Dual-Polarized 2D Beam-Scanning Antenna Based on Reconfigurable Reflective Elements

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Abstract: In this paper, a dual-polarized antenna operating at 3.5 GHz is presented with 2D beam-scanning performance. The steerable beam is realized based on a 2×2 active reflective metasurface. The active metasurface is composed of folded annular rings and cross dipoles embedded with voltage-controlled varactor diodes. By tuning the capacitance values of the varactors, the reflective phase of the metasurface is reconfigured to tilt the main beam. To verify the scanning performance, a prototype is fabricated and measured. At 3.5 GHz, the measured scanning ranges are from −25° to 29° and −27° to 29° in the *XOZ* and *YOZ* planes, respectively.

Keywords: dual-polarized antenna; reflective metasurface; 2D beam scanning; varactor diode

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1 Introduction

Beam-scanning antennas have been attracting the interest of investigators for a long time. They have been widely adopted in modern wireless communication systems due to their remarkable ability to balance the requirements of gain and coverage. Compared with omnidirectional antennas, they can obtain a higher gain in a certain desired direction and suppress the interference between neighbor cells. Meanwhile, a steerable beam is capable of satisfying the dynamic distributions of users by time and space. Therefore, numerous ideas about beam-scanning antennas have been proposed.

Among the feasible designs, beam-scanning antennas based on metasurface have attracted great interest from investigators due to the characteristics of light weight, low cost, and ease of fabrication. A mechanical beam-steering antenna using a single-layer passive frequency selective surface (FSS) was presented in Ref. [1], achieving a scanning range of −30° to 30° in the elevation plane via FSS rotation. By applying a Positive-Intrinsic-Negative Diode (PIN)-loaded active metasurface over the square patch antenna[2], the main beam could be switched from −30° to 30° with a faster response. In Ref. [3], a 1D beam-switching antenna was proposed based on a PIN-loaded reflector. The maximum tilting angle is 30° by controlling the states of diodes. In Ref. [4], a 2D beam-switching antenna was presented at 5.5 GHz based on a 6×6 reconfigurable partially reflective surface (PRS). By controlling the states of PIN diodes in different sections of PRS, a ±47° beam switch could be achieved in the azimuth plane. Based on the cylindrical metasurface surrounding an active dipole, a 360° beam horizontal sweeping and a discrete elevation switching between −22° and 22° were achieved in Ref. [5]. To achieve continuous beam scanning, a novel phased array was proposed in Ref. [6] for 5G millimeter-wave wireless communications. Different from the traditional phased arrays that employ phase shifters to electronically control the beam direction, the ±60° scanning beam was realized based on a 256-element active electromagnetic (EM) surface fed by a horn.

Likewise, a 196-element reflective metasurface in Ref. [7] was used to change the beam direction of an antenna, which enabled continuous beam scanning within ±20° by controlling PIN diodes loaded on phase delay lines. In Ref. [8], a varactor-controlled reflective metasurface fed by a monopole was designed to steer the beam within ± 50° in elevation directions

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in a single polarization. For dual-polarized use, Ref. [9] proposed a beam-scanning cross dipole antenna loaded with an active reflective metasurface with fewer component counts, achieving ±20° beaming scanning via varactor reconfiguration.

In this paper, a beam-scanning antenna is presented based on a 2×2 active reflective metasurface. For dual-polarization use, the surface is excited by a printed cross dipole. By tuning the voltages applied across the varactors, the reflective phases of the elements can be reconfigured thus deflecting the beam direction in the *XOZ* and *YOZ* planes.

2 Design of Beam-Scanning Antenna

2.1 Reconfigurable Reflective Element

The proposed reconfigurable reflective element is illustrated in Fig. 1. The element consists of two Rogers RO4003 dielectric substrates (ε_r=3.55, tanδ = 0.002 7) with a 6 mm thick air spacing between them. A cross and a cross-shaped ring are separately printed on the top and bottom sides of the upper dielectric substrate with a thickness of 0.508 mm. Four varactors are embedded in the cross to adjust the equivalent electrical length of the cross strips. The capacitance values of the four varactors are equal to C_1. As a result, the resonance frequency of the cross is tunable with the varactor value C_1 changing. Four inductors and metal vias are used to connect the cross strips to the cross-shaped folded annular ring. Compared to a square ring, the cross-shaped design lengthens the path of the surface current without expanding the transversal dimensions. The ground plane is designed on the top side of the substrate with a thickness of 0.813 mm. The element features a symmetric structure for polarization-insensitive frequency response.

