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Dual-Polarized Omnidirectional Antenna With High Isolation Based on the Theory of Characteristic Modes

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ABSTRACT A dual-polarized antenna with omnidirectional radiation and high isolation performance is proposed in this paper. The proposed antenna consists of courtyard-shaped metal frame, feeding network, and metal background. Working mechanism of the proposed antenna is analyzed by the theory of characteristic modes. Two orthogonal polarizations can be achieved by utilizing the orthogonal current distributions on the courtyard-shaped metal frame. In order to obtain the horizontal-polarized mode, eight slots etched on the walls of the courtyard-shaped metal frame are excited. A feeding network is placed at the inner part of courtyard-shaped metal frame for a compact design. Measured results show that the proposed antenna can cover the impedance bandwidth of 1.80–2.81 GHz for both polarizations with their corresponding isolations better than 35 dB. A peak gain of 7 dBi and a gain ripple less than 3 dB in the horizontal radiation plane are achieved. The proposed antenna can be applied in the indoor wireless communication.

INDEX TERMS Dual-polarized, omnidirectional radiation pattern, theory of characteristic modes (TCM).

I. INTRODUCTION

With the rapid development of wireless communication technology, more attention are paid to the indoor antenna distribution systems [1]. In these systems, the properties of bandwidth and omnidirectional radiation pattern are preferred. Wideband antenna is preferred since it can incorporate many wireless communication standards [2]–[4]. Therefore, the discone antennas and the biconical antennas have been widely applied for their simple structure and wide impedance bandwidth [5]. As the forefront equipment of 4G/5G mobile communication system, dual-polarized omnidirectional antenna can not only provide a 360 degree signal coverage, but also improve the communication quality and transmission speed through multipath propagation characteristic without increasing the bandwidth and transmitted power [6]. There is a growing need for dual-polarized antenna with omnidirectional radiation patterns and wide impedance bandwidth.

In recent decade, several dual-polarized antennas with omnidirectional patterns are designed. A typical method to designing dual-polarized omnidirectional antenna is the utilization of individual antenna elements with orthogonal polarizations. The combination of a notched disk antenna and a wire antenna was reported in [7] to realize dual-polarization properties. A dual-polarized antenna with high isolation was presented in [8], which is realized by two orthogonal slots cutting on the walls of a slender columnar cuboid. Based on the method, a cavity-backed notch for horizontal polarization is used to replace the slot [9]. By using a thin cavity for the horizontal polarization and a coplanar waveguide fed monopole for the vertical polarization, a sabre-like dual-polarized omnidirectional antenna with high performance for low wind drag airborne applications is proposed in [10]. A broadband dual-polarized omnidirectional antenna consisted of a modified low profile monopole and a circular planar loop is presented in [11]. Its operating bandwidth is up to 25% and the isolation is higher than 40 dB over the bandwidth. However, the size of the antenna limits its application. Printed around a dielectric cylindrical barrel, four vertical dipoles and four horizontal dipoles are combined together for omnidirectional radiation [12]. This antenna achieves the bandwidth of 30% (1.7-2.3 GHz) with an isolation of 25 dB for two polarizations. An artificial magnetic conductor (AMC) reflector was applied in a dual-polarized wideband omnidirectional antenna to reduce the height of the antenna [13]. The antenna has an impedance bandwidth (VSWR < 1.8) of 45%, and a size of $1.47\lambda * 1.47\lambda$. Based on this structure, a dual-polarized omnidirectional antenna with compact structure and wideband properties was presented in [14].

The theory of characteristic modes (TCM) was proposed by Garbacz and Turpin [15] and enriched by Harrington and Mautz [16] in 1970s. A series of conductors with mutually orthogonal feature's patterns can be exactly used to explain the electromagnetic problems for arbitrarily shaped conductor. The TCM provides a physical explanation on the operating mechanism of antennas. Based on the excitation with different characteristic modes on each element of multi-element antenna, a 484 ports antenna using 121 physical antenna elements is achieved to make the size reduction [17]. The computational formula and the numerical analysis are hard to give an insight on the radiation phenomena of the antenna. TCM is a useful tool to design dual-polarized omnidirectional antennas. It is used to depict the characteristic modes property of their structures.

