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Generation of coupled radio frequency orbital angular momentum beam with an optical-controlled circular antenna array

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ABSTRACT

A circular antenna array (CAA) principle for generating radio frequency orbital angular momentum (RF-OAM) beams with dual-opposite-states is proposed in an optical-controlled system. At this condition, the pre-existing restrictions of antenna amount for CAA system is extended. It is worth noting that the simulative beam patterns show almost no distortion in this superposition states case. In the following control experiment, transmission characteristics, including Error Vector Magnitude (EVM), Signal to Noise Ratio (SNR) and receiving power, are all improved significantly in each proposed coupled OAM channel, compared to ones in single-state OAM beam. The EVM can be decreased from 4.82% to 4.59% in average, and the receiving power is increased by 2.7 dB at the same transmission condition, which indicates effective propagation distance can be increased.

1. Introduction

Recently, orbital angular momentum (OAM) of electromagnetic (EM) waves has attracted more and more attention, as a result of its intrinsic advantages in providing new degrees of freedom for communications. Due to the orthogonality of the OAM eigenstates [1], the OAM mode division multiplexing (OAM-MDM) technique can meet the exponentially increasing demand for transmission capacity. The OAM beam has a helical phase front comprising a spatial azimuthal phase term $\exp(il\varphi)$, where l is the topological charge of OAM state (an unbounded integer) and φ is the transverse azimuthal angle [2]. OAM has found practical applications in wireless communication ranging from optics to radio [3–6]. With the rapid development of digital media, dense coding and channel sharing techniques can no longer meet the growth of communications in radio band [7], thus leading to imperious demands in developing new spatial degrees of freedom for communications. Therefore, introducing and developing new methods to apply OAM techniques in the EM spectrum is a promising way to solve this problem.

The rapid growth in wireless data usage also presents a challenge to telecommunication network operators and service providers to ensure that the capacity of their networks are capable of supporting the increasing demand, while utilizing the available spectrum efficiently. The radio frequency (RF) OAM opens a door to increase the wireless channel capacity in an infinite manner. Unlike multiple-input-multiple-output (MIMO) approach in RF communication, OAM multiplexing is one technique utilizing the rotational EM degrees of freedom instead of translational degrees [8]. Both OAM and MIMO approaches can be applied simultaneously to enhance system capacity potentially with proper antenna spacing [9]. Compared to the mature MIMO technique, researches about the emerging RF-OAM will promote the combination of these two techniques readily bringing broader prospects for wireless communications.

The first step to make OAM applications possible is the generation of OAM beams. Many approaches have been proposed and demonstrated for generating OAM, such as using spiral phase plate (SPP) [10] and diffractive phase holograms (DPH) [11,12]. RF-OAM beams generated by a circular antenna array (CAA) has been proved by Thidé et al. in Ref. [13] via some numerical experiments. Unlike the converter method [10] that creates OAM beams using the spatial phase distribution generated by a set of filters, purer and more accurate RF-OAM beam based on CAA could be generated in a simple optical-controlled system that is independent of manufacturing techniques. Moreover, it is very convenient to realize OAM beam multiplexing in CAA system, which is compatible with present optoelectronic systems without additional complex devices [14] and alignments. In SPP and DPH multiplexing systems, many collimators will be used to make OAM beams with different states couple. And the alignment will seriously affect practical applications and operations. Besides, owing to the natural advantages of optical spectral process, such as high frequency and large bandwidth,

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processing electrical signals in optical domain has more potential in future communications [15]. In addition, it is a reasonable way to detect rotational objects using coupled OAM beams [16]. Therefore, the optical-controlled CAA system has superiority in communication and detection.

In this paper, CAA is applied to create dual-opposite-states RF-OAM beams in an optical-controlled system. The amount of antennas to generate dual coupling OAM states can be reduced is firstly proposed. In another word, more OAM states can be achieved in a same antenna array to increase the communication channel. Numerical simulations as well as experiments are performed to verify it. By comparing multiple groups of simulative results with diverse OAM states in different CAAs, optimized pure OAM beams are obtained in dual-opposite-state coupling way. Furthermore, a proof-of-concept experiment is established by an optical-controlled system using a CAA incorporating with four antennas to generate OAM beams with the states of ±2, which is out of the former restrictions of antenna amount. At last, control experiments are conducted to confirm the superiority of coupled OAM beams in the transmission performance by comparing coupled OAM beam's constellations to the beam's in single OAM state in the same OAM beam generation system. In addition, higher received power can be achieved in dual-opposite-states. In another words, the effective propagation distance can be increased in this case, which may contribute to the applications for detection and remote sense. The good performance of multiplexing OAM beams may lead to more advantages, such as enhancing the communication capacity, on the wireless communication with same antenna system. That means it is convenient and efficient to upgrade the existing radio frequency radar system with a high channel capacity and additional spatial information. After solving some key technologies like OAM beam steering and partial receiving, applications of communication and detection system using RF-OAM beam will be widely used with low cost in the future.

