Dynamic instability of self-induced bidirectional waveguides in photorefractive media

Philip Jander, Jochen Schröder, and Cornelia Denz

Institute of Applied Physics, Westfälische Wilhelms-Universität, Correnssstrasse 2, D-48149 Münster, Germany

Milan Petrović

Institute of Physics, P.O. Box 57, 11001 Belgrade, Serbia

Milivoj R. Belić

Texas A&M University at Qatar, P.O. Box 5825, Doha, Qatar

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We report on the experimental observation of a dynamic instability in the interaction of counterpropagating self-trapped beams in a photorefractive strontium barium niobate crystal. While the interaction of copropagating spatial optical solitons exhibits only transient dynamics, resulting in a final steady state, the counterpropagating geometry supports a dynamic instability mediated by intrinsic feedback. Experimental observations are compared with and found to be in qualitative agreement with numerical simulations. © 2005 Optical Society of America

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The formation of stable self-trapped beams (commonly called optical spatial solitons) in photorefractive (PR) media[1] has been the topic of intensive research in the past decade,[2] primarily owing to potential applications in all-optical switching. Prior investigations have largely been confined to copropagating solitons, which exhibit characteristic interaction behavior: Individual solitons can attract or repel as well as exchange energy and fuse or mutually excite a new soliton.[2] However, given one-sided boundary conditions, such nonlinear optical beams generally exhibit no dynamic behavior beyond initial transient dynamics.

A recent series of reports on spatial solitons consisting of counterpropagating (CP) waves[3–7] indicates growing interest in the interaction of CP self-trapped beams. CP geometry adds intrinsic feedback to the soliton interaction. In general, CP waves coupled with feedback are often found to exhibit instabilities[8–10] and related phenomena, such as pattern formation.[11] Hence one can expect qualitatively new properties to result from the interaction of CP solitons.

Recently, we predicted the existence of continuing aperiodic dynamics in the interaction of localized CP beams, based on a numerical treatment of a dynamic one-dimensional saturable Kerr model,[6,12,13]

$$i\partial_z F + \partial_x^2 F = \Gamma E_0 F, \tag{1}$$

$$-i\partial_z B + \partial_x^2 B = \Gamma E_0 B, \tag{2}$$

$$\tau\partial_t E_0 + E_0 = -\frac{|F|^2 + |B|^2}{1 + |F|^2 + |B|^2}, \tag{3}$$

where F and B are the CP wave envelopes, E_0 is the screening space charge field induced by the PR effect, and Γ is the PR coupling constant. With appropriate scaling, all the variables are made dimensionless.[6]

Commonly applied as an approximation to the PR nonlinearity, this model captures the basic dynamic effects of self-focusing and interaction of mutually incoherent CP waves in a medium with slow response time. Beam bending and repulsive forces between solitons with a specific finite distance are not represented. Numerically, we found a broad range of localized self-focused states with nonconstant and nonstationary beam profiles to be of interest. In particular, the model demonstrated a threshold medium length beyond which no stable temporally stationary solutions could be found, in contrast with the usual interaction behavior observed in copropagating solitons. We stress that such solutions can be accessed only with a model incorporating time dependence.[6]

In this Letter we present for the first time to our knowledge experimental confirmation of the numerically predicted instability, using mutually incoherent CP self-trapped beams in a PR cerium-doped strontium barium niobate (Ce:SBN:60) crystal (Fig. 1). The crystal is biased by an external dc field along the transverse x direction, coinciding with the crystallographic c axis. Both beams are obtained from a single laser source and rendered mutually incoherent by a mirror oscillating with a period significantly shorter than the relaxation time constant of the PR material. The beams' polarizations are also selected along the x axis, taking advantage of the high electro-optic r_{33} coefficient of SBN. Propagating in the $+z$ and $-z$ directions, both beams individually self-focus, as a result of the PR screening of the external field,[1] which has a value of 1.3 kV/cm. The diameter of each beam (x axis) is 25 μm FWHM, and the power of each is 1 μW. To help the formation of PR screening solitons, the interaction region is illuminated by white light. The beams' power and the level of nonlinearity are adjusted such that each of the beams individually forms a spatial soliton. To demonstrate both above-

