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# Compact triple-passband bandpass filter based on new modified stepped impedance resonators

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ABSTRACT

This study proposed a triple-passband bandpass filter with compact size, low loss and high passband selectivity. The filter includes two coupled stepped impedance resonators (SIRs) and two embedded stub-loaded stepped impedance resonators (SL-SIRs), connected with coupling scheme at the symmetric plane of the filter. The filter is designed to have triple-passband at 2.4, 3.5 and 5.2 GHz for worldwide interoperability for microwave access (WiMAX) applications. By properly tuning the impedance ratio and physical length ratio of the SL-SIRs, the three passbands can be easily determined, at the same time, achieving the high passband selectivity and wide stopband. Besides, the transmission zeros near passband edges of each passband are generated by the proposed filter with cross-coupling structure. The measured results are in good agreement with the full-wave electromagnetic (EM) simulation results.



## 1. Introduction

Multi-band and multi-service applications are widely and aggressively developed, especially in the radio frequency (RF) devices of the wireless communication systems. Bandpass filters (BPFs) play a key component for selecting the desired and high resolution signals at front-end of wireless communication systems. Designing a multiband filter with compact size and high performance is becoming an important issue and carried out in many literatures.

Stepped impedance resonators (SIRs) are known and usually used to shift the high order resonant modes for developing the multi-band BPFs. In [1], the ring-like SIR with embedded coupled open stubs resonators were realize two passbands individually and several transmission zeros aside the passband. In [2], a pair of asymmetric SIRs with cross-coupled arrangement was proposed to achieve the dual-band characteristic with high passbands selectivity. In [3], a compact tri-band bandpass filter based on $\lambda/4$ resonators was proposed. The filter is realized by coupling the two dual-band SIRs with synthesized frequency response. In [4], composite resonators consisting of three split ring resonators was proposed and designed for the tri-band filter. These works provide very good ideas for multiband filters and truly inspired us to study the compact SIR-based multiband filters.

Recently, stub-loaded resonators (SLRs) are the new structure for developing the triple-passband filters [5,6]. In [5], a new resonator configuration to design a triple-passband filter with high passband selectivity and compact circuit size was proposed. The filter includes two multipath-embedded stepped impedance resonators (SIRs), connected with magnetically coupling via a hole technique at the symmetric plane of the filter. In [6], the tri-band filter using the stub-loaded SIRs was proposed for the first time. However, circuit size and wide stopband are an issue and needed to be further improved.

This study proposed a new triple-passband filter using the SIRs and the embedded SL-SIR. The filter includes two coupled half-wavelength SIRs and two embedded SL-SIRs, connected with coupling scheme at the symmetric plane of the filter. The half-wavelength SIRs are designed at 2.4/5.2 GHz. The embedded SL-SIRs are designed to have two resonant paths (path 1 for 3.5 GHz and path 2 for 5.2 GHz) and its resonant modes (1st and 2nd mode) can be easily determined to very close or far away for highly design freedom. Each resonant path generates its own passband and there is good isolation between the three passbands. The proposed filter provides compact size and out-of-band isolation between each passband with transmission zeros conducted by the cross-coupling structure.

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## 2. Filter design

Fig. 1(a) shows the coupling structure of the proposed filter. The 1st passband at 2.4 GHz is generated by resonator $1^{I}$ and $2^{I}$ (by coupled SIRs). The embedded stub-loaded stepped impedance resonators include dual propagation paths at 3.5 GHz (2nd passband) and 5.2 GHz (3rd passband), as indicates the superscript of II and III. In Fig. 1(b), the filter is composed of the half-wavelength SIRs (resonator $1^{I}$ and $2^{I}$) and the embedded SL-SIRs (resonator $3^{II, III}$ and $4^{II, III}$). The resonator $1^{I}$ and $2^{I}$ are able to only control the performance of 1st passband. The resonator 3 ($3^{II}$ and $3^{III}$) and 4 ($4^{II}$ and $4^{III}$) are able to simultaneously control the performance of 2nd and 3rd passbands. The filter is simulated, designed and fabricated on the substrate duroid 5880 with dielectric constant $\varepsilon_r = 2.2$, loss tangent $\tan\delta = 0.0009$ and thickness of 0.787 mm. The simulation work is done by using the full-wave electromagnetic (EM) simulator [7].

