Single Layer Transmit-array with Beam-Steering and Polarization Switching

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Abstract **─** In this paper, a single layer multi-polarization transmit-array operating at C-Band is designed using ring groove with a single split as the element. The rotational orientation of each element can provide the required phase shift. The elements have identical dimensions, but the rotational orientation of each element is selected to provide a specific transmit-array function. The transmit-array has three working conditions which can change the polarization of the incident wave and set separation beam direction at the same time. The thin single-layer transmit-array without dielectric substrate is designed, simulated and measured based on a horn antenna. The measurement result shows that the transmit-array can switch the linear polarization incident wave to left-circularly polarized wave and right-handed circular polarized wave with separation beam of ± 30 azimuth angles separately. The measured results are in agreement with the theoretical and simulation results.

Index Terms **─** Beam steering, phase modulation, polarization switching, transmit-arrays.

I. INTRODUCTION

In the last few years, a kind of transmit-array [1-3] has attracted much attention in millimeter-wave applications. There are two types of transmit-array: one is based on them M-FSS structure [4, 5], the other one is based on the reception–transmission structure [6, 7]. Some of the current phased transmit-array research is directed towards optimization of individual phasw1e-agile elements for beam-forming antennas. The appropriated phase shift of each element creates a phase distribution across the elements of the array. This distribution of phase shift has a lensing effect if it approximates the propagation delay. Transmit-array allows the use of large feed antennas or multiple feeds without compromising the radiation aperture compared to reflect-arrays.

At present, many metamaterial antennas with bandwidth and beam tunability have been studied [8-10]. Luo et al. report a microelectromechanical system (MEMS)-modulated scanning beam metamaterial antenna based on surface micromachining process [11]. The antenna is implemented by cascading periodical metamaterial modules to make an electromagnetically homogeneous waveguide, of which the MEMS cantilevers are monolithically integrated in each unit as a radio frequency (RF) switch to modulate the phase constant, and thereby to realize the scanning beams in the fixed frequency around 8GHz. Ke et al. report a leaky-wave antenna working 9.1GHz with programmable beam scanning [12]. The leaky-wave antenna is orthogonally arranged and composed of sixteen metallic J-shaped units in the composite right-left handed (CRLH) formation to obtain tunable metamaterial properties programmable radiation patterns. The radiation patterns can be changed by controlling gap's state with open or close.

Most of the planar air-fed transmit-array antenna adopts multi-layer frequency select surface (M-FSS) element structure. In 2011, Rudi et al. [2] adopted rectangular patch and cross dipole structure as a transmit-array element, compensated phase by rotating the array element, designed a five-layer planar air-fed transmit-array antenna work at 12.4GHz. The transmit-array antenna contains 349 transmission elements, which is designed to collimate the radiation from a feed horn into a beam pointing 20˚ from broadside. In 2014, Yang Fan designed a three-layer planar air-fed transmit-array antenna in *x*-band, using swasti-type transmission array element. The insertion loss of the transmit-array element in the working band is always higher than 4.2dB. The

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element can realize the transmission phase shift of 360 degree, and the transmit-array antenna has the advantages of high gain and wide band [5].

The multilayer transmit-array antenna has the disadvantage of complex array structure, the high profile and poor transmission performance, so reducing the antenna's vertical profile is an important development direction.

In this paper, a single layer transmit-array is presented to improve the complex structure of traditional multiple layers transmit-array. The single-layer metal transmit-array without dielectric substrate is designed, which is consists of ring groove with a single split. The rotational orientation of each element can provide the required phase shift. The transmit-array effect is created by the phase shifters, which collimate radiation from the feed and steer the resulting beam in the desired direction. The transmit-array is designed to work in three polarized situations: under the linear-polarization (LP), left-hand-circular-polarized (LHCP) and right-hand-circular-polarized (RHCP). When the transmit-array is placed at the front of the transmitting antenna, it can change the polarization of the incident wave and set separation beam direction at the same time, which can achieve the application of split beam detection and polarization conversion. When the transmit-array is placed at the front of the receiving antenna, the beam of the incident waves is separated as it passes through the transmit-array, that achieve low scattering. This transmit-array can be widely used and developed in detection systems of electronic warfare.

