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Differential Filtering Quad-Band Antenna Based on Enhanced Folded-Dipole

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ABSTRACT: In this paper, a high-selectivity differential filtering quad-frequency antenna is proposed, consisting of two pairs of parallel enhanced folded dipoles and a diplexer. The diplexer employs unbalanced-to-balanced feeding, enabling the desired frequencies and transmission zero points by adjusting the lengths and distances between the stepped impedance resonators. Moreover, enhanced folded dipoles are arranged on either side of the substrate, which can feature a more compact structure and achieve multi-band radiation performance. For verification, a prototype of the proposed differential filtered quad-band antenna is fabricated and measured, having a size of $80\,\text{mm} \times 94.2\,\text{mm} \times 1\,\text{mm}$ ($1.10 \times 1.29 \times 0.0137\lambda_g$ at 2.53 GHz). Measured results show that the relative impedance bandwidths with $|S_{11}| < -10\,\text{dB}$ at the center frequencies of 2.53, 2.89, 3.30, and 3.68 GHz are 1.97%, 1.00%, 2.25%, and 2.04%, and the corresponding gains are 4.56, 2.82, 3.93, and 3.43 dBi, respectively, revealing its stable radiation performance and excellent anti-interference ability.

1. INTRODUCTION

With the development of wireless communication technology, radio frequency (RF) front-end devices and antennas are heading towards miniaturization [1–3] and multi-band characteristics [4–6]. As essential components of RF front-end devices, duplexers are subject to increasingly higher requirements. Previously, most of duplexer designs utilized unbalanced circuits, but such designs gradually became inadequate in the case of increasingly complex electromagnetic environments. To deal with this issue, a series of balanced duplexer [7, 8] designs with anti-interference capability [9, 10] have emerged. Balanced duplexers, as energy transmission devices, do not radiate energy, which are so favorable in the antenna design. Nevertheless, currently there are relatively few designs integrating balanced duplexers with antennas. Besides, compared to traditional single-ended antennas, differential antennas [11, 12] exhibit strong anti-interference capability and can effectively suppress common-mode noise. Inspired by that, integrating balanced duplexers with differential antennas to further enhance the performance and efficiency of the overall design as well as reduce interference is one very interesting topic to be explored.

In recent years, plenty of research progress has been reported on balanced feed devices and differential antennas. A compact left-hand circularly polarized antenna with a simple structure for dedicated short-range communications (DSRC) was proposed in [13]. By controlling the major and minor axes of the elliptical slots, the antenna balances mode amplitudes and controls the phase difference, achieving circular polarization with an axial ratio (AR) of less than 3 dB at 5.8 GHz. However, the antenna uses an unbalanced feeding scheme, which is ineffective in suppressing interference signals in variable environments. By introducing a cloverleaf-shaped dielectric resonator with T-shaped feedlines in a balanced feeding manner, a differentially polarized filtering dielectric resonator antenna with stable in-band gain and symmetrical radiation patterns was achieved in [14]. However, the antenna requires a higher profile to achieve relevant performance. In [15], a differential filtering slot antenna was proposed, which employed differential mode operation and exhibited good filtering performance by distributing the positions of resonant frequencies of the slot radiator and dual-mode resonator properly. However, the antenna had a high profile and was limited by its fixed structure, thus its performance was basically determined, and it was no longer possible to add transmission zero points by increasing the number of elements. Different from the above research, this paper integrates the balun filter with enhanced folded dipoles to design a differential filtered four-band antenna. The differential antenna proposed in the manuscript integrates filtering function and has good anti-interference ability in complex electromagnetic environments. Additionally, the antenna exhibits superior frequency selectivity, helping to reduce unnecessary interference from other frequency bands and improving the signal-to-noise ratio of communication systems. It is particularly suitable for scenarios that require reliable communication, such as wireless communication, Internet of Things (IoT) devices, drone communication, and medical devices. Specifically, the proposed antenna has the following advantages:

(1) In the proposed design, an enhanced folded dipole is etched on both sides of the dielectric, achieving miniaturization of the antenna design while maintaining performance compared to traditional folded dipoles. Such compact structure provides flexibility for multi-frequency design of the enhanced folded dipole.

