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Wideband Fabry-Perot Cavity Antenna With a Shaped Ground Plane

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ABSTRACT This paper proposes a novel approach to broaden the 3-dB gain bandwidth of Fabry–Perot cavity (FPC) antennas by utilizing a shaped ground plane. The shaped ground plane is flat in the middle to accommodate the source antenna, and then angled up in the shape of trapezoids. Compared with an FPC antenna with a traditional flat ground plane, the 3-dB gain bandwidth of the one with a shaped ground plane is improved from 11% to 20.2% with the maximum realized gain and the 10-dB impedance bandwidth almost unchanged. To validate the feasibility of the proposed approach, an FPC antenna prototype has been designed, fabricated, and measured. It consists of a U-slot rectangular microstrip patch antenna as the source, a Rogers RT6006 superstrate as the partially reflective surface, and the proposed shaped ground plane. Measured results on input reflection coefficients and radiation patterns agree well with simulated ones. Therefore, this new approach can be an effective way to enhance the gain bandwidth without increasing the cavity profile or using multi-layer superstrate structures.

INDEX TERMS Wideband antenna, Fabry-Perot cavity antenna, partially reflective surface.

I. INTRODUCTION

Fabry-Perot Cavity (FPC) antenna has attracted significant attention due to its merits of high gain, simple structure, and low profile. It usually consists of a microstrip antenna as the radiating source, a metallic planar ground plane, and a partially reflective surface (PRS) superstrate which is located approximately half a wavelength above the radiator to enhance the directivity. Electromagnetic waves radiated from the source experience multiple reflections and transmissions within the cavity formed by the ground plane and the atop superstrate [1]. When certain resonance conditions are satisfied, the waves transmitted through the PRS can be in phase [2], thus enhancing the antenna directivity. Unfortunately, the resonance condition is usually realized in a small bandwidth, thereby narrowing the impedance and radiation bandwidths of FPC antenna.

Recently, a number of novel FPC antennas have been reported in the literature to broaden the 3-dB gain bandwidth, mainly by employing two approaches. The first one is to utilize array antennas as the radiating source [3]–[6]. The experimental results in [3] show that the directivity and 3-dB gain bandwidth are increased with more array source elements. By incorporating the array source, the electric fields tend to be well distributed, which leads to a more efficient radiation. Therefore, the 3-dB gain bandwidth is enhanced. However, this approach may need more space for the array source, which enlarges the overall antenna dimensions. Furthermore, array source employs extra feed networks, which may increase design complexity and bring more losses. The second approach is to optimize the PRS structure by utilizing gradient index metamaterial-based superstrates [7]–[11], or multi-layer superstrates with input reflection phases increasing with frequency [12]–[14]. In [7], a broadband FPC antenna with a single-layer PRS is proposed. By employing dissimilar size PRS units, the phase difference from the spherical wave-front can be compensated, thus leading to an increased 3-dB directivity bandwidth from 7.99% to 12.2%. The FPC antenna proposed in [8] achieves a 3-dB gain bandwidth of 15.7% by employing a single-layer double-sided dipole-type PRS structure. In [12], a wideband FPC antenna using a three-layer PRS superstrate is presented, which achieves a 3-dB gain bandwidth of about 15%. By utilizing a multi-layer all-dielectric PRS structure, the antennas in [13] realize a 3-dB gain bandwidth of 25.8%. Additionally, the gain bandwidth can be improved by exciting higher-order modes in the cavity. In [15], multiple quasi-Laguerre–Gaussian beam modes are excited due to the employment of a spherically modified cavity. By optimizing the resonant frequencies of different modes, the proposed antenna can realize a 24.7% 3-dB gain bandwidth. However, the overall height of the multilayer or the second-order modified FPC antenna exceeds 1 λ (λ is the wavelength in free-space), which may limit their usages in low-profile applications.

