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Self-repeating properties of four-petal Gaussian vortex beams in quadratic index medium

Defeng Zou [a,b], Xiaohui Li [a,b,*], Tong Chai [a,b], Hairong Zheng [a,*]

[a] School of Physics & Information Technology, Shaanxi Normal University, Xi'an, 710119, Shaanxi, PR China
[b] National Demonstration Center for Experimental X-Physics Education, Shaanxi Normal University, Xi'an, 710119, Shaanxi, PR China

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ABSTRACT

In this paper, we investigate the propagation properties of four-petal Gaussian vortex (FPGV) beams propagating through the quadratic index medium, obtaining the analytical expression of FPGV beams. The effects of beam order n, topological charge m and beam waist ω_0 are investigated. Results show that quadratic index medium support periodic distributions of FPGV beams. A hollow optical wall or an optical central principal maximum surrounded by symmetrical sidelobes will occur at the center of a period. At length, they will evolve into four petals structure, exactly same as the intensity distributions at source plane.

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1. Introduction

During the past several decades, emerged insight into practical applications of free space optical communications and optical trapping has culminated in the concept of the vortex beams [1–5]. There have been reports that vortex beams could not only give rise to angular momentum around the propagation direction [6], but also possess polarization properties which correspond to the specific point on a higher-order Poincaré sphere [7]. So far, a variety of vortex beams have been studied theoretically or experimentally, such as Laguerre–Gaussian vortex beams [8,9], Airy–Gaussian vortex beams [10], Gaussian Schell-model vortex beams [11,12], and anomalous vortex beams etc. [13,14].

Very recently, a new kind of vortex beams called four-petal Gaussian vortex beams have attracted much interest. Lina Guo et al. investigated the propagating properties of FPGV beams propagating through a paraxial ABCD optical system [15]. It is demonstrated that spiraling wavefronts of the FPGV beams can modulate the beam profiles and carry on the orbital angular momentum. Moreover, Dajun Liu et al. studied the average intensities of FPGV beams propagating through the turbulence atmosphere [16]. Results show that FPGV beams maintain their four-petal profiles near the source plane and evolve into Gaussian-like structure in the far field. Also the research has been extended to the partially coherent case. The characteristics of the partially coherent four-petal Gaussian vortex beams in uniaxial crystals and turbulence atmosphere are studied [17,18].

As an ideal media for long-distance optical transmission, quadratic index medium has been widely studied to implement graded index waveguides, fibers and lenses [19–22]. To the best of our knowledge, there has been no report about the properties of FPGV beams propagating through the quadratic index medium. In this paper, we derive the analytical expression of FPGV beams in the quadratic index medium by using the Collins integral formula. Based on the Split Step Beam Propagation Method, propagation characteristics of FPGV beams are investigated. Results show that inhomogeneity has profound effects on the propagation dynamics of FPGV beams. They could support periodic intensity distributions of FPGV beams. At the source plane, they have the four petals structure. A hollow optical wall structure or a central principal maximum surrounded by symmetrical sidelobes will occur at the half of a periodic distance. Eventually, they will evolve into the four petals structure at a periodic distance, which is exactly the same as the intensity distributions at source plane.

2. Theoretical model

2.1. Four-petal Gaussian vortex beam

At the source plane, the electric fields of the FPGV beam can be expressed as:

* Corresponding author at: School of Physics & Information Technology, Shaanxi Normal University, Xi'an, 710119, Shaanxi, PR China.
E-mail addresses: lixiaohui@snnu.edu.cn (X. Li), hrzheng@snnu.edu.cn (H. Zheng).

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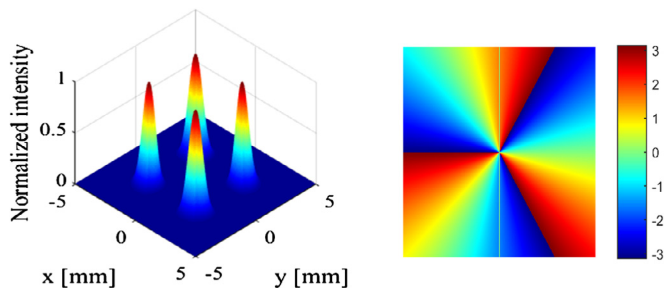

(a) (b)

Fig. 1. Normalized intensity distributions (a) and phase distributions (b) of a FPGV beam with $n = 3$, $m = 3$ at the source plane. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

$$E(x, y, 0) = \left(\frac{x_0 y_0}{\omega_0^2}\right)^{2n} \exp\left(-\frac{x_0^2 + y_0^2}{\omega_0^2}\right)(x_0 + iy_0)^m, \tag{1}$$

where ω_0 is the beam waist, n represents beam order and m is the topological charge of spiral phase plate. Equation (1) will be reduced to a common Gaussian beam if the beam order n and topological charge m is set to be $n = 0$, $m = 0$. Fig. 1 shows the normalized intensity distributions and phase distributions of a FPGV beam at the source plane. We can see that FPGV beam has four equal petals with the equal intervals. The equiphase contours take on threefold diverging rays and the number of contours is equal to the topological charges m exactly. It has been reported that not only the shape, but also the space of the four petals varies with the beam order n and topological charge m, which is different from the properties of four-petal Gaussian beams without vortex [15]. Accordingly, we can control the initial incident beam intensity distributions by choosing reasonable beam order n or topological charge m.

