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# Compact Wideband Folded Dipole Antenna With Multi-Resonant Modes

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**Abstract**—A compact and wideband folded dipole antenna with multi-resonant modes is presented in this paper. Three resonant modes are obtained by using a modified planar folded dipole and its coupled feeding structure. Incorporating with the shorting pins and parasitic patches, multiple resonant modes in the antenna are manipulated, shifted, and then combined for increasing the impedance bandwidth. Using this concept, a prototype of multi-mode folded dipole is designed, fabricated, and measured. The experimental results show that the proposed antenna achieves a bandwidth of 80% from 1.57 GHz to 3.68 GHz, while occupying a compact size of  $0.3\lambda_0 \times 0.15\lambda_0 \times 0.05\lambda_0$  ( $\lambda_0$  is the wavelength in free space at the lowest operating frequency). Furthermore, a simple and effective design to achieve good omnidirectional radiation performance is developed by placing two proposed folded dipoles back to back. The antenna exhibits a flat gain variation of less than 1.27 dB over a broad bandwidth (82%) in the horizontal plane. Such a compact, wideband, planar antenna is a promising candidate for indoor signal coverage, wireless access points, and micro base stations in 2G/3G/4G/5G and WLAN/WiMAX wireless communication systems.

**Index Terms**—Folded dipole antenna, multi-resonant modes, omnidirectional radiation, wide bandwidth.

## I. INTRODUCTION

WITH the development of wireless communication technologies, it has become increasingly desirable for modern communication devices to integrate multiple communication standards, such as 2G/3G/4G/5G and WLAN/WiMAX, into one single system. Therefore, antennas with broadband performance are highly demanded for the multi-standard coverage. Dipole antennas are widely used in many wireless communication systems. To achieve broadband

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operation, various designs of dipole antennas have been reported, such as modifying the shape of the dipole arms [1]-[3], improving feeding methods [4]-[5], loading parasitic radiators [6]-[8], and employing magnetoelectric complementary structures [9]-[10]. As a typical transformation of the single dipole, the folded dipole antennas (FDAs) are employed in many applications [11]-[14] owing to the wideband impedance characteristics. Many research works have been carried out [15]-[19] to improve the operation bandwidth of FDA. In [15], by compensating the mutual coupling, a four-element FDA array with 53.2% (1.19–2 GHz) bandwidth is developed at the expense of increasing the size of antenna. By using the formulas in [16], a wideband asymmetric coplanar strip FDA is designed in [17]. Through optimizing the widths of the asymmetric coplanar strip, this FDA exhibits a broad bandwidth of 55%. Besides, by loading different types of slots on 3-D FDAs, 57% and 67% bandwidths are achieved in [18] and [19], respectively. However, these reported antennas suffer unstable gain in their operating bands.

In this paper, a novel multi-resonant modes approach is proposed to enhance the bandwidth of the FDA. This approach is inspired by the dual-resonant cavity model of microstrip antennas [20]-[21]. In our design, multiple resonant modes in the antenna are generated, manipulated, shifted, and then combined for increasing the operation bandwidth. Through the FDA evolution from a linear model to a planar structure, the 1st-order and 3rd-order modes are manipulated and shifted towards each other. A pair of shorting strips is symmetrically introduced to optimize the input impedances of the two modes. In this way, a wideband planar folded dipole antenna (PFDA) is obtained with dual-resonant modes. To further improve the bandwidth of the dual-mode PFDA, a capacitively coupled feeding structure is employed, which generate a new resonant mode at the higher frequency. Moreover, a pair of parasitic patches is utilized to shift the additional resonance and obtain good impedance matching. Finally, a triple-resonant modes PFDA is achieved with a board bandwidth of 80% from 1.57 GHz to 3.68 GHz. To the best knowledge of the authors, it is a new exploration to manipulate, shift, and combine multi-resonant modes to enhance FDA impedance bandwidth. It is the first time that this approach to design a compact wideband planar antenna based on the multi-mode FDA is presented.

Additionally, omnidirectional radiation performance is also

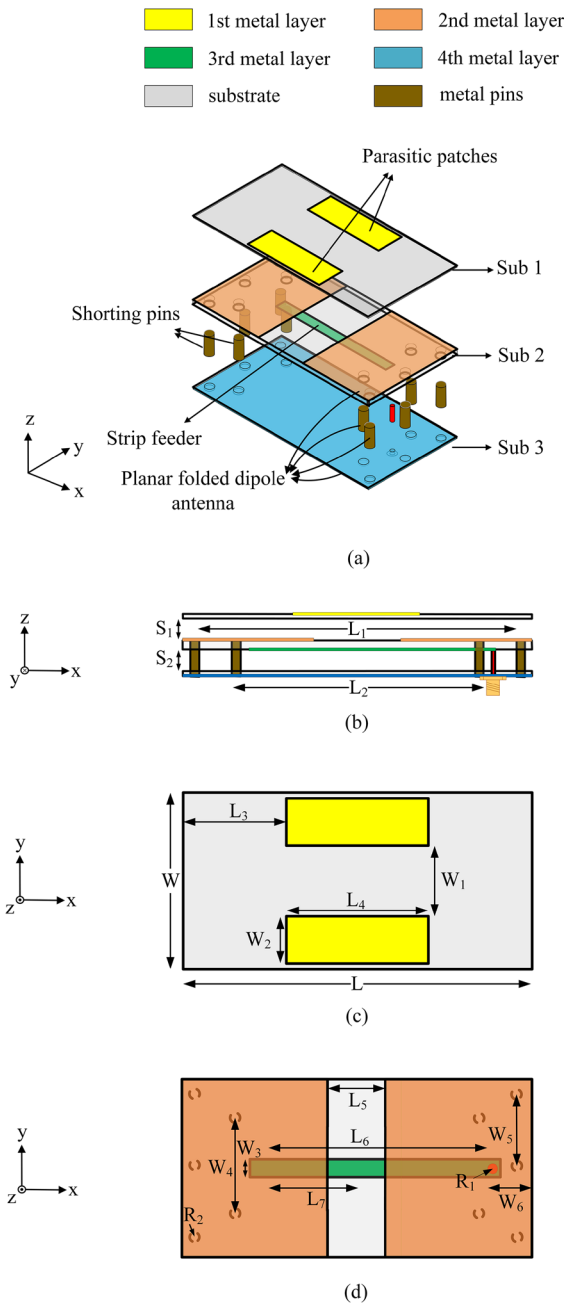


Fig. 1. Configuration of the proposed antenna: (a) 3D view, (b) side view, (c) top view of Sub 1, (d) top view of Sub 2. Dimensions are  $L = 60$ ,  $L_1 = 54$ ,  $L_2 = 42$ ,  $L_3 = 19$ ,  $L_4 = 22$ ,  $L_5 = 15$ ,  $L_6 = 37$ ,  $L_7 = 15$ ,  $W = 30$ ,  $W_1 = 12$ ,  $W_2 = 8$ ,  $W_3 = 2.8$ ,  $W_4 = 14$ ,  $W_5 = 12$ ,  $W_6 = 7$ ,  $R_1 = 0.5$ ,  $R_2 = 1.4$ ,  $S_1 = 4$  and  $S_2 = 4$  (unit: millimeter).

