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Enhanced Bandwidth of a Horizontally Polarized Omnidirectional Printed Antenna Array Based on Dual-Dipole Structure

Yu-Liang Yang*, **Fu-Shun Zhang**, **Hong Zhang**, **and Hong-Yin Zhang**

Abstract—In this paper, a horizontally polarized (HP) omnidirectional antenna array with a broadband characteristic is presented. The proposed antenna consists of a circular array based on four planar arc dual-dipole structures, a wideband 1-to-4 feeding network with baluns, four reflectors and twelve directors. The arc dual-dipoles with four etched slots are introduced to obtain the broadband characteristic. By using twelve directors in front of the dipoles, the gain variation in the horizontal plane is improved. In addition, the reflector elements are able to improve the gain for the middle frequency band. With the concept, a prototype antenna with an overall size of $0.66\lambda_L \times 0.66\lambda_L \times 0.01\lambda_L$ (λ_L is the free-space wavelength at the lowest frequency) is fabricated and measured. The designed antenna exhibits a relative impedance bandwidth of 98.3% (1.245–3.652 GHz) for $|S_{11}| < -10\,\text{dB}$. The HP omnidirectional patterns provide a gain variation less than 3.0 dB over the frequency band 1.245–3.519 GHz (95.5%). Within the impedance bandwidth, the cross-polarization level is lower than $-20\,\text{dB}$ in the horizontal plane.

1. INTRODUCTION

Omnidirectional antennas have attracted great attention in indoor and urban wireless communication systems owning to the advantage of serving 360° full uniform signal coverage of surrounding environment. In addition, the horizontally polarized (HP) antenna with an omnidirectional pattern is preferred to harvest the polarization resource and maximize a system's capacity [1]. Furthermore, the HP antenna is needed in polarization diversity systems for improving the reliability of a communication link [2]. Meanwhile, the bandwidth of antenna directly determines the data rate of communication. To satisfy the requirements for higher data rate and multiple-band communication, the system's antenna bandwidth also needs to be largely increased [3]. Consequently, there is no doubt that enough attention should be paid to design a wideband HP omnidirectional antenna.

As we all know, the traditional way to design an HP omnidirectional antenna is to utilize a small loop antenna with good omnidirectional radiation performance. However, the disadvantage is the difficulty of impedance matching due to small resistance and high reactance. Subsequently, the Alford antennas [4, 5] appear to obtain balance between impedance matching and radiation performance. Nevertheless, these methods have a weakness of narrow bandwidths (about 6%). The concept of rotating electric field method is applied to conventional slot dipoles in [6] and an antenna array in [7], but their relative bandwidths are 15.4% and 39.4%, respectively. In addition, some new techniques are employed in [8–10]. The antenna in [8] with four pairs of printed dipoles distributed on the front and back of the substrate and the antennas [9] consisting of 3, 4 or 5 printed dipoles possess a bandwidth of 39.6% and 45.5%, respectively. A tune disk with four square-shaped perturbations and four pairs of tapered parallel transmission lines are utilized in [10]. The impedance bandwidth is improved up to 51%. However, its size is as large as $0.91\lambda_L \times 0.91\lambda_L \times 0.01\lambda_L$ (λ_L is the free-space wavelength at the lowest

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frequency). The antenna in [11] with a modified annular ring slot and modified printed arc dipole array has a low profile, but the bandwidth is only 11.1%. In [12–15], dipoles are introduced to produce HP omnidirectional radiation patterns. Nevertheless, they cannot be mounted in constrained space due to the relatively high profiles. To further widen the bandwidth, a broadband feeding network is designed to be applied to the dipole array in [16] and [17]. Owning to the broadband feeding network introduced, the impedance bandwidth of over 50% can be obtained. However, the gain variation in [16] in the horizontal plane is up to 5.0 dB, and the profile in [17] is as high as 26.7 mm ($0.11\lambda_L$). By introducing mutual coupling method, the antenna in [18] has a bandwidth of 70.2%. But the cross-polarization level is poor of −15 dB, and the dimension is as large as $0.85\lambda_L \times 0.85\lambda_L \times 0.01\lambda_L$.