In this paper, a new approach to enhance the 3-dB gain bandwidth of FPC antennas is proposed. It is well known that the reflection phases caused by different reflection paths, which are transmitted from the source antenna, are non-cophasal [7]. Therefore, the resonance condition can be realized only at a narrow range of frequencies. By shaping the ground plane to modify the inner cavity, the cavity height is decreased gradually and the reflection phase differences can be compensated. This way, the resonance condition can be achieved in a wider operating frequency range. Therefore, the FPC antennas with the shaped ground structure can achieve more than 20% 3-dB gain bandwidth without resorting to complicated array source or complicated PRS structures. Compared to other designs with similar cavity profile, this approach can realize a relatively wide gain bandwidth with simple structure. Moreover, this approach can be also combined with the aforementioned two methods to achieve a much larger bandwidth.

The rest of this paper is organized as follows. Section II describes the operating mechanism of the new FPC antenna by analyzing the electric field distribution in the cavity and conducting parametric studies. In Section III, an antenna prototype is designed and comparisons between the theoretical and experimental results are given. Finally, conclusions are drawn in Section IV.

II. SHAPED GROUND STRUCTURE AND ANALYSIS

A. ANTENNA STRUCTURE

The proposed antenna structure is shown in Fig. 1 (a). It consists of a U-slot rectangular patch antenna as the source sitting in the middle, a shaped ground plane and a single-layer dielectric PRS placed half a wavelength atop from the source. The shaped ground plane is flat in the center, and the part surrounding the patch is angled up in the shape of trapezoids. The lateral dimension of the antenna is 2.75λ × 2.75λ (λ is the free space wavelength at 5.5 GHz). The PRS structure is constructed on a 5.5-mm-thick Rogers RT6006 substrate ($\varepsilon_r = 6.15$, $tan\delta = 0.0019$). It is supported by four dielectric spacers at the four corners.

Fig. 1(b) gives the details of the side view (from the y-z plane) of the whole antenna structure as shown in Fig. 1(a). The ground plane is angled up from the location that is 22.5 mm away from the center of the patch antenna. The height of the edge (h_c) and the angle (θ) of the shaped ground plane are chosen to be 8 mm and 8.66°, respectively.

The U-slot patch antenna is printed on a 3-mm-thick Rogers RT5880 ($\varepsilon_r = 2.2$, $tan\delta = 0.0009$) substrate. The U-slot source antenna is designed according to the procedure described in [16]. The details of the source antenna are shown in Fig. 1(c): the width and length of the patch antenna are 14.5 mm and 30 mm, respectively. The horizontal part of the U-slot is 10 mm in length with the vertical part 9 mm in length. The width of the U-slot is 1 mm. The source is fed by a coaxial probe at the center.