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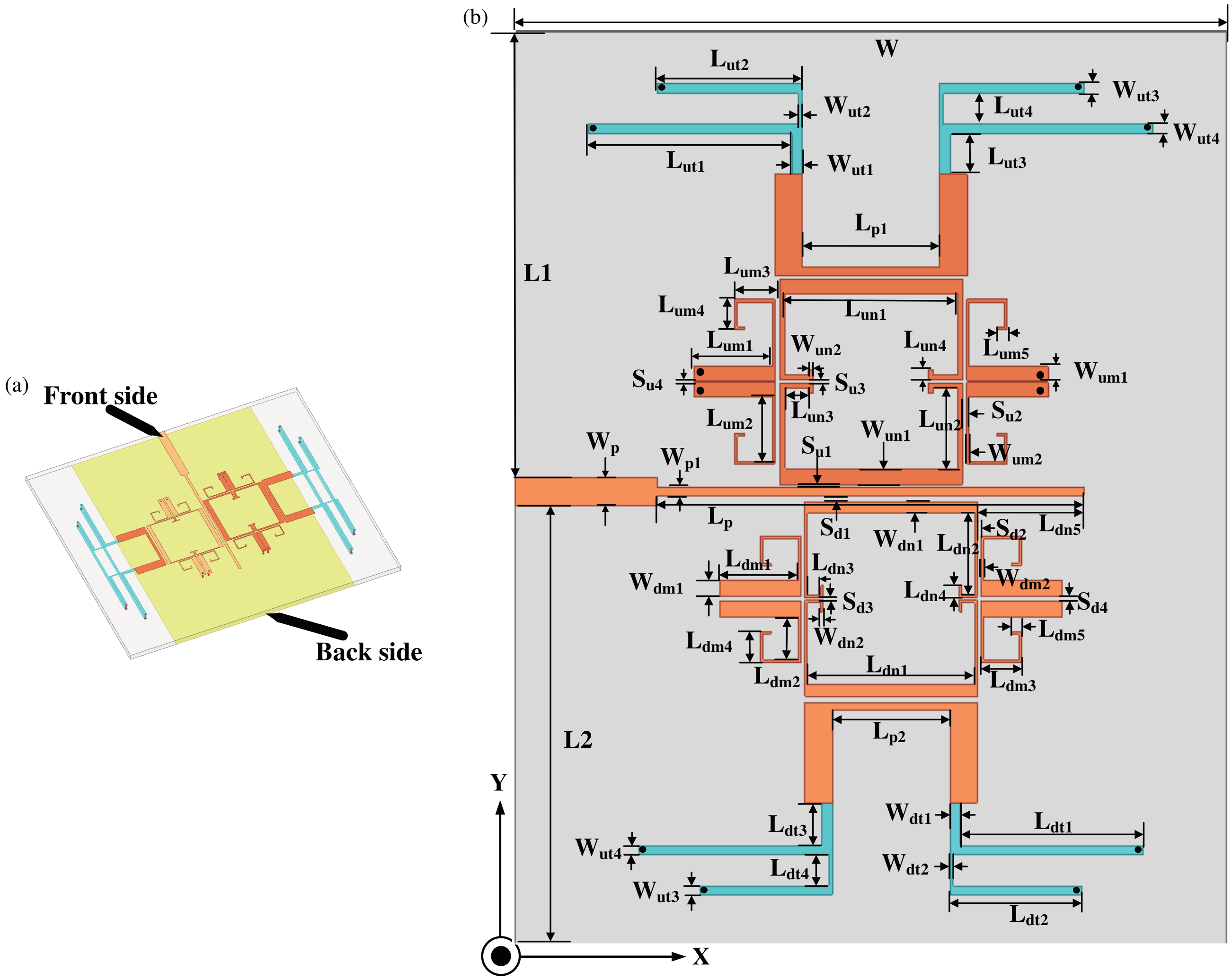

FIGURE 1. Antenna structure schematic diagram. (a) 3-D view. (b) Front view. (units: mm) $W = 80.00$, $W_p = 2.70$, $W_{p1} = 2.70$, $L_1 = 46.00$, $L_2 = 45.50$, $L_p = 42.00$, $L_{p1} = 13.60$, $L_{p2} = 11.60$, $W_{um1} = 1.40$, $W_{um2} = 0.25$, $W_{un1} = 1.50$, $W_{un2} = 0.50$, $W_{dm1} = 1.60$, $W_{dm2} = 0.25$, $W_{dn1} = 1.2$, $W_{dn2} = 0.25$, $L_{um1} = 7.75$, $L_{um2} = 6.35$, $L_{um3} = 3.50$, $L_{um4} = 2.50$, $L_{um5} = 1.00$, $L_{un1} = 17.00$, $L_{un2} = 8.00$, $L_{un3} = 2.30$, $L_{un4} = 1.00$, $L_{dm1} = 7.75$, $L_{dm2} = 4.15$, $L_{dm3} = 3.50$, $L_{dm4} = 2.50$, $L_{dm5} = 1.00$, $L_{dn1} = 16.50$, $L_{dn2} = 8.10$, $L_{dn3} = 1.30$, $L_{dn4} = 1.00$, $L_{dn5} = 10.50$.

(2) The filter power divider employs an unbalanced to balanced circuit design, achieving effective common-mode suppression. The filter's resonant frequency, number of frequency bands, and transmission zeros can be adaptively designed by adjusting the number and dimensions of stepped impedance resonators (SIRs).