In this paper, a wideband horizontally polarized omnidirectional antenna array is realized by adopting four printed arc dual-dipole elements. The feeding network is composed of four microstrip baluns and a four-way power divider. Reflectors and directors are used to improve gain and omnidirectional radiation performance. The measured results indicate that an impedance bandwidth of 97.9% (1.253 GHz ∼ 3.657 GHz) for $|S_{11}| < -10$ dB is obtained, and all the rest of the details are provided in the following sections.

2. ANTENNA GEOMETRY

Figure 1 shows the geometry of the HP omnidirectional antenna array printed on an FR4 substrate. The proposed antenna consists of a circular array based on four planar arc dual-dipole structures, a wideband 1-to-4 feeding network with baluns, four reflector elements and twelve directors. Four planar arc dual-dipoles, reflector elements and director elements are printed on the bottom plane of the substrate. The feeding network with baluns is printed on the top plane of the substrate. The substrate of Φ 160 mm × 1 mm for the antenna is FR4 ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$). A 50-Ω coaxial cable is connected to the wideband power divider at the center of the substrate.

Figure 1(a) depicts the parameters of the structures on the bottom plane of the proposed antenna. Four arc dual-dipole elements are same in size. Four reflector elements between the feeding network and four arc dual-dipole elements, and twelve directors are distributed symmetrically on the bottom plane. The reflector elements are identical in structure.

In addition, the parameters of the structures on the top plane are shown in Figure 1(b). The feeding network is located at the center of the substrate symmetrically. And the network consists of

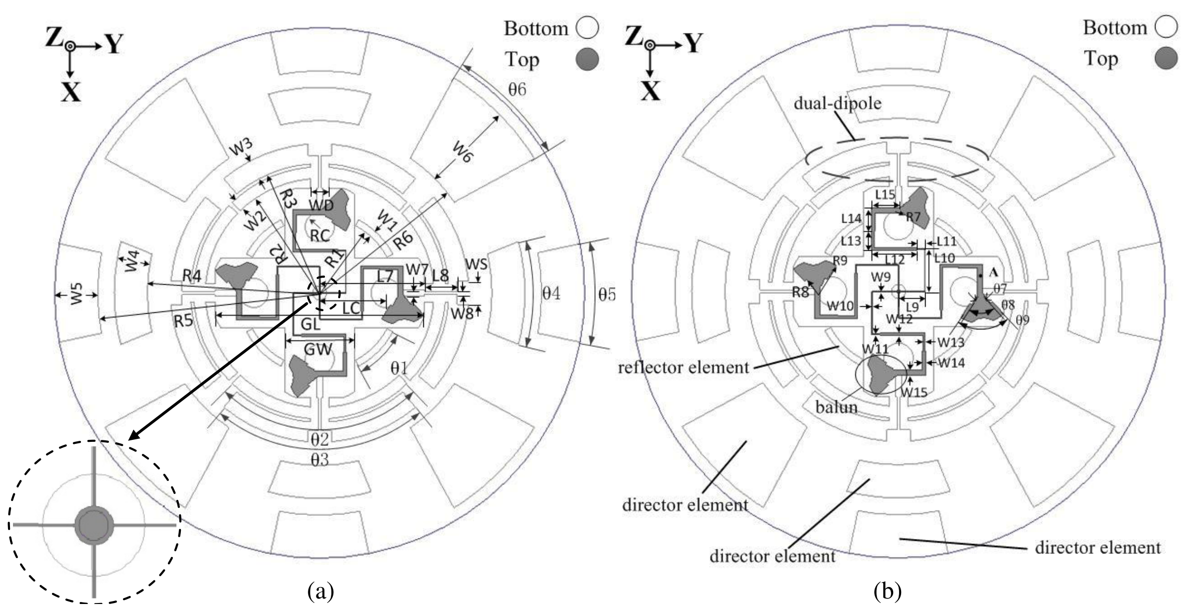


Figure 1. Geometry of the HP omni-directional antenna array. (a) Parameters of the structures on the bottom plane, and (b) parameters of the structures on the top plane.

Table 1. Dimensions on the proposed antenna.

