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Soliton switching in inhomogeneous nonlocal media

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ABSTRACT

We address a simple way to achieve routing of optical spatial solitons via soliton interactions in the inhomogeneous nonlocal media. We reveal that the variation of the nonlocality disturbs the solitons pairs and splits them into two individual solitons which have the same escape angle but opposite deflection directions. In particular, the escape angle monotonically increases with the increase of the nonlocality variation rate. We demonstrate that the soliton pairs could form self-consistent waveguides that are able to controllably guide a weak signal by any output positions.

1. Introduction

Nonlocal spatial solitons refer to the non-diffracting beams which are able to produce their own dielectric waveguide and propagate without spreading in nonlocal materials. These self-trapping beams have been found in such different materials as photorefractive crystals [1], thermal materials [2], atomic vapors [3], Bose–Einstein Condensates [4] and nematic liquid crystals [5], due to different physical mechanisms, yet these solitons have many properties in common. In particular, they obey the same nonlocal nonlinear Schrödinger equations. Since the pioneering work of Snyder and Mitchell [6], extensive work has been devoted to nonlocal spatial solitons, not only for their fundamental physics but also for their potential applications via the manipulation of the soliton path [7–14]. Thus far, the control of the soliton trajectories is more challenging, but it has also been achieved, largely by soliton–soliton and soliton–defect interactions [15–24], refraction and deflection at the voltage-controlled boundaries [25,26].

One of the most fascinating features of the shape-invariant wave packets is the interaction of the self-confined beams which exhibit particle like behaviors under certain conditions. Such phenomenon makes them an excellent candidate for signal processing and light manipulating with light itself [27]. It is now known that the nonlocality dramatically affects soliton interactions, e.g., out-of-phase bright solitons could attract each other [17–19]; two dark solitons can also attract each other [28–30]. These phenomena are a direct consequence of the nonlocality with no counterpart in the local medium. Very recently, it is found that the propagation of single soliton as well as soliton pairs is dramatically affected by a variation of the longitudinal nonlocality of the materials [21–33]. However, for the soliton pairs, the variation of the longitudinal nonlocality only decelerates or accelerates the interaction process, but it does not split them into two individual solitons. Therefore the question arises as to whether the variation of the longitudinal nonlocality can be used to split the soliton pairs into two individual solitons. This suggests yet another question, namely, whether the longitudinal nonlocality management could offer a number of new opportunities for beam manipulation.

In this letter, we propose two types of longitudinal nonlocality management to induce the self-splitting of the soliton pairs, and thereafter to control the soliton trajectories. In addition, we demonstrate that the soliton pairs could form self-consistent waveguides that are able to effectively guide a weak beam, including the beam shape and the beam pathway.

2. Theoretical model and equations

We consider the optical beams that propagate in medium with a nonlocal cubic nonlinearity, described by the following coupled

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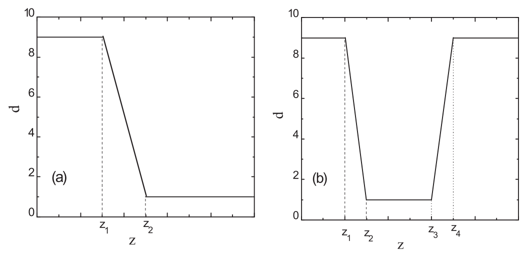

Fig. 1. Two types of nonlocality management. (a) Type I nonlocality and (b) type II nonlocality.

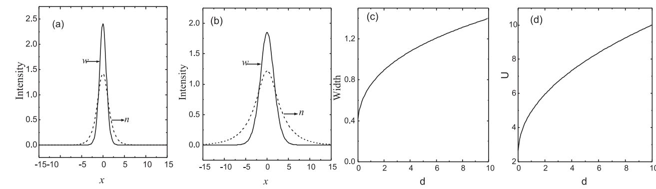

Fig. 2. Intensity and refractive distributions for single solitons in nonlocal nonlinear materials with (a) $d = 4$ and (b) $d = 9$. (c) Width of single solitons versus the nonlocal length of the cubic nonlinearities. (d) Energy flow versus the nonlocal length of the cubic nonlinearities.

equations for the dimensionless field amplitude u and refractive index n [11,28,31].

$$i\frac{\partial u}{\partial z}+\frac{1}{2}\frac{\partial^2 u}{\partial x^2}+nu=0, \quad (1)$$

