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

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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.

key words: Dual-band bandpass filter, multiple coupling paths, signal interference, transmission zero, wide stopband

Classification: Microwave and millimeter wave devices, circuits, and hardware

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 [3-7], stepped-impedance resonators (SIRs) [8-11], stub-loaded resonators (SLRs) [12-21], other types multi-mode resonators (MMRs) [22-25], 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 the 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 a 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 \( f_H \).

References

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DOI: 10.1587/elex.16.20190127
Received March 7, 2019
Accepted March 11, 2019
Publicized March 22, 2019

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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 \((Y_1, \theta_1)\), a high impedance middle section \((Y_2, \theta_2)\), a short-circuited high impedance section \((Y_3, \theta_3)\), and an open-ended stub section \((Y_4, \theta_4)\). Among the multiple resonances of the OSL-SSIR, the two fundamental resonances with frequencies \(f_s\) and \(f_f\) 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 \(f_s\) is occurred at the T-shaped resonator, and all line sections of the OSL-SSIR have influence on this resonance. On the other hand, as illustrated in Fig. 1(c), the resonance at \(f_f\) is happened at the straight quarter-wavelength SIR, and the open-ended stub has no effect on this resonance. According to above analysis, the input admittances \(Y_{in}\) and \(Y_{out}\) at the two resonant frequencies \(f_s\) and \(f_f\) can be derived as

\[
Y_{in} = Y_{in1} + Y_{in3} \quad \text{at } f_s \tag{1}
\]

\[
Y_{out} = Y_{out1} + Y_{out2} + Y_{out3} \quad \text{at } f_f \tag{2}
\]

where

\[
Y_{in1} = Y_1 \frac{jY_3 \tan \theta + jY_4 \tan \theta_2}{Y_2 - Y_1 \tan \theta \tan \theta_2} \tag{3}
\]

\[
Y_{in2} = jY_4 \tan \theta \tag{4}
\]

\[
Y_{in3} = -jY_1 \cot \theta \tag{5}
\]

To simplify the design, we assume that \(Y_2 = Y_3 = Y_4\) and define the admittance ratio \(K = Y_1/Y_2\). Then, the two resonance frequencies \(f_s\) and \(f_f\) can be determined from the resonance condition \(Y_{in} = 0\) and \(Y_{out} = 0\), respectively, which result in the following two equations:

\[
Y_2(K \tan \theta \tan \theta_2 - 1) \cot \theta_1 + K \tan \theta_1 + \tan \theta_2 = 0 \quad \text{at } f_s \tag{6}
\]

\[
Y_2(K \tan \theta \tan \theta_2 - 1)(\tan \theta_2 - \cot \theta_3) - K \tan \theta_1 - \tan \theta_2 = 0 \quad \text{at } f_f \tag{7}
\]

From (6) and (7), it is seen that \(\theta_3\) has only effect on the higher resonance frequency \(f_f\), but no effect on \(f_s\). 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 shows the variation of the two resonance frequencies \(f_s\) and \(f_f\) with different \(\theta_1, \theta_2, \theta_3, \theta_4\).

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 \(M_{ij}^* = 0.0831\) and \(M_{ij}^* = 0.0499\), and the external quality factors of the two passbands \(Q^* = 13.30\) and \(Q^* = 22.16\) are calculated from the following well-known formulas:

\[
M_{ij}^* = \frac{FBW}{\sqrt{g_ig_j}} \quad \text{for } i = 1 \text{ to } n-1 \tag{8}
\]

\[
Q^* = \frac{g_0g_i}{FBW} \tag{9}
\]

Fig. 4(a) shows the variation of the simulated coupling coefficients between two neighboring OSL-SSIRs with the short-circuited stub width \(W_s\) and the diameter \(d\) of the short-circuited via-hole. It is seen that with the increase of \(W_s\),
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 shows the variation of the coupling coefficients with the folded line length \( L_L \) (when \( S_H = 1 \text{mm} \)) and the gap width \( S_H \) (when \( L_L = 5.8 \text{ mm} \)) 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 \( W_f = 0.25 \text{mm} \)). 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.

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 mm \( \times \) 6.5 mm excluding the feeding structure, which is about \( 0.13 \lambda_g \times 0.05 \lambda_g \), where \( \lambda_g \) is the guided wavelength at the center frequency \( f_L = 1.5 \text{GHz} \) of the lower passband.

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.

![Photograph of the fabricated dual-band BPF.](image)

![Simulated and measured responses of the proposed DB-BPF. (a) Local frequency range response. (b) Wide frequency range response.](image)
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 (6.42%).

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 TZ2 is produced by the open-ended stub of the OSL-SSIR. TZ3, TZ4, TZ5, and TZ6 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.

A comparison of this work with previous DB-BPFs is given in Table 2 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 and 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 1 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    | P-I    | −90°| −90°| 90° | 180° (Out Phase)  | TZ2              |         |
|          | Resonance| P-III  | −90°| −90°| 90° | +270°             |                  |         |
|          | Above    | P-I    | −90°| −90°| 90° | −270°             | 180° (Out Phase) | TZ3     |
| Band II  | Below    | P-I    | −90°| −90°| 90° | 180° (Out Phase)  | TZ4              |         |
|          | Resonance| P-III  | −90°| −90°| 90° | +270°             |                  |         |
|          | Above    | P-III  | −90°| −90°| 90° | −270°             | 180° (Out Phase) | TZ5     |

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.

### Table 2 Comparison with previous DB-BPFs.

| Ref. | CF/GHz | FBW/% | IL/dB | RL/dB | TZs | Supp. | Size ($g_0^2$) |
|------|--------|-------|-------|-------|-----|-------|----------------|
| [1]  | 3.25/3.32 | 27.7/19.2 | 0.62/0.91 | 20/20 | 4   | 2.76μm | 0.18/0.40     |
| [2]  | 3.065/3.34 | 10.0/3.7 | 0.19/2.4 | 13/15 | 4   | NA    | 0.13/0.26     |
| [3]  | 3.15/3.35 | 5.96/5.19 | 1.40/1.15 | 22/20 | 3   | 2.33μm | 0.06/0.14     |
| [4]  | 2.71/1.05 | 10.38/7.2 | 0.2/0.9 | NA   | 2   | 7.01μm | 0.06/0.14     |
| [5]  | 3.78/4.83 | 11.3/10.7 | 1.38/1.82 | 14/36 | +13 | 10.5μm | 0.16/0.31     |
| This work | 1.51/3.68 | 4.28/2.6 | 1.55/1.63 | 28/21 | 6   | 6.46μm | 0.05/0.13     |

### 5. Conclusion

This work was supported in part by the Grant-in-Aid for Scientific Research (KAKENHI 17K06373) from the Japan

Table 1 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 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 generated on the low skirt and upper skirt of the higher passband, respectively, as shown in Fig. 7(b).
Society for the Promotion of Science, and in part by the National Science Foundation of China (No. 61461020, 61728106), in part by the Young Natural Science Foundation of Jiangxi Province (No. 20171BAB212001) and Application Incubation Foundation (2018BBE58016).

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