Parameter	$R1$	$W1$	$R2$	$W2$	$R3$	$W3$	$R4$	$W4$	$R5$	$W5$
Value (mm)	23	2	34.5	3.5	39	6	52	10	67	13
Parameter	$R6$	$W6$	$L7$	$W7$	$L8$	$W8$	LC	RC	GL	GW
Value (mm)	49	27.5	31.6	1.8	9.9	1	19.9	4.4	31.5	21
Parameter	WS	WD	$L9$	$W9$	$L10$	$W10$	$L11$	$W11$	$L12$	$W12$
Value (mm)	7	5.4	8	0.1	13	0.2	2.5	0.4	13.5	0.8
Parameter	$L13$	$W13$	$L14$	$W14$	$L15$	$W15$	$R7$	$R8$	$R9$	
Value (mm)	5.7	0.7	7	1.1	8.2	1.4	3	5.5	10.5	
Parameter	$\theta1$	$\theta2$	$\theta3$	$\theta4$	$\theta5$	$\theta6$	$\theta7$	$\theta8$	$\theta9$	
Value (deg)	34	88	80	29	21.4	26	50	60	76	

a four-way microstrip power divider and four microstrip baluns. The fan-shaped part of the balun is composed of three fan-shaped structures with different radii and radians. The balun is used not only for unbalance-balance transition, but also for impedance transformation. The detailed geometry and dimensions of the proposed antenna are given in Figure 1 and Table 1 after optimization using the HFSS (High Frequency Structure Simulator) software.

3. ANTENNA DESIGN

There are three designing challenges for the proposed antenna array: 1) a wideband element, 2) a broadband feeding network, and 3) a relatively high gain within the operating frequency band. To begin with, the bandwidth of the array element should be enhanced to obtain a wider array's bandwidth. Thus, a modified dual-dipole is designed herein, and it owns radiation properties similar to a conventional dipole. The lengths of the long and short dipoles of the dual dipoles are influenced by the lower and upper operating frequencies [19], respectively. The designed dual-dipole can be regarded as a combination of a wide-strip planar dipole and a conventional dual-dipole. Then the dual-dipole is modified into an arc dual-dipole further, which can provide a wider beamwidth. Acting as array element, they can achieve good omnidirectional radiation performance. After adjusting the dimensions of a single element carefully, four dual-dipoles are arranged to form a circular array. Without the feeding network, the elements' separation distance is optimized for better omnidirectional radiation pattern. The simulation is carried out with the assistance of the HFSS.

Accordingly, a wideband feeding network is designed to feed four arc dual-dipole elements. The feeding network is composed of a 4-way power divider and four microstrip baluns. As pointed out in Figure 1(b), the input impedance (looking at point "A") of the balun is selected as 50-Ω initially. The theoretical analysis of the wideband balun can be found in [20]. So the baluns can be simplified as four 50-Ω impedance loads. Each 50-Ω impedance is transformed into a 200-Ω impedance by four segments of microstrip lines with different characteristic impedances. Then, four 200-Ω impedances in center point are connected in parallel and matched to a 50-Ω coaxial cable.

The last challenge is how to obtain a relatively high gain within the operating frequency band. In this design, four reflectors and twelve directors are presented. Because the bandwidth is wide, three different directors are designed to excite different resonant frequencies. The directors are introduced to improve gain, gain variation and impedance matching to a great extent. Figure 2 depicts the current distribution of the antenna with directors at 2.0 GHz. As can be observed, a loop counterclockwise in-phase current distribution occurs on the dual-dipoles, which demonstrates that a good horizontally polarized (HP) omnidirectional field can be obtained. Due to mutual coupling between the dual-dipoles and directors, a relatively strong current is generated on the directors, indicating that the directors are effectively excited. The effect of director elements on gain and gain variation of the proposed antenna is shown in Figure 3 with/without director elements. From Figure 3(a), we can see that the gain is apparently increased when the directors are introduced. Especially, for the upper frequency band, the gain is increased more than 3 dBi. Figure 3(b) shows gain variation of the antenna with/without director

