Design and Simulation of A Dual-Frequency Multi-Mode Vortex Microstrip Array Antenna

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Abstract. In order to improve the communication capacity and spectrum utilization, a design scheme of dual-frequency and multi-mode vortex microstrip array antenna is proposed. This antenna is composed of 8 rectangular microstrip patches, and 8 elements with the same structure are distributed at equal intervals on a concentric circle. The optimal structure of the antenna is determined by modeling 3D electromagnetic field simulation software and optimizing patch size. Simulation results show that the antenna has good impedance matching at the resonance point of 1.9 GHz and 2.45 GHz. When different phase excitation is applied to each element, the antenna produces seven effective vortex electromagnetic waves with different modes.

1. Introduction
It is urgent to develop a new technology to increase the capacity of wireless communication. Orbital Angular Momentum (OAM) antenna has the characteristics of high spectrum utilization and strong anti-interference ability, which provides a new way of thinking for solving the problems faced by radio communication technology [1, 2]. In 2014, Yan et al. verified the application of orbital angular momentum multiplexing technology in MMW communication system with a transmission distance of 2.5 meters through experiments, and the spectral efficiency was 16 bit/s/Hz [3]. This makes the method of using OAM vortex electromagnetic wave antenna to carry out radio communication become the hot spot of domestic and foreign experts and scholars.

Up to now, there are a variety of methods to obtain OAM vortex electromagnetic waves, such as time-varying array antenna [4], spiral or hole phase plate [5, 6] and phased array antenna [7, 8]. In order to obtain high-quality vortex electromagnetic wave, a kind of nut type radiation patch is adopted in reference [9] to design a vortex electromagnetic wave antenna with single frequency operation by controlling the position of feeding points. However, due to the asymmetry between the position of feeding points and the symmetry axis, the gain of the antenna is not ideal. In reference [10], a ring patch circular array is proposed, and the performances of eddy electromagnetic wave are compared by feeding different phase differences. However, it did not propose a specific solution on how to realize dual-band work of the antenna. In reference [11], a small-sized semi-circular slot patch unit is adopted to generate an OAM beam at a specific frequency center. The slot size has a great influence on the performance of the antenna, and the antenna design complexity is relatively large. In some applications, dual frequency operation can improve the overall performance of the microwave
transmission system. Therefore, it is of certain significance and reference value to design microstrip array antenna with different OAM mode vortex electromagnetic wave under the background of dual-frequency operation of microstrip antenna.

Based on this, the rectangular microstrip patch is used as a unit to distribute 8 arrays with the same structure equally spaced on a concentric circle. A rectangular vortex microstrip array antenna with resonant frequencies of 1.9GHz and 2.45GHz is designed. Through simulation optimization, the array antenna achieves a good impedance matching at the resonant frequency. When the patch elements are excited by different phases, the array antenna generates seven kinds of effective OAM vortex electromagnetic waves with different modes.

2. Microstrip array antenna structure design
The rectangular patch shown in figure 1 is adopted as the array element. The whole array is composed of 8 elements with the same structure, which are uniformly arranged around the center of the circle. The included angle between the two adjacent elements is 45°. Through the optimization of electromagnetic simulation software, the rectangular patch unit working at the center frequency of 1.9 GHz and 2.45 GHz was obtained with the length L of 40 mm and the width W₀ of 37.1mm. Figure 2 is a microtrap array antenna model designed by electromagnetic simulation software.

In order to minimize sidelobe radiation and keep the coupling between the elements at a relatively low level, the distance between the center of each element and the center of the circle is set to \( r=0.6\lambda \)\(^{[12]}\), where \( \lambda \) is the working wavelength of the low-frequency resonance point of the dual-frequency array antenna. The feeder port is arranged on the back side of the dielectric substrate by means of coaxial feeding. For n-element OAM circular array antenna, in order to realize the generation of eddy electromagnetic beam with different OAM modes by the array antenna, all radiation elements are excited by equal amplitude signals, but the feeding phase between array elements increases or decreases successively, and the change of phase shift between array elements is
\[ \Delta \phi = \frac{2\pi l}{N} \]  

(1)

Where, \( l \) is OAM mode. The phase rotation around the axis of the array will change \( \frac{2\pi l}{N} \) radians, and the difference in the feed phase is \( \Delta \phi \), resulting in different OAM modes.

3. Analysis of working mechanism of antenna

This article obtains from the rectangular unit patches, microstrip array antenna radiation characteristics were studied, according to the theory of modes \([13, 14]\), the work for the dual-band antenna, the antenna unit production and dielectric constant \( \varepsilon_r = 4.4 \), \( h = 1.6 \) mm thickness of the dielectric substrate, the length and width of patch corresponding to different resonant frequency and the feed point in a corner of the patch diagonal, the resonant frequency of the \( f_{mn} \) in the \( TM_{mn} \) model can be expressed as follows:

\[ f_{mn} = \frac{c}{2\sqrt{\varepsilon_e}} \sqrt{\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W}\right)^2} \]  

(2)

Where, \( c \) is the speed of light, and \( \varepsilon_e \) is the equivalent dielectric constant of the dielectric plate, which can be calculated by the following formula

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

(3)

The antenna array element model is shown in figure 3. Point A (\( x, 0 \)) on the X-axis is the 50\( \Omega \) feeding point of the excitation \( TM_{10} \) mode. Since point A is located on the center line of the y direction of the radiant patch, no other \( TM_{m0} \) (\( n = 1, 3, 5, \ldots \)) will be excited. Point B (0, \( y \)) on the Y-axis is the 50\( \Omega \) feeding point of the excitation \( TM_{01} \) mode. Since point B is located on the center line of the x direction of the radiant patch, no other \( TM_{0m} \) (\( m = 1, 3, 5, \ldots \)) will be fired. If the feeding point is placed at point C in position (\( x, y \)), then the antenna can excite \( TM_{01} \) mode and \( TM_{10} \) mode at the same time, and the input impedance of 50\( \Omega \) can be obtained in both modes.

