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Magneto-Electric Dipole Antenna (MEDA)-Fed Fabry-Perot Resonator Antenna (FPRA) With Broad Gain Bandwidth in Ku Band

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ABSTRACT One planar Fabry–Perot resonator antenna (FPRA) with broad gain bandwidth is proposed in this paper. Magneto-electric dipole antenna (MEDA) is used as the feeding antenna providing good impedance matching and stable radiation pattern over the whole Ku band. Then, gain enhancement is realized by loading with one partially reflective surface, which consists of a single dielectric slab with 2-D patches array on both surfaces. Unlike the sharply negative phase slope of conventional cover designs, the proposed one produces a much gentle reflective phase gradient with both negative and positive phase slopes. Thus, the gain property of the MEDA is obviously improved along the whole band. One prototype is fabricated for verification and the results show that the proposed antenna has a wide impedance bandwidth, which is 56.25% for S11 < -10 dB, ranging from 11.5 to 18.7 GHz. It possesses a 3-dB gain bandwidth of 35% from 12.3 to 17.2 GHz with a peak gain of 11.2 dBi at 14 GHz. Compared with the unloaded type, gain enhancement of about 1.5 $\sim$ 5 dBi is achieved. Due to the advantages of simple structure and broad gain bandwidth, this method is a good option to design antennas in satellite communication systems in future.

INDEX TERMS Broadband high gain, magneto-electric dipole antenna (MEDA), Fabry-Perot resonator antenna (FPRA).

I. INTRODUCTION

With the development of modern wireless systems, such as space exploring, radar and satellite communication systems, there is increasing demand for the antenna with high gain property. One gain enhancement method is placing partially reflective surfaces (PRSs) in front of an antenna [1], [2]. Many designs add high-permittivity covers such as metallic rods or grids together with the ground plane to construct a Fabry-Perot resonant antenna (FPRA) [3], [4]. However, due to their inherent sensitivity to frequency, these antennas usually have narrow operating bandwidth. The 3-dB gain bandwidth is usually below 5%. In order to achieve equiphase wave at the radiation aperture and increase gain bandwidth, many scholars have researched on the loading cover structures. Various types of element structure, such as single array consisting of square-loops, rings, cross-dipoles slots cut elements [5]–[7], or elements of gradated size [8] are proposed. Some designs even utilize two or more layers of periodic metallic structures [9]–[14]. These designs have enhanced the gain property and the 3-dB gain bandwidth even reached as much as 20%. However, they are complicated in fabrication because of multi-layers structures.

In order to realize broadband high gain FPRA, both of the stable wideband feeding antenna and the PRS which producing a reflection phase curve with gentle slope are crucial. On the one hand, wideband feeding antenna should be well matched in the cavity when PRS is loaded. Typically wideband feeding antennas in free space would be mismatched when placed in the cavity, thus antenna feeding mechanism becomes prohibitive to the bandwidth and efficiency. Offset feed reduces the reflective wave absorbed but increases side lobe and cross polarization, owing to its asymmetry structure. Slot array is another option as the excitation and improved bandwidth could be achieved maintaining high gain property. Nevertheless, it makes sense at the cost of complicated design and fabrication [15].

Comparing with the feeding antennas such as single dipole, slot coupling- or probe-fed patch antenna, magneto-electric dipole antenna (MEDA) is one valuable candidate with advantages of simple structure, perfect radiation pattern of low cross-polarization and back radiation levels, and stable gain over a wide frequency band range [16], [17]. Thus MEDA is chosen as the feeding part for the first time in this design.

On the other hand, conventional PRS structure produces a reflection phase curve with a negative slope and the gain bandwidth is restricted by the slope ratio. Therefore the PRS structure with gentle phase shift curve is needed for designing FPRA with broad gain bandwidth. Y. H. Ge proposed one PRS with positive reflection phase gradients which provide the wideband performance required by EBG resonator antennas. The PRSs was composed of a single dielectric slab with two-dimensional arrays printed on both surfaces. With this PRS structure, the EBG resonator antenna owns 3-dB gain bandwidth of 15.7% [18].

