The Scattering Characteristics of Vortex Radio-Frequency Waves for Wireless Communication

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Abstract. As a solution to the shortage of transmission capacity, the vortex radio frequency waves have been applied to wireless transmission technology. The potential of vortex radio frequency waves applying to the fields of wireless communication, radar detection and radar imaging will be invaluable. The scattering characteristics of the vortex waves are the basis for its application in radar detection imaging and identification. This paper focuses on the theoretical derivation, including the main effects on the scattering characteristics, and the future applications and prospects of scattering characteristics. The state of art in research area is reviewed, followed by a brief discussion on future directions.

1. Introduction

With the increasing demand of transmission capacity, the spatial structure of RF has become the latest solution to solve the problem of spectrum scarcity. In order to realize space division multiplexing, radio frequency (RF) waves need to realize different oscillation modes. Among them, the orbital angular momentum (OAM) is a set of special modes. The RF carrying OAM is called vortex RF wave, and its phase wavefront presents a spiral structure [1-3].

When applied to radio frequency communication, multiple vortex RF waves can share the same frequency and improve transmission capacity, thus providing a solution for spectrum scarcity [4]. In addition to the case that the divergence is not serious, the orthogonality of OAM vortex mode makes the vortex RF almost free from interference, and modulating the required information on it will greatly improve the information transmission and information acquisition ability of RF [3].

In the traditional radar detection technology, information modulation is mainly carried out in time domain, frequency domain, polarization domain and other fields. The far-field plane wave is usually used in the simulation. The development of vortex RF wave makes the wavefront information modulation ability attractive. Under the radiation of vortex RF radiation field, the RF wave at different targets will form radiation field excitation with different distribution, and the target scattering echo will contain more target information, and the radar imaging resolution will be improved if it is used in radar imaging [5]. In addition, theoretically, vortex RF waves can generate infinite kinds of mutually orthogonal modulation modes, so it can achieve high performance Resolution imaging can improve the efficiency of imaging solution at the same time [6-7].

In summary, vortex RF waves have a high possibility to be widely used in radar detection and identification technology in the future, and the scattering characteristics of target is the basis of radar detection and identification. Therefore, it is very important to study the scattering characteristics of vortex RF. In the first section, the basic definition and generation of vortex RF are introduced. The second section focuses on the theoretical derivation of vortex radio frequency, the main effects on the
scattering characteristics, and the future applications and prospects of scattering characteristics of vortex radio frequency waves. In the last section, the future research direction of vortex RF scattering characteristics is pointed out.

2. Definition of Vortex RF waves

According to Maxwell's classical electromagnetic theory, electromagnetic field can carry energy and momentum simultaneously. Momentum is divided into linear momentum and angular momentum. Similar to classical mechanics, electromagnetic angular momentum is defined as $J = r \times P$, and total angular momentum is defined as follows:

$$J = \varepsilon_0 \int r \times (E \times B) \, dr$$

In equation (1), epsilon is the vacuum dielectric constant, $E$ and $B$ represent the electric field strength and magnetic field strength respectively. In classical mechanics and atomic physics, angular momentum is further divided into spin angular momentum (SAM) and orbital angular momentum (OAM), that is $J = L + S$, $L$ represents OAM, $S$ represents SAM, and they can be expressed as:

$$L = \varepsilon_0 \int \text{Re}\{iE^* (\hat{L} \cdot A)\} \, dV$$

$$S = \varepsilon_0 \int \text{Re}\{(E^* \times A)\} \, dV$$

$A$ is the vector bit, and $\hat{L}$ can be expressed as $\hat{L} = -i(r \times \nabla)$. Generally speaking, SAM is related to the polarization state of RF wave, while OAM is related to the spatial structure of electromagnetic field (such as phase structure, polarization structure, etc.), which shows that the wavefront rotates around the axis where the RF wave propagates. The radio frequency wave carrying OAM and showing a rotating front is called vortex radio frequency wave [1].

As described in [3], in shape, the vortex RF wave has a vortex structure invisible to human eyes. From the quantum level, when the RF wave carries OAM with a particle size of $\ell \hbar$, the $\exp(i\ell \phi)$ azimuth phase difference will be generated, which will cause the wavefront to rotate. Among them, $\ell$ is an integer (positive and negative) called OAM mode, which represents the number of integral around a closed loop of beam. The modulus of this integer is the number of interleaved vortex wavefront and $\hbar$ is Planck constant.