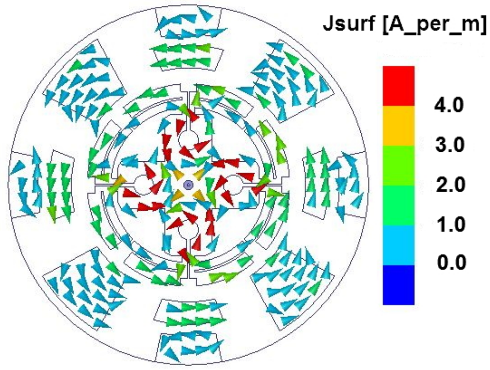


Figure 2. Current distribution of the antenna with directors at 2.0 GHz.

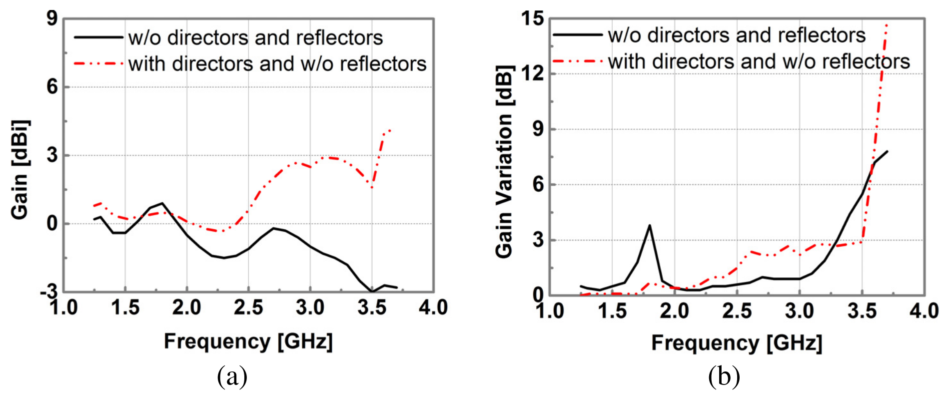


Figure 3. (a) Simulated gain in the horizontal plane with/without directors. (b) Simulated gain variation in the horizontal plane with/without directors.

elements. For the lower frequency band, the gain variation is lowered by adding directors. Although the gain variation is increased in the middle frequency band, the bandwidth with gain variation less than 3 dB in the horizontal plane increases by 40.9%. In addition, due to the mutual coupling between the dual-dipoles and directors, the simulated $|S_{11}|$ of the proposed antenna is also influenced. Figure 4 plots the curves of simulated impedance of the proposed antenna with/without directors. Figure 5 shows the simulated $|S_{11}|$ with/without director elements. As shown in Figure 4, the directors significantly suppress the input reactance and improve the input resistance. Therefore, the impedance matching can be apparently improved, which can also be validated from Figure 5. Namely, from Figure 5, the simulated $|S_{11}|$ is lowered effectively by adding directors, and good impedance matching is obtained.

From Figure 3(a), we can see that the gain with directors is relatively low for the middle frequency band, and the minimum gain is less than 0 dB. Reflector can be used to improve the F/B gain ratios. So, four reflectors may be introduced to improve the gain for the middle frequency band. Normally in Yagi antenna, the director size is smaller than the dipole, and the reflector size is larger than the dipole used in it. However, the directors and reflector have no absolute relationship with the driven element in size, for instance, the antenna in [21]. The magnitude and phase of the currents in the directors and reflectors are determined not only by their sizes but also by their spacing to the adjacent elements. Similarly, for the proposed antenna, the current phase of the reflector leads the current phase of the dual-dipole at 2.2 GHz as an example, so basic array [22] leads to the conclusion that radiation field in the direction of dual-dipole will be enhanced. Figure 6 shows the simulated gain in the horizontal plane with/without reflectors. In Figure 6, the simulated gain is increased by introducing reflectors for the middle frequency band. Due to the limitations of size and structure, the reflectors are difficult to design effectively. Even so, the simulated gain with reflectors increases by up to 0.5 dB for the middle frequency band.

