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A Single-Layer Reflect-Transmit-Array Antenna With Polarization-Dependent Operation

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ABSTRACT In this paper, a novel low-profile, dual-polarized reflect-transmit-array antenna is proposed to independently control the forward and backward beams. A single-layer polarization-dependent element is designed with $0.1 \lambda_0$ -thickness at 10 GHz, which comprises only two layers of metal patches printed on a dielectric substrate and two metallized vias. Through changing the polarization direction of the incident wave, the operating mode of the proposed array can be easily shifted among reflection mode, reflection-transmission mode, as well as transmission mode. To verify the design concept, a circular reflect-transmit-array ($D = 250$ mm) is designed, fabricated, and measured. The measured results indicate a 1 dB bandwidth of 17% (9.8-11.5 GHz) in reflection mode and a measured peak gain of 24.2 dB at 10.5 GHz. Moreover, a 1 dB bandwidth of 6% (9.7-10.3 GHz) can be achieved in transmission mode, and the measured peak gain is 24.6 dB at 10 GHz. The results prove that the proposed design is promising for bidirectional wireless communication applications.

INDEX TERMS Low-profile, reflectarray, transmitarray, bidirectional.

I. INTRODUCTION

Metasurfaces have been widely studied for their remarkable capability to manipulate electromagnetic waves flexibly. The flat array using the metasurface elements has many advantages, such as low profile, lightweight, and low fabrication complexity.

In the last decades, a lot of efforts have been devoted to improve performances of the reflectarrays (RAs) and transmitarrays (TAs), including broadband operation [1], [2], multi-band operation [3], [4], multi-beam applications [5], and reconfigurability [6], [7].

The TA antennas have attracted a growing interest in the high-gain antennas area because they combine lens and microstrip array antennas with the advantages of high efficiency, high gain, low profile and light weight. [1]. Compared with the RA antennas, the TA antennas eliminate the effect of feed blocking, which increases the efficiency and

reduces the side lobes. Generally, the transmitting element requires a four-layer structure to achieve a 360° phase shift range with high transmission efficiency [5]. Therefore, some techniques are used to reduce the profile of the element, such as Huygens metasurface [8] and metallized vias [9]. By introducing metallized vias between the upper and lower patches, the transmitting element can be designed on one substrate with high transmission efficiency.

To meet the requirements of the rapid development of communication systems, the bidirectional antenna combining the RA and the TA is the trend [10]–[13]. Bidirectional antennas have two opposite beam directions to achieve better coverage, making them potential in narrow, long, and straight communication scenarios.

A frequency selective surface (FSS) is used in [10] as the ground of the RA, which achieves controllable capability of reflection in K/Ka-bands and transmission in Ku-band by changing the operation frequency of the feed. Similar to [10], a dual-band phase-shifting surface array has been proposed using double-ring FSS as the ground [11]. On the other hand,

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the grid polarizer is also widely used as the ground of the RAs. Some reflect-transmit arrays with the polarization-dependent operation have been presented [12], [13]. The grid polarizer is printed on the bottom of the third dielectric substrate to reflect the TE incident wave and transmit the TM incident wave. By switching the rotation of the feed, the array alternately operates in transmission mode and reflection mode [12]. Furthermore, the unit cell is composed of four metallic layers printed on four substrates, in which two orthogonal-positioned grid polarizers are printed on the bottom of the substrates. By adopting this arrangement, the transmitted wave in the cross-polarization direction would be reflected on the second grid polarizer. Consequently, the cross-polarization level of the array would be reduced [13].

Recently, a novel high-gain reflect-transmit-array antenna consisting of single-layer FSS-type elements has been proposed [14]. This array with simultaneous bidirectional coverage utilizes the cross-polarization wave and forms bidirectional beams based on the field continuity condition. Furthermore, a single-layer reconfigurable bidirectional antenna has been presented in [15]. The proposed element with two PIN diodes can reverse the induced current directions by turning diodes ON or OFF, so the bidirectional beams would simultaneously change.

