmission zeros to improve the selectivity and upper-stopband performance. To verify the proposed approach, a prototype of tri-band BPF centred at 2.4/3.5/5.2 GHz for WLAN/WiMAX applications is designed and fabricated for demonstration, indicating good agreement with the theoretical expectation.**

***Index Terms*—Tri-band bandpass filter, triple-mode resonator, fractional bandwidth.**

I. INTRODUCTION

The demands of multiple separated frequency bands for filters become more and more important in wireless communication applications. Low cost and easy integration are the key issues in microwave circuit. To meet these requirements, the new wireless LAN standards have been developed. The development of transmission standards brought the rapid growth of front-end RF devices and circuits. The most important issue is the multi-band operation ability. In the wireless communication system, filters with small size, low cost, easy fabrication, higher performance, and multi-frequencies have attracted much interest. Usually, dual and tri-band filters can be realized with the stepped-impedance resonators because of their multiband behavior [1]–[4]. In [1-2], the dual and tri-band filter was realized by cascaded multiband resonators. In [3], the tri-band bandpass filter was designed using a combined quarter-wavelength resonator. A tri-section stepped-impedance resonator [4] could also be used to design the tri-band filter; by properly determining the impedance ratio, three passbands at any desired frequencies can be obtained. However, the resonance frequencies of the stepped-impedance resonator are dependent, complicating the filter design.

Another widely used method to design tri-band filters is the stub loaded resonator (SLR) [5-7]. The three desired frequencies can be conveniently controlled by tuning the lengths of half-wavelength resonator, open/short-stub [5] and [6], open stub loaded and quarter-wavelength resonator [7]. Recently, a new method to design tri-band bandpass filters based on square ring short stub loaded resonators has been presented [8]. The square ring loaded resonator (SRLR) has been successfully proven in the design of a tri-band filter [9]. The SRLR can generate a tri-band response by tuning its geometric parameters and realize the high-order tri-band. However, for these structure difficult tuning of center frequencies and the selectivity needs to be improved. By employing dual-mode resonators, i.e., crossed open-short stub loaded resonators and tri-section stepped impedance resonators, the tri-band bandpass filter with controllabed bandwidths has been presented [10]. The disadvantage of this method is that the relatively complex structure can make the design difficult.

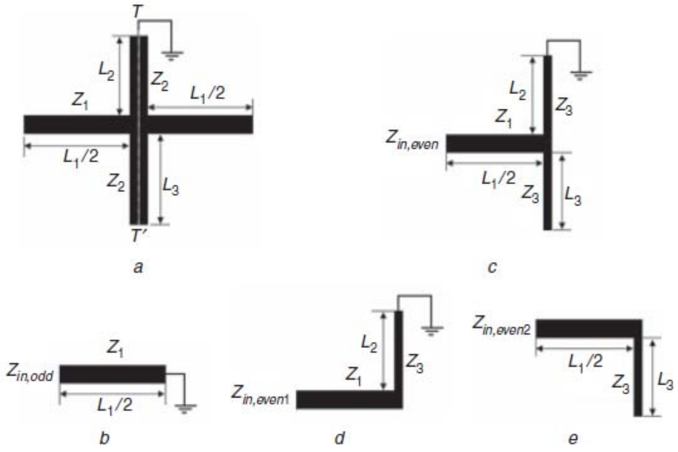


Fig. 1 Conventional crossed open and short stub loaded resonator (a) Crossed open and short stub resonator. (b) Odd-mode equivalent circuit. (c) Even-mode equivalent circuit. (d) Part I of even-mode equivalent circuit. (e) Part II of even-mode equivalent circuit.

In this letter, the modified triple-mode resonators for designing a miniaturised tri-band bandpass filter is proposed. It is found that the first and third resonant frequencies can be easily controlled by changing the dimensions of the short stub and square ring, whereas the second passband frequency is fixed. Moreover, the filter has been implemented with multiple transmission zeros, resulting in high selectivity.

II. ANALYSIS AND DESIGN OF PROPOSED FILTER

Fig. 1(a) shows the layout of crossed open and short stub loaded resonators consists of a common microstrip half-wavelength resonator, an open stub and a short stub loaded. For odd-mode and even-mode excitation, the equivalent circuit are shown in Figs. 1(b) and (c). To get a new resonator with similar characteristics, the open stub replaced by square ring as shown in Fig. 2(c) and (d).