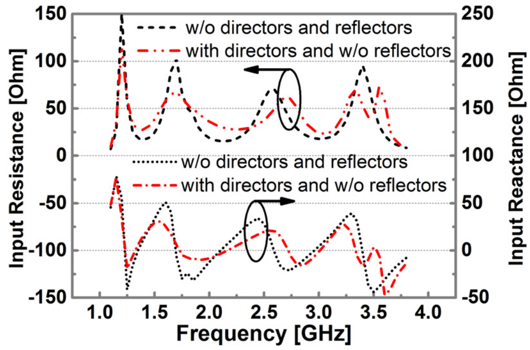


Figure 4. Simulated impedance of the proposed antenna with/without directors.

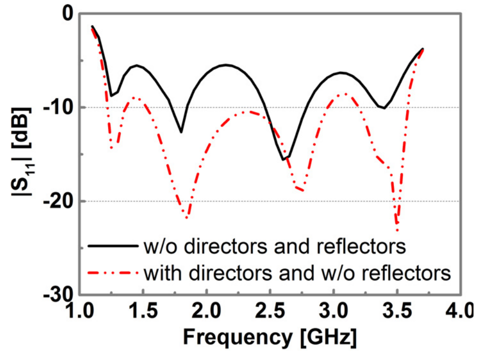


Figure 5. Simulated $|S_{11}|$ of the proposed antenna with/without directors.

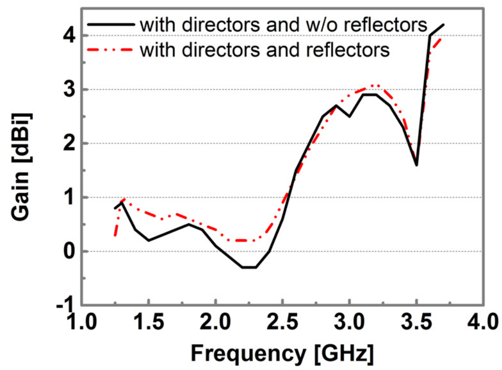
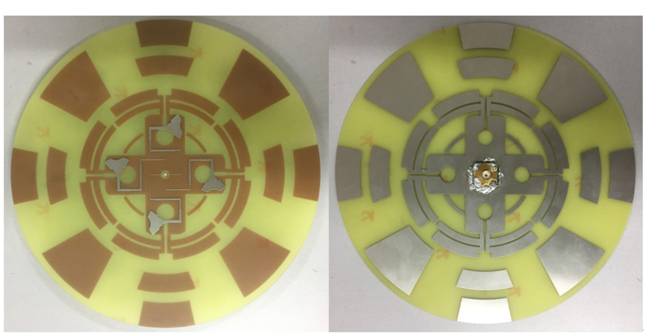


Figure 6. Simulated gain in the horizontal plane with/without reflectors.

4. EXPERIMENTAL RESULTS

With the optimized structure and dimensions given in Figure 1, the fabricated HP omnidirectional antenna array is pictured in Figure 7. The simulated and measured $|S_{11}|$ of the proposed antenna are given in Figure 8. In Figure 8, the simulated and measured impedance bandwidths for $|S_{11}| < -10\,\text{dB}$ are about 98.3% from 1.245 GHz to 3.652 GHz and 97.9% from 1.253 GHz to 3.657 GHz, respectively. A good agreement between simulated and measured $|S_{11}|$ is obtained.

Radiation characteristics are also studied, and the gain is measured by the three-antenna gain



(a) (b)

Figure 7. Fabricated HP omni-directional antenna array. (a) Top view. (b) Bottom view.

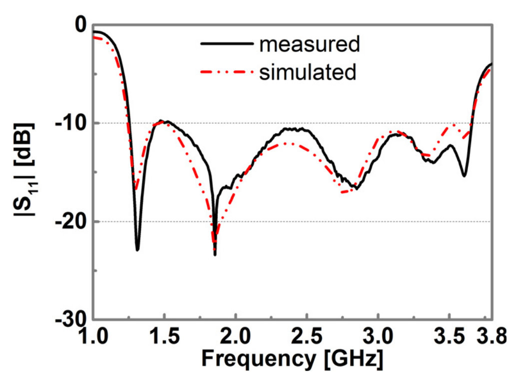


Figure 8. Measured and simulated $|S_{11}|$ of the proposed antenna.