required for many wireless communication applications, such as indoor signal coverage, wireless access points, and micro base stations. Based on the multi-mode PFDA, a simple and effective design to achieve omnidirectional radiation performance is developed by placing two of the proposed PFDA's back to back. The resulted antenna exhibits good omnidirectional radiation patterns in the horizontal plane with flat gain variation of less than 1.27 dB. The presented compact broadband antenna is a good candidate for indoor signal coverage, wireless access points, and micro base stations in 2G/3G/4G/5G (1.7–2.7 GHz, 3.4–3.6 GHz), WLAN 2.4 GHz and WiMAX 2.5/3.5 GHz applications.

## II. ANTENNA CONFIGURATION AND WORKING PRINCIPLE

### A. Antenna Configuration

The configuration of the proposed multi-mode folded dipole antenna is shown in Fig. 1. The antenna has a four-layer configuration and it is printed on three F4B substrates (relative dielectric permittivity  $\epsilon_r = 2.2$ , loss tangent  $\tan\delta = 0.001$ ). These substrates have the same size of  $60 \times 30 \text{ mm}^2$ , and the thicknesses of them are 0.5 mm, 1.5 mm and 0.5 mm from top to bottom, respectively. There are two air layers between the substrates. The planar folded dipole is composed of two separate rectangular coppers on Sub 2, a rectangular copper sheet on Sub 3, and four rows of shorting pins that connect these two layers. Besides, a pair of parasitic patches is symmetrically etched on Sub 1. To excite the antenna, a planar capacitively coupled feeding strip is used. For practical implementation, a  $50 \Omega$  SMA connector is mounted below the antenna. The inner conductor is connected to the feeding strip through Sub 3, and its outer conductor is soldered to the metal sheet on the bottom side of Sub 3. To obtain the impedance and radiation performances, the antenna is simulated by using the ANSYS High Frequency Structure Simulator (HFSS).

### B. Shift of the Resonant Modes of a Folded Dipole

A linear folded dipole can be analyzed by assuming that its current is decomposed into a transmission line mode and an antenna mode [22]-[23]. The input impedance of the FDA is calculated by

$$Z_{in} = \frac{4Z_t Z_d}{2Z_d + Z_t} \quad (1)$$

where  $Z_t$  is the input impedance of transmission line mode, and  $Z_d$  is the input impedance of a regular dipole.  $Z_t$  and  $Z_d$  are obtained from

$$Z_t = j \frac{\eta}{\pi} \ln \left[ \frac{g + \sqrt{g^2 - d^2}}{d} \right] \tan \left( \frac{kl}{2} \right) \quad (2)$$

$$Z_d = \frac{R_r + jX_m}{\sin^2 \left( \frac{kl}{2} \right)} \quad (3)$$

where  $g$  is the spacing between the two larger sides,  $d$  is the diameter of the FDA,  $l$  is the length of FDA's larger sides,  $R_r$  and  $X_m$  are the input resistance and reactance of the linear dipole, respectively [23].

In this design, the length  $l$  of a linear FDA is chosen to be 60 mm, which is the half wavelength of 2.2 GHz. Substituting  $l = 60 \text{ mm}$ ,  $g = 6 \text{ mm}$ ,  $d = 0.5 \text{ mm}$  into equations (1)-(3), the frequency response of the FDA's input impedance is calculated and shown in Fig. 2. The widely used operating band of the FDA is at the range where its input impedance is approximately  $300 \Omega$  [23], as indicated by the shaded area around 2.2 GHz in Fig. 2. Note that there are two additional resonances appeared on both sides of the original working band. In order to illustrate the operation principle of the linear FDA, Fig. 3 presents the schematic diagram of three different current modes. From the vector current distributions in Fig. 3(a)-(c), it can be seen that three current modes resonated at 1.3 GHz, 2.2 GHz, and 3.3

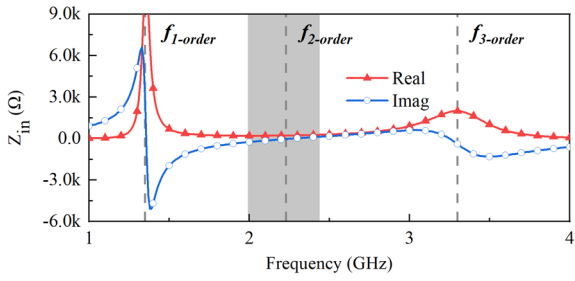


Fig. 2. Calculated input impedance of the linear FDA.

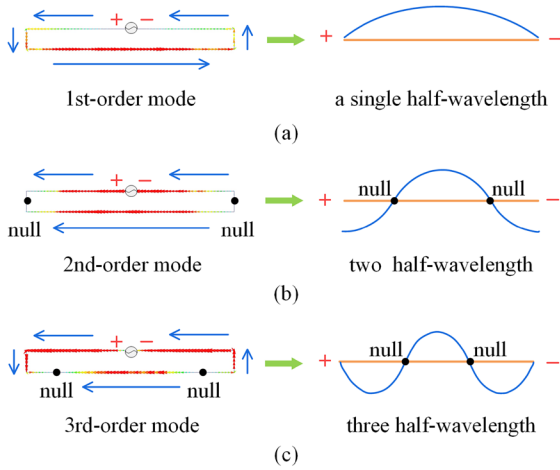


Fig. 3. Schematic diagram of 1st-order, 2nd-order, and 3rd-order modes of the linear FDA at (a) 1.3 GHz, (b) 2.2 GHz, and (c) 3.3 GHz.

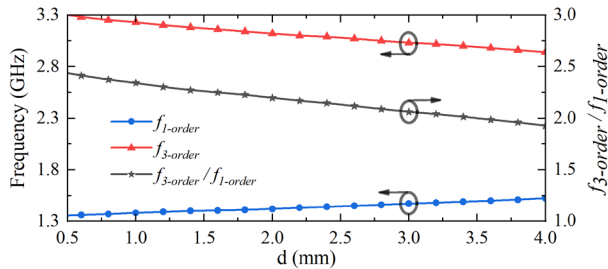


Fig. 4. Calculated  $f_{1\text{-order}}$ ,  $f_{3\text{-order}}$ , and  $f_{3\text{-order}}/f_{1\text{-order}}$  as the functions of  $d$ .

