Counterpropagating nematicons in bias-free liquid crystals

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Abstract: We experimentally investigate the interaction of two counter-propagating spatial optical solitons (*nematicons*) in bias-free nematic liquid crystals. We demonstrate the existence of vector solitons composed of two nematicons propagating in opposite directions and analyze their stability versus relative distance and input power. We observe the dynamic instability of two counterpropagating nematicons in the form of time-dependent splitting and spatial entanglement.

OCIS codes: (190.6135) Spatial solitons; (160.3710) Liquid crystals.

References and links

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#120382 - $15.00 USD Received 24 Nov 2009; revised 24 Jan 2010; accepted 28 Jan 2010; published 1 Feb 2010

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1. Introduction

Among the simplest processes in nonlinear optics is the mutual interaction of two counter-propagating (CP) beams [1]. Several phenomena such as phase conjugation, Bragg reflection by volume gratings, wave-mixing are based on these interactions. A simple CP beam geometry can give rise to a complicated dynamic behavior, including mutual beam self-trapping and complex spatiotemporal instabilities [1].

Earlier fundamental concepts motivated the studies of spatial optical solitons created by two beams propagating in opposite directions, and it was shown that mutual self-trapping of two CP beams can lead to the formation of a novel type of *vector soliton* [2, 3], for both coherent and incoherent interactions. More detailed analyses [4–8] revealed that CP solitons may display a variety of instabilities, accompanied by nontrivial temporal and spatial dynamics. The first experimental studies of spatial solitons in counter-propagation geometries [9, 10] demonstrated the existence of mutually trapped composite or vector solitons when each of the interacting beams significantly affects the propagation of the other. The experimental study of CP solitons in a bulk medium was conducted later by Jander *et al.* [11], who observed not only the formation of vector solitons but also the dynamic instability of CP self-trapped beams in a photorefractive

#120382 - $15.00 USD Received 24 Nov 2009; revised 24 Jan 2010; accepted 28 Jan 2010; published 1 Feb 2010

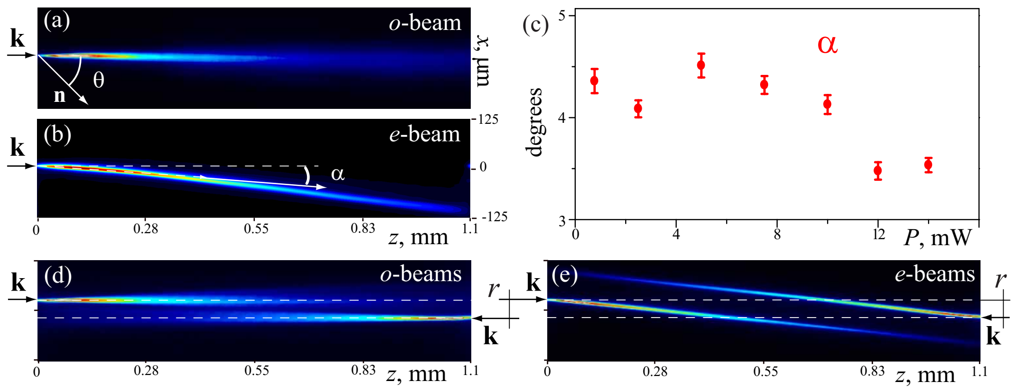

Fig. 1. Experimental images of the radiation scattered from a single beam: (a) Linear diffraction of an *o*-beam ($P = 2.5$ mW) and (b) self-trapping and walk-off of the *e*-solitary beam ($P = 14$ mW). (c) Walk-off angle α vs power, as defined in (b). (d,e) Two CP beams launched in NLC cell with offset $r = 40\,\mu$m and the input power $P = 2.5$ mW.

medium, predicted earlier in the theoretical modeling of the time-dependent beam dynamics [4]. More importantly, while the interaction of copropagating spatial optical solitons exhibits only transient dynamics and eventually results in a final steady state, the CP geometry demonstrates a dynamical (spatio-temporal) instability mediated by an intrinsic feedback [11].

In this paper we experimentally address the interaction of two CP nematicons, i.e. spatial optical solitons in nematic liquid crystals [12,13]. We employ *a bias-free geometry* of the liquid crystal cell and generate a novel class of *vector nematicons* consisting of two self-trapped beams propagating in opposite directions. We observe both stationary states and dynamic instabilities of two CP beams in the form of splitting and spatial entanglement.

