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Reconfigurable Single-/Dual-Wideband Bandpass Filters Based on a Novel Topology

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Abstract: Based on a new topology, a series of single-/dual-wideband bandpass filters (SWB/DWB BPFs) with reconfigurable masses of properties are presented. The proposed design starts from a dual-wideband passive filtering structure, which owns five transmission zeros in the stopbands and three transmission poles in each passband. Then, three capacitors are employed as the tuning elements. By controlling these three capacitors, DWB BPFs with different reconfigurable properties, including three independently tunable passband edges, tunable center frequency of lower passband with fixed absolute bandwidth, tunable bandwidth of lower passband with fixed center frequency, and switchable lower passband, can be realized. In addition, SWB BPF with tunable bandwidth also can be achieved by varying the inserted capacitors. For verification, a prototype with different capacitors is designed and fabricated. As the measured and simulated results agree well with each other, a simple design approach of reconfigurable SWB/DWB BPFs can be verified.

Keywords: single-/dual wideband; bandpass filter; tunable bandwidths; tunable center frequency; switchable passband

1. Introduction

In the high-data telecommunication systems, single-/dual-wideband bandpass filters (SWB/DWB BPFs) with compact size and good responses play an important role, and various approaches have been proposed for such filters [1–5]. For example, SWB BPF without reflection can be designed by using multilayered substrate [2]. Meanwhile, DWB BPF with a controllable stopband has been designed based on terminated multi-mode resonator [4]. Although all the desired responses can be achieved in the above filters, they still could not satisfy the requirements of modern multi-service wireless systems, which need filters with different reconfigurable properties to reduce the design complexity, cost, and size.

Early developments in reconfigurable BPFs mainly focused on center-frequency tuning [6–10]. For example, the center frequency of a four-pole SWB BPF can be varied from 1.05 GHz to 1.40 GHz while its corresponding absolute bandwidth is fixed about 134.5 MHz [8]. However, little effort has been devoted to DWB ones with fixed absolute bandwidths. Later, research on the switchable passbands

and tunable bandwidths were added [11–23]. Compared to SWB BPFs with tunable bandwidth [11–14] and dual-band BPFs with switchable passbands [15–17], much less efforts have been devoted to DWB ones with tunable bandwidths, and only six *IEEE* journal papers have been reported [18–23]. As the tunable-bandwidth filters in [18–20] are based on in-parallel BPF cascades, some drawbacks, i.e., small bandwidth and tuning ranges, and limited center frequency ratio, exists. To tackle these, an alternative method based on one transmission path is proposed [21–23]. However, some tunable properties, such as independently tunable bandwidth of lower passband with fixed center frequency, have never been reported. In addition, no more than two passband edges can be tunable independently in a reported DWB BPF. The lack of study on DWB BPFs with tunable bandwidths will largely restrict the development of modern telecommunication. Therefore, it is very important to explore novel topologies, whose aim is to design SWB/DWB BPFs with new and numerous reconfigurable properties in designing advanced transceivers for practical applications of high-performance systems effectively and conveniently.

In this paper, a novel topology for the design of SWB/DWB BPFs with masses of reconfigurable properties is proposed. The novel topology is based on a DWB passive filtering structure, which is formed by a T-shaped resonator with two parallel-coupled lines (PCLs) and three open-ended stubs. After theoretically analyzing, it is found that the passive filtering structure owns three transmission poles (TPs) in each passband and five transmission zeros (TZs) in the stopbands. Three capacitors are then inserted as the tuning elements. By controlling the inserted elements, it is found that three passband edges can be independently tunable. In addition, other reconfigurable properties, i.e., tunable center frequency of lower passband with fixed absolute bandwidth, tunable bandwidth of lower passband with fixed center frequency, and switchable lower passband, can be directly derived. Furthermore, SWB BPFs with independently tunable first passband edge can also be designed by using the proposed topology. To verify these, a prototype with different capacitors is designed and measured. To the best of the authors' knowledge, a single prototype, which can achieve SWB BPFs with tunable bandwidth, and DWB BPFs with tunable bandwidths, tunable center frequency, and switchable passband simultaneously, has never been reported before.

