Incoherent interaction between one- and two-dimensional solitons in noncentrosymmetric photorefractive media*

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The incoherent interaction between solitons with different transverse dimensions in a noncentrosymmetric photorefractive crystal is studied both in theory and in experiment. An anomalous incoherent interaction between one- and two-dimensional solitons, whose attractive and repulsive effects depend on the soliton separation, is numerically demonstrated by employing an anisotropic model. By launching a one-dimensional green beam and a two-dimensional red beam into a biased SBN:60 crystal, the hybrid-dimensional soliton interaction is performed. The experimental results are in good agreement with the numerical ones.

Keywords: soliton interaction, optical spatial soliton, photorefractive effect

PACC: 4265, 4265S, 7820W

1. Introduction

Light propagating in a nonlinear bulk medium can evolve into a self-localized state, better known as spatial solitons, which is attributed to the balance between diffraction and nonlinearity. In the past decades, optical spatial solitons have attracted intensive research interest due to their tight links to similar phenomena in other nonlinear systems beyond optics.[1,2] So far, varieties of spatial solitons, such as bright,[3−7] dark,[4,8,9] vortex,[10−12] and vector solitons,[13−15] have been demonstrated in many kinds of materials with Kerr, saturable and nonlocal nonlinearities. One of the most fascinating properties of optical spatial solitons is soliton interactions (collisions), which may have a future application in all-optical communication.[16] To date, both coherent and incoherent interactions of solitons have been investigated mainly for the same dimensional solitons in bulk nonlinear media.[17−19] It has also been revealed that the solitons can be controlled by the beam interactions in some nonlinear isotropic discrete systems.[20−23] Recently, it has been demonstrated that the interactions between one-dimensional (1D) and two-dimensional (2D) solitons exhibit many meaningful phenomena including strong inelastic collision and inhomogeneous mutual forces, which may be used as fibre–waveguide couplers.[19] The photorefractive crystal as a nonlocal and saturable nonlinear medium provides an ideal setting to observe the hybrid-dimensional soliton interaction. To our knowledge, only the centrosymmetric photorefractive crystals, potassium lithium tantalate niobate (KLTN), has been utilized to observe the interaction between 1D and 2D solitons, which was numerically analysed by an isotropic Kerr model.[24] However, it is well established that most photorefractive crystals are noncentrosymmetric and inherently anisotropic. The anisotropicity of the photorefractive effect plays a nontrivial role in determining the soliton shapes and interaction processes. Therefore, new phenomena may be expected to emerge during the hybrid-dimensional soliton interactions in noncentrosymmetric photorefractive media. In this paper, we present our theoretical and experimental results on the incoherent interaction between 1D and 2D solitons in strontium barium niobate (SBN:60), a noncentrosymmetric photorefractive crystal. It is shown that both attractive and repulsive forces can be found during the incoherent soliton interactions, depending on the initial soliton separation.

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2. Theory model

The equations governing the incoherent interaction between two mutually incoherent light beams with different dimensionalities in photorefractive crystals can be described by the dimensionless anisotropic model[25]

$$\left(\frac{\partial}{\partial z}-\frac{\mathrm{i}}{2}\frac{\partial^2}{\partial x^2}\right)B_1(x,z)=\mathrm{i}\frac{\partial\varphi}{\partial x}B_1(x,z), \tag{1a}$$

$$\left(\frac{\partial}{\partial z}-\frac{\mathrm{i}}{2}\nabla^2\right)B_2(x,y,z)=\mathrm{i}\frac{\partial\varphi}{\partial x}B_2(x,y,z), \tag{1b}$$

$$\nabla^2\varphi+\nabla\varphi\cdot\nabla\ln(1+I)=\frac{\partial}{\partial x}\ln(1+I), \tag{1c}$$

