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The propagation of spiraling elliptic sine soliton in nonlocal nonlinear media

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ABSTRACT

We study a novel spiraling elliptic sine soliton (SESS) in nonlocal nonlinear media by split-step Fourier method, and find that the profile and phase of such soliton have complicated structures. Numerical results show that the topological charge and ellipticity have profound effects on the propagation dynamics of SESS. Concretely, for the same ellipticity, the different topological-charge SESS have the same critical power, cross-term phase coefficient, rotation period, and different critical orbital angular momentums (OAM). However, the critical power, cross-term phase coefficient, rotation period and OAM will increase as the increase of ellipticity. In addition, as the ellipticity and topological charge increase, the stability of the beam will decrease.

Introduction

Nonlocal nonlinearity has attracted a lot of attentions in recent years [1,2]. One of the epoch-making studies is that, under strong nonlocal conditions, Snyder and Mitchell approximate the conventional nonlocal nonlinear Schrödinger model which requires abstruse mathematics to a linear model, the S-M model [3]. Nonlocal nonlinearities are ubiquitous in many physical medium, for example, the nematic liquid crystal [4], lead glass [5], atomic gas [6], Bose–Einstein condensates [7]. Spatial nonlocality makes optical solitons have some novel properties, for instance, it can suppress the catastrophic collapse of (1 + 2)-dimensional optical solitons [2], suppress the angular vector instability of rotating optical solitons to form a stable transmission of the vortex solitons [8,9], and support the transmission of multiple spatial optical solitons [10,11].

In recent years, the OAM carried by optical beam or its photons has also been investigated a lot. The spiraling optical beam carrying the OAM, means that the electric field varies inside the beam, and a significant effort of such a field is that a torques can be generated and make the beam rotate [12]. OAM can be created artificially using a variety of tools, such as using spiral phase plates [13], spatial light modulators [14] and q-plates [15]. In addition, OAM have been applied in optical tweezers and microscopy [16], furthermore, it has a lot of potential applications ranging from quantum-information to telecommunications [17]. It has been demonstrated that OAM has two contributions for the propagation of spiraling beam [18]. Firstly, it can suppress the collapse of optical soliton in Kerr media. Secondly, it maintains the elliptical waveform of the beam.

In this paper, we investigate a novel SESS and perform numerical simulation to derive its characteristics in nonlocal nonlinear media, and found that the propagation of it relatively depended on the ellipticity and topological charge.

Theoretical model

The nonlocal nonlinear Schrödinger equation (NNLSE) which modeling the propagation of optical beams can be described as [18–23]

$$i\frac{\partial \phi}{\partial z} + \frac{1}{2}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\phi + \phi \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} R(x-x', y-y')|\phi(x', y', z)|^2 dx'\, dy' = 0, \tag{1}$$

where $\phi(x, y, z)$ is the complex amplitude envelope, z represents the longitudinal coordinate, x and y stand for the cross-sectional coordinates. $R(x, y)$ represents the nonlocal response function, and we could set it as the normalized symmetrical Gaussian-shaped

$$R(x, y) = \frac{1}{\pi\sigma^2}\exp\left[-\frac{x^2 + y^2}{\sigma^2}\right] \tag{2}$$

where σ represents the material characteristic length of nonlocal response function.

A family of SESS to Eq. (1) with sinusoidal term and integer topological charge m can be introduced as follow

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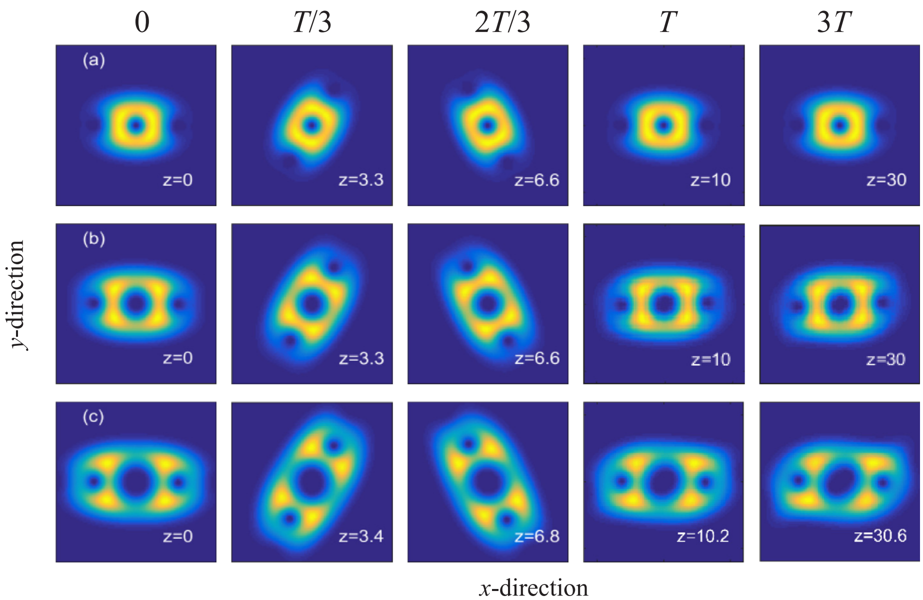

