DESIGN OF A TRIPLE-PASSBAND MICROSTRIP BAND-PASS FILTER WITH COMPACT SIZE

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Abstract—This paper presents the triplepassband microstrip band-pass filter (BPF) with compact size. Two sets of the coupled asymmetric stepped impedance resonators (SIRs) and uniform impedance resonators (UIRs) are arranged for generating the triple-passband properties. It is convenient to control the triple-passband properties by tuning the impedance ratio (K) and length ratio (γ) of the asymmetric SIRs. The UIRs are also employed to enhance the coupling between the coupled resonators at 3rd passband. The filter is designed at 2.4/5.2/8.2 GHz and achieves nearly 50% circuit size reduction compared with the previous works. This study provides a simple method to design a triple-passband filter with compact circuit size. Experimental verification is provided, and good agreement has been found between simulation and measurement.

1. INTRODUCTION

Recently, the development in multi-band/multi-service wireless communication systems has created more potential, such as the combination of wireless local area networks (WLANs) at 2.4/5.2 GHz and global system for mobile communications (GSM) at 0.9/1.8 GHz,
or WLANs and global position system (GPS) at 1.575 GHz, or WLANs and automotive radar system at 8.2 GHz [1–12]. Multi-passband filters become key components in the front-end of these portable wireless communication devices.

Triple-passband bandpass filters play an important role in the modern tri-band transceiver. Several researches have been reported [10–12]. Traditionally, the triple-passband or the multi-passband bandpass filters can be realized with the combination of two or more single-passband filters. However, this method would cost a large circuit size and additional external networks [13]. Till now, some methods have been reported [10–12]. Zhang et al. proposed the triple-passband filter (at 1.8/2.4/3 GHz) with two sets of coupled stub-loaded resonators and half wavelength resonators [10]. The three passband frequencies can be easily adjusted to desired values by changing the dimensions. However, the design procedure is too complex to narrow the design freedom for controlling the three passband properties. Chen and Chu proposed the triple-passband filter (at 2.4/3.5/5.25 GHz) using assembled half-wavelength resonator, which comprises a stepped impedance resonator (SIR) and a common half-wavelength resonator [11]. However, the design parameters are too complex, and the circuit size is large. Chen et al. proposed the triple-passband filter (at 2.5/3.6/5.1 GHz) using alternately cascaded multiband resonators [12]. However, large circuit size in the design has become problematic issues.

In this paper, we propose a new triple-passband filter with compact size using the coupled asymmetric stepped impedance resonators (SIRs) and uniform impedance resonators (UIRs). The asymmetric SIRs is different from the conventional because the conventional SIRs have dual discontinued steps, causing more loss and larger circuit area. The use of the asymmetric SIRs can provide the compact circuit size and more design freedom. Moreover, the half-wavelength UIRs are designed at 8.2 GHz and coupled to the asymmetric SIRs for enhancing the 3rd passband. The proposed filter is designed at 2.4/5.2/8.2 GHz for the combination of WLAN (2.4/5.2 GHz) and automotive radar system (8.2 GHz) applications. The triple-passband filter has been designed and fabricated with microstrip technology. This study provides a simple and effective method to design a low-loss compact quad-band BPF without complex design and fabrication process. The measured results are in good agreement with the full-wave simulation ones.
2. DESIGN OF THE TRIPLE-PASSBAND FILTER

Figure 1(a) shows the layout of the proposed filter. The filter mainly depends on two asymmetric SIRs (resonator 2 and 3) and uniform impedance resonators (UIRs) (resonator 1 and 4) with feeding input/output (I/O) 50 Ω lines. Both the asymmetric SIRs are constructed by a high-impedance section with only one low-impedance section. Therefore, the asymmetric SIR has compact circuit size and more design freedom than the conventional SIRs [14, 15]. Resonant conditions can be easily determined by the dimension of the asymmetric SIR in very wide frequency range. The coupling gap ($S_3$) is a critical parameter to determine the properties of the triple-passband responses in this work.

Figure 2(a) shows the layout of the asymmetric SIR. The impedance ratio and length ratio are defined as $K = Z_2/Z_1$ and $\gamma = \theta_2/(\theta_1 + \theta_2)$. The effects of discontinuities and open-end can be neglected so as to derive the equation of input admittance $Y_{in}$ seen from the open-end as follows

$$Y_{in} = jY_2 \frac{K(\cot \theta_2 - \tan \theta_2) + (\cot \theta_1 - \tan \theta_1)}{0.5(\cot \theta_1 - \tan \theta_1)(\cot \theta_2 - \tan \theta_2) - 2K}$$  \hspace{1cm} (1)

The resonant conditions of the asymmetric SIR occurs while $Y_{in} = 0$. Fig. 2(b) shows the normalized ratios of $f_{s1}/f_{01}$ and $f_{s2}/f_{01}$ of the asymmetric SIR. Compared with the conventional SIRs [15, 16], higher resonant modes of the asymmetric SIR can be easily shifted far away or close to fundamental resonant mode without increasing the discontinued step-impedance sections. Therefore, it is easy to design a multi-band or wideband filter with compact circuit size. The filter