Except for the introduction in Section 1, the discussions of proposed topology with emphasis on TP/TZ analysis and reconfigurable properties are presented in Section 2. In Section 3, the design and implementation of the reconfigurable SWB/DWB BPFs are illustrated with the comparison with the simulated and experimentally measured results. A conclusion is summarized in Section 4.

2. Operation Principle and Design

As shown in Figure 1, the novel topology is composed of a passive filtering structure with three capacitors. The passive filtering structure starts from a terminated T-shaped resonator with open terminations, whose characteristic impedances and electrical length are Z_3 , Z_2 , Z_3 , and $\theta = \pi/2$ at the operating frequency f_0 , respectively. Thus, its input impedance can be written as

$$Z_{in}^T = jZ_2 \frac{2Z_2 \tan^2 \theta - Z_3}{(2Z_2 + Z_3) \tan \theta} \quad (1)$$

Based on (1), it is apparent that the T-shaped resonator owns a pole f_{p1}^T and two zeros of f_{z1}^T , f_{z2}^T . For arbitrary Z_2 and Z_3 , the relationship of $f_{z1}^T < f_{p1}^T = f_0 < f_{z2}^T$ exists. To incorporate it for a dual-band BPF with good filtering responses, extra poles and zeros should be introduced, while the intrinsic pole of f_{p1}^T must be eliminated. Therefore, a pair of PCLs and three shunt open-ended stubs are added. The parameters of Z_{oe} , Z_{oo} , and θ present the characteristic impedances and electrical length of PCLs, while Z_1 , Z_4 , Z_1 , and θ_L , θ , θ_R denote those of the added stubs, where $\theta_L = \theta_1 + \theta_2$, and $\theta_R = \theta_1 + \theta_3$.

Figure 1. The novel topology for the proposed filters ($\theta_L = \theta_1 + \theta_2$, $\theta_R = \theta_1 + \theta_3$).

2.1. Transmission Poles and Zeros

To simplify the theoretical analysis, we assume $\theta_L = \theta_R = \theta$ at first. Under this condition, the passive filtering structure is symmetrical. Hence, its TPs can be determined by using even–odd-mode analysis method. Figure 2 depicts the odd- and even-mode equivalent circuits. After analyzing the odd-mode equivalent circuit in Figure 2a, its input admittance can be written as

$$Y_{ino} = \frac{2jA \tan \theta}{(A^2 - B^2) - B^2 \tan^2 \theta} + j \frac{1}{Z_1} \tan \theta \quad (2)$$

where

$$A = Z_{oe} + Z_{oo} \quad (3)$$

$$B = Z_{oe} - Z_{oo} \quad (4)$$

Figure 2. (a) Odd- and (b) even-mode equivalent circuits ($\theta_L = \theta_R = \theta$).

Under the condition that Y_{ino} is zero, two odd-mode resonant frequencies can be determined as

$$f_{op1} = f_0 - \frac{2f_0}{\pi} \arctan \left(\sqrt{\frac{A^2 - B^2 + 2AZ_1}{B^2}} \right) \quad (5)$$

$$f_{op2} = f_0 + \frac{2f_0}{\pi} \arctan \left(\sqrt{\frac{A^2 - B^2 + 2AZ_1}{B^2}} \right) \quad (6)$$