Figure 1 shows the change of wave front when different OAM mode are taken. When the mode is positive, the wave front rotates clockwise around the axis in the direction of RF wave propagation. If negative is taken, the wave will rotate anti-clockwise, and 0, there is no OAM. In particular, at the singularity of OAM center phase, each phase value has a corresponding phase value with phase difference. Therefore, the center strength of vortex RF wave is zero.

![Figure 1: Variation of vortex RF wavefront at different $\ell$.](image)

OAM is usually carried by single or multiple orthogonal RF waves, which can be circular symmetry or cylindrical symmetry. Due to this orthogonality, RF waves with different OAM modes can be synthesized into new vortex RF waves. Figure 2 shows the radiation pattern of OAM antenna simulated by 4nec2. The number of dipoles is 8, the frequency is 300MHz, and the corresponding wavelength is 1m. Therefore, the aperture size is 1m, the dipole antenna length is 0.5m, and the material is copper.
3. OAM Scattering Characteristics

3.1. Derivation of Scattering Theory

In order to facilitate calculation, \( N \) antenna-array elements with radius \( R \) are arranged to transmit vortex RF wave with the coordinate origin as the center. The propagation direction is set as Z axis, and an object is introduced at the center of transmitting and receiving antenna, as shown in Figure 3.

If the centroid of the object is \((0, 0, z)\), and its polar coordinates are \((Z, 0, 0)\), the additional phase shift of each array element, then the field strength of the wave source at the centroid is:

\[
E(p) = -j \frac{\mu_0 \omega}{4\pi} \sum_{n=0}^{N-1} e^{i\Phi_n} \int |z - z_n|^{-1} e^{i\theta z_n} d V
\]

\[
\approx -j \frac{\mu_0 \omega d e^{|z|}}{4\pi} i^{|z|} J_{\ell}(0)
\]

\( \mu \) is the permeability in vacuum, \( \omega \) is the angular frequency of RF wave, \( k = \omega/c \) is the wave number, \( c \) is the velocity of light in vacuum, \( \Phi \) is the azimuth angle of antenna, \( j \) is the current density of transmitting antenna, \( d \) is the oscillator length of wave source, and \( J_{\ell}(0) \) is Bessel function. Using the amplitude approximation, \( |z - z_n| = t = \sqrt{z^2 + R^2} \), \( z_n \) is the position vector of element \( n \).

Assuming that the scattering is an ideal point scattering behavior, the echo at the receiving end is:

\[
E_p^r = \left[ -j \frac{\mu_0 \omega d e^{i\theta z}}{4\pi z} \right] \cdot E(p) \times \int |z - z_n|^{-1} e^{i\theta z_n} d V
\]

The finite difference time domain (FDTD) is widely used in the study of plane scattering, which requires the introduction of vortex RF wave. Therefore, the electric field matrix formed by the vortex signal should be imported into the original emission field, so that the emission source can be converted into vortex RF wave.

3.2. Factors affecting the scattering characteristics

The scattering characteristics of vortex RF waves are related to the geometric characteristics of the target and the value of OAM mode carried by the signal itself.

By using the FDTD method in reference [11], it is verified that the OAM attenuation increases with the increase of the scattering radius of the target. When the OAM modes are the same, the proportion of the original angular momentum energy in the scattering echo decreases with the increase of the
object radius, that is, the proportion of the distorted angular momentum in the scattering echo increases with the increase of the object size. When the object size is constant, the OAM mode value of vortex RF wave is different, and the proportion of energy in echo is also different. In a certain range, with the increase of mode number, the proportion of original orbit angular momentum in echo decreases gradually.

In addition, reference [12] also verified that there is a certain relationship between the scattering electric field and energy spectrum and OAM mode. When the vortex RF wave scatters on the object, the electric field intensity decreases, the area with the center field strength 0 increases, and the range with the field strength not 0 also increases; the larger the OAM mode value, the greater the attenuation at the peak of the electric field intensity. At the same time, a new OAM will be generated in the scattering echo, and the original OAM will have a certain attenuation. Therefore, it is verified that there is a certain relationship between OAM mode value and OAM attenuation.

