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Design of a Compact and High Selectivity Tri-Band Bandpass Filter Using Asymmetric Stepped-impedance Resonators (SIRs)

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Abstract—In this article, a compact tri-band microstrip bandpass filter (BPF) using asymmetric stepped-impedance resonators (SIRs) is proposed. Only one set of asymmetric SIRs are used in designing this filter to achieve triple passband response with high selectivity and band-to-band isolation level. By properly selecting the impedance and electrical length ratios of the asymmetric SIRs, the tri-band BPF is designed. By using a cross-coupled configuration and 0° feed structure, high selectivity frequency responses with six transmission zeros are achieved. The three bands of the proposed tri-band filter are located at 1.57/3.9/7 GHz, respectively, and the circuit size is much smaller in comparison with previous works using the same substrate. Measured results are in good agreement with electromagnetic (EM) simulation.

1. INTRODUCTION

In recent years, various new technologies have emerged and been thoroughly investigated in modern wireless communication systems. In particular, multi-service technology is widely and aggressively developed. Thus, as one of the key components in wireless communication systems, multi-band planar bandpass filters (BPFs) have gained much attention. Great efforts have been made to design multi-band BPFs, and various designs have been reported [1–9]. Half-wavelength [1] and quarter-wavelength [2] SIRs have been utilized to design quad-band or tri-band BPFs, whereas tri-section SIRs are used to design tri-band filters [3, 4]. However, the design procedure is comparatively complicated. In [5] and [6], the combination of stub-loaded resonators (SLRs) and half-wavelength SIR is introduced. Recently, the design method to achieve high performance multi-band BPFs using multimode resonators (MMRs) has attracted much attention [7–9]. Asymmetric SIRs with only one discontinuity can also be used to construct multi-band BPFs with the merit of compact circuit size, low loss, and more design feasibility [10–18]. However, it is still a big challenge to design filters with compact circuit size and high selectivity.

In this paper, a compact tri-band BPF using only one set of asymmetric SIRs is introduced. By properly selecting the impedance ratio (K) and electrical length ratio (α) of the proposed asymmetric SIRs, the tri-band BPF centred at 1.57/3.9/7 GHz is obtained. The three passbands are determined by the fundamental, first and fourth resonant frequency of the asymmetric SIR, respectively. By arranging the two SIRs in a cross-coupled configuration, these three resonant frequencies of both resonators couple together and form the desired passbands. Also, with the help of a cross-coupled configuration and an improved 0° feed structure, high selectivity and isolation frequency responses with six transmission zeros are achieved. The proposed filter is simulated by a commercial EM simulator IE3D, and the fabricated results are in good agreement with the simulated results. Furthermore, the overall circuit size is very compact and achieves a 58% reduction in comparison with previous work [16] using the same substrate.

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2. DESIGN PROCEDURE

The specific configuration of the proposed tri-band BPF is shown in Figure 1. This filter is mainly constructed by only one set of asymmetric SIRs and a pair of $50\,\Omega$ I/O ports. The two feed lines are in a configuration of improved 0° feed structure which is different from the conventional one due to the rotationally symmetric arrangement [7]. The proposed asymmetric SIR with only one discontinuity is constructed in two sections, i.e., the high-impedance and low-impedance sections, as shown in Figure 2(a). Generally, the physical length ratio of conventional SIR is selected to be the same in order to simplify the design procedure and realize the minimum circuit size. However, that leads to less design freedom. On the contrary, the asymmetric SIR can control resonant frequencies by changing both the impedance (K) and the electrical length (α) ratios. Therefore, the asymmetric SIR has compact circuit size and more design freedom than the conventional SIR.

