A Novel Compact Tri-band Bandpass Filter with Good Selectivity

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Abstract— A novel tri-band bandpass filter (BPF) based on multi-mode resonators is presented. The resonant modes of the resonators can be analyzed by the even- and odd-mode analysis method. The bandwidths of first and second passbands can be independently controlled. Furthermore, five transmission zeros (TZ) are introduced at the adjacent of the passbands in a narrow frequency range to improve the selectivity, resulting sharp skirts. Due to the small multi-mode resonator and tight coupling structure, the overall size of the proposed filter is really compact ($0.19\lambda_0 \times 0.18\lambda_0$). λ_0 is the wavelength of the center frequency of first passband in the substrate. Finally, a prototype to demonstrate the performance of the filter is designed and fabricated. The measured 3-dB fractional bandwidths for the three passbands (2.22, 2.98 and 3.5 GHz) are found to be 8.4%, 2.7% and 6.1%, respectively. The measurement shows good agreement with the simulation.

1. INTRODUCTION

In recent years, the filters, which are an indispensable part of RF front ends, have gained a lot of attention because of the rapid development of modern communication systems, such as wireless local area networks (WLAN), global system for mobile communications (GSM), the third generation (3G), the fourth generation (4G), and worldwide interoperability for microwave access (WiMAX), etc.. Due to the demands on working in multiband, the multiband bandpass filters, especially tri-band filters [1–13], have becoming a popular research issue.

Among these works, there are several typical design methods. One is to utilize multi-order of resonators [1–3]. With independent coupling paths, passbands can be easily controlled. However, the circuit sizes and insertion loss are always large. Another method is to use the hybrid microstrip/defect ground structure (DGS) technology [4, 5]. The dimensions of the device can be abated as the cost of increased design complexity. Also, it is a popular way to use multi-mode resonators to design tri-band BPFs by controlling the modes suitably [6–13]. In these reported works, shorted and open stubs are always connected to the main resonator for more modes and the circuit sizes are small. However, it is still hard to improve the selectivity of the filters, especially in a narrow frequency range.

In this paper, novel multi-mode resonators are introduced for designing tri-band filters. The formation of passbands can be analyzed by even-odd-mode method. Each passband can be controlled by tuning the corresponding parameters. Furthermore, five transmission zeros are generated to improve the sharp skirts of the BPF. The measured performance of the fabricated filter shows good agreement with the proposed theory.

2. FILTER DESIGN

Figure 1 shows the layout of the proposed compact tri-band bandpass filter. The tri-band bandpass filter consists of two multi-mode resonators and the coupling input/output. As the two resonators are only coupled with the in/out ports, the filter structure can be divided into two independent parts with the original parameters.

As depicted in Figure 2, the even-odd-mode analysis method can be adopted here since the Resonators a and b are symmtrical to the centre plane. The resonant conditions of Resonator a

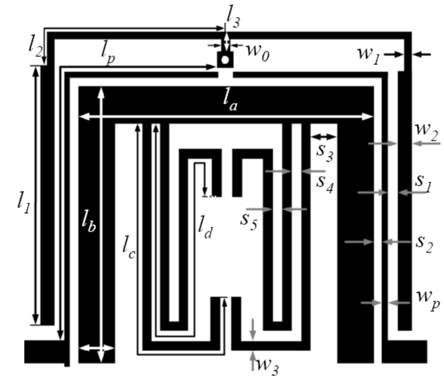

Figure 1: Layout of the poposed compact tri-band bandpass filter.

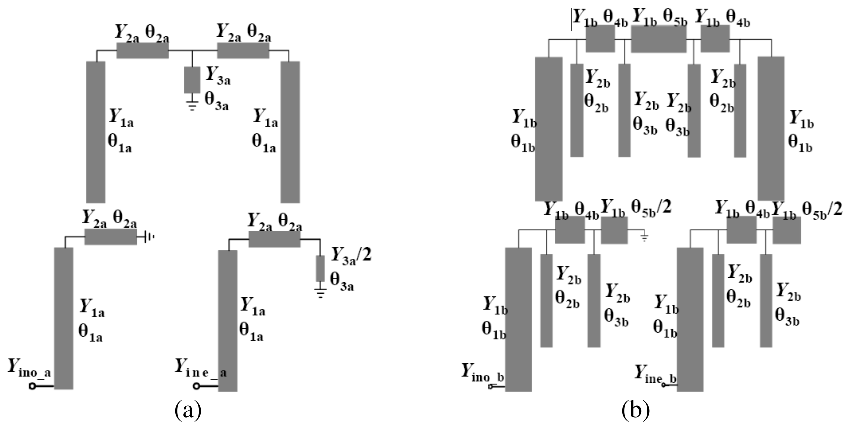

Figure 2: (a) Resonator a and its even- and odd-modes. (b) Resonator b and its even- and odd-modes.