(3) By integrating balun into the filter design, the proposed design can mitigate the impact of external environmental interference. In addition, the filter can be directly connected to enhanced folded dipole without additional matching network, reducing the complexity of the antenna design.

2. DESIGN OF DIFFERENTIAL FILTER ANTENNA

2.1. Overall Structure

The overall structure of the differential filter antenna is shown in Figure 1, which consists of two pairs of parallel enhanced folded dipoles and a duplex filter. The antenna is etched on a substrate of F4BM-265 ($\varepsilon_r = 2.65$, $\tan\delta = 0.004$) with a thickness of 1 mm. The upper and lower layers of each antenna are connected through metal vias with a diameter of 0.5 mm.

In the differential antenna, by bending the traditional dipole downward, an enhanced folded dipole is formed. The resonant frequency of the antenna is determined by the arm length of the improved folded dipole. The enhanced structure is more compact, and improved folded dipoles with different arm lengths can be connected in parallel to achieve multi-frequency operation. Within the filtering power divider, multiple SIRs [16] are employed for frequency selection. Due to the structural characteristics of SIR, the resonant frequency is inherently dictated by its dimensions. To achieve a desired number of passbands, multiple SIRs with varying resonant frequencies are coupled together, allowing for precise tuning of these frequencies to align with specific application requirements. However, this method

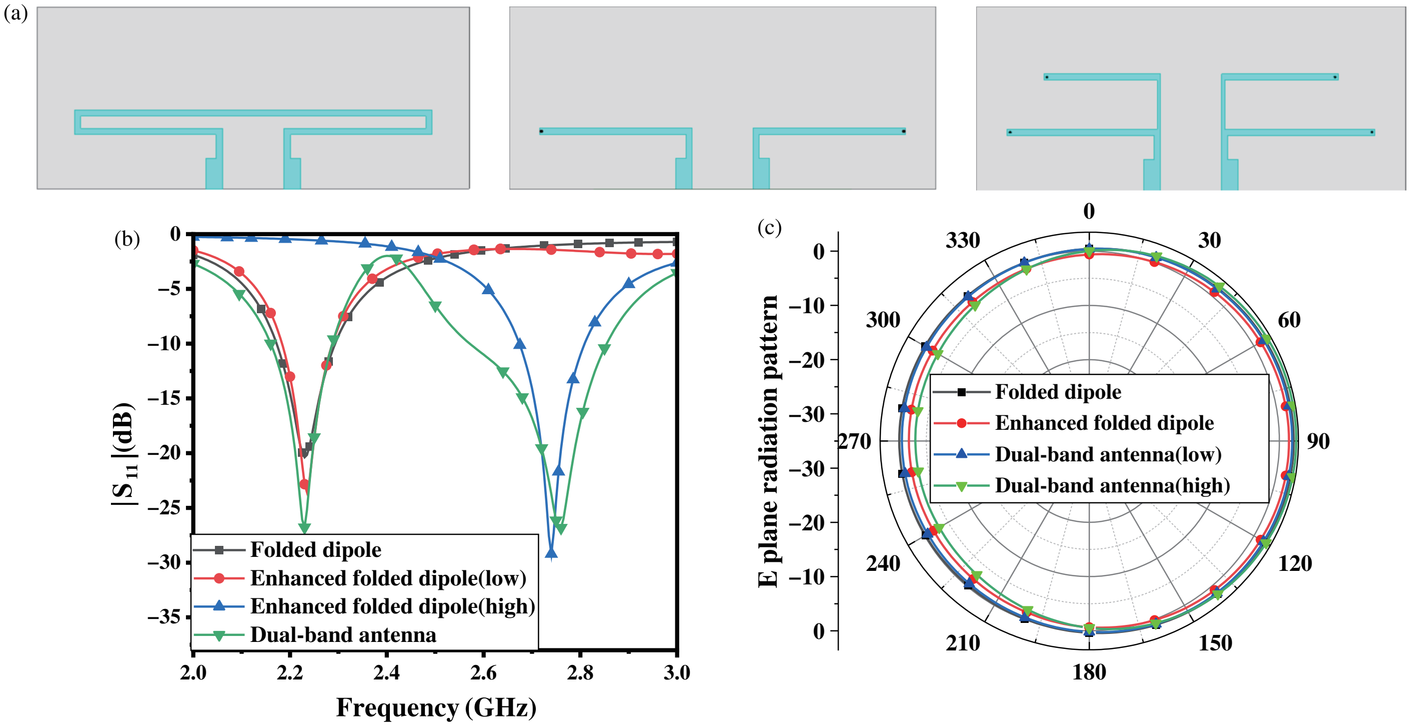

FIGURE 2. Comparison of several half-wave dipoles. (a) Structure. (b) $|S_{11}|$. (c) Radiation pattern.

