

# Dual-Mode Dual-Band Bandpass Filter with High Cutoff Rejection by Using Asymmetrical Transmission Zeros Technique

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**Abstract**—A dual-mode dual-band bandpass filter with high cutoff rejection using an asymmetrical transmission zeros technique is presented here. Two dual-mode filters are combined to form a dual-band filter by sharing the input and output coupled-feed line, which is more flexibly designed and maintains a small circuit size. Controllable asymmetrical transmission zeros (TZs) at lower- and upper-sideband locations of dual-band filters are designed to achieve the high-selectivity dual-mode dual-band bandpass filter. Unwanted signals are suppressed by the location of the TZs between the first and second passbands, which gives a much-improved signal selectivity for the dual-band bandpass filter. The two passbands are centered at 1.8 and 2.4 GHz, respectively. The first and second passbands' insertion losses are only 0.9 dB and 1.1 dB, respectively, and the measured return losses are better than 20 dB. Three transmission zeros are located between the two passbands, which achieve rejection levels about 40 dB attenuations from 1.9 to 2.3 GHz.

## 1. INTRODUCTION

In modern wireless and mobile communication systems, a filter is a significant component in both the receiver and transmitter's RF front ends. It can be made using different materials. Well-known filter structures are planar filters because they can be manufactured utilizing printed circuit technology. Due to their compact size, light weight, and low cost, planar filters are appropriate for commercial application integration [1]. Multiband bandpass filter (BPF) is a vital device within the receiver and transmitter's RF/microwave front ends. Dual-band filters have been represented widely as an essential circuit block in modern wireless communication systems. A variety of dual-band filter techniques have been studied in the literature. A bandpass filter and band-stop filter are cascaded in the form of a dual-band filter [2]. This technique is designed in the form of a wideband and then uses a band-stop filter to separate the wideband into two bandpass filters (dual-band filter). A step-impedance resonator for multiband responses is designed in a cascaded multiband filter [3]. The dual-band filter has two tunable passbands by incorporating step-impedance resonators in a comb-filter topology [4]. The dual-band filter uses coupling feed structures to feed signals to the resonator filter, but this requires a dual-band matching network [5]. Cross-coupled filters with a dual-passband quasi-elliptic function response have a high order resonator filter to achieve sharp cutoff, and a high order filter is required, which introduces more complexities [6]. Cascading multiple  $\lambda/2$  stepped-impedance resonators (SIRs) uses distributed parallel-coupled microstrip lines [7] and has an increase in circuit size. As mentioned earlier, most of the research works are based on a single-mode resonator filter design in which the sharp cutoff responses are dependent on the filter degrees.

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In addition, many design approaches have been proposed to develop dual-band BPFs for multi-service communication systems — for example, the interdigital dual-band interdigital BPF with controlled bandwidth using a coupled interdigital resonator [8] and half-mode substrate integrated waveguide (HMSIW) resonators [9]. However, they have a complex structure. A varactor-tuned microstrip dual-band BPF is based on tri-mode stub-loaded stepped-impedance resonators [10]. Moreover, the multiband bandpass filter design concept is to add some extra coupled-resonator sections in a single-circuit filter to increase the degrees of extracting coupling coefficients of a multiband filter [11]. A controllable multi-mode resonator is designed and implemented based on substrate integrated suspended line (SISL) technology, but a complicated structure and technology are required [12]. Dual-band microstrip filters using folded open-loop ring resonators with second-order filter [13] use a long, cumbersome coupled-feed line. A dual-band bandpass filter has a flexible band by control and simple layout, but incorporates high order degree filters with a single-mode resonator [14]. However, increasing the number of resonator filters is the prime parameter to design a filter with shaft cutoff rejection, and a more complex circuit is also produced. A single-mode open-loop resonator focuses only on the odd-mode resonance, as presented in [15, 16]. This resonator is used as a basic structure of the dual-mode resonator. Typically, an even-mode resonance will occur at twice of the fundamental resonant frequency and degrade the filter response at the fundamental mode frequency. The use of an even-mode can make a doubly tuned circuit more compact but also offers significantly low insertion loss [17, 18].

Furthermore, designing a dual-band bandpass filter with high cutoff rejection out of the passband is still challenging. Using an alternative technique to develop a dual-band filter with a simple structure and efficient frequency responses was presented using a coupled line feeder [8]. Due to the small size and high cutoff rejection of the resonator filter, the dual-mode resonator is widely used to achieve this kind of requirement. Moreover, it is also necessary to consider the out-of-band signal rejection in the dual-band filter in order to improve the passband signal. The first and second frequency bands' proximity can be improved by using asymmetric filter responses [19].

This paper presents a dual-mode dual-band bandpass filter with high cutoff rejection using the asymmetrical transmission zeros (TZs) technique. The idea behind this efficiency improvement of dual-band frequency responses is that the dual-mode dual-band bandpass filter structure has controllable TZs near the passband by using a tuning, opened-end stepped impedance resonator, which enables a compact circuit size. This opened-end stepped-impedance resonator achieves ease of asymmetrical frequency response and broad stopband rejection. This efficient technique can suppress the attenuation between the first resonant frequency and the second resonant frequency. The two independent dual-mode bandpass devices are efficiently designed using the same coupled feed lines to combine them. This method provides an easy design and fabrication process.

## 2. ANALYSIS OF DUAL-MODE RESONATOR STRUCTURE

A dual-band filter with high cutoff rate frequency responses is based on combining two independently different dual-mode resonator filters in this research work. Sharing the same coupled feed input/output at the middle of two independent dual-mode filters to form a dual-mode dual-band filter behavior makes the structure easier to assemble. The asymmetrical TZs method is applied to design the dual-mode dual-band filter to offer higher cutoff rejection. The controllable TZs at the lower or higher sideband are introduced in this section. Each step for both the dual-mode resonator filters for the first and second channels is presented here. The independent design of the two dual-mode filters in the dual-mode dual-band filter is mentioned in the following steps:

Step 1: The first dual-mode filter is designed at the center frequency of 1.8 GHz with 50 MHz bandwidth, and the TZ is placed at the upper sideband.