The scattering characteristics of high-order Bessel vortex beam (hobvb) are discussed in reference [13]. Hobvb is a typical vortex RF wave, which has the characteristics of non diffraction propagation, small central spot diameter, good direction and long propagation distance. The scattering of typical targets (sphere and aircraft) by hobvb is studied by using "surface integral equation method", RCS) is used to measure the scattering characteristics of hobvb.

In the case of maintaining the far-field, the RCS intuitively provides a scattering characteristic to the object, and this characteristic is independent of the antenna itself and the distance between the antenna and the object [14]. As long as the antenna keeps enough distance from the target object, and the transmitted wave maintains local level at the target object, and the scattered wave maintains the local level at the receiver, the RCS remains unchanged. Note that these characteristics are in the near field it will change.

The influence of OAM on the RCS distribution of E-plane and H-plane is given [15]. The experimental results show that the RCS decreases with the increase of OAM mode carried by the beam, which means that the smaller the backscattering ability of vortex RF wave is, the smaller the echo power is.

For the influence of OAM mode on vortex RF wave scattering, BU Xiang Xi et al. [16] also used RCS calibration measurement method to study the backscattering characteristics of vortex RF wave generated by ideal conductive wedge by changing the shape of wedge. The results show that the RCS fluctuation of vortex RF wave is different from that of planar RF wave due to its unique spatial distribution, and varies with OAM mode of incident wave. In some incident directions, the RCS of vortex RF wave is much higher than that of plane wave, the echo power is higher and the detection ability is stronger.

In addition, the experiments different from [16] are based on the scattering characteristics of the plane. With the author's in [17], the scattering of vortex RF wave to a typical target object corner reflector are studied. The results show that different from the conclusion that the RCS obtained in [16] varies with OAM mode, when the target object is an angle reflector, the RCS fluctuation of vortex RF wave is similar to that of plane RF wave, and is not affected by OAM modes. On the basis of RCS, reference [17] defined the OAM based RCS: orcs, and the energy equation was as follows:

\[
E_{\text{oam}} = E_0 J_1(k \rho \rho) \{ x \cos(\omega t - k z + \ell \phi) + y \sin(\omega t - k z + \ell \phi) \}
\]

When the target object is a plane reflector and OAM mode is 0, orcs is RCS, and there is only a slight error between them. When OAM mode is not 0, the peak value of ORCS is not in the direction of specular reflection (RCS main lobe direction), but in the angle of RCS side lobe, and the angle of main lobe increases with the increase of topological charge. When the target area is the same, the larger the width, the peak value of orcs increases, while the width narrows. The larger the target area, the larger the peak value and side lobe. In addition, there is no doubt that the peak value increases with the enhancement of the incident vortex RF wave.

When the object is a cylinder and OAM mode is not 0, the peak value of ORCS is no longer in the 90° direction, and the OAM mode increases, and the distance between the two peaks increases. And
when the height or radius increases, the main lobe increases. The peak value increases with the increase of the incident vortex RF wave.

Therefore, it is concluded in reference [18] that the RCS Based on OAM is highly dependent on the characteristics of the target object, such as width, area shape, OAM mode and beam frequency of the vortex RF wave itself. The peak value of OAM based ORC is no longer in the direction of specular reflection, and its position is affected by OAM mode. The ORC value increases with the increase of target size or signal frequency.

In reference [19], four groups of experiments on vortex RF waves were carried out: (a) scattering to a simple object (a single metal ball); (b) scattering to a complex object (two metal spheres side by side); (c) RCS diversity of backscattering; (d) RCS diversity of bistatic scattering wave, which was measured by RCS, was obtained. Different vorticity RF waves have the same RCS fluctuation for simple objects, but for complex targets, different RCS can be identified from the same incident angle, which makes the RCS diversity. This diversity can be used to detect weak targets traditionally detected by plane wave.

3.3. Research and Prospect

The scattering characteristics of targets are the basis of radar detection and identification. The influence of target radius and OAM modulus on the scattering characteristics of vortex RF wave is verified in reference [7]. These conclusions will have a great impact on the application of vortex RF wave in the field of wireless detection and wireless transmission in the future. How to avoid the attenuation of spiral spectrum in scattering will be the focus of future research.