II. DESIGN PRINCIPLES AND METHODS

A. Scattering parameters of rotated element

The reflection and transmission properties of this transmit-array can be represented as a scattering matrix. When the elements are rotated with the z-axis by an angle ψ, scattering matrix can be defined as equation (1) and equation (2), which relates circularly polarized wave modes [2]:

$$B^{CP} = S_{\psi}^{CP} A^{CP}, \tag{1}$$

$$\begin{bmatrix} b_1^l \\ b_1^r \\ b_2^r \\ b_2^l \end{bmatrix} = \begin{bmatrix} S_{11}^{lr} & S_{11}^{ll} & S_{12}^{ll} & S_{12}^{lr} \\ S_{11}^{rr} & S_{11}^{rl} & S_{12}^{rl} & S_{12}^{rr} \\ S_{21}^{rr} & S_{21}^{rl} & S_{22}^{rl} & S_{22}^{rr} \\ S_{21}^{lr} & S_{21}^{ll} & S_{22}^{ll} & S_{22}^{lr} \end{bmatrix} \begin{bmatrix} a_1^r \\ a_1^l \\ a_2^l \\ a_2^r \end{bmatrix}. \tag{2}$$

The vector components are labeled with a superscript that indicates the hand of polarization: *l* indicates left-hand circular polarization (LCP) and *r* indicates right-hand circular polarization (RCP). The superscript and subscript of each CP scattering parameter are labeled in order: for example, S_{12}^{rl} relates the right-hand component scattered at Port 1 to the left-hand component incident on Port 2.

The scattering matrix for linearly polarized modes can be transformed into the matrix for circularly polarized modes by:

$$S_{\psi}^{CP} = [T^{XY\to CP}][S_{\psi}^{XY}][T^{XY\to CP}]^{-1}, \tag{3}$$

where $T^{XY\to CP}$ is the coordinate transformation from cartesian to circular element vectors:

$$T^{XY\to CP} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -j & 0 & 0 \\ 1 & j & 0 & 0 \\ 0 & 0 & 1 & -j \\ 0 & 0 & 1 & j \end{bmatrix}. \tag{4}$$

The values of each CP scattering parameter are determined:

$$\begin{aligned} S_{11}^{lr} &= S_{11}^{rl} = S_{22}^{rl} = S_{22}^{lr} = \frac{1}{2}(\Gamma_x + \Gamma_y) \\ S_{12}^{ll} &= S_{12}^{rr} = S_{21}^{rr} = S_{21}^{ll} = \frac{1}{2}(T_x + T_y) \\ S_{11}^{rr} &= S_{22}^{ll} = \frac{1}{2}(\Gamma_x - \Gamma_y)e^{+j2\psi} \\ S_{11}^{ll} &= S_{22}^{rr} = \frac{1}{2}(\Gamma_x - \Gamma_y)e^{-j2\psi} \\ S_{12}^{rl} &= S_{21}^{lr} = \frac{1}{2}(T_x - T_y)e^{+j2\psi} \\ S_{12}^{lr} &= S_{21}^{rl} = \frac{1}{2}(T_x - T_y)e^{-j2\psi} \end{aligned}, \tag{5}$$

where Γ_x and Γ_y are the reflection coefficients to x- and y-polarized waves, T_x and T_y are the transmission coefficients.

Note that the above formulas indicate that when the elemental antenna is rotated, four of the above parameters are phase advanced by twice the rotation angle, four are phase delayed by twice the rotation angle, and eight remain unchanged. The phase shifted components are all due to the polarization anisotropy of the element, they are proportional to the difference between Γ_x and Γ_y, or T_x and T_y.