The $f_{s1}^{SIR}/f_0$ and $f_{s1}^{SL-SIR}/f_0$ can be achieved by properly choosing the $\alpha_1$ value with specific $K_1$ value. In this work, we choose the $K_1 = 0.7$ and $\alpha_1 = 0.28$ for 1st passband and $K_2 = 0.6$ and $\alpha_2 = 0.28$ for 2nd passband as indicated by marked point A and B, as shown in Fig. 2(b).

Fig. 3(a) shows the transmission line model of the embedded SL-SIR. The embedded SL-SIR is composed of a half-wavelength SIR ($2[(Z_3, \theta_3), (Z_4, \theta_4)]$) and a stub-loaded stepped impedance section ($(Z_5, \theta_5), (Z_6, \theta_6)$). The embedded SL-SIR can simultaneously control the resonant modes to 2nd and 3rd passband (3.5 and 5.2 GHz) and resulting in the high in-band isolation. By properly tuning the dimension of the embedded SL-SIR, such as impedance ratio ($K_2 = Z_4/Z_3$ and $K_3 = Z_6/Z_5$) and length ratio ($\alpha_2 = \theta_4/(\theta_3+\theta_4)$ and $\alpha_3 = \theta_6/(\theta_5+\theta_6)$), the arrangements of each resonant mode become more flexible. The embedded SL-SIR can be analyzed to even- and odd-mode along the symmetric plane of the filter, as shown in Fig. 3(a). The resonant modes of the embedded SL-SIR can be derived by setting $Y_{ine} = Y_{ino} = 0$ and expressed as

$$Y_{ine} = \frac{-2Z_3Z_4(Z_3\cot\theta_3 - Z_4\tan\theta_4)(2Z_6\cot\theta_6 - 2Z_5\tan\theta_5)}{-jZ_4(Z_3\cot\theta_3 - Z_4\tan\theta_4)(2Z_5 + 2Z_6\cot\theta_6\tan\theta_5) + -j2Z_5(2Z_6\cot\theta_6 - 2Z_5\tan\theta_5)(Z_4 + Z_3\cot\theta_3\tan\theta_4)} \quad (3)$$

In order to fulfill the requirements for each passband, the resonant frequencies of half-wavelength SIR and embedded SL-SIR should be analyzed in detail. The structure of a half-wavelength SIR is shown in Fig. 2(a). The impedance ratio $K_1$ ($= Z_2/Z_1$) and physical length ratio $\alpha_1$ ($= \theta_2/(\theta_1+\theta_2)$) of the half-wavelength SIR are varied to adjust the fundamental resonances ($f_0$) and the higher resonant frequencies over the wide frequency range. Similarly, the embedded SL-SIR also includes a half-wavelength SIR. The impedance ratio and physical length ratio of the embedded SL-SIRs are defined as $K_2$ ($= Z_4/Z_3$) and $\alpha_2$ ($= \theta_4/(\theta_3+\theta_4)$). For an example of the resonator $1^{I}$ and $2^{I}$, the resonance conditions are determined by $K_1 \cot\theta_2 = \tan\theta_1$ (odd mode) and $K_1 \cot\theta_2 = -\cot\theta_1$ (even mode) [8]. Therefore, we can find the resonance conditions as follows:

$$K_1 \cdot \cot\left(\frac{1}{2}\alpha_1 \cdot \theta_T^{SIR}\right) = \tan\left(\frac{1}{2}(1-\alpha_1)\cdot\theta_T^{SIR}\right) \quad (1)$$

$$K_1 \cdot \cot\left(\frac{1}{2}\alpha_1 \cdot \theta_T^{SIR}\right) = -\cot\left(\frac{1}{2}(1-\alpha_1)\cdot\theta_T^{SIR}\right) \quad (2)$$

