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A Simple Low-Profile Coaxially-Fed Magneto-Electric Dipole Antenna Without Slot-Cavity

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ABSTRACT A simple coaxially-fed magneto-electric dipole (ME dipole) antenna is designed and experimentally evaluated. The proposed antenna does not require the conventional quarter-wavelength slot cavity for generating the magnetic dipole mode, and only consists of two simple rectangular horizontal patches, a vertical semi-rigid coaxial cable and a square ground plane. It makes the fabrication easier and can reduce the production cost. Also, as the quarter-wavelength slot cavity is removed in the proposed design, the thickness of the antenna can be reduced to 21 mm, i.e., 16.4% of the free space wavelength at the center frequency. The low-profile antenna shows comparable wide impedance bandwidth of 41.03% ($S_{11} \leq -10\ dB$), and a more stable and higher realized gain from 7.90 - 9.74 dBi (± 0.92 dB variation) over the operating frequency band from 1.86 GHz to 2.82 GHz (centered at 2.34 GHz). The maximum gain has increased around 9.4% when compare with that of the highest reported. While the gain variation in the passband of the proposed antenna is about 58% lower than that of those ME dipole antennas reported in the literature. The radiation mechanism and the effects of the critical parameters of the antenna are also explained with the assistance of the parametric study presented.

INDEX TERMS High gain, low-profile, coaxcially-fed, magneto-electric dipole, wideband antenna.

I. INTRODUCTION

ELECTRIC dipoles and magnetic dipoles (slot antennas) are two types of well-known basic antenna elements. They have very simple, but complementary radiations features; the radiation pattern of an electric dipole has the shape of an "inverted-8" in the E-plane and an omni-directional radiation pattern in the H-plane, while the radiation patterns of a magnetic dipole is vice versa [1], [2]. Theoretically, combining these two sources of identical amplitude and phases will produce an antenna with similar radiation patterns in the E- and H-planes [2], [3]. Based on this concept, a wideband unidirectional antenna named as magneto-electric dipole antenna has been reported [4], it consists of a horizontal planar dipole (electric dipole) and a vertical quarter-wavelength slot cavity (magnetic dipole). The two complementary dipoles radiate at the adjacent frequency bands to provide the wide impedance bandwidth, stable and high gain, and similar radiation patterns in both E- and H-planes across the operation frequency band. Besides, as the electric dipole mode and magnetic dipole mode operate at adjacent frequency bands, it shows a "W" shaped curve in VSWR vs. frequency plot [4]–[8].

Given the features mentioned above, a series of designs has been reported. A microstrip line fed ME dipole which stacks an electric dipole on top of a shorted bowtie patch is reported [5], it has 60% of impedance bandwidth (VSWR ≤ 2). A beamwidth reconfigurable ME dipole fed by a Γ-shaped probe has been presented in [6]; the reported antenna supports dynamic beamwidth reconfigurability in the H-plane by controlling the on/off-state of the pin diodes which are connected to the strip grating reflector. To reduce the profile of the antenna, a microstrip line fed magneto-electric dipole antenna, consisting of a horizontal planar dipole and a pair of vertically oriented folded shorted slot cavity is reported [7], [8]. In order to accommodate the increasing number of service frequency bands, Dual-band ME dipole antennas have been designed to support this demand [9]–[11]. By implementing different feeding methods, ME dipoles with different polarisation have

TABLE 1. Comparison with state-of-art ME dipole antennas.

	Proposed antenna	[8]	[19]	[13]
Center Frequency (GHz)	2.34	2.40	1.48	1.44
Bandwidth (VSWR≤2)	41.0%	52.6%	92.0%	68.0%
Measured Maximum Gain(dBi)	9.7	8.9	7.7	9.6
Height	$0.164\lambda_o$	$0.169\lambda_o$	$0.250\lambda_o$	$0.240\lambda_o$
Quarter-Wavelength Cavity	None	Yes	Yes	Yes
In-Band Gain Variation (dB)	1.8	4.3	4.9	6.6
No. of Feed Points	1	1	2	2

also been reported, such as dual polarization [12]–[14] or circular polarisation [15]–[17].