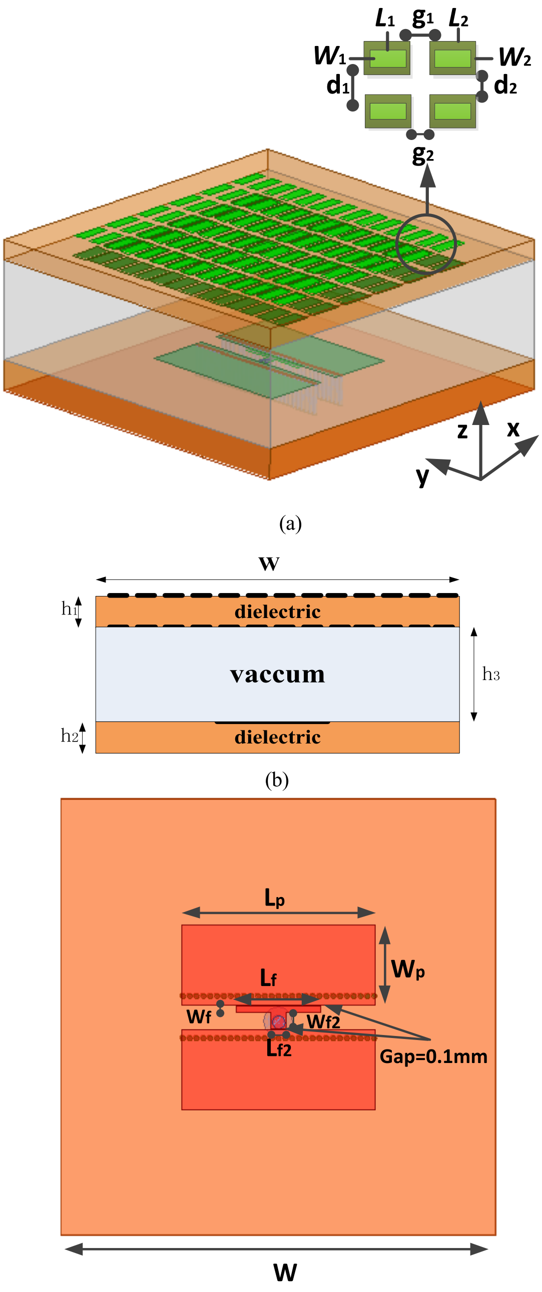
In this work, one patch antenna combining the advantages of both the above MEDA and PRS structure is designed. Probe-fed broadband MEDA is designed in single substrate layer. The PRS structure behaves as a phase-correcting grating cover to improve the radiation performance. Due to the gentle phase shift characteristics of the PRS, large band of smooth phase shift dynamic range is achieved. Thus gain enhancement is achieved over the whole Ku band. The measured results of one fabricated prototype show that the 3-dB gain bandwidth is 35%, which is much wider than the previously reported ones. Besides, this design simplifies the fabrication of MEDA and reduces the size of the cover. The antenna are optimized based on the full wave simulation software HFSS. The working principle and parameter analysis were given in the following sections in details.

II. ANTENNA STRUCTURE AND ANALYSIS

A. FEEDING ANTENNA

Fig. 1 shows the general configuration of the proposed antenna. It is composed by two parts: the feeding antenna and metallic PRS. It is well known that feeding mechanism plays an important role on producing suitable field distribution at the aperture. Thus MEDA is introduced in this design because of its advantages of almost identical radiation pattern in both E- and H-plane, insensitive to frequency variation and performs stably over wide band range.