4. Simulation results of microstrip array antenna

Simulation results of antenna return loss are shown in figure 4. At the resonant frequencies of 1.9 GHz and 2.45 GHz, the return loss of rectangular microstrip array antenna is -18 dB and -26 dB, respectively. The antenna can work in L and S band at the same time.
Patch size is the main factor affecting the performance of microstrip antenna. Simulation changes the patch size, and the analysis results are shown in figure 5. The results of antenna return loss are different when the width of patch is different. When the width $W$ changes from 36 mm to 39 mm, the resonant frequency of antenna TM$_{01}$ mode is basically unchanged at 2.45 GHz, and the resonant frequency of TM$_{10}$ mode will decrease with the increase of the width. When $W=37$ mm, the resonant frequency is about 1.905 GHz, and the patch width corresponding to the antenna at the resonant frequency of 1.9 GHz is obtained through optimization is 37.1 mm.

Figure 6 shows the different OAM mode beam electric field amplitude diagram generated by the array antenna when the phase offset of each array element is $0^\circ$, $\pm 45^\circ$, $\pm 90^\circ$, $\pm 135^\circ$ and $\pm 180^\circ$, respectively. When the array element is fed the same zero-phase shift signal, the antenna has no helical phase front electromagnetic beam, indicating that the OAM mode $l = 0$. OAM mode $l = -1$, indicating that the phase difference between two adjacent array elements is $+45^\circ$, at which time the array antenna generates a clockwise spiral phase front. OAM mode $l = +1$, indicating that the phase difference between two adjacent array elements is $-45^\circ$, at which time the array antenna generates a counterclockwise spiral phase front. When the phase shift signal of $\pm 45^\circ$ integer multiple is fed to each array element successively, the antenna can emit eddy electromagnetic wave with different rotation directions. For an $N$ element microstrip array antenna, theoretically the maximum value of OAM modal $l_{\text{max}}$ can be generated to satisfy the following equation:
$$-\frac{N}{2} \leq l_{\text{max}} \leq \frac{N}{2} \tag{4}$$

When the OAM mode changes from $l = \pm 1$ to $l = \pm 3$, the hollow area of the radiated electromagnetic wave will gradually expand, and the directivity of the array antenna will change accordingly. When a signal with a phase offset of $\pm 180^\circ$ is fed to each array element of the antenna, it means that the OAM mode $l = \pm 4$, and the phase distribution of the radiated vortex electromagnetic beam is deformed irregularly, and the beam electric field distribution is deformed violently. Because the number of array elements determines the maximum OAM mode generated by the array antenna.

Figure 7 is the 3D radiation pattern of the rectangular microstrip array antenna in different modes. As can be seen from the figure, when the OAM mode is in, the direction of the main lobe is perpendicular to the antenna array, and the energy is relatively concentrated. As the number of OAM
modes increases, hollow areas of different sizes will appear in the direction of beam axis. When each array element is fed signals with phase offset of ±135° and ±180° respectively, corresponding OAM modes \( l = \pm 3 \) and \( l = \pm 4 \), the main lobe of the antenna beam becomes smaller and gradually becomes side lobe, electromagnetic wave energy diffused in multiple directions, and the directivity of the array antenna deteriorates accordingly.

In theory, the OAM electromagnetic wave generated by vortex electromagnetic microstrip array antenna has rotability and complete symmetry. In other words, it is possible to observe whether the curves on both sides of \( \theta = 0° \) are completely symmetric through the radiation direction diagram of the antenna's EH surface. Figure 8 shows the gain direction of XZ plane of the array antenna under different OAM modes. It can be seen that the curve of the designed rectangular vortex microstrip array antenna is symmetric near \( \theta = 0° \). Electromagnetic waves carrying various OAM modes will radiate energy along the direction of signal propagation. However, electromagnetic waves with higher OAM modes are more likely to diverge than those with lower OAM modes and will appear concave in the middle of the direction diagram. When a signal of equal amplitude but with a phase offset of ±180° is fed to each antenna element, that is, OAM mode \( l = \pm 4 \), the beam formed by the array antenna falls sharply along the Z axis, and electromagnetic energy divergence is obvious on both sides of \( \theta = 0° \).
5. Conclusion
A novel dual-frequency multi-mode vortex microstrip array antenna is designed and fed by coaxial line. Good impedance matching was achieved at the resonant frequencies of 1.9 GHz and 2.45 GHz respectively by modeling the 3D electromagnetic field simulation software and optimizing the size of the patch element. Compared with other methods adopted at present, based on the theory of cavity mode and combined with the feeding technology of phased array antenna, this paper makes the array elements distributed on the same concentric circle surface are fed with excitation of different phases, and seven kinds of effective different modes of OAM vortex electromagnetic waves are obtained at the resonance point.

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