High isolation and broad impedance bandwidth are two important factors for dual-polarized omnidirectional antenna. High isolation means the low Envelope Correlation Coefficient, which can improve the system capacity. In [18], planar slot antenna with an isolation of 59dB was proposed for WLAN application. However, its ripple of horizontal pattern is greater than 3dB. Planar antenna for WLAN application [19] and dual-band application [20], and 3D structure for broadband systems were proposed. As the frequency increases, the antenna performance is unstable. A ripple of 5.4 dB at 2.8GHz will have an impact on signal coverage. Without the metal reflector, a compact structure with a relative bandwidth of 45% was introduced in [21]. With the help of TE and TM waves, dual-polarized antennas were designed for omnidirectional radiation patterns [22]–[26]. Multiband dual-polarized antennas were introduced in [23] and [27]. Three HP elements are used to produce HP waves. A wideband planar double-segmented loop antenna can combine its resonant modes with adjacent resonant frequencies for wideband application. However, a larger ripple of horizontal pattern limits its application in wireless communication system. By combining an inverted-cone monopole for vertical polarization and a modified cross bow-tie dipole for horizontal polarization, compact antenna for base station/WLAN application was proposed in [28].

Comparing with these published antennas, we have proposed a novel design method for dual-polarized omnidirectional antenna. Instead of designing vertical polarized (VP) and HP elements respectively, the TCM is applied to analyze the common radiator. The characteristic mode parameters are given to analyze the performance of a courtyard-shaped metal frame. Two primary modes are individually fed to form orthogonal polarizations. Although our design does not have the smallest size, it still has many advantages, such as an impedance bandwidth of 44% and an isolation better than 35dB. Meanwhile, the stable omnidirectional radiation patterns and a ripple less than 3 dB make it could be a potential choice for indoor wireless communication application.

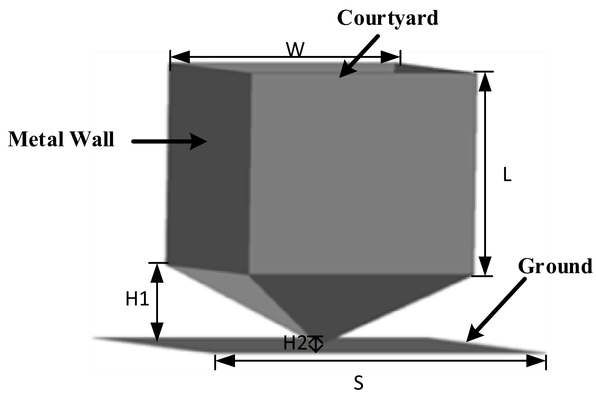


FIGURE 1. Initial structure.

II. DESIGN AND ANALYSIS

Based on the method of moments (MOM), the total electric current on any conductor surface can be expressed as a sum of characteristic currents J_n with different coefficients, which can be expressed as:

$$J = \sum_n a_n J_n = \sum_n \frac{1}{1 + j\lambda_n} V_n J_n \tag{1}$$

Where J_n is characteristic current, λ_n is eigenvalue, $\alpha_n\alpha_\mathrm{n}$ expresses the proportion of characteristic current J_n in total current J, and V_n expresses the Modal Excitation Coefficient (MEC) for the n-th mode. Usually, two parameters, Modal Significance (MS) and Characteristic Angle (CA), are also used to describe the resonating condition of antenna. They are expressed as the following forms:

$$MS = \left| \frac{1}{1 + j\lambda_n} \right| \tag{2}$$

$$CA = 180^\circ - \tan^{-1} \lambda_n \tag{3}$$

In order to design a dual-polarized omnidirectional MIMO antenna, TCM is used to find the required modes. The proposed initial structure is shown in Fig. 1 and its corresponding parameters are listed in the Table 1. Four metal sheets with the size of $W*L$ form a courtyard-shaped frame, and a trapezoidal-gradient structure is connected to their bottoms. A square metal background with side length S is placed at the bottom of the whole structure as a reflector. The distance from upper part to the reflector is H_2, and the height of the whole structure is $L+H_1+H_2$. The proposed design is not planar and low-profile, this is because that appropriate dimensions are needed for dual-polarization broadband antenna with conical beams.

TABLE 1. Parameters of the initial structure (Unit: mm).

parameter	L	W	H1	H2	S
value	80	95	30	1	140

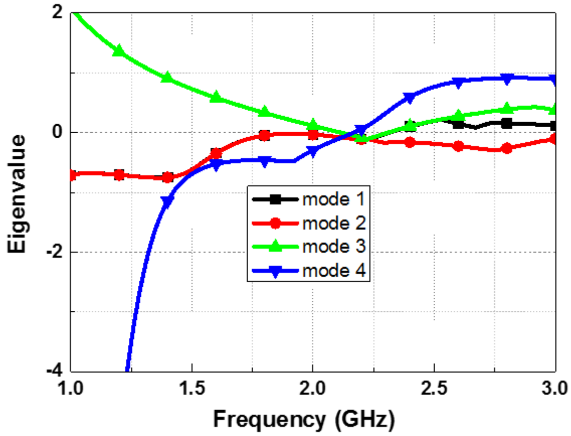


FIGURE 2. Eigenvalues of the first four modes.

