Dual-Mode Dual-Band Bandpass Filter with Asymmetrical Transmission Zeros

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Abstract—This paper presents a high-selectivity dual-mode dual-band bandpass filter with good cutoff signal rejection. The high-selectivity dual-mode dual-band bandpass filter is designed by an asymmetrical transmission zero (TZ). The asymmetrical transmission zeros next to the upper sideband of the first resonant filter and the TZ at the lower sideband of the second passband filter are combined to form a dual-mode dual-band filter. The locations of the TZ are designed at the side passbands of the filters in order to filter out unwanted signals, obtain good cutoff rate in the stopband, and give much improved signal selectivity for the dual-band bandpass filter. One dual-mode filter is designed at the center frequency of 1.8 GHz and the other's desired performance at 2.4 GHz. The two filters can be combined using the coupled feed lines in which these coupled feed lines present a simple structure of dual-mode dual-band bandpass filter. The insertion loss of the dual-mode dual-band bandpass filter is less than 1.2 dB, and the rejection between two transmission bands is about 18 dB from 1.9 to 2.35 GHz. This high-performance dual-mode dual-band bandpass filter can be used in many wireless communication systems.

1. INTRODUCTION

Nowadays, filter is an important and essential component in the RF front ends of both the receiver and transmitter in modern wireless and mobile communication systems. It can be designed and fabricated on various materials. Particularly, popular filter structures are planar filters because they can be fabricated using printed circuit technology and are suitable for commercial applications due to their compact size, light weight, and low-cost integration [1]. In modern multi-service and multi-band communication systems, multiband bandpass filter (BPF) is an important and essential component in the RF/microwave front ends of both the receiver and transmitter. Dual-band filters have been proposed and exploited extensively as a key circuit block in dual-band wireless communication systems [2–7]. Recently, various design approaches have been reported to develop dual-band BPFs for multi-band communication systems [8–13]. However, due to limited degrees of freedom in design parameters, the design of dual-band BPFs is still challenging to the designers [14].

Based on the single-mode open-loop resonator such as in [15, 16] this single-mode resonator structure focuses only on the odd mode resonance. Although an even mode resonance is present, this is approximately at twice the fundamental resonant frequency and therefore is of little use in single band filter synthesis. Consequently, the even mode will appear as the first spurious harmonic, which degrades the filter response. Dual-mode filters also make use of the even-mode and therefore behave as a doubly tuned circuit. These filters are not only more compact but also offer significantly less insertion loss [17, 18].

In addition, it is challenging to design a dual-band bandpass filter with high cutoff rejection out of passband. An alternative technique to design dual bands with a simple and efficient design method for a dual-band bandpass filter and ease of fabrication process was proposed by using a coupled feed structure [8]. To achieve the realized prototype, the technique for size reduction and high cutoff signal rejection by using dual-mode resonator can be presented. Moreover, the considerable attenuation of the out of signal rejection in the dual-band filter is also required to discriminate the proximity in frequency of the first and second frequency band. Asymmetric filter responses can be used to achieve this kind of requirement.

In this paper, a simple dual-mode dual-band bandpass filter with asymmetrical transmission zeros is presented. The dual-mode dual-band bandpass filter structure enables a compact and easy asymmetrical frequency response which also requires considerable attenuation between the proximity in frequency of the first and second resonant frequencies. The coupled feed lines are easily employed to combine the proposed two dual-mode bandpass devices which are combined to form a dual-mode dual-band bandpass filter.

2. DUAL-MODE DUAL-BAND RESONATOR FILTER ANALYSIS

To design a high performance dual-band filter, two different dual-mode resonators are combined to form a dual-mode dual-band filter. The dual-mode dual-band filter can be designed by using two dual-mode filters with asymmetrical TZ. This technique offers higher cutoff rejection than the same side band of TZ at the lower or higher sideband. To verify the new design technique, both dual-mode for the first and second channels are presented in this section. The dual-mode dual-band design is based on an independent design of two dual-mode filters as following steps.

Step 1: design a dual-mode filter in the first resonant frequency between ports 1 and 2 at center frequency of 1.8 GHz with 50 MHz bandwidth, and the transmission zero is produced at upper center frequency sideband.

Step 2: design a dual-mode filter in the second resonant frequency at center frequency of 2.4 GHz with 50 MHz bandwidth, and the transmission zero is produced at lower center frequency sideband.

