

Nonlocality-controlled interaction of spatial solitons in nematic liquid crystals

Wei Hu, Tao Zhang, Qi Guo, Li Xuan, and Sheng Lan

Citation: *Appl. Phys. Lett.* **89**, 071111 (2006); doi: 10.1063/1.2337268

View online: <http://dx.doi.org/10.1063/1.2337268>

View Table of Contents: <http://apl.aip.org/resource/1/APPLAB/v89/i7>

Published by the [American Institute of Physics](#).

Additional information on *Appl. Phys. Lett.*

Journal Homepage: <http://apl.aip.org/>

Journal Information: http://apl.aip.org/about/about_the_journal

Top downloads: http://apl.aip.org/features/most_downloaded

Information for Authors: <http://apl.aip.org/authors>

ADVERTISEMENT



HAVE YOU HEARD?

Employers hiring scientists
and engineers trust
physicstodayJOBS



<http://careers.physicstoday.org/post.cfm>

Nonlocality-controlled interaction of spatial solitons in nematic liquid crystals

Wei Hu, Tao Zhang, and Qi Guo^{a)}

Laboratory of Photonic Information Technology, South China Normal University, Guangzhou 510631, People's Republic of China and Laboratory of Light Transmission Optics, South China Normal University, Guangzhou 510631, People's Republic of China

Li Xuan

State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, People's Republic of China

Sheng Lan

Laboratory of Photonic Information Technology, South China Normal University, Guangzhou 510631, People's Republic of China

(Received 25 March 2006; accepted 12 July 2006; published online 18 August 2006)

The authors demonstrate experimentally that interaction between nonlocal solitons in nematic liquid crystals (NLCs) can be controlled by the degree of nonlocality. For a given beam width, the degree of nonlocality can be modulated by changing the pretilt angle θ_0 of NLC molecules through bias voltage V . As V increases (so does θ_0), the degree of nonlocality decreases. When the degree of nonlocality is below a critical value, the solitons behave in the way like their local counterpart, i.e., in-phase solitons attract while out-of-phase solitons repulse each other. Such a voltage-controlled interaction between the solitons can be readily implemented in experiments. © 2006 American Institute of Physics. [DOI: 10.1063/1.2337268]

The interaction properties of two spatial optical solitons depend on the phase difference between them, their coherence,^{1,2} and the nonlinear nonlocality of the materials in which the solitons propagate. For a local Kerr-type nonlinearity, two coherent bright solitons attract (or repulse) each other when they are in phase (or out of phase). On the other hand, if the solitons are mutually incoherent³ or the nonlinear nonlocality of the materials is strong enough,⁴⁻⁶ the soliton interaction is always attractive, independent of the phase difference. Very recently, Ku *et al.*² demonstrated both theoretically and experimentally that the interaction of the solitons can be controlled by varying their total coherence. Thus, the two out-of-phase solitons can repulse or attract each other, depending on whether the coherence parameter is below or above a threshold. Similar dependence of the interaction behavior on nonlocality was also theoretically predicted by Rasmussen *et al.*⁷ based on the (1+1)-dimensional model of the nematic liquid crystal (NLC), i.e., there exists a critical degree of nonlocality above which the two out-of-phase solitons will attract each other.

The NLC with a pretilt angle induced by an external low-frequency electric field has been confirmed^{8,9} to be a typical material with the strongly nonlocal (referred also as highly nonlocal in some papers^{4,8,9}) nonlinearity. In the previous works concerning the single soliton propagation⁸⁻¹⁰ and the soliton interaction^{5,7,11} in the NLC, however, the peak of the pretilt angle was always made to be $\pi/4$ in order to maximize the nonlinearity. As will be seen later, the degree of nonlocality can only be modulated by changing the beam width in this case, which is not convenient in practice. Recently, Peccianti *et al.* have shown that¹² the nonlocality can be varied by changing the pretilt angle via a bias voltage. In this letter, we use the (1+2)-dimensional model with an

arbitrary pretilt angle¹² to describe the (1+2)-dimensional soliton interaction in the NLC. By defining a general characteristic length of the nonlinear nonlocality for the NLC, a voltage-controlled degree of nonlocality is shown to be achieved conveniently. In experiments, we observe the nonlocality-controllable (through the change of the bias voltage) transition from attraction to repulsion of the two out-of-phase solitons in the NLC.