To the authors' best knowledge, all the magneto-electric dipole antennas reported so far have the same feature: a vertical quarter-wavelength slot cavity created by a pair of conductor walls are utilized to generate the magnetic dipole mode. The fabrication of such vertical walls in the millimeter-wave frequency bands may be challenging. However, our recent study reveals that even without the quarter-wavelength vertical slot cavity, it is still possible to generate the magnetic dipole mode by directly activating the slot formed by the gap between the two horizontal rectangular patches with a coaxial cable. Table 1 shows a comparison of the features of the proposed antenna and the other ME dipole antenna designs reported for the readers' interest. In addition, the reported designs usually separate the electric and magnetic dipole modes far apart to maximize the impedance bandwidth [4]–[8]. In contrast, the magneto-electric dipole antenna presented in this paper in addition to achieving a considerable wide bandwidth, it also utilizes the single combined electric and magnetic mode to provide more stable and higher gain across the passband. The simulations were performed by using CST Microwave Studio [18]. Prototype antennas have also been fabricated to verify the antenna performances. The measurement results agree well with the simulations.

II. ANTENNA GEOMETRY

Fig. 1 shows the geometry of the proposed antenna with the detailed physical and electrical dimensions. Basically, the antenna consists of two horizontal rectangular patches that form the electric dipole, a coaxial cable serves as the feed-line and a square ground plane. The two horizontal patches are separated by a narrow gap. Such gap forms an open-ended slot antenna geometry and operates as the magnetic dipole. The size of each patch is 30 mm × 60 mm (L × W). The gap between the two patches (Gap) is 1 mm. A semi-rigid coaxial cable (RG402, 50Ω, ∅3.58 mm) positioned at the center of the ground plane, is utilized to excite the magneto-electric dipole antenna. As shown in Fig. 1, the inner and outer conductors of the top end of the cable are connected to the middle of the edges of the two horizontal

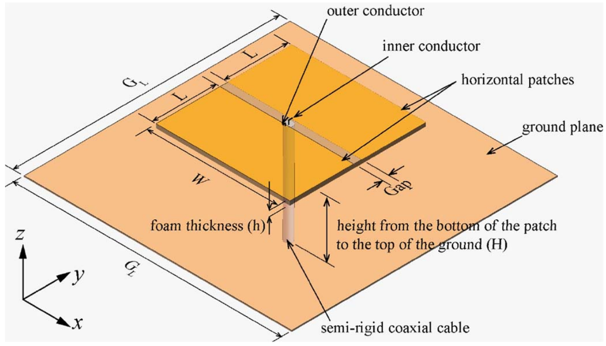

FIGURE 1. The geometry of antenna prototype. Dimensions: G_L = 130 mm ($1.01\lambda_o$); L = 30 mm ($0.234\lambda_o$); W = 60 mm ($0.468\lambda_o$); Gap = 1 mm ($0.008\lambda_o$); H = 21 mm ($0.164\lambda_o$); h = 1.5 mm ($0.011\lambda_o$).

patches. The bottom end of the coaxial cable is connected to a SMA connector under the ground plane. It is worth mentioning that the outer conductor of the semi-rigid cable is also connected to the ground plane. With such connection, the geometry of the proposed antenna is no longer balanced. Therefore, like the other ME dipole antennas reported in the literature, a balun is not necessary. The square aluminum ground plane on the bottom of the antenna is also employed as a reflector of the radiating elements to provide a unidirectional radiation pattern and higher front-to-back ratio.

III. PRINCIPLE OF OPERATION

Magneto-electric dipole antennas usually have the features of high gain and wide bandwidth. Such advantages come from the fact that the electric dipole and the magnetic dipole are excited simultaneously with the same signal amplitude and phase. In addition, the ground plane on the bottom side of patches creates a strong reflection, which helps the antenna to achieve even higher gain and reduce the back-lobe level.

In Fig. 2 and Fig. 3, the electric field and the magnetic field distributions of the proposed antenna at the center frequency at different time of a cycle have been presented respectively, with T being the period of one cycle. For the electric dipole mode, at time t = 0 and T/2, the electric field on the horizontal patches travels in the positive and negative y-direction respectively. Therefore, the electric dipole is mainly excited at those moments. While at time t = T/4 and 3T/4, the magnetic field flows in positive and negative x-direction respectively, and it has the strongest distribution along the long edges of the gap. At these moments, the magnetic dipole is strongly excited.