![Figure 1](image-url)  \hspace{1cm} Figure 1. Layout of the proposed triple-passband bandpass filter.
Figure 2. (a) Layout and (b) normalized ratios of $f_{02}/f_{01}$ and $f_{03}/f_{01}$ of the asymmetric stepped impedance resonator.

is designed at $f_{01} = 2.4 \text{GHz}$, $f_{02} = 5.2 \text{GHz}$ and $f_{03} = 8.2 \text{GHz}$ ($f_{02}/f_{01} = 2.17$ and $f_{03}/f_{01} = 3.4$) with $K = 0.45$ for the asymmetric SIR (resonator 2 and 3 shown in Fig. 1). The length ratio $\gamma$ can be explicitly determined as 0.2 which is marked as point A. In this work, the design parameters of $\gamma = 0.2$ with $\theta_1 = 71^\circ$ and $\theta_2 = 17^\circ$ and $K = 0.45$ with $Z_1 = 158 \Omega$ and $Z_2 = 73 \Omega$ are chosen for generating the triple-passband properties. The asymmetric SIRs are realizable. The highest practical limit of impedance realization is typically 190 omega for the Duroid 5880 substrate.

The filter is fabricated on the Duroid 5880 substrate with relative dielectric constant $\varepsilon_r = 2.2$, loss tangent $\tan \delta = 0.0002$ and thickness $h = 0.787 \text{mm}$. The 3-dB fractional bandwidths (FBWs) of the 1st, 2nd and 3rd passbands are $\Delta_1 = 6\%$ at $2.4 \text{GHz}$, $\Delta_2 = 4\%$ at $5.2 \text{GHz}$ and $\Delta_3 = 2\%$ at $6.8 \text{GHz}$ with the passband ripple of 0.01 dB. Only the design procedure for the 1st passband will be considered without taking the generality losses into account. The lumped element values of the low-pass prototype filter are found to be $g_0 = 1$, $g_1 = 1.3782$, $g_2 = 1.2693$, $J_1 = -0.2492$ and $J_2 = 0.9772$ [17]. The coupling coefficients ($M$) and external quality coefficient ($Q_e$) are calculated as

\begin{align*}
M_{23} &= \frac{\text{FBW} \cdot J_2}{g_2} \\
M_{14} &= \frac{\text{FBW} \cdot J_1}{g_1} \\
M_{12} &= M_{34} = \frac{\text{FBW}}{\sqrt{g_1 g_2}}
\end{align*}

(2)
where $J_1$ and $J_2$ are the admittance inverter constant \[17\]. In this work, $M_{12} = M_{34} = 0.048$, $M_{23} = 0.049$ and $M_{14} = -0.011$ at 2.4 GHz, $M_{12} = M_{34} = 0.028$, $M_{23} = 0.029$ and $M_{14} = -0.006$ at 5.2 GHz and $M_{12} = M_{34} = 0.018$, $M_{23} = 0.018$ and $M_{14} = -0.004$ at 8.2 GHz. The calculated $Q_{e1} = 11.5$ at 2.4 GHz, $Q_{e2} = 34.5$ at 5.2 GHz and $Q_{e3} = 68.9$ at 8.2 GHz. When the two coupled asymmetric SIRs synchronously tuned to have a close proximity, the coupling coefficients $(M_{i,j})$ can be obtained from the two resonant modes by using full-wave electromagnetic (EM) simulation \[18\]

$$M_{i,j} = \frac{f_H^2 - f_L^2}{f_H^2 + f_L^2}$$

where $f_H$ and $f_L$ are defined to be the higher and lower of the two resonant modes, and $i$ and $j$ are the indexes of the asymmetric SIRs (resonator 2 and 3) as shown in Fig. 1. Fig. 3(a) shows the frequency response of the filter with and without UIRs enhancement. Obviously, the 3rd passband (8.2 GHz) is enhanced by using the UIRs. The 3rd passband is probably eliminated without UIRs enhancement due to the weak higher resonant frequencies existing in the asymmetric SIRs. The length of UIRs is designed approximately to half-wavelength at 8.2 GHz. Furthermore, the distance of the coupling gap ($S_3$) should be near 0.2 mm for achieving lower insertion loss. Fig. 3(b) shows the current distributions of the filter operated at 2.4, 5.2 and 8.2 GHz. We can verify that the EM waves are transmitted in the filter through the

![Image](image.png)

**Figure 3.** (a) Frequency response of the filter with and without UIRs enhancement and (b) current distributions of the filter operated at 2.4, 5.2 and 8.2 GHz.
Figure 4. Coupling coefficient of (a) $M_{23}$ and (b) $M_{12} = M_{34}$ for 1st, 2nd and 3rd passband simultaneously.

diagram. 3rd passband is enhanced by the UIRs, and low insertion loss and good passband selectivity of the each passband can be well achieved. Fig. 4 shows the coupling coefficient of $M_{23}$ and $M_{12} = M_{34}$ for 1st, 2nd and 3rd passbands. The coupling spacing ($S_2$ and $S_3$) can be tuned to satisfy the coupling degree between the adjacent SIRs.