Step 3: finally, the dual-mode dual-band bandpass filter is based on two dual-mode filters with coupled-feeders, which are combined to form a dual-mode dual-band filter.

Based on a single mode open-loop resonator, a dual-mode resonator filter can be designed as in [15, 16] in which a single mode resonator focuses only on the odd mode resonance. Generally, an even mode resonance of a single-mode resonator is present approximately twice at the fundamental resonant frequency, and even-mode is of little use in single band resonator filter synthesis. For this reason, even mode will emerge as the first spurious response which degrades the filter performance. On the other hand, the even-mode of dual-mode filters may also be used as a doubly tuned circuit [17].

The even mode resonance can be moved close to the operating frequency band (the odd mode). Therefore, a second order response can be created by these two poles. The schematic layout of the dual-mode filter is shown in Fig. 1. An open circuited stub is added and placed in the center of the filter to lower the even mode resonant frequency. The extended stub shown has no effect on the odd mode [17]. Hence, the two modes can be tuned independently.
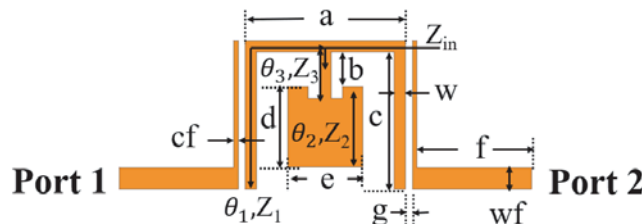

Figure 1. Schematic layout of dual-mode microstrip with stub-loaded resonator.
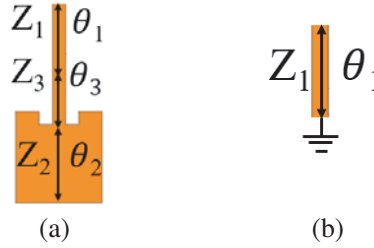
Figure 2. (a) Equivalent even-mode resonator. (b) Odd-mode resonator.

The equivalent circuits of even and odd modes at resonant mode are shown in Fig. 2. The even mode resonator is represented by an open-circuited half wavelength type resonator while the odd mode is represented by a short-circuited quarter wavelength resonator.

The dual-mode resonator by using the stepped impedance can be illustrated as an example design. The use of stepped impedances reduces the length of the open circuited stub. It can also be employed to achieve dual-mode performance [18]. The open circuited stub consists of two sections of different impedances as illustrated in Fig. 1. Dimensions are calculated using equations

$$\theta_1 \cong \frac{\pi}{2} \tag{1}$$

The stepped impedance stub (Z_2, Z_3) is connected to the middle of the resonator (Z_1), where αZ_2 and βZ_3 represent the even mode equivalent impedances of the sections with impedances Z_2 and Z_3. Let $R = \beta Z_3 / \alpha Z_2$ so $R > 1$ for the stepped impedance resonator where $\beta Z_3 > \alpha Z_2$. The electrical length θ_2 is given approximately by [17].

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

The electrical length (θ_3) of the open circuited stub may be defined from [17]

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

where θ_x ($x = 1, 2, 3$) corresponds to electrical length of section in Fig. 1, and c is the speed of light in vacuum.

For the demonstration of the dual-mode dual-band filter, dual-mode microstrip filters are based upon a microstrip U-shaped resonator which is loaded by an open-ended stepped-impedance resonator. The dual-mode filters are designed on an RT/Duroid substrate having a thickness $h = 1.27\,\text{mm}$ with relative dielectric constant $\varepsilon_r = 6.15$. The filters are simulated by IE3D full-wave EM simulations. The resonator is coupled to the input and output ports with a feed structure having a line width (cf) and coupling spacing (g) as shown in Fig. 1. The odd and even modes refer to the first two resonating modes. These two modes can have the same or different modal frequencies which depend on the dimensions of the stepped resonator.