Let us consider the (1+2)-dimensional model of light propagation in a cell containing the NLC. The configuration of the cell and the coordinate system are the same as in the previous works.⁸⁻¹³ The optical field polarized in x axis with envelope A propagates in z direction. An external low-frequency electric field E_{rf} is applied in x direction to control the initial tilt angle of the NLC. The evolution of the paraxial beam A and optically induced angle perturbation Ψ can be described by the system,^{12,13}

$$2ik\partial_z A + \nabla_{\perp}^2 A + k_0^2 \epsilon_a^{op} \sin(2\theta_0) \Psi A = 0, \quad (1)$$

$$\nabla_{\perp}^2 \Psi - \frac{1}{w_m^2} \Psi + \frac{\epsilon_0 \epsilon_a^{op}}{4K} \sin(2\theta_0) |A|^2 = 0, \quad (2)$$

where θ_0 and K are the same with that in the Ref. 12, $\nabla_{\perp}^2 = \partial_x^2 + \partial_y^2$, $k^2 = k_0^2(n_{\perp}^2 + \epsilon_a^{op} \sin^2 \theta_0)$, $\epsilon_a^{op} = n_{\parallel}^2 - n_{\perp}^2$, $\epsilon_a^{rf} = \epsilon_{\parallel} - \epsilon_{\perp}$, and the parameter $w_m > 0$ for $|\theta_0| \leq \pi/2$, which reads

$$w_m = \frac{1}{E_{rf}} \left\{ \frac{2\theta_0 K}{\epsilon_0 \epsilon_a^{rf} \sin(2\theta_0) [1 - 2\theta_0 \cot(2\theta_0)]} \right\}^{1/2}. \quad (3)$$

In Eq. (2), the term $\partial_z^2 \Psi$ has been canceled out because the dependence of Ψ on z is proven to be negligible.^{7,13}

Introducing the normalization that $X = x/w_0$, $Y = y/w_0$, $Z = z/(2kw_0^2)$, $a = A/A_0$, and $\psi = \Psi/\Psi_0$, where $A_0 = 4\sqrt{\pi K/\epsilon_0/k_0 \epsilon_a^{op} w_0^2}$, $\Psi_0 = \sin(2\theta_0)/k_0^2 w_0^2 \epsilon_a^{op}$, and w_0 the initial beam width, we have the dimensionless system,

^{a)}Electronic mail: guoq@senu.edu.cn

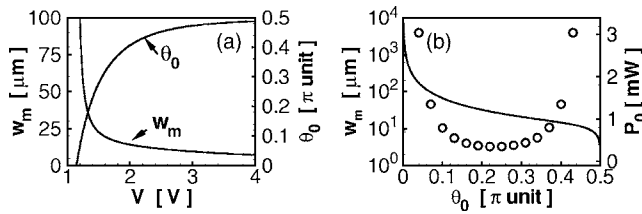


FIG. 1. (a) The characteristic length w_m and the pretilt angle θ_0 of the NLC vs the bias voltage V . (b) The characteristic length w_m (a solid curve) and the critical power of a single soliton (circles) vs the pretilt angle θ_0 . The parameters are for a 80- μm -thick cell filled with the NLC (TEB30A) and the critical power is a numerical result.

$$i\partial_z a + \nabla_{XY}^2 a + \gamma\psi a = 0, \quad (4)$$

$$\nabla_{XY}^2 \psi - \alpha^2 \psi + 4\pi|a|^2 = 0, \quad (5)$$

where $\nabla_{XY}^2 = \partial_X^2 + \partial_Y^2$, $\gamma = \sin^2(2\theta_0)$, and $\alpha = w_0/w_m$. For a symmetrical geometry, Eq. (5) has a particular solution $\psi(x, y) = (4\pi/\alpha^2) \int R(x-x', y-y') |a(x', y')|^2 dx' dy'$, and $R(x, y) = (\alpha^2/2\pi) K_0(\alpha\sqrt{x^2+y^2})$, where K_0 is the zeroth order modified Bessel function.