IV. SIMULATION AND EXPERIMENT RESULTS

A prototype antenna, as shown in Fig. 4, has been fabricated to verify the performances of the proposed design. A semi-rigid cable is used to realize the coaxial cable modeled in the simulation. The two horizontal patches are made of thin adhesive copper foil. In order to support the thin copper layer on the top of the semi-rigid cable, a piece of 1.5 mm thick polystyrene foam has been used. The polystyrene foam has a

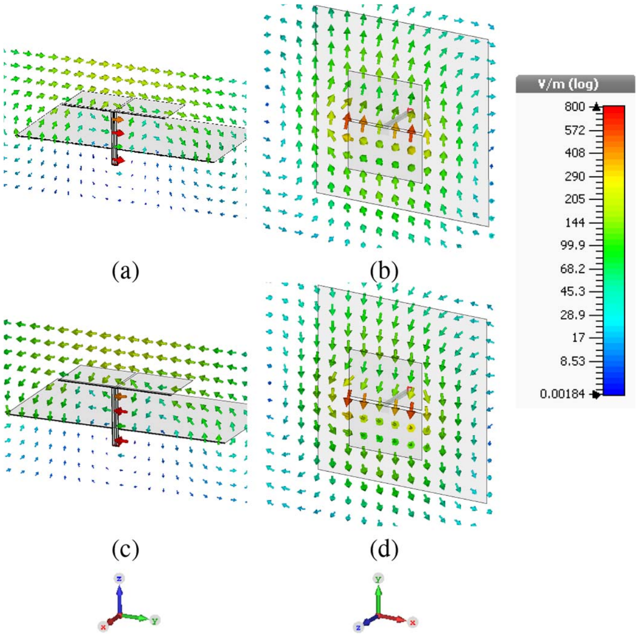

FIGURE 2. E-field of electric dipole mode. yz plane (a) t = 0; (b) t = T/2; xy plane (c) t = T/2; (d) t = T/2.

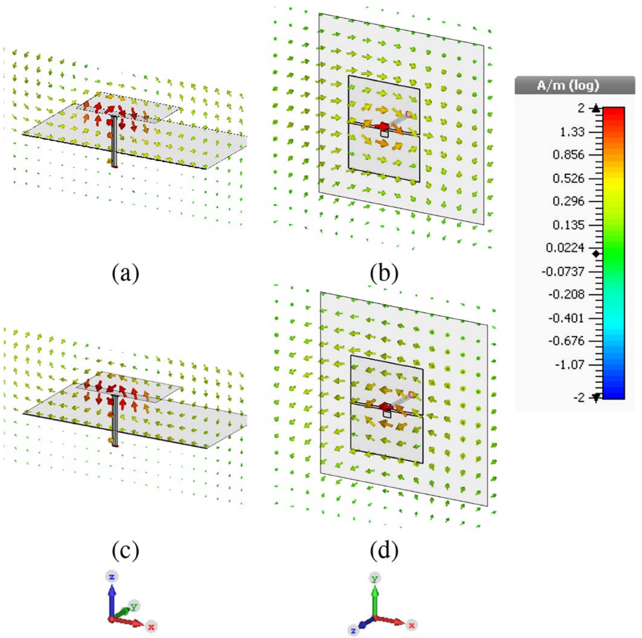

FIGURE 3. H-field of magnetic dipole mode. xz plane. (a) t = T/4; (b) t = T/4; xy plane (c) t = 3T/4; (d) t = 3T/4.

dielectric constant of 1.04 [20], which is close to that of air. The measured S_{11} was obtained by using a vector network analyzer and the antenna gain and radiation patterns were measured in an anechoic chamber.

A. S_{11} AND REALIZED GAIN

The simulated and measured S_{11} and the realized gain results are shown in Fig. 5. It can be observed that the discrepancy between the results are reasonable. The measured impedance bandwidth ($S_{11} \leq -10$ dB) is 41.03% from 1.86 GHz - 2.82 GHz. In addition, the prototype antenna has a stable gain, less then 2 dB fluctuation, across the operating frequency band. The maximum measured gain achieved is 9.74 dBi at 2.8 GHz.

FIGURE 4. The photography of fabricated prototype antenna.