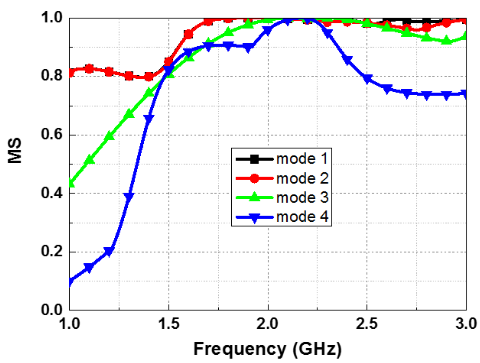


FIGURE 3. Modal Significances (MS) of the first four modes.

In order to obtain horizontal and vertical polarizations of the proposed structure, full wave simulation method is used to analyze the geometry's characteristic. The eigenvalues λ_n of the proposed antenna's first four resonant modes λ_n are shown in Fig. 2. When the eigenvalue of one mode is close to zero, it means that the antenna easily resonates at that frequency. It can be seen from Fig. 2 that the eigenvalues of the mode 1 and mode 2 are in the vicinity of zero within the entire frequency range. The eigenvalues of mode 3 and mode 4 are close to zero when frequency is higher than 2 GHz. It means that they have narrow resonating bandwidth.

In order to observe the resonating frequency of the proposed antenna conveniently, MS and CA parameters are depicted in Fig. 3 and Fig. 4, respectively. According to the Formula (2), the value of MS is between zero and one. When the antenna is in resonating status, the eigenvalue of its corresponding mode is zero and the MS equals to 1. From Fig. 3, it can be seen that MS of mode 1 and mode 2 are approaching to 1 within the frequency range of 1.6~3.0 GHz, with a small ripple at 2.7 GHz of mode 2. In Fig. 4, the curves

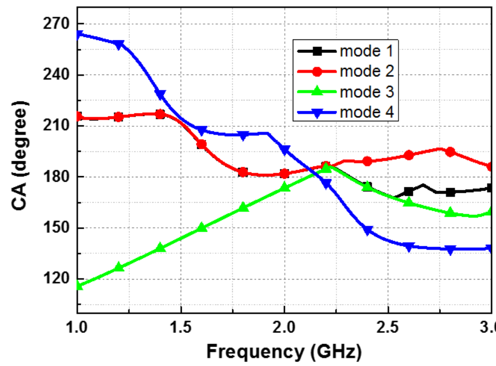


FIGURE 4. Characteristic Angles (CA) of the first four modes.

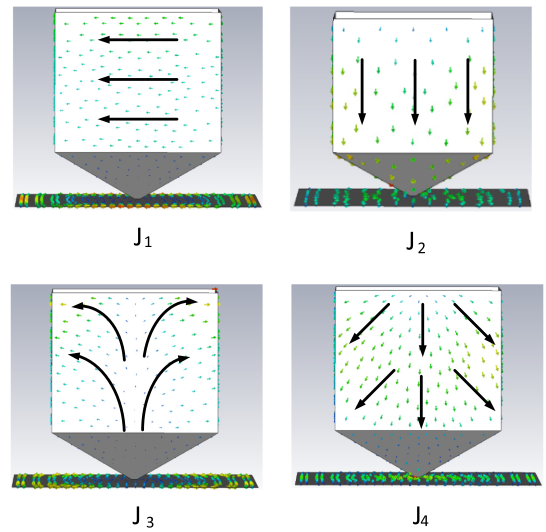
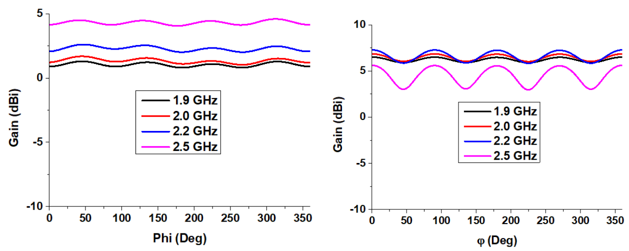


FIGURE 5. Characteristic current of the first four modes.

