Study of propagation of Airy array vortex beams in turbulent atmosphere

Xu Yan, Lixin Guo, and Teng Gong
School of Physics and Optoelectronic Engineering
Xidian University
Xi'an, China
E-mail: yanxu_wuli@163.com

Mingjian Cheng
State Key Laboratory of Pulsed Power Laser Technology
National University of Defense Technology
Hefei, China
E-mail mjcheng_optic@163.com

***Abstract*—A circular phased-locked Airy beam array carrying orbital angular momentum (OAM) propagating through turbulent atmosphere is investigated in detail. The results testify that the OAM modes generated by the array are closely associated with the number of beamlets, requiring the number of beamlets at least twice more than the values of the OAM topological charge to transmit signal precisely. Furthermore, through multiple-phase-screen simulations, it is shown that the anti-jamming performance of an Airy beam array is significantly enhanced.**

Keywords—Atmospheric optics; Atmospheric propagation; Airy array vortex beam

I. INTRODUCTION

When a light beam propagates through the atmospheric turbulence, it is subject to extra beam spreading, beam wander, and scintillation. These optical turbulence effects strongly worsen the performance of free-space laser communications. Therefore, the key point that most research studies interesting is determining how to reduce the turbulence-induced degradation. Recently, the structural light beams inherently having the non-diffracting and self-healing propagation features upon propagation is utilized as an information carrier. Among these special structural beams, including Bessel, Bessel-Gaussian and Airy beams, Airy beam has the self-accelerating property which can be easily controlled, and its peak intensity can be repositioned on a given detector after transmitting through an random media in recent study[1]. Moreover, as it is well known, the OAM modes can not only increase the system capacity, but also resist turbulence-induced distortions.

Therefore, an optical vortex embedded within an Airy beam that has attracted the attention of many scientists, and considerable researches have been done to study the properties of the Airy beam carrying OAM in turbulent media. Using the Wigner distribution function, the beam wander of an Airy vortex beam in turbulent atmosphere is investigated, and the results indicate that the larger value of topological charge is, the minor beam wander effect [2]. What's more, [3] reports that the beam wander behavior of an Airy beam is mainly depend on its kurtosis parameter. The effect of the variation of partially coherent Airy beam parameters on its propagation properties through turbulent media are studied [4], finding that higher partial coherence and stronger turbulence will result in more spreading effect. However, these researches are restricted to a single Airy beam. Drawn a comparison with a single Airy beam, [5] shows that the scintillation of the Airy beam array is distinctly reduced and close to the theoretical minimum. [6] also indicates that the four-beamlets Airy array has an enhanced self-healing capacity at arbitrary obstructed positions upon propagation. Furthermore, the array usually has been proposed to provide the high-power output than that of a single laser beam and effectively expand its application area.

In this work, the properties of a circular Airy beam array carrying OAM propagates in turbulent atmosphere have been reported. Based on multiple-phase-screen numerical simulations, the role of the number of array element in the formation of the OAM modes is explored. This array has also shown the focusing property due to the self-accelerating property of Airy beam. The phase purity of Airy beam arrays is significantly preserved in consequence.

II. THEORETICAL ANALYSIS OF AIRY ARRAY VORTEX BEAM

A. Airy array vortex beam model

The optical field of the j-th Airy beam array beamlet at the source plane has the following form:

$$E_j = Ai(\frac{X}{x_0})Ai(\frac{Y}{y_0})\exp\left[a\cdot\left(\frac{X}{x_0}+\frac{Y}{y_0}\right)\right] \tag{1}$$

where

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \cos(\frac{j-1}{n}\cdot 2\pi+\pi) & \sin(\frac{j-1}{n}\cdot 2\pi+\pi) \\ -\sin(\frac{j-1}{n}\cdot 2\pi+\pi) & \cos(\frac{j-1}{n}\cdot 2\pi+\pi) \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} d \\ d \end{bmatrix} \tag{2}$$

where $Ai(\cdot)$ Ai is the Airy function, x_0 and y_0 denote transverse scales, $0 \le a \le 1$ is the truncation factor, X and Y are rotation matrixres, d is the transverse displacement parameter, and j=1,2,3,…, n, n represents beamlet number. Here, x_0 and y_0 are taken to be 0.012m and a=0.1.

Using Eqs.(1) and (2), the optical field of the phased-locked coherent Airy array beam in the transmitter plane can be expressed as:

$$U=\sum_{j=1}^{n} Ai(\frac{X}{x_0})Ai(\frac{Y}{y_0})\exp\left[a\cdot\left(\frac{X}{x_0}+\frac{Y}{y_0}\right)\right]\exp(il\frac{2\pi}{n}) \quad (3)$$

where l is the topological charge of the array beam.