The proposed reflective element is modeled in the High-Frequency Structure Simulator (HFSS) and simulated with periodic boundaries. According to the parameters of Skyworks SMV1430 varactor diodes, the varactors are modeled as a tunable capacitor in series with a 3 Ω resistor and a 0.45 nH inductor. Fig. 2 shows the simulated results of the reflective amplitude and phase response. A smooth reflective phase response is observed from 2.5 GHz to 4.5 GHz. When the capacitance value C_1 changes from 0.31 pF to 1.1 pF, the phase curve moves to a lower band thus changing the reflective phase in the operated band. In other words, there is a phase shifting between the reflected and incident waves due to the phase compensation by the element. As Fig. 2 shows, the phase shifting at 3.5 GHz is about 214° with a reflective amplitude no lower than −2 dB. The cross-polarization component of the reflected wave remains below −27 dB.

2.2 Beam Steering Antenna Design

To operate the varactors, the DC bias circuit is designed as shown in Fig. 3. The varactor anodes loaded on each element are connected via the cross strip. A central grounding metal

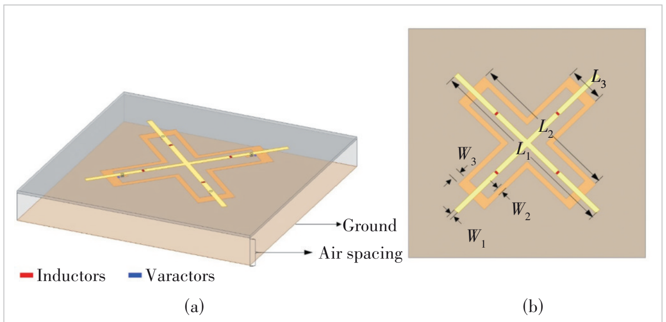


Figure 1. Geometry of the proposed reconfigurable reflective element: (a) 3D view; (b) top view (L_1=38.5 mm, L_2=30 mm, L_3=7 mm, W_1=1 mm, W_2=1 mm, and W_3=2 mm)

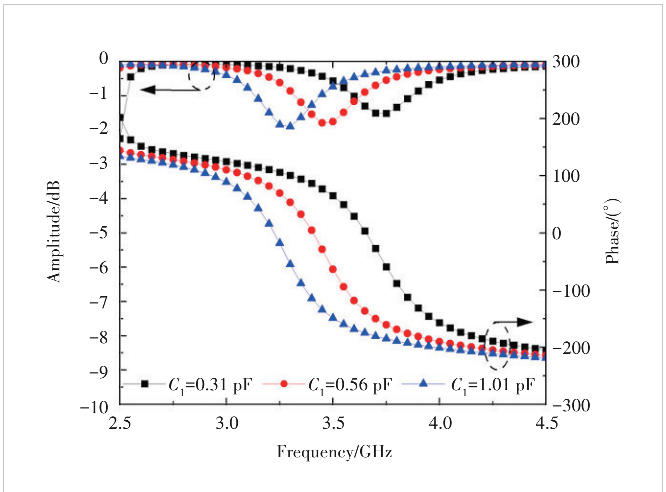


Figure 2. Reflective amplitude and phase response versus frequencies at different capacitance values of each varactor

