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Vortex stabilization by means of spatial solitons in nonlocal media

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Abstract

We investigate how optical vortices, which tend to be azimuthally unstable in local nonlinear materials, can be stabilized by a copropagating coaxial spatial solitary wave in nonlocal, nonlinear media. We focus on the formation of nonlinear vortex-soliton vector beams in reorientational soft matter, namely nematic liquid crystals, and report on experimental results, as well as numerical simulations.

Keywords: optical vortex, spatial solitons, self-action effects, liquid crystals

(Some figures may appear in colour only in the online journal)

1. Introduction

Light beams carrying optical vortices have attracted growing attention during the past decades \cite{1–4}. Such complex beams are usually associated with a ring-like intensity structure with a zero value at the centre, where the electromagnetic field vanishes, with a phase distribution spiralling around it. Besides their rich and intriguing properties, including phase singularities, internal energy circulation and the unique features of their linear and angular momentum distributions, optical vortices offer a wide range of prospective applications in such areas as micro-manipulation \cite{5–9}, optical encoding/processing of information \cite{10–14}, sensitivity and resolution enhancement in optical measurements \cite{15, 16}. Optical vortex beams can be generated in different types of linear \cite{1–4, 17} and nonlinear media \cite{18}. However, they are usually prone to strong dynamical instabilities in self-focusing nonlinear media local azimuthal modulations of the initial donut shape and split it into fragments which fly away from the initial vortex ring \cite{18}.

Nevertheless, as was shown in a few theoretical papers, if the nonlinearity is accompanied by spatial nonlocality, so that the overall nonlinear perturbation in the medium extends far beyond the beam waist in the transverse plane \cite{19}, the propagation of an optical vortex can be stabilized. In particular, stable propagation of spatially localized vortices may become possible in highly nonlocal nonlinear media with a self-focusing response \cite{20, 21}. This prediction was confirmed by experimental results on the existence of stable vortex solitons with unit topological charge in thermal nonlinear media \cite{22}. Nonlocal spatial solitons were also found to be able to stably guide and route vortex beams across an interface or around a defect by counteracting the diffraction and instabilities enhanced by such refractive perturbations \cite{23}. An intense vortex and a co-propagating spatial soliton are expected to form a stable vector soliton in a self-focusing nonlocal media \cite{18}, in a similar fashion to bright vector solitons with light of different colors \cite{24, 25}, spiralling solitons with angular momentum \cite{26–29} and multi-hump soliton structures consisting of two (or more) components which mutually self-trap.
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Figure 1. (a) Perspective and (b) top views of the planar cell; the ellipses indicate the oriented molecules; (c) experimental setup: L_{1,2} are the green (\( \lambda_0 = 671 \) nm) and red (\( \lambda_0 = 532 \) nm) cw lasers, \( \lambda_0/2 \)—half wave plates, BS—beam splitters, DH—vortex hologram, M—mirrors, MO_1—10 \times microscope objective, MO_2—20 \times microscope objective, NLC—sample, F—filter, CCD—charge-coupled device camera.

[18, 30–32]. As was reported in recent theoretical and numerical studies [33], such two-component vector vortex solitons may be stable in nematic liquid crystals (NLCs) due to the strong reorientational nonlinearity of such soft matter [34, 35] and the stabilizing character of the resulting nonlinear, nonlocal potential generated by the superposition of both beam components [33, 36]. Thus, an important challenge in nonlinear singular optics remains to reveal the physical mechanisms which will allow the experimental observation of stable optical vortices in realistic nonlinear media.

In this paper, we observe experimentally and describe theoretically the formation of stable two-component vector vortex solitons in NLCs. These vector solitons appear in the form of two-wavelength self-trapped beams with one of them components carrying a phase singularity and being stabilized by its nonlocally enhanced interaction with the other transverse localized beam, a fundamental spatial soliton. We also find that such vector beams can be generated for certain ranges of the soliton excitation, that is the input beam power.

2. Sample and experimental results

For our experiments we used a planar cell realized by polycarbonate slides held parallel to one another and separated by 110 \( \mu \)m across \( y \) in order to contain the 6CHBT NLC mixture. The cell structure is sketched in figures 1(a) and (b). The planar interfaces between the polycarbonate and the NCLs provide molecular anchoring by means of mechanical rubbing, ensuring that the elongated molecules are orientated with their main axes in the plane (\( x, z \)) of the slides, at an angle \( \theta_0 = \pi/4 \) with the input wavevector \( k \) along the \( z \)-direction. Two additional 150 \( \mu \)m thick glass slides at the input and output interfaces seal the cell to prevent lens-like effects and avoid light depolarization. The maximum propagation length along the \( z \)-axis was 1.1 mm from the input to the output facets.

