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Voltage-driven beam bistability in a reorientational uniaxial dielectric

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We report on voltage controlled bistability of optical beams propagating in a nonlocal reorientational uniaxial dielectric, namely, nematic liquid crystals. In the nonlinear regime where spatial solitons can be generated, two stable states are accessible to a beam of given power in a finite interval of applied voltages, one state corresponding to linear diffraction and the other to self-confinement. We observe such a first-order transition and the associated hysteresis in a configuration when both the beam and the voltage reorientate the molecules beyond a threshold.
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Optical bistability manifests in systems where nonlinear light-matter interactions combine with feedback in such a way that two stable states can coexist for the same excitation and are occupied depending on the previous evolution, i.e., on the system's own history.[1] In the past decades, a number of optically bistable configurations exploiting nonlinearity in dispersive and/or absorptive processes have been proposed for optical logic devices and memory elements, most of them based on resonant cavities.[2–4] Feedback was also exploited in conjunction with propagating beams undergoing self-action, particularly self-focusing, when light in an intensity-dependent medium induces a graded refractive index profile which acts as a distributed converging lens.[5] Bistable optical transmission of a beam undergoing self-focusing was demonstrated in the eighties with the aid of an external mirror.[6,7] Light self-action in self-focusing media is also known to support the formation of optical spatial solitons which, at the fundamental order in transparent Kerr-like dielectrics, are shape and size invariant self-trapped beams propagating as guided modes within the graded refractive index they nonlinearly induce.[8] Spatial optical solitons have been extensively investigated in numerous nonlinear media, either in the local or in the nonlocal limits.[9] In the latter, in particular, such solitons are stable even in two transverse dimensions,[10] paving the way to "light guiding light" using all-optical waveguides for signal processing and routing.[11–14] Optical bistability with optical spatial solitons (i.e., two stable solitons coexisting at the same input beam power) was predicted by Kaplan in local materials exhibiting specific nonlinear responses, without external feedback.[15] Recently, we introduced and demonstrated a novel kind of optical bistability in a reorientational material, namely, nematic liquid crystals (NLCs), where a stable two-dimensional spatial soliton and a diffractive beam coexist for the same excitation within a finite range, giving rise to a hysteretic loop versus input beam power[16,17] as well as incidence angle.[18] Since nonlinear reorientation is usually accompanied by a large electro-optic effect through the static or low-frequency electric field of an applied bias, at variance with the standard all-optical approach in this Letter we experimentally investigate the occurrence of bistability between diffracting and self-confined beam states in NLCs subject to a fixed optical excitation and a variable voltage bias.

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Nematic liquid crystals are mesophases consisting of elongated molecules which possess no positional order but a high degree of orientational order around a mean direction, the so-called molecular director $\boldsymbol{n}$.[19] Macroscopically, NLCs behave at optical frequencies as uniaxial dielectrics, with optic axis along the director $\boldsymbol{n}$ and birefringence $\Delta n = n_\parallel - n_\perp$ (usually positive) between the refractive indices associated to electric fields parallel and orthogonal to $\boldsymbol{n}$, respectively. Defining the orientation θ as the angle between the optic axis and the wave vector $\boldsymbol{k}$ of a propagating beam, ordinary and extraordinary waves travel at phase velocities c/n_o and c/n_e, respectively, with $n_o = n_\perp$ and $n_e = 1/\sqrt{\cos^2\theta/n_\perp^2 + \sin^2\theta/n_\parallel^2}$.[20] Owing to molecular and optical anisotropy of NLCs, with typical birefringence larger than 0.1 in the visible and near-infrared, intense light waves polarized as extraordinary eigenfields (i.e., with electric field $\boldsymbol{E}$ oscillating in the plane $(\boldsymbol{n},\boldsymbol{k})$) tend to reorient the induced molecular dipoles through the action of a torque $\boldsymbol{\Gamma} = \epsilon_0\Delta\epsilon(\boldsymbol{n}\cdot\boldsymbol{E})(\boldsymbol{n}\times\boldsymbol{E})$, with $\Delta\epsilon = n_\parallel^2 - n_\perp^2$ the optical anisotropy. The latter acts against the elastic forces in the liquid to increase the orientation θ and, in turn, the refractive index n_e. Such reorientational response can be simply described in the scalar approximation (single elastic constant) and neglecting the walk-off angle by