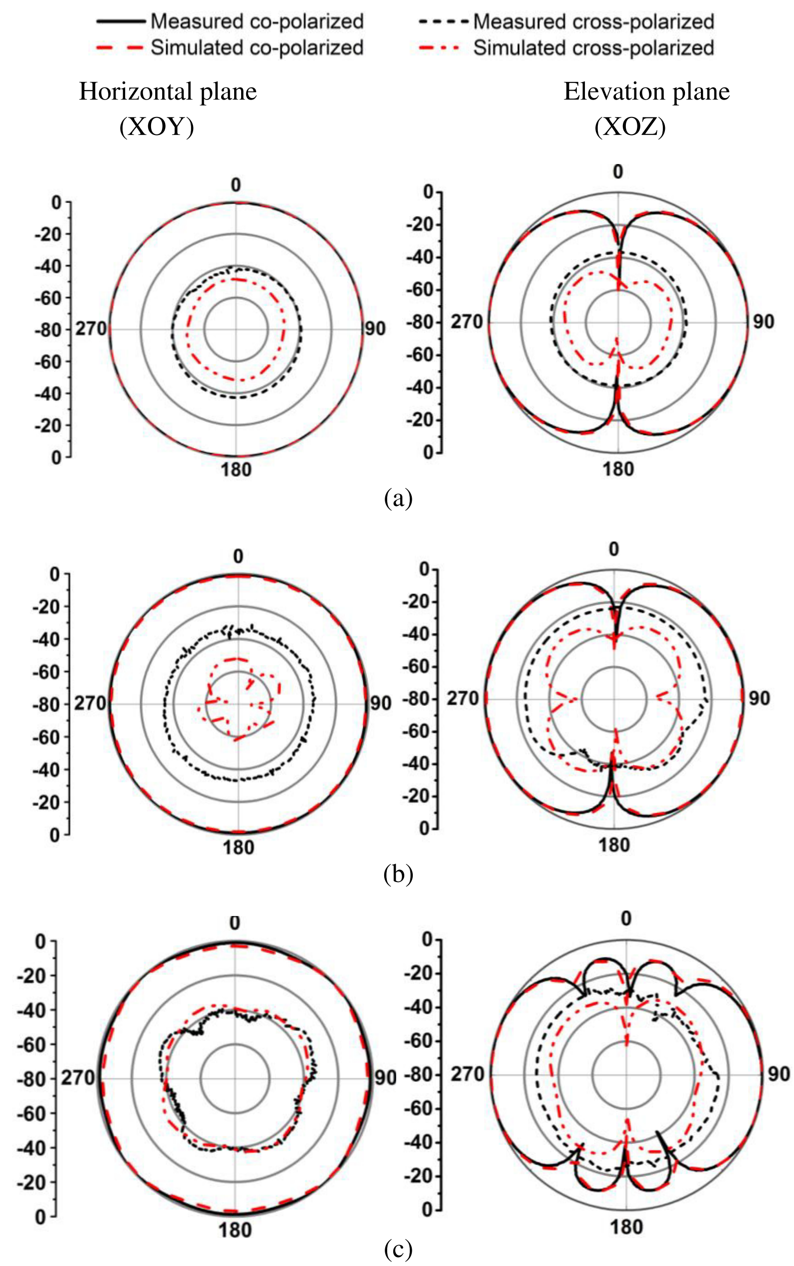


Figure 9. Measured and simulated radiation patterns in the horizontal and elevation planes. (a) 1.3 GHz, (b) 2.3 GHz, (c) 3.3 GHz.

measurement method. Figure 9 shows the simulated and measured radiation patterns in the horizontal and elevation planes at 1.3 GHz, 2.3 GHz, 3.3 GHz, respectively. As can be seen, a good omnidirectional radiation performance is obtained in the horizontal plane, and the measured gain variations for the three frequencies are 0.7 dB, 1.2 dB, and 2.2 dB, respectively. The measured cross-polarization level is less than -28.3 dB in the horizontal plane for the three frequencies. Figure 10 plots the curves of the simulated and measured gains, and simulated and measured radiation efficiencies of the proposed antenna. Considering the manufacturing error and measurement error, the measured results are slightly different from the simulated ones. As shown, the measured gains are between 0.1 dBi and 4.6 dBi, and the simulated efficiency is more than 80% in most operating frequency band.

