Optics Communications 403 (2017) 358–369

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Propagation dynamics of off-axis symmetrical and asymmetrical vortices embedded in flat-topped beams

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A R T I C L E   I N F O

Keywords:
Flat-topped beam
Optical vortices
Propagation dynamics
Off-axis vortices

A B S T R A C T

In this paper, propagation dynamics of off-axis symmetrical and asymmetrical optical vortices(OVs) embedded in flat-topped beams have been explored numerically based on rigorous scalar diffraction theory. The distribution properties of phase and intensity play an important role in driving the propagation dynamics of OVs. Numerical results show that the single off-axis vortex moves in a straight line. The displacement of the single off-axis vortex becomes smaller, when either the order of flatness N and the beam size $\omega_0$are increased or the off-axis displacement d is decreased. In addition, the phase singularities of high order vortex beams can be split after propagating a certain distance. It is also demonstrated that the movement of OVs are closely related with the spatial symmetrical or asymmetrical distribution of vortex singularities field. Multiple symmetrical and asymmetrical optical vortices(OVs) embedded in flat-topped beams can interact and rotate. The investment of the propagation dynamics of OVs may have many applications in optical micro-manipulation and optical tweezers.

1. Introduction

The propagation and interaction of phase singularities, in particular of OVs, is of interest from a theoretical viewpoint [1–7] and for important practical applications, such as in optical data storage, microscopy [8], optical tweezers [9]. Phase singularity is a point phase defect, where the amplitude of the wave is zero and the phase is indeterminate, but in its neighborhood the phase values circulate between 0 and $2\pi m$ (here m being an integer representing topological charge of the vortex). The phase distribution of the wave front [4] is continuous and differentiable at every point just except at the optical vortex core. Vortex influences the phase distribution of the whole wave front, though it is a point defect. During the propagation of an optical beam in atmosphere, OVs are created and destroyed in such a way that the total topological charge remains conservation. Propagation study of singularities in the wave front of a vortex beam is a complex problem in theory. Generally speaking, near or far-field approximations of diffraction can be used to solve this kind of problem.

In recent years, the propagation dynamics of OVs have attracted interesting attention. OVs in linear and nonlinear media may exhibit propagation dynamics similar to hydrodynamic vortex phenomena [10]. The propagation dynamics of an OV is influenced by the change of the wave-front slope at the vortex position, and the rotation rate increase with the increase of the wave-front slope [11]. The propagation dynamics of an arbitrary vortex pair through an astigmatic optical system have been studied [12]. OVs were generated by three different types of custom-designed wave fronts in experiment [13]. The dynamics of OVs have also been examined in a nonuniform Bose–Einstein condensate [14].

The Gouy phase, as a fundamental property in a focused field, has been studied extensively [15–17]. The Gouy phase of focused, radially polarized light has been observed phase shift of 2π or π for the transverse and longitudinal component, respectively [18]. The intensity and phase distribution of a Gaussian beam with an off-axis vortex in a high NA system have been analyzed [19], it is found that the initial position of the off-axis vortex in the incident beam strongly influences the distance of the transverse focal shift, but does not have an effect on the Gouy phase along the central axis. Polarized beams represent an important member of the family of vector beams, the focusing properties of radially polarized hollow Gaussian beam (HGB) and circularly polarized vortex beams with on-axis spiral optical vortex have been investigated by vector diffraction theory [20,21]. The tight focusing behavior of vector beams with multiple polarization singularities was explored. It is

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http://dx.doi.org/10.1016/j.optcom.2017.07.037
Received 17 April 2017; Received in revised form 9 July 2017; Accepted 10 July 2017
Available online 5 August 2017
0030-4018/