For the even-mode equivalent circuit in Figure 2b, its input admittance can be expressed as

$$Y_{ine} = j\frac{1}{Z_1} \tan \theta + \frac{2Y_L A \tan \theta + 4j \tan^2 \theta}{2A \tan \theta + jY_R(B^2 \tan^2 \theta + B^2 - A^2)} \quad (7)$$

where

$$Y_R = j\frac{1}{2Z_4} \tan \theta + \frac{1}{2Z_{in}^T} \quad (8)$$

When Y_{ine} is zero, two pairs of even-mode resonant frequencies can be obtained as

$$f_{ep1} = f_0 - \frac{2f_0}{\pi} \arctan \sqrt{\frac{\Delta_2 + \sqrt{\Delta_2^2 - 4\Delta_1\Delta_3}}{2\Delta_1}} \quad (9)$$

$$f_{ep2} = f_0 - \frac{2f_0}{\pi} \arctan \sqrt{\frac{\Delta_2 - \sqrt{\Delta_2^2 - 4\Delta_1\Delta_3}}{2\Delta_1}} \quad (10)$$

$$f_{ep3} = f_0 + \frac{2f_0}{\pi} \arctan \sqrt{\frac{\Delta_2 - \sqrt{\Delta_2^2 - 4\Delta_1\Delta_3}}{2\Delta_1}} \quad (11)$$

$$f_{ep4} = f_0 + \frac{2f_0}{\pi} \arctan \sqrt{\frac{\Delta_2 + \sqrt{\Delta_2^2 - 4\Delta_1\Delta_3}}{2\Delta_1}} \quad (12)$$

where

$$\Delta_1 = Z_2^2 B^2 \quad (13)$$

$$\Delta_2 = 2Z_2^2(4AZ_4 + 2AZ_1 + 8Z_4 + A^2 - B^2) + B^2(Z_2Z_3 + Z_3Z_4 + 4Z_2Z_4) \quad (14)$$

$$\Delta_3 = (Z_2Z_3 + Z_3Z_4 + 4Z_2Z_4)(2AZ_1 + A^2 - B^2) + 4Z_2Z_3Z_4(A + 2Z_1) \quad (15)$$

To achieve sharp skirt selectivity and ensure high isolation levels, TZs are essential. For this topology, its TZs can be determined by using even-odd-mode analysis method and S-parameters theory together. The transmission coefficient S_{21} can be written as

$$S_{21} = \frac{Y_0(Y_{ine} - Y_{ino})}{(Y_{ino} + Y_0)(Y_{ine} + Y_0)} \quad (16)$$

After some algebraic operations, three TZs can be obtained and written as

$$f_{z1} = \frac{2f_0}{\pi} \arctan\left(\sqrt{\frac{Z_3}{2Z_2}}\right) \quad (17)$$

$$f_{z2} = f_0 \quad (18)$$

$$f_{z3} = 2f_0 - \frac{2f_0}{\pi} \arctan\left(\sqrt{\frac{Z_3}{2Z_2}}\right) \quad (19)$$

It is apparent that the passive filtering structure owns six TPs and three TZs when $\theta_L = \theta_R = \theta$, and all the TPs and TZs are symmetrical to f_0 . In addition, the relationships of $f_{z1} < f_{ep1} < f_{op1} < f_{ep2} < f_{z2} = f_0 < f_{ep3} < f_{op2} < f_{ep4} < f_{z3}$ always hold for arbitrary Z_1 , Z_{oe} , Z_{oo} , Z_2 , Z_3 , and Z_4 . Hence, the proposed topology is suitable to design triple-mode DWB BPFs. Furthermore, the filter bandwidths are mainly controlled by the locations of $f_{ep1,2,3,4}$, while the skirt selectivity near the first and fourth passband edges are mainly determined by those of f_{z1} and f_{z2} . To better understand this, TPs/TZs with respect to different characteristic impedances of Z_1 , Z_2 , Z_3 , Z_4 , Z_{oo} , and Z_{oe} , are shown in Figure 3.

Obviously, the locations of f_{ep1} and f_{ep4} are sensitive to Z_2 and Z_3 , while the locations of f_{ep2} and f_{ep3} are mainly determined by Z_{00} and Z_{0e} . Reflected to filter responses, the first and fourth passband edges will move closer to each other as Z_2 decreases or Z_3 increases, and the second and third ones will move apart as Z_{00} decreases or Z_{0e} increases. Hence, a filter with a wide bandwidth should own large Z_2 and small Z_3 , while a filter with a large center frequency ratio need choose small Z_{00} and large Z_{0e} . For the rest of the parameters, they are used to ensure good matching in each passband and sharp skirt near the first and fourth passband edges.

