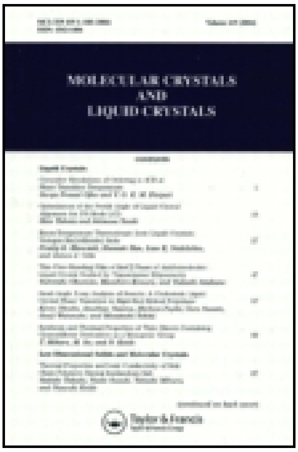

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Coherent and Incoherent Spatial Solitons in Bulk Nematic Liquid Crystals

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Nematic liquid crystals are suitable materials for nonlinear wave propagation. A reorientational nonlinearity can be observed at very low optical intensities and the saturating response of the medium allows for the formation of 3D solitary waves. In this paper we review our recent theoretical and experimental results on spatial soliton formation in a nematic liquid crystal cell. Optical induced waveguiding at mW powers with either a coherent or an incoherent pump is demonstrated. Spatial readdressing of a signal beam in the soliton-waveguide is also shown.

Keywords: liquid crystals, spatial solitons, all-optical steering, incoherent spatial solitons.

I. INTRODUCTION

From the 60's scientists have been searching for optical materials able to support nonlinear effects and, in particular spatial solitary waves or *solitons* because of their role in the development of light-controlled readdressing and switching devices.[1-2] What most of such materials have in common is that pulsed laser sources are needed to comply with the high peak power requirements. From this standpoint, liquid crystals represent a promising alternative: in spite of their slow response, reorientational optical nonlinearities can be excited at very low optical intensities, 10^9 times lower than in Carbon Disulfide.[3-4]

A spatial soliton can be observed through a reorientational response via the inherent dependence of the refractive index on the optical intensity in a positive uniaxial crystal. When a light beam propagates in the medium, the refractive index increase in the axial and most intense region of the beam causes a self-focusing effect which can balance linear diffraction.[5] In this case, the spot size does not change versus propagation distance and the field distribution is a particular eigen-solution of the corresponding nonlinear propagation equation. For a local and instantaneous Kerr dependence in one transverse dimension (1+1D), the relevant model is an integrable system in the form of the nonlinear Schroedinger equation and one of its solutions is the fundamental soliton: the index perturbation forms a waveguide able to confine the beam in the direction normally (linearly) subject to diffraction.[6-7] The latter is also a heuristic way to define a spatial soliton in a phenomenological sense, and can be extended to more than one transverse dimensions and to more complex nonlinear mechanisms, provided that the transverse dimension of the beam does not change over distances well exceeding the characteristic diffraction length.

In two transverse dimensions (2+1D), however, only media exhibiting a saturable Kerr-like and/or nonlocal response permit the formation of stable spatial solitons without incurring into filamentation and catastrophic collapse.[8-9] Both saturation and nonlocality of the nonlinear index change characterize the reorientational response of nematic liquid crystals, which relies on the light-induced perturbation of the angle between the constituent molecules and the electric field vector of the optical beam in the presence of elastic bounding forces.[3-4]

II. BASIC PHYSICS

A nematic liquid crystal (NLC) contains rod-like molecules which tend to be aligned to one another by elastic forces. The alignment, described by a director field $\hat{n}(x,y,z)$, is usually defined by the boundary conditions at the interfaces confining the liquid medium. Intense enough electric fields can induce the reorientation of the molecules through dipolar interaction: when the field vector is normal to the alignment direction, the effect has an intensity threshold known as "Freédericks transition".[3-4] A beam propagating in the medium can therefore induce the reorientation of the molecules, increasing the refractive index in a positive uniaxial: in this way the beam nonlinearly affects its own propagation in the NLC and can eventually give rise to a spatial solitary wave or *soliton*.