The layout of proposed tri-band filter is shown in Fig. 3. In addition, to improve the selectivity of the filter, the skew-symmetrical 0^0 feeding structure [11] is introduced to realize input and output ports of the filter. Which could create extra transmission zeros at the adjacent three passbands, sharp passband skirts of the filter have been observed. This coupling structure makes a very compact circuit. The filter is constructed on a substrate with relative permittivity of 4.4, thickness of $h = 0.8$ mm and loss tangent of 0.0009.

A. Characteristic of the Crossed Stub Loaded Resonators

In addition, Z_1 and Z_2 are the characteristic impedance of the half-wavelength line and the stub, and L_1, L_2 and L_3 denote the lengths of half-wavelength resonator, short stub and open stub, Y denotes characteristic admittance of the central resonator and the stubs, and θ, θ_{s1} and θ_{s2} denote the electrical lengths of half-wavelength resonator, short-stub and open-stub, respectively. The resonator is symmetrical and thus odd- and even-mode analysis can be used for characterization. The input admittance of the crossed resonator is

$$Y_{in} = jY \frac{2\tan\theta + \tan\theta_{s2} - \cot\theta_{s1}}{1 - \tan\theta(\tan\theta + \tan\theta_{s2} - \cot\theta_{s1})} \quad (1)$$

Firstly, a special resonance condition will be considered. When $\theta = 90^0$

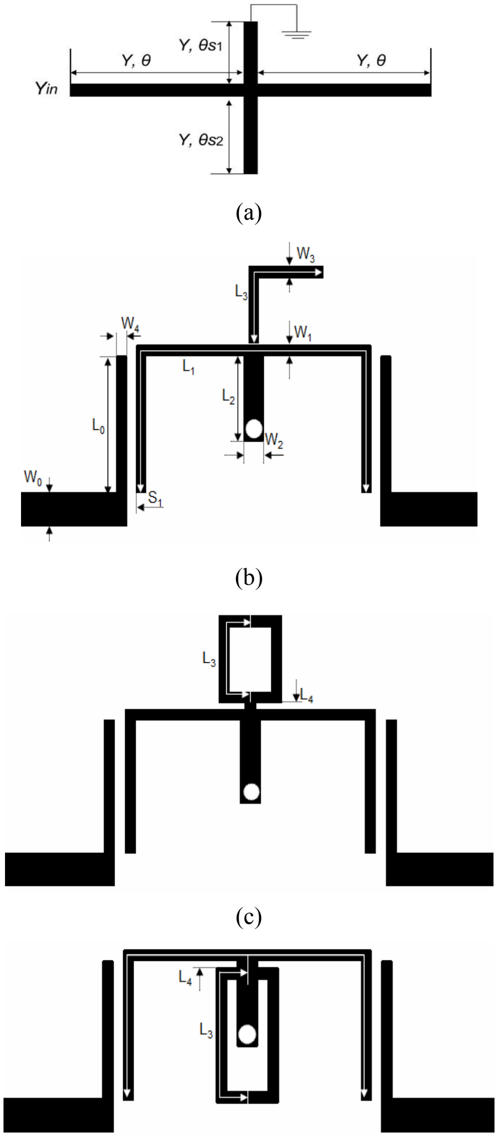
$$Y_{in} = \lim_{\theta \to 90^0} jY \frac{2 + (\tan\theta_{s2} - \cot\theta_{s1})/\tan\theta}{1/\tan\theta - (\tan\theta + \tan\theta_{s2} - \cot\theta_{s1})} = 0 \quad (2)$$

Actually, this special frequency is the second resonant frequency f_2 of the crossed resonator. The first resonant frequency f_1 and third resonant frequency f_3 can be obtained from the condition $Y_{in} = 0$. From (1)-(2), the first and the third resonant conditions can be expressed as

$$\begin{cases} 2\tan(k_1 * 90^0) + \tan(k_1 * \theta_{s2}) - \cot(k_1 * \theta_{s1}) = 0 \\ 2\tan(k_2 * 90^0) + \tan(k_2 * \theta_{s2}) - \cot(k_2 * \theta_{s1}) = 0 \end{cases} \quad (3)$$

Where $k_1 = f_1/f_2$ and $k_2 = f_3/f_2$, according to (3), we could obtain the frequency ratio values (k_1, k_2) from the given stub lengths θ_{s1} and θ_{s2}. Similarly, the stub lengths can be deduced from the given frequency ratios according to (3).

