

A Topological Charge Continuously Tunable Orbital Angular Momentum (OAM) Electromagnetic Wave Generation Method Based on Fixed-length Delay Line Mixing Circuit

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Abstract – To overcome the drawback of complex structure and high cost attributed from the utilization of phase shifters to generate OAM in the conventional schemes, this paper proposes a new method for generating OAM based on a fixed delay line. By deriving the proposed system with fixed delay line theoretically, the relationship between the frequency of the input signal on the delay line and the topological charge of the OAM is obtained, and the topological charge of the generated OAM can be controlled by controlling the frequency. Furthermore, this paper proposes a vortex beam pointing control method based on phased array scanning, so as to realize the beam steering of OAM. It is then verified by using electromagnetic simulation, and the simulation results show that the proposed method is feasible. The proposed method not only has the advantages of simple structure and low cost, but also can generate OAM with continuously adjustable topological charge by controlling the frequency, which has the functions of topological charge reconstruction and dynamic adjustment.

Index Terms – beam steering, continuous topological charge, delay line, vortex electromagnetic waves.

I. INTRODUCTION

In recent years, to increase the channel capacity and spectrum utilization, and to make the communication network more reliable and secure, the Orbital Angular Momentum technology [1, 2] has been introduced. The electromagnetic wave-carrying OAM is called vortex electromagnetic wave, and its wavefront phase is different from the plane structure of traditional plane wave due to carrying orbital angular momentum [3]. This feature provides a new direction for increasing information transmission capacity and improving spectral efficiency [4]. It is mentioned in [5] that vortex electromagnetic waves carry information about geometric shapes

and material properties. Additionally, the orbital angular momentum multiplexing technology of vortex electromagnetic waves has extremely efficient frequency utilization and anti-interference ability [6], and has good application prospects. The research of vortex electromagnetic waves in optics has been relatively mature. Compared with the great role played by vortex electromagnetic waves in the field of optics, it cannot fully play the role of vortex electromagnetic waves in the field of wireless communication [7].

According to the existing literature, it can be determined that the main methods of generating orbital angular momentum are: helical reflector structure [8], transmission helical structure [9], transmission grating structure [10], and array antenna [11, 12]. At present, the method of using array antennas to excite vortex electromagnetic waves has been widely studied [13], but due to the high cost of phase-shifting devices in the array, it is not conducive to mass production and manufacturing. To reduce the cost of phased arrays that generate vortex electromagnetic waves, international researchers have adopted a variety of methods to reduce the cost of phased arrays, mainly in the following aspects: improving phase-shifting devices [14], reducing the cost of phase-shifters number [15], and make a reasonable array [16], so the related theory of vortex electromagnetic wave is still worthy of in-depth study.

II. GENERATION OF VORTEX ELECTROMAGNETIC WAVES BASED ON A FIXED DELAY LINE

The schematic diagram of the vortex electromagnetic wave generated by the uniform circular array is shown in Fig. 1 [17]. Based on the method of fixed delay line, the phase offset between each array element is controlled, so as to generate continuous topological charge OAM by changing the frequency. However, this

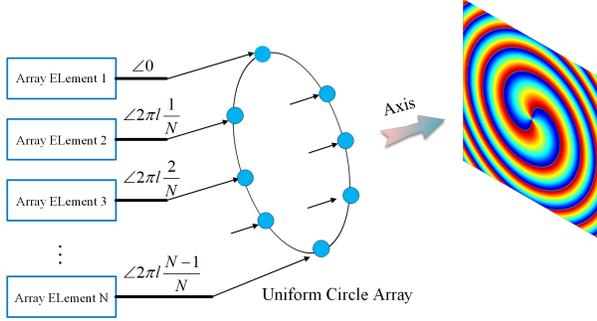


Fig. 1. Schematic diagram of vortex electromagnetic wave generated by uniform circular array.

approach causes the beam's transmit frequency to vary with its topological charge. Since most communication systems require a constant transmit frequency, a heterodyne mixer can be added to each antenna element so that the radio frequency (RF) transmit signal appearing at each antenna element is the result of mixing an intermediate frequency (IF) signal and a local oscillator (LO) signal.