When the designed transmit-array working under the LP waves, the prototype is designed to split an incident wave into left and right circularly polarized wave. The effect is similar to a Wollaston prism, which separates an incident wave into two linearly polarized beams. The transmit-array decomposes an incident wave into its CP components and redirects the power from each component into two separate beams. The prism effect occurs because S_{21}^{lr} and S_{21}^{rl} have equal magnitudes but opposite phase shifts. However, the gradient will have opposite signs for the scattered fields associated with S_{21}^{lr} and S_{21}^{rl}. When LCP and RCP modes are incident from the same direction, they will scatter into two beams in different directions. Fields scattered in the negative beam are mostly associated with the S_{21}^{lr} parameter; fields in the positive beam are mostly associated with the S_{21}^{rl} parameter. The phase of eight parameters are unaffected by element rotation and the fields they scatter will always form beams in the same direction. Ray diagrams associated with these four scattering parameters are shown in Fig. 1.

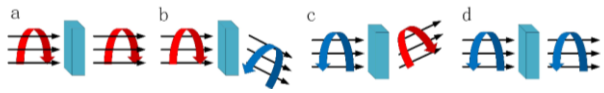

Fig. 1. Ray diagram representation of the waves transmitted through a array configured to split circular polarization. Scattering associated with: (a) $S_{21}{}^{rr}$, (b) $S_{21}{}^{rl}$, (c) $S_{21}{}^{lr}$, and (d) $S_{21}{}^{ll}$.

B. Ideal phase-shifting element

When the line polarization wave propagates along the -*z* direction, the main polarization direction is along the *x*-axis direction so that the linear polarization incident wave can be expressed as [6]:

$$\overrightarrow{E_1} = E_0 e^{jkz} \cdot \hat{u}_x . \tag{6}$$

For the transmit-array, when the antenna element is rotated ψ by the *z* axis, the vector equation of the transmission beam is changed:

$$\overrightarrow{E_t} = \frac{1}{2} E_0 e^{jkz} [e^{j2\psi} (T_x - T_y) \hat{u}_x) + (T_x + T_y) \hat{u}_x] . \tag{7}$$

As shown in equation (7), the transmission beam consists of two linear polarized wave components. The first part is composed of the linear polarized wave with the phase advance twice of the element rotation Angle(ψ), the second part is the linear polarization wave with the phase independent of the rotation Angle(ψ). The design goal of transmit-array is transforming the linear polarization incident wave to the left and right circular polarization beam. Therefore, it is necessary to divide the transmission array into two parts; the phase compensation is respectively carried out with the center line of the array as the axis of symmetry. When the counter-clockwise rotation is set to the positive direction for phase compensation at the right side of the array, the transmission beam can be expressed as:

$$\overrightarrow{E_t} = \frac{1}{2} E_0 e^{jkz} [e^{j2\psi} (T_y - T_x) j\hat{u}_y) + (T_y + T_x) j u_y] . \tag{8}$$

Add the equation (7) to the equation (8), the transmitted beam after superposition can be expressed as:

$$\overrightarrow{E_t} = \frac{1}{2} E_0 e^{jkz} [e^{j2\psi} (T_x - T_y)(\hat{u}_x - j\hat{u}_y) + (T_x + T_y)(\hat{u}_x + j\hat{u}_y)]. \tag{9}$$

As shown in equation (9), the transmission beam consists of two circular polarized wave components. The first part is located in the left half of the array, which is composed of left-circularly polarized waves with the phase advance twice of the element rotation Angle(ψ), The second part is located in the right half of the transmit-array, which is composed of right-circular polarization wave with the phase independent of the rotation Angle(ψ). To make the beam amplitude of the left and right circularly polarized wave closed, the array element should satisfy the following formula:

$$T_x \gg T_y . \tag{10}$$

For the beam separation transmit-array, using the rotary phase modulation technique, the transmit-array element needs to meet the requirements of a high insertion loss in *x*-axis polarization direction and low insertion loss in the direction of *y*-axis polarization. The change of element transmission phase is not twice as much as the element rotation angle, the rotation angle of each array element needs to be calculated separately.