The operation of resonant frequencies against the length of stepped impedance resonator has been investigated using IE3D full-wave EM simulations. The dual-mode resonator is designed to achieve the desired resonant frequencies. The fundamental frequency is fixed by the length of the microstrip U-shaped resonator (a and c). Even-mode characteristic can be achieved by adjusting the length of the loaded stepped open circuit stub (d and e). Two input/output microstrip lines with $50\,\Omega$ characteristic impedance are used to feed the proposed dual-mode stepped stub loaded resonator. As can be seen in Fig. 3, the stepped open-stub loaded length does not affect the S_{21} response at odd-mode resonant frequency as shown in Fig. 3(a) at $1.8\,\text{GHz}$ and in Fig. 3(b) at $2.4\,\text{GHz}$, while the even-mode resonant frequency is flexibly controlled by changing the length of stepped-impedance (d). An inherent transmission zero (TZ) can be easily tuned to optimize the response. The TZ causes an asymmetric response. It can be illustrated that the TZ is produced as a direct result of the open-circuited stub. When the even mode resonant frequency appears below that of the odd, the TZ actually occurs on
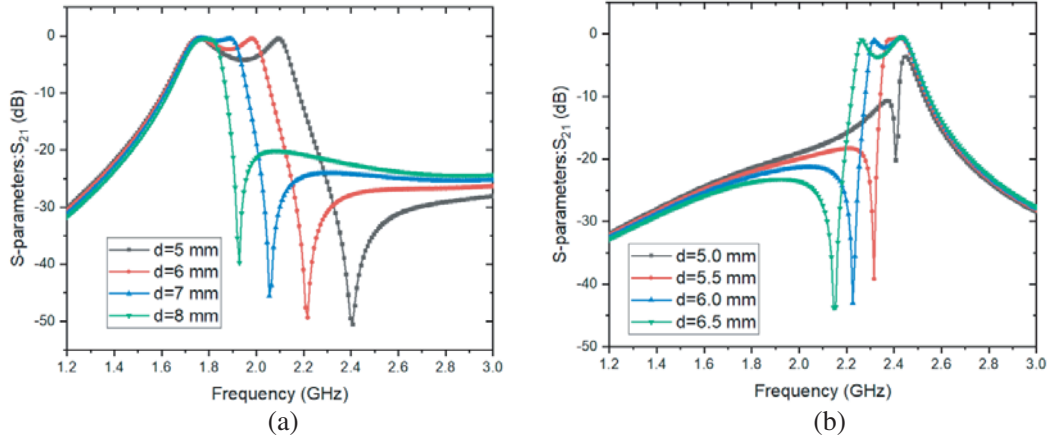
Figure 3. Simulated response of transmission zero located at (a) upper side band of the center frequency of 1.8 GHz, (b) lower side band of the center frequency of 2.4 GHz with different length of loaded stepped-impedance.

the lower stopband. This property can be used to improve selectivity of either the upper or the lower stopband.

From Fig. 3, it can be seen that the stepped open-stub loaded length does not affect the S_{21} response at odd-mode resonant frequency while the even-mode resonant frequency is flexibly controlled by changing the length of stepped-impedance (d). The transmission zero (TZ) can be easily tuned to optimize the response from upper to lower sideband. The TZ can improve selectivity of either the upper or the lower stopband. Therefore, the proposed dual-mode dual-band filter with controllable TZ can be used to improve dual-band responses. The next sections (3 and 4) show the frequency performance of the dual-mode dual-band bandpass filter with controllable transmission zeros which introduce the TZs in the same and different sidebands.

3. DUAL-MODE DUAL-BAND BANDPASS FILTER WITH TRANSMISSION ZEROS IN THE UPPER SIDE-BAND

Based on the dual-mode resonator structure shown in Fig. 1, the proposed dual-mode microstrip filters are based upon an open loop resonator which is loaded by a stepped impedance open stub. The filters are designed on an RT/Duroid substrate having a thickness $h = 1.27$ mm with relative dielectric constant $\varepsilon_r = 6.15$. The filters are simulated by IE3D full-wave EM simulations. The dual modes are excited via capacitive couplings by ports 1 and 2. The odd and even modes refer to the first two resonating modes. These two modes can have the same or different modal frequencies which depend on the dimensions of the stepped resonator placed at the middle of resonator.

The current distributions of the proposed filters by using EM field solvers IE3D at 1.8 GHz and 2.4 GHz are shown in Figs. 4(a) and 4(c), respectively. Figs. 4(b) and 4(d) show EM simulated S-parameters of the dual-mode resonator filter at 1.8 GHz and 2.4 GHz, respectively. It can be seen that both dual-mode filters have the TZs at the upper side band of the resonant frequency.