2.2. Mathematical formulation

For quadratic index medium, the intensity dependent refractive index varies as $n(r) = n_0(1 - a^2r^2/2)$. n_0 is the refractive index along the spatial axis and a describes measurement of the parabolic dependence of the index $n(r)$ [19]. It represents isotropic case when $a = 0$. While it corresponds to a medium with weakly inhomogeneity when $0 < a^2 \leqslant 1/2$, namely, the change in the refractive index can be neglected within a wavelength.

Considering optical field $E(r, z, t) = \psi(r, z)\exp(i\omega t)$, where ω is the circular frequency and $k = n_0\omega/c$ the wave number. The paraxial wave equation of the slowly varying envelope $\psi(r, z)$ in quadratic index medium can be expressed as follows [23]:

$$2ik\frac{\partial\psi(r_\perp, z)}{\partial z} + \nabla_\perp^2\psi(r_\perp, z) - k^2a^2r^2\psi(r_\perp, z) = 0, \tag{2}$$

where $\nabla_\perp = \partial^2/\partial x^2 + \partial^2/\partial y^2$ is the two dimensional transverse Laplacian operator. Based on the ABCD optical transformation matrix methods, the mathematical expression of FPGV beams propagating through the quadratic index medium can be derived. The transformation matrix of the quadratic index medium is expressed as follows [24]:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \cos(az) & \frac{1}{a}\sin(az) \\ -a\sin(az) & \cos(az) \end{pmatrix}. \tag{3}$$

Within the framework of the paraxial approximation, FPGV beams passing through the quadratic index medium obey well known Collins integral formula [25]:

$$\begin{aligned} E_n(x, y, z) = {} & \frac{i}{\lambda B}\exp(-ikz)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_n(x_0, y_0, 0) \\ & \times \exp\Big\{-\frac{ik}{2B}\big[A\big(x_0^2 + y_0^2\big) - 2(xx_0 + yy_0) \\ & + D\big(x^2 + y^2\big)\big]\Big\}dx_0dy_0, \end{aligned} \tag{4}$$

where $E_n(x_0, y_0, 0)$ and $E_n(x, y, z)$ correspond to the input electric fields and output electric fields, respectively. Recalling the following integral formulas [26]:

$$(x_0 + iy_0)^m = \sum_{s=0}^{m} \frac{m!i^s}{s!(m-s)!}x_0^{m-s}y_0^s, \tag{5}$$

$$\begin{aligned} & \int_{-\infty}^{+\infty} x^n \exp(-px^2 + 2qx)dx \\ & = n!\exp\left(\frac{q^2}{p}\right)\left(\frac{q}{p}\right)^n\sqrt{\frac{\pi}{p}}\sum_{k=0}^{[n/2]}\frac{1}{k!(n-2k)!}\left(\frac{p}{4q^2}\right)^k. \end{aligned} \tag{6}$$

By substituting Eqs. (1), (5), and (6) into Eq. (4) and carrying on some tedious calculations, the approximate analytical expression of the FPGV beams passing through the quadratic index medium can be obtained as follows:

$$\begin{aligned} & E(x, y, z) \\ & = \frac{i\pi}{\lambda pB\omega_0^{4n}}\exp\left[-ikz - \left(\frac{ikD}{2B} + \frac{k^2}{4pB^2}\right)(x^2 + y^2)\right] \\ & \quad \times \sum_{s=0}^{m}\frac{m!i^s(2n+m-s)!(2n+s)!}{s!(m-s)!}\left(\frac{q_{x_0}}{p}\right)^{2n+m-s} \\ & \quad \times \sum_{u_1=0}^{[(2n+m-s)/2]}\frac{1}{u_1!(2n+m-s-2u_1)!}\left(-\frac{p}{4q_{x_0}^2}\right)^{u_1} \\ & \quad \times \left(\frac{q_{y_0}}{p}\right)^{2n+s}\sum_{u_2=0}^{[(2n+s)/2]}\frac{1}{u_2!(2n+s-2u_2)!}\left(-\frac{p}{4q_{y_0}^2}\right)^{u_2}, \end{aligned} \tag{7}$$

where $p = \frac{1}{\omega_0^2} + \frac{ikA}{2B}$, $q_{x_0} = \frac{ikx}{2B}$, $q_{y_0} = \frac{iky}{2B}$ are the auxiliary parameters.

3. Simulation and discussion

In this section, we investigate the evolution behavior of FPGV beams in quadratic index medium by using the Split Step Beam Propagation Method, in which diffraction and inhomogeneous effects can be treated independent of each other. The parameters of the FPGV beam are set to be $\lambda = 0.63$ μm, $\omega_0 = 1.0$ mm. Numerical results are given to illustrate the influences of the beam order n, topological charge m and beam waist ω_0. For convenience, the intensity distributions of the beam have been normalized at arbitrary propagating distance z.

Fig. 2 shows the evolution behavior of a FPGV beam at different propagation z with $n = 3$, $m = 3$. It shows that although quadratic index medium cannot support FPGV beams as stationary solitons, it can keep them in periodical intensity distributions. The self-repeating modulation periodic distance is given by $z_m = \pi n_0/\sqrt{n_2}$, in which $n_0 = 1.5$ and $n_2 = 0.01$ m^{-2} correspond to the linear and nonlinear refractive coefficient, respectively [27]. We select a period as $z/z_m = 0$, 0.3, 0.5, 0.7, and 1. It can be seen that in the

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