3. RESULTS

Figure 5 shows the photograph of the proposed filter. Size of the fabricated filter is $21 \times 13 \text{mm}^2$, approximately $0.26\lambda_g \times 0.15\lambda_g$ (where $\lambda_g$ is the guided wavelength on the substrate at the 1st passband). In this work, we choose $\gamma = 0.2$ ($\theta_1 = 71^\circ$ and $\theta_2 = 17^\circ$) and $K = 0.45$ ($Z_1 = 158\Omega$ and $Z_2 = 73\Omega$) for the asymmetric SIRs. To improve the selectivity of the passbands, the position of the I/O lines ($L_6 = 6\text{ mm}$) with 50\,$\Omega$-line is well designed for the optimum external quality factor ($Q_e = f_0/\delta_{3-\text{dB}}$, where $f_0$ and $\delta_{3-\text{dB}}$ express the center frequency and the 3-dB bandwidth of the passband) by using the full-wave EM simulation [18].

Figure 6 shows the simulated and measured frequency responses of the fabricated filter. Measured results of the filter are characterized in an HP 8510C network analyzer. The fabricated filter has measured center frequency ($f_{01}$, $f_{02}$ and $f_{03}$) at 2.4/5.2/8.2 GHz, the measured 3-dB fractional bandwidth (FBW) of 6.4/3.8/2.4%, the minimum insertion loss ($|S_{21}|$) of 1.1/1.2/2.1 dB and the return loss ($|S_{11}|$) of 22/22/26 dB. The arrangement of the resonators provides to generate the cross coupling. The transmission zeros near each passband will occur due to the multipath effects. Slight mismatch between
Figure 5. Photograph of the fabricated filter.

![Photograph of the fabricated filter.](image)

Figure 6. Simulated and measured frequency responses of the fabricated filter. \((W_1 = 1.3, W_2 = W_3 = W_4 = 0.2, S_1 = 0.2, S_2 = 1.2, S_3 = 0.2, L_1 = 9, L_2 = 8.7, L_3 = 6, L_4 = 4.3, L_5 = 12.8, L_6 = 6\) and \(L_7 = 2\). All are in mm.)

Table 1. Comparisons with other proposed triple-passband filters.

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<tr>
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<tbody>
<tr>
<td>Substrate height</td>
<td>0.762/2.94</td>
<td>0.8/2.55</td>
<td>0.508/3.38</td>
<td><strong>0.787/2.2</strong></td>
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<td>((\text{mm})/\varepsilon_r)</td>
<td></td>
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<tr>
<td>1st/2nd/3rd Passbands</td>
<td>1.8/2.4/3</td>
<td>2.4/3.5/5.2</td>
<td>2.5/3.6/5.1</td>
<td><strong>2.4/5.2/8.2</strong></td>
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<td>((\text{GHz}))</td>
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<tr>
<td>(</td>
<td>S_{11}</td>
<td>(\text{dB}))</td>
<td>20/15/15</td>
<td>18/16/13</td>
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<tr>
<td>(</td>
<td>S_{21}</td>
<td>(\text{dB}))</td>
<td>0.9/1.6/0.8</td>
<td>2/2.4/1.7</td>
</tr>
<tr>
<td>3-dB FBW ((%))</td>
<td>4.9/3.5/5.7</td>
<td>2.5/1.7/5</td>
<td>4/4/6</td>
<td><strong>6.4/3.8/2.4</strong></td>
</tr>
<tr>
<td>Circuit Size ((\text{mm}^2))</td>
<td>625.4</td>
<td>528</td>
<td>945.8</td>
<td><strong>273</strong></td>
</tr>
<tr>
<td>((\lambda_g \times \lambda_g))</td>
<td>((0.22 \times 0.27))</td>
<td>((0.31 \times 0.29))</td>
<td>((0.68 \times 0.28))</td>
<td>((0.26 \times 0.15))</td>
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the simulated and measured results might be due to the fabrication errors or the variation of material properties. Table 1 summarizes the comparison of the proposed filter with other reported triple-passband filters [10–12]. The proposed filter has a very compact circuit size and lower insertion loss.

4. CONCLUSION

A compact triple-passband bandpass filter has been presented in this paper. The filter is designed at 2.4/5.2/8.2 GHz using two coupled asymmetric SIRs and UIRs. By tuning the impedance ratio and length ratio of the asymmetric SIRs, each center frequency of the triple-passband can be well controlled. Moreover, the UIRs can effectively enhance the 3rd passband properties. The average level of the isolation between the passbands is greater than 30 dB. Nearly up to 50% size reduction is achieved compared with previous works. This study provides a simple and effective method to design a triple-passband bandpass filter with compact circuit size. The superior features indicate that the proposed filter has a potential to be utilized in multi-service wireless communication systems.

REFERENCES