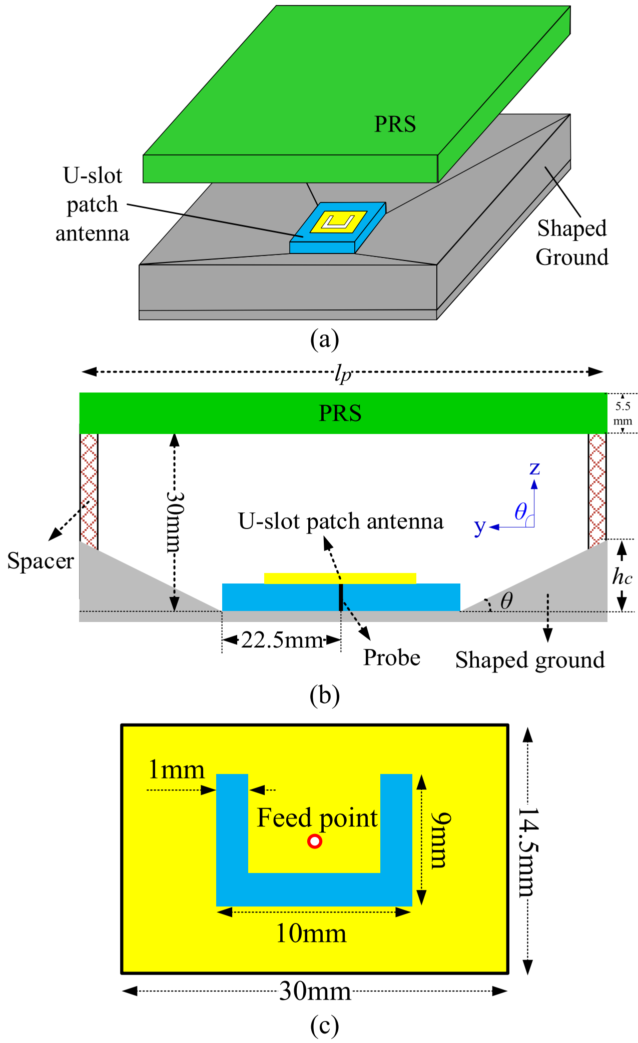

FIGURE 1. Antenna structure (a) perspective view, (b) side view from the y-z plane, (c) U-slot patch antenna.

The FPC antenna with a flat ground plane and with a shaped ground plane are simulated by using CST Microwave Studio [17]. It can be seen from Fig. 2 that by employing the shaped ground plane, the 3-dB gain bandwidth is enhanced from 11.3% to 20.2% with almost no effect on the maximum gain values. The gain bandwidth improvement is due to the fact that the electric field (E-field) tends to be well-distributed when employing the shaped ground plane. The detailed field analysis is illustrated in the following paragraphs.

B. FIELD DISTRIBUTION ANALYSIS

Fig. 3 shows the E-field distributions of the H plane (y-z plane) for the FPC antennas with flat ground and shaped ground at 5.0 GHz, 5.6 GHz, and 6.2 GHz, respectively. It is seen from Fig. 3(a) that at 5.0 GHz, the energy is more uniformly distributed for the FPC antenna with flat ground

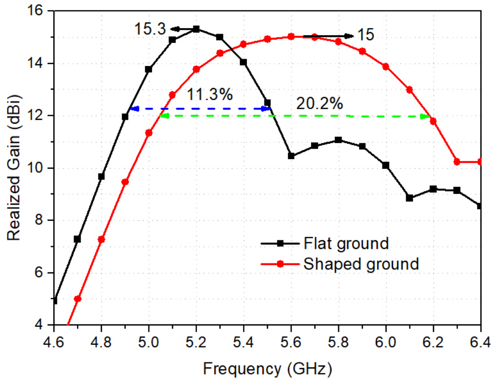

FIGURE 2. Bandwidth comparison of the FPC antenna with the flat ground plane and with the shaped ground plane.

than the shaped one. Moreover, the illuminated area on the PRS for the FPC antenna with flat ground is larger than the shaped one. Therefore, the realized gain of the FPC antenna with flat ground is higher than that of the shaped one, as shown in Fig. 4(a).

At 5.6 GHz, for the FPC antenna with flat ground, the E-field strength in the middle of the cavity shown in the blue circle is smaller than that in the edges, as shown in Fig. 3(b), thus the gain at the boresight is reduced and the main beam has high sidelode levels. This case, the gain bandwidth is reduced. On the other hand, for the FPC antenna with shaped ground, the E-field strength is greater in the center, enabling the main beam to be radiated towards the boresight with almost no sidelobe, as shown in Fig. 4(b).

At 6.2 GHz, as seen in Fig. 4(c), the main beam is split with two main side lobes for the FPC antenna with flat ground, which is caused by the increasing E-field strength at the edges of the cavity (marked in blue circle in Fig. 3(c)). In this way, its gain is reduced significantly, which decreases the gain bandwidth. For the FPC antenna with shaped ground, the E-field strength at the edges of the cavity is much lower. Therefore, its main beam is still at the boresight direction with stable gains. This way, the 3-dB gain bandwidth is increased as shown in Fig. 2.