III. DESIGN OF THE SPLIT RING ELEMENT AND TRANSMIT-ARRAY

The conceptual model diagram of planar air-fed transmit-array antenna is shown in Fig. 2 (a). The whole antenna system is illuminated by a focal source such as horn antenna. In this paper, the horn antenna is used as the feed antenna.

The feed antenna is located on the focus of the single layer transmit-array. The transmit-array is made of numerous split ring elements with variable rotation angles, as shown in Fig. 2 (a). The focal length ratio of the feed antenna in this paper is 0.8. The transmit-array element is single-layer pure metal structure. It is investigated in the C-band and can split an incident wave according to its circular polarization components. The effect of this transmit-array antenna is similar to the Wollaston prism, that a Wollaston prism divides an incident wave into two linearly polarized beams [2].

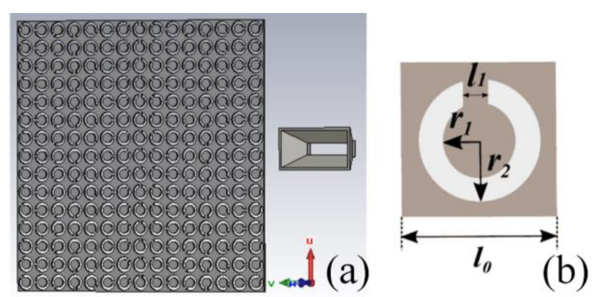

Fig. 2 (a) Conceptual model diagram of transmit-array and (b) the details of ring groove with a single split. (structure parameters: l_0=15 mm, r_2=6mm, r_1=4mm, and l_1=2mm).

A. Design of the transmit-array element

The transmission coefficients of these elements are individually designed so that the spherical phase front from the feed source is converted into a planar phase front [2]. Each element needs to satisfy the requirements of total transmission and phase compensation. In this paper, a single layer transmission element is presented, which is shown in Fig. 2 (b). The element is a square structure, the gray part of the element is copper, and the white part is a hollowed-out split ring made of air. The element is made of pure perforated metal without dielectric substrate. The array of the pure copper structure has strong structural strength and can adapt to engineering application. The element thickness is 1 mm.

The element of ring groove with a single split mentioned above was designed to work at C-band and simulated by full-wave simulations. The simulated scattering parameter of the element is shown in Fig. 3 (a). Figure 3 (b) shows that the insertion loss of the element in the *x*-axis polarization direction is close to 0 near the 5GHz, the transmission performance is ideal. The insertion loss of the element in the *y*-axis polarization direction at 5GHz is below -10db, the transmission performance is poor, which meet the equation (10).

Figure 3 (c) shows the simulation result of the transmission phase and phase difference of the single layer element in the x-axis and y-axis. The transmission phase difference of the element in the *x*-axis and *y*-axis is about 90 degrees at 5GHz. In the frequency range of 0~9GHz, the maximum difference of transmission phase between the two orthogonal directions of x axis and y axis is 142 degrees. The transmission phase of the transmit-array element in the orthogonal directions of x and y axes does not need to satisfy the phase difference of 180 degrees. Figure 3 (d) shows the relationship between element rotation angle and the change of phase. In the subsequent transmit-array design, this relationship is used to determine the rotation angle of the element.

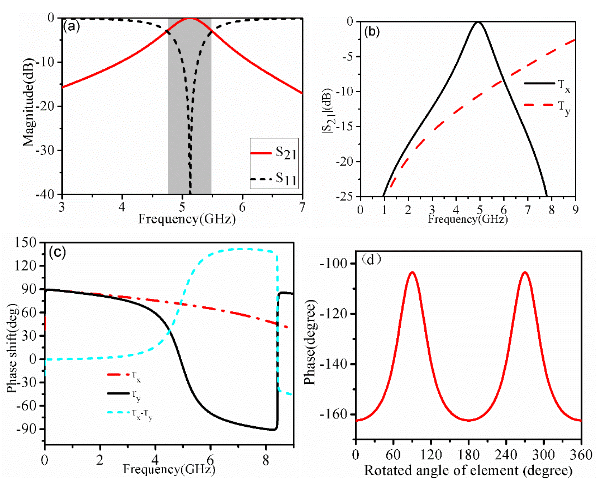

Fig. 3. (a) The scattering parameter of the element, (b) insertion loss of the element in the direction of the orthogonal polarization, (c) the transmission phase and phase difference of the element in the orthogonal direction, and (d) relationship between element rotation angle and the change of phase.