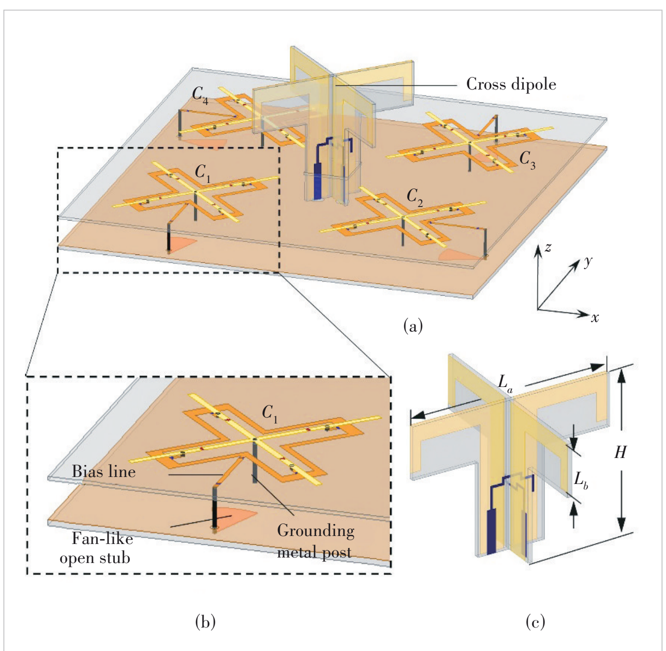


Figure 3. Geometry of the proposed antenna: (a) 3D view; (b) structure of bias circuit for varactors; (c) printed cross dipole

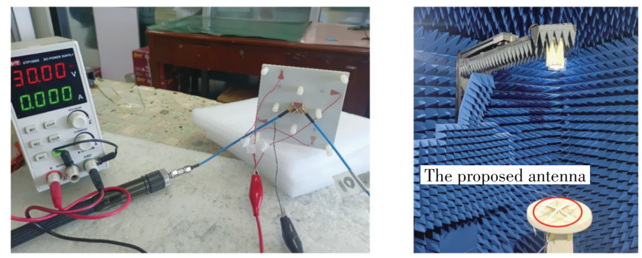
post with a diameter of 0.6 mm sets the anode potential to zero. The cathodes of the varactor diodes are connected by the cross-shaped ring to share a common biasing point. Another metal post is designed through the ground plane at a distance of 17.9 mm away from the grounding post. A hole is etched on the ground plane to isolate metal posts from the ground plane. At the bottom end of the post, a fan-like open stub acts as a low-pass filter for isolating the RF signal from the DC bias signal. Together with the post, the bias line stretching from the cross-shaped ring is designed to offer positive electrical potential to the cathodes of the diodes. As a result, the four shunt diodes are reverse biased with the same capacitance value.

To achieve a 2D scanning beam, the proposed element is arranged along the x and y directions to form a 2×2 reflective surface. A printed cross dipole operating at 3.5 GHz radiates ±45° polarization electromagnetic waves and feeds the surface. The four elements are set surrounding the cross dipole and share a common ground. Fig. 3 shows that the bias structures of the elements are designed in central symmetry. The overall size of the proposed antenna is about $1.05\lambda_0 \times 1.05\lambda_0 \times 0.3\lambda_0$, where λ_0 is the 3.5 GHz free-space wavelength. The capacitance values of different elements are C_1, C_2, C_3, and C_4 respectively (Fig. 3). Therefore, four independent DC bias voltages are needed. When the bias voltage applied across the varactors of each element varies, the re-radiating phase of the reflective element is changed. According to the in-phase superposition principle, the wavefront will incline thus letting the beam squint. In summary, beam scanning can be achieved by tuning the bias voltages of the reflective surface.

3 Simulation and Measurement Results

The proposed antenna is simulated, fabricated, and measured to further verify its scanning performance, as shown in Fig. 4. Nylon support components are used to obtain a 6 mm thick air spacing between the reflective surface and the common ground. The desired values of C_1, C_2, C_3, and C_4 are controlled by corresponding voltages U_1, U_2, U_3, and U_4. The proposed antenna is simulated and measured at five states as listed in Table 1.

Fig. 5 shows the simulated and measured S parameters for different states. Within the operated band from 3.4 GHz to 3.6 GHz, the measured S_{11} values are less than −11.0 dB, while the simulated S_{11} is less than −11.2 dB.



(a) (b)

Figure 4. Fabricated antenna prototype under measurements: (a) *S* parameter measurement setup and (b) radiation pattern measurement setup

Table 1. Beam states of the proposed antenna and the setup of varactors

Beam State	Varactor Capacitance/pF				Varactor Biasing Voltage/V			
	C_1	C_2	C_3	C_4	U_1	U_2	U_3	U_4
I	0.31	0.31	0.31	0.31	30	30	30	30
II	0.31	1.10	1.10	0.31	30	0	0	30
III	1.10	0.31	0.31	1.10	0	30	30	0
IV	0.31	0.31	1.10	1.10	30	30	0	0
V	1.10	1.10	0.31	0.31	0	0	30	30