C. IMPEDANCE MATCHING ANALYSIS

Fig. 5 shows the effects of the shaped ground on the impedance matching of the FPC antenna. It can be seen that the FPC antenna with shaped ground has larger variations of the resistance and reactance than the FPC antenna with flat ground. As a result, as shown in Fig. 6, the 10-dB impedance bandwidth for the FPC antenna with flat ground (21%) is slightly wider than that of the shaped one (19.7%). However, the difference is relatively small and can be acceptable for most of the applications.

D. PARAMETRIC STUDY

To illustrate the influence of the shaped ground plane, a parametric study of its dimensions has been conducted. Their effects on the reflection coefficients and the realized gains of the antenna are investigated.

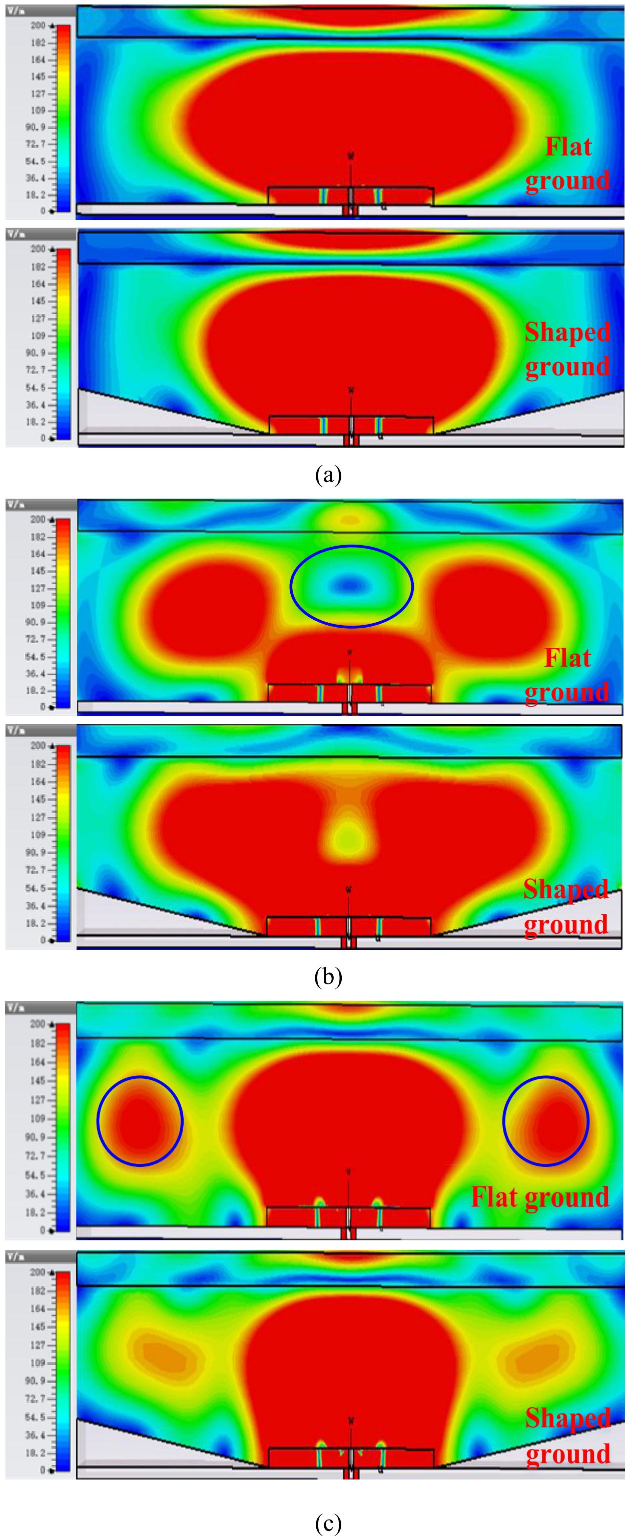

FIGURE 3. E-field distributions of H plane at different frequencies. (a) 5.0GHz. (b) 5.6GHz. (c) 6.2GHz.

