LETTER

Individually controllable dual-band bandpass filter with multiple transmission zeros and wide stopband

Pin Wen^{1,2}, Zhewang Ma^{1a)}, Haiwen Liu³, Shuangshuang Zhu³, Baoping Ren^{1,2}, Xuehui Guan², and Masataka Ohira¹

Abstract In this paper, a compact dual-band bandpass (DB-BPF) with multiple transmission zeros and wide stopband is developed. The DB-BPF consists of a pair of open-ended stub-loaded short-circuited stepped-impedance resonators with easy control of their two fundamental resonant modes. Moreover, multiple geometrical parameters in both the external feeding structure and the internal couplings between neighboring resonators are employed to make the individual control of the two passbands possible. Furthermore, the introduced multiple coupling paths between the resonators produce transversal signal interference which creates multiple transmission zeros. As a result, the selectivity of the passbands is improved significantly, and the stopband of the filter is extended greatly. A DB-BPF with center frequencies of 1.5 GHz and 3.65 GHz, and fractional bandwidths (FBWs) of 5% and 3% is fabricated, and its measured response agrees well with the predicted one.

Keywords: dual-band bandpass filter, multiple coupling paths, signal interference, transmission zero, wide stopband

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Dual-band bandpass filters (DB-BPFs) with controllable dual-passbands and wide stopband play an important role in low interference and multiservice wireless communication systems, and up to now, many design methods have been proposed with insert a bandstop performance resonators [1, 2], consist of two different size or type resonators with common feed structure [3, 4, 5, 6, 7], stepped-impedance resonators (SIRs) [8, 9, 10, 11], stub-loaded resonators (SLRs) [12, 13, 14, 15, 16, 17, 18, 19, 20, 21], other types multi-mode resonators (MMRs) [22, 23, 24, 25], and substrate integrated waveguide (SIW) structures [26, 27]. In [1], a synthesizing method is presented to design dual-band by consist of a wideband bandpass filter and a stopband filter. In order to improve the controllable of two passband, two slot resonators are combined with microstrip T-stub feed structures is proposed in [7]. It is improved the controllable of the two passbands, but the circuit size is relatively large. A more compact DB-BPF

using a pair of composite open-loop resonators is reported in [19]. However, weak coupling exists between the outer and inner open-loops which leads to a smaller attenuation in stopband. A composite resonator with a pair of individually controllable resonant modes is presented in [21], and a DB-BPF with controllable center frequencies is developed. However, the stopband performance of the filter needs is not favorable.

In [14], a DB-BPF with an ultrawide stopband is designed by using T-shaped and open stubs. In [28], the transversal signal interaction concept is adopted to generate multiple transmission zeros which results in an ultra-wide stopband of the proposed DB-BPF. However, the external coupling of these two filters are hard to controllable, so their bandwidths are also not changeable independently.

In this paper, an open-ended stub-loaded shorted-circuited stepped-impedance resonator (OSL-SSIR) is analyzed at first. Next, a dual-band BPF is proposed, and its external and internal coupling behaviors are investigation in detail. Multiple mixed electric- and magnetic-coupling paths are introduced to produce transversal signal interference and multiple transmission zeros (TZs). Descriptions on the mechanism of the TZs are provided. Finally, a DB-BPF is designed, fabricated, and its measured response is compared with the simulated one.

2. Analysis of the OSL-SSIR

Fig. 1. (a) Transmission line model of the OSL-SSIR. (b) Current distribution of OSL-SSIR resonating at f_L . (c) Current distribution of OSL-SSIR resonating at f_H .