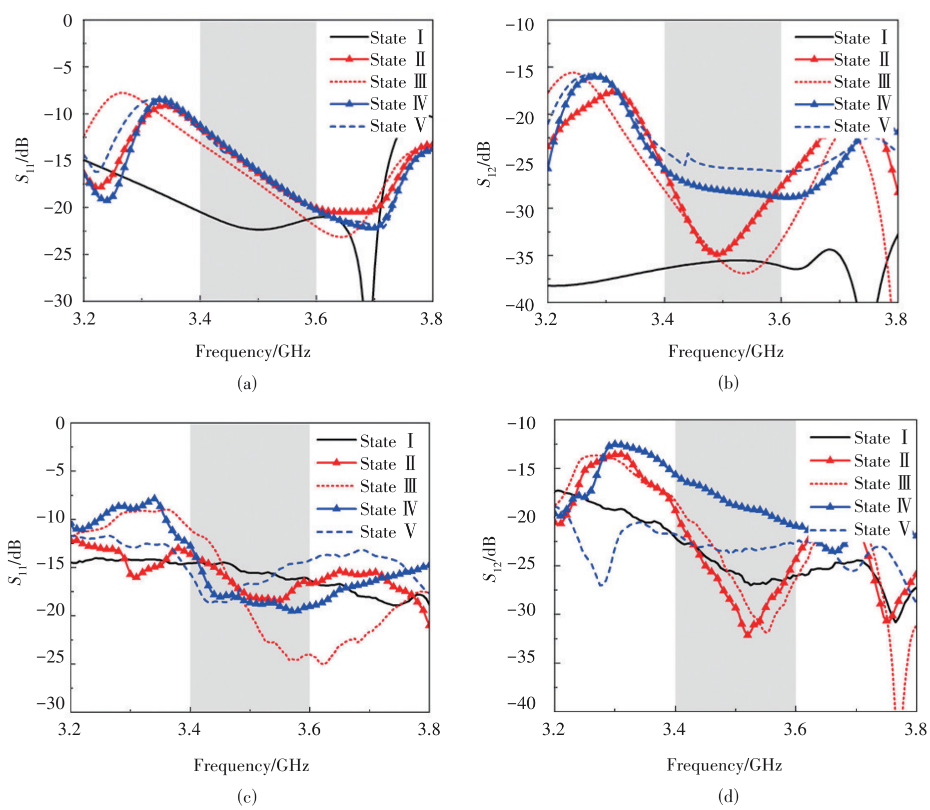


Figure 5. *S* parameters at different beam states: (a) simulated S_{11}; (b) simulated S_{12}; (c) measured S_{11}; (d) measured S_{12}

The measured S_{12} is less than −15.6 dB, while the simulated S_{12} is less than −23.8 dB.

The radiation patterns for various steering states were measured using a near-field antenna measurement system in an anechoic chamber. Fig. 6 shows the simulated and measured radiation patterns for 45° polarization in both the *XOZ* and *YOZ* planes when Port 1 is excited. By reconfiguring the bias voltages, the main beam can be deflected as anticipated.

When all bias voltages are set to 30 V, the main beam points directly upwards without beam steering, corresponding to State I. By adjusting U_2 and U_3 to 0 V, the measured steering angle at 3.5 GHz is −25°, which corresponds to State II. When bias voltages U_1 and U_4 are tuned to 0 V, while U_2 and U_3 remain at 30 V, the antenna operates in State III with a steering angle of 29° in the *XOZ* plane. Similarly, when the bias voltages are configured for States IV and V, the maximum scanning range in the *YOZ* plane spans from −27° to 29°. The measured results align well with the simulated ones, indicating the accuracy and reliability of the proposed antenna design.

4 Conclusions

In this paper, a continuous beam steering antenna based on the 2×2 active reflective metasurface is modeled and fabricated. By changing the voltages applied on the active reflective metasurface, the proposed antenna can steer the beam in both the *XOZ* and *YOZ* planes in the frequency range of 3.4 – 3.6 GHz. The measured reflection coefficient is less than −10 dB and the port isolation is greater than 15 dB. The measured scanning ranges are −25° to 29° and −27° to 29° in the *XOZ* and *YOZ* planes, respectively. The antenna is a good candidate for application to beam reconfigurable communication systems.