Fig. 7(a) shows the effects of the edge height of the ground plane h_c on the antenna performance. The variation of h_c has little effect on the impedance bandwidth. In terms of radiation performance, the 3-dB gain bandwidth is increased

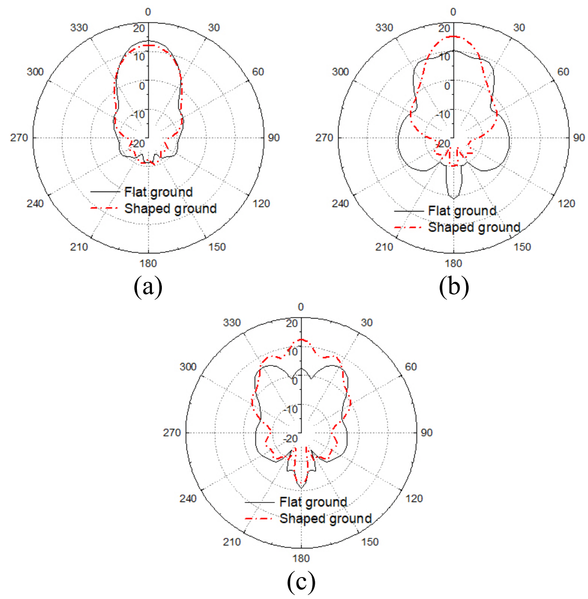

FIGURE 4. Simulated H-plane patterns at different frequencies. (a) 5.0GHz. (b) 5.6GHz. (c) 6.2GHz.

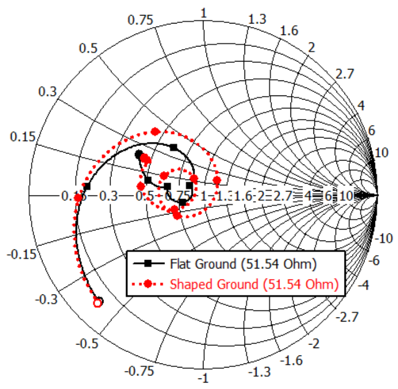

FIGURE 5. The effects of the shaped ground on the impedance.

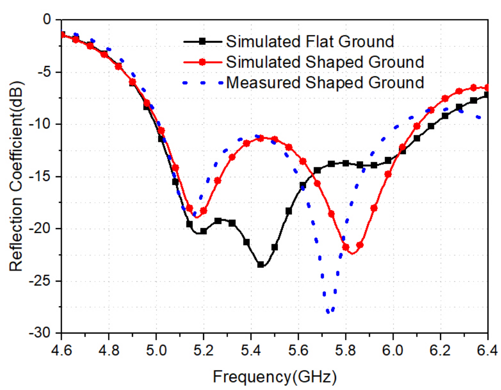

FIGURE 6. Reflection coefficients of the FPC antenna with flat ground/ shaped ground and the measured result.

with h_c, but the maximum realized gains is decreased with an increasing h_c, as shown in Fig. 7(b). When h_c exceeds 8 mm, the variations of the impedance matching and the gain

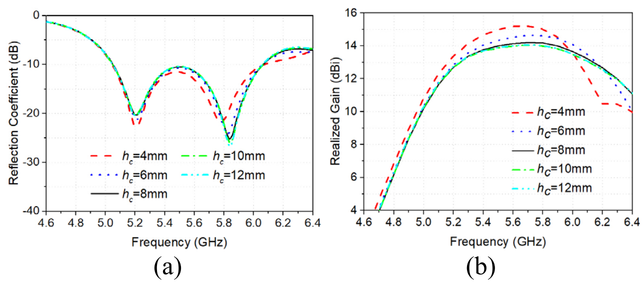

FIGURE 7. The effect of height h_c.