Based on the basic principle of the above-mentioned uniform circular array to excite vortex electromagnetic waves, this paper proposes a phase shifter-free vortex electromagnetic wave generation system, which includes a LO signal source and an IF signal source. The output end of the LO signal source is connected to the delay line, which is respectively connected to the input end of the heterodyne mixer. The other input terminal of each heterodyne mixer is connected to the IF signal source. The output terminals of each heterodyne mixer are connected to an antenna unit and the antenna units are arranged in a circle at equal intervals. The specific schematic diagram is shown in Fig. 2. From Fig. 2, the specific method of exciting the vortex electromagnetic wave is based on the determined antenna element number and the initial vortex electromagnetic wave modulus. The phase shift of the LO signal entering each heterodyne mixer is determined, so as to obtain the length of each delay line. The heterodyne mixer is connected with the LO signal source through the delay line; the LO signal and the IF signal entering into it are mixed through the heterodyne mixer, then each mixed frequency signal is mixed through the antenna unit. The signal is transmitted to complete the generation of the vortex electromagnetic wave. Finally, the vortex electromagnetic wave with continuous topological charge can be obtained by changing the frequency of the LO signal. Accordingly, the relationship between the frequency of the LO signal and the topological charge of the generated vortex electromagnetic wave can be derived.

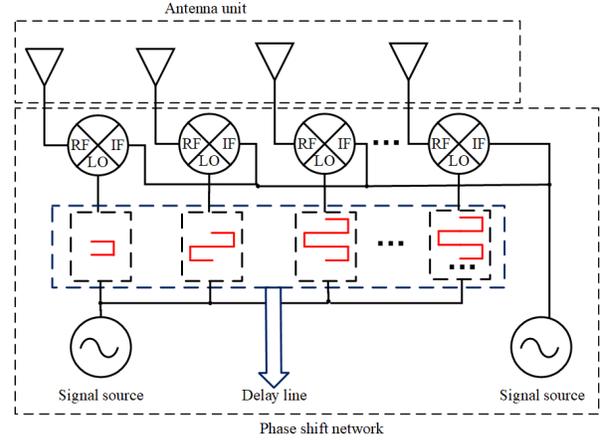


Fig. 2. Phase-shifting network structure based on delay line.

Set the IF signal and the LO signal:

$$S_{IF} = A \cos(\omega_1 + \psi_1), \quad (1)$$

$$S_{LO} = A \cos(\omega_2 + \psi_2), \quad (2)$$

It is known after mixing the two signals that if the frequency of the LO signal increases by $\delta\omega$, to ensure that the frequency of the output RF signal does not change after mixing, the frequency of the IF signal needs to be reduced by $\delta\omega$. Assuming the length of the delay line is l' , according to the phase shift constant of the delay line, the phase shift $\delta\psi$ it can produce is:

$$\delta\psi = l' \omega \sqrt{\epsilon\mu}, \quad (3)$$

It can be seen from Fig. 2 that if the delay line acts on the LO signal source, the LO will add a phase shift generated by the delay line and combined with Equation (3), namely:

$$S_{LO} = A \cos((\omega_2 + \delta\omega)t + \psi_2 + l'(\omega_2 + \delta\omega)\sqrt{\epsilon\mu}), \quad (4)$$

The initial phase of the signal source ψ_1, ψ_2 can be set to 0. Assuming that the number of antenna elements is M , to obtain a vortex electromagnetic wave with a topological charge of l , the phase offset required by the m th antenna element $\delta\psi_m$ is:

$$\delta\psi_m = \frac{2lm\pi}{M}, \quad (5)$$

Then according to Equations (3) and (5), the length of the delay line corresponding to the m th antenna unit can be calculated as:

$$l'_m = \frac{2lm\pi}{M\omega_m\sqrt{\epsilon_m\mu_m}}, \quad (6)$$

where ω_m is the angular frequency of the LO signal entering the m th delay line, ϵ_m is the dielectric constant of the m th delay line, and μ_m is the permeability of the m th delay line.

The above derivation process and conclusion are under the premise that the number of array elements of the antenna array is large enough, but the number of

array elements of the antenna array is an important factor affecting the topological charge of the vortex electromagnetic wave. Although the topological charge number of vortex electromagnetic waves can take any integer value in theory, the maximum number of topological charges that can be generated is determined by the number of array elements of the antenna array that generates vortex electromagnetic waves compared with conventional arrays. The range of topological charges that can be generated by a circular phased array is:

$$-\frac{M}{2} < l < \frac{M}{2}, \quad (7)$$

where M represents the number of elements of the antenna array. When the topological charge l is greater than or equal to M , there will be no pure helical phase wavefront generation, which means that no perfect vortex electromagnetic wave can be obtained.

It can be seen from the above derivation that when the length of delay line is fixed, the number of OAM topological charge increases by 1 for every doubling of the signal frequency applied on the delay line. Within the range of OAM topological charges allowed by the number of array elements, the structure can produce OAM with tunable continuous topological charges only by adjusting the frequency.