The experimental setup for the generation of two-component, two-color vector vortex solitons is shown in figure 1(c). One beam component (red) carries the extraordinarily polarized single-charge vortex beam generated by a fork-type amplitude diffraction hologram (DH) using a cw laser beam at wavelength \( \lambda_{01} = 671 \) nm and power \( P_a \). The second (green) component is an extraordinarily polarized fundamental Gaussian beam of wavelength \( \lambda_{02} = 532 \) nm and power \( P_g \). Figure 2 illustrates the input beams, with figures 2(a) and (d) depicting the corresponding input intensity distributions, figures 2(b) and (e) the schematic phase fronts and figures 2(c) and (f) the intensity profiles of each beam: the green Gaussian beam (left) and the red single charged vortex (right). The two co-polarized beams were injected into the NLC with collinear Poynting vectors along \( z \) by a 10 \times microscope objective (MO_1). The input waists were \( w_a \approx 7 \mu \)m and \( w_b \approx 4 \mu \)m for the vortex and fundamental Gaussian beams, respectively. With the half-wave plates \( \lambda_{01}/2 \) and \( \lambda_{02}/2 \) we controlled the polarization state of both beams. In order to study the singular phase structure of the
vector vortex beams we used a Mach–Zehnder arrangement (beam splitters BS$_1$ and BS$_3$, mirrors M$_1$ and M$_2$). The output intensity after propagation was monitored by collecting the light at the output using a 20× microscope objective (MO$_2$) and a high-resolution CCD camera. We monitored the evolution at both wavelengths, but in order to prevent chromatic effects and record the output images of the (red) vortex or green (fundamental) beams separately, we used either red or green filters (F) placed in front of the camera.

We initially investigated the linear and nonlinear behavior of either component when each beam propagated in the absence of the other. As visible in figures 3(a) and (c), for low input powers of both beams, $P_{g,r} < 0.9$ mW, the self-focusing is too weak to overcome diffraction. On increasing the power

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**Figure 2.** Each vector beam component, i.e. a Gaussian (left) or a single-charge vortex (right) propagating separately in the NLC cell. (a) and (d) Measured input intensity distributions; (b) and (e) schematic wavefront views and (c) and (f) normalized intensity profiles of each beam from the input images (a) and (d).

**Figure 3.** Measured output intensity distributions (a)–(d) and corresponding normalized intensity profiles (e)–(h) of Gaussian (a), (b), (e), and (f) and vortex (c), (d), (g), and (h) components propagating separately for various input powers $P_g$ and $P_r$. 

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of the green component to $P_r > 2.4 \text{ mW}$ the fundamental Gaussian beam undergoes self-focusing and the transverse intensity distribution at the output visibly reduces, so that a spatial soliton is formed, also called a nematicon in these materials (see figure 3(b)) [35]. On the other hand, increasing the input power of the beam which carries angular momentum to $P_r > 5 \text{ mW}$ leads to its self-focusing; however, such a beam is affected by strong dynamic instabilities which tend to amplify local azimuthal modulations of the initial ring shape and so split the vortex beam into two fragments (figure 3(d)) [20]. Such a symmetry-breaking azimuthal instability is enhanced by the nonsymmetric configuration of the planar cell and the related anisotropy in the induced refractive index profile. This dynamics is consistent with recently reported results on the astigmatic deformation of a vortex beam in a planar NLC cell and its transformation into a dipole-like transverse distribution [29]. Figures 3(e)–(h) show the normalized $x$ cross-sections of the intensity profiles in the plane $(x, y)$ for two different powers of both components, as acquired from the output images in figures 3(a)–(d).