GHz represent the 1st-order, 2nd-order, and 3rd-order modes, which indicate half, one, and one and a half wavelength modes along the antenna, respectively. However, these modes are far away from each other, and the input impedances around  $f_{1\text{-order}}$  and  $f_{3\text{-order}}$  are very high.

The 1st-order and 3rd-order modes of FDA can be manipulated and shifted by varying the diameter  $d$  of the folded dipole. By calculating the first resonant frequency and the third resonant frequency based on (1)–(3), the relationship between  $f_{1\text{-order}}$ ,  $f_{3\text{-order}}$ , and  $d$  can be expressed in an intuitive way as follows

$$f_{1\text{-order}} = F_1(d) \quad (4)$$

$$f_{3\text{-order}} = F_3(d) \quad (5)$$

The calculated  $f_{1\text{-order}}$ ,  $f_{3\text{-order}}$ , and  $f_{3\text{-order}}/f_{1\text{-order}}$  as the functions of  $d$  are shown in Fig. 4. It shows that  $f_{1\text{-order}}$  is a monotonically increasing function of  $d$  and  $f_{3\text{-order}}$  is a monotonically decreasing function of  $d$ , within the range of 0.5–4.0 mm. This also reveals that the ratio of  $f_{3\text{-order}}$  to  $f_{1\text{-order}}$  is reduced as  $d$

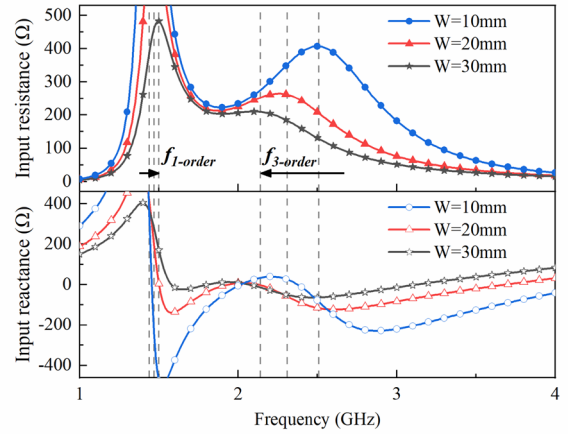


Fig. 5. Simulated input impedances of the PFDA for various  $W$ .

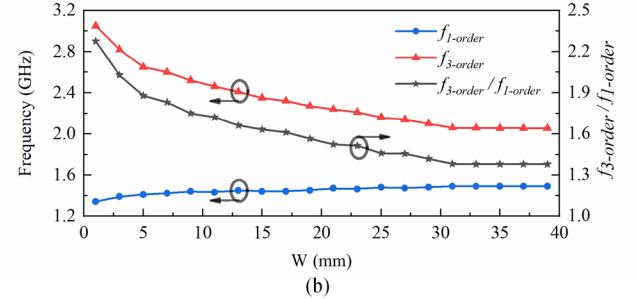
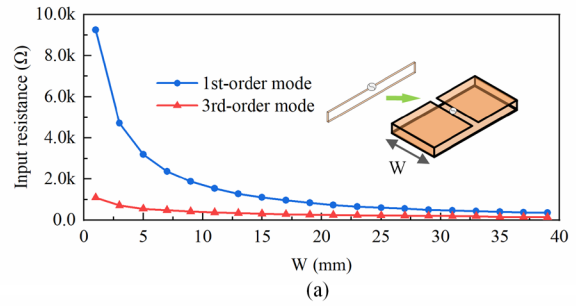


Fig. 6. (a) Simulated input resistances, (b) resonant frequencies and  $f_{3\text{-order}}/f_{1\text{-order}}$  as a function of  $W$  at 1st-order and 3rd-order modes.

increases, which predicts the two resonant modes will be shifted towards each other by increasing the diameter of the FDA. However, due to the structural constraint of the linear FDA, the diameter  $d$  cannot be larger than the spacing  $g$  between the two larger sides to further decrease  $f_{3\text{-order}}/f_{1\text{-order}}$ .

To make the 1st-order and 3rd-order modes closer together, the structure of the FDA is evolved from the linear model to a planar structure. Increasing the width of the PFDA can have the same effect as the increase of the FDA diameter [23]. In this way, 1st-order and 3rd-order modes can be manipulated and shifted towards each other in a greater extent, which leads to a wideband response of the multi-mode FDA. Fig. 5 shows the simulated input impedance of the PFDA. When increasing the width  $W$ , it can be seen that the first resonance of the input impedance moves to the higher frequency, while the third resonance shifts to the lower frequency. The 1st-order and 3rd-order modes of the PFDA are shifted towards each other, and the ratio of the two modes can be manipulated by adjusting the width  $W$ . Besides, the increase of the PFDA width contributes to the reduction of the input resistance. Fig. 6 shows

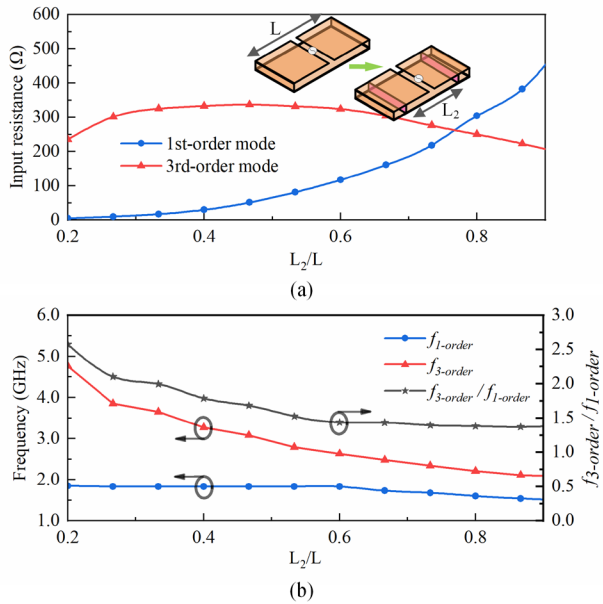


Fig. 7. (a) Simulated input resistances, (b) resonant frequencies and  $f_{3\text{-order}}/f_{1\text{-order}}$  as a function of  $L_2/L$  at 1st-order and 3rd-order modes.

the simulated input resistances and resonant frequencies of the 1st-order and 3rd-order modes vary with the different  $W$ . By increasing the width  $W$  to 40mm, the input resistances for both resonant modes decrease significantly. Meanwhile, the ratio of  $f_{3\text{-order}}$  to  $f_{1\text{-order}}$  is also notably reduced as  $W$  increases. The  $f_{3\text{-order}}/f_{1\text{-order}}$  steadily approaches the minimum value of 1.4 after  $W$  reaches 30mm. Considering the miniaturization of the antenna, the width of PFDA is chosen to be 30 mm in the design.