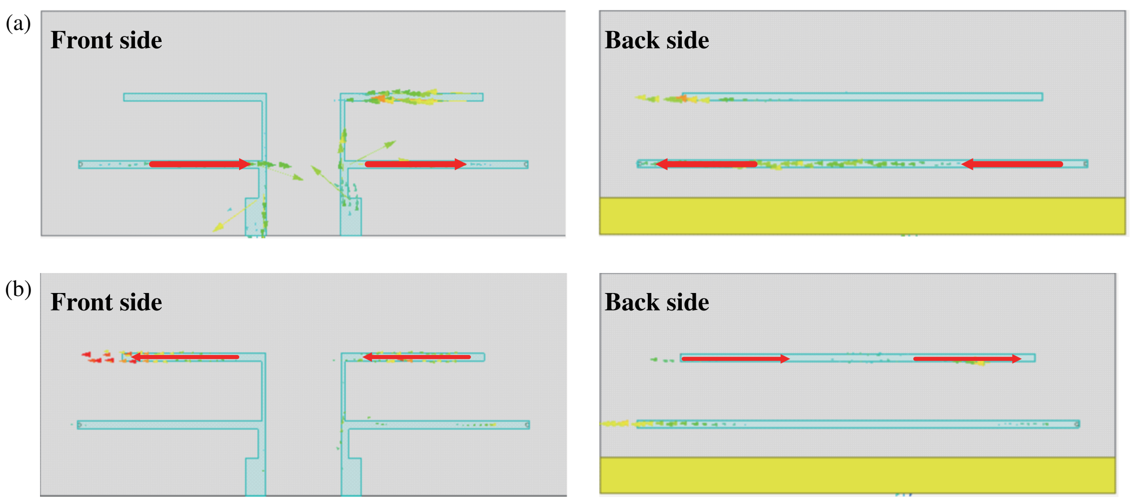

FIGURE 3. Differential dual-band antenna current distribution diagram. (a) 2.33 GHz (b) 2.75 GHz.

of control primarily governs the operational frequency of each band, offering limited capability to manipulate the bandwidth of those bands.

2.2. Differential Dual-Band Antenna

A comparison of several different dipoles is provided in Figure 2. The proposed enhanced folded dipole demonstrates similar performance to traditional folded dipole but offers a more compact structure and enables multi-frequency design through parallel connection.

By paralleling two enhanced folded-dipoles, dual bands are achieved, where the long arm radiates low-frequency signals, and the short arm radiates high-frequency signals. The differential dual-band antenna operates in the low-frequency range of 2.16 GHz–2.28 GHz, with a center frequency of 2.33 GHz and a relative bandwidth of 5.4%. The antenna also operates in the high-frequency range of 2.57 GHz–2.84 GHz, with a center frequency of 2.75 GHz and a relative bandwidth of 9.8%.

To further verify the working mechanism, the current distributions of the enhanced folded dipole at both resonance frequencies are provided, as shown in Figure 3. It can be observed that the current is mainly concentrated on the long-arm (short-arm) when the antenna works at the low frequency (high frequency). For convenience, the radiation pattern of the antenna