B. Design of transmit-array

After satisfying the requirement of transmission, the requirement of phase compensation needs to be met simultaneously. It is well known that the wave radiated by a horn antenna can be nearly regarded as a spherical wave [13]. When the spherical wave passes through the transmit-array, each element in the array should have phase modulation to make up for the presence of the optical path difference. The sequential rotation technique [4] is used to compensate phase for each element in the transmit-array.

The geometry of the single-layer transmit-array is shown in Fig. 4 (b). When the spacing of elements is less than one half wavelength, the mutual coupling effect between elements is strong, the overall performance of the antenna is greatly affected. When the element spacing is too large, the main lobe decreases and the sidelobe increases. In general, when l_0 stands for the cycle length of the elements, and the α represents the angle between the main beam and the vertical direction, the cycle length of the elements should be satisfied: $0.5\lambda < l_0 < \lambda/(1+\sin\alpha)$. In this paper, $l_0=0.6\lambda$ is selected as the element spacing for this transmit-array.

The left and right sides of transmit-array are completely symmetric, No. 8 of transmit-array is the symmetric center line. It contains 225 elements, and their phase shift distribution is provided by the rotation. The prism effect occurs because the transmission waves have equal magnitudes but opposite phase shifts [5]. The left side elements of the transmit-array are rotated clockwise, and the right ones are counterclockwise.

Assume that the focal length is *f*, the cross slot at the position coordinate (*x*, *y*) needs to be rotated by an angle $\psi(x,y)$ relative to the central ones[14-18]. Element rotations are set according to:

$$\psi(x,y) = -\frac{1}{2}kx\sin 30^{\circ}. \tag{11}$$

The rotated angle of each element is shown in Fig. 4 (a).

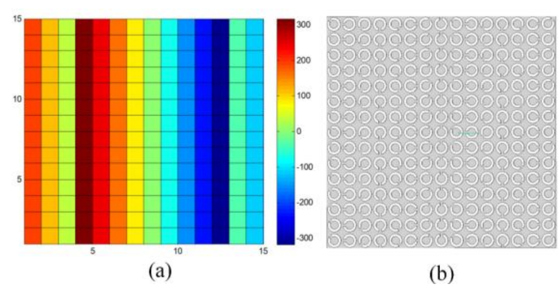

Fig. 4. (a) Rotated angle of each element and (b) Schematic diagram of transmit-array.

C. Function of designed beam array antenna

The transmit-array achieves not only polarization switching but also beam-steering. Electronic beam steering can be obtained by changing the phase distribution on the transmit-array [6]. The elements phase on both sides of the symmetry axis are adjusted independently, correction of transmission phase delay, compensate the space phase difference of the elements, the electromagnetic waves could combine in two directions, so the separation beam is obtained in two directions.

When setting clockwise direction as the positive direction of element phase compensation, the polarization conversion array obtained by the phase compensation in a clockwise direction can only be applied to the right-handed circular polarized feed antenna. Set the counterclockwise direction as the positive direction of element phase compensation, the polarization conversion array obtained by the phase compensation in counterclockwise direction can convert the left-circularly polarized incident wave into the right circular polarized wave. Therefore, the transmit-array is divided into two parts: the left half is set clockwise as the positive direction of phase compensation, the right side is set counterclockwise as the positive direction of phase compensation.

When the waves pass through the transmit-array, the polarization of the incident wave will be changed: from LHCP to RHCP, RHCP to LHCP, LP to LHCP and RHCP. When working under the LP wave, the incident wave will scatter into two beams as LHCP and RHCP sat ± 30 azimuth angles, as shown in Fig. 5 (a); When working under the LHCP wave, the incident wave will scatter into two RHCP wave sat ± 15 azimuth angles, as shown in Fig. 5 (b); When working under the RHCP wave, the incident wave will scatter into two LHCP wave sat ± 15 azimuth angles, as shown in Fig. 5 (c). The measured radiation patterns are compared later.