Fig. 1(a) shows the transmission line model of the open-ended stub-loaded short-circuited stepped-impedance resonator (OSL-SSIR), which consist of four sections: a low impedance section (Y_1, θ_1), a high impedance middle section (Y_2, θ_2), a short-circuited high impedance section (Y_3, θ_3), and an open-ended stub section (Y_s, θ_s). Among

¹Graduate School of Science and Engineering, Saitama University, Saitama 338–8570, Japan

²Department of Information Engineering, East China Jiaotong University, Nanchang 330013, China

³Department of Electronic and Engineering, Xi'an Jiaotong University, Xi'an 710049, China

a) ma@ees.saitama-u.ac.jp

the multiple resonances of the OSL-SSIR, the two fundamental resonances with frequencies f_L and f_H are adopted to form the two passbands, respectively. The corresponding current distributions of the two resonances are shown in Fig. 1(b) and (c), respectively. It is observed from Fig. 1(b) that the resonance at f_L is occurred at the straight quarter-wavelength SIR, and the open-ended stub has no effect on this resonance. On the other hand, as illustrated in Fig. 1(c), the resonance at f_H is happened at the T-shaped resonator, and all line sections of the OSL-SSIR have influence on this resonance.

According to above analysis, the input admittances Y_{inL} and Y_{inH} at the two resonant frequencies f_L and f_H can be derived as

$$Y_{inL} = Y_{in1} + Y_{in3} \quad @f_L \quad (1)$$

$$Y_{inH} = Y_{in1} + Y_{in2} + Y_{in3} \quad @f_H \quad (2)$$

where

$$Y_{in1} = Y_2 \frac{jY_1 \tan \theta_1 + jY_2 \tan \theta_2}{Y_2 - Y_1 \tan \theta_1 \tan \theta_2} \quad (3)$$

$$Y_{in2} = jY_s \tan \theta_s \quad (4)$$

$$Y_{in3} = -jY_3 \cot \theta_3 \quad (5)$$

To simplify the design, we assume that $Y_2 = Y_3 = Y_s$ and define the admittance ratio $K = Y_1/Y_2$. Then, the two resonance frequencies f_L and f_H can be determined from the resonance condition $Y_{inL} = 0$ and $Y_{inH} = 0$, respectively, which result in the following two equations:

$$Y_2(K \tan \theta_1 \tan \theta_2 - 1) \cot \theta_3 + K \tan \theta_1 + \tan \theta_2 = 0 \quad @f_L \quad (6)$$

$$Y_2(K \tan \theta_1 \tan \theta_2 - 1)(\tan \theta_s - \cot \theta_3) - K \tan \theta_1 - \tan \theta_2 = 0 \quad @f_H \quad (7)$$

From (6) and (7), it is seen that θ_s has only effect on the higher resonance frequency f_H , but no effect on f_L . Therefore, the two resonance frequencies can be individually controllable by adjusting the open-end stub, and this is very important in the design of DB-BPF.

Fig. 2. Variation of f_L and f_H with different θ_1 , θ_2 , θ_3 , and θ_s .

Fig. 2 shows the variation of the two resonance frequencies f_L and f_H with different electrical lengths of θ_1 , θ_2 , θ_3 , and θ_s when $K = 2$ and $Y_2 = 0.008$ S. When one of θ_1 , θ_2 , θ_3 , and θ_s is chosen as the variant, the other three are given electrical lengths from the following values: $\theta_1 = 27.5^\circ$, $\theta_2 = 20.5^\circ$, $\theta_3 = 18.5^\circ$, $\theta_s = 27.5^\circ$. It can be observed that with the increase of θ_1 , θ_2 , or θ_3 , both f_L and

f_H decrease. On the other hand, with the increase of θ_s , only f_H decreases, while f_L remains almost unvaried. So, it is easy to make individual control of these two frequencies.

3. Design of a dual-band BPF

Based on the above analysis, a compact DB-BPF is designed in this section. The configuration of the proposed DB-BPF is illustrated in Fig. 3, which consists of two OSL-SSIRs, a common short-circuited magnetic coupling stub, and a pair of parallel-coupled feed lines. For size reduction, the low impedance sections and the open stubs of the OSL-SSIRs are folded.

Fig. 3. Configuration of the proposed dual-band BPF.