As is described in Fig. 1 (c), a pair of horizontal planar patches acts as an electric dipole. Two rows of metallic vias, which are located at the inner edge of each half electric dipole, account for the magnetic dipole radiation. The probe excites the magnetic dipole by pin-coupling. Meanwhile, one T-shaped strip connected to the probe excites the electric dipole by capacitive-coupling. Thus it could excite both electric and magnetic dipoles simultaneously. In order to obtain a better impedance matching condition, the feeding point is not right in the coordinate center but close to the narrow feeding strip with size of $L_{f2} \times W_{f2}$. And the gaps between the feeding structure and the two edges of the two main electric radiating patches are finally optimized as 0.1mm.



(a)

(b)

(c)

FIGURE 1. Geometry of the proposed antenna: (a) Overall view; (b) side view; (c) top view of the ME dipole.

In previously reported MEDAs, the magnetic dipole is formed by the vertically-oriented quarter-wavelength patch antenna. In this work, two rows of parallel metallic vertical vias are used to realize the function of quarter-wavelength patch. It has simpler structure and better radiation performance. The configuration of the MEDA is designed based on the substrate of Rogers RT/duriod 5880 with thickness of 3 mm.

B. PRS STRUCTURE

The MEDA acts as a feeding antenna in the bottom layer. The metallic cover is suspended above sharing the same ground plane with the MEDA. In-between the two is the air-filled layer. In order to reduce the profile of the whole antenna, the PRS structure is consisted by two periodic patch arrays printed on both the top and bottom surfaces of a single Rogers 5880 substrate. The overall size of the antenna is 30 × 30 × 15mm^3.

The reflection phase characteristics of the periodic metallic structure plays critical role on the FPRA. Considering the two patch arrays printed on both sides of the same substrate, the working principle could be analyzed. On one hand, with the surface current and the coupling made by the patch arrays on both sides, negative phase slope could be obtained in such band. On the other hand, the gap between patches of the same surface behaves as capacity and the coupling made by slots would produce positive phase slope in such band. The vital point is tuning the two bands by parameter optimization to get smooth phase slope in a wide frequency band range. In this design, positive reflective phase gradients as well as the negative slope is realized by the metallic grating cover. Actually the reflection phase curve is mainly determined by the size of periodic patch unit, the gap spacing between the unit elements, and the thickness of the PRS substrate.

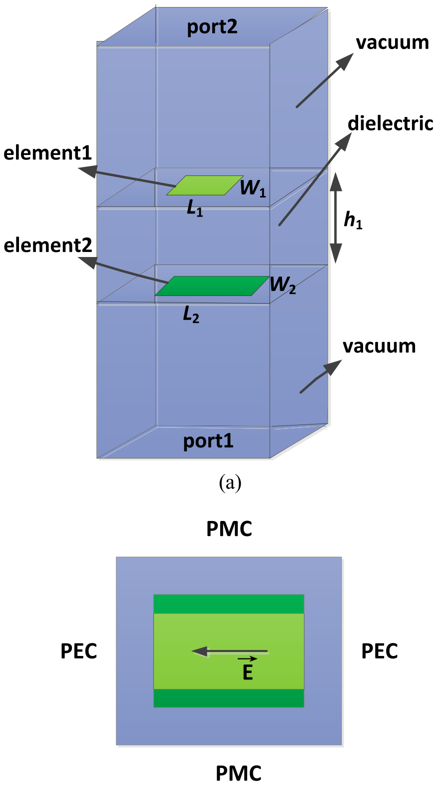
C. PARAMETER ANALYSIS

When the phase curve of the PRS layer slopes gently, the gain bandwidth of FPRA can be enhanced obviously. Parameter optimization should be made to get wideband characteristics. The performance of periodic metallic grating structure can be characterized by single unit cell with HFSS software.