2. Theoretical analysis and simulation

The concept and principle for generating OAM beams by antenna arrays is that identical spiral phase structure can be found in a beam with pure OAM states [17]. Actually, the EM field of the CAA can be resolved into OAM beam structures with pure OAM states via a discrete Fourier transform (DFT). In order to study the characteristic of CAA EM field, we suppose that each antenna is located along the circle with the same interval, and the antennas are fed gradual increasing phase signals with an increment step of $2\pi l/N$. Gaussian wave is used as the original source in each antenna. CAAs with N elements are used to generate the OAM radio beams, and θ represents the angle between the CAA plane and the direction from the center of CAA to the field point. The array factor of such a CAA can be expressed as

$$G \approx N i^{l} e^{il\varphi} J_{l}\left(\frac{kD}{2}\sin\theta\right) \tag{1}$$

where D is the diameter of the array, and $k = 2\pi/\lambda$ is the wave number. For practical applications, the number of antennas N is finite and integral in a circle, thus there is an upper limit on the OAM state. As a consequence, it can be deduced that the OAM with the expected state l will be obtained via CAA as long as l conforms to the following condition [13]:

$$-\frac{N}{2} < l < \frac{N}{2} \tag{2}$$

OAM beams with too large values of $l(|l| \geq N/2)$ will not produce a stable OAM mode number. The beam pattern will be distorted without a continuous rotational phase front. However, the limitation of l is changed, when the generated OAM beams are coupled with two states which have the same module but opposite sign, such as $l = \pm 1$. Because of the circular symmetry of these dual OAM beams, the phase gradient direction of each state can be converted mutually. For Eq. (1), the superposition of the array factors G remains constant for two OAM states with contrary signs. Therefore, the value range of l is expanded for this dual-opposite-states case, and the constraint condition is extended to

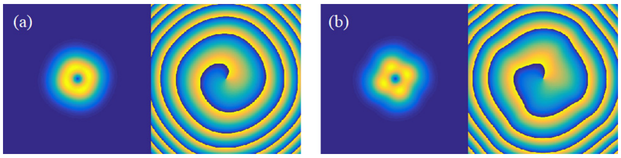

Fig. 1. Simulated intensity (left) and phase (right) of the generated OAM beams using four antennas in both (a) and (b). The observed distance is 30 times the wavelength with the array diameter of (a) 2 times and (b) 4 times the wavelength.

$$-\frac{N}{2} \leq l \leq \frac{N}{2} \tag{3}$$

In addition, the dual-opposite-state OAM beams generated by CAAs have high accuracy. It is worth noting that commonly the generated OAM beam is not pure in state. Actually, errors and disturbances in experiments will lead a non-integer OAM state which can be decomposed into a Fourier series superposition of standard integral OAM states [18]. Obviously, the expected OAM state l is the main component, and the redundant components are high-order-state clutters which need to be eliminated. Once the OAM beams with both states of $\pm l$ are coupled using CAA, the other orders of states from errors and disturbances will be counteracted judging from the derivation of Eq. (1).

To illustrate this transmission model, a group of simulations is made in different conditions. Gaussian wave is transmitted from each antenna with designed different phase. And a received plane is defined at a certain distance to acquire intensity and phase information. Fig. 1 shows the simulative results of the OAM beam intensity and phase using a 4 antennas array with the state of +1 which is received at a distance of thirty times wavelengths along the propagation axis. According to Eq. (1), the diameter of the arrays and the number of antennas are the main influencing factors to the accuracy and quality of OAM beams. In order to get a desirable simulation effect, four antennas are used to form the CAA. The array diameters of Fig. 1(a) and Fig. 1(b) are 2 times and 4 times the wavelength, respectively. In this simulation, based on Eq. (2), only 3 OAM states (−1, 0 and +1) can be achieved with 4 antennas. Obviously, with the increase of antenna array radius, the distortion becomes more serious. Furthermore, it can be seen from Fig. 1(a) that the simulative result still remains slight distortion compared to the ideal model with the OAM state of +1.

In fact, better performance of OAM beams can be achieved by using more antennas with the same OAM state. In another word, the OAM mode purity will be improved while increasing the number of antennas. For instance, 16 antennas are sufficient to generate desirable OAM beams for this case, comparing to the ideal model. The OAM mode purity can reach 99% with 16 antennas to generate the state of ±2 in this simulation. As shown in Fig. 2, the simulative results of the dual coupled OAM beams with the states of contrary signs are obtained by varying the amount of antennas, while the receiving distance and array diameter are kept unchanged. As a matter of convenience for comparison analysis, the array diameters in Fig. 2 and the ones in Fig. 1(a) are set at the same size. Different amounts of antennas N ($N = 2, 4, 16$) are applied in the simulations of the coupling OAM beams with $l = \pm 1$ in Fig. 2(a) and $l = \pm 2$ in Fig. 2(b). Compared with the first simulation, the OAM states number is extended with the states of −2 and +2 in a 4 antennas system in this special coupling method. Obviously, there is no difference in each two groups of the figures, which indicates that the distortions are avoided through the way of using CAA to generate the dual-opposite-state OAM beams. Besides, the conditions of $N = 2$ in Fig. 2(a) and $N = 4$ in Fig. 2(b) demonstrate that the limitation of l in Eq. (2) can be broken up and alternatively it satisfies Eq. (3). Similar conclusions can be obtained with $N = 6, 8 \ldots$ to generate OAM states of $l = \pm 3, \pm 4 \ldots$ in the same conditions.