To prevent the symmetry-breaking azimuthal instability of the vortex beam in the planar NLC cell we studied the interaction of two mutually incoherent two-color components — a vortex and a Gaussian beam—co-propagating in the cell as co-polarized coaxial wavepackets. Both components were extraordinarily polarized (input $E$-field along the $x$-axis) and launched with the same Poynting direction along $z$. Figure 4 shows the results for two series of experiments for different input powers of the red vortex beam, namely $P_r = 5 \text{ mW}$ (figures 4(a)–(e)) and $P_r = 8 \text{ mW}$ (figures 4(f)–(j)). These values of $P_r$ were high enough to excite nonlinear effects and instabilities in the absence of the fundamental Gaussian beam. In both sets of experiments we kept $P_r$ constant while we gradually changing the input power of the green beam $P_g$. Firstly, we monitored the power dependent dynamics of a two-color vector soliton at $P_r = 5 \text{ mW}$, using the red bandpass filter in front of the CCD camera in order to block the green light. For low powers of the green nematic, $0 < P_g \ [\text{ mW}] < 3.8$, the initially ring-shaped (red) vortex beam transformed into a dipole-like mode due to the symmetry breaking azimuthal instability, which is similar to the dipole-like vector solitons observed in other systems [37, 38]. A further increase of the input power, $3.9 < P_g \ [\text{ mW}] < 5.5$, led to a dramatic reshaping of the intensity distribution of the vortex, see figure 4(b). Noteworthy, at higher powers $5.6 < P_g \ [\text{ mW}] < 8.5$ we observed a remarkable stabilization of the intensity profile of the red vortex and the formation of a vector vortex soliton which, in the red component, had an annular shape around a dark core, see figure 4(c). At higher excitations, $P_g > 8.6 \text{ mW}$, the spatial dynamics was amplified and the vector beam developed temporally unstable intensity distributions [39], as seen in figure 4(d).

We also observed an analogous behavior of the vector beam at the other values of $P_r$. Figures 4(f)–(i) present experimental results for a two-color vector vortex beam propagating at $P_r = 8 \text{ mW}$ in the same NLC cell. As expected, at relatively low input powers $0 < P_g \ [\text{ mW}] < 4.8$, the symmetry-breaking mechanism of the vortex beam leads to its azimuthal instability. However, at higher power excitations, $4.9 < P_g \ [\text{ mW}] < 8$, the composite beam is converted into a stable circularly symmetric vector vortex soliton. Finally, as expected, for higher powers $P_g > 8.1 \text{ mW}$ we observe a temporally unstable behavior. By comparing both cases for various values of the input power, i.e. $P_r = 5 \text{ mW}$ and $P_r = 8 \text{ mW}$, we see that a stable vortex soliton can exist for a
3. Vector vortex-beam equations

To model the experiments presented above, let us consider the propagation of two beams of polarized, monochromatic light of wavenumbers $k_{01}$ and $k_{02}$ through a cell containing undoped NLCs. As in the experiments, the $z$-direction is taken as the propagation direction of the beam, with the $(x, y)$ coordinates orthogonal to this. In the absence of the optical wave-packets the nematic molecules lie at an angle to the coordinate orthogonal to this. In the absence of the optical anisotropy of the nematic molecules, owing to its interaction with the nonlocal potential induced by the green light, the nematic molecules are constrained to rotate in the $(x, y)$ plane under the influence of the electric fields of the optical beams. Let us denote the extra (nonlinear) rotation of the nematic molecules due to the optical beams by $\theta$. It can be assumed that this extra rotation is small, $|\theta| \ll \theta_0$. Then in the slowly varying, paraxial approximation the equations for the electric field envelopes $A_1$ and $A_2$ of the beams and the optically induced rotation $\theta$ are [24, 34, 35, 43]

$$2i k_{01} n_{01} \frac{\partial A_1}{\partial z} + D_1 \nabla^2 A_1 + k_{01}^2 \beta n_{21}^2 \sin(2\theta_0) A_1 \theta = 0,$$

$$2i k_{02} n_{02} \frac{\partial A_2}{\partial z} + D_2 \nabla^2 A_2 + k_{02}^2 \beta n_{22}^2 \sin(2\theta_0) A_2 \theta = 0,$$

$$K \nabla^2 \theta + \frac{1}{4} \epsilon_0 \beta n_{21}^2 \sin(2\theta_0) |A_1|^2$$

$$+ \frac{1}{4} \epsilon_0 \beta n_{22}^2 \sin(2\theta_0) |A_2|^2 = 0,$$  \hspace{1cm} (1)

with the Laplacian $\nabla^2$ in the transverse $(x, y)$ plane. The quantities $n_{01}$ and $n_{02}$ are the background refractive indices of the medium and $\beta n_{21}$ and $\beta n_{22}$ are the optical anisotropies at the two-wavelengths, respectively [35, 43]. In general, $\beta n_{21}^2 = n_{11}^2 - n_{22}^2$, with $n_{11}$ and $n_{22}$ being the refractive indices for electric fields parallel and perpendicular to the optic axis (director) of the NLC, respectively. In the present work the values $n_1 = 1.67$ and $n_2 = 1.51$ are used, as for the nematic mixture 6CHBT at room temperature [44, 45], which is the reorientational medium used in the experiments. The parameters $D_1$ and $D_2$ are the diffraction coefficients at the two-wavelengths and $K$ is the scalar elastic constant of the NLC.