In this paper, an X-band single-layer reflect-transmit-array antenna with polarization-dependent operation is presented. the shared aperture technology is adopted in this design to reduce the number of substrates of the element. Besides, combining the advantages of single-layer dual-polarization transmission element [9] and sub-wavelength wideband element [16], [17], a novel unit cell, which consists of two metal layers printed on a single substrate drilled with two metallized vias, is proposed and analyzed. It is noted that the designed element has the ability to independently control the reflection and transmission phases by adjusting different geometric parameters. To verify the capability of the designed element, a planar array including 178 elements is designed, fabricated, and tested. The proposed antenna can work in different modes by changing the polarization direction of the incident wave, so as to satisfy various applications of modern wireless communication systems.

This paper is organized as follows. Section II introduces the proposed unit cell and analyzes the effects of the isolated patches on the scattering characteristics of the element. In section III, a single-layer reflect-transmit-array antenna is designed and fabricated, with the results of simulation and measurement compared. Finally, conclusions are drawn in section IV.

II. ELEMENT DESIGN

The geometry of the proposed single-layer unit cell is illustrated in Fig. 1. It is composed of two metallic layers (yellow parts) printed on a 3 mm F4BM substrate ($\epsilon_r = 2.2$, $\tan \delta = 0.001$, $h = 3$ mm) and two metallized vias (red parts) between the metallic layers. To avoid the unwanted grating lobes, the element spacing is set as 15 mm ($P = 15$ mm, corresponding

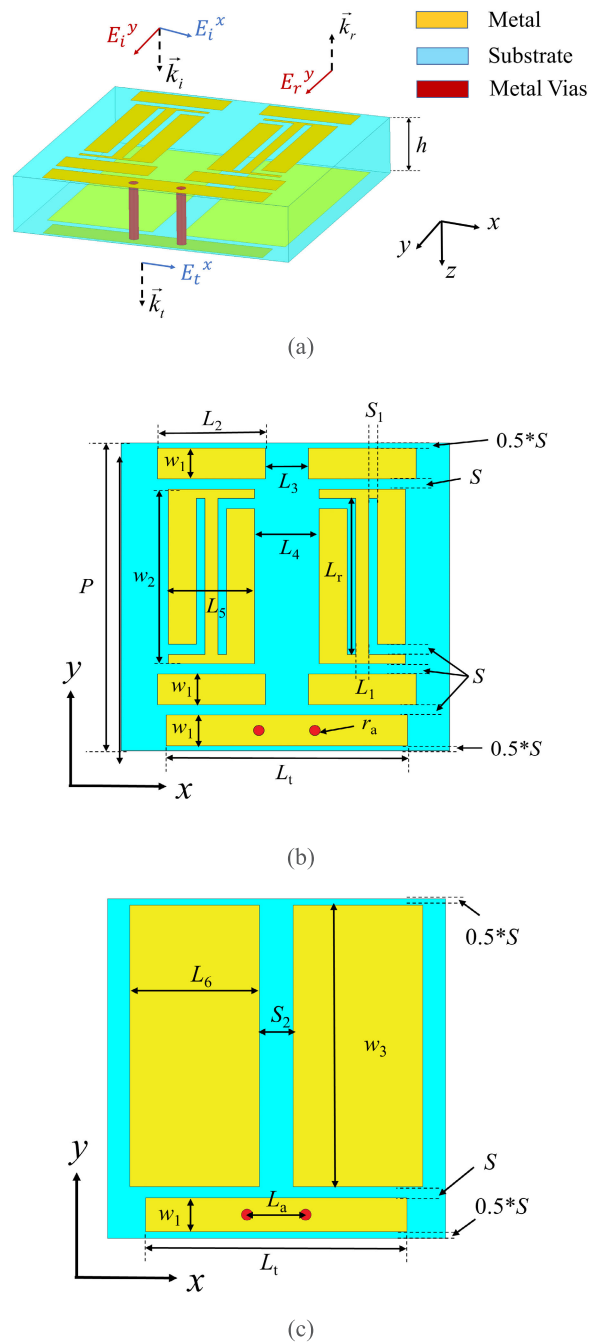


FIGURE 1. Proposed element configuration from (a) perspective view, (b) top view, (c) bottom view.

to $0.5\lambda_0$, where λ_0 is the free-space wavelength at 10 GHz). The detailed dimensions of the proposed unit cell are shown in Table 1.