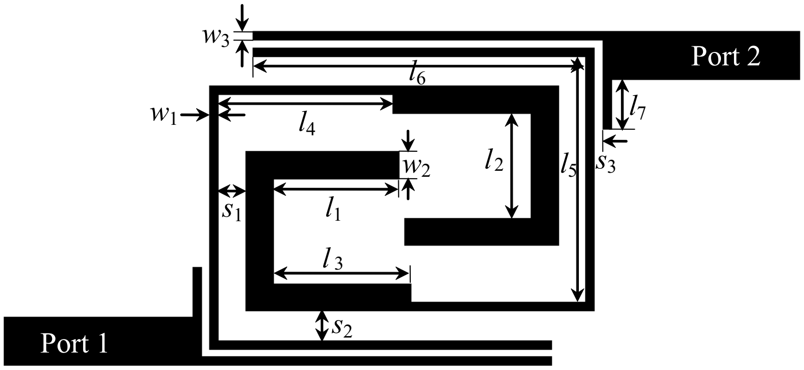
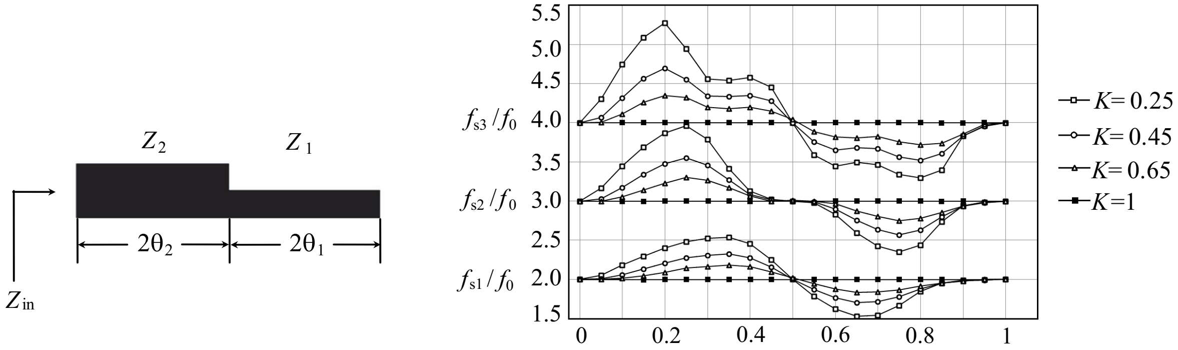


Figure 1. Specific configuration of the proposed tri-band BPF. ($w_1 = w_3 = 0.2$, $w_2 = 1.44$, $s_1 = 1.7$, $s_2 = 1.8$, $s_3 = 0.1$, $l_1 = 6.63$, $l_2 = 5.52$, $l_3 = 7.26$, $l_4 = 9.44$, $l_5 = 13.45$, $l_6 = 17.76$, and $l_7 = 2.63$. Unit: mm).



(a) (b)

Figure 2. (a) Schematic and (b) normalized ratios of f_{s1}/f_0, f_{s2}/f_0, and f_{s3}/f_0 for an asymmetric SIR with impedance ratios $K = 0.25$, 0.45, 0.65, and 1.

Figure 2(a) depicts the schematic of proposed asymmetric SIR. By folding the two sections and arranging in a pseudo-interdigital configuration, the proposed tri-band BPF shown in Figure 1 is obtained. The impedance ratio is defined as $K = Z_2/Z_1$, and the electrical length ratio is $\alpha = \theta_2/(\theta_1 + \theta_2) = 2\theta_2/\theta_t$, where Z_1, $2\theta_1$, Z_2, $2\theta_2$ are the impedance and electrical length of high- and low-impedance sections, respectively, and the total electrical length of proposed asymmetric SIR is defined as $\theta_t = 2(\theta_1 + \theta_2)$. The input impedance is

$$Z_{in} = jZ_2 \frac{-Z_1 \cot 2\theta_1 + Z_2 \tan 2\theta_2}{Z_2 + Z_1 \cot 2\theta_1 \tan 2\theta_2} \tag{1}$$

The resonant condition is $Z_{in} = \infty$, that is

$$Z_2 + Z_1 \cot 2\theta_1 \tan 2\theta_2 = 0 \tag{2}$$

$$Z_2/Z_1 = K = -\cot 2\theta_1 \tan 2\theta_2 \tag{3}$$

When substituting $\alpha = 2\theta_2/\theta_t$ into (3), the relationship of the resonant modes between K and α is obtained:

$$K = -\cot(1-\alpha)\theta_t \tan \alpha\theta_t \tag{4}$$

Figure 2(b) illustrates the normalized ratios of the first (f_{s1}), second (f_{s2}), and third (f_{s3}) spurious resonant frequencies to the fundamental resonant frequency (f_0) for an asymmetric SIR with $K = 0.25$, 0.45, 0.65, and 1. It is obtained from Equation (4) by varying K and α, and periodical value of θ_t are obtained: θ_0, θ_{s1}, θ_{s2}, θ_{s3}, ... Then, normalized frequency ratios of f_{s1}/f_0, f_{s2}/f_0, and f_{s3}/f_0 for an asymmetric SIR with different K and α are:

$$\frac{f_{sn}}{f_0} = \frac{\theta_{sn}}{\theta_0} \quad (n = 1, 2, 3, \ldots) \tag{5}$$

And Figure 2(b) is plotted accordingly.