B. Atmospheric turbulence model

By employing the multiple-phase-screen numerical simulations, the influence on OAM modes induced by atmospheric turbulence is explored. Firstly, the modified Von Kármán spectrum is utilized to develop the refractive-index fluctuations [7]:

$$\phi_n(\kappa)=0.033C_n^2\cdot\left(\kappa^2+\kappa_0^2\right)^{-11/6}\exp\left(-\kappa^2/\kappa_m^2\right) \quad (4)$$

Where C_n^2 is a constant value, representing turbulence strength. The $\kappa_0=2\pi/L_0$ and $\kappa_m=5.92/l_0$, with l_0 and L_0 being the inner and outer scale sizes. κ is the spatial frequency. With the help of the well-known Markov approximation [7], the trlation between phase and refractive spectra has the following form:

$$\phi_\varphi(\kappa)=2\pi k^2\Delta z\phi_n(\kappa) \quad (5)$$

Δz is the propagation distance. According to [8], the phase fluctuations of turbulent atmosphere can be expressed as:

$$\varphi(x,y)=FFT\left[C\cdot\frac{2\pi}{N\Delta x}\cdot\sqrt{\phi_\varphi(\kappa)}\right] \quad (6)$$

where $FFT[\cdot]$ represents the fast Fourier transformation, Δx is the grid spacing, and C is an $N\times N$ array of complex random numbers obeying the complex circular Gaussian statistics.

III. SIMULATION

Based on Eqs. (1)-(3), the influences of the number of the Airy beamlets on the OAM states formation of the array are numerically calculated and the results are shown in Fig.1. In Fig.3, the first and third rows correspond to the intensity distributions while the second and fourth rows to the spiral phase patterns with m=3 and 5, respectifely; the first, second, and third columns correspond to the number of beamlets with $n=2\cdot l-2$, $n=2\cdot l$, and $n=2\cdot l+10$, respectively, while the last row to the ring Airy beam. It is clear that when the number of array element is less than double value of topological charge, the Airy array can not format a given OAM mode. (see first column). As the number increases to the double value of topological charge, we can see that, there is the phase topological structure corresponding to the designed OAM mode but still existing some differences compared with the ring Airy vortex beam (second column versus last column). With the number of array element increase continuously, this difference is decreasing. Therefore, we indicate that the number of beamlets should be at least twice more than the values of the OAM topological charge for transmitting signal precisely.

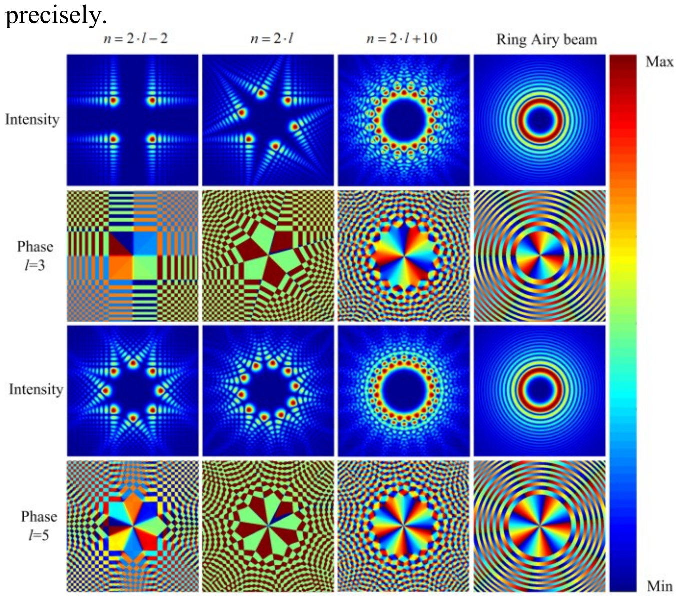

Fig.1. Intensity and phase images of the vortex beams with m=3 and 5. The first, second, and third columns correspond to the array beam with different elements while the last row to the ring Airy beam.

To show the performances of the Airy array vortex and single Airy vortex beams, the far-field intensity and spiral phase distributions through turbulent atmosphere with $C_n^2=2.5\times10^{-15}\mathrm{m}^{-2/3}$ at the distance of 2.8km are plotted in Fig.2. As illustrated in Fig.2, the Airy vortex beam keeps the intensity feature of the diagonal symmetry, but its spiral phase information lost. However, the Airy array vortex beam not only present the focusing ability obviously, but also preserve its spiral phase marked as the white dotted lines which indicates the Airy array vortex beam is an superior information carrier to communications .

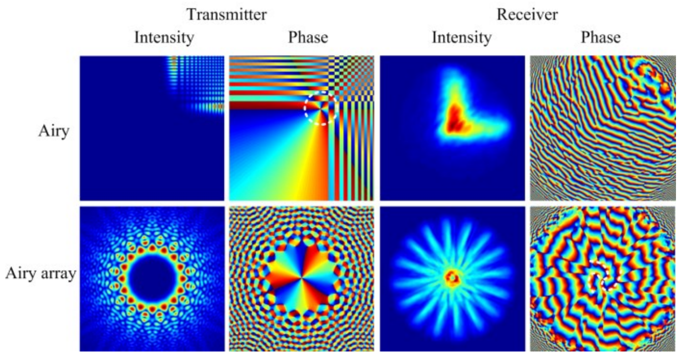

Fig.2. Intensity and phase images of the vortex beams with m=3 before and after propagating through atmospheric turbulence with $C_n^2=2.5\times10^{-15}\mathrm{m}^{-2/3}$

IV. CONCLUSION

In brief, through numerical simulations, we have demonstrated that the appropriately chosen number of an Airy beam array elements is necessary to format an OAM modes. Compared with a single Airy vortex beam, the phase purity of the array vortex beam propagating in the turbulent atmosphere is significantly preserved.

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