Design of Polarization Reconfigurable Antenna Based on Metasurface

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Abstract—Metasurface has unique electromagnetic characteristics, and the polarization reconfigurable antenna can change its polarization characteristics without changing the operating frequency and radiation pattern. To study the effect of metasurface on the polarization characteristic of electromagnetic waves, a polarization reconfigurable antenna based on metasurface is proposed in this paper. The antenna is composed of metasurface and planar slot antenna, both of which adopt Rogers4350B, with a radius of 39mm, a thickness of 1.524mm, and dielectric constant of 3.48, as the circular dielectric substrate. The metasurface is rotated around the center of the planar slot antenna to reconstruct the metasurface-based antenna into left-handed circular polarization, right-handed circular polarization, and linear polarization antenna. The antenna’s operating frequency is about 4.4GHz, and the operating frequency band (S11<-10dB) is about 3.15GHz-4.47GHz, including 3.6GHz-4.2GHz, the downlink frequency range of satellite communication C band, which is of great significance for research.

Keywords—polarization reconfigurable, metasurface, planar slot antenna

I. INTRODUCTION

Traditional antennas have been unable to meet the needs of more and more advanced communication systems. The proposed "reconfigurable antenna" can integrate multiple antennas or multiple functions in a single antenna, which significantly improves the performance of the antenna[1, 2]. Reconfigurable antennas[3] can be divided into polarization reconfigurable, frequency reconfigurable, and pattern reconfigurable antennas according to their functions. The polarization reconfigurable antenna can change its polarization characteristics without changing the operating frequency and radiation pattern and can also switch between two linear polarizations, two circular polarizations, and between linear and circular polarizations. At present, there are two main ways to realize the reconfiguration of polarization: electrically-controlled adjustment and mechanical adjustment. The former realizes polarization reconfiguration by using radio frequency switching elements such as diodes and PIN tubes, and the latter by adjusting the structure of each antenna component.

The metamaterial is an artificial composite material with unique characteristics that natural materials do not have. The metasurface can be listed as the metamaterial with a two-dimensional structure and is a relatively hot research topic in the field of the antenna. It can combine with the polarization reconfigurable antenna[4, 5] by means of mechanical rotation, avoiding the influence of electronic components on antenna performance and thus can significantly help improve the antenna performance.

Based on previous studies on polarization reconfigurable antennas[1,4-9], this paper proposes a polarization reconfigurable antenna based on metasurface. The influences of the rectangular side length a, the tangent angle radian b, and the metasurface matrix element spacing c on reflection coefficient and axial ratio were analyzed to determine the appropriate size. Then, the performance of the antenna is verified by experimental simulation.

II. ANTENNA DESIGN

A. Structure principle of the antenna

When the metasurface matrix elements have no tangent angle radian, they are symmetric, as shown in Fig. 1. When the metasurface is covered over the planar slot antenna, which is linear polarization, so the electric field vector E can be decomposed into two orthogonal vectors, the orthogonal vectors $E_1$ and $E_2$, which are equal. Hereby the same RLC equivalent circuit can be used. If the magnitudes of $E_1$ and $E_2$ are not equal, the equivalent circuit of the RLC circuit will change.
Equivalent circuit:

\[ Z = 2R + j\omega L + \frac{1}{j\omega C} = R' + jX' \]  

(2 - 1)

Where, \( Z \) represents the impedance, \( L \) is the inductive reactance and \( C \) indicates the capacitance generated by the clearance between two symmetric matrix elements.

When the metasurface matrix elements have a tangent angle radian, as shown in Fig. 2, they are asymmetric, and then the impedances of \( E_1 \) and \( E_2 \) are \( Z_1 \) and \( Z_2 \) of different sizes, respectively:

\[ Z_1 = R'_1 + jX'_1 \]  

(2 - 2)

\[ Z_2 = R'_2 + jX'_2 \]  

(2 - 3)

The tangent angle radian will increase the distance of clearances between two symmetric matrix elements. The increase of \( X'_1 \) will make the inductive reactance of \( Z_1 \) smaller than that of \( Z_2 \). Therefore, we can change the phase difference between \( Z_1 \) and \( Z_2 \) by changing the size of the tangent angle radian. When \( |Z_1| = |Z_2| \), \( \angle Z_1 - \angle Z_2 = 90^\circ \), then \( |E_1| = |E_2|, \angle Z_1 - \angle Z_2 = 90^\circ \), \( E_2 \) is \( 90^\circ \) lagged behind \( E_1 \), and then the electromagnetic wave radiated by the antenna is the left-handed circularly polarized wave. When \( \theta \) is rotated \( 90^\circ \) clockwise, \( X'_2 \) increases, which makes the inductive reactance of \( Z_1 \) larger than that of \( Z_2 \), then \( E_1 \) is \( 90^\circ \) ahead of \( E_2 \), and thus the left-handed circularly polarized wave will become a right-handed circularly polarized wave. When \( \theta \) is rotated clockwise by \( 45^\circ \) or \( 135^\circ \), \( E_1 \) and \( E_2 \) have the same amplitude and phase, and it is a linearly polarized wave.