Several solutions for $\theta_T^{SIR}$ ($= 2(\theta_1+\theta_2)$) are dependent on the choice of $K_1$ and $\alpha_1$. Fig. 2(b) shows the relations between the normalized $f_{s1}^{SIR}/f_0$ and $f_{s1}^{SL-SIR}/f_0$ curves for a half-wavelength SIRs with different ($K_1$, $\alpha_1$) and ($K_2$, $\alpha_2$). The curves would be very useful for achieving the desired passbands of the triple-passband.

$$Y_{ino} = \frac{1}{jZ_4}\frac{K - \tan\theta_3\tan\theta_4}{\tan\theta_3 + K\tan\theta_4} \quad (4)$$

Fig. 3(b) shows the relations between the normalized $f_{si}^{SL-SIR}/f_0$ versus length ratio $\alpha_2$ with length ratio $r^{SL-SIR}$ of the embedded SL-SIR. The even- and odd-mode of the embedded SL-SIR are corresponded to $[f_{s2}^{SL-SIR}/f_0, f_{s4}^{SL-SIR}/f_0]$ and $[f_{s1}^{SL-SIR}/f_0, f_{s3}^{SL-SIR}/f_0]$, respectively. To simplify the design, the parameters of the sections of [$Z_3$, $Z_4$, $Z_5$, $Z_6$] are fixed, to change the length ratio $r^{SL-SIR}$ ($= 2\theta_s/\theta_T^{SL-SIR}$, where $\theta_s = \theta_5 + \theta_6$, and $\theta_T^{SL-SIR} = 2(\theta_3+\theta_4)$) and $\alpha_2$. It is found that even mode ($f_{s2}^{SL-SIR}/f_0$) can be designed very close to odd mode ($f_{s1}^{SL-SIR}/f_0$) while $r^{SL-SIR} = 0.4$. Using the embedded SL-SIR, the even modes can be tuned within very wide frequency range and without affecting the odd modes. Therefore, the design of multi-band filters with very close passbands can be easily achieved and having a high isolation between the passbands. Fig. 3(c) shows the fundamental and higher order resonant frequencies of the half-wavelength SIRs (resonator $1^{I}$ and $2^{I}$) and the embedded SL-SIRs (resonator $3^{II, III}$ and $4^{II, III}$). The fundamental frequencies of embedded SL-SIRs are located at 3.5 and 5.2 GHz, respectively, and the half-wavelength SIR is located at 2.4 GHz and 5.2 GHz. The higher order resonant frequencies of each resonator can be blocked by controlling the structure dimensions of the proposed resonators. For the desired

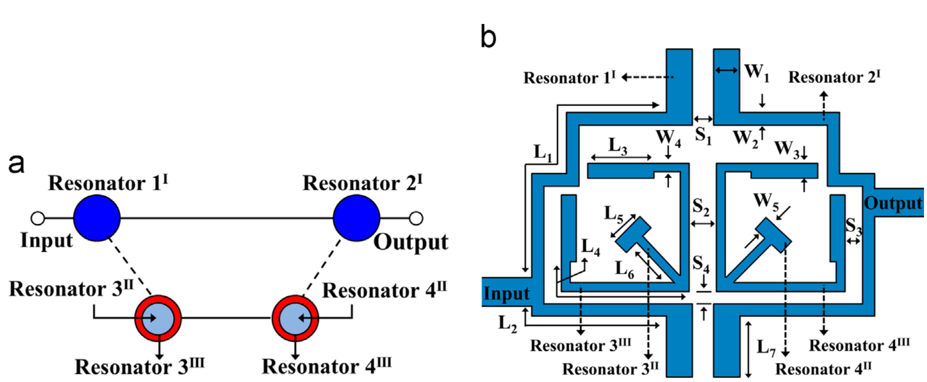


**Fig. 1.** (a) Coupling structure and (b) the configuration of the triple-passband filter. (Resonator $1^{I}$ and $2^{I}$ are the stepped impedance resonators (SIRs) and resonator 3 ($3^{II}$ and $3^{III}$) and 4 ($4^{II}$ and $4^{III}$) are the embedded stub-loaded stepped impedance resonators (SL-SIRs)).