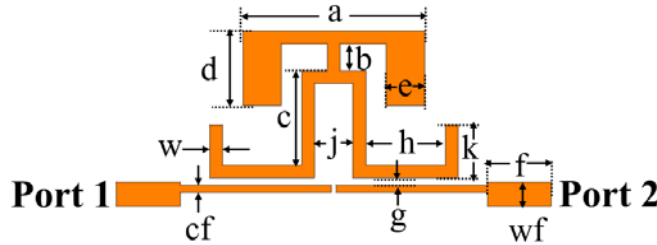
Step 2: The dual-mode filter is designed at the center frequency of 2.4 GHz with 80 MHz bandwidth, and the TZ is placed at the lower or upper sideband. When the controllable TZ is changed, the cutoff rate of the proximity frequency is improved.

Step 3: Finally, the dual-mode dual-band bandpass filter is achieved by combining the two dual-mode filters with coupled-feeders, in which the two dual-mode filters are designed independently and combined by using the same coupled-feed line to form a dual-mode dual-band filter.

Typically, a single-mode resonator filter considers only the odd-mode resonance, as in [15, 16], as

the even-mode is of little use in single-band resonator filter synthesis. Because even-mode will appear as the first spurious response, which degrades the filter performance, by the way, the even-mode of dual-mode filters can be useful to make a doubly tuned circuit [17], which will create a circuit with small size and low insertion loss.

As the dual-mode resonator filter is designed by using the advantage of even-mode resonance, which tunes the second frequency (even mode) to the operating frequency band (the odd mode), a two-pole second order filter can be created by this dual-mode resonator behavior. The schematic topology of the dual-mode filter is shown in Figure 1. When the open-circuited stub is added and placed in the center of the filter, the even-mode moves to lower the resonant frequency near the fundamental frequency (odd mode). The extended stepped-impedance open stub shown has no effect on the odd mode [17]. Therefore, the two modes (odd mode and even mode) can be tuned independently.



**Figure 1.** Structure of the proposed dual-mode microstrip with stub-loaded resonator.

Figure 2 shows the equivalent circuits of even and odd modes at a resonant frequency. The even-mode resonator is represented by a stepped-impedance open-circuited half-wavelength type resonator, while a short circuited quarter-wavelength resonator represents the odd mode.



**Figure 2.** (a) Equivalent layout of the even-mode resonator; (b) odd-mode resonator.

For an example demonstration, the stepped impedance resonator can be tuned as the dual-mode resonator filter design. The open-circuited stub length is reduced and can also be easily employed to achieve dual-mode filter performance [18]. Two sections of different impedances can be demonstrated as the open-circuited stub illustrated in Figure 1. The calculation of dual-mode resonator dimensions is described by using the following equations

$$\theta_1 \cong \frac{\pi}{2} \quad (1)$$

The stepped impedance stub ( $Z_2$ ,  $Z_3$ ) connects to the middle of the resonator ( $Z_1$ ) to tune the even mode close to the odd mode, where  $\alpha Z_2$  and  $\beta Z_3$  are the even-mode equivalent impedances of the open stub sections with impedances  $Z_2$  and  $Z_3$ . Let  $R = \beta Z_3 / \alpha Z_2$ , then  $R > 1$  for the stepped impedance resonator and  $\beta Z_3 > \alpha Z_2$  also satisfies the stepped-impedance condition, which reduces the length of the open-stub resonator. The electrical length  $\theta_2$  is obtained by [17].

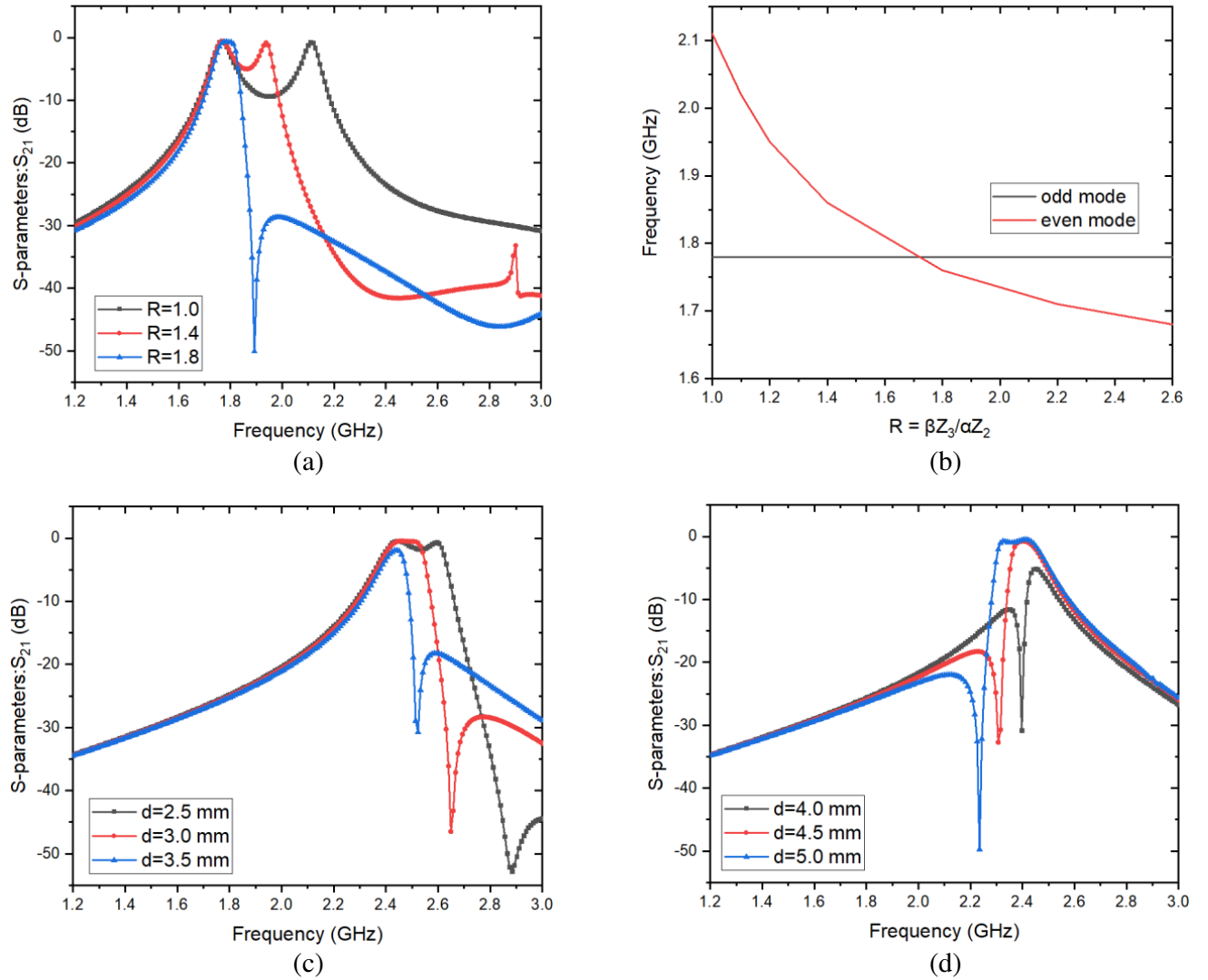
$$\theta_2 = \cos^{-1} \left( \sqrt{\frac{R(R-1)}{(R^2-1)}} \right) \quad (2)$$