2. Experiments

Earlier studies of spatial solitons in nematic liquid crystals (NLC) considered the propagation of individual nematicons [12–14] and interactions of two copropagating [15–18] and CP [19–21] nematicons. In planar geometries, voltage-biased liquid crystal cells [22] have been recently joined by unbiased cells with in-plane reorientation [18, 23–25], similar to the approach we undertake hereby.

In experiments we use a planar cell of length $L = 1.1$ mm consisting of two polycarbonate slides spaced by 100 μm and filled with 6CHBT [26,27], an NLC with relatively low absorption and refractive indices $n_e = 1.6718$ and $n_o = 1.5225$ at room temperature (23C) and at 532nm. The inner surfaces of the slides are unidirectionally rubbed in order to align the NLC molecular director $\mathbf{n}$ in the plane (x,z) at $\theta = 45^\circ$ with respect to the z-axis. Such boundary conditions in (x,z) are analogous to the bulk pre-alignment in (y,z) by an external bias voltage [22]. Two additional glass slides are attached perpendicularly to z from two opposite sides of the cell in order to define air-NLC input/output interfaces, avoiding lensing and depolarization due to NLC meniscus. A beam from a cw laser ($\lambda = 532$ nm) with wave-vector $\mathbf{k}$ parallel to the z-axis is coupled into the cell using a $10\times$ objective, resulting in an input waist $w = 2\ \mu$m. A half-wave plate controls the input polarization state and the nematicon evolution is monitored with a CCD camera collecting the light scattered out of the top slide.

First, we study the propagation of a single beam for various excitations. Figures 1(a,b) show the experimental results for ordinary (o) and extraordinary (e) beams. We observe that the o-beam (polarization $\parallel y$) diffracts, whereas the e-beam experiences self-focusing at $P \geq 2$ mW

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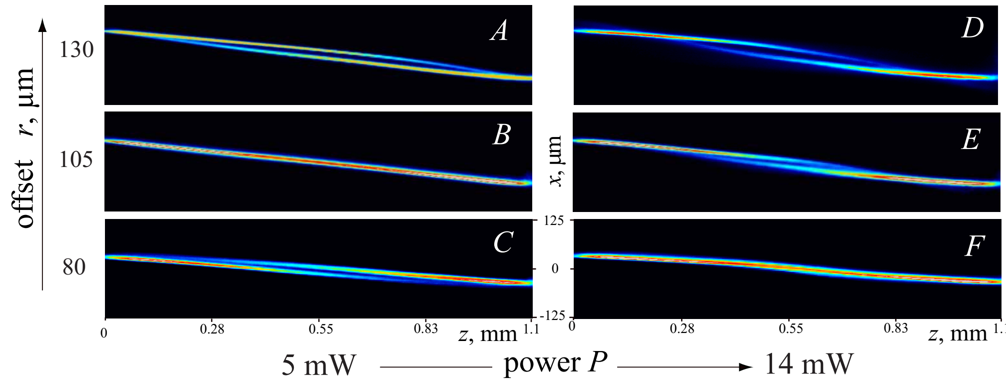

Fig. 2. Interaction of CP solitons for various input separations r: (A, D) r=130 μm, (B, E) r=105 μm, and (C, F) r=80 μm; input powers in each beam are 5 mW (left panel) or 14 mW (right panel). (A, C, D) - soliton attraction; (B, F) - bound state with single common waveguide; (E) - instability.

and forms a self-localized state, a nematicon. However, due to high birefringence in our geometry, the nematicon propagates with walk-off with respect to z [28–30]. The decay of the walk-off angle α with the input power, predicted theoretically [30], is plotted in Fig. 1(c). At small powers the beam propagates along a nearly straight line, with an angle α with the z-axis determined by the linear (plane-wave) walk-off, e.g. $\alpha = 4.58^\circ$ for $P = 2.5$ mW. At higher powers, however, the soliton has a bent trajectory with a z-dependent walk-off [30, 31], as shown in Fig. 1(b) for $P = 14$ mW.

Our main goal here is to study the interaction of two CP nematicons. In order to generate two CP beams, we split one beam into two with a beam-splitter, then launch the two beams from opposite sides of the cell using 10$\times$ objectives. We align the input beams in the same (x, z) plane, i.e. at equal distances from top and bottom slides. When the two inputs propagate towards each other with a finite impact parameter r [the offset, see dashed lines in Figs. 1(d,e)], we observe that two CP o-polarized beams diffract and remain parallel to z. In contrast, two e-beams form nematicons and bend in opposite transverse directions due to walk-off [see Fig. 1(e)], so that their separation (along x) increases as compared to the offset $r = 40\,\mu$m, cf. Figs. 1(c,d) for $P = 2.5$ mW. Since the walk-off depends on the input power, the interaction of CP nematicons depends on both, the offset r and the input power P; below we explore these dependencies in more details.