As analyzed in [6], by tuning the short stub length from 1^0 to 80^0, k_1 varies from 0.97 to 0.35. While tuning the open stub length from 10^0 to 90^0 , k_2 varies from 2.8 to 1.01. To sum up, the first three resonant frequencies can be controlled effectively by tuning the physical parameters of the crossed resonator.



(a)

(b)

(c)

(d)

Fig. 2 (a) Crossed open and short stub resonator. (b) Conventional filter using crossed open and short stub resonator_structure1 (W_0 = 1.5mm, W_1 = W_3 = W_4 = 0.5mm, W_2 = 1mm, L_1 = 24.2mm, L_2 = 3.8mm, L_3 = 7.8mm, S_1 = 0.5mm). (c) The proposed filter using modified resonator_structure2 (L_3 = 6mm, L_4 = 0.3mm). (d) The proposed filter using modified resonator_structure3 (L_3 = 8mm, L_4 = 0.3mm).

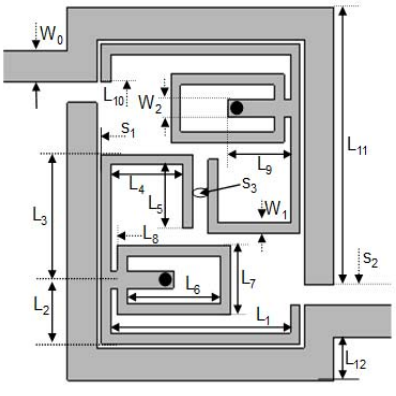


Fig. 3 Layout of the proposed tri-band bandpass filter

As above analysis and discussion in [5], the first odd- and even-mode frequencies of crossed open and short stub loaded resonartor (Fig. 1) can be calculated approximately as follows:

$$f_{odd1} = \frac{c}{2L_1\sqrt{\varepsilon_e}} \tag{4}$$

$$f_{even1} = \frac{c}{2(L_1 + 2L_2)\sqrt{\varepsilon_e}} \tag{5}$$

$$f_{even2} = \frac{c}{(L_1 + 2L_3)\sqrt{\varepsilon_e}} \tag{6}$$

While c is the light speed in free space, ε_e the effective dielectric constant of the substrate.

Equation (4) is based on the special case: $Z_1 = 2Z_2 = Z_3$. From (4)-(6), when $L_2 > 0$ and $2L_3 < L_1$ we could obtain $f_{\text{even1}} < f_{\text{odd1}} < f_{\text{even2}}$. Thus, the first three resonant frequencies of the crossed open and short stub loaded resonartor could be controlled by tuning L_1, L_2 and L_3.

B. Characteristic of the Modified Resonators

The basis structure of a crossed stubs loaded resonator is shown in Fig. 2(a). To reduce the size of filter, to get a new resonator with similar characteristics, the open stub replaced by square ring as shown in Fig. 2(c) and (d). The simulated insertion loss characteristics of different structures under the weak coupling as shown in Fig. 4. To obtain desired center frequencies of three passband at 2.4, 3.5 and 5.2 GHz, the physical length L_3 and L_4 are chosen to be L_3 = 7.8mm with structure 1, L_3 = 6mm, L_4 = 0.3mm with structure 2 and L_3 = 8mm, L_4 = 0.3mm with structure 3, while the other dimensions are fixed. The frequency characteristic of the proposed resonator (Fig. 2(d)) can be fully demonstrated as in Fig. 5, which illustrates the change of the first three resonant frequencies of the filter under the different square ring length L_3 and the short stub length L_2, while the other dimensions are fixed. From Fig. 5(a), it can be seen that by changing the short-stub length L_3, the third passband frequency f_{even2} can be shifted within a wide range, meanwhile, when f_{odd1} and f_{even1} are fixed. In addition, Fig. 5(b) shows the simulated insertion loss of the filter in cases of different length L_2, the first passband f_{even1} can be shifted within a wide range, when f_{even2} and f_{odd1} are fixed. So in the filter design, to obtain desired passband frequencies, f_{odd1} can be determined by adjusting the length of the L_1 then f_{even1} can be controlled simply by tuning the length of short stub L_2, and f_{even2} can be determined by adjusting the length of L_3.