Fig. 2 shows the characterization model of the unit cell. The effect of the parameters variation of the unit cell on the phase characteristics of the PRS has been analyzed. The lengths of both two elements have great impact on the reflection phase curve. As Fig. 3 depicts, when the length of element 1 differs from element 2 (no matter $L_1 < L_2$ or $L_1 > L_2$), the phase shifting curve decreases sharply from 12GHz to 17GHz and the reflection phase variation exceeds over 180ř. In this case, minimum reflection magnitude is small and the phase gradient of the increasing (or decreasing) phase is large. Hence, the PRS could not achieve equi-phase wave at the aperture and fail to enhance the gain bandwidth. The widths of two patches (W_1, W_2) also can be tuned to possess smooth reflection phase curve. When W_1 is smaller than W_2, the resonance becomes weaker. As a result, the reflection magnitude increases and the reflection phase produces gentle phase gradient during the operating band.

Although the unit cell model given above helps us to understand the effect of the cell parameters on the transmission and reflection coefficients of the grating cover, it is usually valid only on case of infinite dimensions. However, the cover size is finite. Thus strict analysis should also consider the mutual coupling between elements. Furthermore, the losses caused by dielectric, conductors or surface waves should also be taken into consideration. Optimization should be made for the whole antenna structure combining the feeding part and phase grating cover. Fig. 4 depicts the impact of h_1 and g_1 on the impedance matching and gain property of the proposed antenna. Larger thickness enhances the radiation pattern, but deteriorates the impedance matching condition. Meanwhile, smaller h_1 could not guarantee wide gain bandwidth as expected. The gaps of the element in crosswise (g_1, g_2) have great impact on the |S11|. In view of the analysis, the values of g_1 and g_2 are equally set as 1 mm. Finally we design a 14 × 6 element periodic metallic patch array on both top and bottom surfaces of the substrate. The optimized parameters are given in Table 1.

It should be noted that the impedance matching condition and the gain property should be considered together when the



(a)

(b)

FIGURE 2. Characterization model of the unit cell of the grating cover: (a) Explode view; (b) top view.

TABLE 1. Optimized parameters of the proposed FPRA (Unit: mm).

Parameters	W	h_2	h_1	h_3	L_1	L_2	W_1	L_{f2}	L_f
Value(mm)	30	3	2.5	9.5	3.2	3.2	1.4	1.2	1.8
Parameters	L_p	W_p	W_2	g_1	g_2	d_1	d_2	W_{f2}	W_f
Value(mm)	15.6	6.4	1.6	1	1	0.4	0.8	1.3	0.5

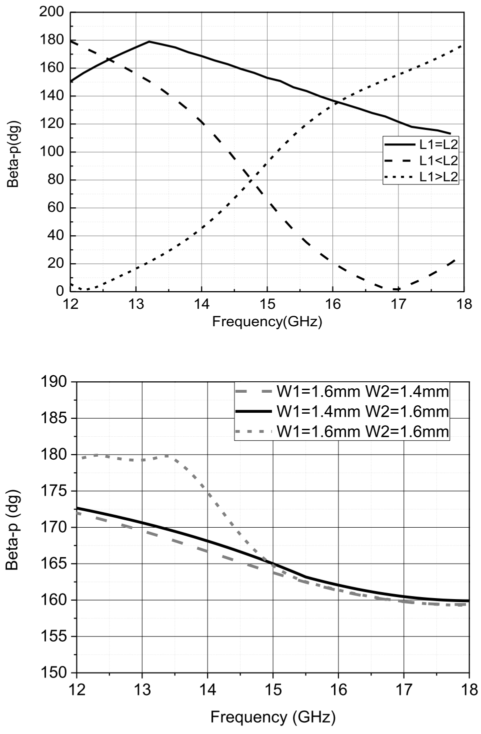
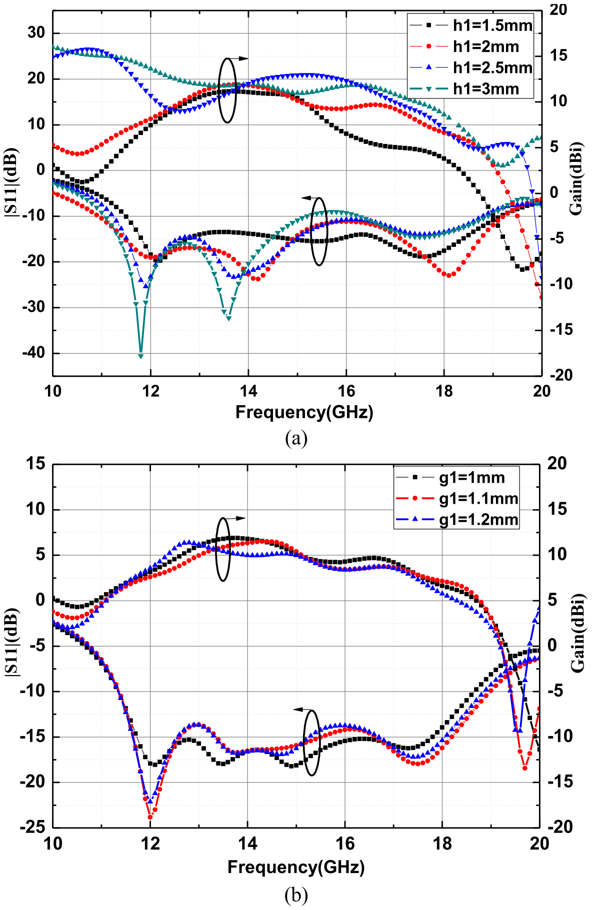