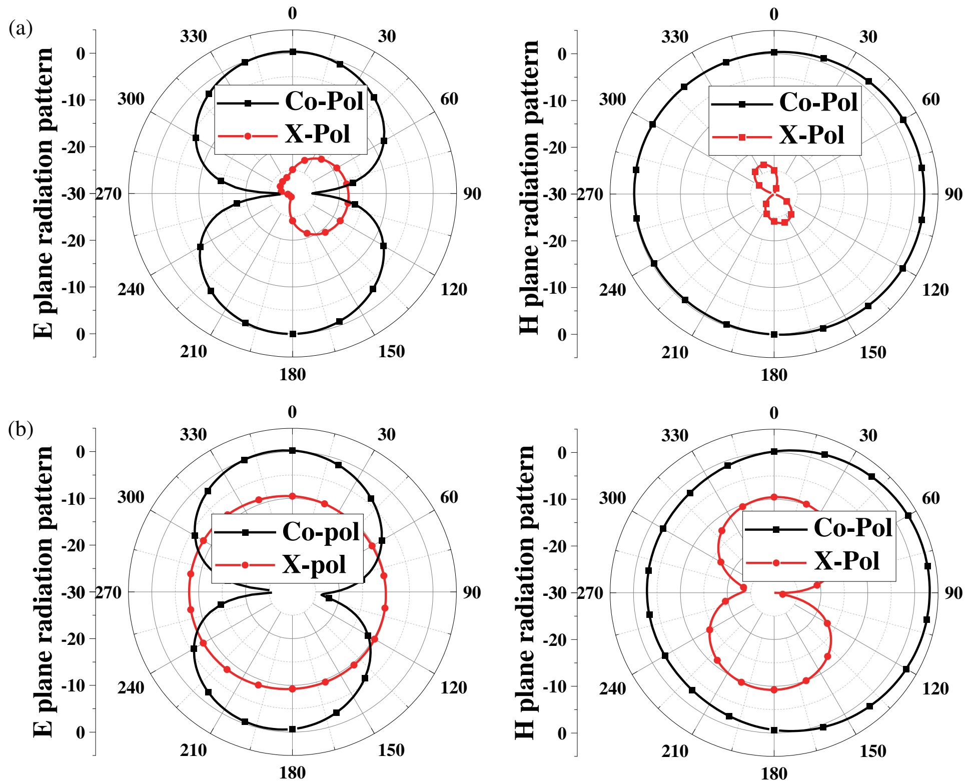

FIGURE 4. Antenna radiation pattern. (a) 2.33 GHz, (b) 2.75 GHz.

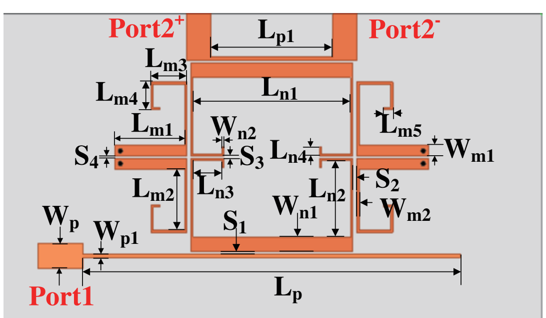

FIGURE 5. Structure diagram of the low-frequency band-pass filter.

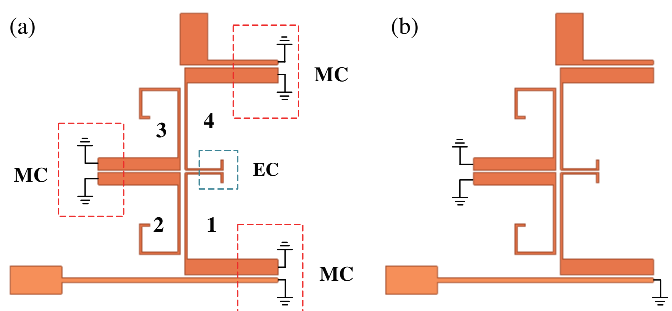

FIGURE 6. Circuit odd and even mode analysis. (a) Odd-mode circuit. (b) Even-mode circuit.

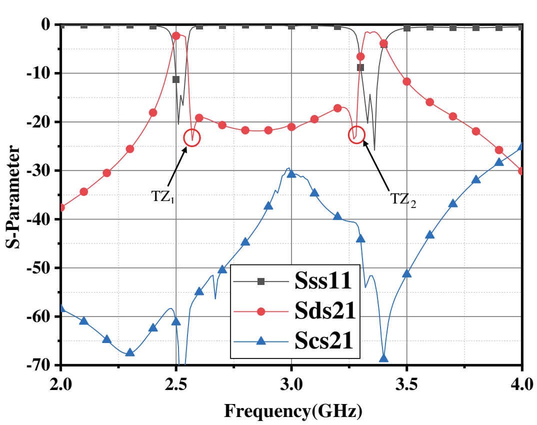

FIGURE 7. S-parameters of low-frequency filter.

is shown in Figure 4. The radiation direction is along the $+y$ direction. Besides, the realized gain of the antenna is 2.1 dBi at the low frequency with 3 dBi at the high frequency. The cross-polarization of the antenna is less than 20 dB at the low frequency and remains less than 18 dB at the high frequency. It can be observed that the antenna exhibits good radiation pattern stability within the operating frequency band.

2.3. Quad-Band Duplexer

The duplexers designed in this paper consist of two parallel independent filters, and both filters employ a similar resonant structure. The balun is integrated into the filter design by utilizing the phase variation of the feedline. Without loss of generality, a low-frequency band-pass filter is employed as an example for illustration, with its structure shown in Figure 5. The length

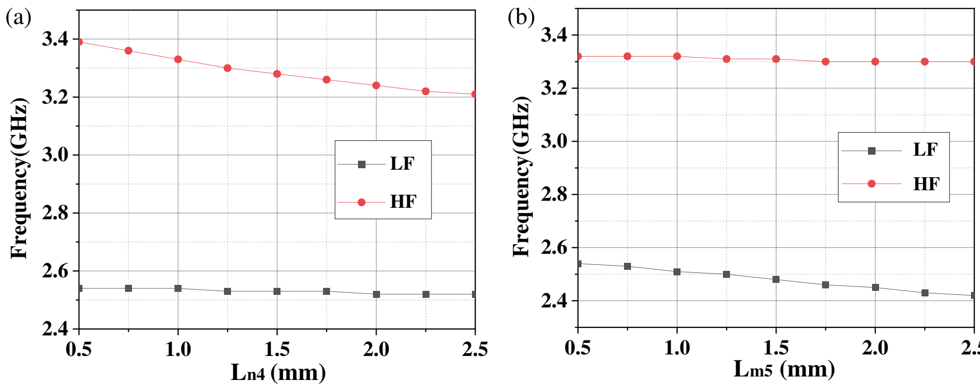

FIGURE 8. Curve of the center frequency variation with L_{n4} and L_{m5} in the passband. (a) L_{n4}. (b) L_{m5}.