In conclusion, through the FDA evolution from the linear model to the planar structure, the 1st-order and 3rd-order modes can be manipulated and shifted towards each other, and the input resistances of the two modes are also reduced at the same time. However, owing to an initial difference in the input resistance of the linear FDA at the 1st-order and 3rd-order modes in Fig. 2, the resistance difference between the two modes is still large, about 300Ω.

### C. Optimizing the multi-mode input impedance

In order to optimize the input impedance of the 1st-order and 3rd-order modes, a pair of shorting strips is symmetrically introduced in the design. As shown in Fig. 7, it can be seen that the input resistances at the 1st-order and 3rd-order modes can be manipulated by controlling the distance  $L_2$  between the shorting strips, especially for the 1st-order mode. To adjust the input impedances of the two modes, the value of  $L_2/L = 0.75$  is selected with the same input resistance for the 1st-order and 3rd-order modes of PFDA and a minimum ratio of  $f_{3\text{-order}}/f_{1\text{-order}}$  is maintained. By comparing the resistances of PFDA with and without the shorting strips in Fig. 8, it can be observed that the input resistances difference between the two modes becomes small after introducing a pair of shorting strips with  $L_2/L = 0.75$ , and the maximum values of dual-mode input resistances are close to 260 Ω. Thus, a conclusion can be drawn that the shorting strips play a critical role in adjusting and optimizing the impedance properties of the two resonant modes. As

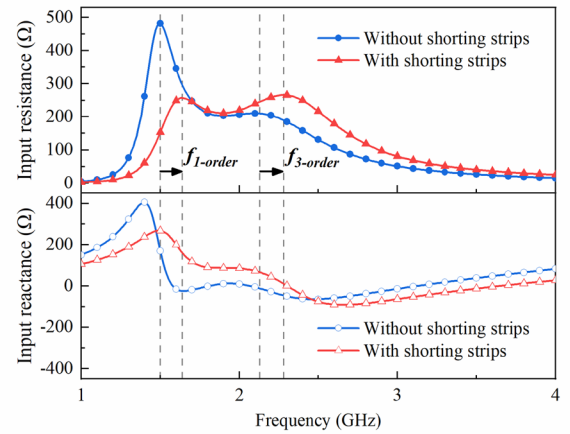


Fig. 8. Simulated input impedances of the PFDA without and with shorting strips when  $L_2/L = 0.75$ .

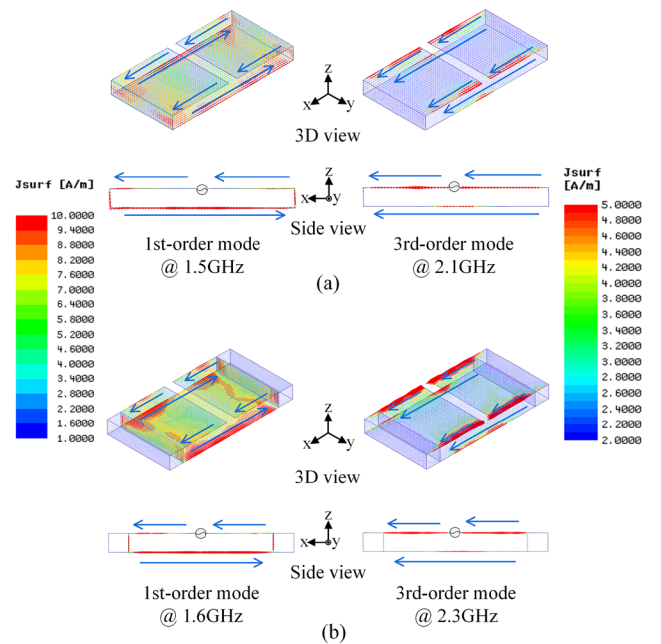


Fig. 9. Surface current distributions of the PFDA (a) without and (b) with the shorting strips.

mentioned above, by employing the planar configuration with two shorting strips, the 1st-order and 3rd-order modes of the PFDA are manipulated, shifted, and then combined.

To further investigate the operation mechanism of the PFDA, the surface current distributions of PFDA are given in Fig. 9. At the 1st-order mode, the large current density is observed along the bottom side of the PFDA, with and without the introduced shorting strips. The surface current distributions exhibit a single half-wavelength resonance, which refers to the 1st-order mode of the antenna. Whereas, three half-wavelength distributions are observed along the whole PFDA for the 3rd-order mode excitation. It can be seen that the surface current distributions are mainly concentrated along the edges of the PFDA. The observed current distributions are consistent with the design concept, which validate the dual resonant modes of the antenna. Besides, owing to the introduction of shorting strips, the resonant current paths of PFDA along the  $x$ -axis are shortened



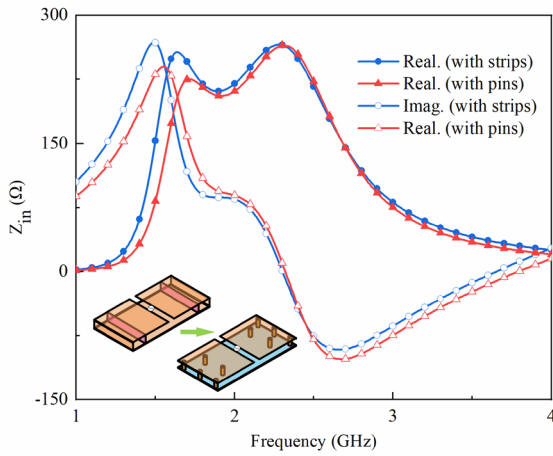


Fig. 10. Simulated input impedances of the PFDA with shorting strips and with shorting pins.

at both the 1st-order and 3rd-order modes. This lead to the two modes shifting towards the higher frequency simultaneously as shown in Fig. 8. It is worth noting that the ratio between  $f_{3\text{-order}}$  and  $f_{1\text{-order}}$  remains almost unchanged because the shift of the two resonant modes is synchronous towards the higher frequency.

#### D. Feeding and Matching Methods

To facilitate the antenna fabrication with PCB technology, four rows of shorting pins are applied in the design to replace the shorting strips and metal side frames. As shown in Fig.10, it is clear that the use of the shorting pins has little effect on the input impedance of the dual-mode PFDA.

In order to further enhance the bandwidth of the dual-mode PFDA and improve its impedance matching to 50 Ω, effective feeding and matching methods for PFDA are developed.