To excite dual passbands, two different dual-mode filters must be located between two transmission lines terminated at open end. Each resonant dual-mode can provide a path coupled signal energy from one microstrip feed line to the other at around resonance. The coupled microstrip feed lines are introduced as an input/output (I/O) structure. Generally, a smaller gap, narrower line, and longer line lengths can increase the coupling degree and lower the insertion loss. As such, the coupled gap, line width, and line lengths can be properly tuned to achieve stronger I/O coupling or a smaller external quality factor of the dual-mode filter.

The structure of proposed dual-mode dual-band filter is shown in Fig. 5(a). The two dual-mode filters are coupled by an appropriately designed matching coupled-feed line that has the width of input feed 50 Ω line. A photograph of the fabricated dual-band filter is shown in Fig. 5(b). The current distributions of the proposed dual-mode dual-band filters by using EM field solvers IE3D at 1.8 GHz
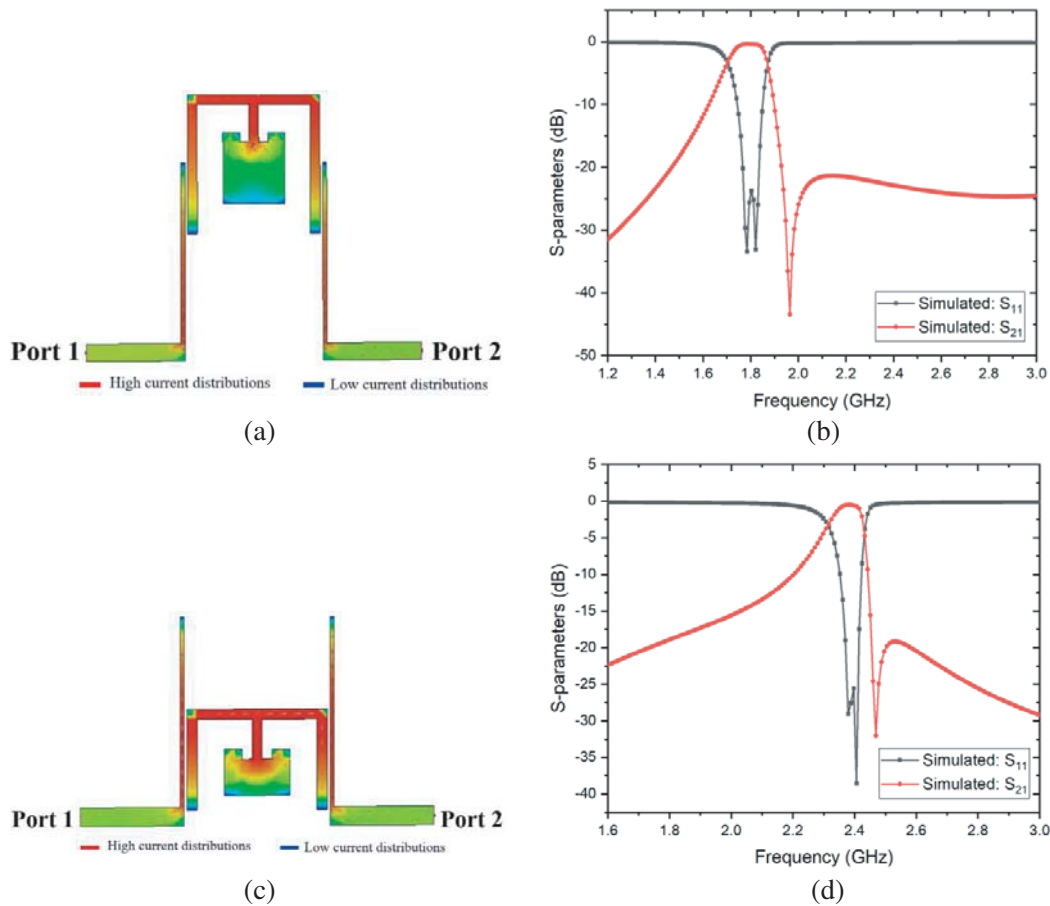
Figure 4. Simulated results of dual-mode resonator filters with upper sideband transmission zeros. (a) Current distributions at 1.8 GHz. (b) S-parameters at 1.8 GHz. (c) Current distributions at 2.4 GHz. (d) S-parameters at 2.4 GHz.