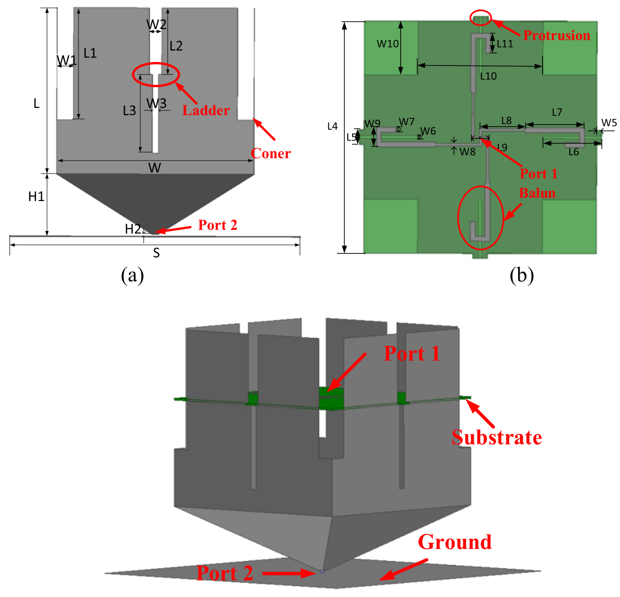
of mode 1 and mode 2 have gradual slope near 180°, which means a broadband property can be realized by exciting the mode 1 and mode 2, respectively. Similar to Fig. 2, the curves plotted in Fig.3 and Fig.4 show that mode 3 and mode 4 also have narrow resonating bandwidth.

The characteristic currents distribution at the frequency of 2.0 GHz related to the first four eigenvalues are illustrated in Fig. 5. All currents were normalized to the maximum value in order to facilitate comparison. Eigenvectors J_1 and J_2 are characterized by horizontal and vertical currents, respectively. Thus, they can be used as the dominate modes in antenna application. The rest of the eigenvectors J_3 and J_4 are high order modes, which means that they can be taken into account only at high frequency. Considering the rational symmetric of the proposed antenna, a loop current along four metal wall is formed with mode 1, which can produce omnidirectional radiation. For mode 2, the current distribution is similar to that of the monopole antenna. Thus, the omnidirectional radiation property can also be produced. Fig. 6 shows the simulated H-plane radiation patterns of proposed structure at different frequencies. Omnidirectional radiations can be seen for vertical and horizontal polarizations. The performance of antenna are stable for both polarizations. When the



(a) (b)

FIGURE 6. H-plane radiation patterns at different frequencies. (a) HP element, (b) VP element.



(a) (b)

(c)

FIGURE 7. Geometry of the proposed antenna. (a) Modified courtyard-shaped structure. (b) Feeding network. (c) Final structure.

frequency increases, the ripples of horizontal plane radiation pattern become larger. The azimuth cut is selected nearby theta $= 30°$ for the smallest ripple of H-plane radiation patterns.

III. PARAMETER STUDY

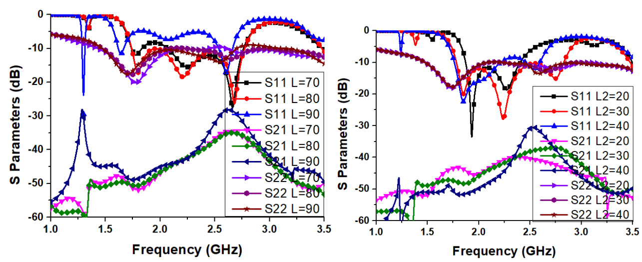
According to the above analysis, the horizontal and VP modes should be excited to achieve a dual-polarized omnidirectional antenna. The feeding structure of the VP mode is simple. The outer metal of the coaxial line is connected to the ground, while the inner metal is connected to the upper part of the proposed structure. In order to obtain a horizontal loop current, four metal walls need to be excited simultaneously. Some modification of the initial structure should be carried out. Firstly, four corners of the courtyard-shaped frame are removed with the size of $L1*W1$, and then each metal wall is independent. Secondly, slots with different widths are designed at the middle of each metal wall, as shown in Fig. 7(a). Thirdly, a broadband feeding network with four broadband baluns and an impedance matching circuit is designed to excite horizontally polarized modes, as illustrated in Fig. 7(b). The matching circuit between the

TABLE 2. Parameters of the modified structure (Unit: mm).

parameter	L	W	L1	W1	L2	W2
value	80	95	54	8	32	6
parameter	L3	W3	H1	H2	S	
value	38	3	30	1	140	

TABLE 3. Parameters of the feed network (Unit: mm).

parameter	L4	L5	W5	L6	W6	L7	W7
value	95	6	2	24	1	24	2
parameter	L8	W8	L9	W9	L10	W10	L11
value	19	1	7	8	51	22	8



(a) (b)

FIGURE 8. S parameters of proposed antenna with key parameters. (a) *L*, (b) *L2*.

four broadband baluns and a 50 Ohm coaxial line is placed at the port 1. Operating principle of the feeding network has been described in detail in [29]. The feeding network is placed at the interior part of the courtyard-shaped frame, while the protrusions on the edge of the microstrip substrate are laid in the ladder of the slot. The final structure of the proposed dual-polarized omnidirectional antenna is shown in Fig. 7(c). The parameters of the final courtyard-shaped frame and the feeding network are listed in the TABLE 2 and 3, respectively.