The detailed view of the top and bottom metal layers is shown in Fig. 1(b) and (c). To introduce the working principle in detail, the proposed element is divided into reflection, transmission, and isolation sections based on the function. Owing to the collective effects of these sections, the unit cell can operate with orthogonally linear polarization (LP). In other words, the transmission mode works at x-polarized

TABLE 1. Parameters of the proposed element.

Parameter	Value(mm)	Parameter	Value(mm)
P	15	S_1	0.4
W_1	1.5	S_2	1.5
W_2	8.5	L_1	0.6
W_3	12.5	L_2	5
L_r	0.5~8	L_3	2
L_t	5~14.5	L_4	3
L_a	2.6	L_5	4
r_a	0.25	L_6	5.8
s	0.5		

illumination, and the reflection mode works at y-polarized illumination (shown in Fig. 1(a)). Furthermore, the reflection-transmission mode works at simultaneous illumination of both x- and y- polarization.

Concrete design procedure is shown as below.

A. REFLECTION SECTION DESIGN

First of all, the phase delay line technology is adopted to design the reflection section. The reflection section consists of two patches with a pair of inverted L-shaped slots, and the patches are mirrored about the central line of the unit cell. The patch sizes $W_2^*L_5$ are fixed for all unit cells, but the length L_r of the slots are adjustable to realize different equivalent delay line lengths. Finally, the path of the surface current will change to achieve the phase variation.

Usually, the reflect-transmit-array antenna can realize the reconfigurability using the grid polarizer or the FSS as the ground. Unfortunately, the above methods are improper because the proposed single-layer element operates in transmission mode and reflection mode at a single frequency band. As displayed in Fig. 1 (c), an II-shaped metal layer printed on the bottom of the substrate is employed to avoid this dilemma, which would significantly increase the transmission coefficient of the unit cell compared with a whole square patch. Meanwhile, the reflection coefficient is higher than -1 dB.

The proposed element is established and simulated using HFSS from ANSYS, in which master-slave boundaries and floquet port excitations are employed. The simulated reflection responses of the proposed element are shown in Fig. 2(a). A 310° phase shift range with a reflection magnitude greater than -1 dB is obtained at 10 GHz when L_r varies from 0.5–8 mm.

For further reducing the cross-polarization of the antenna, two patches of the reflection section are mirrored along the y-direction. By adopting this arrangement, as displayed in Fig. 3, two pairs of surface currents along the x-axis for the reflection section would have opposite directions. Because the cross-polarization fields are mainly excited by the cross-direction currents, the effect of the currents in the x-direction would be canceled by adopting mirrored arrangement [18], which means that the cross-polarization level of the antenna would be reduced.

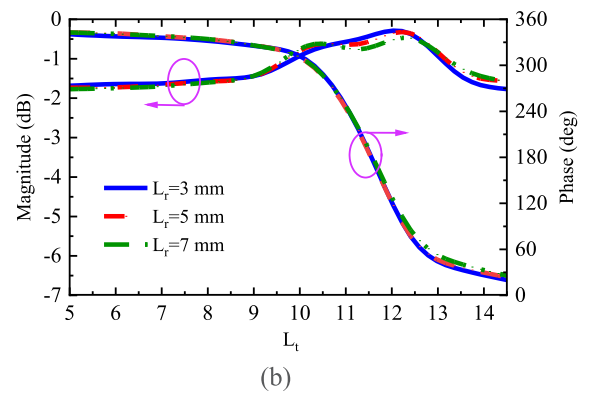
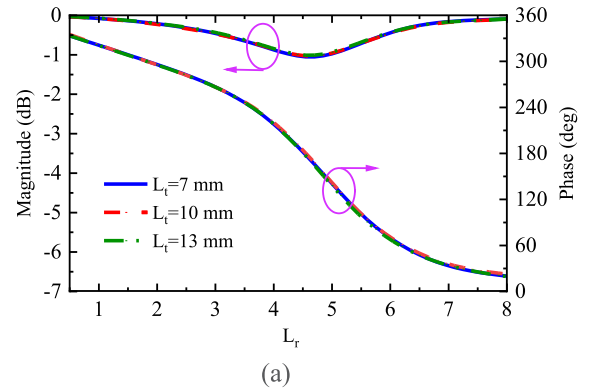


FIGURE 2. The scattering parameters of the proposed element. (a) Reflection responses with different parameters of L_r . (b) Transmission responses with different parameters of L_t .