In order to obtain the desired triple passbands located at 1.57, 3.9, and 7 GHz, the impedance ratio K and electrical length ratio α are determined as $K = 0.45$ and $\alpha = 0.35$ according to Figure 2(b). In this work, Z_1 is chosen as $152\,\Omega$, and Z_2 $68.4\,\Omega$.

The fundamental resonant frequency of the proposed asymmetric SIR can be obtained by Equation (6) [6]:

$$f_0 \simeq \frac{c}{2(L_1 + L_2)\sqrt{\overline{\varepsilon_{\mathit{eff}}}}} \tag{6}$$

where

$$\overline{\varepsilon_{\mathit{eff}}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[\left(1 + 12\frac{h}{\overline{w}}\right)^{-0.5} + 0.04\left(1 - \frac{\overline{w}}{h}\right)^2 \right] \tag{7}$$

is the effective dielectric constant calculated using the average width $\overline{w} = (w_1 + w_2)/2$ of two sections of the asymmetric SIR, and L_1, L_2 are the physical lengths of the high- and low-impedance lines, respectively. Once the fundamental resonant frequency is determined, the spurious resonant frequencies f_{s1}, f_{s2}, and f_{s3} can be determined by referring to Figure 2(b). By coupling the two resonators, the first two resonant modes f_0 and f_{s1} are coupled together. Their coupling coefficients are dominated by s_1 and s_2, which are tuned to form the first two passbands and obtain the desired bandwidths. The coupling between resonators is denoted by coupling coefficient M :

$$M = \frac{f_H^2 - f_L^2}{f_H^2 + f_L^2} \tag{8}$$

where f_H and f_L are defined to be the higher and lower resonant modes of the two resonant modes of the proposed asymmetric SIR. Bandwidths of the three passbands are affected by M. When M is too small, the coupling between the two resonators is not enough and leads to high insertion loss; when M is too large, the coupling between the two resonators is redundant and leads to the split of resonant modes. The proper value of M is obtained by tuning coupling gaps and lengths between the two resonators using a full-wave EM simulator (IE3D in this work). However, due to the weak coupling with f_{s2} and f_{s3}, it is difficult to form passbands for these two resonant modes. Thus, in order to achieve the desired tri-band BPF, strong couplings between the feed lines and resonators are needed. Then the spacing s_3 and the length l_7 are adjusted to satisfy the desired coupling strength of f_{s3} to form the third passband.

3. RESULTS

In order to demonstrate the validity of the above-mentioned design method, the proposed tri-band BPF is designed and fabricated on Rogers Duroid 5880 substrate with a thickness of 0.787 mm, a dielectric constant ε_r of 2.2, and a loss tangent of 0.0009. The schematic of designed filter is shown in Figure 1. It was simulated by the full-wave EM simulator IE3D.

Based on the design method described above, the structural parameters are obtained as follows: $w_1 = 0.2\,\mathrm{mm}$, $w_2 = 1.44\,\mathrm{mm}$, $w_3 = 0.2\,\mathrm{mm}$, $s_1 = 1.7\,\mathrm{mm}$, $s_2 = 1.8\,\mathrm{mm}$, $s_3 = 0.1\,\mathrm{mm}$, $l_1 = 6.63\,\mathrm{mm}$, $l_2 = 5.52\,\mathrm{mm}$, $l_3 = 7.26\,\mathrm{mm}$, $l_4 = 9.44\,\mathrm{mm}$, $l_5 = 13.45\,\mathrm{mm}$, $l_6 = 17.76\,\mathrm{mm}$, and $l_7 = 2.63\,\mathrm{mm}$. The overall dimensions are $15.85\,\mathrm{mm} \times 20.24\,\mathrm{mm}$, i.e., approximately $0.113\lambda_g \times 0.145\lambda_g$, where λ_g is the guided wavelength at the center frequency of the first passband (1.57 GHz). It is obvious that the proposed BPF is very compact in size.