Table 1. Dimensoins of microstrip dual-mode dual-band resonator filter with upper sideband transmission zeros.

| Dimensions	$f_1 = 18\,\text{GHz}$	$f_2 = 24\,\text{GHz}$
Resonator width (w)	1 mm	1 mm
Feed width (wf)	1.87 mm	1.87 mm
Coupling-feed width (cf)	0.4 mm	0.4 mm
Coupling-feed length (t)	21 mm	21 mm
Space between coupling-feed and dual-mode resonator (g)	0.3 mm	0.3 mm
Resonator length (a)	14 mm	14 mm
Resonator length (b)	3 mm	3 mm
Resonator length (c)	13.75 mm	9.1 mm
Patch length (d)	7.8 mm	4.52 mm
Patch width (e)	6.55 mm	6.55 mm
Feed length (ft)	10 mm	10 mm
Distance(s) of the two band passes	2 mm	

(a)

(b)

(c)

(d)

(e)
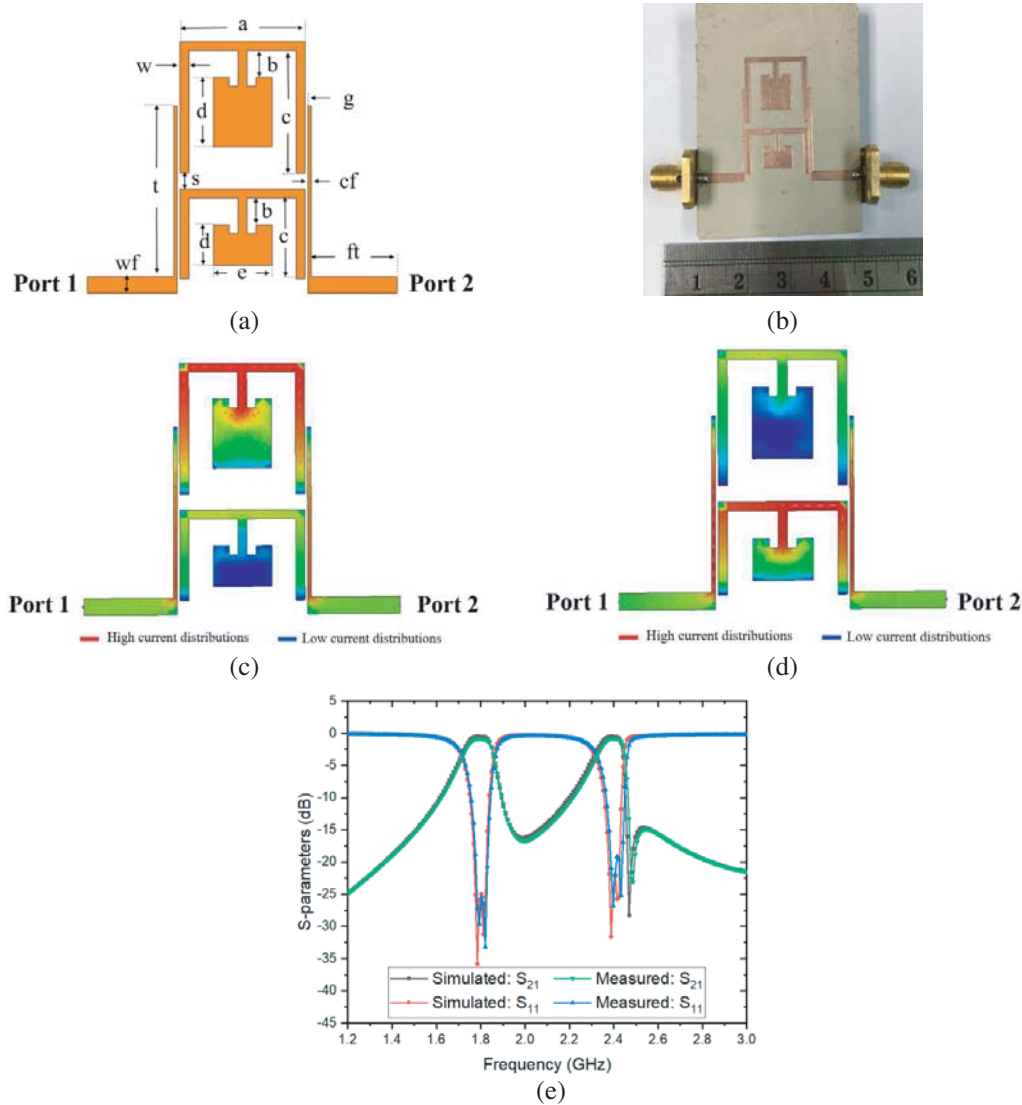
Figure 5. (a) Layout. (b) Photograph of fabricated structure. (c) Simulated current distribution of dual-mode dual-band resonator filters at 1.8 GHz. (d) Simulated current distribution of dual-mode dual-band resonator filters at 2.4 GHz. (e) Simulated and measure response of the center frequency of 1.8 GHz and 2.4 GHz with upper sideband transmission zeros.