3. Results and discussions

Typical experimental results on the interaction of CP solitons are presented in Fig. 2. As expected from the single beam case, an increase in excitation $P \geq 2$ mW leads to self-focusing and the formation of nematicons. For a given offset r and small powers the beams do not interact, as in Fig. 1(e). We reveal the absence or presence of attraction by blocking one of the beams and observing the other one which relaxes (in time) to its independent trajectory. For higher P the two CP beams remain spatially separated but their attraction leads to additional bending, clearly visible by comparing Fig. 2(A) and Fig. 2(D) for $r = 130\,\mu$m. Another example of attracting nematicons is shown in Fig. 2(C) for $P = 5$ mW and $r = 80\,\mu$m.

The bound state or vector of two CP nematicons is formed for specific parameters r and P, as visible in Figs. 2(B, F). The power-dependent formation of a vector nematicon from two initially separated beams can be appreciated by comparing Figs. 2(C) and 2(F) for a given input

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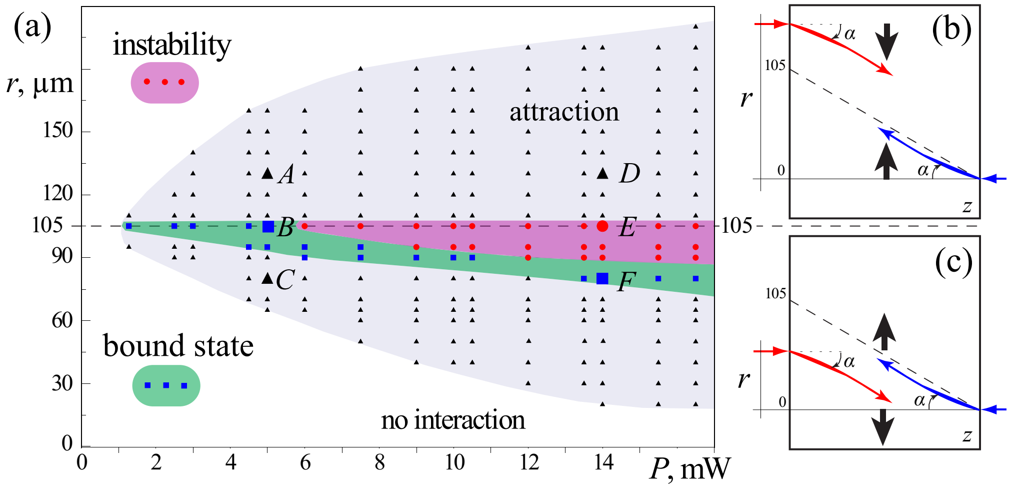

Fig. 3. (a) Scenarios of CP soliton interaction shown on the plane (P, r). The points A to F correspond to the regimes shown in Fig. 2. (b, c) Sketches of two distinct regimes of interaction between forward (red arrows) and backward (blue arrows) nematicons, separated by a critical value of the offset $r = 105\,\mu$m. In both cases, the nonlinear attraction pulls the two CP solitons towards each other, either acting in the same (b) or in the opposite (c) direction with respect to the transverse walk-off indicated by black arrows.

offset $r = 80\,\mu$m. In contrast, the sequence of Figs. 2(B) and 2(E) for $r = 105\,\mu$m shows how the CP bound state (vector nematicon) breaks down due to an increase in power, as apparent in Fig. 2(E) with the development of a transverse instability.

Our results can be mapped into parameter regions to describe different scenarios of interactions, see Fig. 3(a). In all the experiments the beams are launched with wavevectors parallel to z and equal powers P; since the interaction is *incoherent*, the key parameters governing the dynamics are the offset r and the excitation power P. For powers below a threshold value, no interaction is observed (blank area) and each nematicon's path does not bend when the CP soliton of the pair is launched, see Fig. 1(e). Such threshold is offset-dependent and it can be identified at the boundaries of the gray area of attraction marked with black triangles in Fig. 3(a). An increased power moves the system into the domain of mutual attraction, where we observe the bending of the two trajectories towards each other and propagation remains stationary, see Figs. 2(A, D, C). Vector nematicons [Figs. 2(B, F)] form when parameters lie in the green area with blue squares, while the instability [Fig. 2(E)] arises in the narrow region marked with red circles in Fig. 3(a).