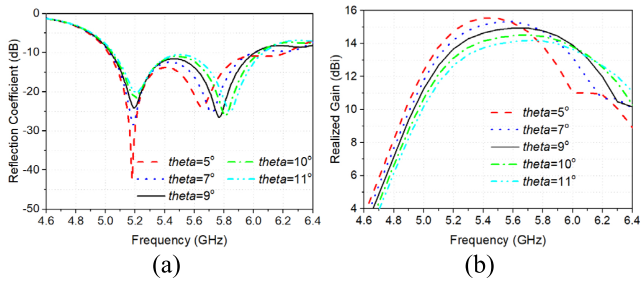

FIGURE 8. The effect of angle θ.

bandwidth are not that obvious. Fig. 8 gives the effects of the angle θ on the antenna performance. θ has significant effects on both the impedance bandwidth and the 3-dB gain bandwidth. As θ increases, the 10-dB impedance bandwidth and 3-dB gain bandwidth are enhanced with decreased maximum gains.

The design principle of this work is concluded as below:

1) Based on the operating frequency, design and optimize the performance of the source antenna;
2) Select an appropriate superstrate structure according to the bandwidth requirements and calculate the cavity height according to the resonance condition of FPC antenna [2],
   which is

$$L_r = \left(\frac{\varphi}{\pi} - 1\right)\frac{\lambda}{4} + N\frac{\lambda}{2} \quad N = 0, \pm 1, \pm 2 \ldots, \quad (1)$$

3) Fix the optimized cavity height and employ the shaped ground. At first, decide the value of h_c to make the modified FPC antenna have a similar maximum gain level with the one which has a flat ground. Then, optimize the value of θ to make a performance compromise between the impedance matching, the maximum gain, and the 3-dB gain bandwidth.

Based on the parameter analysis, h_c and θ are chosen as 8 mm and 8.66°, respectively, which can achieve an excellent matching and radiation performance.

III. ANTENNA PERFORMANCE

Based on the above analysis and results, an antenna prototype shown in Fig. 9 has been designed, fabricated, and measured. Nylon spacers and M3 nylon bolts are used to support the PRS. It is found that truncated PRS can realize a more

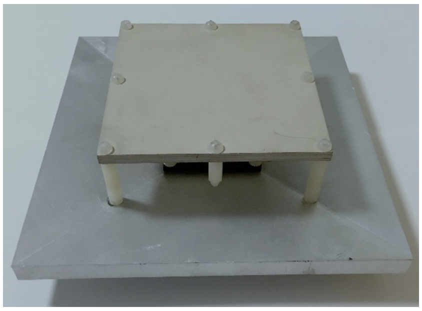

FIGURE 9. **Prototype of the proposed antenna.**

efficient illumination [18]. In this work, the dimension of the dielectric PRS superstrate (L_p) is truncated from 150 mm to 90 mm (1.65λ) to further improve the gain bandwidth. The other dimensions of the proposed antenna are the same as that described in Section II.

A. INPUT REFLECTION COEFFICIENTS

The input reflection coefficients of the antenna were measured using an E5063A Agilent network analyzer. For brevity, the simulated and measured reflection coefficients are also shown in Fig. 6. It is observed that the measured 10-dB impedance bandwidth can cover a frequency band from 4.96 GHz to 6.02 GHz. There is a small discrepancy between the simulated and measured results. It can be attributed to the fabrication tolerances, such as the inaccuracies in the angle and the height of the shaped ground plane.

B. FAR-FIELD RADIATION PATTERNS

The radiation patterns and the realized gains of the proposed antenna were measured by using a spherical near-field antenna measurement system NSI-700s-50. The orientations of the rectangular coordinate system in all radiation pattern figures are the same as the one shown in Fig. 1.

