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Nematic liquid crystals: A suitable medium for self-confinement of coherent and incoherent light

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Nematic liquid crystals exhibit a saturable, noninstantaneous nonlinear response through light-induced reorientation. In such a material, we demonstrate that $(2+1)$-dimensional spatial solitary waves can be generated at milliwatt power levels not only with a coherent optical beam, but also with incoherent excitations. Self-trapping also allows the efficient guidance of a weak copolarized probe.

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Nematic liquid crystals (NLC's), in specific (highly birefringent) orientations of their molecular directors, are positive uniaxials subject to a reorientational nonlinear response when excited by an intense optical beam [1]. Although several experiments have ascertained the nature and features of this nonlinearity due to the interaction between the electric field and the induced dipoles [2], it is only recently that the formation of spatial solitary waves or *solitons*, i.e., field eigendistributions of self-induced waveguides [3], has attracted interest and has been investigated in specific NLC configurations [4–7]. Rather than referring to the rigorous definition in terms of eigensolutions of an integrable nonlinear system [8], we use the term *soliton* in a phenomenological sense, with specific reference to the observable propagation of a transversely invariant beam through compensation of diffraction with self-focusing over distances well exceeding the diffraction length [9,10]. In this scenario, the significant birefringence and polarization sensitivity, large nonresonant nonlinearity, and transparency of NLC's are all attractive—and in some instances intriguing— features when compared to glasses, semiconductors, and organics. At variance with previously observed undulation and filamentation [4], thermally induced solitary waves [5] and one plus one-dimensional (1+1D) self-confinement [6], diffraction can be overcome in bulk NLC's and results in stable $(2+1)$D spatial solitons through a refractive index increase mediated by the reorientational response [7]. The latter is inherently saturable, and can therefore prevent catastrophic collapse even in the fully 3D case, in contrast to ideal Kerr media [11]. To sustain a soliton, a linearly polarized optical field exerts a torque on the induced (prealigned) molecular dipoles of a positive uniaxial NLC, orienting them toward the optical axis [1,2]. This can be accomplished at low input powers either by using a dye dopant to enhance the torque and overcome the Fréedericksz threshold (present when the field vector and NLC molecular director are normal to each other) [5,12], or by launching a combination of TE and TM polarizations in a planar thin film waveguide [6]. However, to ensure that thermal effects do not prevail on reorientation, a better suited approach consists in lowering the required soliton excitation by introducing a pretilt to the molecules of a planarly anchored NLC, in such a way as to set them at an (optimal) angle $\theta_o \approx \pi/4$ with the linearly polarized E-field vector of the beam and so eliminate the threshold. A nonlinear optical perturbation of amplitude A leads to $\Delta\theta = \theta_0 - \theta(A)$, which, modeled by the equation

$$4K\nabla_\perp(\Delta\theta) + \epsilon_0\epsilon_a|A|^2 \sin 2\theta(A) = 0, \qquad (1)$$

with $\epsilon_a = n_e^2 - n_o^2$ the birefringence and K the Frank constants (assumed equal for splay, bend, and twist of the molecules) [2], results in an index increase Δn that can be regarded as weak and treated in the framework of the slowly varying envelope approximation [7]. In addition to the above features, however, the NLC is a slowly responding medium, i.e., one capable of averaging out rapid variations in the optical excitation. It has been previously demonstrated only in photorefractives, which also exhibit a relatively slow nonlinearity, that the noninstantaneous and saturable response to a "speckled" or spatially incoherent optical beam with fast point-to-point phase fluctuations allows the formation of "incoherent" solitons [13]. This class of spatial solitons, excited by a beam with a low degree of spatial coherence, can be described by an infinite set of coupled nonlinear Schrödinger-like equations to account for the broadened angular power spectrum [14,15], and has recently been enriched by the discovery of gray, dark, antidark, and elliptical incoherent solitons in photorefractives [16].

In this Rapid Communication, using the technique employed in [7] to introduce a director preorientation, we report on the formation and propagation of 3D spatial solitary waves in planarly oriented undoped NLCs regardless of the degree of spatial coherence of the input light beam at microwatt power excitations. In either the coherent or partially incoherent case, the spatial solitons can also confine a copolarized signal beam at a different wavelength, thereby suggesting important implications in terms of all-optical routing.