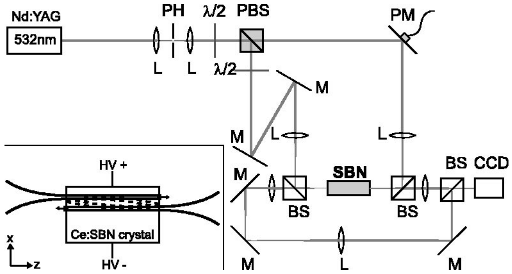

Fig. 1. Experimental setup. Two beams are rendered mutually incoherent with an oscillating piezo-mounted mirror (PM) and focused on opposite faces of a PR Ce:SBN60 crystal. Both crystal faces are imaged onto a CCD camera, allowing for synchronous observation of reflections of both exit and input beams (Ms, mirrors; Ls, lenses; PH, pinhole; PBS, polarizing beam splitter; BS, beam splitter). Inset, CP soliton interaction in the numerical model (no beam bending, only attractive forces). Two beams individually self-focus in the PR medium (solid curves). Propagating in close proximity, incoherent beams attract, as the combined intensity of both beams creates a common lens (dashed curves) HV, high voltage.

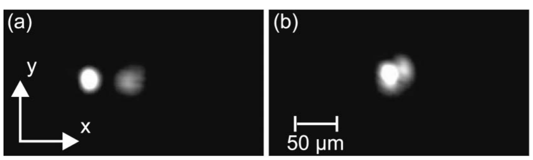

Fig. 2. Images of one exit face. (a) Separated beams: The beam leaving the crystal is visible as the bright spot. The second beam entering the crystal at this plane is visible in reflection (faint spot). (b) Strong interaction and the splitting of beams: Although most of the output beam overlaps with the input beam, a fraction is split off into a second channel. Images (a) and (b) correspond to $t=9$ s and $t=417$ s of the time series displayed as Fig. 3(b).

and below-threshold behavior with a single crystal sample, we utilize two medium lengths by rotating the crystal about its c axis, thus yielding $L_1=5$ mm and $L_2=23$ mm.

Because the actual evolution of CP beams within the PR medium is not accessible in this experiment, images of beam outputs at the crystal faces are recorded (Fig. 2). Besides each beam leaving the medium, a reflection of the CP input is recorded as a lateral reference. Initially, both beams are adjusted such that their inputs and outputs overlap on both ends of the crystal, if propagating independently and in a steady state, including the shift through beam bending. This configuration was chosen to minimize the possible effects of beam bending[7] on the stability of a fully overlapping state [Fig. 3(a)].

For comparison with numerical simulations, experimental data are reduced to one transverse dimension: The images obtained on the exit faces of the crystal are projected onto the x axis. As these data are plotted over time, one gets a representation of the dynamics of the beam exiting a crystal face [Figs. 3(a)–3(c)]. Although changes parallel to the y axis are not represented, most of the observable dynamics is confined to the x axis, owing to the significance of the c axis for the PR effect.

Considering a medium of short length ($L_1=5$ mm), the output beams on both crystal surfaces initially shift their position in the experiment [Fig. 3(a), $t<20$ s], as well as in corresponding simulations (not shown), converging to an overlapping steady state ($t>20$ s). Because the solution is stable and stationary, the considered medium length is below the predicted dynamic instability threshold.

In the case of a significantly longer medium ($L_2=23$ mm) the beams initially self-focus separately [Fig. 3(b), $t<30$ s] and attract and overlap ($30\text{ s}<t<60$ s). However, this state is unstable and yields to irregular repetitions of repulsion and attraction. This process does not feature any visible periodicity and is observed for time spans that are orders of magnitude longer than the time constant of the system. The reported dynamic state [Fig. 3(c)] can be seen to directly correspond to numerical simulations of the