We define w_m in Eq. (3) as the general characteristic length of the nonlinear nonlocality for the NLC,¹⁴ then it is obvious that the factor α in Eq. (5) indicates the degree of nonlocality, as defined in Ref. 15 for the specific case of Gaussian response function. A monotonous function of θ_0 on E_{rf} can be approximated as¹² $\theta_0 \approx (\pi/2)[1 - (E_{\text{Fr}}/E_{\text{rf}})^3]$ when E_{rf} is higher than the Fréederichsz threshold E_{Fr} . Therefore, we can clearly observe from Eq. (3) that w_m is determined only by E_{rf} (or by the bias V), or equivalently by the peak-pretilt angle θ_0 for a given NLC cell configuration, as shown in Fig. 1. When the bias is properly chosen so that $\theta_0 = \pi/4$,⁸ w_m is fixed and α can be modulated only by changing w_0 . This is the case discussed in Ref. 7. With the decrease of the bias, θ_0 goes from $\pi/2$ to 0, then α varies from ∞ to 0 for a fixed w_0 and the degree of nonlocality increases from locality to strong nonlocality. As a result, the voltage-controlled degree of nonlocality through the medium of the pretilt θ_0 of the NLC can be achieved conveniently. Figure 1(b) also

shows that the critical power reaches its minimum nearby $\theta_0 = \pi/4$, and as the pretilt angle approaches $\pi/2$, the critical power increases sharply.

To show the influence of the pretilt angle θ_0 (or equivalently the degree of nonlocality for a fixed w_0) on the interaction between the two solitons, we have carried out numerical simulations directly based on the original equations [Eqs. (1) and (2) in Ref. 13]. The simulation results show that there exist critical values for the degree of nonlocality below (or above) which two out-of-phase solitons will repulse (or attract) each other. The critical values depend on the initial separation and relative angle in the (y, z) plane between the solitons. These results agree with the prediction based on the (1+1)-dimensional model.⁷ The critical degree of nonlocality for the two parallel solitons is very weak so that the corresponding critical pretilt angle θ_{0c} is very close to $\pi/2$, leading to a very high critical power for the soliton state [see Fig. 1(b)]. However, the use of a relative angle will significantly increase the critical degree of nonlocality and make θ_{0c} not be close to $\pi/2$. Hence, the critical powers for different pretilt angles around θ_{0c} do not differentiate too much. This makes it possible to observe the soliton states at a fixed input power for different pretilt angles (or different bias voltages).¹⁶ Figure 2 presents the simulation results of two solitons with a relative angle of 0.57° for different values of θ_0 . We can see that for $\theta_0 \leq \pi/4$, the nonlocality is strong enough to guarantee the attraction of both the in-phase and the out-of-phase solitons. However, the degree of nonlocality becomes lower than the critical degree of nonlocality when $\theta_0 = 0.45\pi$. In this case, the out-of-phase solitons begin to repulse each other and the in-phase solitons remain attraction.

The experimental setup is illustrated in Fig. 3. The laser beam from an argon-ion laser is split into two beams, then they are combined together with a small separation through the other beam splitter and launched into a 80- μm -thick NLC cell by a $10\times$ microscope objective. The beam width at the focus w_0 , the separation d_s , and relative angle β between the two beams are measured by an edged-scanning beam profiler when the NLC cell is removed. The phase difference between the two beams is adjusted by the rotation of a 1.8-mm-thick parallel-face plate, and measured through the