Our samples were 1-cm-wide glass cells containing the "E7" NLC ($n_o = 1.53$, $n_e = 1.77$ at room temperature). Two plane parallel glass slides, coated with (i) indium tin oxide for the application of an external voltage and (ii) SiO_2 to allow the planar NLC orientation, were mounted at separations of either 75 or 50 μm, while a third SiO_2-coated slide was attached perpendicularly to the other two in order to define the air-NLC input interface. The latter prevented the formation of a meniscus and the undesired depolarization of

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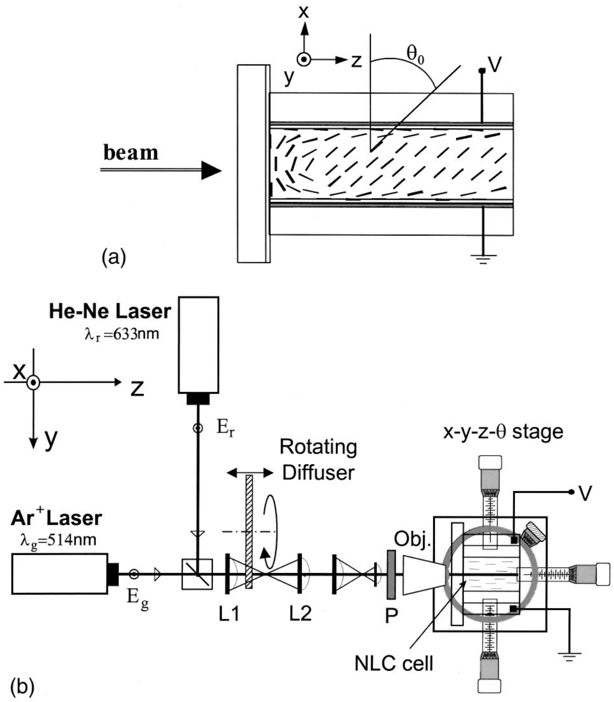

FIG. 1. Schematic drawing of the (a) NLC cell and (b) experimental setup. The rotating diffuser and the optics around it ($L1$ and $L2$, polarizer P) allowed us to study the effects of partial incoherence. The microscope objective (Obj.) was a 20× lens with numerical aperture (NA) of 0.4. Additional wave plates, filters, polarizers, and the Fourier transform lens are not shown.

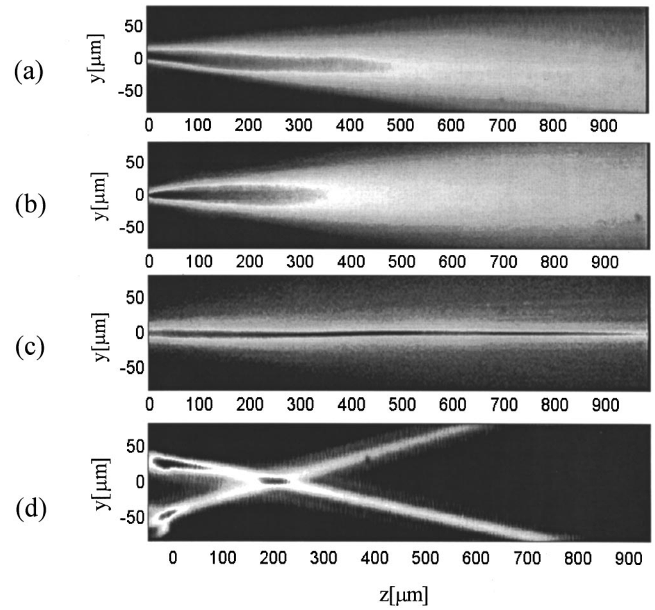

FIG. 2. Experimental results with a 2-mW spatially coherent Ar$^+$ beam in a 75-μm-thick NLC cell. (a) Diffraction of a **v**-polarized beam, with an 11° angular divergence (the visible slant is due to the microscope positioning); (b) diffraction of an **x**-polarized beam (e ray) without director pretilt (no voltage bias); (c) spatial soliton formation from an e-ray beam in a cell with $V = 1$ V (rms); (d) collision of two solitons as in (c), but launched 80 μm and 20° apart from each other at nearly opposite angles with respect to **z**; the direction of propagation of each individual soliton remains unchanged after collision.

