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Propagation characteristics of modified hollow Gaussian beams in nonlocal media under off-waist incident condition

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ABSTRACT

In this paper, we focus on the evolutions of modified hollow Gaussian beams in highly nonlocal media under the off-waist incident condition. Two alternative analytical expressions describing the beam evolution are deduced, and the analytical expressions of the on-axis intensity, the second-order moment beam width, and the mean radius of curvature of the beam are all given. Numerical simulations are carried out to illustrate the propagation characteristics. The results show that, under the off-waist incident condition, the evolution of the beam width is always periodical whatever the beam power is, even when the beam power is equal to the critical power. The transversal pattern evolution is not symmetric about the middle of the evolution period. These results are much different from those under the on-waist incident condition.

1. Introduction

In the past decades, many investigations focus on the propagation characteristics of laser beams in various optical media. Recently, a new type model of nonlinear media was established in theory, i.e. the highly nonlocal model [1]. The nonlinearity of this medium is spatially nonlocal, which leads to many new novel phenomena. Subsequently, it is proved that both lead glasses and nematic liquid crystals are typical highly nonlocal media [3–6]. Most recently, Shahmoon et al. found that the highly nonlocal nonlinearity also exists in the atomic media [7]. One of the most striking points is that spatial optical solitons are easily accessible in highly nonlocal media. So far, in nonlocal media, many new types of spatial optical solitons are proposed in theory and observed in experiments, such as multipole solitons [3,8–10], surface solitons [11–13], three-dimensional solitons [14,15], vortex solitons [3,16], spatiotemporal solitons [17,18], lattice soltions [19,20], ring dark and antidark solitons [21,22], Gausssian and high-order Gaussian solitons [1,2,23–26]. These solitons are shape-invariant during propagation in nonlocal media. Besides these nonlocal shape-invariant solitons, the propagation characteristics of optical beams in nonlocal media have also attracted much attention, and some novel characteristics have been revealed, such as the self-organization of light [27], the self-induced mode transformation [28], the self-induced fraction Fourier transform [29,30], and the power-variation-induced three-dimensional non-uniform scaling [31]. Therefore, the propagation characteristics of shape-variant optical beams have been extensively explored in nonlocal media recently, such as elliptic beams [32,33], Lorentz-Gaussian vortex beam [34], hollow beams [35,36], anomalous hollow beams [37], anomalous vortex beams [38],

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four-petal Gaussian beams [39], Airy beams [40,41] etc. However, we find that most of investigations on nonlocal beams is under the on-waist incident condition. Few papers pay attention to the off-waist incident case.

On the other hand, dark hollow beams with their central intensity being zero have also attracted much attention since they can be applied into in guiding and manipulating atoms. Up to now, many new models of hollow beams have been proposed, such as hollow Gaussian beams, anomalous hollow beams, anomalous vortex hollow beams, hollow sine beams, hollow sinh-Gaussian beams, hypergeometric Gaussian beams, flat-topped hollow beams, hollow vortex Gaussian beams. Among these hollow beams, the modified hollow Gaussian beam (MHGB) has its unique advantages [42,43]. Both the beam size and the central dark size of a MHGB can be adjusted by choosing different beam parameters. In this paper, we focus on the effect of the off-waist incidence on the propagation characteristics of MHGBs in highly nonlocal media. The results show that the propagation characteristics under the off-waist incident condition are much different from those under the on-waist incident condition. A set of analytical expressions are given to describe the beam propagation and the propagation characteristics. The propagation characteristics are illustrated by the numerical simulations.

2. Analytical expressions

The propagation characteristics of an optical beam in nonlinear media are governed by the well-known nonlinear Schrödinger equation (NLSE) [6,27,44–48]. For the highly nonlocal case, in cylindrical coordinates, the NLSE can be simplified as [1,2,23–26]

$$2ik\frac{\partial E}{\partial z} + \frac{1}{r}\frac{\partial E}{\partial r} + \frac{\partial^2 E}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 E}{\partial \theta^2} - k^2\gamma^2 P_0 r^2 E = 0 \tag{1}$$

with E being the complex optical filed of a beam, $\gamma^2 > 0$ being a constant related with the nonlocal response of the nonlinear media, $P_0 = \int_0^{2\pi}\int_0^{\infty} |E|^2 r dr d\theta$ being the beam power of an optical beam.

The optical field of MHGBs on the beam waist plane is expressed as [42]

$$E(r_0, \theta_0) = C_0 \left[\frac{(n+1)r_0^2}{w_0^2}\right]^n \exp\left[-\frac{(n+1)r_0^2}{w_0^2}\right] \tag{2}$$

with w_0 being the beam waist width of a fundamental Gaussian beam, n being the beam order, $C_0 = \left[4(n+1)P_0/n\pi\Gamma(2n)w_0^2\right]^{1/2}$ being a constant that is related with the beam power P_0, and $\Gamma(\cdot)$ being a gamma function.

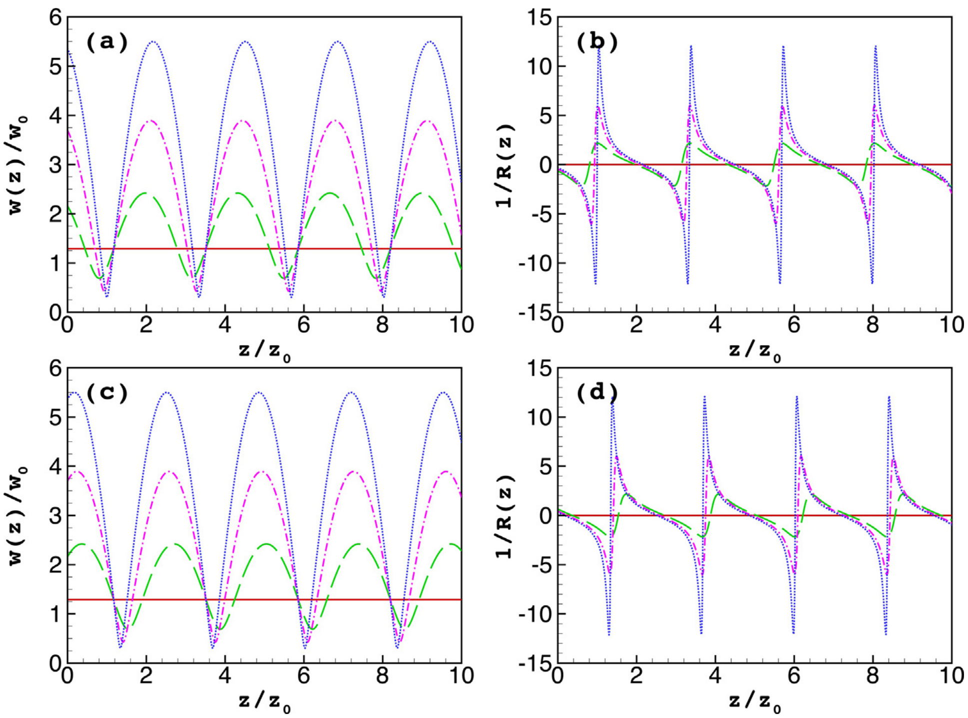

Fig. 1. Evolutions of the beam width and the mean radius of curvature for different z_d. (a) and (b): the solid, dashed, dash-dotted, dotted lines represent, respectively, $z_d = 0$, z_0, $2z_0$, and $3z_0$. (c) and (d): the solid, dashed, dash-dotted, dotted lines represent, respectively, $z_d = 0$, $-z_0$, $-2z_0$, and $-3z_0$. The beam power is $P_0 = P_c^{(2)}$ and the beam order is $n = 2$.