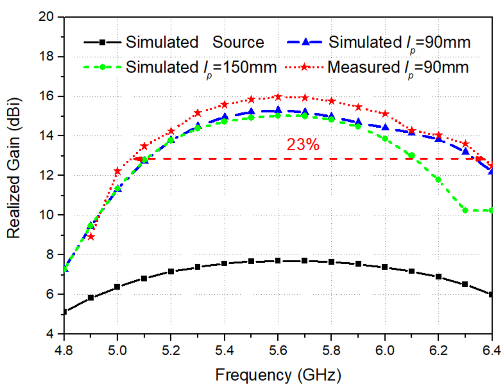

FIGURE 10. **Realized gains of the proposed antenna and the source antenna.**

Fig. 10 gives the simulated and measured realized gains of the FPC antenna with shaped ground with different PRS sizes. The maximum simulated gain for the source antenna is 7.8 dBi (black solid curve with square symbol). As already described in Fig. 2, the proposed antenna with a 150 mm × 150 mm PRS size can realize a 3-dB gain bandwidth of 20.2% (green dash curve with circle symbol), compared to the 11.3% bandwidth of the FPC antenna with flat ground with the same size of PRS. By truncating the PRS size from 150 mm to 90 mm, the 3-dB gain bandwidth is further increased to 23% (blue solid curve with triangle symbol). The measured 3-dB realized gain bandwidth of the prototype with a 90 mm × 90 mm size PRS is 23% and its maximum gain is over 16 dBi, which agree reasonably well with the simulated results. The difference between the simulated and measured realized gains is less than 0.8 dB, which can be attributed to the alignment errors and fabrication inaccuracies.

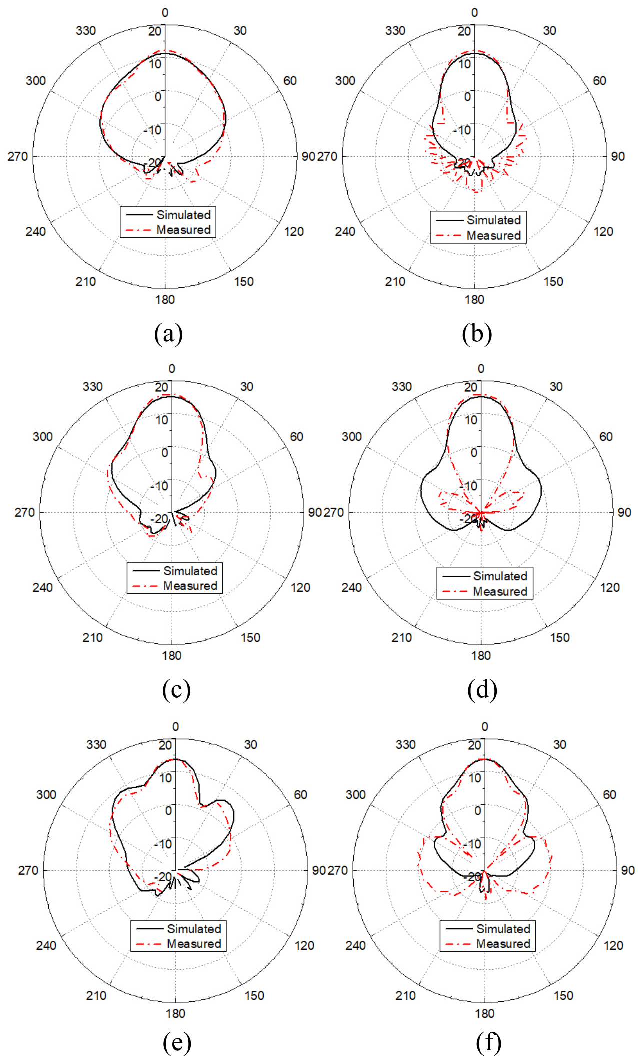

FIGURE 11. **Radiation patterns of the proposed antenna. (a) 5.0GHz E-plane. (b) 5.0GHz H-plane. (c) 5.6GHz E-plane. (d) 5.6GHz H-plane. (e) 6.2GHz E-plane. (f) 6.2GHz H-plane.**

Simulated and measured radiation patterns are compared at 5.0 GHz, 5.6 GHz, and 6.2 GHz shown in Fig. 11. It is observed that the measured patterns agree well with the simulated ones. The main beam directions for different operating frequencies remain at the boresight direction with no pattern split. The sidelobe level is below 9.5 dB.