Fig. 11(a) shows the simulated input impedance of the dual-mode PFDA, which is driven by an ideal lumped port in the simulation by using ANSYS HFSS. The lumped port connects the two open ends of PFDA with a gap of 4 mm. Note that the input impedance of the dual-mode ideal fed PFDA exhibits strong inductive component around the 1st-order mode in Fig. 11(a). To obtain good impedance matching, a  $\Gamma$ -shaped coupled feeding structure is employed in Fig. 11(b), which consists of a rectangular feeding strip and an inner conductor of 50 Ω SMA connector. By using this feeding structure, the energy can be coupled to two open ends of PFDA through the feeding strip to excite the antenna. In this way, a capacitive compensation can be provided by the overlapping areas between the feeding strip and the top side of the PFDA. Through the use of this capacitively coupled feeding structure, the input reactance can be decreased from 160 Ω to 30 Ω while the input resistance is reduced from 240 Ω to 100 Ω, as shown in Fig. 11(b). Moreover, a new resonance at 3.8 GHz is introduced by the coupled feeding strip (CFS). However, the additional CFS resonant mode is too far away from the 1st-order and 3rd-order modes.

To shift the CFS mode towards the two original modes, a pair of parasitic patches is introduced in Fig. 11 (c). The effects of the patch length  $L_4$  on the input impedances and the resonant frequencies of the three modes are illustrated in Fig. 12. It is worth noting that after  $L_4$  increases to 22 mm, the input

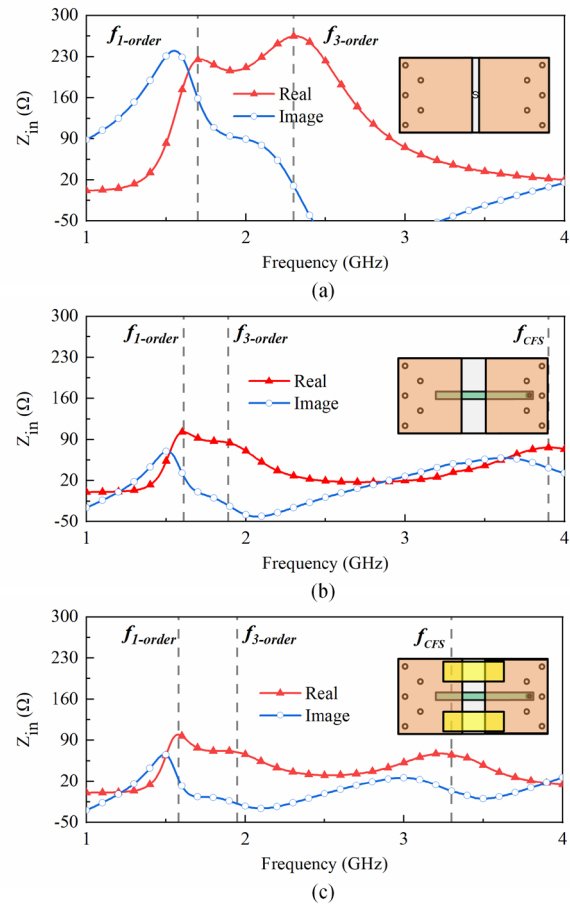


Fig. 11. Simulated input impedances of various PFDA involved in the design evolution process. (a) Ideally fed antenna, (b) coupled fed antenna, (c) coupled fed antenna with parasitic patches.

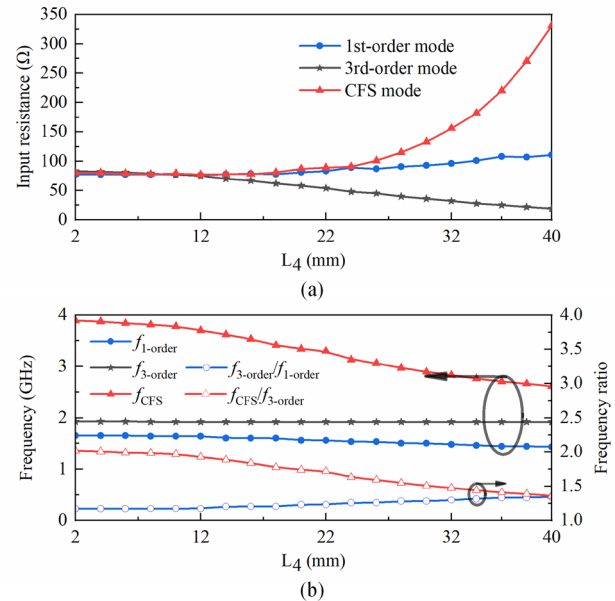


Fig. 12. (a) Simulated input resistances, (b) resonant frequencies and corresponding ratios as a function of  $L_4$  at 1st-order, 3rd-order and CFS modes.

resistances of 3rd-order mode and CFS mode dramatically change in different ways. The resistance in CFS mode sharply increases to more than 300 Ω while the resistance of 3rd-order mode slowly falls below 50 Ω. Considering the impedance

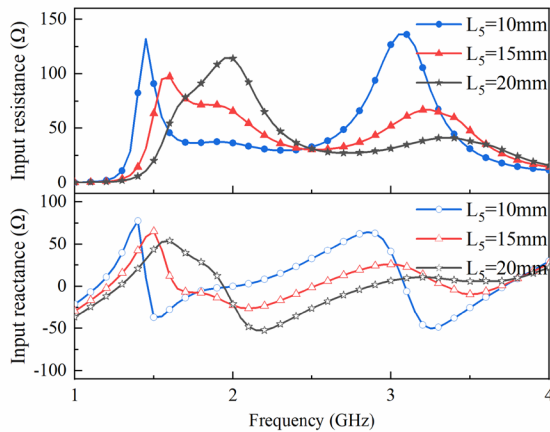


Fig. 13. Simulated input impedances of the proposed antenna for various  $L_5$ .

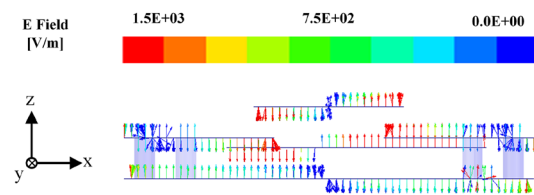


Fig. 14. Electric field distributions of the proposed PFDA at 2.2 GHz.

matching and the uniform frequency ratios between the resonant modes, the length  $L_4$  of parasitic patches is chosen to be 22 mm as the optimized value.

Besides, in this design, the gap width  $L_5$  between the two open ends of PFDA can greatly affect the input impedance characteristics, as shown in Fig. 13. It can be observed that as  $L_5$  increases, the resonant modes of the FPDA shift to the higher frequencies. When  $L_5 = 15$  mm, the smallest resistance variation range can be obtained across the whole operating frequency band. Therefore, to realize the wideband impedance matching, the value of  $L_5 = 15$  mm is selected in this design. The simulated results indicate that the resonant frequencies and the resistance variation range can be simultaneously controlled by adjusting the gap width  $L_5$ .