The second-order filter is designed to operate at 1.5 GHz and 3.65 GHz, with a fractional bandwidth (FBW) of 5% and 3%, respectively. The lumped circuit elements of the low-pass prototype filter are $g_0 = 1$, $g_1 = 0.6648$, $g_2 = 0.5445$, and $g_3 = 1.2210$, when the two passbands of the DB-BPF have Chebyshev responses with a 0.04321-dB ripple in both passbands [29]. The required coupling coefficients $M_{12}^I = 0.0831$ and $M_{12}^{II} = 0.0499$, and the external quality factors of the two passbands $Q_e^I = 13.30$ and $Q_e^{II} = 22.16$ are calculated from the following well-known formulas:

$$M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \quad \text{for } i = 1 \text{ to } n - 1 \quad (8)$$

$$Q_e = \frac{g_0 g_1}{FBW} \quad (9)$$

Fig. 4(a) shows the variation of the simulated coupling coefficients between two neighboring OSL-SSIRs with the short-circuited stub width W_d and the diameter d of the short-circuited via-hole. It is seen that with the increase of W_d , the coupling coefficient of the lower passband (Band I) increases gradually, while the coupling coefficient of the higher passband (Band II) varies little. Fig. 4(b) illustrates the variation of the coupling coefficients with the folded line length L_L (when $S_H = 1$ mm) and the gap width S_H (when $L_L = 5.8$ mm) between two neighboring OSL-SSIRs.

Fig. 5 shows the variation of the simulated external quality factors of the OSL-SSIR with the length L_f of parallel-coupled feed line and the gap width C_f (when the width of parallel-coupled feed line $W_f = 0.25$ mm). It is seen that both the external Q values of the two passbands reduce with the increase of L_f . Also, as expected, with the increase of coupling gap C_f , both the external Q values of the two passbands become larger.

Fig. 4. Simulated coupling coefficients by a EM simulator. (a) Variation with W_d and d . (b) Variation with L_L when $S_H = 1$ mm, and variation with S_H when $L_L = 5.8$ mm.

Fig. 5. Variation of the simulated external quality factors of two passbands with L_f and C_f when $W_f = 0.25$ mm.

Based on the above analysis, both the center frequencies and bandwidths of the two passbands can be individually controlled with appropriately chosen geometrical parameters of the proposed filter structure showing in Fig. 3. The finally obtained dimensions for the given design specifications of the DB-BPF are illustrated in Fig. 3.

4. Performance of the dual-band BPF

The designed DB-BPF is fabricated on a Rogers RO4003C substrate with a relative dielectric constant of 3.38 and a thickness of 0.813 mm. The photograph of the fabricated DB-BPF is shown in Fig. 6. The filter occupies an area of $16.0 \text{ mm} \times 6.5 \text{ mm}$ excluding the feeding structure, which is about $0.13\lambda_g \times 0.05\lambda_g$, where λ_g is the guided wavelength at the center frequency $f_L = 1.5$ GHz of the lower passband.

Fig. 6. Photograph of the fabricated dual-band BPF.

In Fig. 7(a) and (b), the simulated frequency response of the DB-BPF by EM simulator is illustrated in solid lines. It is observed that the two passbands are centered at 1.5 and 3.65 GHz, and their corresponding FBW is 5.1% and 3.2%, respectively, which agree well with the desired specifications.

Fig. 7. Simulated and measured responses of the proposed DB-BPF. (a) Local frequency range response. (b) Wide frequency range response.

The measured response of the filter is drawn in Fig. 7(a) and (b) by dotted lines, which agree well with the simulated result. The measured maximum insertion loss of the two passbands, centered at 1.51 GHz and 3.68 GHz, are approximately 1.55 dB and 1.63 dB, respectively. The measured corresponding 3-dB bandwidths are 64.72 MHz

(4.25%) and 95.72 MHz (2.60%), respectively. The measured return loss is better than 20 dB in both passbands. In addition, the stopband with a rejection level better than 20 dB is extended to 9.6 GHz ($6.4f_0$).

on the both sides of the lower passband, as shown by TZ₂ and TZ₃ in Fig. 7(b). Similarly, the P-II and P-III are also out of phase at both below and above resonance of the higher passband (Band II). As a result, TZ₄ and TZ₅ are

Table I. Phase shifts of each coupling path between the DB-BPDs in Fig. 8.