and b can be achieved when $\mathrm{Im}[Y_{ine}] = 0$, $\mathrm{Im}[Y_{ino}] = 0$. The resonant modes can be expressed as

$$Y_{ino\_a} = jY_{1a} \cdot \frac{Y_{1a}\tan\theta_{1a} - Y_{2a}\cot\theta_{2a}}{Y_{1a} + Y_{2a}\cot\theta_{2a}\tan\theta_{1a}} \tag{1}$$

$$Y_{ine\_a} = jY_{1a} \cdot \frac{Y_{2a} \cdot \frac{2Y_{2a}\tan\theta_{2a} - Y_{3a}\cot\theta_{3a}}{2Y_{2a} + Y_{3a}\cot\theta_{3a}\tan\theta_{2a}} + Y_{1a}\tan\theta_{1a}}{Y_{1a} - Y_{2a} \cdot \frac{2Y_{2a}\tan\theta_{2a} - Y_{3a}\cot\theta_{3a}}{2Y_{2a} + Y_{3a}\cot\theta_{3a}\tan\theta_{2a}}\tan\theta_{1a}} \tag{2}$$

$$Y_{ino\_b} = Y_{1b} \cdot \frac{Y_{load1} + jY_{1b}\tan\theta_{1b}}{Y_{1b} + jY_{load1}\tan\theta_{1b}}, \qquad Y_{ine\_b} = Y_{1b} \cdot \frac{Y_{load2} + jY_{1b}\tan\theta_{1b}}{Y_{1b} + jY_{load2}\tan\theta_{1b}} \tag{3}$$

$$Y_{load1} = jY_{1b} \cdot \frac{Y_{2b}\tan\theta_{3b} + Y_{1b}\tan\theta_{4b} - Y_{1b}\cot\frac{\theta_{5b}}{2}}{Y_{1b} - \left(Y_{2b}\tan\theta_{3b} - Y_{1b}\cot\frac{\theta_{5b}}{2}\right)\tan\theta_{4b}} + jY_{2b}\tan\theta_{2b} \tag{4}$$

$$Y_{load2} = jY_{1b} \cdot \frac{Y_{1b}\tan\frac{\theta_{5b}}{2} + Y_{2b}\tan\theta_{3b} + Y_{1b}\tan\theta_{4b}}{Y_{1b} - \left(Y_{1b}\tan\frac{\theta_{5b}}{2} + Y_{2b}\tan\theta_{3b}\right)\tan\theta_{4b}} + jY_{2b}\tan\theta_{2b} \tag{5}$$

It can be seen from formulas (1)–(5) that the resonant modes of Resonator a and b can be tuned by changing lengths of corresponding sections. The calculated results are shown in Figure 3. As depicted in Figure 3(a), the first even and odd mode of Resonantor a are selceted to design the passbands. While increasing the independent even-mode part l_3, the f_{even_a1} decreases and the f_{odd_a1} keep constant. By the same method, the resonant modes of Resonator b can be confirmed, as depicted in Figures 3(b) and (c). There are four resonant frequencies during the range 2.7 GHz–4 GHz. It is notable that all the resonant modes are influenced by l_c except for f_{odd_b1} and f_{odd_b1} decrease while increasing l_d, meanwhile, f_{even_b2} and f_{odd_b2} almost keep constant.

Based on the modes analysis above, to confirm the generation of passbands ulteriorly, Figure 4 shows the filter coupling scheme. The first passband are independently generated by f_{even_a1} and f_{odd_a1} which are based on Resonator a. Meanwhile, the second and third passbands are mainly obtained by Resonator b. Resonant modes f_{odd_b1} and f_{even_b1} *form* the second passband, simultaneously, the third passband is made up by resonant modes f_{odd_2} and f_{even_b2}.