The main working principle of proposed antenna can be explained with the study of several key parameters. The height L of courtyard-shaped frame and the length $L2$ of slot, are the two key parameters of proposed structure, also they have great influence on the performance of antenna. When the height of courtyard-shaped frame is changed from $L = 70$ *mm* to $L = 90$ *mm*, it can be observed that the matching of HP element is changed largely and the isolation is reduced from 35 dB to 30 dB. Meanwhile, the matching and resonant frequency of VP element has some varieties with the parameter L. When $L2$, the length of slot, increases from *20 mm* to *40 mm*, it can be obtained that the bandwidth of HP changes greatly. The antenna has a wider bandwidth at the nearby of $L2 = 30$ *mm*. The isolation will continue to deteriorate as $L2$ increases. Meanwhile, the parameter $L2$has no influence on the VP element.

IV. EXPERIMENT RESULTS

The final structure of the proposed antenna was simulated, fabricated and tested. Fig. 9 shows a photograph of the antenna prototype and back side of feeding network. The metal walls are made of copper sheet with a thickness

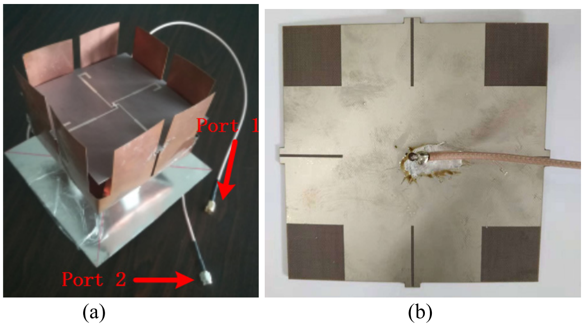


FIGURE 9. Photograph of the fabricated antenna and its testing environment. Sample, (b) Back side of feeding network.

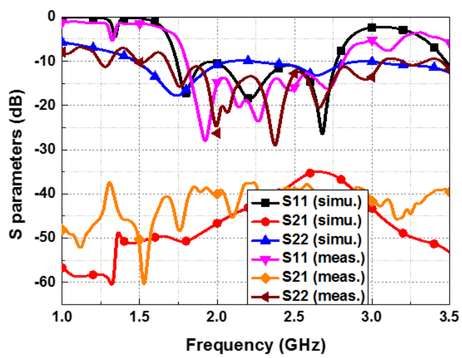


FIGURE 10. Comparison between the simulated and measured results.

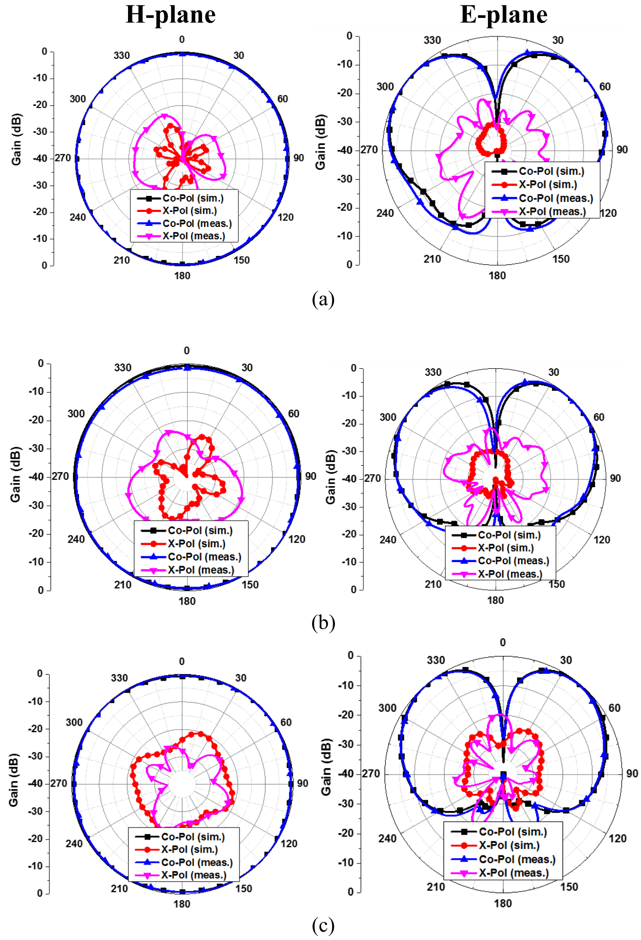


FIGURE 11. Radiation patterns of horizontal polarization. 1.8 GHz, (b) 2.2 GHz; (c) 2.5 GHz.

of 0.3 mm, then weld together to form the courtyard-shaped frame. The feeding network is printed on the substrate of Rogers RT/duroid 5880 with a relative dielectric constant of 2.2, a loss tangent angle of 0.0009 and a thickness of 0.8 mm. Two coaxial lines are connected to the two ports for horizontal and vertical polarization, respectively.