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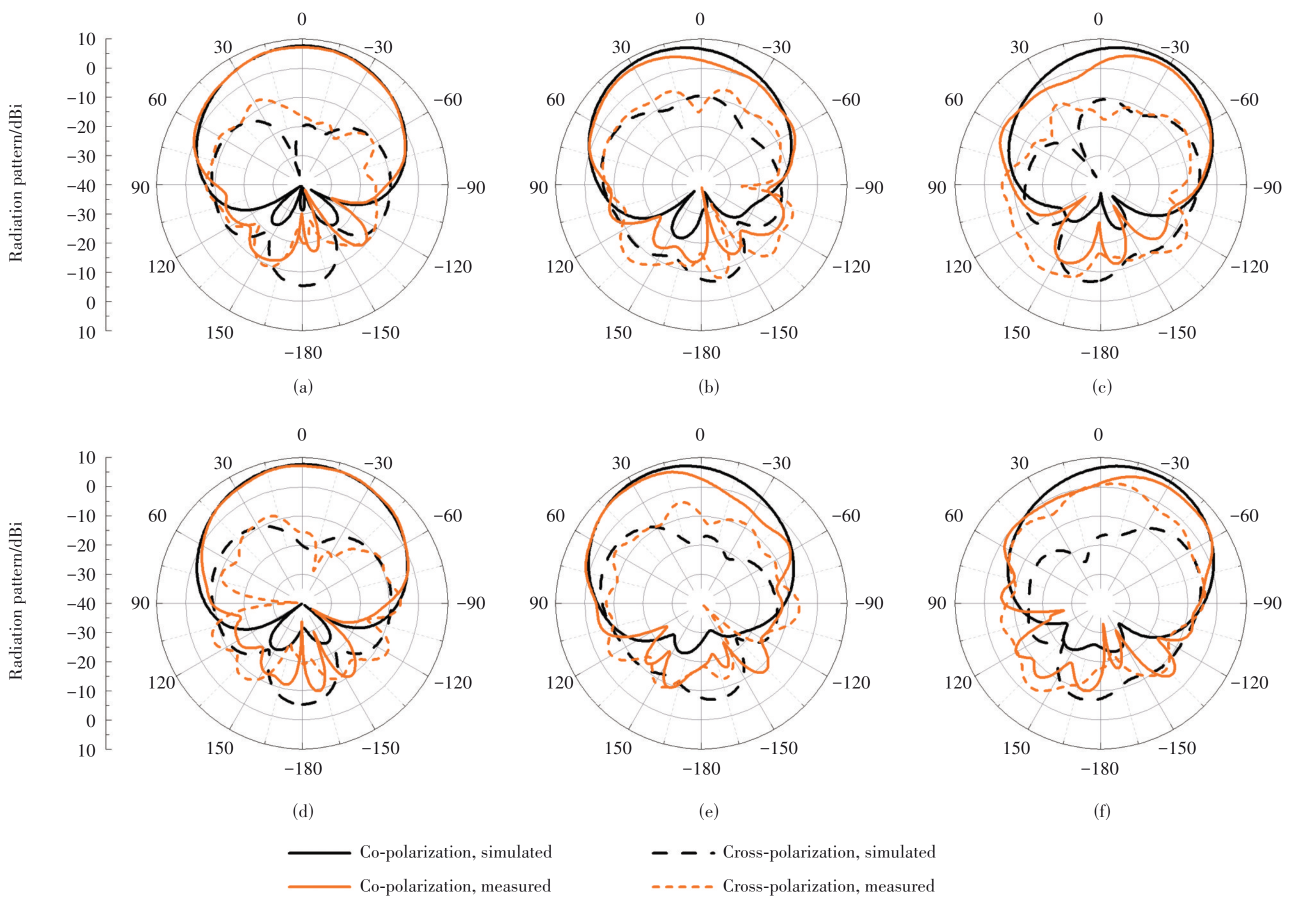

Figure 6. Radiation patterns of different beam states: (a) State Ⅰ in the *XOZ* plane; (b) State Ⅱ in the *XOZ* plane; (c) State Ⅲ in the *XOZ* plane; (d) State Ⅰ in the *YOZ* plane; (e) State Ⅳ in the *YOZ* plane; (f) State Ⅴ in the *YOZ* plane

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Biographies

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