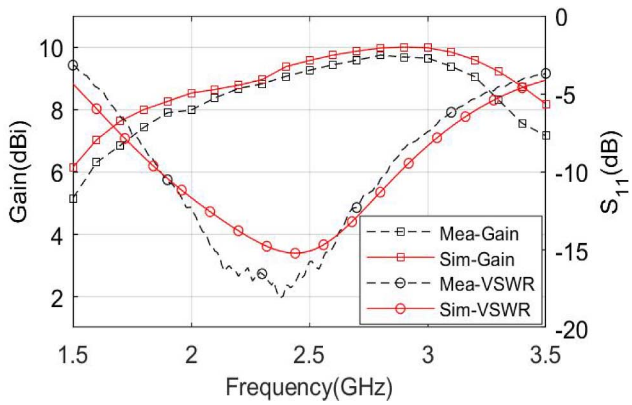

FIGURE 5. Simulated and measured gain and S_{11} versus frequency.

B. RADIATION PATTERNS IN E-PLANE AND H-PLANE

The simulated and measured radiation patterns at different frequency points have been presented in Fig. 6. The main E-plane is in the y-direction and H-plane is in the x-direction, the antenna is linear polarized with about −18 dB cross-polarization level. It should be mentioned that the simulated results of the cross-polarization are not shown in the figures for clarity since they are very low (less than −80 dB). This is the result of the assumptions of the perfectly symmetrical structure and precise excitation point in the simulation model, the ideally symmetrical excitation of the wide electric dipole and magnetic dipole will not excite any cross-polarization, but it is impossible to achieve in the fabrication, particularly when soldering the coaxial cable to the excitation points on the sides of the two horizontal patches in the practical case. In addition, the electric dipole and magnetic dipole are orthogonally located with each other, so the polarization effects is minimum. The measured and simulated co-polarization radiation patterns match well, particularly in the main beam ($-45° < \theta < 45°$). In the passband, from 1.8 GHz to 2.8 GHz, the antenna has stable unidirectional

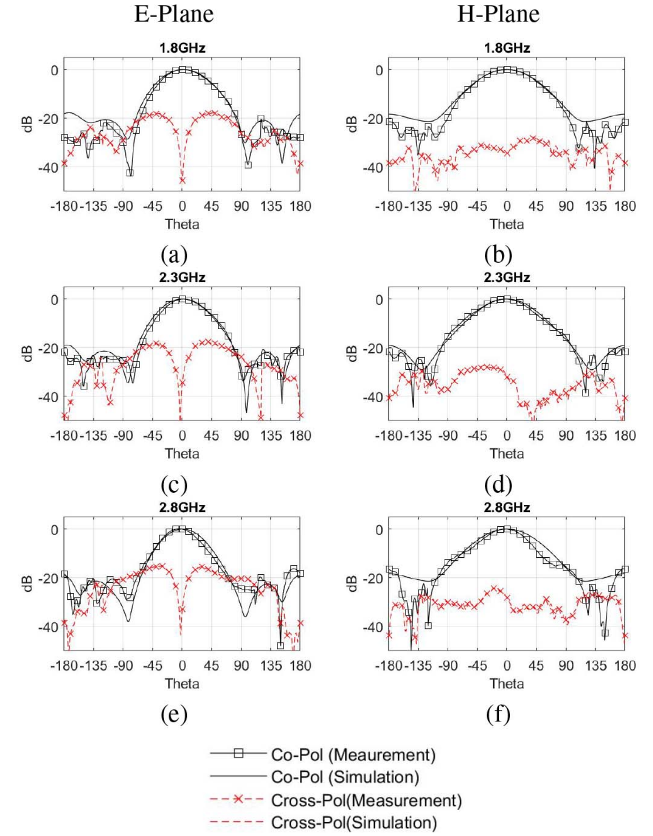

FIGURE 6. Simulated and Measured Radiation Patterns at (a) 1.8 GHz E-plane, (b) 1.8 GHz H-plane, (c) 2.3 GHz E-plane, (d) 2.3 GHz H-plane, (e) 2.8 GHz E-plane, (f) 2.8 GHz H-plane.

TABLE 2. 3-dB beamwidth and front-to-back ratio of the proposed ME dipole antenna.