Fig. 10 shows the comparison between the simulated and measured S parameters of the proposed antenna. It can be found that the measured reflection coefficients show good operating bandwidth of approximate 44% (1.8∼2.81 GHz) for both dual-polarized ports. In addition, the isolations are better than 35 dB over the operating bandwidth for both simulated and measured results. Good agreements between the simulation and measurement are achieved. The shift of resonating frequency for S_{11} is mainly due to the imprecise assembling and manufacturing tolerance. Some ripples of the measured S_{22} and S_{21} should be caused by the coaxial line of the feeding network.

The far field radiation patterns at 1.8, 2.2, 2.5 GHz were measured using a near field measurement method in anechoic chamber of Satimo SG24 antenna Lab. When one of the two ports is excited, the other port is connected with a 50Ω load. For comparison, the simulated results are also given in the corresponding figures. Radiation patterns of the proposed antenna for the horizontal and vertical polarizations are presented in Fig. 11 and Fig. 12, respectively.

It can be found that the ripples in the azimuth plane are less than 3.0 dB for dual polarizations, this is because that the vertical current for vertical polarization and horizontal loop current for horizontal polarization are excited, respectively. The cross polarization levels lower than -15 dB also can be observed from Fig. 11 and Fig. 12. The direction of the maximum radiation is $\theta = 35°$, which is caused by the radiating power reflection to the opposite side by the metal ground. Energy from the antenna is radiated in all directions in a manner determined by its current distributions. The metal ground can reflect the incident EM waves to upper space. The total field above the ground is equal to the sum of the direct and reflected components. Nulls higher than 20 dB are generated for both polarizations. For the horizontal polarization, the omnidirectional property is attributed to the loop current along the metal walls. For the vertical polarization, the effect is similar to a conventional monopole antenna. The measured gains shown in Fig. 13 for dual polarizations are varied from 1.0 dB to 7.0 dB. They are less than the simulated ones about 1dB, which are mainly caused by the losses of the coaxial lines and connectors. It also can be noticed that the gain of horizontal polarization increases as the frequency increases. However, there is an unexpected gain drop after 2.5 GHz for the curve of vertical polarization. This can be attributed to the phase variation of vertical current due to the longer height L and some slots removed from the metal walls.

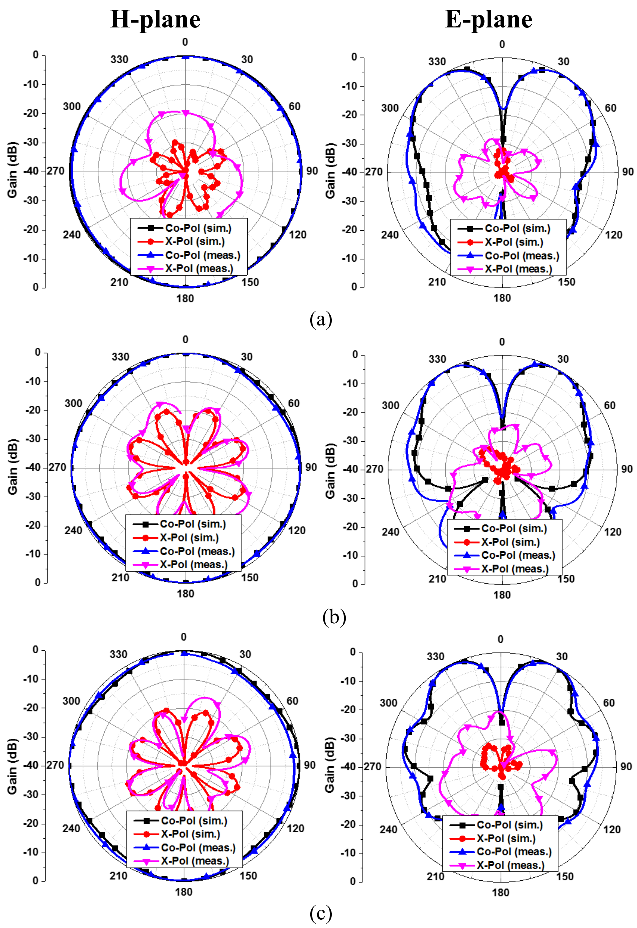


FIGURE 12. Radiation patterns of vertical polarization. (a) 1.8 GHz; (b) 2.2 GHz; (c) 2.5 GHz.