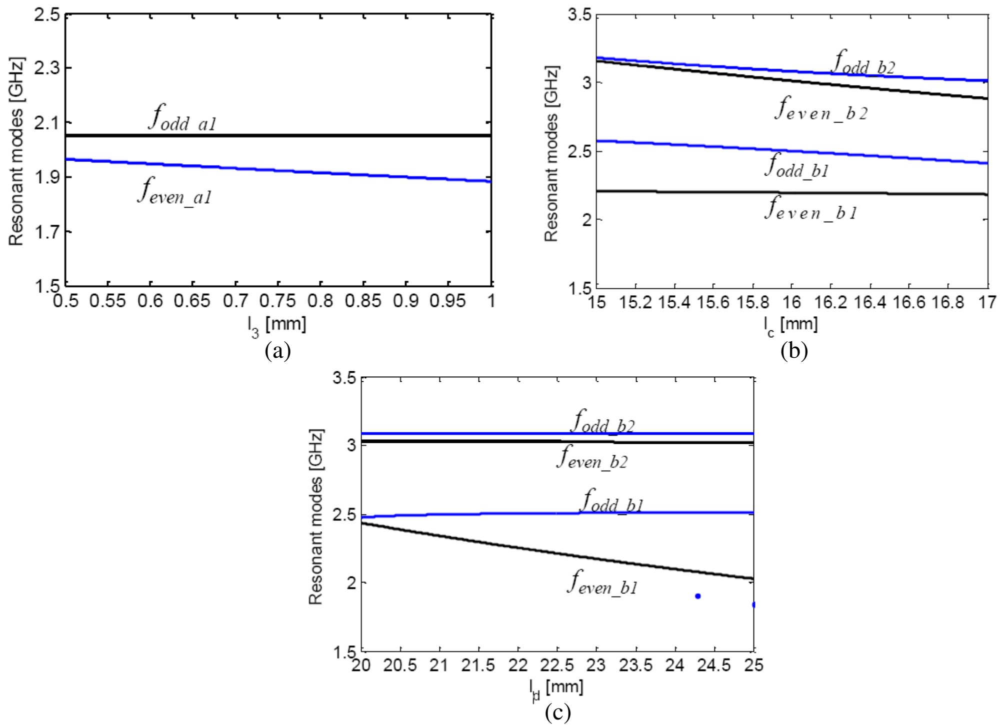

Figure 3: (a) Resonant-mode frequencies of Resonator a for different values of l_3. Other parameters used in the calculated results: $Y_{1a} = 1/71\,\mathrm{s}$, $l_{1a} = 10.8\,\mathrm{mm}$, $Y_{2a} = 1/109\,\mathrm{s}$, $l_{2a} = 8.9\,\mathrm{mm}$, $Y_{3a} = 1/97\,\mathrm{s}$. l_{na} is the corresponding parameter of θ_{na} ($n = 1$, 2, and 3). (b) Resonant-mode frequencies of Resonator b for different values of l_c. Other parameters used in the calculated results: $Y_{1b} = 1/38\,\mathrm{S}$, $l_{1b} = 13.6\,\mathrm{mm}$, $Y_{2b} = 1/97\,\mathrm{S}$, $l_{3b} = 22.7\,\mathrm{mm}$, $l_{4b} = 0.4\,\mathrm{mm}$, $l_{5b} = 5.1\,\mathrm{mm}$. l_{nb} is the corresponding parameter of θ_{nb} ($n = 1$, 2, 3, 4, and 5). (c) Resonant-mode frequencies of Resonator b for different values of l_d. Other parameters used in the calculated results: $Y_{1b} = 1/38\,\mathrm{s}$, $l_{1b} = 13.6\,\mathrm{mm}$, $Y_{2b} = 1/97\,\mathrm{s}$, $l_{2b} = 15.9\,\mathrm{mm}$, $l_{4b} = 0.4\,\mathrm{mm}$, $l_{5b} = 5.1\,\mathrm{mm}$. l_{nb} is the corresponding parameter of θ_{nb} ($n = 1$, 2, 3, 4, and 5).

