Propagation of the Charge-2 Vortex Beam in Bessel Optical Lattices

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Abstract This paper investigates the propagation of charge-2 vortex beam in 0-order and 1-order Bessel lattices induced by non-diffracting Bessel beams in media with focusing nonlinearity. Different stable ring-like vortex solitons can be generated when the lattice depth I_0 matches the intensity of the bias electric field. Simulation results show that the vortex beam with topological charge m=2 can form the stable single-ring and multi-ring vortex solitons in a Bessel lattice.

Key words nonlinear optics; charge-2 vortex beam; Bessel lattice; focusing nonlinearity; vortex-ring solitons

OCIS codes 190.4400; 160.5320; 190.5330

二阶涡旋光在贝塞尔晶格中的传播

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摘要 研究了二阶涡旋光束在0阶,1阶贝塞尔晶格中的传播。贝塞尔晶格是通过无衍射贝塞尔光束在聚焦非线性介质中光诱导产生的,当晶格深度与外加电场强度相匹配时,在聚焦的0阶,1阶贝塞尔晶格中,能产生不同类型的稳定的环形涡旋孤子。仿真结果表明,二阶涡旋光在贝塞尔晶格中能够形成稳定的单环、多环涡旋孤子。

关键词 非线性光学; 二阶涡旋光束; 贝塞尔晶格; 聚焦非线性; 涡旋环孤子

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1 Introduction

Vortex solitons do not exist in a self-focusing nonlinear medium. A ring-like optical beam with a phase dislocation carrying a finite orbital angular momentum[1] decays into the fundamental solitons flying off the original ring[2]. Stable vortex-ring solitons in homogeneous media are known to exist in models with competing cubic-quintic[3], optical lattice[4-5], quasi-periodic structure[6] or quadratic-cubic nonlinearities[7].

The dynamics of vortex solitons in Bessel lattices are being studied extensively due to their radial symmetry. Such lattices support stable vortex solitons[8], spiraling solitons[9], etc. Ring-shaped, rotary solitons in modulated Bessel lattices have also been observed[10-11]. Different order Bessel lattices can be induced by non-diffracting Bessel beams of different orders.

In this study, we observed propagation of charge-2 vortex beams in Bessel optical lattices. We also studied the linear diffraction and nonlinear propagation in a homogeneous medium without the Bessel lattices, and then analyzed the propagation in the lattice under different input conditions. Research on vortex solitons at different transverse lattice scales b_{lin} can be used in multiplexed mode to increase the

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capacity of communication systems.

2 Theoretical model

We consider light propagation along the z axis in a bulk medium. The focusing cubic nonlinearity and transverse modulation of the refractive index are described by a nonlinear Schrödinger equation for the slowly varying envelope Ψ , as follows:

$$\mathrm{i}\frac{\partial \Psi}{\partial z}+\frac{1}{2}\left(\frac{\partial^2 \Psi}{\partial x^2}+\frac{\partial^2 \Psi}{\partial y^2}\right)-\frac{V_0 \Psi}{1+I_g(x,y)+|\Psi|^2}=0, \tag{1}$$

where $V_0=k_0^2 n_e^4 \gamma_{33} x_0^2 E_0/2$ with n_e being the refractive index of the extraordinary polarized beams, γ_{33} being the electro-optic coefficient, and E_0 being the applied electric field along the crystal axis. Further, x, y and z denote the transverse and longitudinal coordinates. The transverse coordinates x, y are measured in the units of x_0, and z is the propagation distance, in units of $k_0 n_e x_0^2$. Consequently, x=1 corresponds to 14 μm , and z=1 corresponds to a propagation distance of 5.80 mm. $I_g(x,y)=I_0 J_{n_J}^2(b_{\mathrm{lin}} r)$ is the Bessel lattice induced by extraordinarily polarized beams, where I_0 is peak intensity of the lattice, J_{n_J} represents the n_J-order of the Bessel function, and b_{lin} is related to the transverse profile of the refractive index. Here, we assume that the c axis of the photorefractive crystal is placed along the x axis with the external biased field E_0, and the initial vortex beam propagates along the z axis, as shown in Fig.1.

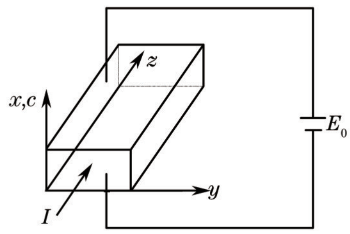

Fig.1 Path installation of light

In this paper, the mathematical model for the initial vortex beam is given as $\Psi(x,y)=A(x+\mathrm{i}y)^m \exp(-x^2-y^2)$, with n_J=0 or 1, A=5, and m=2 (the topological charge of the initial vortex beam). Figure 2 shows the energy distributions of the initial vortex beam and Bessel lattice, Fig.2(b) depicts the phase plane of the initial beam.