Frequency	3-dB beamwidth (°)		Δ(°)	Front-to-back ratio(dB)
	E-plane	H-plane		
2.0GHz	61.8	72.2	10.4	18.4
2.4GHz	56.8	67.8	11.0	19.1
2.8GHz	51.5	60.2	8.7	19.2

radiation patterns in both E- and H-planes. Table 2 summarizes the 3-dB beamwidth and front-to-back ratios at different frequency points (Δ represents the 3-dB beamwidth difference between the E- and H-planes), the proposed antenna has very similar E-plane and H-plane radiation patterns, as Δ is always smaller than 11°. Besides, the 3-dB beamwidth in the E-plane is always smaller than that of the H-plane. It is the results of the fringing field which, as shown in Fig. 3(a) and (c), has elongated the effective length of the electric dipole and created a larger radiation aperture, therefore the directivity in the E-plane is higher.

V. PARAMETRIC STUDY

In order to investigate how the main antenna geometry affects the performance of the antenna, a parametric study is presented in this section. Basically, from our study, the radiating modes of the proposed magneto-electric dipole antenna are controlled by i) the length of the two patches (L), ii) the length of the open-ended slot between patches (W), iii) the height of the patches from the ground plane (H), and iv) the size of the square ground plane (G_L). From the parametric study, we can observed that, the first mode of the antenna is dominated by the electric dipole, the second mode, which is also the major operating mode of the proposed antenna, is composed by both electric and magnetic dipole modes and the third mode is dominated by the magnetic dipole. While the electric dipole and magnetic dipole have almost the same physical size, the effective length of the electric dipole has been elongated by the fringing field (as explained in Section IV). Therefore, the electric dipole mode operates at a lower frequency. The parametric studies of L, W, H and G_L will be demonstrated in the following paragraphs.

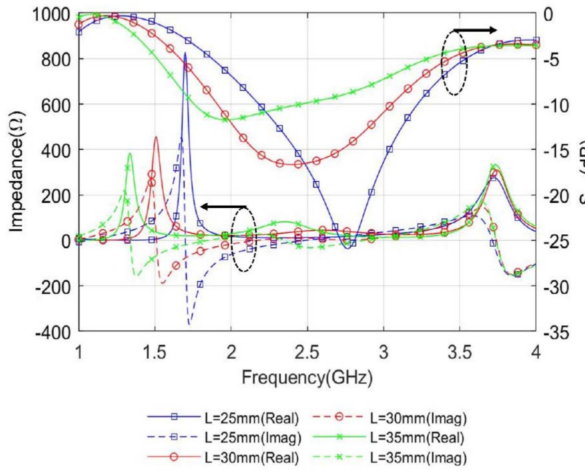

FIGURE 7. Z_{11} and S_{11} of the antenna at different patch length (L).

Firstly, in the y-direction, it can be observed from the antenna geometry that the two patches are operating as a very wide electric dipole antenna (wide dipole). The operating frequency of the electric dipole antenna depends on the length (L) of the two patches. In Fig. 7, the parametric sweep of L has been presented. The first mode (around 1.5 GHz) and the second mode (around 2.4 GHz) of the proposed antenna shifts to lower frequency with longer length L, while the third mode of the antenna (around 3.7 GHz) is not affected significantly.

Secondly, considering in the x-direction, the gap between the two closely spaced horizontal patches operates as a magnetic dipole antenna, despite the two open ends of the slot. The operating frequency of the magnetic dipole antenna depends on the slot length (W). In Fig. 8, it can be observed that the second and the third modes of the antenna have a significant shift with different length of W.

Thirdly, the height of the horizontal patches from the ground plane also affects the field distributions. Unlike a conventional electric dipole, which the electric field always oscillates between the two arms, in the proposed antenna, the electric field also oscillates between the two far edges of two horizontal patches and the ground plane as shown in Fig. 2 (a) and (c). This fringing field affects the operating

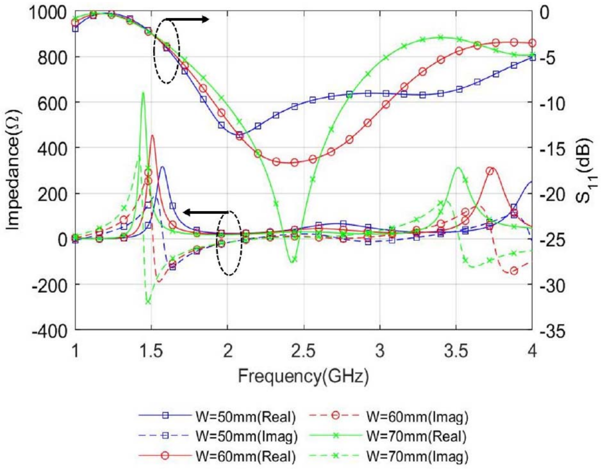

FIGURE 8. Z_{11} **and** S_{11} **of the antenna at different length of slot (W).**