Reference [13] simulates the far-field scattering of HOBVB to aircraft model, and the research results can provide reference for other research on OAM scattering characteristics and scattering mechanism of non-diffractive vortex RF wave in complex radar target field.

In terms of improving detection capability, reference [14] shows that vortex RF wave has stronger detection characteristics than planar RF wave in some directions, and can detect low RCS targets more effectively. When the vortices carry different OAM modes, it may be helpful to detect low RCS targets by increasing the RCS of targets. The theoretical analysis in reference [15] shows that the OAM based radar can improve the target detection performance in the non specular reflection direction. The future work of OAM radar is proposed, including the research on the orc characteristics of complex targets and the experimental measurement of calibrators.

It is known that linear Doppler shift has been widely used to infer the velocity of approaching objects, but it can not detect rotation. Reference [18] studied the detection performance of the light carrying OAM to a rotating object. By analyzing the OAM scattered from the surface of the rotating object, it was observed that the product of the OAM scattering from the surface of the rotating object was directly proportional to the frequency offset of the rotating object, and even when the angular momentum vector was parallel to the observation direction, the rotation frequency offset still existed. Therefore, OAM can also be used for remote detection of revolution in terrestrial and astronomical environments.

The scattering of vortex RF waves by chaff clouds was studied in reference [19]. The results show that after passing through the chaff cloud, the transmitted vortex RF wave no longer has the ideal OAM characteristics, but the information carried by the vortex RF wave is easier to pass through the chaff cloud than other wave types. The reason is that the information carried by the vortex RF wave is located in the azimuth domain (carried by OAM mode value) in addition to the time and frequency domain, so it can be detected by OAM mode value filtering. These characteristics greatly promote the application of vortex RF wave in chaff jamming.

Based on OAM scattering characteristics, LMT and others believe that the measurement method widely used in vortex RF wave radar technology has defects [17, 18]. A multiple signal classification (Music) algorithm is proposed to improve the resolution of the measurement method. Compared with the uncorrelated signal in traditional algorithm, the echo signal of target under MUSIC algorithm is
completely coherent. It can be seen that spatial smoothing technology will be applied to OAM system to solve the problem of coherence. MUSIC algorithm has super-resolution target detection ability.

On the basis of experiments in reference [15], it is concluded that the scattering characteristics of vortex RF waves determine that vortex RF wave has the anti-stealth ability of single static radar and double static radar. Vortex RF wave with large RCS can be applied to anti-stealth radar. Compared with ordinary plane wave, the beam with OAM component can greatly increase the probability of stealth target being irradiated and detected.

Patent [20] conceives a radio RF tag (RFID) based on OAM backscattering. One or more non-zero OAM components are used to transmit vortex RF waves with specified state. The beam is projected on the target to reflect, and receive the beam returned in the direct return path. The OAM component in the returned beam is measured to identify the target on the tag.

The source beam can have multiple OAM components, which provide additional degrees of freedom for processing the returned beam. In addition, OAM components and processing can be "carried" on top of other systems and functions to facilitate integration and expansion of functions. In OAM marking systems, OAM markers may be integrated with, for example, polarization markers, RF sensing or EO ranging. In OAM diversity signal processing system, OAM can be integrated with traditional polarization diversity RF antenna system.

Figure 4 shows the simplest OAM passive electromagnetic label system. The system consists of three parts: (a) antenna array transmitting and detecting vorticity RF waves; (b) The OAM backscatter tag to be activated on the target will capture the detection signal, change the signal in a known way and return the changed signal; (c) the antenna array receiving the detected vortex RF signal, which receives and processes the returned vortex RF wave, improves the signal-to-noise ratio, decodes the information and determines the RFID content by detecting OAM components.

4. Conclusions
The scattering characteristics of vortex RF wave are affected by many factors, such as the size, shape, width (radius) of the target object, the incident frequency of the RF wave, and the OAM mode value of the vortex carried by the RF wave. Due to its unique scattering characteristics, vortex RF wave will be widely used in wireless transmission technology, wireless detection technology, radar detection technology, OAM RF tag technology and so on in the future. Future research will focus on the detection of complex objects by vortex RF wave, diffraction of cold door materials by vortex RF wave, and how to avoid a large number of attenuation in the transmission process.

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