$$d(z)\frac{\partial^2 n}{\partial x^2}-n+|u|^2=0, \quad (2)$$

where $d(z)$ characterizes the nonlocal length of the cubic nonlinearities along the longitudinal axes, which may be different in different parts of the media. On physical ground, the inhomogeneity in the nonlocal length can be realized, e.g., in planar cell with equally-spaced array of parallel indium tin oxide (ITO) electrodes containing undoped nematic liquid crystals, where the inhomogeneous nonlocality could be preset via varying the anchoring at the cell interfaces or the externally applied low-frequency voltage. In this study, two types of $d(z)$ are considered as shown in Fig. 1(a) and (b), respectively. In the first case, called type I nonlocality, we assume that the nonlocality of the front part is bigger than the rear part of the materials. We note that an abrupt change of the nonlocality can result in pronounced oscillations of the beam amplitude. To avoid such oscillations, we propose that there is a junction region $[z_1, z_2]$ between the front and the rear part of the materials. In this area, $d(z)$ shows a very gradual and linear decrease and the linear variation rate of the nonlocality is determined by the length of the junction region. The variation of nonlocality also results in a modification of the linear refractive index along the longitudinal axes. In fact, this does not affect the dynamics of the solitons and soliton pairs (see [31] for details). In the second case, called type II nonlocality, the materials could be mainly divided into three parts with strong, weak and strong nonlocality as shown in Fig. 1(b). For the same reason as in the first case, two narrow junction regions $[z_1, z_2]$ and $[z_3, z_4]$ are used in this case. Although this choice of model is arbitrary, we anticipate that this model could be extended to permit the prediction of the dynamics of soliton pairs in layered nonlocal media. In addition, this model may offer one or more control areas to realize the manipulation of the soliton path.

To study the dynamics of the soliton pairs, we adopt the split-step Fourier method to perform simulations of Eqs. (1) and (2) with input conditions $u|_{z=0}=w(x-x_0)+w(x+x_0)\exp(i\pi)$ which correspond to two identical out-of-phase solitons separated by $2x_0$. Here the solitons solutions can be found in the form $u=w(x)\exp(ibz)$, where, w and b represent the field amplitude and the propagation constant, respectively. In this study, the solitons solutions are achieved by Newton iteration method for $b = 1$. The profiles of intensity and refractive distributions of single solitons with $d = 1$ and $d = 9$ are presented in Fig. 2(a) and (b), respectively. To investigate the impact of nonlinearity on the properties of solitons, we introduce the energy follow $U=\int_{-\infty}^{\infty}\left|w(x)\right|^2dx$ and the integral width of the solitons $W=\sqrt{\int_{-\infty}^{\infty}x^2w^2dx/\int_{-\infty}^{\infty}w^2dx}$. Owing to the physical nature of the nonlocal response of the materials, we notice that the width of soliton-induced refractive index distribution greatly exceeds the width of the soliton beam for $d = 9$. It is important to note that the width of the individual solitons as well as the energy flows of the individual solitons monotonically increase with the increase of the nonlocal length as shown in Fig. 2(c) and (d), respectively. So, it is safe to say, the strong nonlocal soliton pairs which are composed of two out-of-phase strong nonlocal solitons are typically associated with high power requirement, while the weak nonlocal soliton pairs are associated with low power requirement.

Now, there is a general consensus that the variation of the nonlocality of the medium dramatically affects the profiles of the single soliton as well as the dynamics of the soliton pairs. However, regardless of whatever the separation between the soliton pairs, we find that the trajectory of the weak nonlocal soliton pairs is almost not varied when they pass from a weak nonlocal medium to a strong nonlocal medium. Such result is due, at least in part, to the fact that the nonlocality is to effectively weaken the influence of the nonlinearity on the propagation of the beams. In this case, the total power of the weak nonlocal soliton pairs is too small to introduce a big index perturbation to affect their propagation in the junction region. Compared with the weak nonlocal soliton pairs which inject into a strong nonlocal media, the strong nonlocal soliton pairs which inject into a weak nonlocal media may have lots of new phenomena.

We first consider the dynamics of the soliton pairs in nonlocal media with type I nonlocality. In the simulations, we use the following parameters: the junction region is $[z_1, z_2]$, the length of the junction region is L, and the area between the white dashed lines represents the location of the junction region. It is well known that out-of-phase solitons can form the bound state at proper separation in nonlocal medium. In our extensive numerical simulations, we find that, when a nonlocal bound state enters into a weak nonlocal segment, the dynamics of the bound state is dramatically affected by the length of the junction region as shown in Fig. 3(a) and (b). In particular, for large junction length L, the bound state almost evolves into a new weak nonlocal bound state in which the separation between the individual solitons is much smaller than the original bound state. This is due to the fact that the decrease of the nonlocality causes a compression of each individual soliton and the increase of the corresponding peak amplitudes. In this case, their big attractive force can balance their short-range repulsion to form

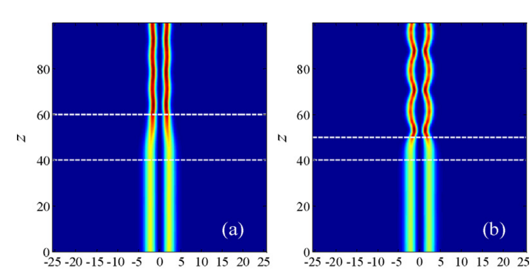

Fig. 3. The dynamics of the bound state in inhomogeneous nonlocal media with type I nonlocality for (a) $z_1 = 40$, $z_2 = 60$ and (b) $z_1 = 40$, $z_2 = 50$.