The simulated and measured frequency responses of the fabricated filter are shown in Figure 3. One can clearly observe that the measured results are in good agreement with the simulated ones. The measured center frequencies (f_1, f_2 and f_3) of the fabricated tri-band filter are 1.57/3.9/7 GHz, with the measured 3-dB fractional bandwidth (FBW) of 4.1/2/3%, the minimum insertion loss (IL: $|S_{21}|$) of 2.0/2.1/1.8 dB and the return loss (RL: $|S_{11}|$) of 22/16/18 dB. Six transmission zeros are generated at 1.31, 2.89, 4.1, 5.24, 5.75 and 8.35 GHz, which greatly improve the band-to-band isolation and selectivity. The isolation level between the first and second passbands is about 40 dB, while that between the second and third passbands is about −27.6 dB. Table 1 tabulates the comparison of the proposed filter with other reported tri-band filters [2, 3, 16]. The proposed tri-band BPF has merits of compact size, high selectivity, low insertion loss, and high band-to-band isolation level.

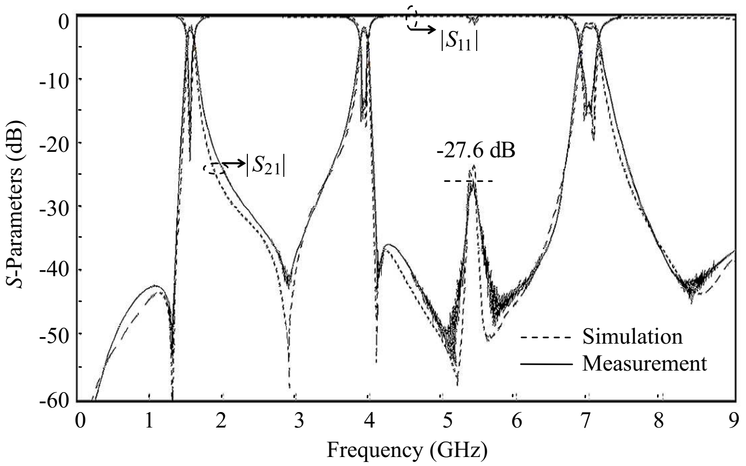


Figure 3. Simulated and measured frequency responses of the designed tri-band BPF.

Table 1. Comparison of the proposed filter with other reported tri-band filters.

	Ref. [2]	Ref. [3]	Ref. [16]	Ref. [19]	This work
Substrate height (mm)/ε_r	1.27/10.8	0.8/2.45	0.787/2.2	0.508/3.5	0.787/2.2
Center frequencies	1.8/3.5/5.8	1/2.4/3.6	2.4/5.2/8.2	2.45/3.5/5.2	1.57/3.9/7
IL (dB)	0.88/1.33/1.77	2.0/1.9/1.7	1.1/1.2/2.1	1.2/1.5/1.6	2.0/2.1/1.8
RL (dB)	21.3/15.84/15.72	14/16/20	22/22/26	16.3/17.9/12.9	22/16/18
FBW (%)	7/5/3.5	N/A	6.4/3.8/2.4	9.6/13.1/7.9	4.1/2/3
Circuit Size ($\lambda_g \times \lambda_g$)	0.108×0.521	0.191×0.191	0.26×0.15	0.18×0.27	0.113×0.145

4. CONCLUSION

In this paper, a compact tri-band microstrip BPF is introduced. This filter is designed at 1.57/3.9/7 GHz using only one set of asymmetric SIRs. The design procedure is discussed in detail. The filter has significant design freedom, because the three passbands can be tuned by properly controlling the resonant modes of the proposed resonators, which are affected by the impedance ratio (K) and electrical length ratio (α). Six transmission zeros are generated at 1.31, 2.89, 4.1, 5.24, 5.75 and 8.35 GHz due to cross-coupling effect and an improved 0° feed structure, which improve the band-to-band isolation and selectivity greatly. The average isolation level is greater than 34 dB. Furthermore, the circuit size is reduced greatly about 58% compared with previous work using the same substrate and height proposed in [16]. Good agreement between the simulated and measured results were obtained. This compact tri-band filter is actually suitable for multi-band and multi-service applications in wireless communication systems.

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