FIGURE 3. The phase characteristics in direction x.



(a)

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FIGURE 4. Parameter analysis of the antenna: (a) |S11| and gain of the antenna with different thickness h_1; (b) |S11| and gain of the antenna with different g_1.

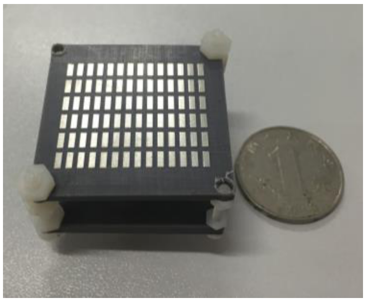


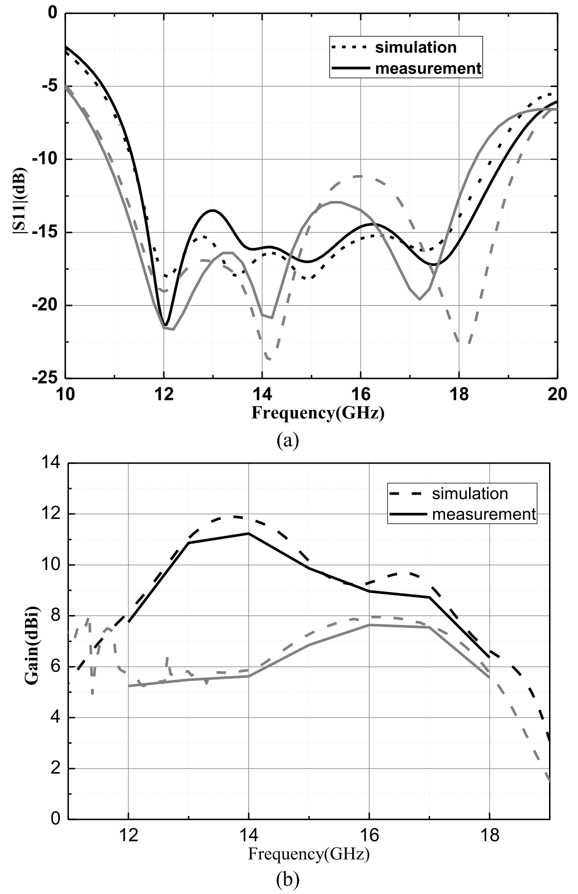
FIGURE 5. Photograph of the proposed antenna. (a) Black = The proposed antenna. (b) Gray = the original ME-dipole antenna.

parameter analysis is done. Also trade-off should be made between the maximum gain at the center frequency and the maximum gains over the whole operating band.