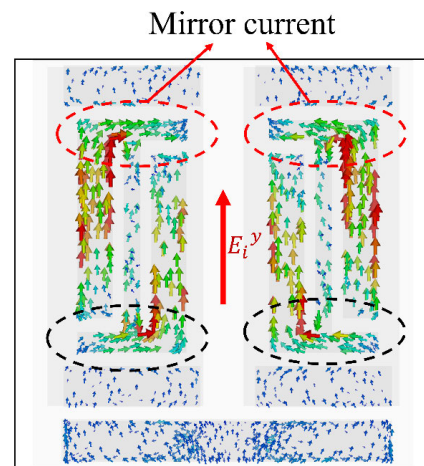
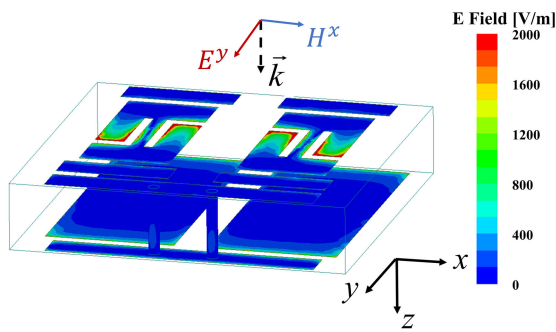


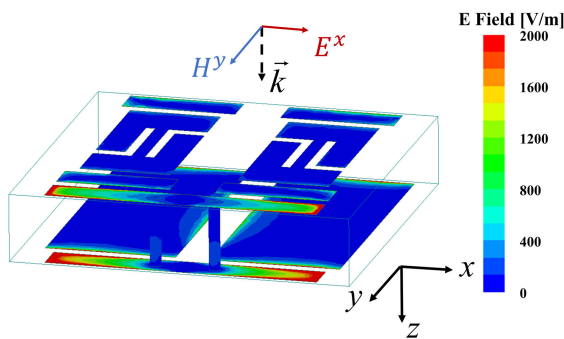
FIGURE 3. Mirroring current distributions of the reflection section with E_i^y .

B. TRANSMISSION SECTION DESIGN

The transmission section, lying between the two reflection sections, consists of two identical dipoles and two metallized vias. Energy transfers between the top and bottom patches are mainly through two vias. Besides, a little energy is transmitted through the gap in the ground. Because the thickness of the substrate is 3 mm, the radius of the metallized vias is set to 0.25 mm to reduce the complexity of processing.



(a)



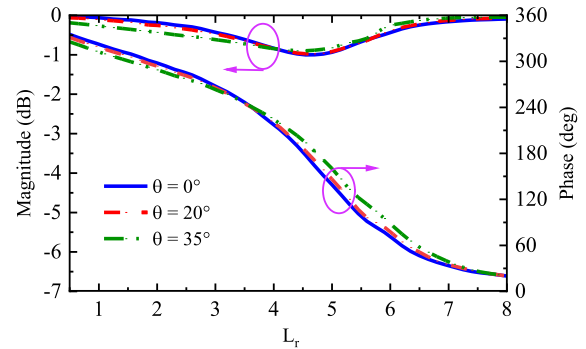
(b)

FIGURE 4. Surface current distributions of the proposed element with (a) E^y and (b) E^x .