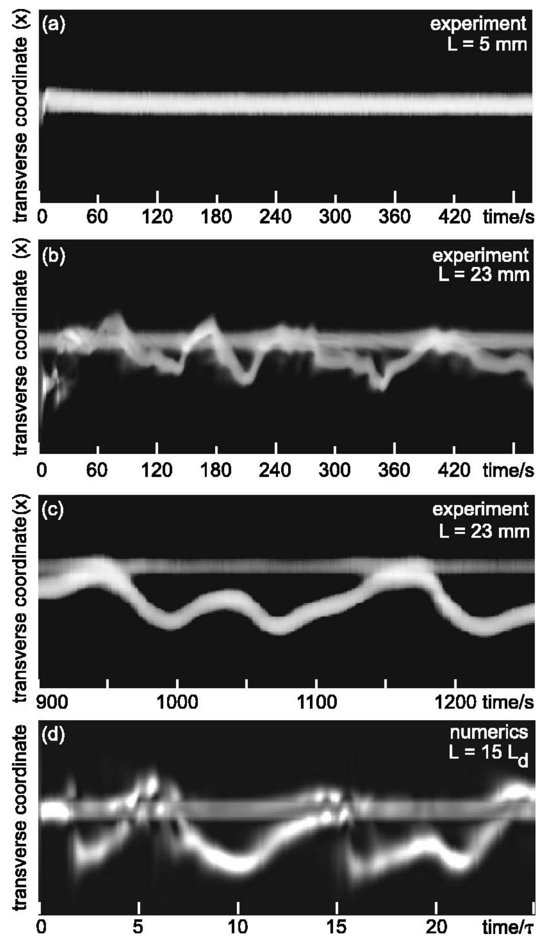

Fig. 3. Temporal plot of system dynamics. (a) Below threshold ($L_1=5$ mm), the resulting stable and stationary state consists of two symmetrically overlapping solitons. (b) Above threshold ($L_2=23$ mm), irregular dynamics are observed. (c) Close up of later development of a similar experiment starting at $t=15$ min. (d) Numerical simulation qualitatively corresponding to experimental parameters for (c). Fast oscillations for which the beams overlap result from confinement to one transverse dimension and can be considered a numerical artifact. In its place, experimental observations feature a splitting of the beams into two parts (compare Fig. 2).

one-dimensional model [Fig. 3(d)]. We chose the parameters for the model to be in a range qualitatively agreeing with the experiment: $L=15$ diffraction lengths, $\Gamma=3$, input intensity of 1.5, input beams with a lateral offset of 0.5 beam diameters to avoid tracking the unstable symmetric solution (both beams overlapping). Similar to the experiment, initial overlap and subsequent repetitions of attraction and repulsion are observed. The time scale agrees well with the experimental data. Because we can rule out external causes for the observed aperiodicity, the observations confirm the predicted existence of a dynamic instability in the interaction of CP self-trapped beams.

Both experimental and numerical data display a transverse asymmetry that is a result of the symmetry-breaking nature of the instability[12]: The transversely symmetric state becomes unstable above threshold. The actual preferred direction manifested in a given experiment or numerical run is sensitive to several parameters, such as the exact initial beam configuration, medium length, displacement by the beam bending effect, and noise effects such as medium inhomogeneities.

The existence of the instability is remarkable because the interaction of CP solitons in the model is generally attractive. The key to the instability is bidirectional feedback provided by counterpropagation. A small transverse displacement in one beam can excite a displacement in the second beam through attraction. Feedback allows for a mutual amplification of displacements above a threshold longitudinal interaction length (i.e., the medium's length in the propagation direction). With a phenomenological model a first threshold interaction length was found beyond which a fundamental mode CP vector soliton becomes unstable against a transverse displacement of the beams.[12,14]

However, for any medium length slightly above this first threshold the system can still relax into a steady state after the vector soliton breaks up. In that case the CP beams propagate in distinct stationary waveguides. Attraction forces the beams to cross repeatedly while at the same time preventing fusion of the waveguides. But for medium lengths far above the threshold one observes the onset of continuing dynamics, never settling into a stationary state. In fact, a second threshold was found numerically[13] that separates stationary and dynamic regimes. The states below the first and above the second numerically found threshold correspond to the two states experimentally distinguished in this work.

In summary, we have demonstrated a dynamic instability in the interaction of CP localized optical beams. Each beam individually forms an optical spatial soliton and converges to a steady state after transient dynamics. Despite mutual attraction, both beams do not necessarily form either a common vector soliton or any other stationary waveguide structure. Instead, a dynamic instability enforces spatial separation of the localized beams while rendering such separated states unstable. A threshold interaction length was found beyond which the interaction leads to nontransient dynamics that is experimentally observable on the exit faces of the crystal. Qualitatively, experimental observations were found to be in good agreement with numerical simulations. Above- and below-threshold states were clearly distinguishable. Quantitative investigation of the threshold, the inclusion of beam bending and repulsive forces observed between PR solitons into the analysis, and a determination whether the observed aperiodic dynamics is chaotic, are challenging experimental tasks and are the subjects of ongoing research.

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14. It should be noted that the threshold parameter is actually the coupling strength, which is the interaction length times the PR coupling constant. Holding the latter at a fixed value, we restricted the investigation to the interaction length threshold.