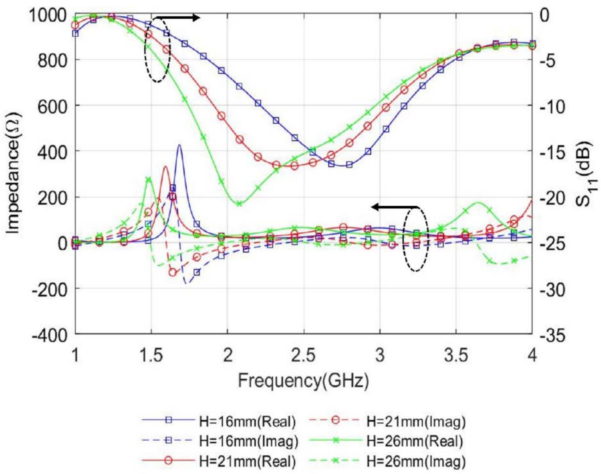

FIGURE 9. Z_{11} **and** S_{11} **of the antenna at different height (H).**

frequency indirectly, thus, in Fig. 9, all the three modes of the antenna shift to higher frequency when H decreases. The field distributions showed in Fig. 7, 8, 9 have also demonstrated the unbalanced feature of the proposed antenna and explained why a balun is not necessary. It can also be observed that the impedance bandwidth of the proposed antenna can be increased if H is increased to 26 mm, but the maximum gain will be reduced and suffered from more variation in the passband.

The ground plane of the proposed antenna serves the purpose of reflecting the wave in the back-lobe direction to the main bore-sight direction. Although theoretically an infinite ground plane can increase the gain of the radiation element by 3 dB, it is not feasible. In order to achieve the best balance between the size of the ground plane and the increased gain, the size of the ground plane need to be sufficient larger than the radiating elements. Otherwise, the gain will be reduced by 1.5 dB if the ground plane is smaller than $0.5\lambda_o \times 0.5\lambda_o$ when compared to that of the infinite ground plane case [21]. In Fig. 10, the simulated S_{11} and gain with different sizes of the ground plane has been depicted, the sizes of ground

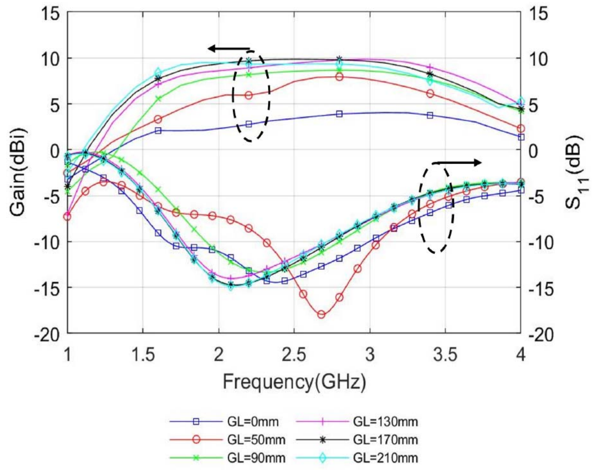

FIGURE 10. **Gain and** S_{11} **of the antenna at different sizes of ground plane (**G_L**).**

plane have been set up as 0 mm (no ground plane), 50 mm ($< 0.5\lambda_o$), 90 mm, 130 mm, 170 mm, 210 mm. It can be noticed that neither S_{11} or gain shows good consistency until G_L is more than 90 mm. However, when G_L is less than or equal to 50 mm, S_{11} is suffered from significant fluctuation and the gain decreases. In these case, the proposed ME dipole antenna operates like a conventional wideband ME-dipole, its gain is lower over the frequency band.

VI. CONCLUSION

A simple low-profile magneto-electric dipole antenna, which demonstrates comparable bandwidth and gain performances, without the vertical quarter-wavelength slot cavity has been presented. The prototype of the proposed antenna has been fabricated to verify the performances. The maximum gain of 9.74 dBi and less than 2 dB gain variation in the passband have been achieved. The impedance bandwidth of the proposed antenna is 41.03%. In addition, the antenna has similar E-plane and H-plane radiation patterns, and a minimum front-to-back ratio of 18.5 dB over the operating frequency band. Last but important, it has a simple and effective structure that makes it easy to be implemented and reduce the production cost.