Fig. 1. The intensity distributions of SESS with different topological charge. The initial parameters are chosen as, $b = 2$, $c = 1$, $\sigma = 20$, $\Theta = 0.38$, (a) $m = 0$, $P = 103570$, $M = 128970$, (b) $m = 1$, $P = 104950$, $M = 296610$, (c) $m = 2$, $P = 105300$, $M = 520030$.

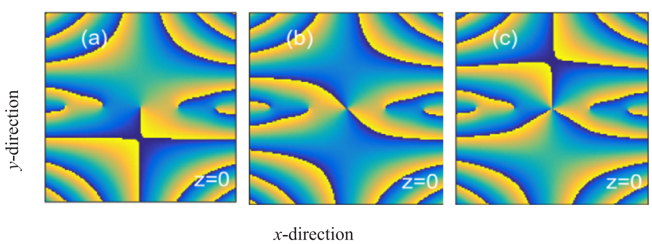

Fig. 2. The initial phase structure of SESS with different topological charge. The parameters are corresponded to Fig. 1 (a) (b) and (c), respectively.

$$\phi(x, y, z)_{|z=0} = A\sin(x+iy)\exp\left[-\frac{x^2}{2b^2}-\frac{y^2}{2c^2}\right](x+iy)^m\exp[\mathrm{i}\Theta xy] \quad (3)$$

where A is in connection with the amplitude of the optical beam, sin ($^x x + iy$) is the sinusoidal term. b and c denote the semi-axes of the elliptic beam, m is the integer topological charge, Θ denotes the cross-term phase coefficient.

We can get the power and OMA of the elliptic beam by inserting Eq. (3) in the form of the following formulas, respectively [18,19]

$$P = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}|\phi|^2 dxdy \quad (4a)$$

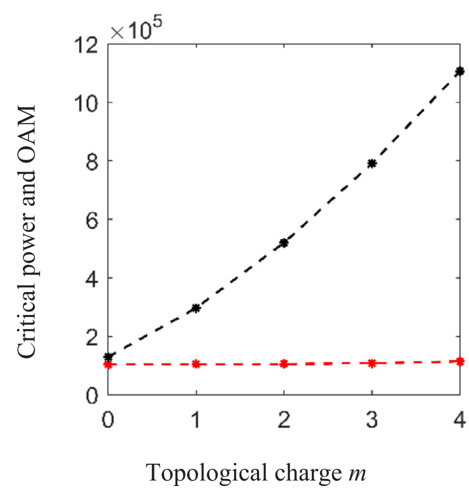

Fig. 4. The critical power (red line) and OAM (black line) of SESS vary with the topological charge. The initial parameters are chosen as $b = 2$, $c = 1$, $\sigma = 20$, $m = 0, 1, 2, 3, 4$, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$M = \mathrm{Im}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\phi^*\left(x\frac{\partial\phi}{\partial y}-y\frac{\partial\phi}{\partial x}\right)dxdy \quad (4b)$$

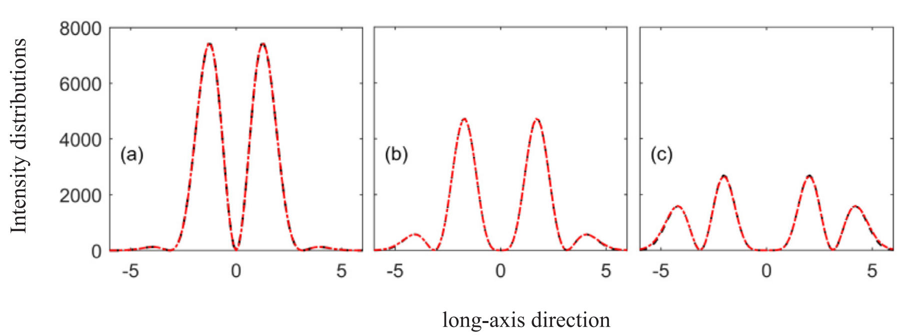

Fig. 3. Profiles of the SESS on the long-axis direction for propagation time t = 0 (red lines) and t = 3*T* (black lines). The parameters are corresponded to Fig. 1(a)–(c), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)