Figure 3. Transmission poles/ transmission zeros (TPs/TZs) with respect to varied characteristic impedances of (a) Z_1 ; (b) Z_2 ; (c) Z_3 ; (d) Z_4 ; (e) Z_{00} ; (f) Z_{0e} (The reference parameters are: $Z_1 = 500 \Omega$, $Z_2 = 40 \Omega$, $Z_3 = 80 \Omega$, $Z_4 = 160 \Omega$, $Z_{00} = 63 \Omega$, $Z_{0e} = 160 \Omega$).

Due to the lack of TZs near the second and third passband edges, the corresponding selectivity is poor under the condition that $\theta_L = \theta_R = \theta$. To deal with this, the electrical length of θ_L and θ_R should be studied. To better demonstrate these, a revised topology for the theoretical analysis is shown in Figure 4. First of all, $\Delta\theta = 1.11(\theta - \theta_L) = \theta_R - \theta$. When $\Delta\theta$ is zero, there is only one TZ between passbands, as analyzed above. As $\Delta\theta$ increases, another two TZs of f_{I1} and f_{I2} are introduced and move apart gradually. Meanwhile, TPs of $f_{ep2,3}$ and $f_{op1,2}$ move apart slightly. For the rest of the TPs/TZs, they are maintained unaltered, as shown in Figure 5. Hence, the skirt selectivity of the passive filtering structure near the second and third passband edges can be improved by generating TZs of f_{I1} and f_{I2} through suitably choosing θ_L and θ_R . Furthermore, the relationships among f_{I1} , f_{I2} , θ_L , and θ_R can be approximately obtained as

$$f_{I1} \approx \frac{\pi}{2\theta_R} f_0 \quad (20)$$

$$f_{I2} \approx \frac{\pi}{2\theta_L} f_0 \quad (21)$$

Figure 4. The revised topology for theoretical analysis ($\theta_L = \theta_1 + \theta_2$, $\theta_R = \theta_1 + \theta_3$).

Figure 5. TPs and TZs with respect to different $\Delta\theta$.

One thing should be noted: whatever the electrical lengths of θ_L and θ_R are, the relationships of $f_{z1} < f_{ep1} < f_{op1} < f_{ep2} < f_{I1} < f_{z2} = f_0 < f_{I2} < f_{ep3} < f_{op2} < f_{ep4} < f_{z3}$ always exist. Hence, the second and third passband edges can be independently controlled by varying θ_L and θ_R , as the ones in [4,23].

2.2. Reconfigurable Properties

To realize the desired reconfigurable properties, some tuning elements should be inserted into the passive filtering structure. At first, a lumped capacitor C_F is employed as one of the tuning elements,

which is located at the middle of the lower stub of T-shaped resonator with open terminations. Under this condition, the input impedance of T-shaped resonator with capacitor C_F can be expressed as

$$Z_{in_CF}^T = Z_2 \frac{Z_{in1} + jZ_2 \tan(\theta/2)}{Z_2 + jZ_{in1} \tan(\theta/2)} \quad (22)$$

where

$$Z_{in1} = jZ_2 \frac{Z_3 \tan \theta + 2Z_2 \tan(\theta/2)}{2Z_2 - Z_3 \tan(\theta/2) \tan \theta} + \frac{1}{j\omega C_F} \quad (23)$$

If the inserted capacitor C_F is large enough, the input impedance of T-shaped resonator with capacitor can be simplified to the one without capacitor. Under this condition, the effect of the inserted capacitor on the filter responses is insignificant. With the decrease in C_F , however, the conditions are changed, and the effect of the inserted capacitor C_F on f_{ep1} is much larger than the ones on $f_{ep2}, f_{ep3}, f_{ep4}$. Reflected to the filter responses, the first passband edge can be independently tunable by altering C_F , while the other three are fixed, as illustrated in Figure 6a, where the 3-dB passband edges with TZs for sharp selectivity are depicted with respect to different C_F .

