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A comparison of far-field properties of radial noncanonical vortex airy beam arrays and radial noncanonical vortex Gaussian beam arrays

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A B S T R A C T

Based on the vector angular spectrum representation and stationary phase method, the analytical far-field vectorial expressions of radial noncanonical vortex Airy beam arrays (NVAiBAs) and radial noncanonical vortex Gaussian beam arrays (NVGBAs) are derived, and used to investigate their far-field vectorial properties, e.g. center optical vortices and energy fluxes of these corresponding beams, where the effect of noncanonical strength, topological charge, initial phase index and the number of beamlet on far-field vectorial properties of these corresponding beams is emphasized, respectively. The results show that the topological charge of center optical vortices in the far field is equal to initial phase index for the case of the radial NVAiBAs, whereas for radial NVGBAs the topological charge not only lies on initial phase index, but also is closely related to the odevity and sign of optical vortices embedded in beamlet, where mathematical analysis is made to explain the topological charge of center optical vortices, and the limitation of the number of beamlet to the topological charge of center optical vortices is also discussed. In addition, energy fluxes of radial NVAiBAs and NVGBAs exhibit different space orientations by controlling noncancial strength and present larger dark zones by increasing topological charge of beamlet, respectively. Finally, the relationship between the center optical vortices and energy fluxes of radial NVAiBAs and NVGBAs in even or odd *N* beamlets is also revealed, respectively.

1. Introduction

Self-accelerating Airy beams have inspired prominent research interests since the pioneering work of Siviloglou and Christodoulides in 2007 [1,2]. Much effort has been devoted to explore their unique properties such as self-healing [3,4], sorting microparticles [5], optical micromanipulation [6–8], plasma physics [9,10] and vacuum electron acceleration [11,12]. On the other hand, optical vortices (OVs) are characterized by the complex zeros of optical wave fields where the phases possess spiral configurations. These spiral phases circulate around OVs $2l\pi$ in either a counterclockwise or clockwise direction determined by the topological charge l [13]. These spiral phases around the OVs circulating anticlockwise, then the sign of topological charge l is positive and negative if the spiral phase circulates clockwise. Canonical or symmetrical OVs are located at the real and imaginary parts of optical wave field vanishing cross at right angles, and they possess spiral phase with uniform variation [14]. While for the case of noncanonical OVs, zeros of the real and imaginary parts of electric field intersect at general angles [15]. Noncanonical OVs possess spiral phase with non-uniform distribution. For example, a canonical or noncanonical OV with different noncanonical strength $\xi+i\eta$ embedded in Gaussian beams exhibit different intensity distributions, respectively, where $\alpha=\arctan(1/\eta sgn(l))$ is the angle between zero lines of real and imaginary of electric field (see Fig. 1).

Recently the interest for the influence of OVs on Airy beams has gradually grown [16–24]. Specially, Mazilu et al. studied the creation and evolution of accelerating OVs embedded in Airy beams [16]. Dai et al. investigated experimentally and theoretically propagation dynamics of OVs imposed on Airy beams [17,18]. Propagation dynamics of the circular Airy beams with on-axis and off-axis OVs was analyzed by Jiang et al. [22]. However, until now optical vortices embedded in Airy beams were considered only in the canonical case, and the effects of noncanonical OVs on Airy beams or Airy beam arrays have not been dealt with.

Generally, the far-field properties for paraxial or non-paraxial cases in scalar field are investigated by using Fraunhofer diffraction method or Rayleigh-Sommerfeld diffraction method, respectively. However, based on the Maxwell equation, the vectorial descriptions and nonparaxial characteristics of laser beams can be dealt with [25,27]. By means of the vector angular spectrum method, the solutions of Maxwell equation can be separated into transverse electric mode (*TE*) and transverse magnetic mode (*TM*) terms of electromagnetic field. Up to now, far-field vectorial

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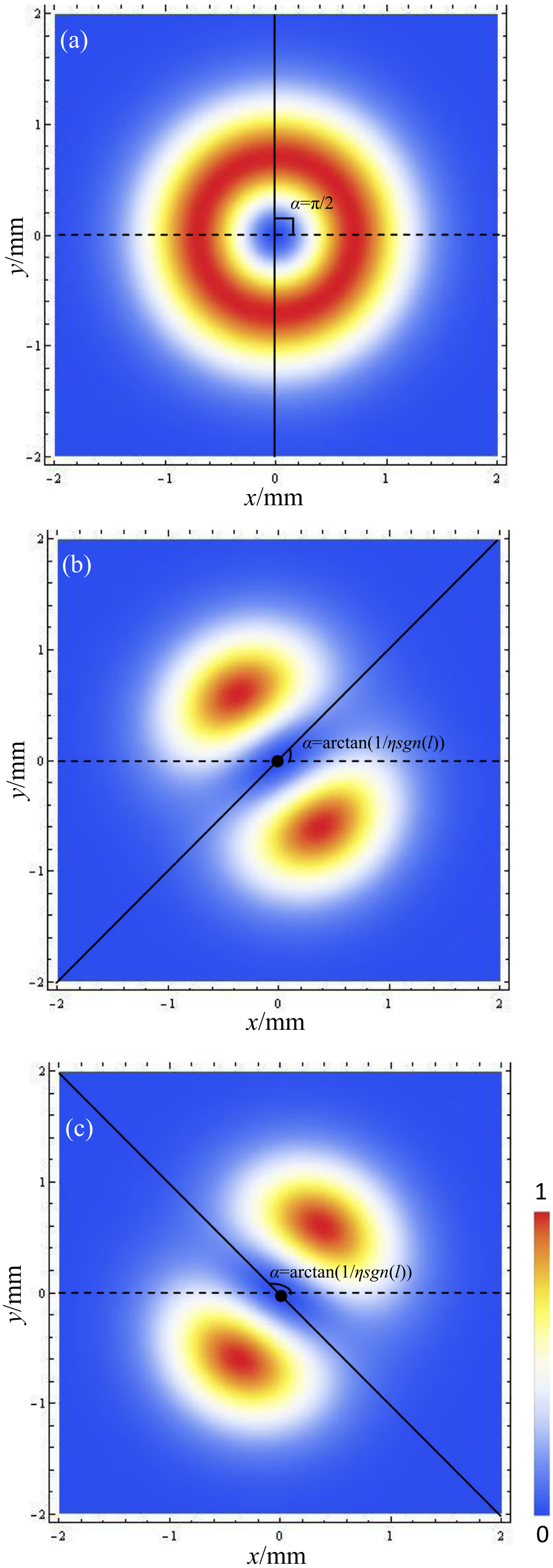