Fig. 14 shows the electric field distribution to provide another insight into the operating principle of the feeding structure. It can be observed that, through the feeding strip, the electric field is coupled to the two open ends of the folded dipole. The electric fields on the left and right sides of the antenna are excited with the same amplitude but opposite phase. The equivalent capacitive loading is formed by coupling the electric fields on the parallel overlapping areas between the feeding strip and the top side of the PFDA. As mentioned above, by employing the capacitively coupled feeding strip and parasitic patches, the proposed antenna can realize good triple-mode operation with wideband impedance characteristics.

### III. RESULTS AND DISCUSSION

#### A. Multi-Mode PFDA

To validate the above design concept, a multi-mode folded dipole was designed, fabricated, and measured. The simulated

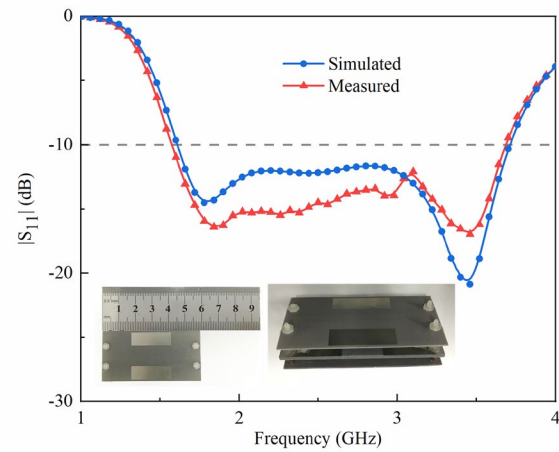


Fig. 15. Measured and simulated reflection coefficients for the proposed antenna.

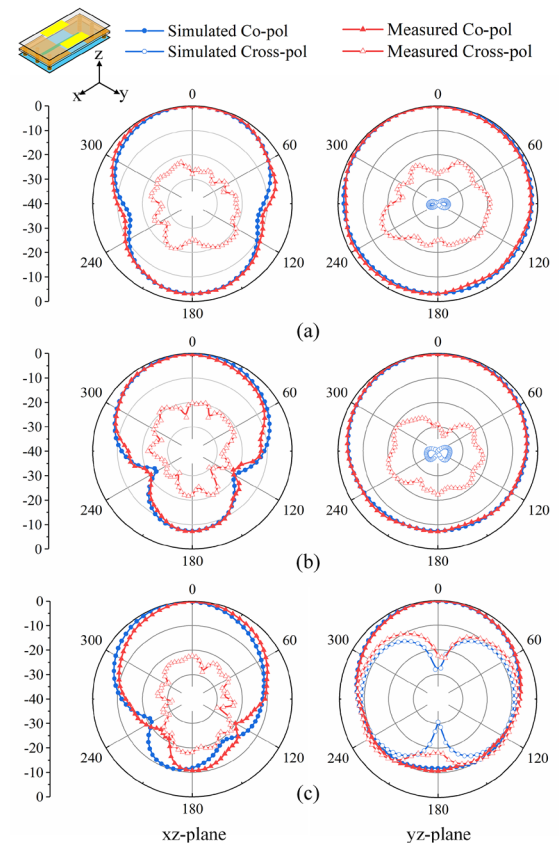


Fig. 16. Measured and simulated normalized radiation patterns for the proposed antenna at (a) 1.6 GHz, (b) 2.6 GHz, and (c) 3.6 GHz.

and measured reflection coefficients are plotted in Fig. 15. Reasonable agreement between the experimental and the simulated results is obtained. The multiple resonant modes are excited to achieve a good impedance matching for the bandwidth of 80% from 1.57 GHz to 3.68 GHz for  $|S_{11}| < -10$  dB, which covers the operating bands for the 2G/3G/4G/5G and WLAN/WiMAX applications.

The radiation characteristics including radiation patterns and antenna gains were measured in a near-field antenna measurement system at Xidian University. Fig. 16 shows the measured and simulated far-field normalized radiation patterns in  $xz$ -plane and  $yz$ -plane at 1.6 GHz, 2.6 GHz, and 3.6 GHz,

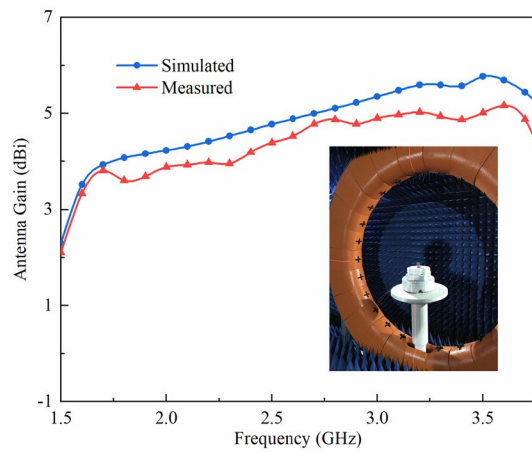


Fig. 17. Measured and simulated peak gains for the proposed antenna.

TABLE I  
COMPARISON OF THE FOLDED DIPOLE ANTENNAS

Ref.	Dimensions ( $\lambda_0$ )	Impedance Bandwidth	Peak gain (dBi)
[13]	0.44×0.44×0.07	12% 26.30-29.75 GHz	5.51
[14]	1.17×0.31×0.01	20% 5.07-6.16 GHz	4.2-4.6
[15]	0.31×0.34×0.11	53% 1.19-2.00 GHz	0.3-1.2
[17]	0.36×0.16×0.00	55% 1.23-2.17 GHz	2.2-2.5
[18]	0.24×0.10×0.05	57% 1.03-1.85 GHz	2.0-5.0
[19]	0.24×0.08×0.04	67% 1.10-2.20 GHz	1.0-4.6
<b>This work</b>	<b>0.30×0.15×0.05</b>	<b>80% 1.57-3.68 GHz</b>	<b>3.3-4.9</b>

\*  $\lambda_0$  is the wavelength at the lowest operating frequency in free space.

respectively. Because of the inherent asymmetry in the  $yz$ -plane, the PFDA exhibits a quasi-omnidirectional pattern with maximum gain in its boresight direction ( $z$ -axis direction). As the frequency increases from 1.6 to 3.6 GHz, the front-to-back ratio of the radiation pattern increases from 3 to 10 dB. Besides, it is observed the proposed antenna has bidirectional radiation in the  $xz$ -plane. The simulated and measured antenna gains are presented in Fig. 17. A stable gain around 4.1 dBi is achieved over the operating band.