The domains in Fig. 3(a) point out a counterintuitive feature, namely an asymmetry with respect to the (dashed) line in $r = 105\,\mu$m. This offset corresponds to a "head-on" collision of the two CP solitons at small powers. Above and below this value a qualitative difference appears between the two configurations sketched in Figs. 3(b) and 3(c), respectively. For offset $r > 105\,\mu$m in Fig. 3(b) the walk-off of the two nematicons, indicated by black arrows, acts in *the same* transverse direction as the mutual nonlinear attraction. Conversely, for $r < 105\,\mu$m in Fig. 3(c), the two nematicons bend away from each other due to walk-off, counteracting the mutual attraction. As a result, bound states of CP nematicons with relatively straight trajectories appear at low powers only for offsets $r \simeq 105\,\mu$m (see the green area in Fig. 3(a)), because they require a lesser amount of curvature in order to merge in a joint waveguide. For $r \leq 105\,\mu$m

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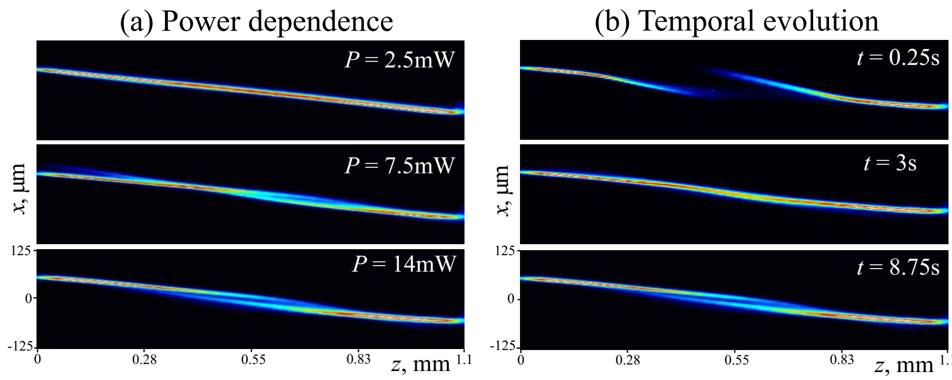

Fig. 4. Breaking of a vector nematicon for $r = 105\,\mu$m. (a) Evolution with P. (b, Media 1) Temporal development of the CP instability for $P = 14$ mW.

(such as in Fig. 2(F) and Fig. 3(a)) vector CP nematicons require larger excitation powers.

Finally, in Fig. 4 we explore the details of the spatio-temporal instability, predicted and observed earlier in other types of CP solitons [1,11]. The power-mediated transition from a stable bimodal CP nematicon to an unstable state is shown in Fig. 4(a) for the threshold $r = 105\,\mu$m. Note that the splitting phenomenon grows with power. At each power, however, the development of the instability requires additional time, as we show in Fig. 4(b) and Media 1 for $P = 14$ mW. The temporal evolution begins with diffraction for times $t < 0.25$ s, followed by self-trapping of nematicons, their strong attraction and merging into a single self-confined waveguide at $t = 3$ s. At this stage [see middle panel in Fig. 4(b)] the formation of a vector nematicon is apparent. This bound CP soliton is unstable and splits into two spatially separated beams for $t > 3$ s. As it can be seen in real time in Media 1, the temporal dynamics does not reach a steady state, yielding spatiotemporal instabilities [1] as a direct consequence of the inertial (slow) character of the reorientational response of liquid crystals [15,23,32].

Another contribution to the instability comes from the asymmetric character of the CP interaction due to losses. As shown in Fig. 1, losses are responsible for different walk-offs along propagation, resulting in slightly curved nematicon trajectories; hence, the interaction between CP nematicons is unequal along z, with power and separation changing in either beams. The time required for forming CP steady bound states is thus much larger than that for copropagating nematicons [25].

4. Conclusions

We have experimentally studied the interaction of two counterpropagating nematicons in a planar bias-free liquid crystal cell. We have demonstrated that such nematicons can form vector solitons with two components propagating in opposite directions, as well as experience dynamic instabilities. We have performed series of experiments varying two key parameters, the transverse separation of CP nematicons r and their excitation power P, and identified the parameter domains where different dynamics can be observed. Of a particular interest for future studies is the appearance of stable curved bound states, or vector counterpropagating nematicons, which can be used as self-adjusting interconnects able to guide an additional weak signal.

Acknowledgements

This work was supported by the projects of the Australian Research Council and the Qatar National Research Foundation (project NPRP 25-6-7-2).