As mentioned in Part A, the second and third passband edges can be independently controlled by varying θ_L and θ_R . Hence, the other two capacitors of C_S and C_T are then inserted into the open-ended stubs with Z_1 for independent tunabilities of these two passband edges. In Figure 6b,c, 3-dB passband edges with TZs for sharp selectivity with respect to different capacitors of C_S and C_T are depicted. Apparently, these two passbands also can be independently tunable by controlling the capacitors of C_S and C_T , respectively.

Figure 6. 3-dB passband edges with TZs for sharp skirt with respect to different (a) C_F ; (b) C_S ; (c) C_T .

According to the theoretical analysis mentioned above, the first and second passband edges can be independently tunable. Thus, the reconfigurable properties, i.e., independently tunable center frequency of lower passband with fixed absolute bandwidth, and independently tunable bandwidth of lower passband with fixed center frequency, can be directly realized by suitably selecting the capacitors of C_F and C_S . Furthermore, it is interesting that the lower passband will disappear when C_F is small and C_S is large enough. Hence, the switchable lower passband also can be achieved. As the third passband edge is independently controlled by the capacitor of C_T , a SWB BPF with tunable bandwidth can be designed too. For verification, a prototype with different capacitors is designed and measured, which will be presented in detail in Section 3.

3. Design Examples

Based on the theory in Section 2, a simple and effective design procedure for the desired prototype can be concluded as:

- (1) On the basis of DWB BPF with the widest bandwidth, initially determine the design parameters of the passive filtering structure, i.e., $Z_1, Z_2, Z_3, Z_4, Z_{00}, Z_{0e}, \theta_1, \theta_2$, and θ_3 .
- (2) Based on the different locations of first and third passband edges, determine C_F and C_T .
- (3) Based on the various locations of second passband edge, determine C_S and θ_3 .
- (4) After slightly optimizing, obtain the final parameters.

On the basis of the above procedure, the design parameters of a reconfigurable DWB BPF with widest fractional bandwidths (FBWs) of 25.7%, 17.5%, and center frequencies (CFs) of 2.82 GHz and 4.12 GHz can be concluded as: $Z_1 = 500 \Omega, Z_2 = 40 \Omega, Z_3 = 80 \Omega, Z_4 = 160 \Omega, Z_{00} = 63 \Omega, Z_{0e} = 160 \Omega, \theta_1 = 40^\circ, \theta_2 = 47.6^\circ, \theta_3 = 54.2^\circ, C_F = C_T = 100 \text{ pF}, C_S = 2.4 \text{ pF}$, and $f_0 = 3.47 \text{ GHz}$. Then, the reconfigurable properties can be achieved by only changing the inserted capacitors. As the fabricated filter is implemented on Rogers RO4003B with dielectric constant of 3.38 mm and thickness of 0.813 mm, its dimensions and layout can be determined with the aid of commercial software, as shown in Figure 7. In this layout, a design skill is used: to enlarge the equivalent value of Z_1 and enhance the coupling strength of PCLs, some parts of the open-ended stubs with Z_1 are parallel to PCLs.

Figure 7. Layout of the fabricated filter ($l_1 = 12.2 \text{ mm}, l_{1_L} = 2.05 \text{ mm}, l_{1_R} = 4.35 \text{ mm}, w_1 = 0.3 \text{ mm}, s_1 = 0.5 \text{ mm}, l_F = 13.6 \text{ mm}, w_F = 0.3 \text{ mm}, s_F = 0.1 \text{ mm}, l_2 = 13.75 \text{ mm}, w_2 = 2.4 \text{ mm}, l_3 = 13.4 \text{ mm}, w_3 = 0.1 \text{ mm}, l_{4_V} = 3.6 \text{ mm}, l_{4_H} = 10.8 \text{ mm}, w_4 = 0.1 \text{ mm}$).