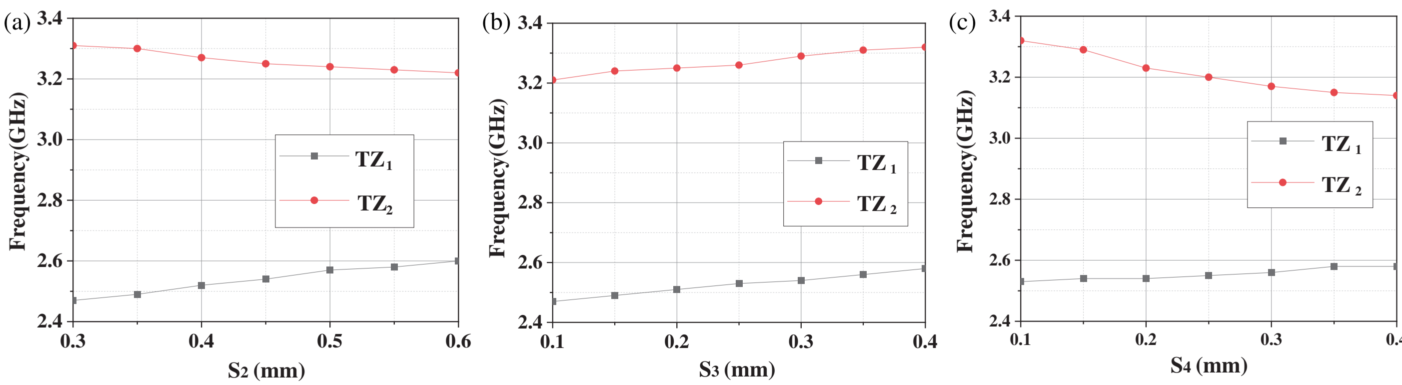

FIGURE 9. Impact of parameters on transmission zeros. (a) S_2. (b) S_3. (c) S_4.

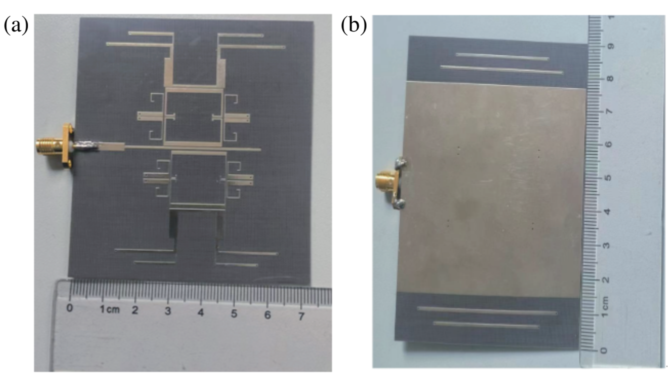

FIGURE 10. Actual manufacturing images of the antenna. (a) Front view. (b) Back view.

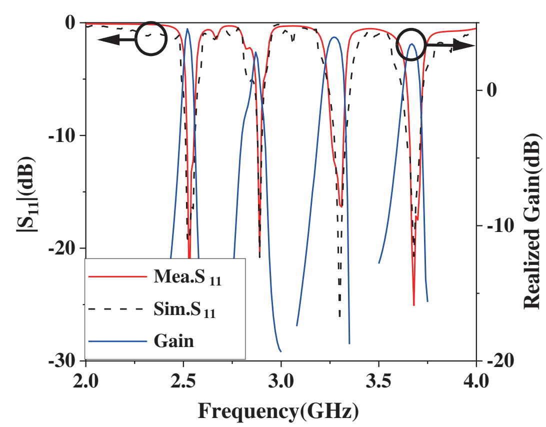

FIGURE 11. S-parameters and gain of the proposed stacked filtering antenna element of differential filtering quad-band antenna.

(Lp) of the feed line is set to be half-wavelength, and the midpoint of the feed line can be considered as a virtual ground point according to the transmission line theory. Under this situation, the filter can be analyzed by odd and even modes.

When odd-mode is excited, the equivalent circuit is shown in Figure 6(a), in which the circuit's symmetry axis is an equivalent grounded point, and the middle resonator can be equivalent to two pairs of SIRs with different specifications. Meanwhile, when even-mode is excited, the equivalent circuit is shown in Figure 6(b). In this case, the circuit's symmetry axis is an equivalent open-circuit point.