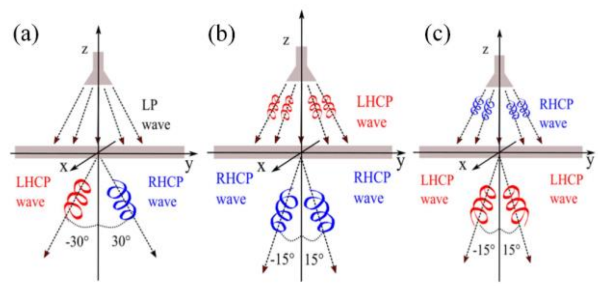

Fig. 5. Operating mode under the: (a) LP, (b) LHCP, and (c) RHCP horn antenna.

IV. SIMULATION AND MEASUREMENT OF THE TRANSMIT-ARRAY

A. Simulation of the transmit-array

Firstly, the operation of the transmit-array under the LP horn antenna is simulated by full-wave simulations. As a focal source with a gain of 12.15 dBi, a WR-187 standard waveguide horn is placed above the transmit-array [19-20]. The focal distance F is 468 mm (F/D = 0.8, Fig. 2) as a tradeoff between the spillover and taper efficiencies. The center frequency of the LP horn antenna is 5GHz. The simulated radiation pattern of the transmit-array is shown in Fig. 6 (a). It is easy to see that the incident wave is divided into two transmission waves: LHCP at +30 azimuth angle and RHCP at -30 azimuth angle. The radiation mode with transmit-array is almost RHCP, and the major lobe points to the desired direction.

Secondly, the second working state is simulated the focal source is a 12.0 dBi right-handed circularly polarized conical horn. The focal distance F is as same as the previous one. The simulated radiation pattern of the transmit-array under the RHCP horn antenna is shown in Fig. 6 (b). The incident wave was divided into two LHCP transmission waves at ±15 azimuth angles. The radiation mode with the transmit-array is almost LHCP, and the major lobe points to the desired direction.

The simulated radiation pattern of the transmit-array under the LHCP horn antenna is shown in Fig. 6 (c), which is rather similar to the result of the RHCP horn antenna used as the feed source, except for the direction of polarization.

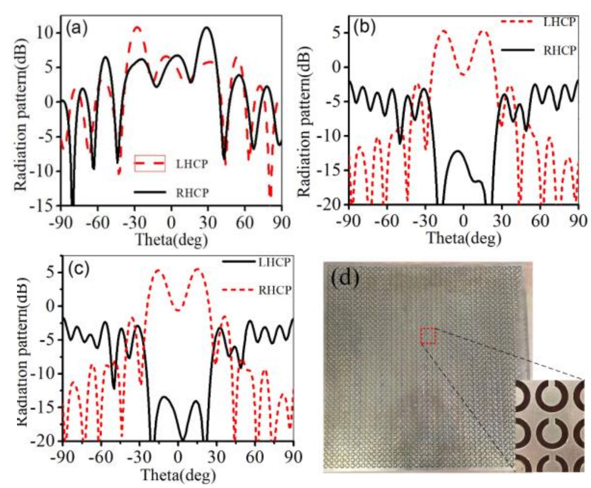

Fig. 6. (a) The simulated radiation pattern of the transmit-array under the LP horn, (b) the simulated radiation pattern of the transmit-array under the RHCP horn, (c) the simulated radiation pattern of the transmit-array under the LHCP horn, and (d) the physical samples of the transmit-array.

B. Measurement of the transmit-array

The design of the single-layer transmit-array is shown in the Fig. 6 (d). To facilitate the test, the design of the single-layer transmit-array is carried out by the periodic extension, which makes the transverse diameter bigger. The overall size of the antenna array is 525mm * 525mm, which contains 35*35=1225 elements. The transmit-array is made of the brass metal plate by laser cutting.