Now, the electrical length ( $\theta_3$ ) of the open-circuited stub may then be found from [17]

$$\theta_3 \cong (\pi + a \tan [-R \tan (\theta_2)]) - \left( \frac{c}{4f_{odd}\sqrt{\varepsilon_{eff}}} \right) \quad (3)$$

In which  $\theta_x$  ( $x = 1, 2, 3$ ) is the electrical length of the section in Figure 1, and  $c$  is the light speed in a vacuum.

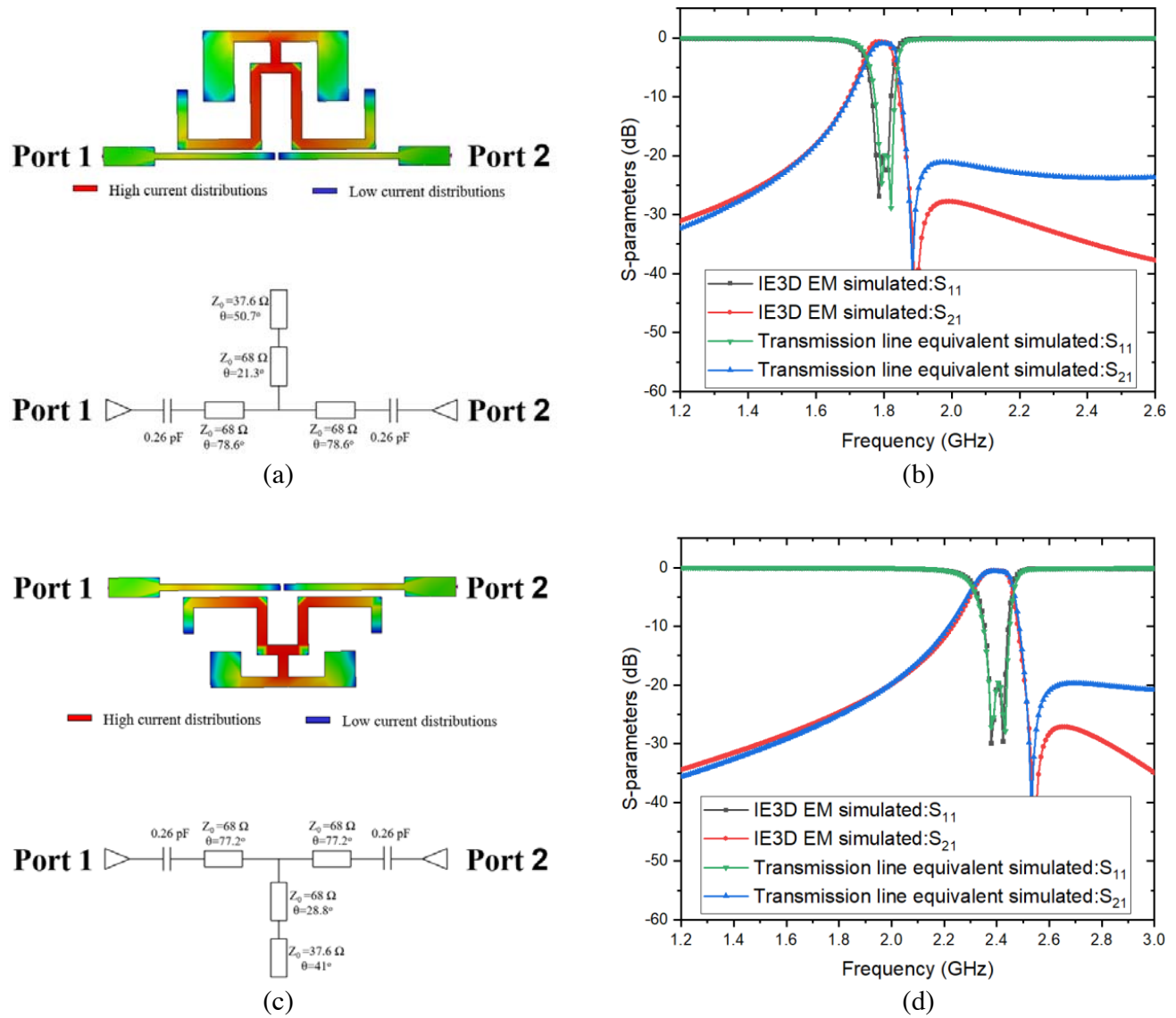
The dual-mode microstrip filters are based upon a microstrip  $\Omega$ -shaped resonator, loaded by an open-ended stepped impedance stub placed in the middle of the microstrip resonator. The dual-mode filters have been designed and fabricated on an RT/Duroid substrate with  $h = 1.27$  mm and  $\varepsilon_r = 6.15$ . IE3D full-wave EM simulator is used to simulate the filter characteristics. The input and output ports are induced to the dual-mode resonator with a  $50\Omega$  feed line having a line width ( $cf$ ) and coupling spacing ( $g$ ), as shown in Figure 1. Upon the external coupling port (input/output port), the first two resonating modes are referred as the odd and even modes. It can be noted that these two modes can appear at the same or different modal frequencies, depending on the size of the stepped-impedance



**Figure 3.** (a) The variation of resonant frequency with the stepped-impedance ratio at 1.8 GHz; (b) plotted variables of  $R = \beta Z_3 / \alpha Z_2$ ; (c) typical frequency responses simulated for transmission zero located at upper sideband of the center frequency of 2.4 GHz; (d) lower sideband of the center frequency of 2.4 GHz with different lengths of the loaded stepped-impedance resonator.

opened-stub resonator placed at the center of the resonator.