Form a certain angle by rotating the metasurface of the antenna. That is when \( \theta = 0^\circ \), the antenna is LHCP, and is RHCP when \( \theta = 90^\circ \) and is LP when \( \theta = 45^\circ \) and \( \theta = 135^\circ \).

B. Antenna structure design

In order to facilitate the rotation angle, the whole antenna structure adopts a circular shape. There is a metal rod in the center of the antenna structure, and the metal rod spans the center of the two dielectric layers and the ground plane so that it is relatively fixed, which also improves the accuracy of the rotation angle.

This design needs to rotate the metasurface, so the shape of the overall metasurface patch is designed as a round patch. The back of the circular dielectric substrate at the top is in direct contact with the slot antenna, and the coaxial feeder is adopted.

The geometric structures of the metasurface and the slot antenna in the metasurface polarization reconfigurable antenna are shown in Fig. 3 and Fig. 4, respectively.

![Figure 3. Geometric structure of the metasurface](image)

![Figure 4. Geometric structure of the planar slot antenna](image)

The polarization modes of the antenna at different rotation angles of the metasurface are shown in Fig. 5.

![Figure 5. The polarization modes of the antenna at different rotation angles](image)
Therefore, this communication would concentrate on the elaboration and verification of the proposed approach for realizing a mechanically operated design capable of reconfiguring multiple characteristics of the antenna rather than the design of a new specific structure of MS.

The antenna was designed, simulated, and optimized. Moreover, the influences of the rectangular side length a, the tangent angle radian b, and the metasurface matrix element spacing c on reflection coefficient and axial ratio were analyzed to determine the appropriate size. Choose relatively good parameters, the experimental simulation results of S11, the Axial Ratio, and the gain of E-plane and H-plane are analyzed. In the end, the frequency range and axial ratio characteristics of the metasurface polarization reconfigurable antenna are verified by experimental simulation.

III. SIMULATION RESULTS AND ANALYSIS

The simulation software HFSS was used in this paper to perform the experimental simulation of the metasurface polarization reconfigurable antenna. The S11 reflection coefficients in left-handed and right-handed circular polarization states are shown in Fig. 6 (a). The center frequency is about 4.42GHz, the operating frequency is in the range of 3.15GHz-4.47GHz, the S11 reflection coefficient curves for the left-handed and right-handed circular polarization are nearly identical, and the impedance bandwidth is about 1.32GHz, with the relative bandwidth of 34.6%.

![Reflection Coefficients in LHCP and RHCP Polarization States](image)

(a) Reflection Coefficients in LHCP and RHCP Polarization States

The S11 reflection coefficients of the line polarization after the metasurface rotation of 45° and 135°, respectively, are shown in Fig. 6 (b). The center resonance point of the reflection coefficient is shifted about 3.5 GHz-3.6 GHz after rotating 45 degrees and 135 degrees. The reflection coefficient (S11<-10dB) is about 3.33-4.07 GHz for line polarization after 45 degrees of super-surface rotation and about 3.01-3.78 GHz for line polarization after 135 degrees of rotation. The resonant frequencies of the two centers are shifted, but the frequency bandwidth is almost the same, about 0.75 GHz.
The influences of changes in antenna parameters $a$, $b$, and $c$ on the axial ratio were analyzed. Axial Ratio is an important factor to measure the circular polarization characteristics of the antenna. We need to pay attention to whether the axial ratio in the frequency band is less than 3dB.

By analyzing the results of S11, the parameters $a=18\text{mm}$, $b=7\text{mm}$, $c=1\text{mm}$ are chosen to simulate the axial ratio of the antenna at the center frequency of 4.4GHz, as shown in Fig. 8. The axial ratio bandwidth of LHCP antenna is about 4.35GHz-4.47GHz; the axial ratio bandwidth of RHCP antenna is about 4.28GHz-4.60GHz. The Axial Ratio bandwidth of LHCP is about 0.12GHz; the Axial Ratio bandwidth of RHCP is about 0.32GHz. At the center frequency of 4.4GHz, the axial ratio bandwidth of RHCP is 0.2GHz wider than that of LHCP. The Axial Ratio bandwidth of LP is greater than 25dB after rotating 45 degrees and 135 degrees. Conforms to design requirements.
The antenna's gain operating at the center frequency of 4.4GHz was analyzed, as shown in Fig. 9 and Fig. 10. Moreover, according to the experimental simulation, the antenna gain exceeds 4dBi in planes E and H at LHCP and RHCP.

The axial ratio of LHCP and RHCP, as well as LP-45° and LP-135°, are also shown in the figures. The antenna has a relatively large impedance bandwidth and relative bandwidth, which are 34.6% and 1.32GHz, respectively, and where the reflection coefficient s11 is about 3.15 GHz-4.17 GHz. Covering the downlink frequency range of satellite communication C band, and the antenna gain is also favorable; however, its bandwidth of reconfigurable polarization is narrow, RHCP has a slightly larger polarization bandwidth than LHCP, where LHCP and RHCP are about 0.12 GHz and 0.35 GHz, respectively.

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