and 2.4 GHz are shown in Figs. 5(c) and 5(d), respectively. Measurements are carried out using Agilent Vector Network Analyzer. The dimensions of dual-mode dual-band filter are listed in Table 1. Fig. 5(e) presents insertion losses (S_{21}) of 1.05 dB and 1.25 dB, and return losses (S_{11}) better than 24.2 dB and 18 dB, at 1.8 GHz and 2.4 GHz, respectively. From Fig. 5(e), the dual-mode dual-band filter presents an out-of-band rejection better than 15 dB over the frequency range from 1.9 GHz to 2.1 GHz. The excess losses in the measurements are believed due to the SMA connectors and fabrication errors.

4. DUAL-MODE DUAL-BAND BANDPASS FILTER WITH TRANSMISSION ZEROS IN THE UPPER AND LOWER SIDE-BAND

The dual-mode dual-band bandpass filter with high cutoff rejection out of passband is introduced in this section. An alternative technique to design dual-band with a simple and efficient design method
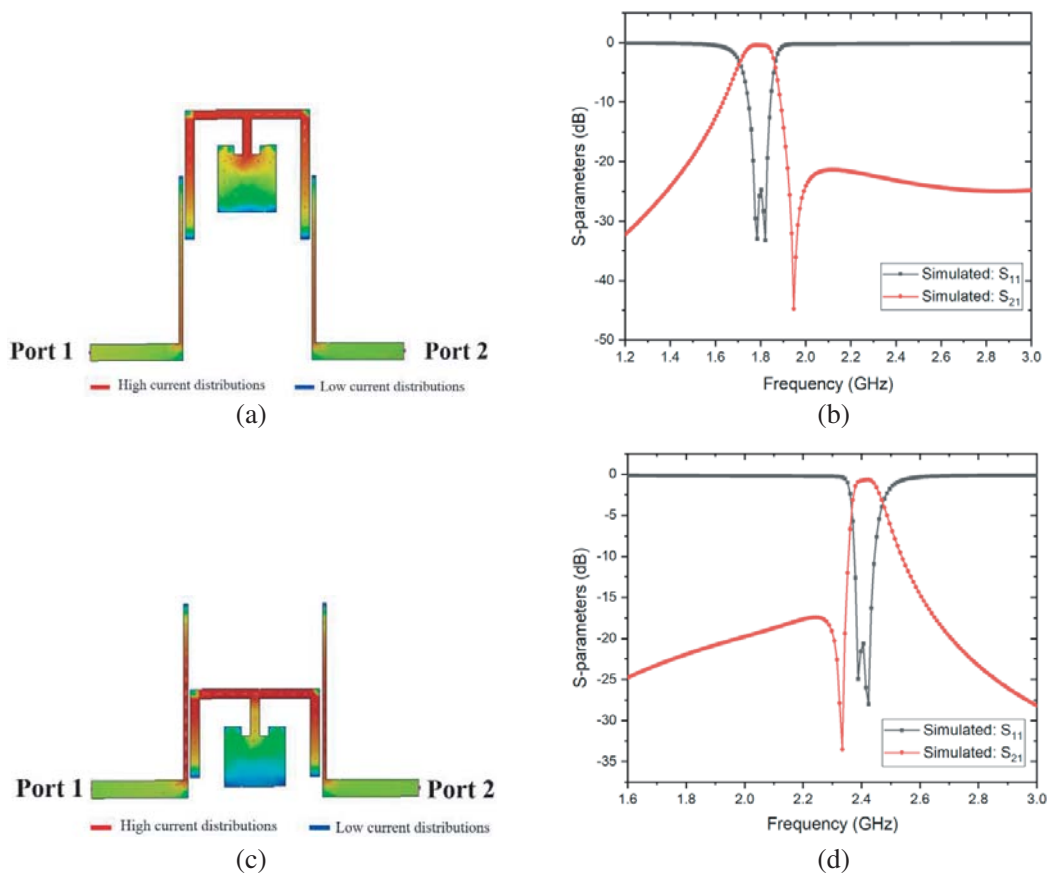
Figure 6. (a) Simulated results of dual-mode resonator filters. (a) Current distributions at 1.8 GHz. (b) S-parameters at 1.8 GHz with upper sideband transmission zero. (c) Current distributions at 2.4 GHz. (d) S-parameters at 2.4 GHz with lower sideband transmission zero.