The two-color nematic equations (1) can be simplified by setting $n_1 = n_2 = 1$ and $n_{11} = n_{22} = 1$, $\beta n_{21} = \beta n_{22} = 0$, and $D_1 = D_2 = 1$ and the Frank constant $K = 1.2 \times 10^{-12}$ N.

Finally, the small angle approximation $\sin(2\theta_0) = 2\theta_0$ is made. The input vortex and nematicon at $z = 0$ are taken to have Gaussian profiles, as in the experiments, so that

$$u = a_0 e^{-r^2/\omega^2},$$

$$v = a_1 r e^{-r^2/\omega^2} e^{i\phi},$$  \hspace{1cm} (2)

where $a_0$ and $a_1$ are the amplitudes of the input beams, $\omega$ is the scale width, and $\phi$ is the phase of the input vortex.
where \( r^2 = X^2 + Y^2 \) and \( \varphi \) is the related polar angle.

Figure 5 shows results for an input vortex of power 10.7 mW and radius of 2.35 \( \mu \)m at its maximum without a co-propagating nematicon. In non-dimensional variables, \( w_i = 10 \) and \( a_i = 0.25 \). Figure 5(a) shows the vortex after it has propagated a distance \( Z = 300 \), i.e. the physical distance \( z = 333 \mu \)m. It can be seen that the vortex becomes unstable due to the standard \( n = 2 \) symmetry breaking instability and collapses into two beams [20]. Figure 5(b) shows the evolution of the vortex in the \((X, Z)\) plane \( (Y = 0) \). Clearly the vortex beam spreads apart as it becomes unstable, which is most apparent at the upper end of its propagation range. This is due to it breaking up into two nematics due to the azimuthal instability.

Figure 6 shows the corresponding results when the vortex co-propagates with a nematicon of input power \( 0.85 \) mW and Gaussian radius 3.33 \( \mu \)m, so that \( w_i = 10 \) and \( a_i = 0.5 \). The co-propagating nematicon stabilizes the vortex, in agreement with the experiments. Figure 6(a) shows the vortex at \( Z = 300 \), after propagating a physical distance of 333 \( \mu \)m, and figure 6(c) the co-propagating nematicon after the same propagation distance. Figure 6(b) for the evolution of the vortex shows that it oscillates in amplitude and width, but holds together and does not broaden as for the isolated vortex of figure 5(b). Note, the difference between the evolution of the unstable and stable vortices in the \((X, Z)\) plane \( (Y = 0) \) are most clearly seen around \( Z = 300 \) (see figures 5(b) and 6(b)). The input powers for the vortex and nematicon are similar to those in the experiments, for which the input vortex had power \( 8 \) mW and width at its maximum of 7 \( \mu \)m and the nematicon which stabilised the vortex had a power of \( 4.9 \) mW and a Gaussian width of 4 \( \mu \)m.

A vortex and a nematicon with the nominal powers and widths as used in the experiments (i.e. not accounting for input coupling and propagation losses) are far from steady beams for the nematicon equation (1), so they undergo large...
amplitude and width oscillations. The nematicon may split into two filaments [18], which is typical solitary wave behaviour for large power beams [47]; the vortex initially undergoes significant shape changes, as can be seen from figures 5(b) and 6(b), accompanied by the shedding of diffractive radiation. This is partly due to the Gaussian profile (11) not being the exact vortex solution of the nematic equations (3)–(5), so radiation shedding moves it towards the vortex solution.

4. Conclusions

In conclusion, we have shown experimentally and numerically that two-component vector vortex solitons, for which one of the components carries an optical vortex with a single topological charge, can be stabilized using the nonlocal reorientational nonlinearity of NLCs. We have found that the coupling with the fundamental soliton avoids astigmatic transformations of the input vortex into spiralling dipole states that can occur in this anisotropic medium when a vortex carrying beam propagates alone. Remarkably, such composite vector solitons are observed for comparable powers of the red and green light components, indicating a strong nonlinear coupling between them. We expect that our results will further stimulate the generation of, till now, elusive types of composite solitons, such as multi-pole or multi-ring complexes and their periodic dynamical transformations and oscillations. The great potential of such controllable stable routing of vortex-carrying excitations and the information encoded in their nontrivial phase distributions requires further detailed studies.

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