where $\nabla=\hat{x}(\partial/\partial x)+\hat{y}(\partial/\partial y)$, $B_1(x,\ z)$ and $B_2(x,\ y,\ z)$ are the amplitudes of the extraordinarily polarized 1D and 2D optical fields, respectively, and $I=|B_1(x,\ z)|^2+|B_2(x,\ y,\ z)|^2$, φ is the light-induced electrostatic potential with the boundary condition $\nabla\varphi\ (\boldsymbol{r}\to\infty)\to 0$. The dimensionless coordinates $(x,\ y,\ z)$ are related to the physical coordinates (x',y',z') by the scaling $x'=x_0x$, $y'=y_0y$, $z'=z_0z$, where $x_0=y_0=(kl)^{-1/2}$, $z_0=1/l$ and $l=0.5kn_{\mathrm{e}}^2\gamma_{33}E_0$. Here, k is the wave number, n_{e} is the extraordinary refractive index, and γ_{33} is the electro-optic coefficient. According to the experimental condition, we choose $x_0=y_0=4.17\ \mu$m, and $z_0=0.48$ mm.

The 1D and 2D solitons can be found in the form of $B_1(x,\ z)=b_1(x)\exp(\mathrm{i}\beta_1 z)$ and $B_2(x,\ y,\ z)=b_2(x,\ y)\exp(\mathrm{i}\beta_2 z)$, respectively. Here, β_1 and β_2 are the propagation constant, and the real envelopes $b_1(x)$ and $b_2(x,\ y)$ satisfy the following equations:

$$\left(\beta_1-\frac{1}{2}\frac{\partial^2}{\partial x^2}\right)b_1(x)=\frac{\partial\varphi_1}{\partial x}b_1(x), \tag{2a}$$

$$\nabla^2\varphi_1+\nabla\varphi_1\cdot\nabla\ln(1+|b_1(x)|^2)=\frac{\partial}{\partial x}\ln(1+|b_1(x)|^2), \tag{2b}$$

$$\left(\beta_2-\frac{1}{2}\nabla^2\right)b_2(x,y)=\frac{\partial\varphi_2}{\partial x}b_2(x,y), \tag{2c}$$

$$\nabla^2\varphi_2+\nabla\varphi_2\cdot\nabla\ln(1+|b_2(x,y)|^2)=\frac{\partial}{\partial x}\ln(1+|b_2(x,y)|^2), \tag{2d}$$

where φ_1 and φ_2 with the boundary conditions $\nabla\varphi_{1,2}\ (\boldsymbol{r}\to\infty)\to 0$ are the light-induced electrostatic potentials of $b_1(x)$ and $b_2(x,\ y)$, respectively.

3. Simulations

First, we numerically analyse linear and nonlinear propagations of 1D and 2D probe beams in SBN crystal. Here, we choose $b_1(x)=\exp(-x^2/4)$, $b_2(x,\ y)=\exp[-(x^2+y^2)/4]$ and the normalized propagation distance $z=14$. By employing a beam propagation method (BPM), the linear and nonlinear evolutions of 1D and 2D probe beams in SBN crystal are obtained and the results are shown in Fig. 1, where the top and bottom rows are for 1D and 2D probe beams, respectively. The intensity distributions of the input probe beams are illustrated in Fig. 1(a). In linear regimes, the probe beams experience diffraction, forming broadened profiles at the output [see Fig. 1(b)]. In the presence of nonlinearity, the probe beams maintain their shapes during propagation and evolve into soliton states, because of the interplay between the self-focusing effect and the diffraction [see Fig. 1(c)].

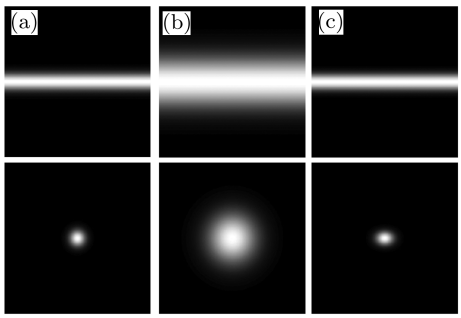


Fig. 1. Simulations on linear and nonlinear propagations of the probe beams in SBN crystal. (a) Input probe beams; (b) and (c) linear diffraction and self-trapped patterns at output, respectively. The top and bottom rows: 1D and 2D probe beams, respectively.