the laser beam upon entering the cell. The NLC director was oriented in the (x,z) principal plane containing the external field (voltage) versor **x** (“e” polarization) and the propagation axis **z** of the optical beam, while the slides were parallel to the (y,z) plane. A sketch of the cell with pretilt (θ_0) is shown in Fig. 1 together with the experimental setup.

We ensured that the power of the beam launched into the cell was low enough not to induce thermo-optic effects through absorption and heating. In our samples, depending on the external bias and optical intensity, the light beam propagating in the NLC would (a) always diffract in x and y if linearly polarized along **y** (o ray); (b) diffract in x and y when polarized along **x** (e ray) if no voltage was applied, despite an initial self-focusing at high intensities; (c) be able to form a spatial soliton when polarized along **x** and traversing the NLC with molecular director pretilted at θ_0 in the (x,z) plane by the external bias (along **x**).

We acquired images of the light scattered out of the transparent cell and, for a meaningful comparison between linear and nonlinear propagation at the same excitations, we varied the beam linear polarization from o to e, respectively. Optical o rays ($\parallel$**y**) were always normal to the director and with fluences below the Fréedericksz threshold, therefore resulting in linear diffraction. Typical results corresponding to cases (a)–(c) above are shown in Fig. 2 for a cw spatially coherent laser beam at 514 nm and a 75-μm-thick cell. It is noteworthy that, despite increases in excitation, in the absence of pretilt (i.e., $\theta_0 = \pi/2$) the diffractive behavior (b) persisted with larger divergences due to an initial self-focusing. When a bias of 1 V (rms at 1 kHz) was applied along the optical axis **x**, for input powers as low as 2 mW (before the cell), we observed self-confinement and solitary waves [Fig. 2(c)] for propagation distances approaching 2 mm, one order of magnitude in excess of the Rayleigh length estimated from the angular divergence [Fig. 2(a)]. Finally, even though the NLC nonlinearity is complicated by a nonlocal, polarization-sensitive, and saturable response as compared to the ideal Kerr case, we verified that two intersecting spatial solitons survive their collision when launched at powers close to threshold. This can be clearly appreciated in Fig. 2(d). The above results are in good agreement with a scalar model derived in the frame of weak perturbation of a lossless medium with a uniform angular distribution of the director in the (e,o) plane [7]. Moreover, they demonstrate the reorientational origin of the 3D spatial soliton visible in Fig. 2(c). Narrower solitons could be obtained in thinner cells, due to the stronger bounds enforced by the anchorage upon the NLC molecules. As in [7], we verified that a weaker collinear copolarized signal beam was guided by the soliton even at longer wavelengths ($633 > 514$ nm), as expected for an optically induced self-waveguide in a saturable Kerr-like medium [3,17].

In our samples, typical optical responses ranged from tens to hundreds of milliseconds, depending on excitation, bias, and cell thickness. While a slow time response would be an issue in applications requiring fast data-stream processing, it allows the liquid crystal to average out rapid intensity varia-

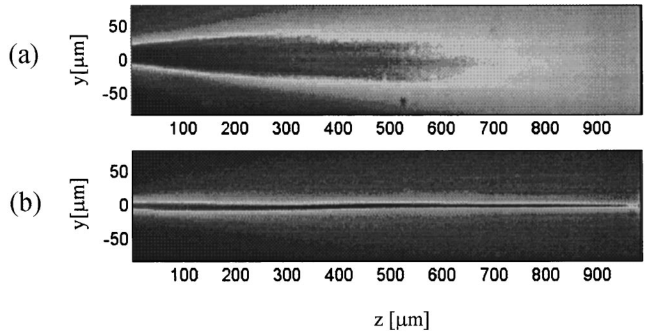

FIG. 3. Experimental results with spatiotemporally incoherent light from an Ar^+ laser, power 2.7 mW. (a) Linear diffraction of a **y**-polarized beam (*o* ray); (b) soliton formed by an **x**-polarized (*e* ray) beam with $V=1$ V (rms).