Based on the uniform circular array with radius A , the number of array elements M is selected as 8, working frequencies of 10 GHz and 4 GHz were selected to conduct electromagnetic simulation. The simulation results are shown in Table 1.

It can be seen from Table 1 that the phase diagrams of electromagnetic waves generated by this method all present the shape of helical phase wavefront, which is a typical feature of vortex electromagnetic waves. The electromagnetic simulation results show that with the increase of the topological charge number, the generated side-lobe of the OAM pattern increases and the zero-depth region increases, indicating that the energy is gradually dispersed with the increase of the topological charge number. Additionally, according to the degree of color alternation, the phase change values of the vortex electromagnetic wave can be obtained respectively as 2π , 4π , and 6π , corresponding to the topological charges of OAM being 1, 2 and 3. It further proves the feasibility of the OAM generation method without phase shifter proposed in this paper, and that the method is suitable for different working frequencies.

The above simulation results show that this method can generate relatively ideal vortex electromagnetic waves. Next, the topological charge of the generated vortex electromagnetic waves is fixed at 1, and the array radius and operating frequency parameters are modified. Phase diagrams of vortex electromagnetic waves corresponding to different operating frequencies. Table 2

Table 1: At different frequencies, OAM with l being 1, 2, and 3 corresponds to 3-D Pattern, Amplitude, and Phase diagrams

\		3-D Pattern	Amplitude	Phase
10 GHz	$l = 1$			
	$l = 2$			
	$l = 3$			
4 GHz	$l = 1$			
	$l = 2$			
	$l = 3$			

Table 2: Phase distribution of radiation field under different array radius and frequency when M is 8

Frequency \ Radius	$\lambda_0/4$	$2\lambda_0$	$3\lambda_0$
4 GHz			
6 GHz			
8 GHz			
10 GHz			

shows the phase diagram results based on the 8-element uniform circular array. Where, λ_0 is the corresponding wavelength when the operating frequency is 10GHz. As can be seen from the table, the array radius and operating frequency will have a certain impact on the OAM. For a fixed frequency, as the array radius increases, the phase image of the OAM begins to appear phase aliasing; for a fixed radius, as the operating frequency increases, the phase image of the OAM begins to appear phase aliasing. This is because the side lobes of the radiation pattern of the uniform circular array increase, and the vortex electromagnetic wave radiation field is in the state

of superposition of the main lobe radiation and the side lobe radiation. When phase aliasing occurs, the vortex electromagnetic wave has not only one OAM mode, but also a superposition of different OAM modes in the main lobe and side lobes. [18] presents an algorithm for vortex beam optimization design that might be needed to optimize the sidelobe level of the vortex beam.

III. GENERATION OF VORTEX ELECTROMAGNETIC WAVES WITH ARBITRARY ORIENTATION BASED ON PHASED ARRAY

To generate a vortex electromagnetic wave with a topological charge number l , the excitation phase of the array element needs an additional phase β_n , which can be expressed as:

$$\beta_n = jl\psi, \quad (8)$$

Therefore, if we want to generate a vortex electromagnetic wave with a topological charge of l and a beam direction of (θ_0, ψ_0) , the radiation function of the array is:

$$G(\theta, \psi) = \sum_{n=1}^N e^{il\psi_n} e^{jka(\sin\theta\cos(\psi-\psi_n) - \sin\theta_0\cos(\psi_0-\psi_n))}, \quad (9)$$

Setting $u = \sin\theta\cos\psi - \sin\theta_0\cos\psi_0, v = \sin\theta\sin\psi - \sin\theta_0\sin\psi_0, \cos\xi = \frac{u}{\sqrt{u^2+v^2}}$, Equation (9) can be simplified as follows:

$$G(\theta, \psi) = \sum_{n=1}^N e^{il\psi_n} e^{jkap\cos(\xi-\psi_n)}, \quad (10)$$

Assuming N is infinite, Equation (9) can be rewritten for derivation, and then compared with the Bessel function of order l , the following formula can be obtained:

$$G(\theta, \psi) = Ne^{il\xi} e^{jl\frac{\pi}{2}} j^{kap}, \quad (11)$$

According to Equation (11), OAM can still be generated by uniform circular array after phased control. Set simulation parameters for electromagnetic simulation verification. The uniform circular arrays with 8 elements are simulated respectively. The array radius is set to a , and the transmit frequency is set to 10 GHz. The 8-element uniform circular array is simulated to analyze whether the vortex beam generated by the antenna array has a specific direction when the topological charge of the vortex electromagnetic wave is different.