The desired operating frequencies against the length of the open-ended stepped impedance resonator placed at the middle of the microstrip  $\Omega$ -shaped resonator have been investigated. The odd-mode (first-mode) frequency is fixed by maintaining the length of the microstrip  $\Omega$ -shaped resonator ( $c, j, h$  and  $k$ ). Even-mode (second-mode) characteristics can be achieved by changing the length of the stepped impedance open circuited stub loaded resonator ( $d$  and  $e$ ). The  $50\Omega$  characteristic impedance lines are used to excite the dual-mode resonator filter's input/output microstrip feeders. When  $R = \beta Z_3 / \alpha Z_2$  then  $R > 1$ . Let  $\beta Z_3 = 68\Omega$  with electrical length  $\theta_3 = 21.3^\circ$  and  $\beta Z_3 = 37.6\Omega$  with electrical length  $\theta_3 = 50.7^\circ$ . Figure 3(a) shows the frequency responses of  $S_{21}$  (odd mode and even mode) with  $R > 1$  at the center frequency of 1.8 GHz. It can be seen that the stepped open-stub resonator's loaded length does not affect the  $S_{21}$  response at the odd-mode resonant frequency. The ratio of  $R$  related to the even and odd-mode is plotted in Figure 3(b). The even-mode frequency is flexibly controlled by changing the



**Figure 4.** Simulated characteristic parameters of dual-mode resonator filters with transmission zeros located at the upper sideband: (a) Current distributions of the operation frequency at 1.8 GHz; (b)  $S$ -parameters of the operating frequency at 1.8 GHz; (c) current distributions of the operating frequency at 2.4 GHz; (d)  $S$ -parameters of the operating frequency at 2.4 GHz.

length of stepped-impedance ( $d$ ), in which the locations of TZs can be changed from the upper sideband to the lower sideband, as shown in Figure 3(c) and in Figure 3(d) at 2.4 GHz. An intrinsic TZ can be easily tuned to optimize the dual-mode filter performance. An asymmetric response is created from the location of TZs, which leads to improving the high selectivity of the dual-mode bandpass filter. It can be explained that the TZ is produced as a direct result of the open-circuited stub, which is used to tune the even-mode frequency.

From Figures 3(c) and 3(d), it can be noted that the TZs are optimized to improve the selectivity of either the upper or the lower stopband. Consequently, the proposed dual-mode resonator filter with controllable TZ can be used to design the dual-band filter with high cutoff rate responses. The locations of TZs are asymmetric responses that depend on the position of even-mode frequency. This is because when the even mode moves close to the fundamental mode, the asymmetric frequency response is due to the even mode's position. If the even mode is put above the odd mode, the TZs will occur at the fundamental mode's upper side. Conversely, if the even mode is below the fundamental mode, the TZs will be produced at the lower fundamental mode site (odd mode).

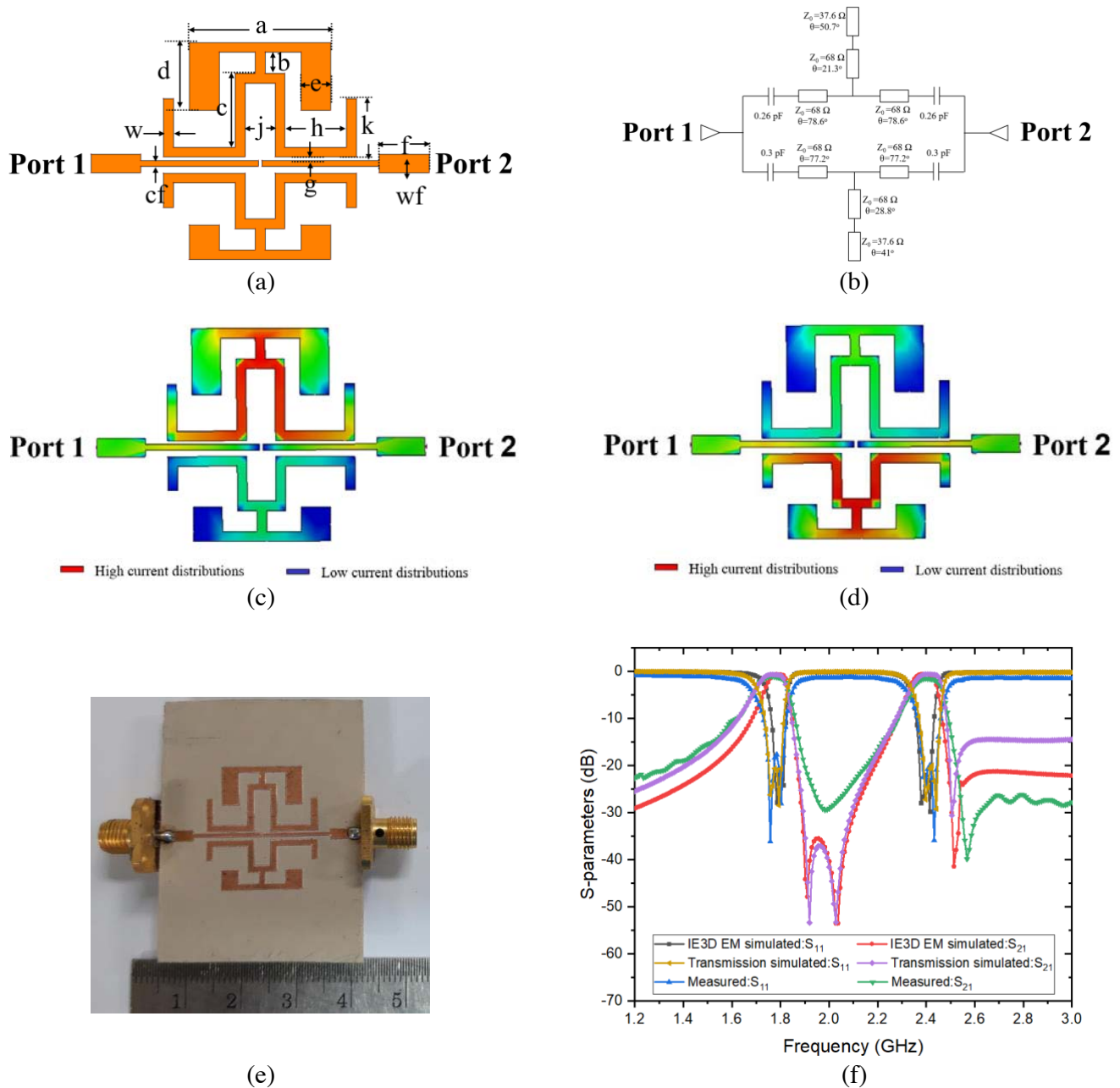
### 3. DUAL-MODE DUAL-BAND BANDPASS FILTER WITH TRANSMISSION ZEROS LOCATED AT THE UPPER SIDEBAND