$$\nabla^2\theta + \frac{\epsilon_0}{2K}\left[\Delta\epsilon\frac{|A|^2}{2} + \Delta\epsilon_{LF}E_{LF}^2\right]\sin(2\theta) = 0, \tag{1}$$

with A the slowly varying beam envelope, E_{LF} the low-frequency electric field, ϵ_0 the vacuum permittivity, K the elastic constant, and $\Delta\epsilon_{LF}$ the electric anisotropy; the term with $\Delta\epsilon_{LF}$ refers to the reorientational torque due to a static or low-frequency electric field across the thickness h of the sample when a bias V is applied between two parallel interfaces. Hence, for a fixed V, an extraordinarily polarized bell-shaped beam with electric field initially non-perpendicular to $\boldsymbol{n}$ can induce a graded index profile; this reorientational response can balance out diffraction and, owing to the nonlocality afforded by the liquid state of the material (through the constant K), yield stable (2+1)D optical spatial solitons at mW power levels.[21–23] Neglecting walk-off of the extraordinary wave, nonlinear beam propagation can be modeled by

$$2ik_0n_e(\theta_0)\frac{\partial A}{\partial z} + D_x\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} + k_0^2\Delta n_e^2(\theta)A = 0 \tag{2}$$

with k_0 the vacuum wave number, D_x the diffraction coefficient along x, and $\Delta n_e^2 = n_e^2(\theta) - n_e^2(\theta_0)$ the nonlinear change in square index governed by Eq. (1) through θ.[24]

Equations (1)-(2) support the generation of stable nonlocal spatial optical solitons in NLCs, self-confined extraordinarily polarized wavepackets also termed *nematicons*.[23,25,26] From Eqs. (1) and (2), an equivalent nonlocal Kerr coefficient $n_2 = 2\epsilon_0\Delta\epsilon\sin(2\theta_0)n_e^2(\theta_0)/(4K)$ can be derived.[24] Conversely, if the input beam is ordinarily polarized, i.e., electric field and director are perpendicular to one another (with $\theta_0 = 0$ and $n_e(\theta_0) = n_\perp$ in Eq. (2)), all-optical reorientation—hence light self-localization—is only possible above a threshold excitation, the optical Fréedericksz transition (FT).[19,27,28] Above threshold, the beam becomes an extraordinary wave, as reorientation breaks the initial symmetry.[18,28] For given NLC mixture and cell thickness, the optical FT depends on both input beam power and width, with narrower beams yielding a lower threshold power for collimated wavepackets.[29] Launching a light beam in NLCs with director initially orthogonal to the electric field, i.e., subject to the optical Fréedericksz transition, an abrupt nonlinear response is expected above a power threshold, leading to a first-order transition between two stable states of the system: one corresponding to the linear behavior before the FT, the other to a self-trapped beam, a nematicon. Such two states are connected by abrupt switching responses taking place at distinct input powers (upward and downward thresholds) and thereby giving rise to a hysteresis loop: this is similar to optical bistability in nonlinear cavities but stems from the inherent link between the FT threshold and the beam width evolution in the sample before and after localization.

We recently demonstrated optical bistability between diffracting and soliton states in NLCs subject to the Fréedericksz transition, with hysteresis in beam width versus optical input power.[16] The experimental results, obtained in the NLC mixture E7, were found to be consistent with a simple model based on Eqs. (1) and (2) in the limit $\theta_0 = 0$, accounting for the FT dependence on beam waist.[17] Since a voltage applied across the NLC thickness plays a role analogous to that of an electric field in the optical FT configuration, in this work we investigate bistability between diffracting and solitary beam states as the bias is varied, i.e., using the voltage as the control input. In fact, owing to the width-dependent optical contribution to FT in a reorientational medium, above FT-threshold beam narrowing through self-focusing and soliton generation results into feedback through a decrease in threshold, supporting both linear and self-confining beams either within an interval of optical powers for a fixed voltage (as reported by Kravets *et al.*[16]) or within an interval of voltages for a fixed optical power. This can lead to a hysteretic response connecting the two beam states when launching an input wavepacket of given size and power below the optical FT, ramping the bias up and down in a loop. Monitoring beam propagation and its transverse localization, we aimed to observe hysteretic changes in beam width versus voltage.