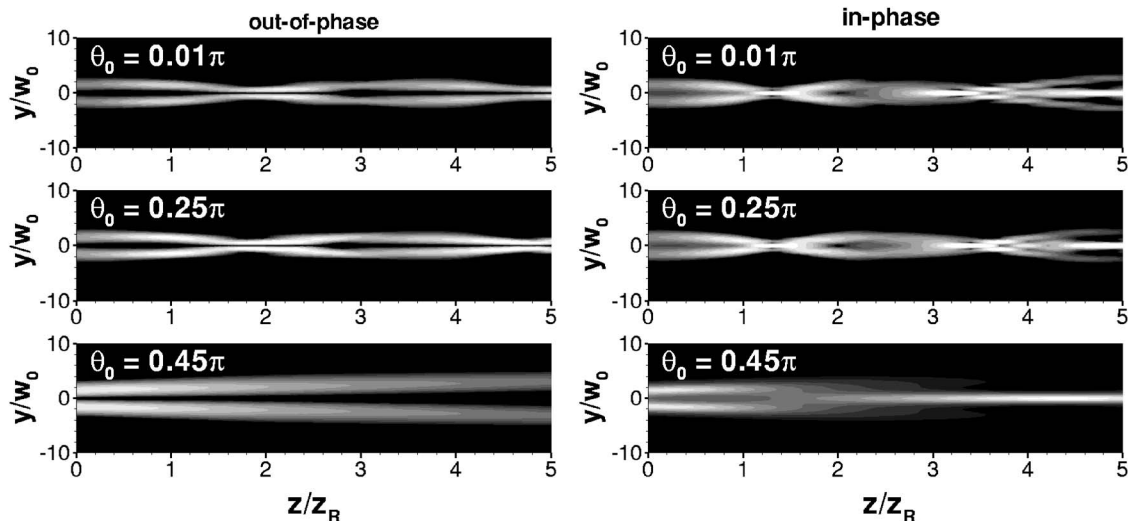


FIG. 2. Numerical simulation results of the interactions of the in-phase and the out-of-phase solitons. The width for each soliton is 4 μm and the input power is 1.1 mW. The separation and the relative angle between two solitons are, respectively, 12 μm and 0.57° ($\tan 0.57^\circ = 0.01$).

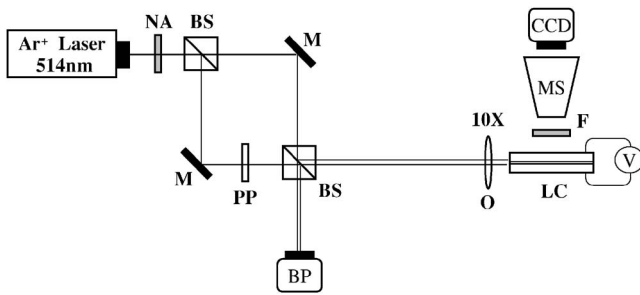


FIG. 3. Scheme of the experimental setup. NA, neutral attenuator; BS, beam splitters; M, plate mirror; PP, parallel-face plate for adjusting the phase difference; O, 10 \times microscope objective; LC, liquid crystal cell; MS, microscope; F, laser-line filter; and BP, beam profiler.

interference pattern by the beam profiler located on the other branch after the second beam splitter. The cell is filled with the NLC TEB30A (from SLICHEM China Ltd.), whose $n_{||}=1.6924$, $n_{\perp}=1.5221$, $K \approx 10^{-11}N$, $\epsilon_a^{\text{op}}=0.5474$, and $\epsilon_a^{\text{rf}}=9.4$. The Freèdericksz threshold $V_t \approx 1.14$ V for the 80- μm -thick cell. The launched power for each beam is fixed to 7 mW when the bias is changed, and the other parameters for the beams in the NLC are $w_0=3.2$ μm , $d_s=10$ μm , and $\tan \beta=0.011$. When the phase difference is adjusted to 0 or π , we record the beam traces for the different biases by the charge-coupled device camera, as shown in Fig. 4.

Let us compare the photos for the in-phase and the out-of-phase solitons when the bias $V=1.4$ V ($\theta_0 \approx \pi/4$). They are almost the same for both cases. It means for $\theta_0 = \pi/4$ the degree of nonlocality is strong enough to eliminate the dependence of the interactions on the phase difference between the solitons. In this case, $w_m \approx 25.3$ μm , which is bigger than the separation of the two beams, and $\alpha=0.126$ for the 3.2- μm -width solitons.

For the bias $V=1.0$ V slightly lower than the threshold $V_t=1.14$ V (a small tilt angle in the sample educes some reorientation at the bias voltage lower than the threshold¹²), the pretilt angle θ_0 is nearly zero and nonlocality is much stronger than that when $V=1.4$ V. For this reason, a second cross point is observed for both the in-phase and the out-of-phase solitons.