The dual-band filter's basic structure is based on the dual-mode resonator structure; this theoretical concept combines the two dual-mode filters in the form of a dual-band bandpass filter response, as shown in Figure 1. The schematic parameters of the dual-mode filter are detailed in Table 1. IE3D full-wave EM simulations simulated the dual-mode dual-band filter. It is useful to analyze the input and output impedances and the microstrip  $\Omega$ -shaped structure's current distributions. Capacitive coupling feeds are used to excite the dual-mode resonator via ports 1 and 2. EM field solver IE3D is used to simulate the current distributions at the center frequencies of 1.8 GHz and 2.4 GHz of the proposed dual-mode resonator filters and the transmission-line equivalent circuit of the second-order filter, as shown in Figures 4(a) and 4(c), respectively.  $S$ -parameters of the dual-mode resonator filter are illustrated in Figures 4(b) and 4(d) at 1.8 GHz and 2.4 GHz, respectively. It is apparent that these dual-mode filters create the TZs at the upper sideband of the resonant frequency.

**Table 1.** Physical dimensions of the microstrip dual-mode dual-band filter with transmission zeros located at the upper sideband.

| Physical dimensions of the dual-mode dual-band filter with transmission zeros situated at the upper sideband of 1.8 GHz and 2.4 GHz | At $f_1 = 1.8 \text{ GHz}$ | At $f_2 = 2.4 \text{ GHz}$ |
|-------------------------------------------------------------------------------------------------------------------------------------|----------------------------|----------------------------|
| The width of the resonator ( $w$ )                                                                                                  | 1.0 mm                     | 1.0 mm                     |
| The width of feed ( $wf$ )                                                                                                          | 1.87 mm                    | 1.87 mm                    |
| The length of coupling line ( $cf$ )                                                                                                | 0.6 mm                     | 0.6 mm                     |
| The gap space between coupling line and dual-mode resonator ( $g$ )                                                                 | 0.35 mm                    | 0.65 mm                    |
| The length of resonator-line ( $a$ )                                                                                                | 14.2 mm                    | 14.2 mm                    |
| The junction of resonator-line and tuning stub ( $b$ )                                                                              | 2.1 mm                     | 2.1 mm                     |
| The length of resonator-line ( $c$ )                                                                                                | 7.4 mm                     | 4.6 mm                     |
| The length of resonator-line ( $h$ )                                                                                                | 6.2 mm                     | 6.2 mm                     |
| The length of resonator-line ( $j$ )                                                                                                | 3.0 mm                     | 3.0 mm                     |
| The length of resonator-line ( $k$ )                                                                                                | 5.8 mm                     | 3.4 mm                     |
| The length of the patch ( $d$ )                                                                                                     | 6.8 mm                     | 3.5 mm                     |
| The width of the patch ( $e$ )                                                                                                      | 3.0 mm                     | 3.0 mm                     |
| The length of feed-line ( $f$ )                                                                                                     | 5.0 mm                     | 5.0 mm                     |

To combine a dual-mode filter in the form of dual passbands, two different dual-mode filters must be placed between two coupling transmission lines terminated at the open end. Each resonant dual-mode filter can provide a coupled signal energy path from one microstrip feed line to the other at around the resonant frequency. Generally, input/output (I/O) feed lines should have a smaller gap, be a narrower line, and have longer line lengths, which increases the Quality factor ( $Q$ -factor) of the resonator filter. When the filter has a high  $Q$ -factor, the filter response will exhibit low insertion loss. The coupled



**Figure 5.** (a) Configuration; (b) the transmission line equivalent circuit; (c) simulated current distribution of the operating frequency of 1.8 GHz; (d) simulated current distribution of the operating frequency of 2.4 GHz; (e) photograph of the fabricated configuration; (f) simulate and measure the response of the operating frequency of 1.8 GHz and 2.4 GHz filter with transmission zeros located at the upper sideband.

gap, line width, and line lengths can be appropriately tuned to achieve a more strongly coupled I/O associated feed of the dual-mode filter.

An appropriately designed matching coupled-feed line couples the two independent dual-mode filters with the input feed  $50\ \Omega$  line. Figure 5(a) shows the schematic structure of the proposed dual-mode dual-band filter. This is proven by the transmission-line equivalent circuit of the second-order filter, as shown in Figure 5(b). EM field solver IE3D is used to excite the current distribution of the proposed dual-mode dual-band filters with TZs located at the upper sideband at 1.8 GHz and 2.4 GHz, as shown in Figures 5(c) and 5(d), respectively. Figures 5(c) and (d) show the electric current distribution over the designed dual-band strip's conductor surface. When the dual-band filter operates in its lower passband (1.8 GHz), most of the electric current tends to flow from Port 1 to Port 2 but not for the resonator filter at 2.4 GHz.