After the pioneering work by Braun *et al.*[10-11] in capillary geometries, self-trapped waves have been demonstrated by Warenghem *et al.* in a capillary filled with a dye-doped NLC[12] and by Karpierz *et al.* with a mixed TE-TM guided mode excitation in thin film planar cells containing a homeotropically aligned NLC.[13] Because of the liquid nature of the medium, it is important to reduce the intensity requirements for the sought reorientational phenomenon and avoid convection and thermal effects. To this extent, in our work we applied an external low frequency electric field to obtain a pre-tilted configuration of directors in a planarly aligned NLC cell.[14] By setting the NLC molecules close to $\pi/4$ with respect to the electric field vector in the beam, the Freédericks threshold is eliminated, the intensity requirement lowered and the effective nonlinear response maximized.[3-4]

Let us consider an input beam with an x-polarized field $\vec{A} = A \cdot \hat{x}$ propagating along z in a bulk NLC. If θ is the reorientation angle of the director in the x-z plane with respect to the propagation direction z, the interaction energy can be written as

$$\begin{aligned} F_{el}(\theta) &= -\frac{\varepsilon_0}{4}\left[\Delta\varepsilon\left(\hat{n}\cdot\vec{A}\right)\left(\hat{n}\cdot\vec{A}^*\right) + n_\perp^{\,2}\left(\vec{A}\cdot\vec{A}^*\right)\right] = \\ &= -\frac{\varepsilon_0}{4}\left[n_\perp^{\,2} + \Delta\varepsilon \sin^2\theta\right]|A|^2 = \\ &= -\frac{\varepsilon_0}{4}\left(\Delta\varepsilon \sin^2\theta\right)|A|^2 + g \end{aligned} \tag{1}$$

where g is independent from θ, and $\Delta\varepsilon = n_\parallel^2 - n_\perp^2$ is the birefringence. In the usual Frank's formalism, the energy associated to the director distortion is given by:[3]

$$\begin{aligned} F_D(\theta) &= \frac{1}{2}K_1\left(\cos\theta\frac{\partial\theta}{\partial x} - \sin\theta\frac{\partial\theta}{\partial z}\right)^2 + \\ &+ \frac{1}{2}K_2\left(\frac{\partial\theta}{\partial y}\right)^2 + \frac{1}{2}K_3\left(\cos\theta\frac{\partial\theta}{\partial z} + \sin\theta\frac{\partial\theta}{\partial x}\right) \end{aligned} \tag{2}$$

where K_1, K_2 and K_3 are the Frank elastic constants for splay, twist and bend, respectively. According to the usual variational approach, the effect of the molecular torque corresponds to the minimum of the total energy $F=F_D+F_{el}$ and is described by an Euler-Lagrange elliptic equation. If the (bias induced) pre-tilt is constant and equal to π/4, in the slowly-varying envelope approximation (SVEA) along z and assuming equal Frank constants $K_1=K_2=K_3=K$, we can write:[10, 14]

$$K\left[\frac{\partial^2\theta'}{\partial x^2}+\frac{\partial^2\theta'}{\partial y^2}\right]+\varepsilon_0\Delta\varepsilon\sin(2\theta)|A|^2/4=0 \quad (3)$$

where $\theta'=\theta-\theta_0$. This equation describes a saturable nonlinearity (θ can never exceed π/2), i. e., one such that the refractive index increase cannot exceed $n_{\|}-n_{\perp}$. The optical propagation can be modeled by a Schroedinger-like equation in a slightly inhomogeneous medium:

$$2ik\frac{\partial A}{\partial z}+\left[\frac{\partial^2 A}{\partial x^2}+\frac{\partial^2 A}{\partial y^2}\right]+k_0^2\Delta\varepsilon\left(\sin^2\theta-\sin^2\theta_0\right)A=0 \quad (4)$$

where $k\approx k_0\sqrt{n_\perp^2+\Delta\varepsilon\sin^2\theta_0}$ is the wavevector and $k_0=2\pi/\lambda$, with λ the wavelength.

Figure 1 is a numerical simulation from equation (3) and (4), for the case of an x-polarized Gaussian beam of power 3.9mW and input waist of 3μm propagating in a symmetric cell. In the absence of the external bias ($\theta_0=0$), the optical irradiance is below the Fréedericks threshold and the beam diffracts in x and y as it proceeds along z. This behavior in the y-z plane is shown in figure 1(a). When the external field is applied ($\theta_0=\pi/4$), no threshold exists and the nonlinear response associated to the excitation and the material parameters gives rise to a (2+1)D spatial soliton which propagates with an invariant transverse profile, as visible in figure 1(b) over distances well in excess of the Rayleigh length.