Fig. 1. Intensity distribution of a canonical or noncanonical vortex embedded in a Gaussian beam with waist width equaling 1 mm for different noncanonical strength $\xi+i\eta$. $l=+1$, (a) $\xi+i\eta=1$; (b) $\xi+i\eta=1+i$; (c) $\xi+i\eta=1-i$. The solid and dashed lines are zeros of the real and imaginary part of electric field, respectively. The real and imaginary parts of electric field cross each other at general angles of $\alpha=\arctan(1/\eta sgn(l))$ $(\eta\neq0)$ for the case of noncanonical vortices, while for canonical vortices of $\xi+i\eta=\pm1$, the zero lines of real and imaginary part of electric field are orthogonal at the location of vortex core.

properties of hollow Gaussian, nonsymmetrical Gaussian, Lorentz-Gauss, elliptical Gaussian vortex, Airy and vortex Airy beams etc. have been extensively studied [25–31]. These studies mainly focus on the case of a single laser beam. However, the far-field vectorial properties of laser beam arrays [32–44] are not mentioned. The interesting question is what happens for the coherent combination of N identical off-axis noncanonical vortex Airy or Gaussian beamlets based on the vector angular spectrum method.

The motivation of this work is to explore the far-field vectorial properties of radial noncanonical vortex Airy beam arrays (NVAiBAs). The NVAiBAs are formed by the radial coherent combination of N identical off-axis noncanonical vortex Airy beamlets. Meanwhile, we also make a comparison with the corresponding study for the case of radial noncanonical vortex Gaussian beam arrays (NVGBAs) (also see Figs. S1 and S2 of Supplemental materials). The results indicate that the topological charge (TC) of center optical vortices in the far field is equal to initial phase index for the case of the radial NVAiBAs, whereas for radial NVGBAs the topological charge not only lies on initial phase index, but also is closely related to the odevity and sign of optical vortices embedded in beamlet. The topological charge of center optical vortices can affect the symmetry of energy fluxes of radial NVAiBAs and NVGBAs in even or odd N beamlets, respectively. Accordingly, this work provides an alternative way to manipulate the symmetry of energy fluxes by selecting appropriate topological charge of center optical vortices.

2. Analytical vectorial expressions of radial NVAiBAs and NVGBAs in the far field

In the Cartesian coordinate system, radial NVAiBAs are formed by N identical off-axis noncanonical vortex Airy beamlets as depicted in Fig. 2 (also see Fig. S2 of Supplemental materials), where each beamlet with different initial phase φ_j is uniformly located on a circle with radius ρ. The off-axis coordinates of the jth beamlet are $x_j=\rho\cos\theta_j$ and $y_j=\rho\sin\theta_j$ along x and y axes in the input plane, where $\theta_j=2j\pi/N$ is the azimuth angle of the jth beamlet [38,45]. Assume that the jth beamlet linear-polarized in the x-direction propagates toward the half free space $z\geq0$ and the y-direction electric field is equal to zero. At the input plane of $z=0$, the x-direction electric field of the input jth off-axis noncanonical vortex Airy beamlet with different initial phase φ_j is written as [17,38,45]

$$E_j(x,y,0)=F(x,y)\prod_{\chi=x,y}Ai[(\chi-\chi_j)/w_0]\exp[a(\chi-\chi_j)/w_0]\exp[i\phi_j],\tag{1}$$

where $Ai(\bullet)$ represents the Airy function, w_0 is the transverse scale of Airy beamlets, a is the positive exponential truncation factor, (x_j, y_j) denotes the off-axis position, the initial phase $\varphi_j=2jm\pi/N$ and initial phase index of beamlet m here is restricted to integer value.

The noncanonical vortex function $F(x, y)$ is described by [14,15]

$$F(x,y)=\left[(x-x_j)+isgn(l)Q(y-y_j)\right]^{|l|},\tag{2}$$

where l is the topological charge or order number of the nested vortex in each beamlet at $z=0$ plane, (x_j, y_j) is also the off-axis position of noncanonical vortex, $sgn(l)$ is sign function, and if $l>0$, $sgn(l)=1$, for $l=0$, $sgn(l)=0$, and for $l<0$, $sgn(l)=-1$. The value of complex parameter $Q=\xi+i\eta$ stands for the noncanonical strength of the nested vortices and for $Q=\pm1$ the Eq. (2) is simplified to the canonical or symmetrical vortex [15].

In the coherent combination, the total electric field of the radial NVAiBAs at the $z=0$ plane can be expressed as