III. MEASUREMENT RESULTS AND DISCUSSION

Based on the parameters optimization above, a prototype of the FPRA is fabricated and shown in Fig. 5. Measurement experiments have been carried out to validate the design and analysis by using an Agilent N5230A network analyzer and an anechoic chamber. Fig. 6 (a) compares the simulated and measured |S11| of the proposed antenna and the unloaded MEDA. The proposed antenna owns wide impedance bandwidth with |S11| below −10 dB over 11.5-18.7 GHz, relatively 56.25%, while the original MEDA shows 61.67%. The experimental results indicate that the proposed antenna loaded with the metallic PRS basically maintains the broadband property of the MEDA.

The simulated and measured gain curves of the FPRA and MEDA are plotted in Fig. 6 (b). It can be found that the antenna gain has been enhanced greatly in the whole operating band. The original MEDA owns maximum gain of 7.3 dBi and its 3-dB gain bandwidth is 32.5%. The proposed FPRA possesses a relative 3-dB gain bandwidth of 35% from 12.3 GHz to 17.2 GHz with a peak gain of 11.2 dBi at 14 GHz. Gain enhancement of about 1.5∼5 dBi in the whole working band is realized by the PRS. Comparing with traditional FPRA with the same size and the same directivity, the gain bandwidth of this proposed antenna is nearly doubled. In Fig. 7, the radiation patterns of the antenna are plotted at 12 GHz, 15 GHz and 17 GHz, respectively. It indicates that the FPRA provides stable radiation patterns in both E-plane and H-plane, which are similar to those of MEDA. The measured cross polarizations are less than −20 dB at the broadside. The measured radiation patterns at higher frequencies (16 GHz or higher) do not agree well with the simulated ones, it may be due to the measurement errors and assignable noise in higher band.



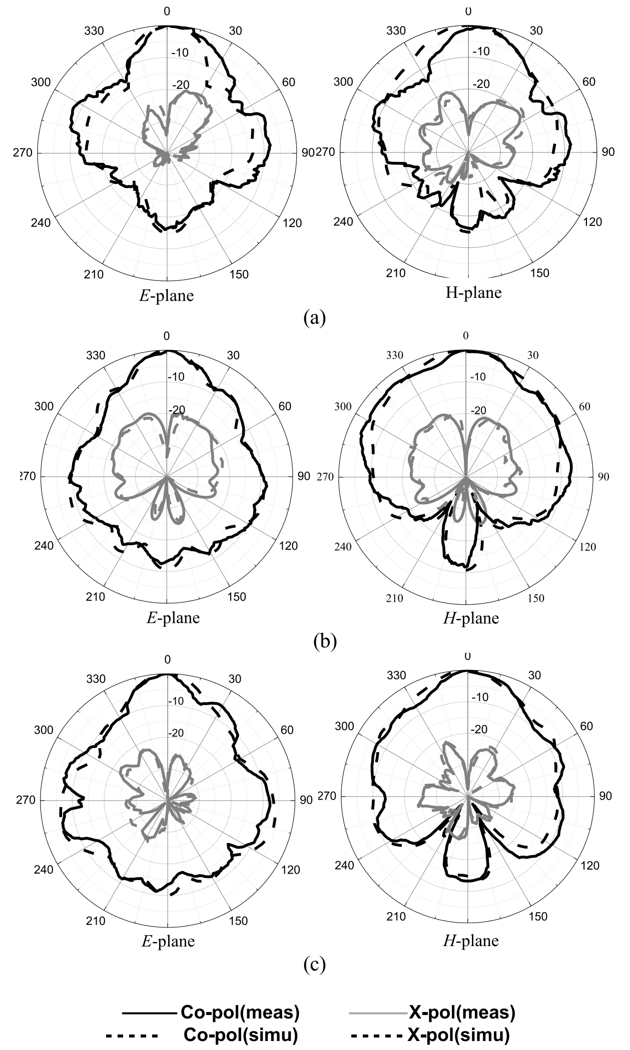
(a)

(b)

FIGURE 6. Simulated and measured performance of the antenna: (a) |S11| of the feeding antenna and the proposed antenna; (b) radiation pattern of the feeding antenna and the proposed antenna.