tions across the beam and, therefore, to support the propagation of incoherent solitons through a reorientation governed by Eq. (1), substituting $|A|^2$ by $\langle |A|^2 \rangle$. To assess this property, reported to date only in photorefractives [13], we inserted a rotating random diffuser in the path of our (multi-longitudinal mode) argon laser at 514 nm [Fig. 1(b)]. The diffuser introduces some losses and a wider angular spreading of the beam propagating through the collimating and focusing optics. Following the diffuser, a linear polarizer *P* guaranteed the desired *E*-field orientation along either **x** or **y**. The effects of the spatial incoherence can be clearly appreciated in Fig. 3(a), showing the linear *speckle-driven* diffraction of such a beam in the NLC cell. The beam size–to–speckle (BTS) average ratio determined the amount of additional diffraction, which was controlled by acting on the spot size at the diffuser when held stationary. A confocal telescope [lenses $L1$, $L2$ in Fig. 1(b)] and an additional lens

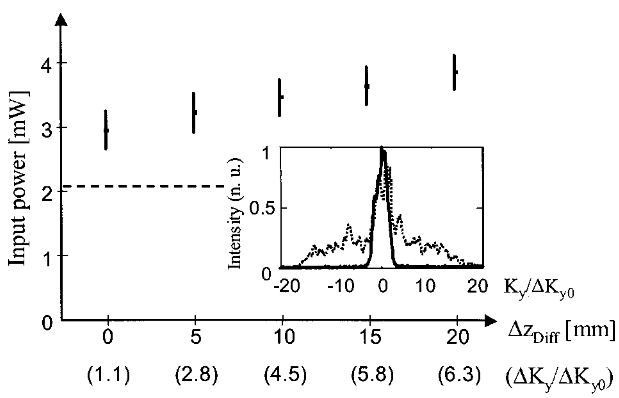

FIG. 4. Spatial soliton threshold versus degree of spatial incoherence in the plane (*y*,*z*). The data were acquired with green light (514 nm) propagating through the rotating diffuser at various positions Δz_{Diff} from the focus of the $L1$-$L2$ telescope [Fig. 1(b)]. Error bars correspond to the uncertainty in estimating the soliton threshold, while the dashed line indicates the coherent case. The abscissa values in parentheses are the standard deviations of the spectra ΔK_y normalized to the coherent value ΔK_{y0} after integration over K_x. The inset shows a comparison between normalized optical Fourier transforms of beams with diffuser at $\Delta z_{\mathrm{Diff}}=0$ (solid line, beam waist ≈ 8 μm) and at $\Delta z_{\mathrm{Diff}}=20$ mm (dashed line, waist ≈ 400 μm).

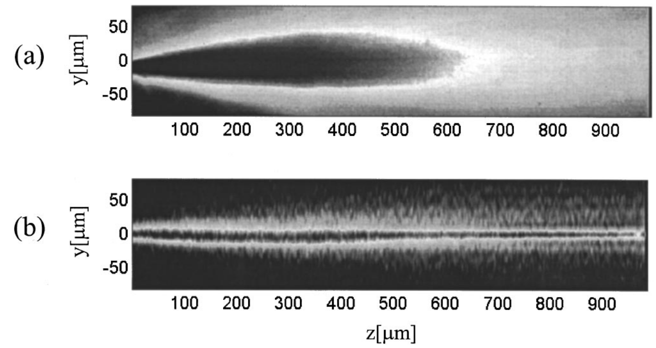

FIG. 5. Experimental results with a spatially incoherent signal from a He-Ne laser, power 100 μW. (a) Linear diffraction of an *o*-polarized beam; (b) *e*-polarized signal confined by the spatial soliton [Fig. 3(b)].

allowed us to estimate the degree of spatial incoherence from the ratio of the width of the optical Fourier spectrum obtained with the diffuser to the one corresponding to the coherent beam. We operated with BTS ratios between 4 and 50, as measured by interfering a second spatially coherent beam with the one employed for the excitation, before the focusing optics. Nevertheless, when properly polarized and launched in a voltage biased cell, albeit spatiotemporally incoherent, the beam self-trapped, as shown in Fig. 3(b) for excitations slightly higher ($2.7>2$ mW) than for its coherent counterpart.

