Orbital Angular Momentum (OAM) Beam Generation Using Simple Ring Patch Antenna for IoT Applications

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***Abstract*—This paper presents the design of a compact circular ring patch antenna for generating orbital angular momentum (OAM) mode at 5 GHz. The TM_{21} mode is created by feeding a circular ring patch with a coaxial probe. The proposed antenna is very simple and compact for producing an OAM mode ($l = 1$), as it only includes one circular ring. All parameters of the proposed antenna are obtained from CST Microwave Studio, such as reflection coefficient (S_{11}), radiation characteristics, electric field distribution, and phase distribution. Simulated results show that there is good impedance matching at 5 GHz with S_{11} less than -10 dB. The radiation pattern exhibits a doughnut-shaped profile with a null along the beam axis, which is a characteristic feature of OAM beams. The phase distribution is continuous over the entire azimuthal range of 0°–360°, as observed from a central point, resulting in a helical wavefront corresponding to the OAM mode ($l = 1$). This antenna configuration represents a low-profile and compact approach to generate OAM. It exhibits a maximum gain of around 10 dB and a radiation efficiency of approximately 90%. Due to its ease of integration with existing technologies, the proposed design can be considered a viable candidate for applications in OAM-based wireless communication systems.**

***Index Terms*—Orbital angular momentum (OAM), ring patch antenna, TM_{21} mode**

I. INTRODUCTION

The need to increase the amount of data being transmitted with increased speed, has driven an interest in how to utilize the available bandwidth and channel capacity. Multiplexing methods have been used, including time division and frequency division multiplexing, however these conventional multiplexing methods are reaching their theoretical limits [1] . Alternative ways to transmit information physically using electromagnetic waves with orbital angular momentum (OAM), are receiving considerable research interest [2]. A helix type of wavefront characterizes OAM and it is most commonly represented mathematically as $e^{i\ell\phi}$ where ℓ, represents the mode. All these modes are theoretically orthogonal, thus multiple separate channels of information can be simultaneously transmitted on a single frequency band which increases spectral efficiency [3]. Because of its unique nature, OAM has generated significant interest in both optical and RF domains for applications ranging from wireless communications to imaging and radar systems. Among the various techniques, antenna arrays are widely used due to their flexibility in controlling phase distribution; however, they suffer from increased complexity, cost, and power consumption as the number of elements increases [4]. Alternatively, single-antenna approaches based on microstrip patch antennas offer a compact and low-cost solution for OAM generation.

Different techniques for creating OAM beams have received considerable research attention. Nevertheless, a critical challenge remains in developing broadband and high-purity OAM beam generation. spiral phase plates (SPPs), used to generate millimeter-wave OAM beams with ultra-low reflectivity, were discussed in [5]. Similarly, a high-gain OAM antenna developed using a splitting SPPs was presented in [6]. Although SPPs have relatively simple configurations, they are typically capable of producing only a single OAM mode. Furthermore, as frequency decreases, their dimensions increase, thereby adding to the overall system cost. Traveling-wave antennas have also been investigated as potential solutions for OAM beam generation. A circular slot antenna capable of generating spiral OAM waves was presented in [7], while OAM multiplexing based on dual-mode OAM operation was demonstrated in [8]. The problem with most of these antennas is that they have large dimensions and are often very narrow band. Another possible method to generate OAM is through compact microstrip antennas. Two-dimensional dual CP microstrip antennas are presented in [9], as well as a multimode CP patch antenna capable of generating OAM in [10]. Array-based techniques are also widely used to generate OAM beams by controlling the phase distribution of multiple elements. A circular phased array designed to generate vortex radio waves was presented in [11]. A dual-polarized microstrip array antenna for dual-mode OAM applications was proposed in [12], while broadband dual-OAM-mode array antennas were reported in [13]. Experimental demonstrations of dual circularly polarized OAM arrays were presented in [14]. However, these approaches require complex feeding networks and increased system complexity. Metasurface-based techniques have also been explored for OAM generation. High-efficiency

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vortex beam generators and dual-mode OAM metasurfaces were proposed in [15]. Although these approaches reduce the number of feeds required, most still need additional structures such as horn antennas, which increase the overall size. Transformation optics has also been employed for OAM generation. A dielectric OAM mode generation lens was developed in [16], and phase-modulation-based convergent lenses were described in [17]. However, these methods involve complex design and fabrication processes. Therefore, there is a need for a simple, compact, and efficient antenna structure capable of generating high-purity OAM modes with reduced complexity.