TABLE 2. Comparison of the simulated performances of the six antennas mentioned.

Ref.	ε_r	Centre Fre. f_0 (GHz)	Max gain (dB)	3-dB gain BW	Antenna Size (λ_0)	Layers of PRS
[1]	1.02	15	21.9	1.2%	5*5*0.55	1
[5]	3.38	10	12.5	2.0%	2*2*0.11	1
[6]	2.2	10	13.8	28%	2.4*2.4*0.5	2
[8]	2.2	13.7	18.3	8%	3.54*3.54*0.6	2
[9]	2.55	14.5	20.8	15.1%	4*4*0.46	3
[11]	2.2	15.5	15	25.8%	2.4*2.4*1.31	2
[13]	2.2	9.85	14	28%	2.4*2.4*1.43	2
[14]	2.55	5.8	19.4	7.24%	3.5*3.5*1	2
[18]	2.2	12	16.2	15.7%	4.5*4.5*0.52	1
proposed	2.2	15	11.2	**35%**	**1.75*1.75*0.75**	**1**



(a)

(b)

(c)

FIGURE 7. Simulated and measured E- and H-planes radiation patterns of the antenna at: (a) 12GHz; (b) 15 GHz; (c) 17 GHz.

As shown in Table 2, compared with the former reported antennas, the proposed antenna owns obviously enhanced 3-dB gain bandwidth by using both the MEDA and the PRS. In the past research, the 3-dB gain bandwidth is 28% by loading with two layers of dielectric superstrates [6], [13]. While the proposed antenna here has a 3-dB gain bandwidth of 35% by loading with only one layer of dielectric superstrate. It can be found that the maximum gain value is not as high as former designs. That's because the electrical size of the cover in this design is the smallest. It can be anticipated that that the maximum gain of the proposed FPRA could also be enhanced with lager PRS and larger metal ground. To sum up, the measured results confirms the effectiveness of our method.

IV. CONCLUSION

In this paper, gain enhancement for one wideband MEDA is realized by loading with a metallic PRS which produces both positive and negative reflective phase gradients. The proposed antenna owns features of simple structure and easy fabrication by using the conventional printed circuit board (PCB) technique. By combining MEDA with PRS structure, the radiation gain of the original design could be enhanced obviously over the whole band. One prototype is fabricated for verification and the results show that the impedance bandwidth is about 56.25% (11.5 GHz-18.7 GHz), among which 35% 3-dB gain bandwidth arranged from 12.3 GHz to 17.2 GHz is realized. Compared with conventional FPRAs, the proposed antenna has achieved the desired performance with easier integration and stable wideband radiation, which could be applied in Ku-band communication systems in future.

REFERENCES

[1] A. P. Feresidis and J. C. Vardaxoglou, "High gain planar antenna using optimised partially reflective surfaces," *IEE Proc.-Microw. Antennas Propag.*, vol. 148, no. 6, pp. 345–350, Dec. 2001.

[2] R. Alkhatib and M. Drissi, "Improvement of bandwidth and efficiency for directive superstrate EBG antenna," *Electron. Lett.*, vol. 43, no. 13, pp. 702–703, Jun. 2007.

[3] A. P. Feresidis, G. Goussetis, S. Wang, and J. C. Vardaxoglou, "Artificial magnetic conductor surfaces and their application to low-profile high-gain planar antennas," *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 209–215, Jan. 2005.