In contrast, when the dual-band filter operates in its second passband (2.4 GHz), an electric current is dominantly distributed in its resonant frequency rather than its first passband filter. The results intuitively interpret the working principle of our proposed dual-band filter. A photograph of the fabricated dual-band filter with TZs at the operating frequency's upper sideband is illustrated in Figure 5(e). The implemented overall size of the dual-mode dual-band filter is  $35\text{ mm} \times 45\text{ mm}$ , approximately  $0.2g$  by  $0.23g$ , where  $g$  is the guided wavelength on the substrate at the lower passband's central frequency (1.8 GHz). Measured results are obtained by using the Agilent Vector Network Analyzer. A two-port calibration can be performed by placing a short end, an open end, and a load end on one port during calibration. Then, the full two-port calibration is concluded through a connection on the two ports. Figure 5(f) shows the comparison between the measured and simulated results, which represent the insertion losses  $|S_{21}|$  of 1.02 dB and 1.15 dB and return losses  $|S_{11}|$  larger than 19 dB and 21 dB, at 1.8 GHz and 2.4 GHz, respectively. As shown in Figure 5(e), the out-of-band rejection of the dual-mode dual-band filter that presents the signal suppression is better than 20 dB over the frequency range from 1.9 GHz to 2.1 GHz. The measured characteristics are found in close agreement with the simulated results. The extra losses in the measurements are acceptable for the SMA connectors and fabrication processes.

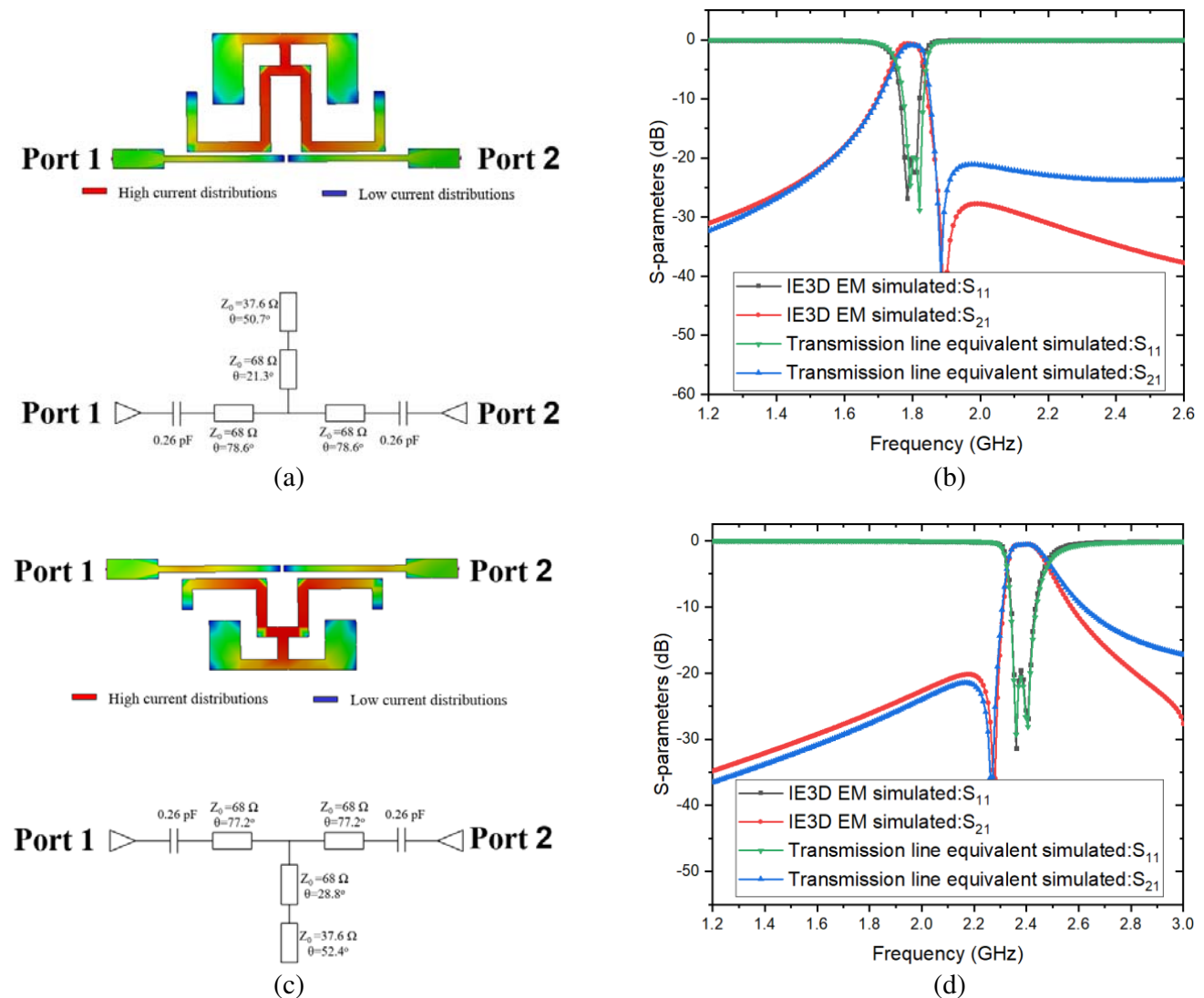
**Table 2.** Physical dimensions of the microstrip dual-mode dual-band resonator filter with transmission zeros located at the upper sideband at 1.8 GHz and lower sideband at 2.4 GHz.