The filtering responses under different cases are measured by a Keysight N5224A network analyzer. For Case A with $C_F = C_T = 100 \text{ pF}$, and $C_S = 2.4 \text{ pF}$, the corresponding measured results are plotted with the simulated ones in Figure 8. Apparently, they agree well with each other, except for some slight discrepancies, which are caused by the fabrication and measured tolerances. Under the condition that the matching is better than 10.0 dB, the measured FBWs are 26.6%, 17.8% with CFs of 2.82 GHz and 4.10 GHz for the first and second passbands, respectively. In addition, over 20-dB insertion loss can be found in the stopband between two passbands from 3.33 GHz to 3.63 GHz, indicating high isolation level. Five TPs for good flatness in the passbands are found at 2.52 GHz, 2.90 GHz, 3.12 GHz,

3.80 GHz, and 4.30 GHz, respectively, while five TZs for sharp skirt and high isolation levels are located at 2.12 GHz, 3.34 GHz, 3.46 GHz, 3.59 GHz, and 4.88 GHz. In addition, the group delay within two passbands is no more than 1.78 ns. The overall size of the fabricated filter is 36.0×25.0 mm.

Figure 8. Filter responses of Case A ($C_F = 100$ pF, $C_S = 2.4$ pF, $C_T = 100$ pF).

3.1. Three Independently Tunable Passband Edges

The simulated and measured S-parameters of Case B with $C_F = 4.7$ pF, $C_S = 2.4$ pF, and $C_T = 100$ pF are shown in Figure 9a. By comparing Case A and B, it is apparent that the first passband edge with matching better than 10.0 dB can independently move upwards from 2.44 GHz to 2.73 GHz with the decreases of C_F from 100 pF to 4.7 pF, while TZ near the first passband edge also moves upwards from 2.12 GHz to 2.42 GHz for sharp skirt. For the other three passband edges and TZs for sharp selectivity, they are unaltered.

Similar to the first passband edge, the second and third ones also can be independently tunable by controlling the capacitors of C_S and C_T . In Figure 9b,c, the simulated and measured results under Case C ($C_F = C_T = C_S = 100$ pF) and D ($C_F = 100$ pF, $C_S = 2.2$ pF, and $C_T = 2.4$ pF) are shown, respectively. Compared with Case A and C, it can be obtained that the second passband edge with matching better than 10 dB moves downwards from 3.19 GHz to 2.96 GHz as C_T increases from 2.4 pF to 100 pF, while TZ near the second passband moves downwards from 3.34 GHz to 3.26 GHz for sharp skirt. By comparing Case A and D, it is obvious that the third passband edge with matching better than 10.0 dB will move upwards from 3.73 GHz to 3.89 GHz with the decrease in C_T from 100 pF to 2.2 pF, while TZs near the third passband are shifted from 3.59 GHz to 3.62 GHz for sharp skirt. For the rest of the passband edges and other TZs, they are unaltered. Hence, the three independently tunable passband edges can be validated.

Figure 9. Cont.

(c)

Figure 9. Filter responses with respect to (a) Case B: $C_F = 4.7$ pF, $C_S = 2.4$ pF, $C_T = 100$ pF; (b) Case C: $C_F = 100$ pF, $C_S = 100$ pF, $C_T = 100$ pF; (c) Case D: $C_F = 100$ pF, $C_S = 2.4$ pF, $C_T = 2.2$ pF.

3.2. Independently Tunable Center Frequency of Lower Passband with Fixed Absolute Bandwidth

As the first and second passband edges can be independently tunable by changing the capacitors of C_F and C_S , respectively, it is apparent that the center frequency of lower passband also can be independently tunable by suitably selecting these two capacitors, while the corresponding absolute bandwidth is fixed. This reconfigurable property is validated by comparing Case B and C. By gradually decreasing C_F from 100.0 pF to 2.4 pF and suitably choosing the capacitor of C_S , the center frequency of lower passband can be continuously shifted from 2.71 GHz to 2.97 GHz, while the absolute bandwidth with matching better than 10.0 dB is about 0.49 GHz. For the upper passband, it is fixed. Hence, the fractional tuning range of lower passband is 9.6%, and the corresponding constant FBW is 18.1%.

