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Counterpropagating Dipole Beams in Nematic Liquid Crystals

A.I. Strinic[a,*], D.M. Jovic[a] and M.R. Belic[b]

[a]Institute of Physics, Pregrevica 118, 11080 Belgrade, Serbia

[b]Texas A&M University at Qatar, P.O. Box 5825, Doha, Qatar

We investigate the behavior of counterpropagating optical beam structures in nematic liquid crystals. We restrict our attention to the dipole–dipole beam arrangements. A time-dependent model for the beam propagation and the director reorientation in nematic liquid crystals is numerically treated in three spatial dimensions and time. Stable dipole beams are observed in a very narrow threshold region of control parameters. Below this region the beams diffract, above the region spatiotemporal instabilities are observed, as the input intensity is increased and also as the distance between the dipole partners is decreased. A transverse beam displacement of counterpropagating dipole beams is also found. The difference between the in-phase and out-of-phase components of the dipole is significant, but only for a smaller distance between the dipole partners.

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1. Introduction

Nematic liquid crystals (NLC) exhibit huge optical nonlinearities, owing to humongous refractive index anisotropy, coupled with the optically-induced collective molecular reorientation. They behave in a fluid-like fashion, but display a long-range order that is characteristic of crystals [1, 2]. Thanks to the optically nonlinear, saturable, nonlocal and nonresonant response, NLC have been the subject of considerable study in recent years, from both theoretical [3, 4] and experimental points of view [5–10].

In an earlier publication [11] we investigated the propagation of laser beams in NLC, both in time and in 3 spatial dimensions, using an appropriately developed theoretical model and a numerical procedure based on the split-step fast Fourier transform technique. Also, we have presented analysis of the counterpropagating (CP) beams in Ref. [12], where we have shown that the spatial solitons exist in a

*corresponding author; e-mail: strinic@phy.bg.ac.yu

narrow region of beam intensities, similar to the case of copropagating beams, but at lower values of the control parameters. Below this region the beams diffract, above the region the beams display periodic and even chaotic behavior. A nonlocal nature of the nonlinearity in NLC allows for interesting interaction possibilities between the two (or more) incoherent beams, or between the components of more complex multicomponent beam structures. We consider here the propagation and interactions of more complex structures, such as CP dipole beams. A pair of stable CP dipole beams is observed in very narrow threshold region of control parameters. We report a symmetry-breaking intersection and a transverse displacement of CP dipole beams. By increasing the input beam intensity, spatiotemporal instabilities are observed. Chaotic behavior is also observed by decreasing the distance between the dipole partners. Differences between the in-phase and out-of-phase components of the dipole beam are also investigated.

2. The model

A useful property of NLC is their ability to change optical properties under the influence of an external electric field, producing a reorientation of the director tilt angle θ. To describe the evolution of the slowly-varying CP beam envelopes, linearly polarized along the x axis and propagating along the z axis, we utilize the paraxial wave equations [4, 5, 8, 9]:

$$2\mathrm{i}k\frac{\partial A}{\partial \mathrm{z}} + \Delta_{x,y}A + k_0^2\varepsilon_a(\sin^2\theta - \sin^2(\theta_{\mathrm{rest}}))A = 0, \tag{1}$$

$$-2\mathrm{i}k\frac{\partial B}{\partial \mathrm{z}} + \Delta_{x,y}B + k_0^2\varepsilon_a(\sin^2\theta - \sin^2(\theta_{\mathrm{rest}}))B = 0, \tag{2}$$

where A and B are the forward and the backward propagating dipole beam envelopes, $k = k_0 n_0$ is the wave vector in the medium and $\varepsilon_a = n_e^2 - n_0^2$ is the birefringence of the medium.

θ_{rest} is the rest distribution of the tilt angle and in the presence of a low--frequency electric field. It is modeled by [5, 8]:

$$\theta_{\mathrm{rest}}(z,V) = \theta_0(V) + [\theta_{\mathrm{in}} - \theta_0(V)]\left[\exp(-z/\bar{z}) + \exp\left(-\frac{L-z}{\bar{z}}\right)\right], \tag{3}$$

with $\theta_0(V)$ being the orientation distribution due to the applied voltage V far from the input interface and L is the propagation distance. θ_{in} is the director orientation at the boundaries $z = 0$ and $z = L$, and $\bar{z}$ is the relaxation distance. We allow for the slow temporal evolution of the angle of reorientation. This evolution is modeled by the diffusion equation [2, 4]:

$$\gamma\frac{\partial\theta}{\partial \mathrm{t}} = K\Delta_{x,y}\theta + \frac{1}{4}\varepsilon_o\varepsilon_a\sin(2\theta)\left(|A|^2 + |B|^2\right), \tag{4}$$

where γ is the viscous coefficient and K is Frank's elastic constant. Hence θ is the overall tilt angle, owing to both the light and the voltage influence. Using the rescaling $\mathrm{z} = zk\mathrm{x}_0^2$, $\mathrm{x} = x\mathrm{x}_0$, $\mathrm{y} = y\mathrm{x}_0$, and $\mathrm{t} = t\tau$, the equations are transformed into a dimensionless form:

$$2\mathrm{i}\frac{\partial A}{\partial z} + \Delta_{x,y}A + k_0^2 x_0^2 \varepsilon_a(\sin^2(\theta) - \sin^2(\theta_{\mathrm{rest}}))A = 0, \tag{5}$$

$$-2\mathrm{i}\frac{\partial B}{\partial z} + \Delta_{x,y}B + k_0^2 x_0^2 \varepsilon_a(\sin^2(\theta) - \sin^2(\theta_{\mathrm{rest}}))B = 0, \tag{6}$$

$$\frac{\partial \theta}{\partial t} = \frac{K\tau}{\gamma x_0^2}\Delta_{x,y}\theta + \frac{\varepsilon_0 \varepsilon_a \tau}{4\gamma}\sin(2\theta)\left(|A|^2 + |B|^2\right), \tag{7}$$

which are then treated numerically in both space and time. Here τ is the relaxation time and x_0 is the transverse scaling length. Equations (5), (6) and (7) form the basis of the model. By solving these equations we will be describing the beam propagation in both space and time. The numerical procedure is as in Ref. [12].

3. Numerical results and discussion

Numerical studies of partial differential equations describing beam propagation in NLC are performed in different conditions and for the CP dipole beams. The initial fields are two incoherent dipole pairs, launched head-on, with the components in-phase or out-of-phase. We increase beam intensity of CP dipole beams for two different values of the distance between the dipole partners. The effect of input intensities variation on the dipole beam propagation is presented in Fig. 1.

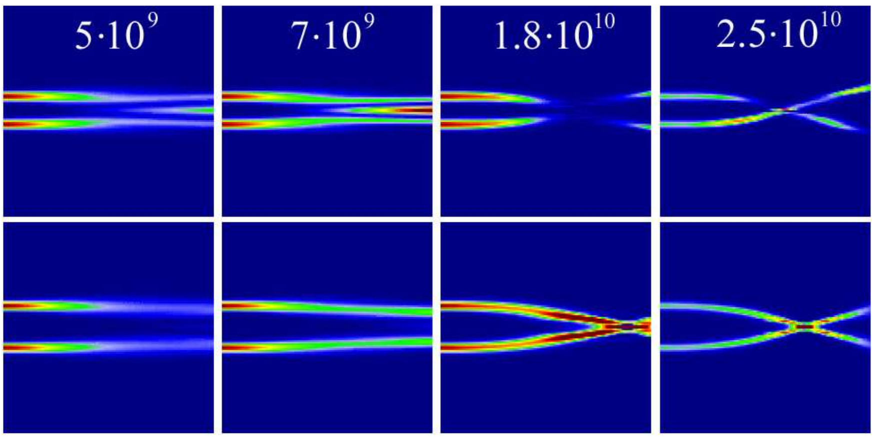

Fig. 1. Forward dipole beam propagation, shown in the (y, z) plane for different input intensities (noted in each of the figures, in $\mathrm{V}^2/\mathrm{m}^2$) and for different distances between the dipole partners: 8 μm (the first row) and 12 μm (the second row). Other parameters are: $\varepsilon_a = 0.5$, FWHM $= 4$ μm and $L = 0.5$ mm.

For smaller intensities the self-focusing is too weak to keep the beams tightly focused, so that they cannot get through localized as solitons. By increasing the beam intensity we achieve stable dipole soliton propagation. For the input intensity $I = 1.8 \times 10^{10}$ $\mathrm{V}^2/\mathrm{m}^2$, during the time of a few τ the dipole partners cross each other and then remain stable for a larger distance between the partners (the