The overall view of test scenarios in an anechoic chamber is shown in Fig. 7 (a). Due to circular polarization wave can be synthesized by linear polarization wave, only the working condition of the transmit-array under the LP wave has been measured. The designed transmit-array has been placed between the LP horn antenna and the waveguide probe. The LP horn antenna working in the 4-8GHz band has been used as the feed antenna, which is located 420mm away from the transmit-array center. The waveguide probe is placed on a robotic arm that can move up, down, left, and right. Performing near-field scanning measurements on the antenna that loading the transmit-array. Then the scan results can be converted into far-field radiation patterns by near-field scanning system.

The contrast of the measured and radiation pattern is shown in Fig. 7 (b) and Fig. 7 (c). The major lobe points to the desired direction (+30° and -30°) and matches the simulation results. Compared with the simulation results, the measured main lobe has a slight shift that may be caused by machining errors or experimental errors. Despite the presence of the shift, the beam-steering function of the transmit-array is well implemented.

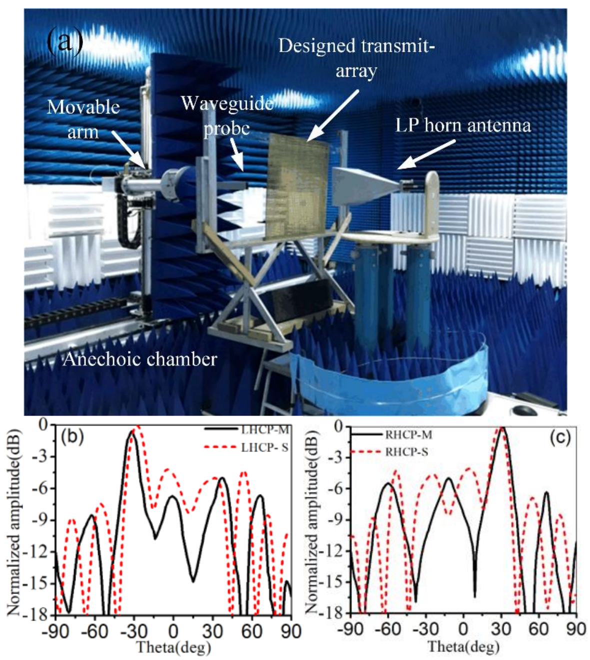

Fig. 7. (a) Overall view in an anechoic chamber, (b) measured and simulated radiation pattern of LHCP, and (c) measured and simulated radiation pattern of RHCP.

To demonstrate the performances of our proposed transmit-array, a comparison with previously published work is shown in Table 1. The transmit-array can change the polarization of the incident wave and set separation beam direction at the same time. The transmit-array has a huge advantage in the number of layers and thickness, which can reduce the disadvantage of complex array structure, the high profile and poor transmission performance.

Table 1: Performance comparison

Ref.	TAF	BSSA	Unit	NL	RS
[2]	PC and BSe	±20°	PRU	5	NO
[3]	PC and BSc	±60°	PDU	4	YES
[7]	Dual-Band Beam-Steering	50°	PDU	7	NO
This work	PC and BSe	±30°	PRU	1	NO

TAF=Transmit-array function, BSSA=Beam separation or scan angle, NL=Number of layers, RS=Reconfigurable situation, PC=Polarization conversion, BSc=beam scanning, BSe=beam separation, PRU=Phase-rotation unit, PDU=Phase-delay unit.

V. CONCLUSION

This paper presents the design and realization of a single layer multi-polarization transmit-array antenna, which is composed of a feed antenna and single layer transmit-array. It overcomes the disadvantages of the multilayer transmit-array antenna about the complex array structure, high profile and poor transmission, which only consists of pure metal transmission type elements according to the sequential rotation technique. It has three working conditions under different polarization of the incident wave, and it can switch the polarization of the incident wave and set separation beam direction at the same time, that can fully adapt to diversified work requirements. The measurement results are in agreement with the theoretical and simulation results.

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