One thing should be noted: only two reported *IEEE* journal papers concern the tunable center frequencies of dual-band BPFs with constant absolute bandwidths, which are presented in [9] and [17]. Unfortunately, their constant FBWs are narrow and no more than 9.3%. Hence, the proposed design should be beneficial to exploration of other tunable-center-frequency DWB BPFs with constant absolute bandwidths.

3.3. Independently Tunable Bandwidth of Lower Passband with Fixed Center Frequency

Among the reported tunable DWB BPFs, there is no report of the independently tunable bandwidth of lower passband with constant center frequency, which will restrict the development of telecommunication. In this part, this desired reconfigurable property is implemented.

As the first passband edge will move downwards with the increase in C_F , and the second one will move upwards with the decrease in C_S , the bandwidth of lower passband can be tunable in continue manners by gradually increasing C_F and decreasing C_S simultaneously, while the corresponding center frequency and upper passband is unchanged. This reconfigurable property can be validated by comparing Case A and E ($C_F = 4.8$ pF, $C_S = 6.2$ pF, $C_T = 100$ pF), whose simulated and measured results are depicted in Figure 10. By suitably decreasing C_F from 100 pF to 4.8 pF and increasing C_S from 2.4 pF to 6.2 pF, the FBW of the lower passband is varied from 26.6% to 9.9%, and the corresponding center frequency is about 2.83 GHz. Meanwhile, TZs near the first and second passband edges are shifted from 2.12 GHz and 2.40 GHz to 3.34 GHz and 3.29 GHz, respectively. Furthermore, the upper passband is unaltered. Hence, DWB BPF with independently tunable bandwidth and fixed center frequency of lower passband can be designed.

Figure 10. Filter responses of Case E ($C_F = 4.8$ pF, $C_S = 6.2$ pF, $C_T = 100$ pF).

3.4. Independently Switchable Lower Passband

Although the switchable dual-band BPFs have been studied extensively, their corresponding passbands are relatively small, as presented in [15–17]. In other words, there is no DWB BPF with independently switchable passbands reported. Therefore, the successful design of DWB BPFs with switchable bandwidth should be beneficial to the modern telecommunication.

As mentioned in Case A with $C_F = C_T = 100$ pF, and $C_S = 2.4$ pF, there are two passbands with FBWs of 26.6% and 17.8%. Then, the lower passband will be changed into a stopband under the condition of Case F with $C_F = 1.5$ pF, $C_S = 100$ pF, and $C_T = 100$ pF, while the upper one is almost fixed, as depicted in Figure 11. Thus, the lower passband can be independently switchable.

Figure 11. Filter responses of Case F ($C_F = 1.5$ pF, $C_S = 100$ pF, $C_T = 100$ pF).

3.5. Independently Tunable First Passband Edge of SWB BPF

Considering that the lower passband will be changed into a stopband by selecting the suitable capacitors of C_F and C_S , and the third passband edge can be independently tunable by controlling the capacitor of C_T , SWB BPFs with tunable bandwidth can be designed based on this novel topology. This is verified by comparing Case F and G. As shown in Figures 11 and 12, the first passband edge of SWB BPFs is shifted from 3.76 GHz to 4.07 GHz with the decrease in C_T from 100 pF to 1.4 pF, while the other one is fixed about 4.50 GHz. In addition, TZ near the first passband edge of SWB BPFs is varied from 3.58 GHz to 3.76 GHz. Thus, a SWB BPF with tunable-bandwidth range of 7.5% can be designed.