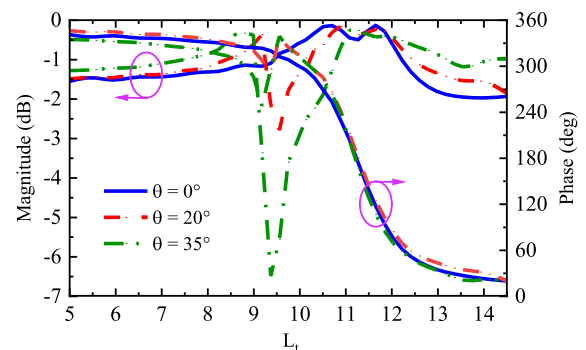
The metallized vias are essential to decrease the element loss significantly and achieve a wide phase shift range with a better transmission magnitude. Besides, the four isolation patches distributed around the dipoles are introduced to improve the transmission magnitude by increasing the coupling between two layers of patches. Through simultaneously adjusting the length L_t of the two dipoles, the unit cell achieves the phase variation of the transmission coefficient. The simulated transmission responses of the proposed element are shown in Fig. 2(b). When L_t varies from 5–14.5 mm, the element achieves a 320° phase shift range with a transmission magnitude greater than -2 dB.

C. ISOLATION SECTION DESIGN

Thirdly, the isolation section needs to be optimized to realize independent control of reflection (only by L_r) and transmission (only by L_t) responses, which plays a vital role in reducing the coupling between the orthogonally polarized incident waves. As shown in Fig. 1 (b), the isolation section consists of four patches distributed around the transmission section. The reason for adopting such a design instead of two longer patches is that the latter would excite stronger surface current distributions than that on the transmission dipoles, which means a significant reduction of the transmission coefficient. As demonstrated in Fig. 2(a), the phase shift curves of the reflection mode remain invariant when the length L_r of the dipoles change. Similarly, as indicated in Fig. 1(b), the same phenomenon can be found about the transmission



(a)



(b)

FIGURE 5. Reflection responses (a) and transmission responses (b) of the proposed element with different oblique incidences.

mode. To show the isolation between the transmission and reflection more intuitively, the surface current distributions of the proposed element are shown in Fig. 4. For the reflection mode, the element is illuminated with the y-polarized wave. In Fig. 4 (a), the reflection section has a strong current distribution but no distribution on the transmission section. Oppositely, the element will work in transmission mode when the illuminated wave is along the x-axis. As shown in Fig. 4 (b), the strong current distribution appears on the transmission patches. The microwave energy is received by the top patch. Then through two metallized vias, energy transfers to the bottom patch. Besides, a little energy is transmitted through the gap in the ground.

Responses of the designed element under oblique incidence are presented in Fig. 5. The maximum incident angle of the element is 35° in this design, which leads to a proper edge illumination level for achieving maximum efficiency. The phase shift curves of the reflection mode remain unchanged with different oblique incidences at 10 GHz. Compared with reflection responses, the transmission responses indicate a more sensitive behavior about the oblique incident angle. As clear in Fig. 5(b), under a large oblique angle of incidence wave, a poor transmission coefficient occurs when L_t varies between 9 and 10. Therefore, adjusting the reference phase at the center of the aperture reduces the distribution of these size elements at the aperture edge. Such arrangement would alleviate the performance deterioration of the

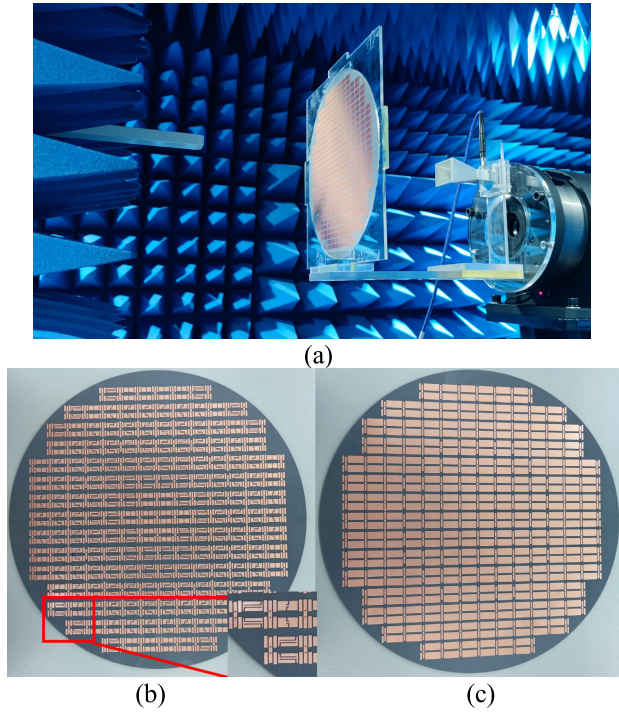


FIGURE 6. Photograph of the measurement setup (a) and the fabricated reflect-transmit array prototype. (b) top layer. (c) bottom layer.