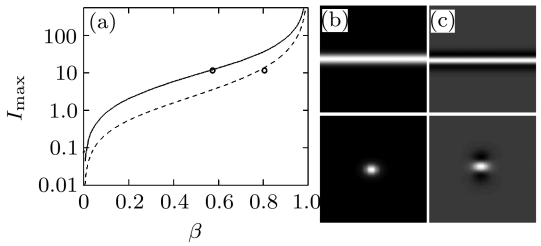


Fig. 2. Numerical results on 1D and 2D solitons. (a) Peak intensity $I_{\max}$ versus propagation constant β, where solid and dash lines are for 1D and 2D solitons, respectively. Figures (b) and (c) are typical soliton intensities and their self-induced indices, where the top and bottom rows correspond to the 1D and 2D solitons, respectively.

The solitary solutions of Eq. (2) can be derived by Petviashvili iteration.[26] The properties of the solitons are illustrated in Fig. 2, where figure 2(a) shows the curves for the maximum intensity $I_{\max}$ of the soliton versus the propagation constant β of the 1D (solid line) and 2D (dash line) solitons separately. Fig-

ure 2(b) illustrates the typical soliton intensity patterns corresponding to the dots in Fig. 2(a). Figure 2(c) is the induced indices by the solitons depicted in Fig. 2(b). The top and bottom rows of Figs. 2(b) and 2(c) correspond to the 1D and 2D solitons, respectively.

According to Eq. (1), we obtain the incoherent interaction between 1D and 2D solitons shown in Fig. 2(b), at different soliton separations for a propagating length of 14. Figures 3(a)–3(d) correspond to soliton separations of 0, 2.34, 3.25 and 7.26, respectively, where the columns from left to right are for the input solitons, the 1D and 2D solitons only at the output, and for the self-induced index of the solitons at the cross section along the x axis of the input facet. For a soliton separation of 0, the two solitons attract each other, and the intensity of the 1D soliton in an overlapping region of two solitons focuses onto its central part, forming a bright dot. Meanwhile, the intensity distribution of the 2D soliton is elongated along the horizontal direction [see Fig. 3(a)]. As the soliton separation increases to 2.34, the 1D soliton bends towards the 2D soliton and the 2D soliton breaks up into two parts [see Fig. 3(b)]. However, for a soliton separation of 3.25 the 1D soliton bends away from the 2D soliton and the 2D soliton flows away from the 1D soliton slightly [see Fig. 3(c)]. When the soliton separation is large enough (7.26), the two solitons remain their shapes and propagate independently [see Fig. 3(d)]. The above anomalous soliton interactions can be interpreted by the self-induced indices of the two solitons. According to the right columns in Fig. 3, it is obvious that the induced indices in the overlapping region of the two solitons have a tight link to their separation. For closely located solitons, the increase of indices in their overlapping region results in the mutual attraction of two solitons. With increasing soliton separation, the indices in the overlapping region of two solitons decrease, which is attributed to the repulsion between the two solitons. If the soliton separation is large enough, two solitons will be slightly influenced by the index change in their overlapping region, leading to the independent propagation of the solitons.