Passband	Location	Path	R1	M12	R2	Total Phase Shift	Phase Difference	Results
Band I	Below Resonance	P-I	+90°	−90°	+90°	+90°	180° (Out Phase)	TZ ₂
		P-III	+90°	+90°	+90°	+270°		
	Above Resonance	P-I	−90°	−90°	−90°	−270°	180° (Out Phase)	TZ ₃
		P-III	−90°	+90°	−90°	−90°		
Band II	Below Resonance	P-II	+90°	+90°	+90°	+270°	180° (Out Phase)	TZ ₄
		P-III	+90°	−90°	+90°	+90°		
	Above Resonance	P-II	−90°	+90°	−90°	−90°	180° (Out Phase)	TZ ₅
		P-III	−90°	−90°	−90°	−270°		

Six transmission zeros (TZs) are observed at 0.44, 1.19, 3.09, 3.49, 4.64, and 7.20 GHz, which are represented by TZ₁, TZ₂, TZ₃, TZ₄, TZ₅, and TZ₆, respectively. These TZs are distributed on either side of the two passbands, which not only enhanced the selectivity of the filter, but also improved significantly the stopband property of the DB-BPF. TZ₁ is the inherent transmission zero of the DB-BPF, while TZ₆ is produced by the open-ended stub of the OSL-SSIR. TZ₂, TZ₃, TZ₄, and TZ₅ are created by transversal signal interference of the multiple mixed electric and magnetic coupling paths [30, 31]. As indicated in Fig. 8(a), there are three signal transmission paths, i.e., P-I, P-II, and P-III for the two passbands. When the phase difference between two paths is odd times of 180°, a TZ will be created. From the current distributions in Fig. 8(b) and (c), we judge that the P-I and P-III provide electric coupling and magnetic coupling respectively for the lower passband, while the P-II and P-III provide magnetic coupling and electric coupling respectively for the higher passband. This judgment can also be verified by the extracted coupling coefficient showing in Fig. 4.

Fig. 8. (a) Coupling paths of the proposed DB-BPF. (b) Simulated current distribution at 1.5 GHz. (c) Simulated current distribution at 3.65 GHz.

Table I lists the phase shifts for each signal path of the designed DB-BPF. It is observed that the two paths are out of phase at both below and above the resonance of the lower passband (Band I). Therefore, two TZs are produced

generated on the low skirt and upper skirt of the higher passband, respectively, as shown in Fig. 7(b).

A comparison of this work with previous DB-BPFs is given in Table II in terms of their center frequencies, 3-dB FBW, insertion losses, return losses, TZs, out-band suppression (Supp.) (which is the ratio of the highest upper stopband frequency with rejection level better 20 dB to the center frequency of the first passband $f_0 = 1.5$ GHz), and circuit size. It is observed that the overall performances of the proposed DB-BPF outperforms the others, especially in the terms of the return loss and circuit size.

Table II. Comparison with previous DB-BPFs.

Ref.	CF/GHz	FBW/%	IL/dB	RL/dB	TZs	Supp.	Size ($\lambda_g \times \lambda_g$)
[1]	3.32/5.32	27.7/19.2	0.62/0.91	20/20	4	$2.70f_0$	0.18×0.40
[2]	3.00/5.34	10.0/3.7	0.19/2.34	13/15	4	NA	0.15×0.26
[3]	1.5/2.35	5.96/7.19	1.43/1.15	22/20	3	$2.33f_0$	0.06×0.14
[4]	2.71/5.05	10.3/8.7	0.2/0.9	NA	2	$7.01f_0$	0.06×0.14
[5]	3.78/4.82	11.3/10.7	1.38/1.82	14/30	>13	$10.5f_0$	0.16×0.31
This work	1.51/3.68	4.25/2.6	1.55/1.63	28/21	6	$6.4f_0$	0.05×0.13

5. Conclusion

A compact second-order DB-BPF with individually controllable passbands and wide stopband is proposed and fabricated using two OSL-SSIRs. The resonance mechanism and frequency variation of the resonator were analyzed in detail. By taking advantages of the OSL-SSIR and multiple mixed electric and magnetic coupling paths, flexible control of the center frequencies and bandwidths of the DB-BPF is achieved, and high selectivity of the passbands and wide stopband are realized. The proposed filter structure and design method are validated well by the measured results.

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