Table 2 shows the performance comparison between the proposed antenna and the mentioned

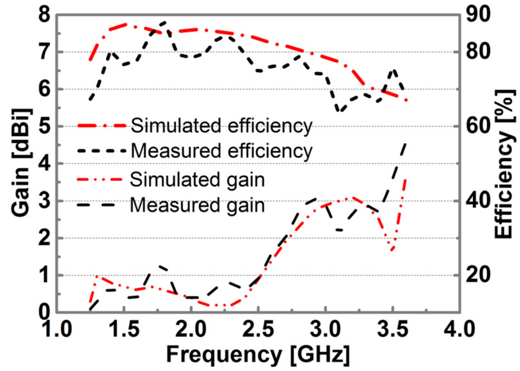


Figure 10. Simulated and measured gains, and simulated and measured radiation efficiencies of the proposed antenna.

Table 2. Comparison between the proposed antenna and the mentioned antennas in references.

Antenna	Impedance bandwidth ($\lvert S_{11}\rvert < -10$ dB)	Gain variation (dB)	Size	Cross-pol (dB)	Number of elements
[6]	15.4%	–	$0.18\lambda_L \times 0.18\lambda_L \times 0.72\lambda_L$	~ 17.5	2
[7]	39.4%	~ 6.4	$0.76\lambda_L \times 0.76\lambda_L \times 2.11\lambda_L$	–	16
[8]	39.6%	–	$0.91\lambda_L \times 0.91\lambda_L \times 0.25\lambda_L$	–	4
[10]	51%	~ 5	$0.45\lambda_L \times 0.45\lambda_L \times 0.01\lambda_L$	–	4
[18]	70.2%	~ 1.5	$0.85\lambda_L \times 0.85\lambda_L \times 0.01\lambda_L$	-15	12
Proposed	98.3%	~ 3	$0.66\lambda_L \times 0.66\lambda_L \times 0.01\lambda_L$	-20	4

Notes: λ_L is the free-space wavelength at the lowest frequency.

antennas in references. In Table 2, it can be observed that the proposed antenna not only possesses the widest impedance bandwidth, but also provides a better cross-polarization level of -20 dB than that in [18] over the whole impedance bandwidth. In addition, the proposed antenna with a small number of radiation elements only occupies a relatively reduced size of $0.66\lambda_L \times 0.66\lambda_L \times 0.01\lambda_L$. Although the sizes in [6] and [10] are smaller, the profile is relatively high, and the bandwidth is much narrower than the proposed antenna. In contrast to [18] which owns a better gain variation, the proposed antenna has a wider impedance bandwidth and smaller size to meet space-constrained applications.

5. CONCLUSION

In this paper, an HP omnidirectional antenna based dual-dipole has been proposed and experimentally studied. A wideband 1-to-4 feeding network for the proposed antenna has also been designed. The measured impedance bandwidths for $|S_{11}| < -10$ dB is about 97.9% (1.253 GHz $\sim$ 3.657 GHz), which has a good agreement with the simulated impedance bandwidths of 98.3% (1.245 GHz $\sim$ 3.652 GHz). The impedance bandwidth covers the operating bandwidth of WLAN (2.4–2.484 GHz), 2G/3G/LTE (1.7–2.7 GHz), Wi-Fi (2.45 GHz) and WiMAX (3.5 GHz). In the case of gain value, there are different requirements in different application environments. However, the gain is relatively low for the application of 2G/3G/LTE. Here, the gain may be improved by adding directors or forming an array (the element is the proposed antenna) in the vertical direction. For the proposed antenna, the gain variation is less than 3 dB from 1.245 GHz to 3.519 GHz (95.5%), and the cross-polarization level is no more than -20 dB over the whole bandwidth. Meanwhile, the proposed antenna has low cost and reduced size. The proposed antenna can also be a good candidate in wireless communication systems.

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