Table I compares the proposed antenna with the folded dipole antennas reported in recently published papers. A compact vertically stacked FDA with a 12% bandwidth is proposed in [13] by utilizing a multilayer PCB technology. In [14], a planar antenna comprising two folded dipoles obtain a very stable gain around 4 dBi with a 20% bandwidth. By compensating the mutual coupling effects, a four-element FDA array achieves a 53% bandwidth at the expense of the increased overall size [15]. By using the formulas in [16], an asymmetric coplanar strip FDA is designed with a self-balanced impedance property, exhibiting 55% bandwidth [17]. In [18] and [19], by loading different types of slots on 3-D FDA, 57% and 67% bandwidths are achieved in compact sizes, respectively.

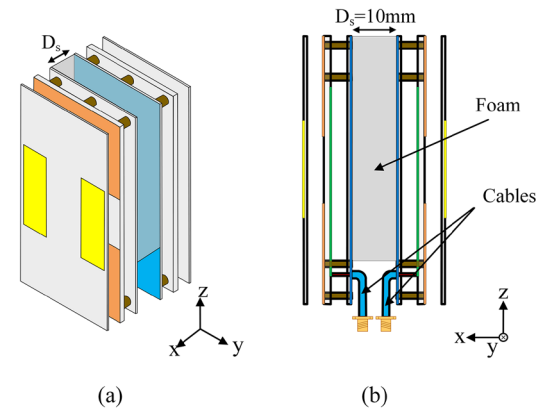


Fig. 18. Configuration of the back-to-back PFDA. (a) 3D view. (b) Side view.

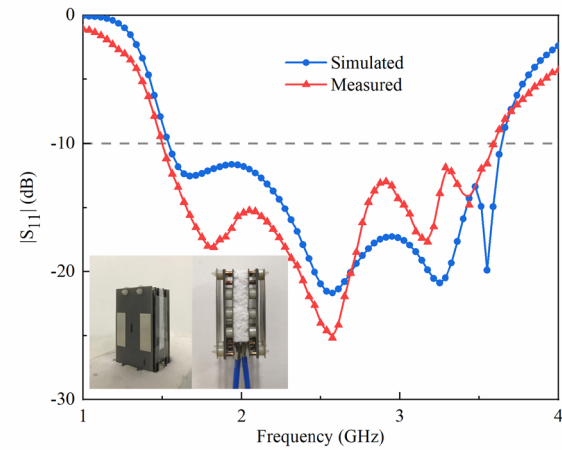


Fig. 19. Measured and simulated reflection coefficients for the back-to-back PFDA.

However, these antennas suffer unstable gain in their operating bands. Compared to these antennas, the proposed multi-mode PFDA exhibits the widest bandwidth of all the FDAs while achieving a compact size.

### B. Back-to-back PFDA

Based on the multi-mode PFDA, a design to achieve omnidirectional radiation performance is developed in this section.

As shown in Fig. 18, two identical PFDA are placed back to back along the  $z$ -axis. The back-to-back PFDA are fed by two 50  $\Omega$  semi-rigid coaxial cables. The inner conductor of the coaxial cable is connected to the feeding strip, while the outer conductor is soldered to the metal sheet on the back. A thin layer of foam ( $\epsilon_r = 1.1$ ) with a thickness  $D_s$  of 10 mm is employed to maintain a separation distance between the two PFDA. The simulated and measured reflection coefficients of the antenna are shown in Fig. 19. Multi-resonant modes are excited to realize a broad bandwidth of 82% (1.5–3.59 GHz). An additional resonance appeared at 3.5 GHz is mainly caused by the mutual couplings between the two PFDA.

Additionally, the operating principle of the back-to-back PFDA with omnidirectional radiation pattern is given in Fig. 20. It is known that the PFDA itself has a quasi-omnidirectional radiation pattern with maximum gain in the boresight direction



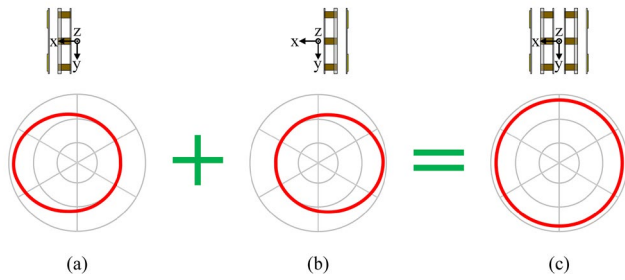


Fig. 20. Operating principle of back-to-back PFDA with omnidirectional radiation pattern at  $xy$ -plane.

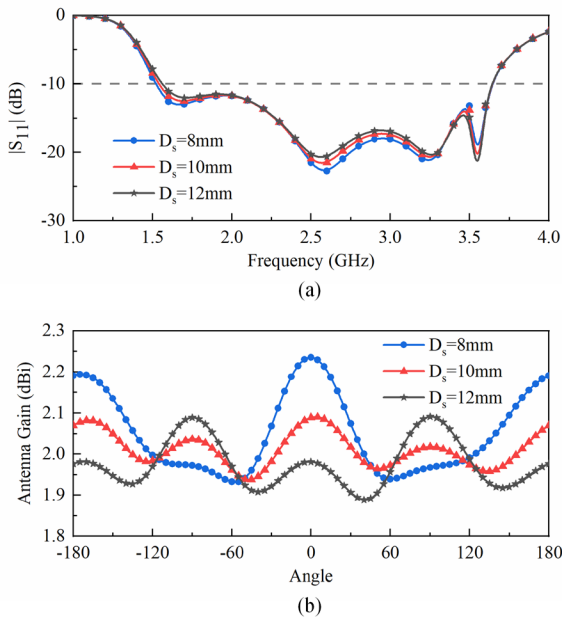


Fig. 21. (a) Simulated reflection coefficients and (b) simulated gain variations in horizontal plane for various  $D_s$ .

( $x$ -axis direction) as shown in Fig. 20(a). And the antenna gain gradually decreases from  $+x$ -axis to  $-x$ -axis direction. When adding the other PFDA in Fig. 20(b) back to back, the gain near the  $y$ -axis is enhanced while the gain in the  $x$ -axis direction is almost unchanged. This leads to a more uniform pattern in the  $xy$ -plane, resulting in an omnidirectional pattern as shown in Fig. 20(c). Fig. 21 illustrates the effect of the distance  $D_s$  on reflection coefficients and gain variations in the horizontal plane ( $xy$ -plane). It can be seen that the antenna keeps a wide impedance bandwidth, and the bandwidth is not sensitive to the distance  $D_s$ . When  $D_s$  increases from 8 to 12 mm, the gain variation in the horizontal plane at 2.6 GHz is changed between 0.14 and 0.31 dB. Therefore, the distance  $D_s$  is chosen as 10 mm for the optimally designed back-to-back PFDA. Also, the radiation characteristics, such as radiation patterns and peak gains, were measured within the operating band for the antenna, as shown Figs. 22 and 23. Thanks to the quasi-omnidirectional radiation of the single PFDA, the back-to-back PFDA achieve a desirable omnidirectional radiation performance in the horizontal plane with a flat gain variation of less than 1.27 dB. Moreover, a reasonably stable gain of around 2.2 dBi within the whole operating band is also obtained.