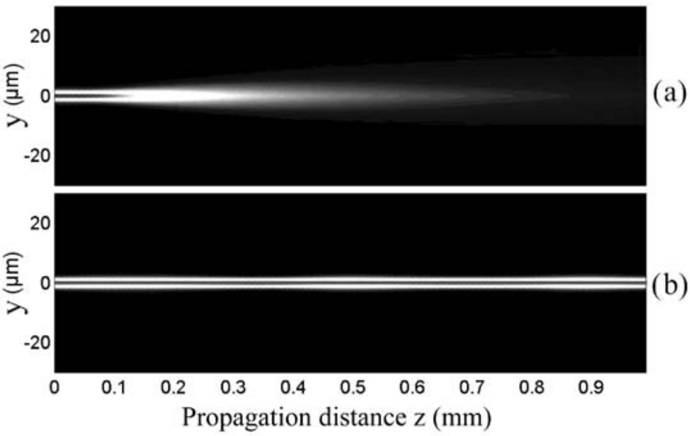

FIGURE 1 Computer simulations of the propagation in the (y-z) plane of a beam launched with a 3µm waist and 3.9mW power. Gray-scale maps of (a) linear diffraction when $\theta_0=0$, (b) solitary wave when $\theta_0=\pi/4$.

III. SAMPLE, SETUP AND EXPERIMENTAL RESULTS

To verify the predicted behavior, we used a planar cell composed of two thin glass walls in a sandwich-like structure (figure 2). Two Mylar spacers defined a 75µm internal thickness of the commercial liquid crystal "E7", a nematic with $n_{\|}=1.737$ and $n_{\perp}=1.519$ at $\lambda=633$nm, $n_{\|}=1.773$ and $n_{\perp}=1.530$ at $\lambda=514$nm.[15] A SiO_2 coating on the interfaces ensured the director planar alignment along z, while Indium-Tin Oxide films (ITO) were deposited as transparent electrodes for the application of the low-frequency bias (figure 2). The input NLC-air interface was a third glass slide able to avoid the formation of an exposed meniscus which could distort the input optical wavefront in an unpredictable way.

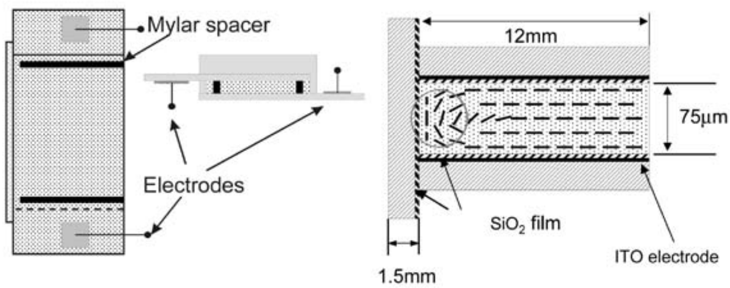

FIGURE 2 Top (left) and side (right) views of the NLC cell. The circle indicates the transition region where the director distribution rearranges owing to the input interface.

An Argon-ion laser beam at λ=514nm was employed to study soliton generation. It was linearly polarized and focused to a waist <2.5μm with a 20x microscope objective. A rotating diffuser in the beam path could be used to alter its spatial (and temporal) coherence in order to investigate the nonlinear effects induced by spectrally widened radiation. A co-propagating linearly polarized He-Ne laser beam could be launched with the Ar^+ light, as sketched in figure 3. The field distribution in the plane (y-z) inside the cell was investigated by collecting the light scattered above it with a microscope and a CCD camera (figure 3, right).

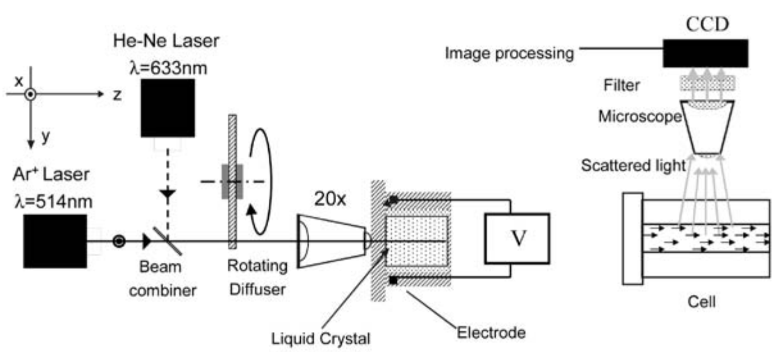

FIGURE 3 (Left) Experimental set-up: pump (Ar^+) and probe (He-Ne) co-propagate through the optics. (Right) The propagation is investigated imaging the out-of-cell scattering.

