Design of a Multimode OAM Vortex Electromagnetic Microstrip Array Antenna

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Abstract. On the basis of the characteristics of electromagnetic wave orbital angular momentum can improve spectrum efficiency, this paper proposes a low profile, more OAM models design of antenna. The antenna subject selection is made of glass fiber epoxy resin substrate, using phased array feed technology under the condition of the limited antenna unit number achieved by each antenna feed different phase excitation. By adjusting the position of the feeding point, the matching of the input impedance of the antenna is improved and the optimal structure of the antenna is determined. The simulation results show that the antenna achieves good impedance matching at the center frequency of 2.45GHz and generates 7 kinds of vortex electromagnetic beams with different OAM modes. The antenna has the characteristics of small size, light weight and low profile, which provides a novel antenna structure for the design of communication terminal antenna array.

1. Introduction
With the rapid development of science and technology and the continuous increase of wireless communication users, the fixed spectrum bandwidth gradually limits the development of wireless communication technology of higher quality. Vortex electromagnetic waves carrying Orbital Angular Momentum (OAM) can have an infinite number of non-interference orthogonal modes at any frequency, showing important application potential in the field of wireless communication research. In 2011, Tamburini et al. realized the first wireless communication experiment based on different modes of orbital angular momentum in the RF band [1]. Since then, how to better apply orbital angular momentum to the field of wireless communication has been the research focus of many scholars [2], [3], [4].

Up to now, methods for generating OAM vortex electromagnetic beam in microwave frequency band are mainly variable array antenna [5], porous medium reflection array [6], circular traveling wave antenna [7], spiral parabolic structure [8], [9], [10] and phased array antenna [11], [12]. Microstrip array antenna has the characteristics of simple structure, low overall profile, easy integration, and the ability to generate multiple modes of orbital angular momentum at the same frequency. In order to generate vortex better performance of electromagnetic wave, the literature [13] OAM wave generated by circular traveling wave antenna outside the cavity of the narrow edge cracks in the metal ring along the load ring horn was the energy concentrated radiation, but this structure can only generate a set of corresponding model, and only can be generated within the scope of narrow-
band vortex wave, this to a certain extent, limits the OAM model of orthogonal reusability. In literature [14], a low-profile rectangular microstrip array antenna is proposed. Two orthogonal polarizations are obtained by excising the quasi-cross aperture of U-shaped and M-shaped microstrip feeders, so as to generate different OAM modes in different polarization states. However, the antenna structure has higher requirements on the size of feeders and the design complexity is relatively large.

In this paper, 8 elements with the same structure are distributed on a concentric circular surface through the connection of the feeder network with rectangular microstrip patches fed by coaxially. By modeling and optimizing the size of the SMT unit, the antenna is satisfied. The antenna is capable of operating in the s-band and generating seven different modes of effective vortex electromagnetic waves at the center frequency of 2.45GHz.

2. Antenna structure design

In this paper, the radiation characteristics of the microstrip array antenna of rectangular element patch are studied [15]. In terms of impedance matching, coaxial feeding is used. The width of patch is calculated from the following formula

\[ w = \frac{c}{f} \left( \frac{\varepsilon_r + 1}{2} \right)^{\frac{1}{2}} \]  

(1)

Where, \( c \) is the speed of light and \( \varepsilon_r \) is the dielectric constant of the dielectric plate.

The length of the radiation patch is generally taken as \( \frac{\lambda_e}{2} \), where \( \lambda_e \) is the guide wave length in the medium, namely

\[ \lambda_e = \frac{c}{f \sqrt{\varepsilon_e}} \]  

(2)

Taking into account the edge shortening effect, the actual length of radiation element \( L \) should be

\[ L = \frac{c}{f \sqrt{\varepsilon_e}} - 2\Delta L \]  

(3)

Where, \( \varepsilon_e \) is the effective dielectric constant and \( \Delta L \) is the equivalent radiation gap length. They can be calculated with the following equation respectively, namely

\[ \varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + 12 \frac{h}{w} \right)^{\frac{1}{2}} \]  

(4)

\[ \Delta L = \begin{cases} 0.412h(\varepsilon_r + 0.3)(w/h + 0.264) & (\varepsilon_r < 2.5) \\ 0.258h(\varepsilon_r - 0.258)(w/h + 0.8) & (\varepsilon_r > 2.5) \end{cases} \]  

(5)

In the working mode of the main mode \( TM_{10} \), the input impedance of the feeding point is the highest at the edge \( (x = \pm L/2) \) of the \( L \) direction of the length of the rectangular radiant patch. The displacement of the feed point in the width direction has little influence on the input impedance. However, when the feed point deviates from the center position in the width direction, \( TM_{1n} \) mode will be excited to increase the cross-polarization radiation of the antenna. Therefore, the position of the feed point in the width direction is generally taken as the center point. The input impedance at the
geometric center of the radiant patch is 0, and TM_{10} mode cannot be excited. The following equation can also be used to directly approximate the position of the feeding point when the input impedance is 50 Ω.

\[ L_1 = \frac{L}{2} \left( 1 - \frac{1}{\sqrt{\xi_{re}}} \right) \]  \hspace{1cm} (6)

\[ \xi_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + 12 \frac{h}{L} \right)^{-\frac{1}{2}} \]  \hspace{1cm} (7)

The basic structure of the designed unit patch antenna is shown in figure 1, with width W=37.26mm and length L=28mm. The whole array is composed of 8 cell antennas of the same structure evenly arranged around the center of the circle. The included Angle between the two adjacent array elements is 45°. The antenna is made on the same substrate with dielectric substrate dielectric constant \( \varepsilon_r = 2.55 \) and thickness \( h=1.5\text{mm} \). Figure 2 is a rectangular array antenna model designed under electromagnetic simulation software.