Table 2. Dimensoins of microstrip dual-mode dual-band resonator filter with upper and lower sideband transmission zeros.

Dimensions	$f_1 = 18\,\text{GHz}$	$f_2 = 24\,\text{GHz}$
Resonator width (w)	1 mm	1 mm
Feed width (wf)	1.87 mm	1.87 mm
Coupling-feed width (cf)	0.4 mm	0.4 mm
Coupling-feed length (t)	21 mm	21 mm
Space between coupling-feed and dual-mode resonator (g)	0.3 mm	0.3 mm
Resonator length (a)	14 mm	14 mm
Resonator length (b)	3 mm	3 mm
Resonator length (c)	13.75 mm	8.5 mm
Patch length (d)	7.8 mm	5.32 mm
Patch width (e)	6.55 mm	6.55 mm
Feed length (ft)	10 mm	10 mm
Distance(s) of the two band passes	2 mm	

by controlling the location of TZ is presented to improve the dual-band response whose two passbands are next to each other. The high-selectivity dual-mode dual-band bandpass filter is designed by an asymmetrical transmission zero (TZ) that shows transmission zeros next to the upper sideband of the first frequency filter (1.8 GHz), and the TZ occurs at the lower sideband of the second passband filter (2.4 GHz) which is formed of back-to-back transmission zeros.

The current distributions of the proposed filters by using EM field solvers IE3D at 1.8 GHz and 2.4 GHz are shown in Figs. 6(a) and 6(c), respectively. Figs. 6(b) and 6(d) show the EM simulated S-parameters of the dual-mode resonator filter at 1.8 GHz and 2.4 GHz, respectively. It can be seen that dual-mode filters have the TZs at the upper side band of the resonant frequency of 1.8 GHz and lower side band at 2.4 GHz.

To design the dual-mode dual-band filter with wide cutoff rate between two resonant frequencies,
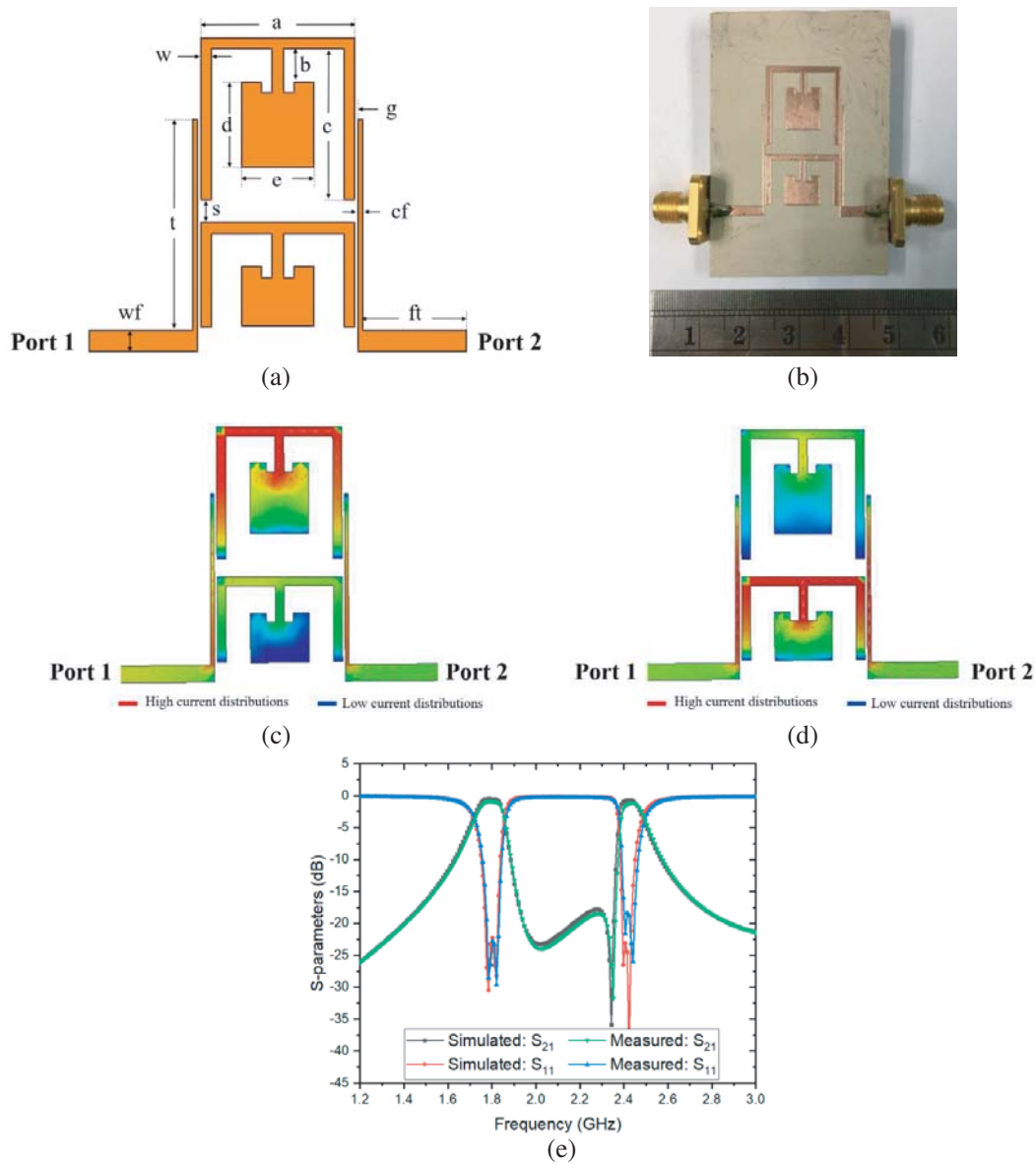