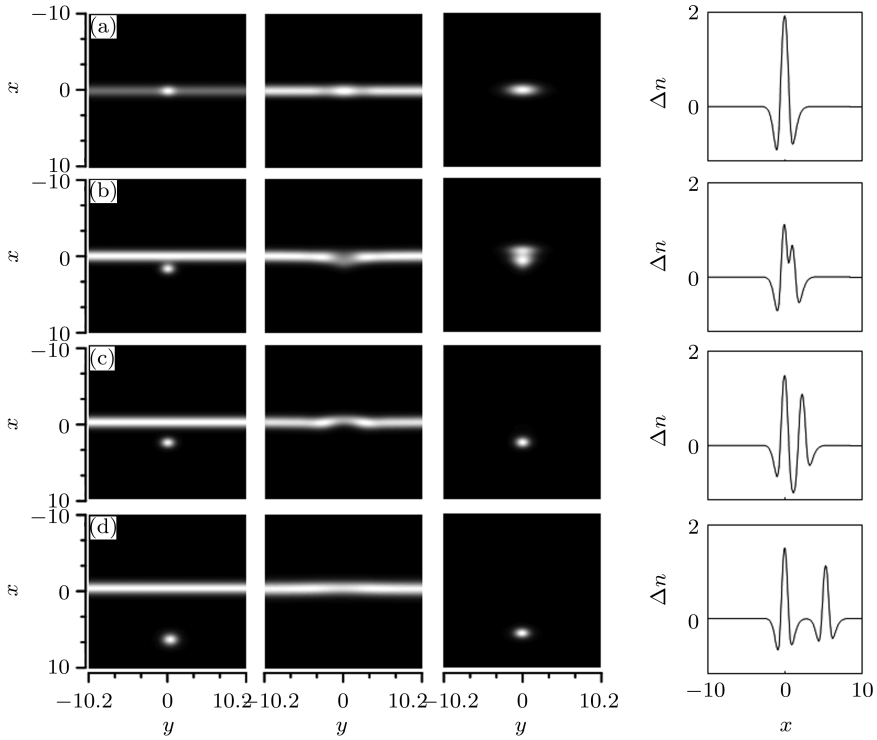


Fig. 3. Numerical results of incoherent interactions between 1D and 2D solitons at different soliton separations: (a) 0, (b) 2.34, (c) 3.25 and (d) 7.26. The columns from left to right are for the input solitons, the 1D and 2D solitons only at the output, self-induced indices by the solitons at the cross section along the x axis of the input facet, respectively.

4. Experimental results

The experimental setup for observing the incoherent interactions between the 1D and 2D solitons is illustrated in Fig. 4. Our experiments are performed in a biased SBN:60 crystal with dimensions of 6.5 mm×6.5 mm×6.7(c) mm and 0.025-wt% chromium doping. To form a 1D probe beam, the beam emitted by a diode pumped solid state laser (DPL, $\lambda = 532$ nm) is focused onto the SBN crystal through a cylindrical lens (CL) after being expanded and collimated by the reversed telescope RT_2. A He–Ne laser beam ($\lambda = 633$ nm) used as the 2D probe beam is incident on the SBN crystal through the reversed telescope RT_1 and lens L_1. Using imaging lens L_2, the two probe beams at the input and output facets of the crystal are monitored by a charge coupled device (CCD). The transition from linear to nonlinear propagations of the probe beams in the SBN crystal can be realized by adjusting the biased voltage. A cold light source is used as an incoherent background illumination to control the saturation of the photorefractive nonlinearity.

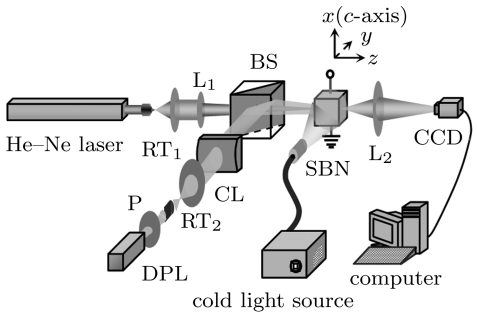


Fig. 4. Experimental setup for observing incoherent interaction between 1D and 2D solitons in a biased SBN crystal. RT's: Reversed telescope; P: Polarizer; CL: Cylindrical lens; BS: Beam split prism; L's: Lenses; DPL: Diode pumped solid state laser.