[4] H. Moghadas, M. Daneshmand, and P. Mousavi, "Analysis of radiation of antennas with a phase-gradient partially reflective surface," *IET Microw., Antennas Propag.*, vol. 9, no. 12, pp. 1323–1330, 2015.

[5] Y. Sun, Z. N. Chen, Y. Zhang, H. Chen, and T. S. P. See, "Subwavelength substrate-integrated Fabry–Pérot cavity antennas using artificial magnetic conductor," *IEEE Trans. Antennas Propag.*, vol. 60, no. 1, pp. 30–35, Jan. 2012.

[6] N. Wang, Q. Liu, C. Wu, L. Talbi, Q. Zeng, and J. Xu, "Wideband Fabry–Perot resonator antenna with two complementary FSS layers," *IEEE Trans. Antennas Propag.*, vol. 62, no. 5, pp. 2463–2471, May 2014.

[7] D. M. Pozar and T. A. Metzler, "Analysis of a reflectarray antenna using microstrip patches of variable size," *Electron. Lett.*, vol. 29, pp. 657–658, Apr. 1993.

[8] K. Konstantinidis, A. P. Feresidis, and P. S. Hall, "Dual subwavelength Fabry–Perot cavities for broadband highly directive antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1184–1186, 2014.

[9] K. Konstantinidis, K. P. Feresidis, and P. S. Hall, "Multilayer partially reflective surfaces for broadband Fabry-Perot cavity antennas," *IEEE Trans. Antennas Propag.*, vol. 62, no. 7, pp. 3474–3481, Jul. 2014.

[10] Z.-G. Liu and W.-X. Zhang, "Broadband reflectarray with element of double-layer slot-loading patches," in *Proc. IEEE Int. Symp. Antennas Propag.*, San Diego, CA, USA, Jul. 2008, pp. 1–4.

[11] N. Wang, J. Li, G. Wei, G. Talbi, Q. Zeng, and J. Xu, "Wideband Fabry–Perot resonator antenna with two layers of dielectric superstrates," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 229–232, 2015.

[12] J. A. Fladie and J. T. Bernhard, "On the radiation characteristics of right- and left-handed microstrip patch antenna designs," *IEEE Antennas Wireless Propag. Lett.*, vol. 5, pp. 563–565, 2006.

[13] N. Wang, L. Talbi, Q. Zeng, and J. Xu, "Wideband Fabry–Perot resonator antenna with electrically thin dielectric superstrates," *IEEE Access*, vol. 6, pp. 14966–14973, 2018.

[14] L. Zhou, X. Chen, and X. Duan, "Fabry–Pérot resonator antenna with high aperture efficiency using a double-layer nonuniform superstrate," *IEEE Trans. Antennas Propag.*, vol. 66, no. 4, pp. 2061–2066, Apr. 2018.

[15] K. Konstantinidis, A. P. Feresidis, and P. S. Hall, "Dual-slot feeding technique for broadband Fabry–Perot cavity antennas," *IET Microw., Antennas Propag.*, vol. 9, no. 9, pp. 861–866, 2015.

[16] K.-M. Luk and H. Wong, "A new wideband unidirectional antenna element," *Int. J. Microw. Opt. Technol.*, vol. 1, no. 1, pp. 35–44, Jun. 2006.

[17] K.-M. Luk and B. Wu, "The magnetoelectric dipole—A wideband antenna for base stations in mobile communications," *Proc. IEEE*, vol. 100, no. 7, pp. 2297–2307, Jul. 2012.

[18] Y. Ge, K. P. Esselle, and T. S. Bird, "The use of simple thin partially reflective surfaces with positive reflection phase gradients to design wideband, low-profile EBG resonator antennas," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 743–750, Feb. 2012.

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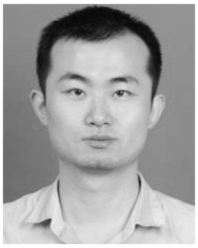

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