In odd-mode resonance, the resonant section of the filter utilizes two pairs of different specifications (1, 4 and 2, 3) SIRs to achieve dual-band functionality. In even-mode resonance, the resonator is composed of a pair of single-ended short-circuit and a pair of double-ended open-circuit SIRs. Since the resonant frequencies of these two pairs of SIRs are different, the resonant frequency of the resonator is moved out of the frequency band range of odd-mode operation. Therefore, in this frequency range, the resonator can only operate in the odd mode state. As shown in Figure 7, the designed low-frequency filter operates at center frequencies of 2.51 GHz and 3.36 GHz, with impedance

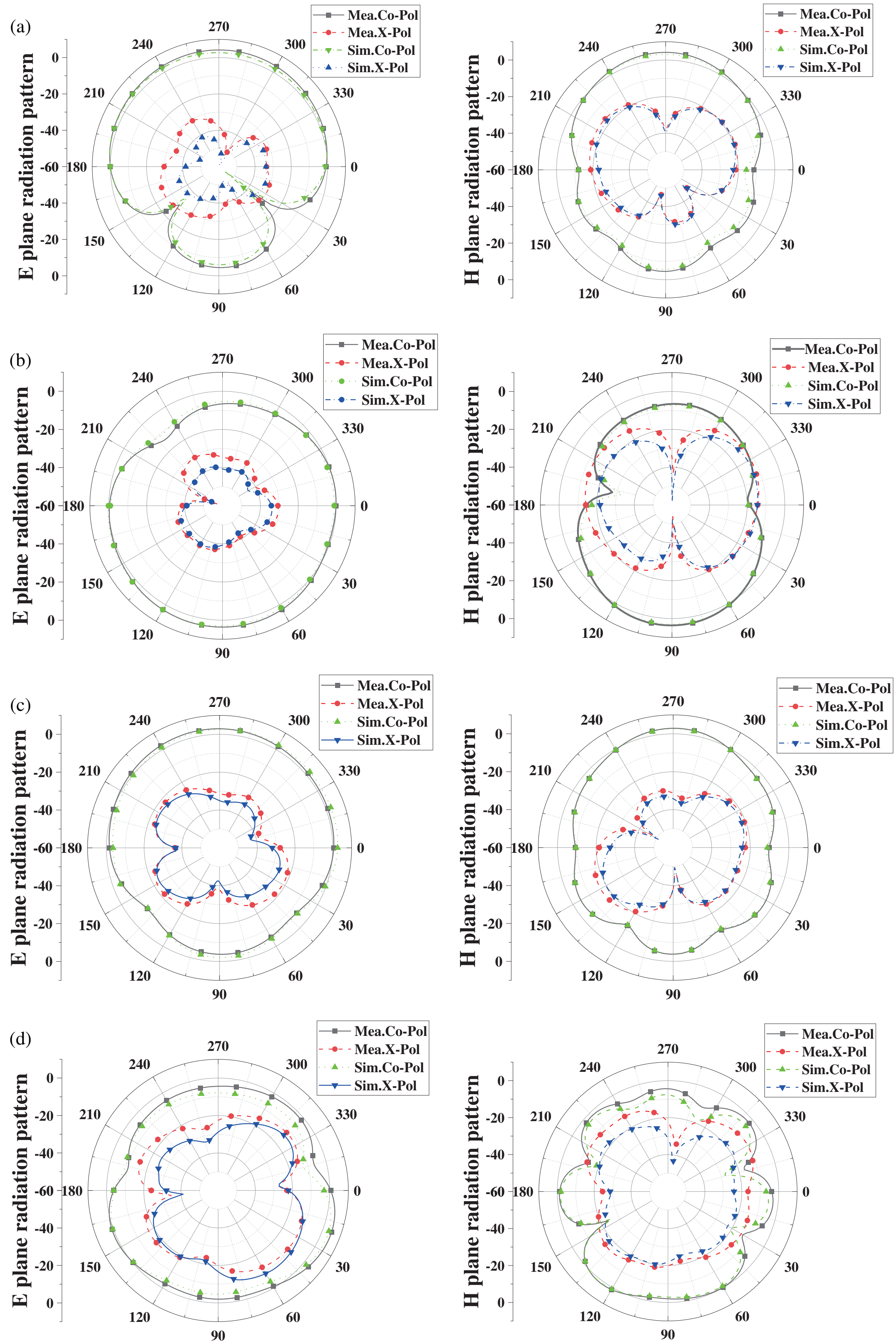

FIGURE 12. Antenna radiation pattern. (a) 2.53 GHz. (b) 2.89 GHz. (c) 3.30 GHz. (d) 3.68 GHz.