Typical experimental results are shown in figure 4 using a gray-scale encoding. In figure 4(a), a 2mW y-polarized beam diffracts with a divergence of 11° (half angle) because the interaction is not favored by a pre-tilt along y, as the bias only acts in the x-direction. The same happens when the beam is x-polarized in the absence of external bias, as visible in figure 4(b). Conversely, with a V=1V (rms) bias and an x-polarized excitation, a spatial soliton is generated and is clearly visible in figure 4(c): the polarization dependence confirms the reorientational nature of the nonlinearity.

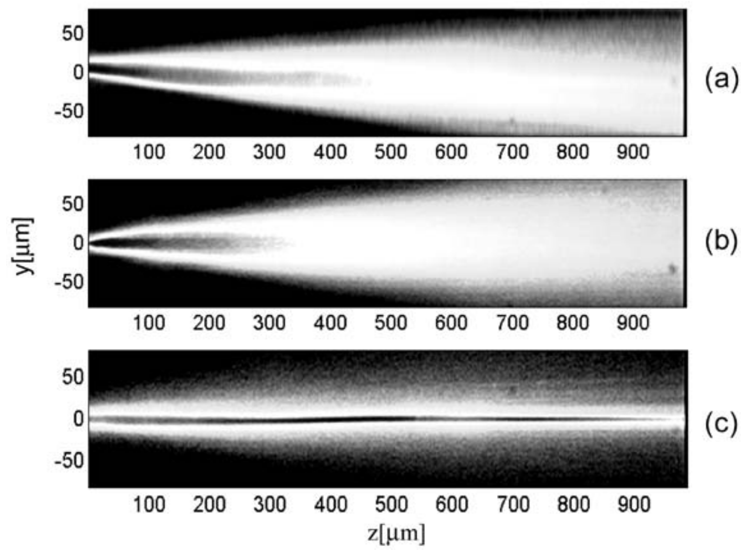

FIGURE 4 Propagation of a focused 2mW Ar^+ beam in the NLC cell. (a) The y-polarized beam diffracts; (b) the x-polarized light diffracts in the absence of a voltage bias (the irradiance is below the Fréedericks threshold); (c) by applying a 1V bias, the x-polarized beam forms a spatial soliton.

According to the well-established understanding of spatial soliton physics in a material with an intensity-dependent refractive index,[7] the soliton is the result of an actual light-induced waveguide confining the Ar^+ light. This could be assessed by trapping and guiding a co-polarized low power He-Ne probe beam at λ=633nm, and the results are shown in figure 5. To collect the scattered light at λ=633nm, a color filter was inserted before the camera. When the Ar^+ pump is not present or is polarized along y, i.e., when the soliton is not formed, the x-polarized probe diffracts as in figure 5(a); in the presence of a (green) spatial soliton, the (red) probe is well confined, as visible in figure 5(b).

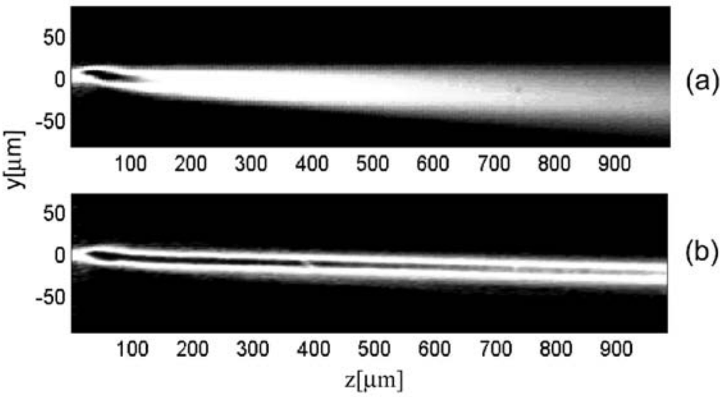

FIGURE 5 Propagation of an x-polarized probe (<100µW) in the NLC cell. (a) Linear propagation in the absence of a "green" soliton; (b) induced confinement in the soliton waveguide, corresponding to the case of figure 4(c).