When the bias V (pretilt angle θ_0) increases, the degree of nonlocality $1/\alpha$ and the characteristic length w_m decrease. For $V=2.4$ V ($\theta_0 \approx 0.45\pi$), we have $w_m \approx 11$ μm , which approximately equals to the separation between the two solitons. In this case, we observe the attraction of the in-phase solitons and the repulsion of the out-of-phase solitons. We also see the two in-phase solitons fused into one soliton, which is qualitatively the same with the numerical simulation result in Fig. 2.

In conclusion, we have investigated theoretically and experimentally the interactions of the nonlocal spatial solitons

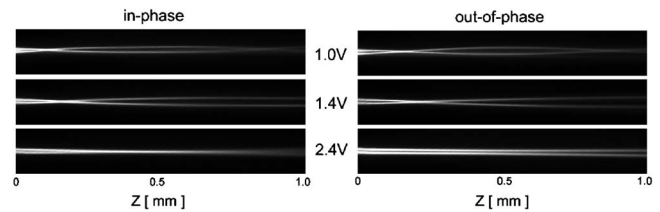


FIG. 4. Photos of the beam traces for the soliton pair propagation in the NLC cell. The biases applied on the LC are 1.0, 1.4, and 2.4 V, corresponding to the pretilt angles of 0.01π , 0.25π , and 0.45π , respectively.

in the NLC when the applied bias is adjusted. It is shown that the voltage-controllable degree of nonlocality in the NLC can be implemented expediently. We experimentally observe the transition from attraction to repulsion of the two out-of-phase solitons in the NLC as the degree of nonlocality decreases via increasing the bias. Such a voltage-controllable soliton interaction might have its potential applications in developing all-optical signal processing devices.

This work was supported by the Natural Science Foundation of Guangdong Province of China (Grant No. 04105804) and partially supported by the National Natural Science Foundation of China (Grant Nos. 60278013, 10474023, and 60277033).

- ¹G. I. Stegeman and M. Segev, *Science* **286**, 1518 (1999), and references therein.
- ²T. S. Ku, M.-F. Shih, A. A. Sukhorukov, and Y. S. Kivshar, *Phys. Rev. Lett.* **94**, 063904 (2005).
- ³D. Anderson and M. Lisak, *Phys. Rev. A* **32**, 2270 (1985).
- ⁴A. W. Snyder and D. J. Mitchell, *Science* **276**, 1538 (1997).
- ⁵M. Peccianti, K. Brzdakiewicz, and G. Assanto, *Opt. Lett.* **27**, 1460 (2002).
- ⁶Y. Xie and Q. Guo, *Opt. Quantum Electron.* **36**, 1335 (2004).
- ⁷P. D. Rasmussen, O. Bang, and Wieslaw Królkowski, *Phys. Rev. E* **72**, 066611 (2005).
- ⁸C. Conti, M. Peccianti, and G. Assanto, *Phys. Rev. Lett.* **91**, 073901 (2003).
- ⁹C. Conti, M. Peccianti, and G. Assanto, *Phys. Rev. Lett.* **94**, 113902 (2004).
- ¹⁰M. Peccianti, A. De Rossi, G. Assanto, A. De Luca, C. Umeton, and I. C. Khoo, *Appl. Phys. Lett.* **77**, 7 (2000).
- ¹¹A. Fratallocchi, M. Peccianti, C. Conti, and G. Assanto, *Mol. Cryst. Liq. Cryst.* **421**, 197 (2004).
- ¹²M. Peccianti, C. Conti, and G. Assanto, *Opt. Lett.* **30**, 415 (2005).
- ¹³M. Peccianti, C. Conti, G. Assanto, A. De Luca, and C. Umeton, *J. Non-linear Opt. Phys. Mater.* **12**, 525 (2003).
- ¹⁴When $\theta_0 = \pi/4$, w_m defined by us will be reduced to the characteristic value R_c defined in Refs. 8 and 13.
- ¹⁵Q. Guo, B. Luo, F. Yi, S. Chi, and Y. Xie, *Phys. Rev. E* **69**, 016602 (2004); N. Cao and Q. Guo, *Acta Phys. Sin.* **54**, 3688 (2005).
- ¹⁶Rigorously speaking, except one of them, they are quasisolitons (breathers) rather than solitons because the fixed input power can only equal exactly one of the critical powers for different biases, but is close to the others in the case under consideration.