C. Tri-band bandpass filter design

To verify the above-mentioned analysis, a tri-band bandpass filter is designed. The layout of the proposed tri-band filter is shown in Fig. 3. In addition, by using the skew-symmetrical 0^0 feeding structure [11], the filter was implemented with ten transmission zeros. Six transmission zeros near the edges of the three passbands are produced to achieve good selectivity. Meanwhile, good lower and upper stopband is achieved by another transmission zeros. Finally, a compact tri-band BPF with center frequencies of passband at 2.4, 3.5 and 5.2 GHz is designed. After optimization using Ansoft HFSS 10.0, the dimensions for this filter are determined as: W_0 = 1.5mm, W_1 = 0.5mm, W_2 = 0.8mm, L_{11} = 12.95mm, L_1 = 9mm, L_2 = 5.85mm, L_3 = 3mm, L_4 = 3.62mm, L_5 = 2.95mm, L_6 = 4.7mm, L_7 = 3.2mm, L_8 = 0.3mm, L_9 = 3.15mm, L_{10} = 1.3mm, L_{12} = 2mm, S_1 = 0.2mm, S_2 = 0.95mm, S_3 = 0.76mm and via diameter is 0.5mm.

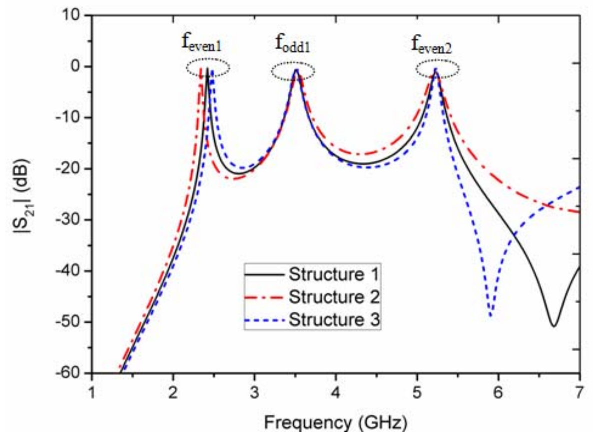
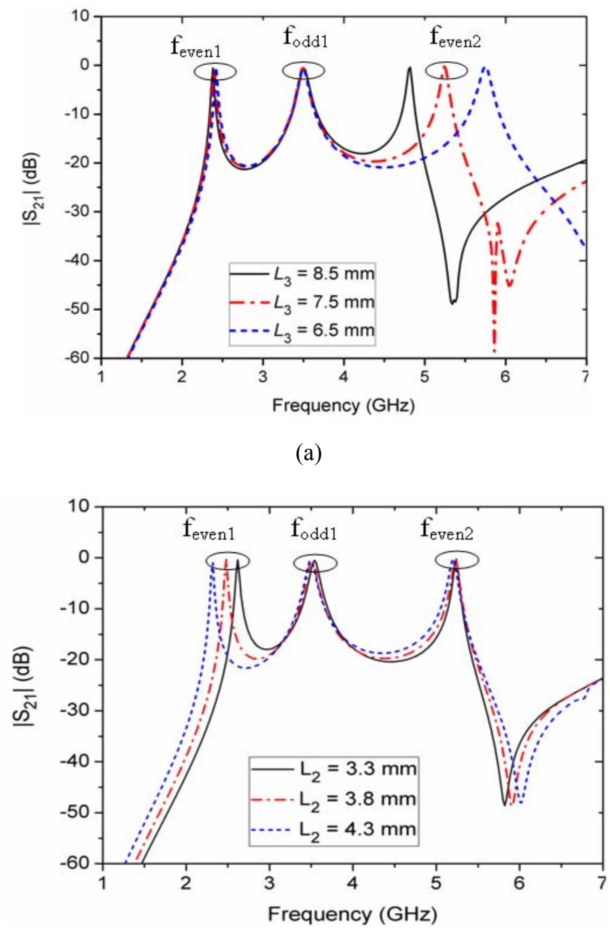


Fig. 4 Simulated frequency response S_{21} parameters of resonator under different structure.