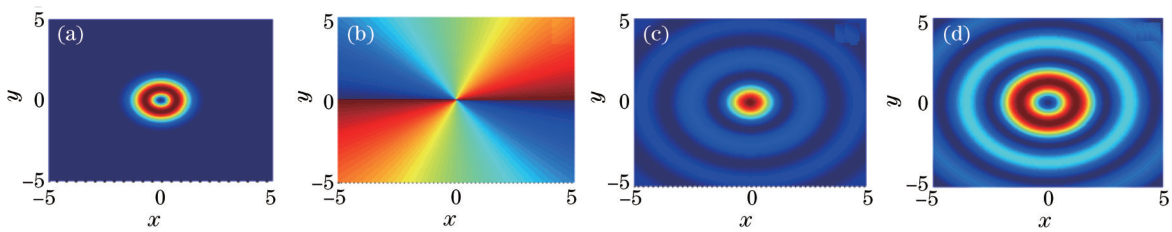

Fig.2 (a) Intensity distribution of initial beam; (b) phase distribution of input beam; intensity distribution of the Bessel lattice for (c) n_J =0; (d) n_J =1

3 Simulation results

First, we present the simulation results of the charge-2 vortex beam in 0-order Bessel lattice. Here, we choose b_{lin}=1.8, V_0=50, n_J=0, and A=5. For comparison, when the nonlinearity is set to zero, the input vortex beam diffracts after z=1.6 (Here, we choose the parameter z=1.6 because the linear diffraction is already obvious at 1.6), as shown in Fig.3(a). The ring-like vortex beam splits into four filaments at z= 3.2 owing to the angular momentum carried by the initial vortex beam in the focusing nonlinear medium without a lattice [Fig.3(b)]. Figure 3(c) shows the output intensity patterns of the vortex beam at a lattice depth of I_0=5. When the lattice depth is low, the suppression of the lattice cannot completely balance the azimuthal instability, so the vortex beam breaks up into several filaments.

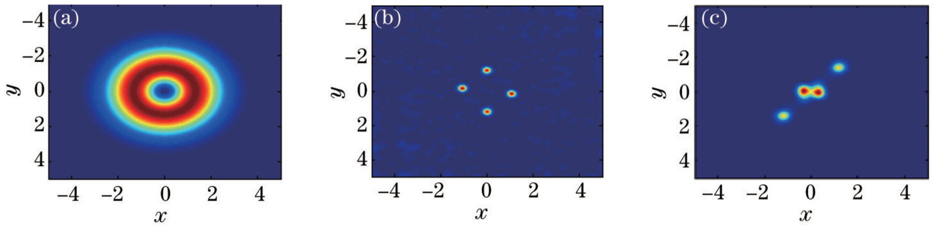

Fig.3 (a) Intensity distribution of linear diffraction at z=1.6; (b) intensity distribution of nonlinear propagation without a lattice at z=3.2; (c) intensity distribution of vortex beam at V_0=50, I_0=5, z=3.2

Next, we study the propagation of the vortex beam for a different transverse lattice scale b_{lin} at V_0=50 and I_0=30 in 0-order Bessel lattices. Figure 4(a) shows that the vortex beam is launching into the center of the lattice at b_{lin}=1.8. Figure 4(b) depicts stable propagation of vortex soliton intensity for z=4.0. Figure 4(d) indicates that most energy of the input beam is distributed on the second channel of the lattice at b_{lin}=4.5, whereas the transverse profile of lattice is compressed. The intensity of the soliton is shown in Fig.4(e). Figures 4(c), (f) show the phase plane of the vortex solitons.

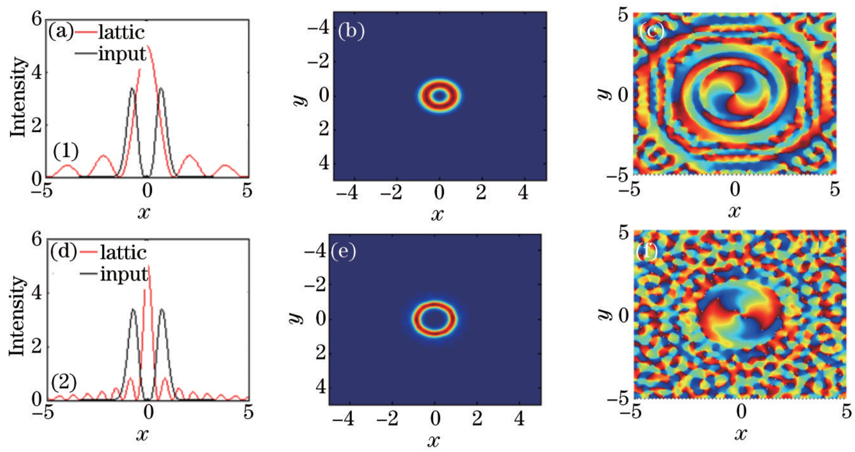

Fig.4 (a), (d) The locations of the initial beam and the lattice for b_{lin}=1.8, b_{lin}=4.5; (b), (e) intensity distribution of vortex soliton at z=4.0; (c), (f) phase distribution of vortex soliton. Here V_0=50, I_0 = 30, n_J =0

Finally, we investigate charge-2 vortex beam propagation for a different transverse lattice scale b_{lin} in 1-order Bessel lattice. Here, the parameters are set as V_0=50 and I_0=30, and the results are presented in Fig.5.