| Physical dimensions of the dual-mode dual-band filter with transmission zeros situated at the upper sideband at 1.8 GHz and lower sideband at 2.4 GHz | At $f_1 = 1.8\text{ GHz}$ | At $f_2 = 2.4\text{ GHz}$ |
|-------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|---------------------------|
| The width of the resonator ( $w$ )                                                                                                                    | 1.0 mm                    | 1.0 mm                    |
| The width of feed ( $wf$ )                                                                                                                            | 1.87 mm                   | 1.87 mm                   |
| The length of coupling line ( $cf$ )                                                                                                                  | 0.6 mm                    | 0.6 mm                    |
| The gap space between coupling line and dual-mode resonator ( $g$ )                                                                                   | 0.35 mm                   | 0.65 mm                   |
| The length of resonator-line ( $a$ )                                                                                                                  | 14.2 mm                   | 14.2 mm                   |
| The junction of resonator-line and tuning stub ( $b$ )                                                                                                | 2.1 mm                    | 2.1 mm                    |
| The length of resonator-line ( $c$ )                                                                                                                  | 7.4 mm                    | 4.6 mm                    |
| The length of resonator-line ( $h$ )                                                                                                                  | 6.2 mm                    | 6.2 mm                    |
| The length of resonator-line ( $j$ )                                                                                                                  | 3.0 mm                    | 3.0 mm                    |
| The length of resonator-line ( $k$ )                                                                                                                  | 5.8 mm                    | 3.4 mm                    |
| The length of the patch ( $d$ )                                                                                                                       | 6.8 mm                    | 4.5 mm                    |
| The width of the patch ( $e$ )                                                                                                                        | 3.0 mm                    | 3.0 mm                    |
| The length of feed-line ( $f$ )                                                                                                                       | 5.0 mm                    | 5.0 mm                    |

#### 4. DUAL-MODE DUAL-BAND BANDPASS FILTER WITH TRANSMISSION ZEROS LOCATED AT THE UPPER AND LOWER SIDEBAND

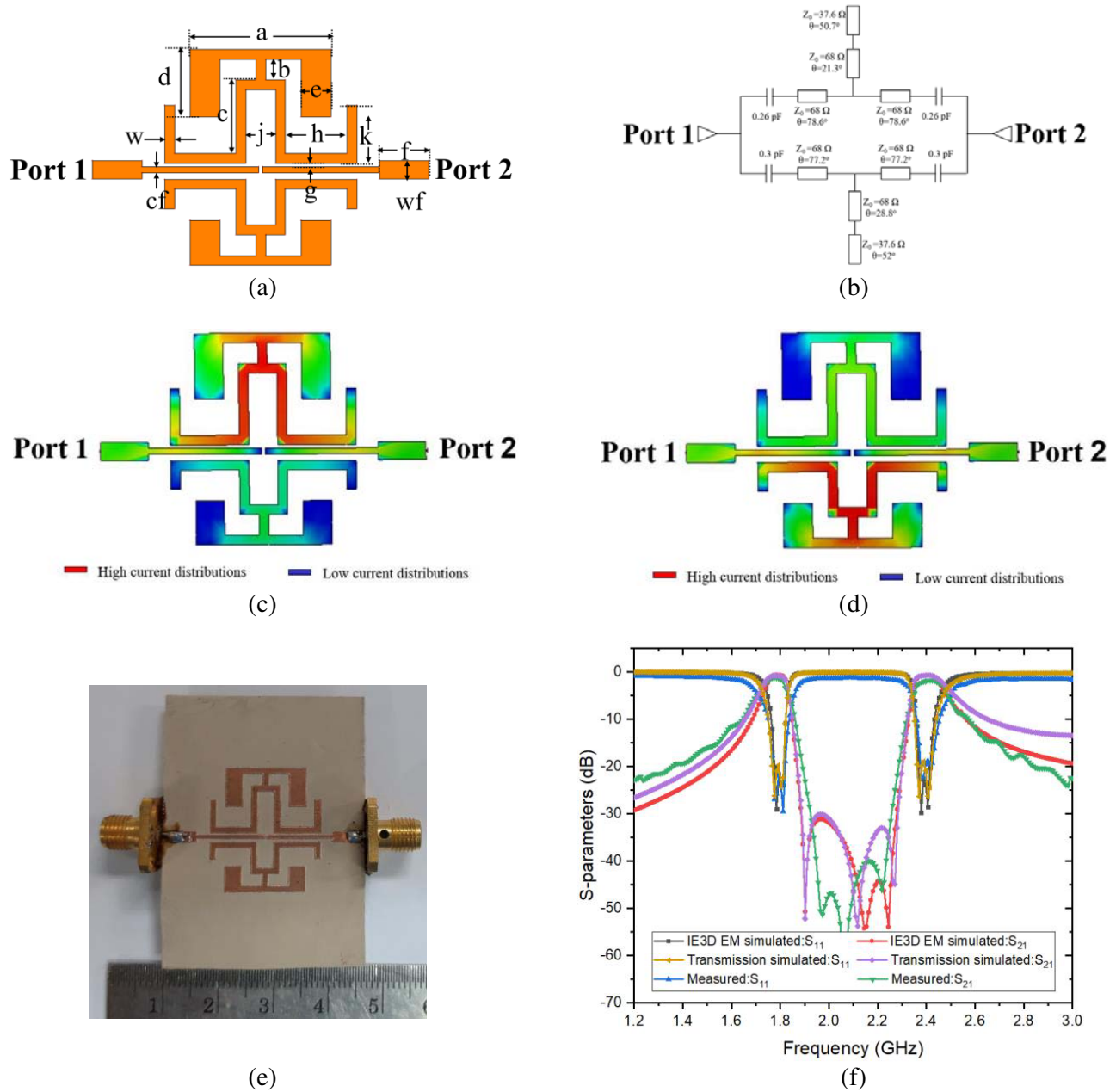
In this section, the dual-mode dual-band bandpass filter with a high cutoff rejection of the passband is introduced. The placement of the TZs at the upper part of the first filter (at 1.8 GHz) and lower sideband of the second filter (at 2.4 GHz) is presented. An alternative technique to overcome the limitation of the out-of-band rejection of dual-band filter in Section 3 by using a simple and efficient design method is presented. The TZs' location is presented to improve the dual-band response in which the two passbands are close to each other. The TZs are next to the first passband filter (1.8 GHz), and the TZs occur at the lower sideband of the second passband filter (2.4 GHz), which is formed of back-to-back TZs. It can be seen that this simple technique can achieve a high rejection performance compared to the dual-band bandpass filter in Section 3.