The reorientational effect consists in the rotation of elongated (non centro-symmetric) molecules in a viscous fluid, subject to an elastic reaction. The liquid crystal response is, therefore, non-instantaneous and rather slow. For this reason, under illumination time-varying in phase and/or amplitude in a timescale shorter than the NLC response time, equation (3) can be rewritten as:

$$K\left[\frac{\partial^2\theta'}{\partial x^2}+\frac{\partial^2\theta'}{\partial y^2}\right]+\varepsilon_0\Delta\varepsilon\sin(2\theta)\left\langle|A|\right\rangle_t^2/4=0 \tag{5}$$

with the brackets "$\langle\ \rangle_t$" indicating a time average. Thus, the NLC nonlinear response to an intense optical excitation depends on its time average. A slow response represents a limit in fast data processing but, as previously reported in photorefractives,[16-17] supports nonlinear phenomena and spatial solitons even when using incoherent light, i.e., in the presence of random and relatively fast changes across the input beam.

In our setup, the insertion of a rotating diffuser (figure 3, left) introduced a random phase modulation of the wavefront, reducing the spatial coherence of the beam and generating a speckle pattern across it. figure 6(a) shows the resulting increase in (linear) beam divergence owing to the correspondingly widened spatial spectrum. Since the diffuser rotation was much faster than the NLC response, however, a slight increase in input power (from 2 to 2.7mW) sufficed to balance out the larger diffraction and obtain self-trapping, generating once again the spatial soliton displayed in figure 6(b). Even in this latter case, the

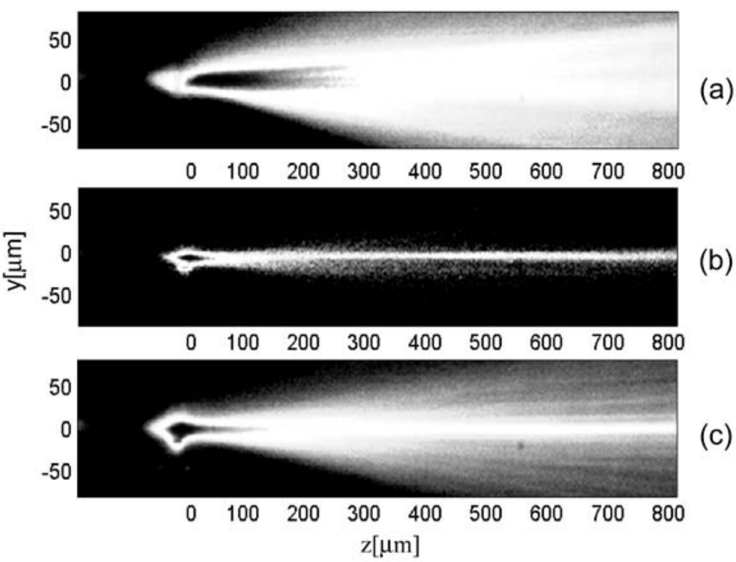

FIGURE 6 Propagation of a partially incoherent beam. (a) Diffraction of a y-polarized Ar^+ beam: stronger diffraction is clearly observed. (b) An *incoherent* spatial soliton is created at 2.7mW. (c) An equally incoherent He-Ne probe is guided by the *incoherent* soliton (some radiated light is also visible).

"incoherent" soliton was able to confine a weaker co-polarized probe at λ=633nm, as we verified with both a coherent and an equally incoherent He-Ne beam co-propagating with the pump through the same diffuser. An example of such an occurrence is visible in figure 6(c): "speckled" light was trapped and confined by a waveguide written by a "speckled" pump.