Figure 1 describes the employed geometry: we used a planar glass cell of thickness $h \approx 100\ \mu$m, with upper and lower interfaces rubbed to obtain a uniform molecular alignment of the mixture E7 ($n_\perp \approx 1.52$, $n_\parallel \approx 1.68$) along the z direction of propagation; input/output facets provided a homeotropic alignment of the NLCs and prevented the formation of menisci and uncontrolled depolarization of the input beam. Indium-tin-oxide transparent electrodes (deposited on the inner interfaces) allowed applying a voltage across x, to an accuracy of 5 mV. An x-polarized Gaussian beam at $\lambda = 1064$ nm was injected with waist $w_0 = 2\ \mu$m in $z = 0$ and wave vector $\boldsymbol{k} \| \hat{z}$; its evolution in yz was imaged through out of plane scattering with a microscope and a CCD camera. Fig. 1(a) shows the basic configuration, with $\theta_0 = 0$ below FT. Experiments were carried out at a temperature $T = 19\ ^\circ$C in order to reduce the thermal noise from molecular fluctuations without reducing the NLC elastic response.[30] Fig. 1(c) illustrates the case of a $P = 2$ mW-beam propagating forward when $V = 0$ V, i.e., below FT: no reorientation takes place and the wavepacket diffracts. Such evolution remains linear even when a voltage is applied but is under the threshold value $V_T(P)$, i.e., the combination of low-frequency and optical electric fields does not overcome the FT.