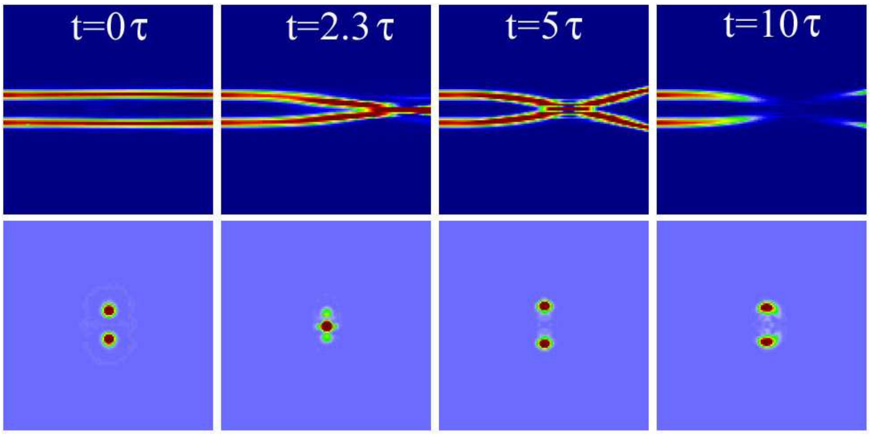

Fig. 2. Intensity distribution of the forward dipole beam in the $(y,\ z)$ plane (the first row) and the $(x,\ y)$ plane (the second row), shown at different times. Parameters: $I = 1.8 \times 10^{10}$ V^2/m^2 and the distance $= 8$ μm. Other parameters are as in Fig. 1.

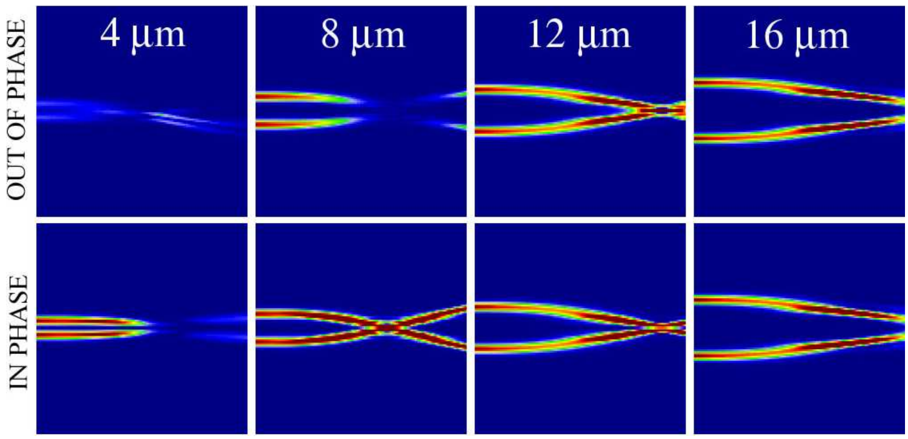

Fig. 3. Dipole beam propagation for different phase relations between the beam partners and for different distances (shown in each figure) between them. Other parameters are as in Fig. 1.

second row). However, for a smaller distance between the partners, they make an additional transverse displacement after crossing each other (the first row). Further increasing the input beam intensity ($I = 2.5 \times 10^{10}$ V^2/m^2) leads to a dynamically unstable behavior in the case of smaller distances between the dipole partners. The effect of the variation of the distance of dipole partners is clearly visible in Fig. 1: a more stable propagation is observed for a larger distance.

One characteristic example from Fig. 1 (the case for $I = 1.8 \times 10^{10}$ V^2/m^2 and the distance $= 8$ μm) is presented again in Fig. 2, but at different times and also in the $(x,\ y)$ plane. At first the dipole partners collapse into one beam, then produce a dipole beam at the output face of the crystal, by crossing each other along the crystal, and at the end make an additional transverse beam displacement. Such a dipole displacement is similar to the displacement of simple CP solitons seen before [13].

Figure 3 presents the comparison between the propagation of dipole beams with components that are out-of-phase (the upper row), and in-phase (the lower row). In the case of components out-of-phase, we notice complex dynamical behavior for smaller distances between the dipole partners. For larger distances the behavior is more stable and very similar for both the in-phase and the out-of-phase cases.

4. Conclusion

We report, for the first time to our knowledge, on the behavior of CP dipole beam structures in NLC. We demonstrate the existence of CP dipole beams in a narrow region of beam intensities. At higher input intensities we see intersection and irregular dynamics of CP beams. By increasing the distance between the beam partners, stable structures are observed. Differences between the in-phase and the out-of-phase components of dipole beams are also investigated. In the case of out--of-phase components, we notice complex dynamical behavior for smaller distances between the dipole partners. The in-phase components of the dipole beam are more stable.

Acknowledgments

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