REFERENCES

[1] C. A. Balanis, *Antenna Theory: Analysis and Design*. Hoboken, NJ, USA: Wiley, 2005.

[2] A. Clavin, “A new antenna feed having equal E- and H-plane patterns,” *Trans. IRE Prof. Group Antennas Propag.*, vol. 2, no. 3, pp. 113–119, Jul. 1954.

[3] D. H. A. Clavin and F. Kilburg, “An improved element for use in array antennas,” *IEEE Trans. Antennas Propag.*, vol. 22, no. 4, pp. 521–526, Jul. 1974.

[4] K. Luk and H. Wong, “A new wideband unidirectional antenna element,” *Int. J. Microw. Opt. Technol.*, vol. 1, pp. 35–44, Jan. 2006.

[5] H. Wong, K. Mak, and K. Luk, “Wideband shorted bowtie patch antenna with electric dipole,” *IEEE Trans. Antennas Propag.*, vol. 56, no. 7, pp. 2098–2101, Jul. 2008.

[6] L. Ge and K. M. Luk, “Beamwidth reconfigurable magneto-electric dipole antenna based on tunable strip grating reflector,” *IEEE Access*, vol. 4, pp. 7039–7045, 2016.

[7] L. Ge and K. M. Luk, “A low-profile magneto-electric dipole antenna,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 4, pp. 1684–1689, Apr. 2012.

[8] L. Ge and K. M. Luk, “A magneto-electric dipole antenna with low-profile and simple structure,” *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 140–142, 2013.

[9] K. He, S. Gong, and F. Gao, “A wideband dual-band magneto-electric dipole antenna with improved feeding structure,” *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1729–1732, 2014.

[10] W. X. An, H. Wong, K. L. Lau, S. F. Li, and Q. Xue, “Design of broadband dual-band dipole for base station antenna,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 3, pp. 1592–1595, Mar. 2012.

[11] S. Yan, P. J. Soh, and G. A. E. Vandenbosch, “Wearable dual-band magneto-electric dipole antenna for WBAN/WLAN applications,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 9, pp. 4165–4169, Sep. 2015.

[12] B. Q. Wu and K. Luk, “A broadband dual-polarized magneto-electric dipole antenna with simple feeds,” *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 60–63, 2008.

[13] Q. Xue, S. W. Liao, and J. H. Xu, “A differentially-driven dual-polarized magneto-electric dipole antenna,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 1, pp. 425–430, Jan. 2013.

[14] Y. Gou, S. Yang, J. Li, and Z. Nie, “A compact dual-polarized printed dipole antenna with high isolation for wideband base station applications,” *IEEE Trans. Antennas Propag.*, vol. 62, no. 8, pp. 4392–4395, Aug. 2014.

[15] Y. Li and K. Luk, “A 60-GHz wideband circularly polarized aperture-coupled magneto-electric dipole antenna array,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 4, pp. 1325–1333, Apr. 2016.

[16] S. X. Ta and I. Park, “Crossed dipole loaded with magneto-electric dipole for wideband and wide-beam circularly polarized radiation,” *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 358–361, 2014.

[17] J. Cao, H. Wang, S. Mou, S. Quan, and Z. Ye, “W-band high-gain circularly polarized aperture-coupled magneto-electric dipole antenna array with gap waveguide feed network,” *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2155–2158, 2017.

[18] *CST STUDIO SUITE v2008-User’s Manual*, CST GmbH, Ilsenburg, Germany, Dec. 2007. [Online]. Available: www.cst.com

[19] S. Liao, Q. Xue, and J. Xu, “A differentially fed magneto-electric dipole antenna with a simple structure,” *IEEE Antennas Propag. Mag.*, vol. 55, no. 5, pp. 74–84, Oct. 2013.

[20] M. Plonus, “Theoretical investigations of scattering from plastic foams,” *IEEE Trans. Antennas Propag.*, vol. 13, no. 1, pp. 88–94, Jan. 1965.

[21] K. F. Tong, K. F. Lee, and K. M. Luk, “On the effect of ground plane size to wideband shorting-wall probe-fed patch antennas,” in *Proc. IEEE-APS Topical Conf. Antennas Propag. Wireless Commun.*, Torino, Italy, 2011, p. 486.