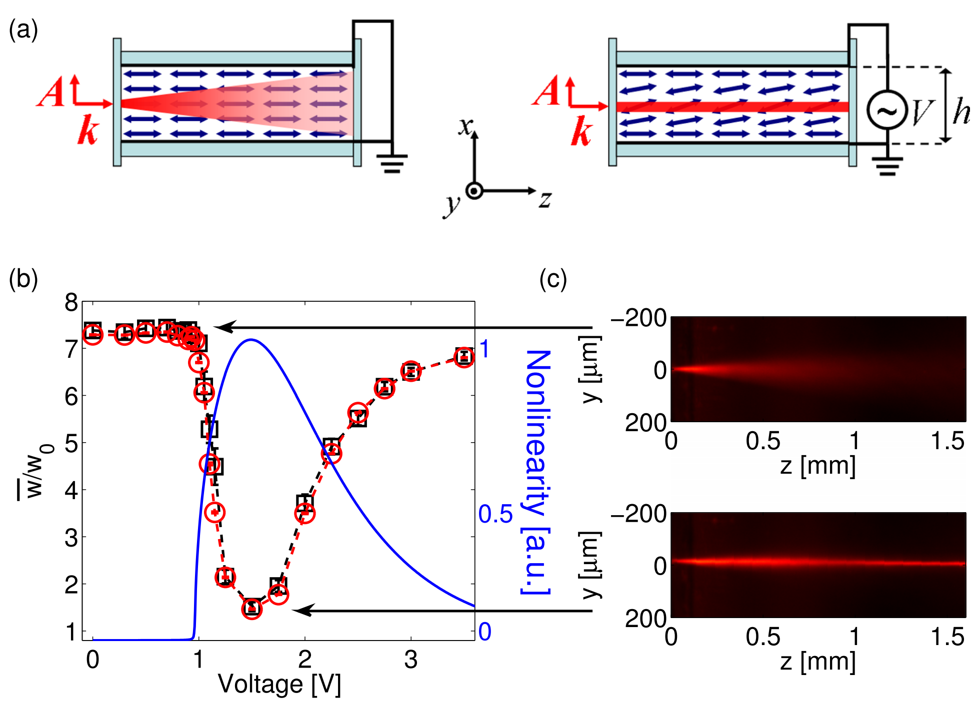

FIG. 1. (a) Sketch of the sample (side view). When no voltage is applied, a light beam of moderate power cannot yield reorientation as its electric field is perpendicular to the molecular director (blue rods, $\theta_0 = 0$). A low frequency electric field along x can combine with the optical excitation (probe) and overcome the FT, allowing beam self-focusing and spatial solitons. (b) Left axis: Average beam width for $P = 2$ mW versus increasing (black squares) and decreasing (red circles) voltage; right axis (blue solid line): equivalent Kerr coefficient $n_2(\theta_0)$ computed from Eq. (1) coupled with the Poisson equation to solve exactly the electro-static problem. (c) Acquired photographs of a 2 mW-beam evolution in yz in the linear regime for $V = 0$ V and as a self-confined spatial soliton for $V = 1.5$ V.

Increasing the (torque due to) voltage, the system approaches the FT and, once the latter is overcome, self-focusing narrows the beam through the light driven nonlinear response; hence, at voltages $V \geq V_T$, molecular reorientation can occur due to the combined action of light and external field. For a given beam power, when the voltage is high enough to bring the system beyond FT, then the beam can undergo self-focusing and self-localization into a nematicon. A narrow self-trapped soliton is visible in Fig. 1(c). As its stronger spatial localization determines a lower FT threshold value, upon decreasing the electric torque, we could expect beam self-confinement to be maintained for lower voltages than the previous V_T, i.e., a hysteresis loop. Fig. 1(b) graphs measured beam width normalized to the input value versus applied voltage: the width was averaged over the whole propagation length to rid of spurious artifacts due to microscopic inhomogeneities and temporal fluctuations. Data points were collected after several minutes, to ensure the complete decay of any transients in the non-instantaneous medium. For $V < 0.9$ V, the overall torque due to both optical and low-frequency electric components cannot overcome the FT, and the beam propagates in the linear regime, i.e., spreading. For $V \geq 1.0$ V, the threshold is overcome and optical reorientation is able to induce a graded director distribution: a refractive potential mediates beam focusing and eventually trapping in the form of a spatial soliton for $V = 1.5$ V, when the nonlinearity is maximum as θ approaches $\pi/4$.[31] Further increases in voltage reduce the depth of the refractive index well and impair self-confinement.[32]

Before the formation of a spatial soliton, intermediate states due to counteracting self-focusing and diffraction are stable. This results in a smooth transition between diffracting and self-confined states, i.e., a second-order transition which does not sustain bistability.[27] Thereby, the curves of beam width for increasing and decreasing voltages in Fig. 1(b) perfectly overlap, at variance with our initial expectation.

In order to support bistability, the system is required to exhibit a first-order transition at the FT,[34] i.e., the switching from diffraction to self-confinement must be abrupt.[15] To this extent, we adjusted the optical component of the reorientational torque by varying the beam power in the range 5–25 mW. Fig. 2 displays the measured average beam width—defined as $\overline{w} = (1/L_z)\int_0^{L_z} w(z)dz$ with $L_z = 1.5$ mm, i.e., the whole length of the cell—versus the applied voltage for various optical powers (Fig. 2(a)) and the corresponding slope of the state transition (Fig. 2(b)): on one hand, the increasing optical torque reduces the electric FT; on the other hand, the transition between diffraction and self-confinement becomes sharper. For $P = 25$ mW, the slope approaches $\pi/2$, hence the transition becomes first-order and bistability can be expected.

Figure 3 shows acquired images of a 25 mW beam evolution as the voltage is ramped up (left) and down (right) in a loop. Diffraction is visible up to $V = 0.88$ V for increasing voltages:

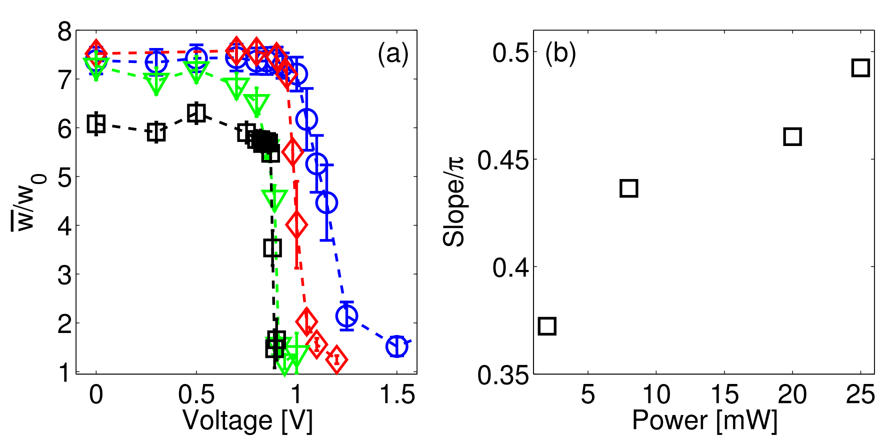

FIG. 2. (a) Average beam width versus (increasing) voltage for various input beam powers (2 mW, blue circles; 5 mW, red diamonds; 20 mW, green triangles and 25 mW, black squares) and (b) the calculated slopes in the transition between diffracting and self-confined states. Some thermal self-focusing is also visible in the ordinary polarization at 25 mW, below the FT-threshold.[33] The voltage threshold V_T decreases for increasing optical power while the slope increases. For $P = 25$ mW, the slope is nearly $\pi/2$, indicating the presence of a first-order transition.

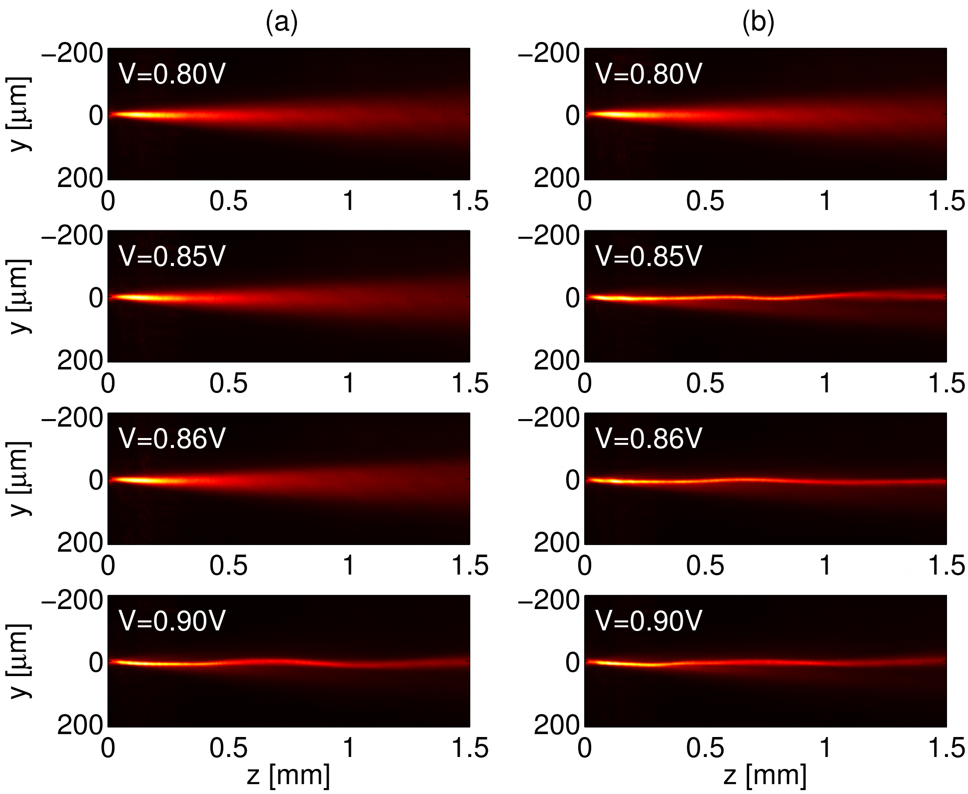

FIG. 3. Acquired photographs of beam evolution in yz at $P = 25$ mW for (a) increasing and (b) decreasing applied voltage. For $V = 0.80$ V, the system is still below FT and the beam diffracts. FT is overcome at $V \approx 0.89$ V and the beam self-traps into a spatial soliton. When the voltage decreases, the beam remains self-focused down to the new threshold $V = 0.83$ V. At the values $V = 0.85$ V and $V = 0.86$ V, the system is bistable, i.e., the input beam either diffracts or self-confines depending on the previous evolution.