First, we observe the linear and nonlinear propagations of the 1D and 2D input probe beams in the crystal separately. The experimental results are shown in Fig. 5, where the top and bottom rows correspond to the evolutions of the 1D and 2D probe beams, respectively. The intensity distributions of the input probe beams are depicted in Fig. 5(a). In the absence of the bias field, the probe beams undergo linear diffraction, and the outputs of the probe beams are illustrated in Fig. 5(b). For the nonlinear light propagation in SBN crystal, due to the balance between self-focusing and linear diffraction, the probe beams can evolve into spatial solitons [see Fig. 5(c)]. Here, we apply a bias field of 1.45 kV/cm in order to make the nonlinearity high enough to suppress the diffraction of the probe beams. Meanwhile, the widths of the soliton beams can be controlled easily by fine-tuning the intensity of the background beam emitted from the cold light source.[7]

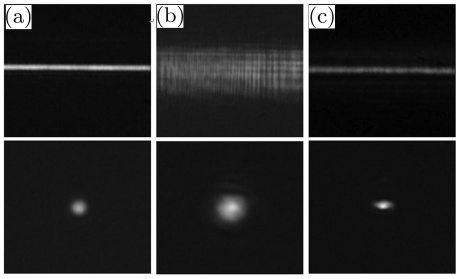


Fig. 5. Observations of linear and nonlinear propagations of 1D (top) and 2D (bottom) probe beams in SBN. (a) Input probe beams; (b) and (c) outputs after linear diffraction and nonlinear propagation, respectively.

With the solitons obtained above, the incoherent interaction of hybrid-dimensional solitons can be performed. Figure 6 depicts the experimental results of the incoherent interaction between 1D and 2D solitons, where the left column is the inputs of the two probe beams, the middle and right columns are the intensity distributions of the 1D and 2D solitons

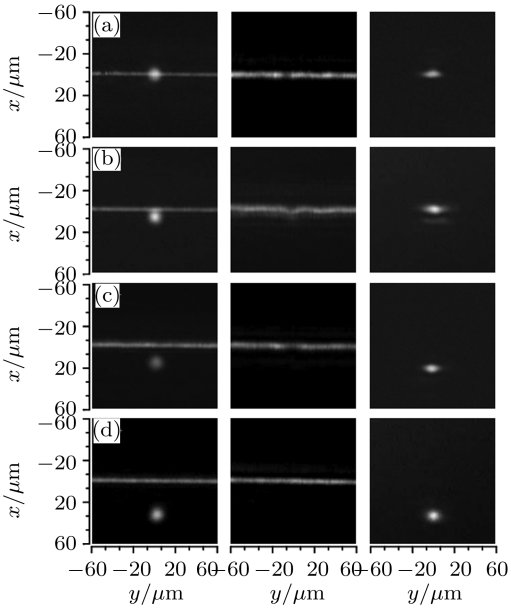


Fig. 6. Experimental demonstrations of incoherent interactions between 1D and 2D solitons at different soliton separations: (a) 0 μm; (b) 9.76 μm; (c) 13.55 μm; (d) 30.27 μm. The left column depicts the input probe beams, and the middle and right columns are for the outputs with 2D and 1D solitons blocked, respectively.

on the rear face of the crystal, respectively. Figures 6(a)–6(d) correspond to soliton separations of 0, 9.76, 13.55 and 30.27 μm, respectively. It can be seen that with the increase of soliton separation, both solitons will initially attract each other [see Figs. 6(a) and 6(b)], then repel each other [see Fig. 6(c)], and finally propagate independently [see Fig. 6(d)]. These results are consistent with our theoretical expectation above.

5. Conclusions

We numerically and experimentally analyse the incoherent interactions between 1D and 2D solitons in photorefractive crystal SBN:60. It is found that such an incoherent soliton interaction is sensitive to the soliton separation because of the anisotropy of the soliton induced index. For closely arranged solitons, attractive force is exhibited between them. With increasing soliton separation, the two solitons will repel each other and finally propagate independently. This type of anomalous soliton interaction encourages us to explore the incoherent interactions of hybrid-dimensional solitons in periodic systems, such as photonics lattices, where the periodical potential will lead to more exciting phenomena.

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