The numerical aperture of the soliton-induced waveguide allowed the signal beam to be trapped even with a significant angular misalignment at the input, with only a small amount of radiated (un-trapped) light. Conversely, once the signal was trapped by the pump in the spatial soliton, a slight change in its direction of propagation forced the probe to follow it, making it possible to steer the weak beam. figure 7 shows an example of soliton-controlled angular steering: the He-Ne light remained confined in the waveguide "written" by the soliton unless the input misalignment exceeded ±2.25°. This maximum angle depends essentially on the magnitude of the index perturbation and, as

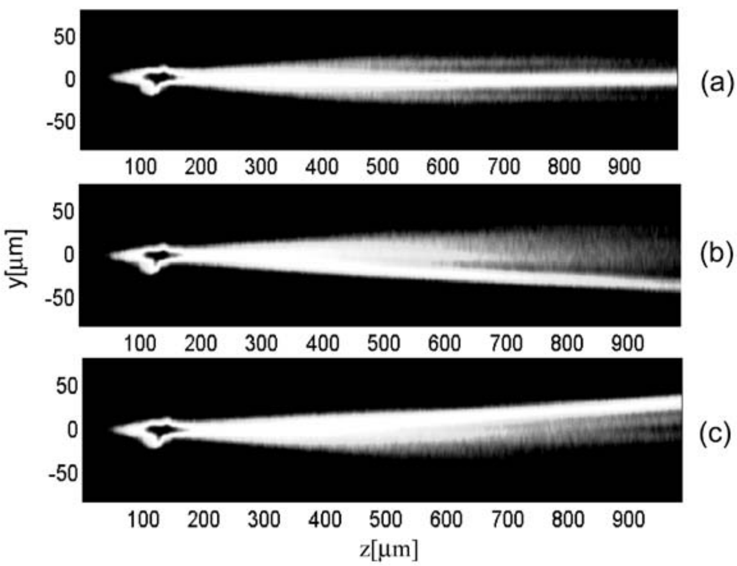

FIGURE 7 Steering of the He-Ne beam by changing the launch direction of the Ar^+ soliton. The input relative angles are: (a) 0°, (b) +2.25°, and (c) –2.25°, respectively.

expected, increases with pump power. With larger misalignments, however, the in-coupling efficiency reduces and a larger portion of signal light is radiated.

The plots in figure 8 are the He-Ne transverse profiles corresponding to the three cases of figure 7. After a propagation distance of 0.9 mm a displacement as large as 70μm is apparent. The latter amounts to more than five resolvable spots upon steering.

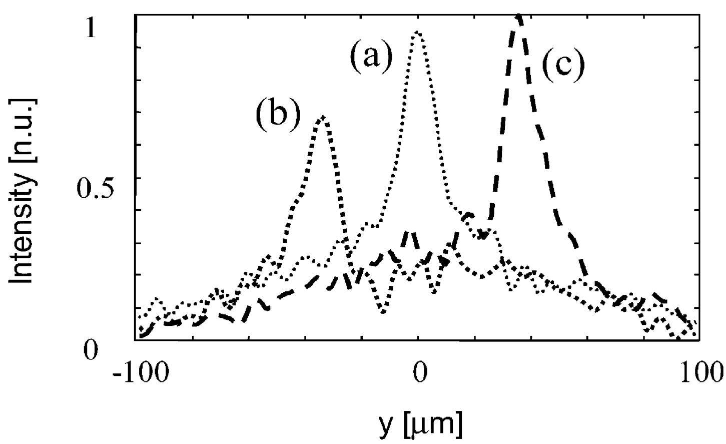

FIGURE 8 Transverse intensity profiles of the probe after propagating for 900μm in the three cases of figure 7. The total spatial shift along y exceeds 70μm.

IV. CONCLUSIONS

We demonstrated that NLC is a suitable material to obtain (2+1)D spatial solitons at mW excitations with both coherent and partially incoherent beams. A low frequency bias allows to eliminate the reorientational threshold, thereby facilitating the insurgence of the nonlinear optical response and the formation of a spatial soliton. The corresponding induced waveguide is able to confine weaker co-polarized beams of different wavelengths.

The NLC weak wavelength dependence and its low power requirement, together with the relaxed constraint on spatial coherence, could enable the development of novel families of switching and processing devices, including the use of LED sources for the control of near infrared signals in optical communications.

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