beyond this value, the beam suddenly narrows down into a spatial soliton. It is important to stress that the voltage is not high enough to cause reorientation on its own: the FT is overcome through the combined action of electric and optical fields and probed via the nonlinear beam. From the confined state at $V \approx 0.90$ V, decreasing the external field, we observe that the system has memory of its previous state: the beam remains self-trapped for $0.89 \text{ V} > V > 0.83$ V, at variance with the former evolution; a lower threshold at $V \approx 0.83$ V accompanies a sharp transition from confined to diffractive states. Fig. 4 summarizes the results versus applied voltage and beam power.

To identify the presence of the hysteresis loop, we evaluated the mean square deviation $\sigma = \sqrt{\sum_m (w_{i,m} - w_{d,m})^2}$ of the beam widths w_i and w_d for increasing and decreasing voltages, respectively. As shown in Fig. 4(a), the deviation between upper (linear beam) and lower (soliton) branches of the width vs power loop is negligible for $P \leq 20$ mW: the curves overlap and the system has no hysteresis. For $P = 25$ mW, σ is considerably larger, indicating an open loop and system hysteresis (width vs voltage at fixed power). The hysteresis cycle is visible in Fig. 4(b), showing bistability in the range between $V = 0.83$ V and $V = 0.89$ V, where the beam can either diffract or localize into a soliton depending on its evolution history.

In conclusion, we have provided experimental evidence that bistability in the propagation of nonlinear beams in a reorientational uniaxial dielectric can be achieved versus applied voltage in a configuration exhibiting threshold, i.e., with optic axis orthogonal to the electric field(s). By tailoring the low frequency and the optical contributions to reorientation in nematic liquid crystals, we were able to excite a first-order transition and hysteresis of the system versus voltage. By varying the bias in a closed loop, in a range of nearly 60 mV, we could observe two coexisting stable states associated to propagating light beams of fixed power: a diffracting (linear) state and a self-confined (solitary) state. These findings, consistent with the stability analysis of nonlinear reorientational

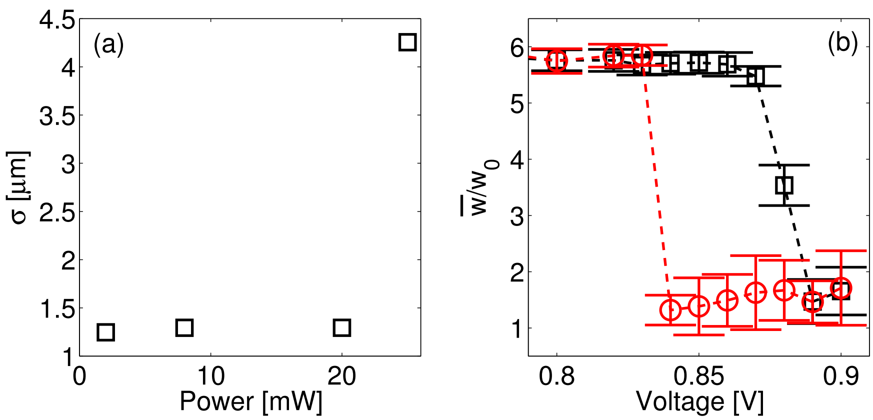

FIG. 4. (a) Mean square deviation σ of beam width versus power for increasing and decreasing voltage. The deviation is negligible up to $P = 20$ mW, while for $P = 25$ mW it dramatically increases. (b) Average beam width versus voltage for $P = 25$ mW and increasing (black squares) and decreasing (red circles) bias. The system is bistable in the interval $V = [0.83,\ 0.89]$ V.

systems[17] (as detailed in a forthcoming publication), illustrate the interplay between electro-optic and all-optical responses in nonlocal uniaxial dielectrics, tracing a route to the implementation and tuning of bistable systems based on nonlinear beam propagation/localization.

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