This paper proposes a compact ring patch antenna for the realization of a single-order OAM mode ($\ell = 1$). The design is based on the excitation of appropriate TM modes to generate the required helical phase distribution. Full-wave electromagnetic simulation is employed to analyze the proposed antenna, while its performance is characterized in terms of return loss, radiation properties, and phase distribution.

II. Theoretical Analysis

The OAM is an intrinsic characteristic of electromagnetic waves linked to the angular spatial distribution of phase. It differs from spin angular momentum which relates to the polarization properties of light and it originates from the helicoidal shape of the wavefront. The $\boldsymbol{E}$ of an OAM beam is described by equation (1):

$$E(\phi) = E_0 e^{jl\phi} \tag{1}$$

where l denotes the OAM mode number and ϕ is the azimuthal angle.

OAM waves have two primary characteristics; a helical phase front and a single point of phase singularity that is located at the center of the beam. The singularities create an area where the intensity of the light is zero (null), forming a "doughnut" shaped light distribution. These properties allow for the concurrent transmission of multiple independent data streams using different frequencies or wavelengths on the same frequency band.

In microstrip patch antennas, OAM modes can be generated by exciting higher-order transverse magnetic (TM) modes. The resonant frequency of a circular patch antenna is given by

$$f_{nm} = \frac{X_{nm}}{2\pi a_e \sqrt{\varepsilon_r}} c \tag{2}$$

where X_{nm} is the root of the Bessel function, a_e is the effective radius, and ε_r is the dielectric constant [14].

The generated OAM mode is related to the TM mode as

$$l = n - 1 \tag{3}$$

which indicates that the excitation of the TM_{21} mode produces a first-order OAM mode ($l = 1$).

OAM mode generation is realized through the superposition of orthogonal degenerate modes having a relative phase offset of 90°. The corresponding $\boldsymbol{E}$ components are given by

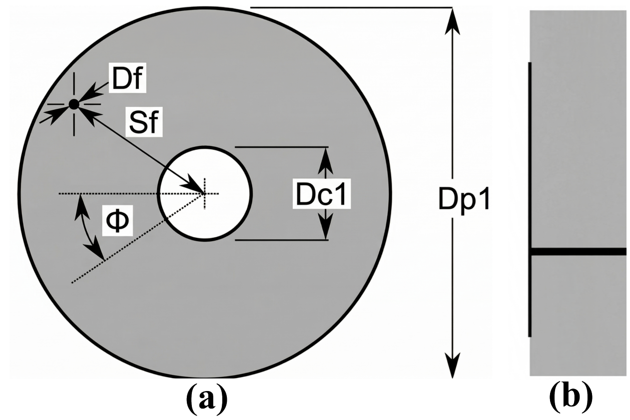

Fig. 1: The proposed ring patch antenna (a) Top view, (b) Side view.

$$E_x = Ae^{-j(n-1)\phi} - Be^{-j(n+1)\phi} \tag{4}$$

$$E_y = -jAe^{-j(n-1)\phi} + jBe^{-j(n+1)\phi} \tag{5}$$

where the dominant term determines the resulting OAM mode. Ring patch antennas are particularly suitable for OAM generation due to their circular symmetry, which supports uniform current distribution along the circumference.

III. Antenna Design

The proposed antenna has a circular metallic patch that is etched onto a dielectric substrate shown in Figure 1. The metallic ring structure was created when one removed the center circle from the solid patch, creating what can be described as a perforation geometry. The ring creates an altered distribution of the surface currents. The perforation also allows for the activation of higher order TM modes to generate the necessary OAM.

A coaxial probe feed is used to excite the antenna, where the inner conductor passes through the substrate and connects to the radiating patch. The feed location is optimized to effectively excite the desired TM mode while minimizing the excitation of undesired modes. The operating principle of the antenna is based on controlling the current distribution through the central cut-out. The inner radius alters the effective radiating area, thereby influencing the resonant frequency, impedance bandwidth, and input impedance. An increased inner radius will decrease the effective area of the patch. This results in an additional impact on both the resonance frequency and impedance of the antenna.