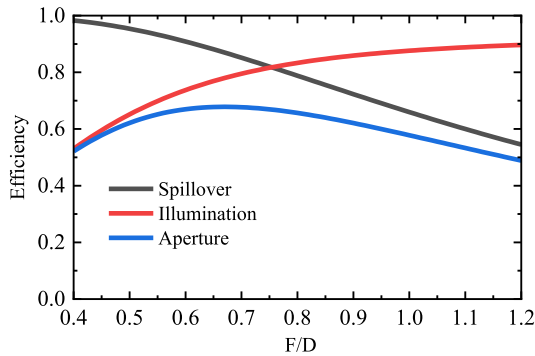


FIGURE 7. The spillover, illumination, and aperture efficiencies versus F/D.

reflect-transmit-array antenna. Besides, a feed horn with a higher gain will significantly improve the transmission characteristic of the planar array.

III. ARRAY ANTENNA DESIGN AND REALIZATION

Based on the proposed single-layer elements, a novel reflect-transmit-array can be designed. The key to designing a high-gain reflect-transmit-array antenna is to choose proper aperture phase distribution in the array aperture for reflect mode and transmit mode, respectively.

The required compensation phase ϕ_i of the i th element can be calculated as the following equation:

$$\phi_i = k(R_i - \vec{r}_i \times \hat{r}_0) + \phi_0 \quad (1)$$

where k is the wavenumber, R_i is the distance between the phase center and the i th element, \vec{r}_i is the position vector of

the i th element, \hat{r}_0 is the unit vector in the main beam direction and ϕ_0 is the relative phase.

In this work, as seen in Fig. 6, the designed array has a circular aperture with a diameter D of 250 mm, consisting of 178 elements, including 178 reflection sections and 193 transmission sections. A horn with a gain 12 dB at 10 GHz is selected as the feed. The focus to diameter ratio (F/D) is an important factor for the aperture efficiency of the array. the spillover efficiency decreases as the focus to diameter ratio is increased, while the illumination efficiency increases. As shown in Fig. 7, the optimum F/D is a nominal value in between. Consequently, the $F/D = 0.67$ ($F = 167$ mm) is selected to achieve the maximum aperture efficiency, which would also provide a proper illumination with an edge taper of -10 dB. The beams of the reflection mode and transmission mode are designed to point at $\phi = 180^\circ, \theta = 0^\circ$ and $\phi = 0^\circ, \theta = 0^\circ$, respectively.

After the focus distance and the beam directions are determined, based on Equation (1), the reflection phase and the transmission phase in the array aperture can be independently derived. Limited by the lower transmission efficiency of some special elements at large oblique incidence angles, the relative phase must be optimized for the transmission mode to achieve the maximum gain. Based on the required compensation phase of each position, the optimal size, L_r and L_t , can be independently determined because there is merely a small coupling between the reflection section and the transmission section. In the arrangement of the elements, as shown in Fig. 6 (b), it is notable that the isolation patches always distribute on the outermost side to ensure the responses of the elements lying on the edge of the array.

The complete reflect-transmit array has been simulated, fabricated, and measured. As shown in Fig. 6 (a), an acrylic holder surrounds the circular array to fix the antenna, transparent for electromagnetic waves. By rotating the holder, the array antenna switches between transmission mode and reflection mode during the testing process. Using the near-field scanning system to measure the fabricated prototype, a waveguide probe and the feed horn were respectively connected to the transmit port and the receive port of a vector network analyzer.