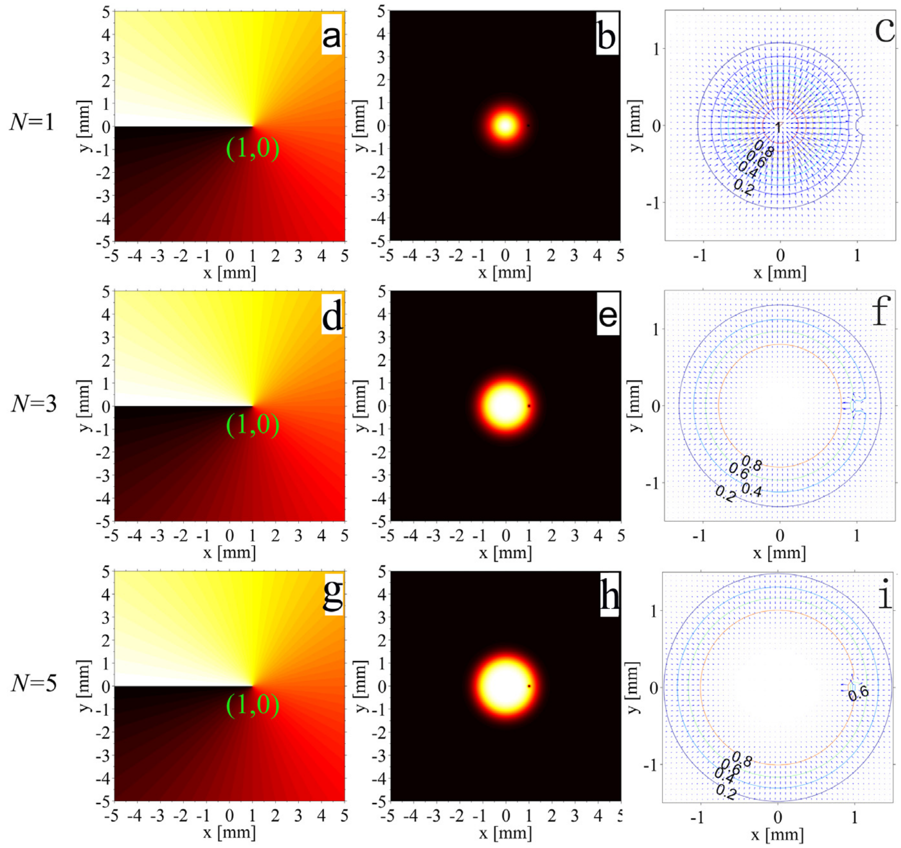

Fig. 1. Distributions of the phase(the first line), intensity(the second line) and intensity gradient(the third line) of the electric field embedded a *tanh* vortex in the source plane with different flatness N. $m = 1$, $\omega_0 = 1mm$.

observed that the ellipticity of the local polarization states at the focal plane could be determined by the spatial distribution of the polarization singularities of the vector beam [22].

Recently, the flat-topped beam(FTB) with a nearly uniform intensity distribution at a certain transverse plane has been extensively investigated [23–27] because of its wide applications in free-space optical communication, material thermal processing, inertial confinement fusion [26], and so on. FTB was introduced by Li in 2002 to describe the beam having a flat-topped transverse profiles [23]. Cai proposed the beams with elliptical flat-topped profiles [28]. The main advantage is that the FTBs can be considered as a linear combination of fundamental Gaussian beams with different beam width. Consequently, it can describe Gauss beam, flat topped beam and plane wave with the change in parameters. It is very important to research the propagation of flat topped beam in optical system. However, to the best of our knowledge, there is no paper present literature dealing with that how the properties of the source beam influence the propagation characteristics of OVs embedded in flat-topped beams. Moreover, the spatial symmetry and asymmetry of singularities field with multiple OVs also have not been theoretically investigated in detail.

In this article, based on the rigorous scalar diffraction theory, the effect of various values of the source parameters (the order of flatness N, the beam size ω_0 and off-axis distance d) and the topological charge on the propagation characteristics of different types of OVs embedded in flat-topped beams are investigated. This paper is organized as follows. In Section 2, the theoretical foundation for the calculations of the propagation dynamics of the OVs embedded in flat-topped beams are given. In Section 3, the phase profiles and intensity distributions at several distances in free space are studied numerically in detail, followed by the conclusions in Section 4.

2. Theoretical analysis

Ginzburg and Pitaevskii [29] reported stationary vortex solutions to nonlinear Schrödinger equation, which can be written as

$$-2ik\left(\partial u/\partial z\right) + \nabla_{\perp}^{2}u + 2k^{2}\left(n_2 E_0^2/n_0\right)|u|^2 u = 0 \tag{1}$$

where $\nabla_{\perp}^{2}u$ is the transverse Laplacian in cylindrical coordinates, u is the normalized field amplitude, n_2 is the coefficient of nonlinear refractive index, and n_0 is the linear index of refraction. It has been shown to transform into two of the principal equations in fluid mechanics: the Bernoulli and the continuity equations [30,31]. One can obtain these equations by writing the complex field envelope $u = f(r,\theta)\exp[is(r,\theta,z)]$, Inserting this expression into Eq. (1), one obtains two coupled equations:

$$-\partial s/\partial z + \mathbf{k}_{\perp}\cdot\mathbf{k}_{\perp} = \nabla_{\perp}^{2}\rho^{1/2}/\rho^{1/2} - P/\rho \tag{2}$$

$$(1/2)\,\partial\rho/\partial z + \nabla_{\perp}\cdot\left(\rho\mathbf{k}_{\perp}\right) = 0 \tag{3}$$

where $\mathbf{k}_{\perp}$ is the transverse wave vector of the beam and $\rho = f^2$ (the intensity) and $P = 2\rho^2$ are analogous to the density and the pressure of a fluid. It is clear from Eqs. (2) and (3) that two of the important terms driving the propagation dynamics in both linear and nonlinear media are the phase gradient $\mathbf{k}_{\perp}$ and the intensity gradient $\nabla_{\perp}\rho$.

The electromagnetic field at any point ρ in space is composed of two parts: amplitude and phase, the general form of expression can be written as:

$$E(\rho) = E_1(\rho) + iE_2(\rho) = A(\rho)\exp[iS(\rho)] \tag{4}$$

the phase can be expressed as:

$$S(\rho) = \arctan\left(E_2(\rho)/E_1(\rho)\right). \tag{5}$$

The phase represents the local propagation direction of the light wave. The phase plane (wave front) of the light wave is consistent with