Selecting the proper radii of the inner circle and outer circle allows the designer to select which of the four possible TM modes are to be exited at 5 GHz. FR4 is used as the dielectric substrate, it has a ε_r = 4.3 and thickness of approximately 1.6 mm. A circular patch made of conductive material with diameter D_{c1} is printed onto the top surface of the substrate. A circular grounding plane with diameter D_{p1} is placed below the patch to serve as a reference and

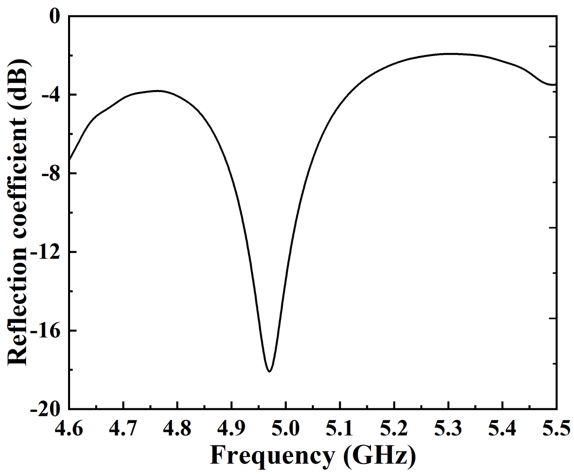

Fig. 2: Simulated reflection coefficient S_{11}

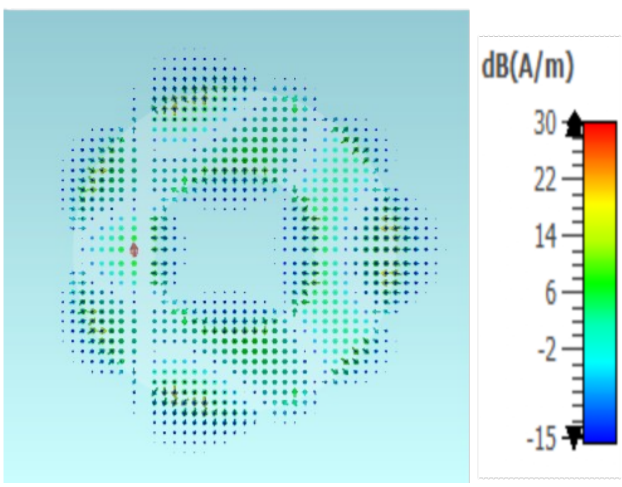

Fig. 3: Electric field distribution.

help reduce back radiation. The location where the feed meets the patch is determined by two parameters; radial distance S_f from the center of the patch and angle Φ relative to a line parallel to the x-axis. The optimized geometrical parameters are: $D_{p1} = 35$ mm, $D_{c1} = 9.6$ mm, $S_f = 17.2$ mm, and $\Phi = 135°$.