Table II compares the performances of the wideband

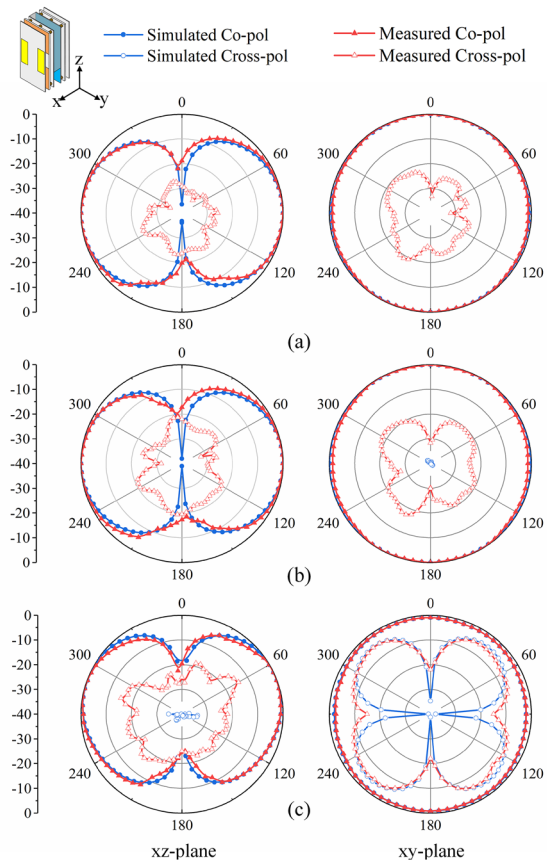


Fig. 22. Measured and simulated normalized radiation patterns for the back-to-back PFDA at (a) 1.6 GHz, (b) 2.6 GHz, and (c) 3.6 GHz.

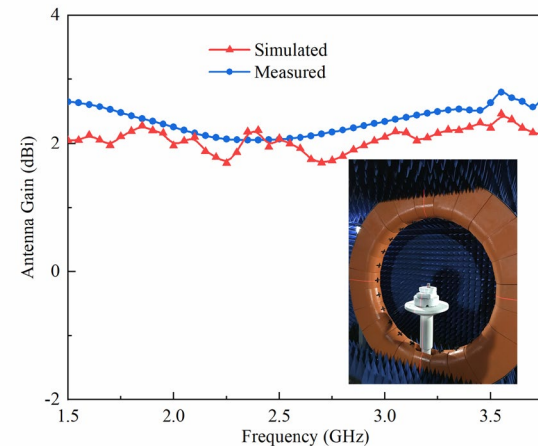


Fig. 23. Measured and simulated peak gains for the back-to-back PFDA.

back-to-back PFDA with the recently published omnidirectional antennas. Designs in [14] and [17] are in the form of printed folded dipoles, and they have the moderate bandwidths of 20% and 55%. By employing planar coaxial collinear radiator [24] and multi-mode dielectric resonator [25], the flattest gain variations of 0.7 dB in the horizontal plane are achieved for these antennas. However, the series structure in [24] leads to a narrow bandwidth and a large size. In [25], a hybrid feed is used, which increases the complexity in the antenna design. By using modified monopole and dipole structures, antennas in [26]-[27] achieve very wide bandwidths

TABLE II  
COMPARISON OF THE OMNIDIRECTIONAL ANTENNAS

Ref.	Dimensions ( $\lambda_0$ )	Impedance Bandwidth	Gain Variations (dB)
[14]	0.31×1.17×0.01	20% 5.07-6.16 GHz	<2
[17]	0.36×0.16	55% 1.23-2.17 GHz	<4
[24]	3.56×0.53×0.04	11% 13.36-14.98 GHz	<0.7
[25]	0.39×0.39×0.17	53% 1.95-3.35 GHz	<0.7
[26]	0.38×0.38×0.27	152% 0.82-6.00 GHz	<5
[27]	0.24×0.24×0.24	194% 0.45-28.40 GHz	<5
<b>Back-to-back PFDAs</b>	<b>0.30×0.15×0.13</b>	<b>82% 1.50-3.59 GHz</b>	<b>&lt;1.27</b>

\*  $\lambda_0$  is the wavelength at the lowest operating frequency in free space.

in omnidirectional antenna designs. However, they suffer large gain variations in the horizontal plane. Through the above comparison, our proposed back-to-back PFDAs achieves a desirable flat gain variation (<1.27 dB) in the horizontal plane over a broad bandwidth (82%) with a compact size.

#### IV. CONCLUSION

A new approach to design wideband and compact multi-mode folded dipole antenna is presented in this paper. By introducing shorting pins, coupled feeding strips, and parasitic patches on the planar folded dipole, three different resonant modes of the antenna can be excited and manipulated. By properly shifting these three modes, the proposed antenna obtains a broad bandwidth of 80% and achieves a compact size of  $0.3\lambda_0 \times 0.15\lambda_0 \times 0.05\lambda_0$ . To validate the design concept, the antenna prototype is fabricated and measured. The experimental results are in good agreement with simulated results. Furthermore, a simple and effective design to realize omnidirectional radiation performance is presented by arranging two back-to-back PFDAs. The antenna exhibits a flat gain variation of less than 1.27 dB over a broad bandwidth (82%) in the horizontal plane. Such a compact, wideband, planar antenna is a promising candidate for many wireless applications, including indoor signal coverage, wireless access points, micro base stations in 2G/3G/4G/5G and WLAN/WiMAX wireless communication systems.

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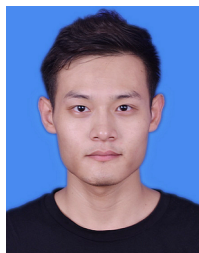
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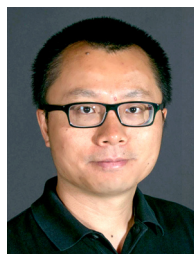


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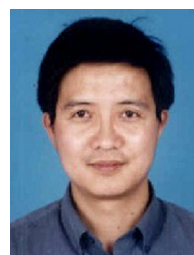
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