Fig. 8 and Fig. 9 present the measured and simulated normalized radiation patterns of the proposed array antenna in two principal planes at 10 GHz. For the reflection mode, the simulated sidelobe levels are below -20 dB in both two principal planes in the direction of maximum radiation. However, the measured sidelobe levels are higher than simulated results, especially on the E plane. Feed blocking is considered to be the leading cause of this deviation. It consequently results in different errors at the E- and H-plane since the feed horn has a rectangular aperture. Besides, as shown in Fig.6 (a), the coaxial cable connected to the feed horn results in a higher sidelobe level around -40° at the H-plane. For the transmission mode, the measured results match well with the simulated results. The measured normalized sidelobe level of the transmission mode is -18 dB in the H-plane, which is

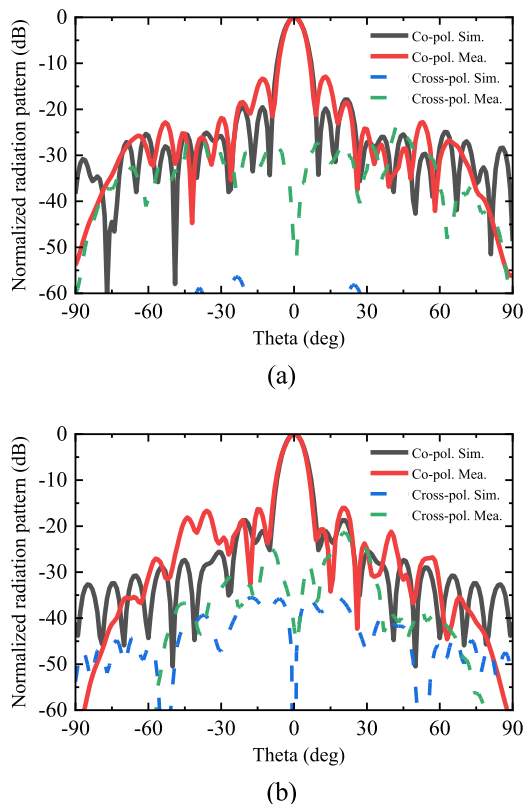


FIGURE 8. Comparison of measured and simulated radiation patterns in reflection mode at 10 GHz. (a) E-plane. (b) H-plane.

slightly higher than that in the E-plane. The discrepancies between simulation results and measurement results are most likely owing to that the actual $\tan\delta$ of F4BM may be larger than 0.001 used in the simulation process and the disturbance from the testing environment.

The simulated and measured gains for the reflect-transmit-array are plotted in Fig. 10, which shows a measured gain of 24.2 dB in reflection mode and 24.6 dB in transmission mode. For the reflection mode, the maximum gain of the prototype appears at 10.5 GHz, which is 0.5 GHz higher than the design frequency. The gain of the feed horn used in this work increases as the operating frequency increases, which is the main cause for this frequency shift.

Because of the feed blocking, the measured aperture efficiency in reflection mode is lower than that in transmission mode, and the aperture efficiencies are approximate 38% and 42%, respectively. Another reason for lower aperture efficiency is that the phase range of the element is lower than 360° , which would lead to large phase errors in the aperture. The measured 3 dB gain bandwidth is 27% (9.3-12 GHz) for the reflection mode and 12% (9.4-10.6GHz) for the transmission mode. The reason for the narrow bandwidth of the transmission mode is that the resonance of the element will be concentrated in the gap on the ground instead of the transmission section as the operating frequency changes.

Finally, comparisons between the proposed antenna and recently published reflect-transmit-array antennas are shown

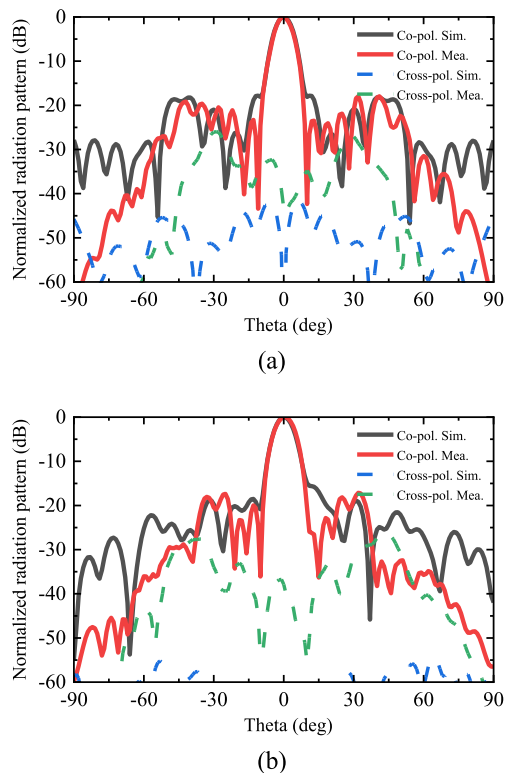


FIGURE 9. Comparison of measured and simulated radiation patterns in transmission mode at 10 GHz. (a) E-plane. (b) H-plane.