The corresponding vortex electromagnetic wave amplitude and purity simulation diagrams are given in Fig. 3. It can be seen from Fig. 3 that for different pitch angles and different horizontal azimuth angles, the amplitude map can have a given orientation. Additionally, for a uniform circular array with an array element number of 8, when the topological charge of the vortex electromagnetic wave is 1, 2 and 3, the beams

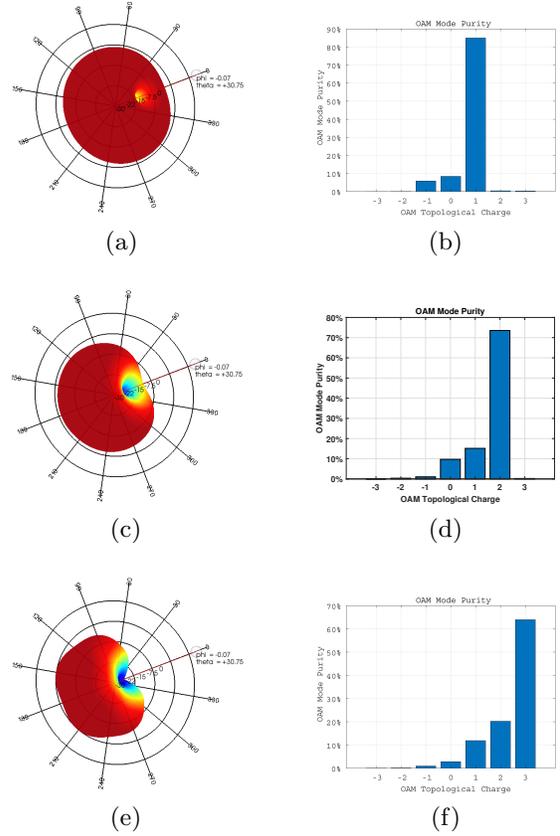


Fig. 3. M is 8, (a), (c), (e) is the amplitude map when L is 1, 2, and 3 respectively and (b), (d), (f) is the amplitude map when L is 1, 2, and 3 respectively.

all have directions, so the beam direction of the vortex electromagnetic wave is not affected by the topological charge of the vortex electromagnetic wave. Therefore, the proposed method for designing vortex electromagnetic waves with arbitrary radiation patterns is feasible.

It can be seen from the purity maps of different topological charge numbers represented by Figs. 3 (d), (e), and (f) that OAM waves with different topological charges still dominate after beam steering, but with the increase of topological charges, the dominant dominance gradually decreases. While the OAM purity decreases, it can be seen that the zero-depth region of the magnitude map relatively increases. This is because the phases of the phased array and the OAM are superimposed on the array antenna at the same time. Although the purity is not as good as before phase control, the main mode still dominates.

IV. CONCLUSION

Due to the high cost and single topological charge of using array antenna for exciting vortex electromagnetic

waves, this work developed a novel method to generate vortex electromagnetic waves by using fixed delay line instead of phase shifters. Based on the fundamental theory analyses, it has been concluded that as when the length of the delay line is fixed, the frequency of the delay line is proportional to the topological charge of the vortex electromagnetic wave. Furthermore, the effects of different array radius and different radio frequency on the phase of vortex electromagnetic waves are discussed. For a fixed frequency, with the increase of the array radius, the phase image of OAM begins to appear phase aliasing; for a fixed radius, as the operating frequency increases, the phase image of OAM begins to appear phase aliasing. The propagation direction of the vortex electromagnetic wave generated by the proposed method is generally the axial direction of the vortex electromagnetic wave. However, to make the vortex electromagnetic wave have a specified beam direction, a vortex beam pointing control method based on phased array scanning is proposed. To make the vortex electromagnetic wave generated by the uniform circular array have a specified direction, it is necessary to add a phase varying on the basis of the phase originally required for exciting the vortex electromagnetic wave, so that the phase difference between the two adjacent array elements is related to the direction. Thereby the angles have a specific relationship so that the vortex beam is directed at a specified angle by adjusting the phase difference. Using the delay lines has greatly reduced the critical issue of high cost and complexity of the phase shifter when the vortex electromagnetic wave is generated by conventional uniform circular phased array. An OAM with continuous topological charge can be generated only by adjusting the frequency, which makes the potential application of vortex electromagnetic wave more practical and meaningful.

ACKNOWLEDGMENT

This research was supported by the Sichuan Province Science and Technology Support Program, (No.2022YFS0193) and Fundamental Research Funds for the Central Universities, (No.ZYGX2021YG LH025).

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