In Figure 13, the photograph of the fabricated filter is given. To vividly demonstrate this topology, the simulated and measured results under different cases are listed in Table 1. One thing should be noted—the insertion loss in the passband is no more than 1.4 dB for all the cases, while the group delay is less than 2.35 ns. To demonstrate the advantages of this design, a comparison with some previous works is presented in Table 2. Obviously, the proposed work can not only be used to

design SWB BPFs with tunable bandwidth, but also DWB BPFs with tunable center frequency, tunable bandwidth, and switchable passband. Considering the new reconfigurable properties, i.e., tunable bandwidth of lower passband with fixed absolute center frequency, the proposed work can reduce the design complicity and circuit size of multi-functional wireless communication systems effectively and conveniently.

Figure 12. Filter responses of Case G ($C_F = 1.5$ pF, $C_S = 100$ pF, $C_T = 1.4$ pF).

Figure 13. The photograph of the fabricated filter.

Table 1. Simulated and measured results under different cases.

		Lower Passband		Upper Passband				Lower Passband		Upper Passband	
		First ¹	Second ²	Third ³	Fourth ⁴			First ¹	Second ²	Third ³	Fourth ⁴
Case A	Simulated	2.48 GHz	3.20 GHz	3.74 GHz	4.48 GHz	Case E	Simulated	2.73 GHz	2.96 GHz	3.75 GHz	4.48 GHz
	Measured	2.44 GHz	3.19 GHz	3.73 GHz	4.46 GHz		Measured	2.70 GHz	2.98 GHz	3.74 GHz	4.48 GHz
Case B	Simulated	2.75 GHz	3.21 GHz	3.74 GHz	4.48 GHz	Case F	Simulated	N/A	N/A	3.78 GHz	4.49 GHz
	Measured	2.73 GHz	3.21 GHz	3.75 GHz	4.49 GHz		Measured	N/A	N/A	3.76 GHz	4.51 GHz
Case C	Simulated	2.48 GHz	2.93 GHz	3.75 GHz	4.47 GHz	Case G	Simulated	N/A	N/A	4.09 GHz	4.49 GHz
	Measured	2.47 GHz	2.96 GHz	3.72 GHz	4.48 GHz		Measured	N/A	N/A	4.07 GHz	4.49 GHz
Case D	Simulated	2.48 GHz	3.19 GHz	3.92 GHz	4.48 GHz						
	Measured	2.44 GHz	3.17 GHz	3.89 GHz	4.47 GHz						

First¹: First passband edge with matching better than 10.0 dB; Second²: Second passband edge with matching better than 10.0 dB; Third³: Third passband edge with matching better than 10.0 dB; Fourth⁴: Fourth passband edge with matching better than 10.0 dB.

Table 2. Comparison with previous works.

	SWB BPFs		DWB BPFs			SWB BPFs		DWB BPFs	
	TBW ¹	TCF ²	TBW ¹	SPB ³		TBW ¹	TCF ²	TBW ¹	SPB ³
[9]	No	Yes	No	No	Filter B in [17]	No	Yes	No	Yes
[10]	No	Yes	No	No	Filter B in [20]	No	No	Yes	No
[12]	Yes	No	No	No	Filter B in [22]	No	Yes	Yes	No
[13]	Yes	No	No	No	This work	Yes	Yes	Yes	Yes
[16]	No	No	No	Yes					

TBW¹: tunable bandwidth; TCF²: tunable center frequency; SPB³: switchable passband.

4. Conclusions

In this paper, a novel topology is presented for the design of SWB/DWB BPFs with different reconfigurable properties. This design is based on a dual-wideband passive filtering structure with three TPs in each passband and five TZs in the stopbands, and three capacitors are used as the tuning elements. By controlling the inserted capacitors, it is found that SWB BPFs with tunable bandwidth, and DWB BPFs with tunable center frequency, tunable bandwidths, and switchable passband, can be achieved simultaneously. For verification, a prototype with different capacitors is designed and fabricated. Obviously, the simulated and measured results are in good agreement. Considering that the proposed design owns novel and masses of reconfigurable properties, it is anticipated that this filter can be broadly used in the modern multi-functional telecommunication systems.

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