![Figure 1. Antenna unit structure diagram](image1)

![Figure 2. Structure diagram of array antenna](image2)

3. Simulation results of microstrip array antenna

![Figure 3. Return loss of array antenna element](image3)
The electromagnetic simulation software was used to conduct a lot of experimental simulation optimization on the array antenna shown in figure 2, and the antenna return loss was obtained as shown in figure 3. At the center frequency of the array antenna 2.45GHz, the return loss is -24.04dB. Since the array is composed of the same patch element and the coupling between the elements is weak, the resonance frequency has a good consistency. By optimizing the patch size, the ideal impedance matching and bandwidth requirements are met.

Figure 4 for the antenna array on the center frequency 2.45 GHz antenna input impedance real part and imaginary part and the change of the coaxial feed point location relation curve. It can be seen that coaxial feed point moves from the center to the edge of radiation patch, input resistance increases gradually from 0 Ω to 100 Ω, input reactance by 15 Ω has shrunk to about -10 Ω. When patch length $L_1$ change to 6.64mm, the input impedance of approximately (50.0-j1.4) Ω.

According to the vortex wave theory, when the array elements are fed with different phase excitation, so that there is an equal phase difference between each element, the array antenna will produce a hollow phenomenon on the central axis, and there is spiral energy radiation around the axis. Figure 5 is the electric field vector diagram of the array antenna at the resonant point 2.45GHz. When the electromagnetic wave of the array antenna is distributed clockwise at the resonant point of 2.45GHz, the OAM mode is negative. When the electromagnetic wave of the array antenna at the resonant point of 2.45GHz is distributed counterclockwise, the OAM mode is positive. The helical electromagnetic wave with different rotation direction indicates that the current direction on the antenna surface changes under different phase excitation conditions. It can be seen from the figure that there is a central cavity in the propagation center of vortex electromagnetic beam, and the electric field intensity near the center point is very weak, and the maximum gain value is offset to both sides. The reason for this phenomenon is that the phases of each element of OAM microstrip array antenna are different and have equal phase difference. The size of the central cavity area is related to the radius of the OAM array antenna and the number of array elements. In the simulation design, the central cavity problem can be improved by optimizing the radius of the microstrip array antenna and the number of patch elements.
The beamfront phase structure does not change with the increase of signal transmission distance. Therefore, the OAM vortex electromagnetic wave generated by the rectangular microstrip array antenna designed in this paper has a complete rotation in theory. That is, it is possible to observe whether the gain pattern at the center axis is completely symmetric through the 3D pattern of radiation from the array antenna. Figure 6 shows the 3D direction of the rectangular microstrip array antenna in different modes. When OAM mode \( l = 0 \), that is, the phase offset of each element is 0°, and the radiated electromagnetic wave energy propagates along the axis of the beam center. When the OAM mode changes, the radiation mode changes differently in the direction of the central axis. For example, when the phase deviation of each antenna element is ±45°, the electromagnetic wave energy radiated by the array antenna is mainly concentrated in the direction of beam axis. With the increase of the number of OAM modes, the phenomenon of beam hollow-out will appear in the axis direction. The larger the number of OAM modes, the area of the hollow area will gradually increase, the main beam will gradually become side lobe, and the electromagnetic wave energy will spread in multiple directions. The larger OAM mode will reduce the increase of array antenna, decrease the directivity of array antenna and increase the area of hollow area in z-axis direction. The results show that when OAM mode \( l = 4 \), the beam falls sharply along the Z-axis direction. The central hole problem can also be improved by optimizing the array radius or changing the number of elements.

4. Conclusion
Based on the principle of orbital angular momentum and phased array feeding technology, a rectangular microstrip array antenna which can work in S-band is designed in this paper. Simulation results show that the array antenna has a low return loss at the center frequency of 2.45GHz. By adjusting the position of the feeding point through 3D electromagnetic field simulation software, the matching of the input impedance of the antenna is improved, and by changing the phase feeding of the array element, 7 kinds of effective OAM electromagnetic beams are generated. This antenna is small
in size, light in weight and low in profile, which has certain reference value for the application of communication terminal antenna array in practical engineering. However, the vortex electromagnetic wave generated by the rectangular microstrip array antenna has a good effect on the lower OAM mode, while the OAM electromagnetic beam structure close to the maximum mode is fuzzy. How to design the vortex electromagnetic wave antenna with wider frequency band and higher gain combined with the feed network construction technology is the next work of this paper.

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