TABLE 1. Differential filtering quad-band antenna pattern.

Frequency (GHz)	Radiation direction	main polarization (dBi)	cross polarization (dB)	Bandwidth (%)
2.53	$+y$	4.56	45	1.97
2.89	$-y$	2.82	26	1.00
3.30	$+y$	3.93	38	2.25
3.68	$-y$	3.43	33	2.04

TABLE 2. Comparison of multi-frequency antennas.

Ref.	Frequency band	Differential antenna	Anti-interference	Size (λ_g^3)
[15]	Single	yes	yes	$2.28 \times 2.28 \times 0.0265$
[16]	Dual	no	no	$0.70 \times 0.70 \times 0.42$
[17]	Single	no	no	$1.28 \times 0.85 \times 0.0296$
[18]	Dual	yes	yes	$1.22 \times 1.22 \times 0.21$
This work	Quad	yes	yes	$1.10 \times 1.29 \times 0.0137$

bandwidths of 2.49 GHz–2.55 GHz and 3.3 GHz–3.38 GHz, respectively. It shows good common-mode suppression capability within the operation frequency.

Note that the frequency band of the filter can be tuned by adjusting the corresponding SIRs. As shown in Figure 6, adjusting the length of branches 1 and 4 (L_{n4}) significantly affects the high-frequency resonance frequency, but has minimal impact on the low-frequency resonance as shown in Figure 8(a). Conversely, adjusting the length of branches 2 and 3 (L_{m5}) has a significant impact on the low-frequency resonance frequency, while it barely affects the high-frequency resonance as shown in Figure 8(b).

Additionally, the filter internally employs a hybrid electromagnetic coupling method to generate transmission zeros. The first transmission zero (TZ_1) on the right side of the low-frequency passband is generated by multi-path coupling inside the resonator, while the second transmission zero (TZ_2) on the left side of the high-frequency passband is achieved by the electromagnetic mix coupling. The distance between the resonant structures can affect the coupling situation. As shown in Figure 9, changing the spacing of the coupling lines can have varying degrees of influence on the two transmission zeros.

3. EXPERIMENT, MEASUREMENT, AND DISCUSSION

Since the high-frequency filter and low-frequency filter have a similar structure, it motivates us to integrate the high-frequency and low-frequency filters with two differential antennas to form a differential filtered four-band antenna. Specifically, the detailed antenna structure is shown in Figure 1 before, and the photographs are shown in Figure 10. Besides, Figure 11 displays the simulated and measured S-parameters, which are in good agreement. It can be observed from Figure 11 that the proposed antenna has four operating frequency bands with the following center frequencies: 2.53 GHz, 2.89 GHz, 3.30 GHz, and 3.68 GHz, respectively. The 10 dB relative bandwidth for each frequency band is 1.97%, 1.00%, 2.25% and 2.04%, respectively. We observes that the proposed antenna exhibits a relatively constrained bandwidth, primarily attributed to the narrow filter bandwidth. Consequently, when the filter and antenna are integrated, the overall antenna bandwidth becomes limited. To enhance the antenna's bandwidth, we offer two specific recommendations: 1. Employ multiple SIRs. By strategically connecting these resonant structures in series or parallel, we can generate additional coupling paths. By tuning the resonant frequencies of two or more SIRs to coincide, we can broaden the passband region, effectively expanding the filter's bandwidth. 2. Adopt a wideband transmission line structure, such as a slotline or microstrip-ground-microstrip configuration, as the transmission medium for the filter. This wider transmission structure inherently supports a broader bandwidth, thereby enabling the antenna to achieve an enhanced frequency range.

The measured and simulated results of the antenna's planar radiation pattern at the center frequencies are shown in Figure 12. Because the ground plane of the duplexer acts as a reflector, the cascaded differential quad-band antenna exhibits directional radiation. For convenience, the detailed data are provided in Table 1, which shows that the measured results are in good agreement with the simulated ones.

To further testify the superiority of the proposed antenna over its counterparts, a comparison between them is made in Table 2. It can be discovered that the proposed antenna utilizes a differential structure to achieve quad-band radiation and has the lowest possible profile height. In addition, employing balanced feeding enhances the interference resistance of the proposed antenna, thus demonstrating its significant advantages in wireless communication application.

4. CONCLUSION

In this paper, a differential filtering quad-band antenna has been proposed, which consists of two pairs of enhanced folded dipoles and a duplex filter. Enhanced folded dipole has exhibited stable radiation characteristics, and its radiation frequency band could be controlled by selecting different arm lengths. Moreover, both the frequency and transmission zeros of the duplex filter could be adjusted by the length of the SIRs and the distance between the SIRs. The proposed antenna has been fabricated and measured, and test results are in good agreement with simulation ones, which has demonstrated that the designed antenna has stable radiation performance and excellent anti-interference ability.

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