The measured E plane cross-polarizations at 5.0 GHz, 5.6 GHz, and 6.2 GHz are all below −15dB as shown in Fig. 12.

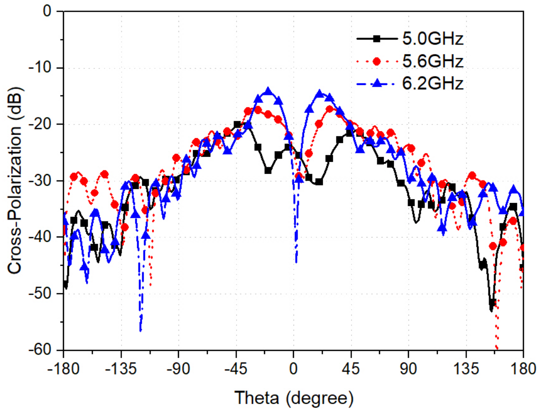

FIGURE 12. Cross polarizations of the proposed antenna.

A comparison of the performance, antenna size, and mechanism of the proposed FPC antenna with some reported designs are described in Table 1. As can be seen from the table, the proposed method can successfully increase the 3-dB gain bandwidth of FPC antenna, which is comparable or even greater than other methods. Therefore, the proposed method can be either used alone or employed with other methods together for wideband FPC antenna designs.

TABLE 1. Comparison of the performance OF broadband FPC antennas.

Ref	Gain (dBi)	3-dB BW	SLL (dB)	Aperture Efficiency	Antenna size	Mechanism
[9]	13.8	28%	-12	33.1%	2.4λ×2.4λ ×0.5λ	Single-layer PRS
[10]	17	16.3%	-10	55%	$2.25\lambda^2\times$ 0.5λ	PRS truncation
[11]	15.9	54.2%	-8	34.4%	$2.83\lambda^2$ ×1.01λ	STPG superstrate
[13]	15	25.8%	-11	43.7%	2.4λ×2.4λ ×1.36λ	Multilayer PRS
[15]	17.7	24.7%	-7	19%	$24.6\lambda^2$ ×1.17λ	2nd-order cavity
Our work	**16**	**23%**	**-9.5**	**41.9%**	**2.75λ×2.75λ ×0.56λ**	**Shaped Ground**

IV. CONCLUSION

A new approach for improving the gain bandwidth of FPC antennas has been presented in this paper. By employing a shaped ground plane, the 3-dB gain bandwidth can be improved to 20.2% with almost no effects on the impedance bandwidth and other radiation characteristics. This technique is suitable for the applications with wideband and low-profile requirements. Furthermore, it can be employed with other bandwidth enhancing methods, such as positive phase gradient index PRS or array source, to further improve the performance of FPC antennas.

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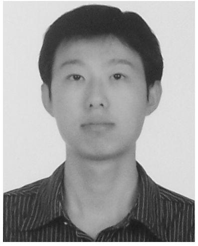

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Dr. Guo has chaired numerous international conferences. He was the International Advisory Committee Chair of the IEEE VTC2017, the General Chair of ISAP2015, iWAT2014 and WPMC'2014, and the TPC Chair of the 2010 IEEE WCNC, and 2012 and the 2007 IEEE ISCIT. He served as a Guest Editor for special issues on Antennas for Satellite Communications and Antennas and Propagation Aspects of 60–90GHz Wireless Communications, in the IEEE Transactions on Antennas and Propagation, Special Issue on Communications Challenges and Dynamics for Unmanned Autonomous Vehicles, the IEEE Journal on Selected Areas in Communications, and Special Issue on 5G for Mission Critical Machine Communications, the IEEE *Network Magazine*.