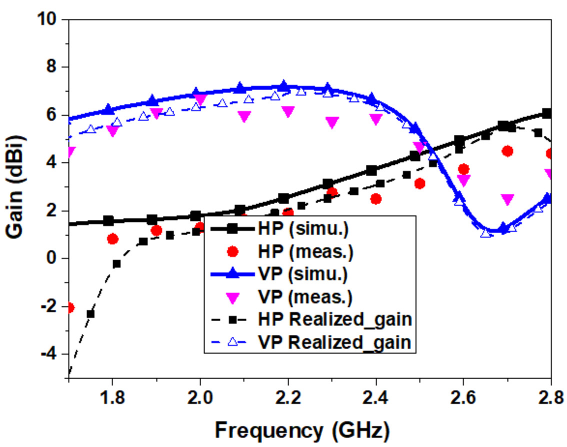


FIGURE 13. Gains of the proposed antenna.

Taking into account the mismatch loss at the feed and the loss of conductor, the realized gain as well as the ratio of the intensity, in a given direction, to the power accepted (input) by the antenna divided by 4π, is about 6.6 and 2.6 dBi at 2.2 GHz for VP and HP elements, respectively. Shown in Fig. 13, the curves of realized gain are close to its corresponding gain, which means the efficiency of antenna is very high across the whole working frequency band.

V. CONCLUSION

In this paper, a dual-polarized omnidirectional broadband antenna based on TCM has been presented. The features of the proposed antenna are analyzed, including eigenvalue, MS, CA and eigenvector. Some modifications are made to excite the horizontal and vertical polarization modes. The measured results show that the proposed antenna has an impedance bandwidth of 44%, an isolation better than 35 dB and stable omnidirectional radiation patterns. Therefore, the proposed antenna can be potentially used in the indoor wireless communication systems.

REFERENCES

[1] X. Chen, S. Guo, and Q. Wu, "Link-level analysis of a multiservice indoor distributed antenna system [wireless corner]," *IEEE Antennas Propag. Mag.*, vol. 59, no. 3, pp. 154–162, Jun. 2017.

[2] Y. Zhao, "Dual-wideband microstrip antenna for LTE indoor base stations," *Electron. Lett.*, vol. 52, no. 8, pp. 576–578, Apr. 2016.

[3] G. Li, H. Zhai, L. Li, C. Liang, R. Yu, and S. Liu, "AMC-loaded wideband base station antenna for indoor access point in MIMO system," *IEEE Trans. Antennas Propag.*, vol. 63, no. 2, pp. 525–533, Feb. 2015.

[4] Z.-Y. Zhang, G. Fu, W.-J. Wu, J. Lei, and S.-X. Gong, "A wideband dual-sleeve monopole antenna for indoor base station application," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 45–48, 2011.

[5] K.-H. Kim, J.-U. Kim, and S.-O. Park, "An ultrawide-band double discone antenna with the tapered cylindrical wires," *IEEE Trans. Antennas Propag.*, vol. 53, no. 10, pp. 3403–3406, Oct. 2005.

[6] G. Tsoulos, *MIMO System Technology for Wireless Communications*. Boca Raton, FL, USA: Taylor & Francis, 2006.

[7] N. Kuga, H. Arai, and N. Goto, "A notch-wire composite antenna for polarization diversity reception," *IEEE Trans. Antennas Propag.*, vol. 46, no. 6, pp. 902–906, Jun. 1998.

[8] Y. Li, Z. Zhang, J. Zheng, and Z. Feng, "Compact azimuthal omnidirectional dual-polarized antenna using highly isolated colocated slots," *IEEE Trans. Antennas Propag.*, vol. 60, no. 9, pp. 4037–4045, Sep. 2012.

[9] Y. Li, Z. Zhang, Z. Feng, and M. F. Iskander, "Design of omnidirectional dual-polarized antenna in slender and low-profile column," *IEEE Trans. Antennas Propag.*, vol. 62, no. 4, pp. 2323–2326, Apr. 2014.

[10] P. Liu, Y. Li, Z. Zhang, and Z. Feng, "Omnidirectional dual-polarized antenna with Sabre-like structure," *IEEE Trans. Antennas Propag.*, vol. 65, no. 6, pp. 3221–3225, Jun. 2017.

[11] X. Quan and R. Li, "A broadband dual-polarized omnidirectional antenna for base stations," *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 943–947, Feb. 2013.

[12] Y. Fan, X. Liu, B. Liu, and R. Li, "A broadband dual-polarized omnidirectional antenna based on orthogonal dipoles," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1257–1260, 2016.