The physical dimensions of the dual-mode dual-band filter are listed in Table 2. EM field solver IE3D is excited to display the proposed filters' current distributions at 1.8 GHz and 2.4 GHz, and the transmission-line equivalent circuits of the second-order filter are shown in Figures 6(a) and 6(c),



**Figure 6.** Simulated characteristic parameters of dual-mode resonator filters with transmission zeros located at the upper and lower sideband: (a) Current distributions of the operation frequency at 1.8 GHz; (b)  $S$ -parameters of the operating frequency at 1.8 GHz; (c) current distributions of the operating frequency at 2.4 GHz; (d)  $S$ -parameters of the operating frequency at 2.4 GHz.

respectively. Figure 6(a) shows the proposed resonator's current distributions by using the IE3D EM simulator. At the fundamental resonant frequency (1.8 GHz), high current distributions are on the resonator at its resonant frequency. On the other hand, at the second resonant frequency (2.4 GHz), high current distributions are on the dual-mode resonator at its resonant frequency, as shown in Figure 6(c). Simulated  $S$ -parameters of the dual-mode resonator filter at 1.8 GHz and 2.4 GHz are illustrated as Figures 6(b) and 6(d), respectively. It can be seen that the dual-mode filters have the TZs at the upper sideband of the operating frequency of 1.8 GHz, and the TZs are present at the lower sideband of 2.4 GHz. This approach was justifiable because the dual-mode resonator's charge distributions are



**Figure 7.** (a) Configuration; (b) the transmission line equivalent circuit; (c) simulated current distribution of the operating frequency of 1.8 GHz; (d) simulated current distribution of the operating frequency of 2.4 GHz; (e) photograph of the fabricated configuration; (f) simulated and measured response of the operating frequency of the 1.8 GHz and 2.4 GHz filter with transmission zeros located at the upper and lower sideband.

different at the upper and lower rejection frequencies, as observed from the full-wave EM simulation. Hence, depending on the tuning stepped-impedance element size, the TZs at the upper and lower rejection frequencies could be swapped.

The dual-mode dual-band bandpass filter's schematic construction with an overall and shaft cutoff rejection rate between two resonant frequencies is shown in Figure 7(a). This is proven by the transmission-line equivalent circuit of the second-order filter, as shown in Figure 7(b). EM field IE3D program is used to solve the current distributions of the proposed dual-mode dual-band filters at 1.8 GHz and 2.4 GHz, as shown in Figures 7(c) and 7(d), respectively. From Figure 7(c), it can be seen that the high current distributions are on the dual-mode dual-band resonator filter at its resonant frequency (1.8 GHz) for the first passband, while low current distributions are on the second resonator when the filter operates at low frequency. This means that each dual-mode filter in the dual-band filter can be designed separately at its resonant frequency, and then the two dual-mode filters can be combined. In other words, when the dual-band filter is designed at 2.4 GHz, the high current distributions are on the resonator at its resonant frequency, as shown in Figure 7(d). A photograph of the fabricated dual-mode dual-band filter with TZs located at the upper and lower sideband of the center frequency of 1.8 GHz and 2.4 GHz, respectively, is provided in Figure 7(e). Figure 7(f) represents insertion losses  $|S_{21}|$  of 1.0 dB and 1.1 dB and return losses  $|S_{11}|$  larger than 22 dB and 20 dB, at 1.8 GHz and 2.4 GHz, respectively. Moreover, the proposed dual-mode dual-band filter with TZs located at the upper sideband of resonant frequency (1.8 GHz) and lower sideband of resonant frequency (2.4 GHz) can generate three TZs. This provides a better shaft cutoff rate in the stopband and gives much-improved selectivity. The rejection level between the two transmission bands is about 40 dB from 1.9 to 2.3 GHz. A stepped-impedance resonator reduces the length of the microstrip open-stub line placed at the middle of the  $\Omega$ -shaped open-loop resonator and tunes the TZ's position from upper sideband to lower sideband. The TZs are allocated between the two passbands. A lower-band filter is designed with its TZ in its upper stopband, while the higher-band filter has a transmission zero in its lower stopband. As a result, the lower- and upper-passbands are well isolated to minimize their mutual interference. This technique can also be a flexible and useful wireless solution for future work. A comparison with some reference dual-band filters is provided in Table 3.

**Table 3.** A comparison with some previous dual-band bandpass filters (NG: Not Given).

| Reference | Resonator type                      | Circuit size<br>( $\lambda_g^2$ ) | Order | 1st/2nd<br>passbands (GHz) | IL<br>(dB) |
|-----------|-------------------------------------|-----------------------------------|-------|----------------------------|------------|
| [10]      | Triple-mode resonator               | $0.19 \times 0.04$                | 3     | 0.9/1.2                    | 2.6/1.8    |
| [12]      | Substrate integrated suspended line | $0.12 \times 0.1$                 | NG    | 1.9/4.85                   | 1.69/2.44  |
| [14]      | Hair-pin microstrip                 | $0.59 \times 0.47$                | 3     | 0.7/0.9                    | 1.41/1.77  |
| [19]      | Dual-mode resonator                 | $0.25 \times 0.27$                | 2     | 1.8/2.4                    | 1.02/1.2   |
| This work | Dual-mode resonator                 | $0.20 \times 0.23$                | 2     | 1.8/2.4                    | 1.0/1.1    |

## 5. CONCLUSIONS

The proposed research work presents a dual-mode dual-band bandpass filter with high cutoff rejection using the asymmetrical transmission zeros technique. Asymmetric frequency response is very flexible and can identify the two too close frequency bands. By placing one transmission zero at the upper sideband of the first resonant frequency band and the other transmission zero at the lower sideband of the second resonant frequency band, the achievement of high cutoff signal rejection is represented by this simple technique. The TZ locations are placed at the side passbands between the first and second resonant frequencies to filter out unwanted signals and provide a good cutoff level in the stopband. The 1.8 GHz/2.4 GHz dual-mode dual-band filters are investigated and measured. The proposed dual-mode dual-band filter had a mid-band loss for each band less than 1.2 dB and exhibited excellent stopband rejection. This technique has achieved more than a 40-dB rejection between the two passbands from 1.9 to 2.3 GHz.

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