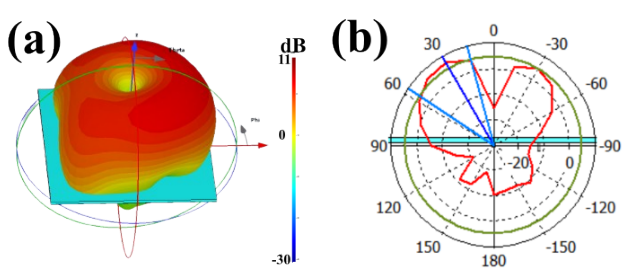

Fig. 4: (a) 3D radiation, and (b) 2D radiation

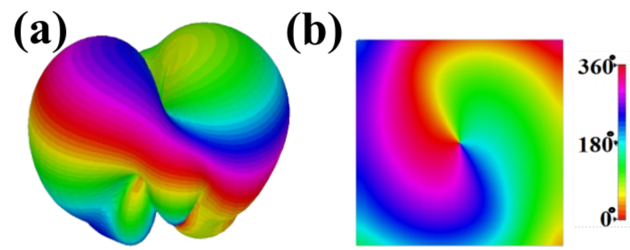

Fig. 5: 3D phase distribution for OAM mode (l = +1), and (b) 2D Phase pattern

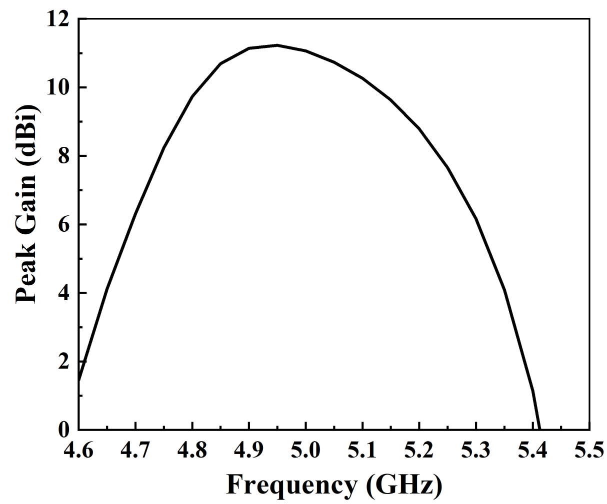

Fig. 6: Gain vs frequency

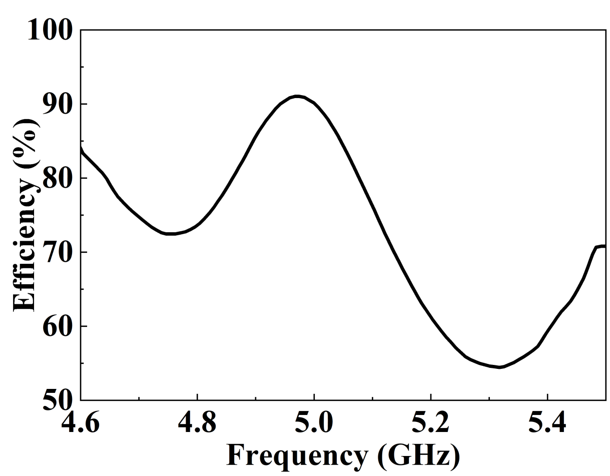

Fig. 7: Total efficiency

IV. Results and Discussion

The performance of a ring-patch antenna will be compared to the theoretical prediction through simulation using CST Microwave Studio. The results are analyzed based on their reflection coefficients, radiation characteristics, electric fields distributions, and phases to confirm that an OAM mode was generated. Figure 2 shows the simulated S_{11}. As it can be seen from this figure, the S_{11} for the antenna is less than –10 dB at 5 GHz. Since the magnitude of the S_{11} is less than –10 dB; there is impedance matching between the source and load as a result of the effective energy transmission.

The distribution of the electric-field magnitudes has been shown in Figure 3. A radial distribution of electric fields was observed with the highest values for the electric fields occurring on the periphery (ring) of the beam while decreasing as one moved toward the center. These distributions correspond to that predicted for the TM_{21} mode and provide evidence of a central phase singularity within the beam. The phase singularity is an essential characteristic of all OAM beams. The Figure 4 shows 3D radiation pattern exhibits a clear doughnut-shaped profile with a null at the center, which is a fundamental characteristic of OAM beams due to the presence of a phase singularity. The 2D radiation pattern further confirms this behavior, where the radiation intensity along the boresight direction approaches zero.

To further validate the OAM mode generation, the phase distribution is analyzed in both 3D and 2D patterns, as shown in Figure 5. The phase profile shows a continuous azimuthal variation from 0° to 360°, which confirms OAM mode $l = +1$. The number of phase rotations clearly indicates the successful generation of the desired mode. Figure 6 shows the antenna achieves a peak gain of approximately 10 dB, which is suitable for practical wireless communication applications. Figure 7 shows the total efficiency is found to be approximately 90%, indicating low losses and effective radiation performance.

V. Conclusion

This paper presented the design and simulation of a compact ring patch antenna for generating OAM mode $l = +1$ at 5 GHz. The antenna has a ring shape and uses a single coaxial fed to excite the TM_{21} mode to create a helical phase front that corresponds to $l = 1$. Simulation results show good impedance match with S_{11} being lower than -10 dB at 5 GHz. Simulated radiation patterns have a doughnut shape with a beam center null showing evidence of the existence of a phase singularity. The phase profile shows a continuously azimuthally varying phase from 0° to 360° which supports the OAM (order $l = +1$) mode. It also gives a maximum gain of around 10 dBi and total efficiency of around 90% proving that it radiates efficiently. Due to simplicity of structure and good radiation properties, the antenna is an efficient candidate for future generations of wireless communications.

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