(a)

(b)

Fig. 5 Simulated frequency response S_{21} parameters of resonator under the weak coupling with different (a) L_3 and (b) L_2.

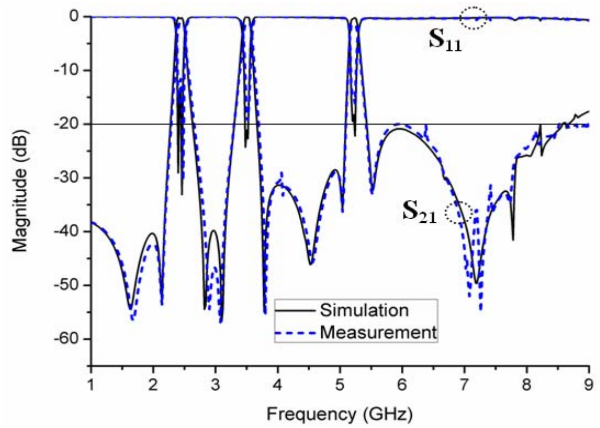


Fig. 6 Measured and simulated results of the tri-band bandpass filter.

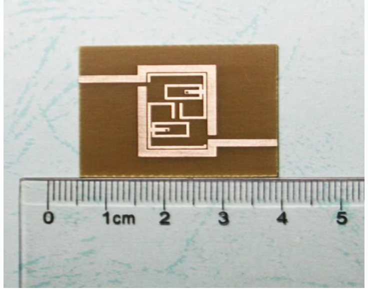


Fig. 7 Photograph of the fabricated tri-band bandpass filter.

III. MEASURED RESULTS AND DISCUSSIONS

A prototype is fabricated to demonstrate the design strategies, the photograph as shown in Fig. 7. The size of the tri-band bandpass filter is 17.4 mm * 13.4 mm (approximately $0.25\lambda_g$ * $0.19\lambda_g$, λ_g is the guided wavelength on the substrate at the center frequency of the first passband), indicating quite compact design. The measurement is accomplished using Agilent 8753ES network analyzer. For comparison, the measured results and simulation results are shown together in Fig. 6. The measured 3-dB fractional bandwidth for the three passbands (2.4, 3.5 and 5.2 GHz) are found to be 142MHz (5.9%), 139MHz (3.9%) and 140MHz (2.7%), respectively. The measured minimum insertion losses including the loss from SMA connectors are 1.1, 1.1, and 1.3 dB, while the return losses are greater than 14, 18 and 16 dB, respectively. Six transmission zeros are generated near the passband edges, resulting in sharp roll-off rejection. Meanwhile, good stopband rejection is achieved by another transmission zeros.

In addition, Table 1 illustrates the comparisons measured results of proposed filter with those previously tri-band BPF structures were also used triple-mode resonator. This presented tri-band BPF is with advantage of compact size and very good selectivity and upper-stopband performance.

IV. CONCLUSION

A novel compact tri-band bandpass filter using the modified triple-mode resonators to reduce the size is presented. The centre frequencies of the three passbands can be conveniently controlled to the desired values and ten transmission zeros are realised at the adjacent three passbands, resulting in very high selectivity. Good agreement is observed between the experiments and theoretical analysis, indicating the validity of the proposed design strategies.

Table 1 Comparisons of Measured Results for Several Tri-band Bandpass Filter Structures

Filter structure	Transmission zero (No.)	Return loss (dB)	Effective circuit size (λ_0)	Upper stopband (-20dB)	Insertion loss (dB)
Ref. [5]	4	<16	0.38×0.15	>4 (2.5f_0)	0.8/0.5/1.2
Ref. [6]	4	18/11/20	0.23×0.19	>6.5 (2.7f_0)	1.4/1.1/1.7
Ref. [7]	3	20/27/22	0.23×0.30	>4.5 (2.5f_0)	0.3/0.3/0.2
Ref. [8]	3	16/15/14	0.20×0.27	>5 (2.7f_0)	1.2/1.1/1.5
Ref. [10]	6	20/20/15	0.20×0.23	>6.5 (2.7f_0)	1.0/1.2/1.6
This work	**10**	**14/18/16**	**0.25×0.19**	**>9 (3.7f_0)**	**1.1/1.1/1.3**

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