Figure 5(a) shows the profile of the vortex beam and Bessel lattice at b_{lin}=1.8. The energy of the input beam is completely contained in the first channel of the lattice. The input vortices become vortex lattice solitons and maintain the structure for z=4.0, as seen in Fig.5(b). A comparison with the vortex lattice solitons shown in Fig.4(b) reveals that the vortex solitons are more localized in 0-order Bessel lattice under the same parameters. The simulation results also indicate that the vortex solitons maintain the structure after a relatively long propagation distance of z=10. The transverse profile of the lattice is compressed at b_{lin}=4.5, and the energy of the input beam is distributed on the first double-rings, as shown in Fig.5(d). The energy involved in the first channel form the inner-ring, the others form the outer-ring after z=4.0 of propagation are shown in Fig.5(e). The intensity distribution is different from vortex solitons that have a single-ring in the 0-order lattice shown in Fig.4(e), with the energy mainly centralized in the outer-ring. Fig.5(g) depicts that part of the energy of the input beam focuses on the center of the lattice at b_{lin}=1.0. Fig.5(h) illustrates that it also take shape in a double-ring circle solition similar to the vortex lattice solitons with unit charge in 1-order Bessel lattice at V_0=50 and I_0=20, as reported in Ref.[12]; the difference is that most of the soliton energy concentrates on the inner channels. Furthermore, we find that the vortex beam cannot form a stable vortex soliton at V_0=50, I_0=20, which proves that the higher the soliton topological charge, the deeper the lattice modulation needed for stabilization. Figures 5(c), (f), (i) depict the three-dimensional plots of the vortex solitons intensity.

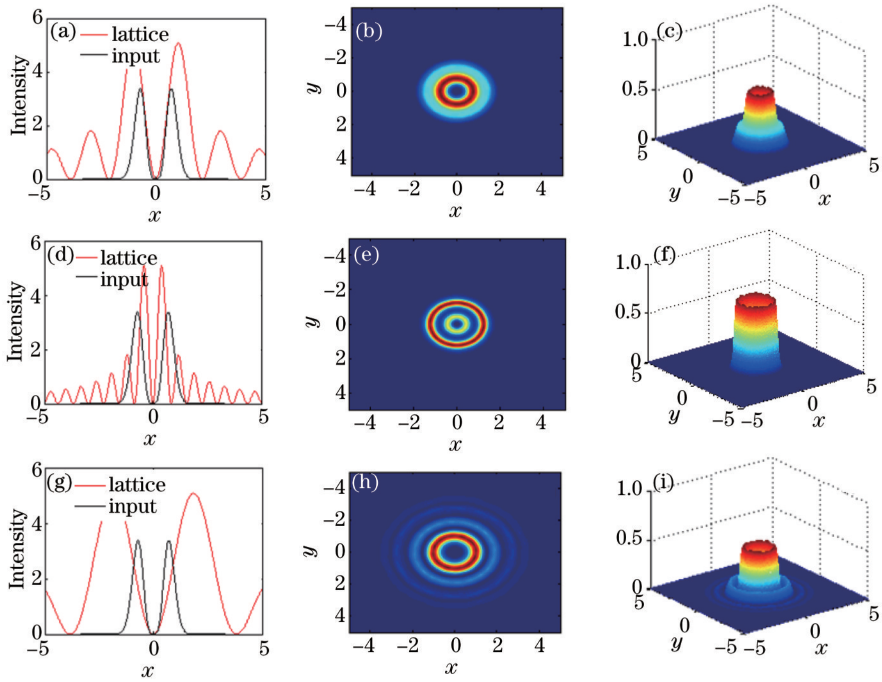

Fig.5 Location of initial beam and lattice for (a) b_{lin}=1.8; (d) b_{lin}=4.5; (g) b_{lin}= 1.0; (b), (e), (h) intensity distribution of vortex solitons at z=4.0; (c), (f), (i) three-dimensional plots of the vortex solitons intensity

4 Conclusion

We show that optical lattices induced by non-diffracting 0-order and, 1-order Bessel beam in media with focusing nonlinearity can support stable single-ring and multi-ring vortex solitons. Simulation results show that with different initial input conditions for the lattices, the input beam could evolve into different kinds of ring-vortex solitons when the lattice depth I_0 can match the intensity of the bias electric field. The results observed here are fundamental to Bessel lattices and can thus provide valuable insight into other systems in nature where similar transport can be observed.

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