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Interaction trajectory of solitons in nonlinear media with an arbitrary degree of nonlocality

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ABSTRACT

The interaction trajectory of solitons in nonlocal nonlinear media is investigated. A simple differential equation describing the interaction trajectories is derived based on the light ray equation. Numerical calculations are carried out to illustrate the interaction trajectories with different parameters. The results show that the degree of nonlocality greatly affects the interaction of solitons. For a strongly nonlocal case, the interaction trajectory can be described by a cosine function. Analytical expressions describing the trajectory and the oscillation period are obtained. For generally and weakly nonlocal cases, the interaction trajectories still oscillate periodically, however it is no longer sinusoidal and the oscillation period increases with the nonlocal degree decreasing. In addition, the trajectory of two solitons launched with a relative angle at the entrance plane is investigated. It is found that there exists a critical angle. When the initial relative angle is larger than the critical angle, the two solitons do not collide on propagation. The influence of the degree of nonlocality on the critical angle is also discussed.

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1. Introduction

Soliton solutions, as a class of solutions of nonlinear equations, have unique characters and have been investigated widely both in theory and in experiments [1–4]. In optics, spatial solitons are self-trapped optical beams without shape change, and who exist in nonlinear media by virtue of the balance between diffraction and nonlinearity. In early times, researchers focus on the optical spatial solitons in local nonlinear media, whose refractive index at a particular point is only related to the beam intensity at that point. Recent years, people found that the nonlocal nonlinearity exists naturally in many physical systems, such as nematic liquid crystals, lead glasses, atomic vapors, Bose–Einstein condensates, and photorefractive crystals. As a result, the nonlocal solitons has attracted considerable interest over the past decades. The nonlocality allows the refractive index of a material at a particular point to be related to the beam intensity at all other material points, which leads to many novel phenomena. It has been shown that nonlocality can support a series of novel solitons, such as stable multipole solitons [5–7], lattices solitons [8–10], vortex solitons [11,12], and surface solitons [13,14]. Except for the solitons whose shapes keep invariant during propagation, some shape-variant optical beams propagating in nonlocal nonlinear media have also been investigated widely, such as Airy beams [15], anomalous vortex beams [16], Lorentz–Gauss vortex beam [17], modified hollow Gaussian beams [18], etc.

For the interaction of nonlocal solitons, the nonlocality leads to many unique properties which are different from the local nonlinear case. As we know, in local nonlinear media, the interaction of two bright solitons depends on their relative phase. They attract each other for the in-phase case, and repel for the out-of-phase case [19]. Dark solitons always repel each other. However, in nonlocal nonlinear media, the bright solitons are always attractive independent of the relative phase [20], even two nonlocal dark solitons can be attractive [21]. Some interactions of solitons have been realized in experiments and been applied to optical communications, light-controlled switch, and so on [22–26]. Recently, Kong et al. gave the analytical theory for the dark-soliton interaction in nonlocal nonlinear materials with an arbitrary degree of nonlocality [27], and Cao et al. studied the interaction between spatial optical solitons in sub-strongly nonlocal nonlinear media [28]. Most recently, Chen et al. studied the interaction of nonlocal dark solitons under competing cubic–quintic nonlinearities [29], and Lem-Carrillo et al. generated the rotary beams by the interaction of moving solitons in nonlocal media [30]. For the application utilizing the soliton interactions, the interaction trajectory of solitons plays an important role. In this paper, the interaction trajectory of solitons in nonlinear media with an arbitrary degree of nonlocality is investigated using the light ray equation. We organize the article as follows. In Section 2, a simple differential equation to describe the interaction trajectory of solitons in nonlocal nonlinear media is derived. In Section 3, we first obtain analytical expressions of the trajectory and the oscillation period for the strongly nonlocal case. Then, some numerical simulations are carried out to illustrate and confirm the analytical results, and last we investigate the trajectories of two solitons when they are launched with a relative angle at the entrance plane. Section 4 draws the conclusion.

2. Theoretical calculations

The nonlinear dynamics of optical solitons in nonlinear media can be described phenomenologically by the nonlinear Schrödinger equation (NLSE) [1,31,32]

$$2ik\frac{\partial \Phi}{\partial Z} + \frac{\partial^2 \Phi}{\partial X^2} + 2k^2 \Delta n \Phi = 0, \tag{1}$$

where $\Phi(X, Z)$ is the complex amplitude of paraxial beams, k is the wave number in the media without nonlinearity, Z is the longitudinal coordinate (i.e. the propagation direction), X is the transverse coordinate. Δn denotes the nonlinear perturbation of refractive index, and it can be expressed as

$$\Delta n = n_2 \int_{-\infty}^{+\infty} R_i(X - X')|\Phi(X', Z)|^2 dX', \tag{2}$$