Figure 7. (a) Layout. (b) Photograph of fabricated structure. (c) Simulated current distribution of dual-mode dual-band resonator filters at 1.8 GHz. (d) Simulated current distribution of dual-mode dual-band resonator filters at 2.4 GHz. (e) Simulated and measure response of the center frequency of 1.8 GHz and 2.4 GHz with upper and lower sideband transmission zeros.

the schematic structure of dual-mode dual-band bandpass filter is displayed in Fig. 7(a). A photograph of the fabricated dual-band filter is shown in Fig. 7(b). Current distributions of the proposed dual-mode dual-band filters by using EM field solvers IE3D at 1.8 GHz and 2.4 GHz are shown in Figs. 7(c) and 7(d), respectively. The dimensions of dual-mode dual-band filter are tabulated in Table 2. Fig. 6(e) represents insertion losses (S_{21}) of 1.02 dB and 1.2 dB and return losses (S_{11}) better than 22.3 dB and 19 dB, at 1.8 GHz and 2.4 GHz, respectively. In addition, the proposed dual-mode dual-band filter can generate two pairs of transmission zeros, which provide a better cutoff rate in the stopband and give much improved selectivity. The rejection between two transmission bands is about 17.5 dB from 1.9 to 2.35 GHz. The use of stepped-impedance resonator reduces the length of the microstrip open stub line placed at the middle of open-loop resonator and also changes the position of TZ from upper sideband to lower sideband.

5. CONCLUSIONS

In this paper, a simple dual-mode dual-band bandpass filter with asymmetrical transmission zeros is presented. A compact dual-mode dual-band bandpass filter with an asymmetric frequency response is easily realized to design with two extremely close frequency bands. The high cutoff signal rejection is achieved by placing the transmission zero at the upper side band of the first resonant frequency band and putting the transmission zero at lower side-band of the second resonant frequency band. The locations of the TZs are designed at the side passbands of the filters in order to filter out unwanted signals, obtain good cutoff rate in the stopband, and give much improved signal selectivity for the dual-band bandpass filter. The 1.8 GHz/2.4 GHz dual-mode dual-band filters are illustrated and measured. The rejection between two passbands is lower than 17.5 dB, and the insertion loss for each band is lower than 2 dB. The measurement results are found in good agreement with the simulation ones. Finally, the proposed dual-mode dual-band filter offers a simple structure, which allows low complexity design and easy fabrication process.

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