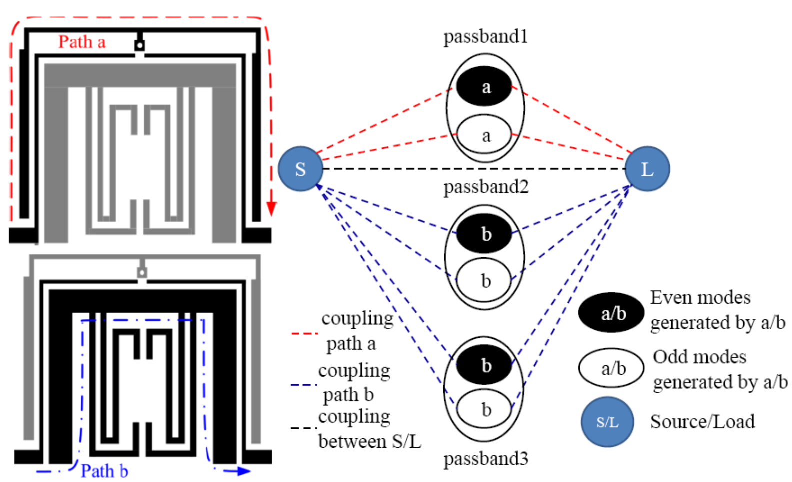

Figure 4: The coupling scheme of proposed tri-band bandpass filter.

3. VERIFICATION BY SIMULATION

To demonstrate the performance of the proposed filter, a compact tri-band filter is designed, fabricated and tested with an Agilent E5071C vector network analyzer, as shown in Figure 5. The dimensions for the filter are presented in Table 1 for $\varepsilon_r = 2.65$, $h = 0.5\,\mathrm{mm}$. The overall size of proposed filter is only $15.8 \times 14.7\,\mathrm{mm}^2$ ($0.12\lambda_0 \times 0.11\lambda_0$). λ_0 is the wavelength of the centre frequency of first passband. The simulation and measurement are also shown in Figure 5. Clearly, The simulation and measurement show good agreement. The distinction between the simulation and the measurement is mainly due to the mismachining tolerance. The measured 3-dB fractional bandwidths for the three passbands (2.22, 2.98 and 3.5 GHz) are found to be 8.4%, 2.7% and 6.1%, respectively. The measured minimum insertion losses including the loss from SMA connectors are 1.4, 3.5, and 1.5 dB, while the return losses are greater than 18.7, 27.6 and 40 dB, respectively. Five transmission zeros are created at 1.95, 2.75, 2.83, 3.14 and 3.66 GHz. These transmission zeros are generated near the passband edges, resulting in sharp roll-off in a narrow frequency range.

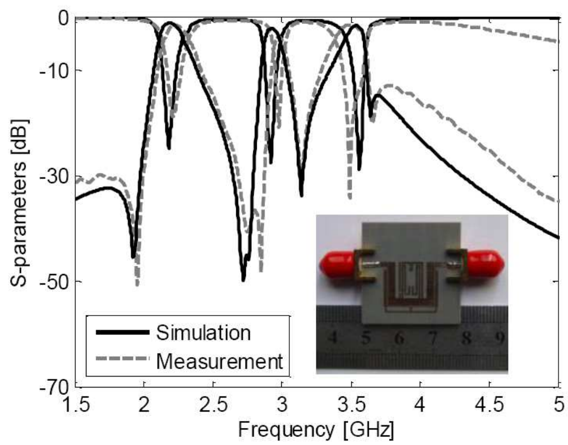

Figure 5: The photograph of fabricated filter and simulated, measured results.

Table 1: The parameters of proposed triple-band BPF (Unit: mm).

l_1	l_2	l_3	l_a	l_b	l_c	l_d	l_p	w_0	w_1	w_2	w_3	w_p	s_1	s_2	s_3	s_4	s_5
10.8	9.2	0.6	13.2	12.6	16.5	23.5	18.4	0.4	0.3	0.7	0.4	0.2	0.2	0.2	1.1	0.4	0.4

4. CONCLUSION

In this paper, a tri-band BPF based on multi-mode resonators is proposed. The passbands can be controlled according to even-odd-mode analysis, and five transmission zeros are introduced at the adjacent of passbands, resulting in high selectivity. Due to the tight resonators and coupling structure, the circuit size is really small. The compactness and high selectivity make the proposed filter attractive for multiband communication systems.

ACKNOWLEDGMENT

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