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The change of optical vortex on the paraxiality of fully coherent and partially coherent Airy beams

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ABSTRACT

The analytical expressions for the degree of paraxiality for fully coherent and partially coherent Airy vortex beams are obtained, respectively, and used to investigate the change of optical vortex on the degree of paraxiality. The results show that the paraxiality decreases when the optical vortex is nested in the Airy beam, while the noncanonical strength of optical vortex contributes nothing to the change of the paraxiality. A larger truncation factor leads to a higher paraxiality, and the effect of topological charge on the paraxiality gradually emerges with the increasing of the truncation factor. For a partially coherent Airy vortex beam, the paraxiality increases with an increase of transverse scale or truncation factor. While it is also shown that there exists critical value of w_{0c} or a_c, where a lower coherence length has an advantage in acquiring a higher paraxiality for $w_0 < w_{0c}$ or $a < a_c$. Whereas for $w_0 > w_{0c}$ and $a > a_c$, a higher coherence length contributes the partially coherent Airy vortex beam to be more paraxial. In addition, the changes between the paraxiality of the partially coherent Airy beams and partially coherent Airy vortex beams become small as the increasing of transverse scale or truncation factor.

1. Introduction

As a new class of diffraction-free beam, i.e. Airy beam, has exhibited unique properties from both theoretical aspects and applications [1]. For example, the propagation along parabolic trajectories in the free space was found by Siviloglou et. al in 2007 [2],3]. Further the self-regeneration ability was also present when the main lobe of the Airy beam is stopped by an obstruction object [4]. In general the propagation of paraxial Airy beam can be dealt with by means of the Helmholtz equation [2]. However the nonparaxial vectorial diffraction integrals should be used for the nonparaxial Airy beam, where the integrals are the exact solution of Maxwell equation [5]. The degree of paraxiality (DP) introduced by Gawhary et.al [6] can evaluate whether a monochromatic optical beam is paraxial or nonparaxial, where the paraxiality can be easily solved in the case of knowing only the field distribution at source plane and ignoring the propagation of the beam. Based on the definition of paraxiality [6], the change of circular aperture on the DP of Gaussian beam is investigated by Zhou [7]. Wang et al. extend the concept of the DP to a partially coherent field [8,9]. The effect of the transverse scale, truncation factor and coherence length on the DP of the Airy beam is analyzed by Dong et. al [10]. Further the paraxiality of some Airy-related beams is also studied by Torre [11], where two paraxiality criteria are discussed in detail.

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In these previous studies, the change of optical vortex on the DP of Airy beams is not considered. Thus, in this paper in contrast to other studies, our main attention is paid to evaluating the DP of the fully coherent and partially coherent Airy vortex beams. The effect of the topological charge and noncanonical strength in different beam parameters on the DP is stressed and illustrated numerically. The results obtained show that the embedded optical vortex can reduce the paraxiality of the Airy beams.

2. Degree of paraxiality of fully coherent Airy vortex beams

Assume that the electric field of a fully coherent Airy vortex beam at $z=0$ in the Cartesian coordinate is expressed as [12,13]

$$E(x,y,0) = [x + isgn(l)Qy]^{|l|} \prod_{\chi=x,y} Ai(\frac{\chi}{w_0})\exp(\frac{a\chi}{w_0}) \tag{1}$$

where Ai is the Airy function, w_0 represents the transverse scale, a is positive exponential truncation factor, sgn is sign function, l is related to the topological charge of the embedded optical vortex and the complex parameter Q=ζ+$i\eta$ is the noncanonical strength of the embedded optical vortex [13], respectively. For $Q=\pm 1$ the optical vortex corresponds to the symmetrical or canonical optical vortex.

The degree of paraxiality (DP) of a monochromatic light beam is defined by [6,14]

$$P = \frac{\iint_{p^2+q^2<1/\lambda^2} \left|A_0(p,q)\right|^2 \sqrt{1-\lambda^2(p^2+q^2)}dpdq}{\iint_{p^2+q^2<1/\lambda^2} \left|A_0(p,q)\right|^2 dpdq} \tag{2}$$

where $A_0(p, q)$ denotes the angular spectrum of the Airy vortex beam at $z=0$, and the wavelength λ is related to the wave number k by $\lambda = 2\pi/k$. The value of P is generally limited by $0<P<1$, and it can be directly determined by the initial field at source planeWhen $P=1$ the light beam is completely paraxial beam and $P=0$ denotes pure nonparaxial beam

The angular spectrum of a fully coherent Airy vortex beam in Eq. (2) is expressed by [10]

$$A_0(p,q) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} E(x,y,0)\exp[2\pi i(px+qy)]dxdy \tag{3}$$

In order to obtain the angular spectrum in Eq. (3) we define this integral as

$$U_{\alpha,\beta} = \iint_{\infty} x^{\alpha}y^{\beta} \prod_{\chi=x,y} Ai(\frac{\chi}{w_0})\exp(\frac{a\chi}{w_0})\exp\left[2\pi i\left(px+qy\right)\right]dxdy \tag{4}$$

The zeroth-order term in Eq. (4) can be described by

$$U_{0,0} = w_0^2 \exp\left\{\left[(a+2\pi ipw_0)^3 + (a+2\pi iqw_0)^3\right]/3\right\} \tag{5}$$

Higher-order terms in Eq. (4) can be derived by the following relations

$$U_{\alpha,\beta} = \frac{1}{(2\pi i)^{\alpha+\beta}} \frac{\partial^{\alpha+\beta}U_{0,0}}{(\partial p)^{\alpha}(\partial q)^{\beta}} \tag{6}$$

On substituting from Eq. (1) into Eq. (3) and using the Eqs. (5)–(6) one can obtain for $A_0(p, q)$ the expression

$$A_0(p,q) = \sum_{t=0}^{|l|} \begin{pmatrix} |l| \\ t \end{pmatrix} [isgn(l)Q]^{|l|-t} \frac{1}{(2\pi i)^{|l|}} \frac{\partial^{|l|}U_{0,0}}{\partial(p)^t\partial(q)^{|l|-t}} \tag{7}$$

where the binomial coefficient

$$\begin{pmatrix} |l| \\ t \end{pmatrix} = \frac{|l|!}{t!(|l|-t)!} \tag{8}$$

For $l=\pm 1$, Eq. (7) can be also simplified as

$$A_0(p,q) = w_0^3\left[(a+2\pi ipw_0)^2 \pm iQ(a+2\pi iqw_0)^2\right] \times$$

$$\exp\left\{\left[(a+2\pi ipw_0)^3 + (a+2\pi iqw_0)^3\right]/3\right\} \tag{9}$$