Figure 4 shows the soliton-threshold power versus degree of induced spatial incoherence in the (*y*,*z*) plane. The values on the vertical axis were measured before the cell, and should be scaled down by a factor of 0.93 taking into account Fresnel reflections at the air/glass and glass/NLC interfaces. Notice that, despite the nominal increase in Fourier spectrum, the presence of apertures (finite NA lenses and cell thickness) in the beam path introduces significant spatial filtering and therefore limits the effective degree of incoherence. The labels on the horizontal axis refer to the beam properties in the (*y*,*z*) plane, monitored through image acquisition as in Fig. 3(b). The linear values (in millimeters) indi-

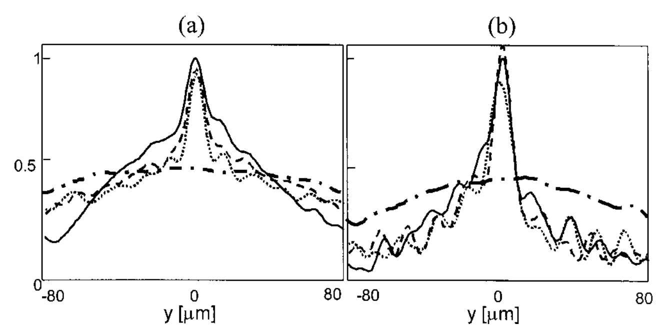

FIG. 6. Experiments with spatially incoherent Ar^+ (pump) and He-Ne (signal) beams (Figs. 3 and 5, respectively). (a) Transverse intensity profiles of the pump sampled at distances $z=500$ (solid line), 700 (dashed line), and 900 μm (dotted line); (b) corresponding profiles for the signal. The thick dot-dashed lines refer to the beam profiles at $z=0.9$ mm after linear propagation (i.e., *o* rays of equal input fluence).

cate the position of the diffuser away from the focal plane of $L1$ and $L2$, while the numbers in parentheses indicate the width of the optical Fourier spectrum with respect to the coherent case. As shown for a typical case in the inset, we evaluated the pertinent spectral width along the wave number K_y after integrating the spatial dependence along K_x. The spectra shown in the inset correspond to the diffuser at $z=0$ (focal plane, solid line) and $z=20$ mm, respectively; although characterized by the same overall integral, they were normalized to the same peak value to emphasize the broadening caused by the increased incoherence.

Finally, the optically induced (soliton) waveguide was able to confine not only a weaker coherent (copolarized and collinear) signal (at 633 nm in our experiment), but also one traversing the same rotating diffuser employed for the pump [see Fig. 1(b)], as visible in Fig. 5. This led us to speculate that the nonlinearly formed waveguide was highly multimode, i.e., able to confine several modes even at the longer wavelength of the probe [15]. Figure 6 shows the acquired profile of these incoherent solitary beams at 514 nm (the writing beam) and 633 nm (the signal). Despite the limited experimental accuracy, the invariance of the transverse width can be clearly appreciated and compared with the linear diffractive case (obtained by launching the *o* ray).

In conclusion, we demonstrated $(2+1)$-dimensional spatial solitons at milliwatt power in electrically biased planar cells with a nematic liquid crystal, not only in the case of coherent excitations but also when employing spatially incoherent beams. The solitons or optically induced channel waveguides were able to confine the writing beam and a weaker signal of equal polarization, regardless of the degree of spatial coherence of either of them.

The reported phenomena are wavelength independent due to the nonresonant nature of the nonlinearity, and are observable with light-emitting diode sources or white light. They appear relevant for the implementation of all optically reconfigurable and readdressable interconnects in transparent optical networks.

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