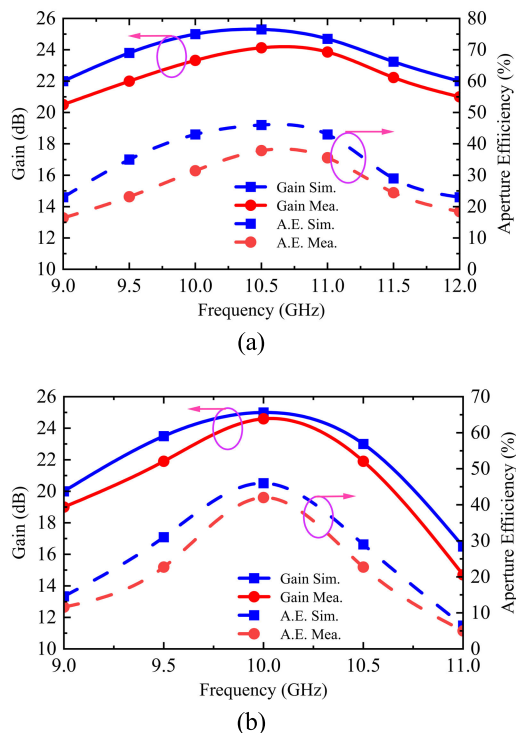


FIGURE 10. The simulated and measured gain and aperture efficiency of the proposed antenna in (a) RA. and (b) TA.

in Table 2. It is found that the profile of the proposed array is lower than the conventional reflect-transmit-array such as [11]. Furthermore, the designed antenna achieves higher

TABLE 2. Comparison between proposed and reported works.

Ref.	Substrate layer	Metal layer	Gain (dBi)	AE (%)	BW (%)	Independent Control
[11]	4	5	R:18.2 T:18.9	R:27 T:21.2	R:14 T:8.4	Yes (Freq.)
[14]	0	1	R:25 T:25.5	R:14 T:15	R:14 T:15	No
[15]	1	1	R:17.2 T:15.4	R:8.2 T:5.4	R:19 T:22	No
This work	1	2	R:24.2 T:24.6	R:38 T:42	R:17 T:6	Yes (Pol.)

aperture efficiency. It's noted that the proposed antenna has more flexible beam control capabilities, based on the direction of polarization, than other low profile reflect-transmit-array. Therefore, it will satisfy the bifunctional operation in modern communication systems.

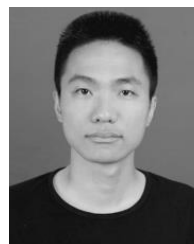
IV. CONCLUSION

In this paper, a low-profile multifunctional space-fed planar array antenna is presented by introducing a novel single-layer polarization-dependent element. To analyze the antenna system performances in terms of different modes, a planar array with a 25 cm-diameter circular aperture consisting of 178 elements is designed and tested. The measured results indicate that 1 dB bandwidth of 17% (9.8-11.5 GHz) can be achieved in reflection mode and that the measured peak gain is 24.2 dB. Furthermore, 1 dB bandwidth of 6% (9.7-10.3 GHz) can be achieved in transmission mode, and the measured peak gain is 24.6 dB. In this paper, the operating mode of the proposed array can be shifted among reflection mode, reflection-transmission mode, as well as transmission mode by rotating the feed horn. Furthermore, If the proposed array is illuminated by a dual-polarized feed, the reflect-transmit-array antenna will be able to automatically change modes. Besides, the low-profile antenna is promising for modern wireless communication systems because of its low cost and multifunctionality.

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