[13] J. Wu, S. Yang, Y. Chen, S. Qu, and Z. Nie, "A low profile dual-polarized wideband omnidirectional antenna based on AMC reflector," *IEEE Trans. Antennas Propag.*, vol. 65, no. 1, pp. 368–374, Jan. 2017.

[14] X.-W. Dai, Z.-Y. Wang, C.-H. Liang, X. Chen, and L.-T. Wang, "Multiband and dual-polarized omnidirectional antenna for 2G/3G/LTE application," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1492–1495, 2013.

[15] R. J. Garbacz and R. Turpin, "A generalized expansion for radiated and scattered fields," *IEEE Trans. Antennas Propag.*, vol. AP-19, no. 3, pp. 348–358, May 1971.

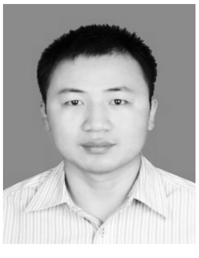
[16] R. F. Harrington and J. R. Mautz, "Theory of characteristic modes for conducting bodies," *IEEE Trans. Antennas Propag.*, vol. AP-19, no. 5, pp. 622–628, Sep. 1971.

[17] D. Manteuffel and R. Martens, "Compact multimode multielement antenna for indoor UWB massive MIMO," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2689–2697, Jul. 2016.

[18] E. A. Soliman, M. S. Ibrahim, and A. K. Abdelmageed, "Dual-polarized omnidirectional planar slot antenna for WLAN applications," *IEEE Trans. Antennas Propag.*, vol. 53, no. 9, pp. 3093–3097, Sep. 2005.

[19] Y. Liu, J. Xue, H. Wang, and S. Gong, "Low-profile omnidirectional dual-polarised antenna for 2.4 GHz WLAN applications," *Electron. Lett.*, vol. 50, no. 14, pp. 975–976, Jul. 2014.

[20] Y. Liu, X. Li, L. Yang, and Y. Liu, "A dual-polarized dual-band antenna with omni-directional radiation patterns," *IEEE Trans. Antennas Propag.*, vol. 65, no. 8, pp. 4259–4262, Aug. 2017.
[21] H. Huang, Y. Liu, and S. Gong, "Broadband dual-polarized omnidirectional antenna for 2G/3G/LTE/WiFi applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 576–579, 2016.
[22] Z. Yang, Y. C. Jiao, Z. Weng, and L. Zhou, "A compact broadband dual-polarized omnidirectional antenna with high isolations for indoor DAS applications," *Microw. Opt. Technol. Lett.*, vol. 59, no. 1, pp. 176–180, Jan. 2017.
[23] D. Comite, P. Baccarelli, P. Burghignoli, and A. Galli, "Omnidirectional 2-D leaky-wave antennas with reconfigurable polarization," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2354–2357, 2017.
[24] D. Guo, K. He, Y. Zhang, and M. Song, "A multiband dual-polarized omnidirectional antenna for indoor wireless communication systems," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 290–293, 2017.
[25] X. Zhao, B. N. Tian, S. P. Yeo, and L. C. Ong, "Wideband segmented loop antenna with dual-polarized omnidirectional patterns for mobile platforms," *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 883–886, Feb. 2017.
[26] K. Fan, Z.-C. Hao, Q. Yuan, J. Hu, G. Q. Luo, and W. Hong, "Wideband horizontally polarized omnidirectional antenna with a conical beam for millimeter-wave applications," *IEEE Trans. Antennas Propag.*, vol. 66, no. 9, pp. 4437–4448, Sep. 2018.
[27] J. Wang, L. Zhao, Z.-C. Hao, and J.-M. Jin, "A wideband dual-polarized omnidirectional antenna for base station/WLAN," *IEEE Trans. Antennas Propag.*, vol. 66, no. 1, pp. 81–87, Jan. 2018.
[28] H. Wen, Y. Qi, Z. Weng, F. Li, and J. Fan, "A multiband dual-polarized omnidirectional antenna for 2G/3G/LTE applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 2, pp. 180–183, Feb. 2018.
[29] X. Quan, R. Lin, and M. Tentzeris, "A broadband omnidirectional circularly polarized antenna," *IEEE Trans. Antennas Propag.*, vol. 61, no. 5, pp. 2363–2370, May 2013.



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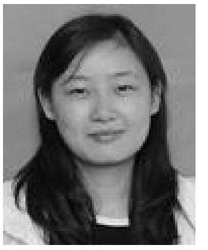

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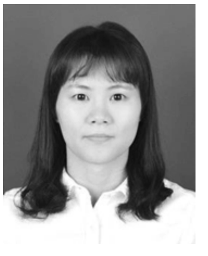

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