Interaction of counterpropagating discrete solitons in a nonlinear one-dimensional waveguide array

Eugene Smirnov, Milutin Stepić, Christian E. Rüter, Vladimir Shandarov, and Detlef Kip

Institute of Physics and Physical Technologies, Clausthal University of Technology, 38678 Clausthal-Zellerfeld, Germany

Received October 31, 2006; accepted November 20, 2006;
posted December 4, 2006 (Doc. ID 76636); published February 2, 2007

We experimentally investigate the interaction of counterpropagating discrete solitons in a one-dimensional waveguide array in photorefractive lithium niobate. While for low input powers only weak interaction and formation of counterpropagating vector solitons are observed, for higher input powers a growing instability results in discrete lateral shifting of the formed discrete solitons. Numerical modeling shows the existence of three different regimes: stable propagation of vector solitons at low power, instability for intermediate power levels leading to discrete shifting of the two discrete solitons, and an irregular temporal dynamic behavior of the two beams for high input power. © 2007 Optical Society of America

OCIS codes: 160.3130, 190.4420, 190.5330, 190.5530.

In the past few decades there has been growing interest in the investigation of light manipulated by light itself. An attractive concept for such all-optical light switching, routing, and steering may be realized by using the interaction of self-trapped optical beams, i.e., spatial optical solitons.[1–3] Depending on parameters such as mutual phase and relative transverse velocity of the colliding beams, both attraction and repulsion and soliton fusion and fission have been observed.[4–6] Even more interesting, in nonlinear periodic media or photonic crystals, so-called discrete solitons may be obtained,[7–10] which offer large potential for future applications by using the inherent multiport structure of the array.

The most simple realization of a periodic (nonlinear) medium is the one-dimensional (1D) case, where nonlinear arrays consist of parallel, weakly coupled waveguides that have been fabricated, e.g., in semiconductors[8] and photorefractives.[9,10] In such arrays, discrete soliton interaction has been investigated for parallel beams showing soliton attraction, repulsion, oscillatory behavior of the two beams, and soliton fusion.[11,12] Further investigations have been devoted to the interaction of narrow discrete solitons with coherent and incoherent probe beams.[13,14] In this Letter, we focus on the interaction of solitons launched in the same channel but propagating in opposite directions. Similar to what has been observed for spatial counterpropagating solitons in bulk media[15–18] and as recently theoretically predicted for photonic lattices,[19] we observe for what is believed to be the first time both instability of the interacting discrete solitons, leading to discrete spatial shifts, and irregular dynamic behaviors for high nonlinearities. Our experimental results are supported by numerical modeling, where three regimes, namely, stable propagation of vector solitons, instability leading to discrete displacements of solitons, and an irregular dynamics, can be distinguished.

Fabrication of the $L=25$ mm long 1D waveguide array with grating period 8.4 μm in x-cut Fe-doped $LiNbO_3$ has been described in Ref. 14. In the experimental setup in Fig. 1 light with wavelength $\lambda = 532$ nm is split into two beams that allow the excitation of single input channels on both facets of the waveguide array by using 20× microscope lenses. The corresponding soliton beams are designated #1 (forward direction) and #2 (backward direction) and propagate in the $\pm y$ direction.

In Fig. 2 we monitor the temporal evolution of nonlinear soliton formation using single-channel excitation when only beam #1 is present. For both input powers used ($P_{in}=1.8$ μW and $P_{in}=20$ μW), a narrow discrete gap soliton is obtained that propagates in the forward $+y$ direction.[14] While the time constant for buildup of the nonlinear index change is reduced by about one order of magnitude for the higher input power, a very similar, highly symmetric temporal buildup is observed in both cases.

For the investigation of counterpropagating solitons we use equal input powers of forward- (#1) and backward- (#2) propagating beams, $P_1=P_2=P_{in}$. Because of the anisotropic nature of the photorefractive nonlinearity in $LiNbO_3$, the interaction is not phase sensitive: Although the forward- and backward-propagating extraordinarily polarized waves are mutually coherent, their interaction is phase insensitive due to the anisotropic nature of the photorefractive nonlinearity in $LiNbO_3$. The two transverse electrically, extraordinarily polarized counterpropagating beams form an interference pattern with a grating

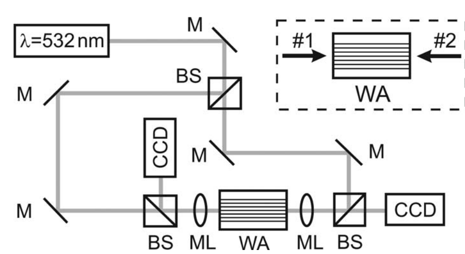

Fig. 1. Experimental setup: ML, microscope lenses; M, mirrors; BS, beam splitters; WA, waveguide array; CCD, CCD cameras. Inset, forward- (#1) and backward- (#2) propagating beams.

vector directed along the propagation direction. As a consequence, a modulated space-charge electric field builds up; however, no appropriate electro-optic tensor element ($r_{eff}=r_{32}=0$) exists for crystals with point symmetry $3m$, and the resulting nonlinear index change is zero.

For lower input powers ($P_{in}=2\ \mu$W) we observe only small deviations from symmetry, and in steady state the two formed discrete solitons are still centered on the input channel. In Fig. 3(a) the first two lines monitor discrete diffraction of beams #1 and #2, while the last two lines show the final steady state of discrete soliton formation. The temporal evolution of the forward-propagating beam (#1) is shown in lines 2 to 8. As can be seen, a rather weak asymmetry in the final soliton profile is present for both beams, which together form a counterpropagating discrete vector soliton.[18,19] When the power is increased to $P_{in}=6\ \mu$W in Fig. 3(b), the asymmetry of the light distributions during buildup becomes more pronounced. In this situation no narrow discrete solitons are formed in steady state after recording for 70 min, and beams #1 and #2 differ slightly in their spatial shape on the output facet. For higher input powers of $P_{in}=12\ \mu$W a lateral shift of the two formed narrow solitons by one channel is observed in Fig. 3(c). Here both solitons are shifted to the same side; however, the direction of this spontaneous symmetry breaking is arbitrary[17]: When the experiment is repeated, both displacements to the left and to the right are observed. For a further increased input power, the light distributions on the output facets become irregular in time, i.e., no steady state can be reached anymore. Qualitatively, the instability in Fig. 3(c) can be understood by first assuming a small lateral distortion (refractive index change) induced by one of the beams, e.g., by nonlocal contributions of charge transport in photorefractives (diffusion mechanism, nonlocal photovoltaic effect, etc.). The second beam is attracted by this local index change and further amplifies the distortion, which again interacts with the first beam. The result is a distortion that grows exponentially in time and finally leads to a lateral shift of both beams.[19]

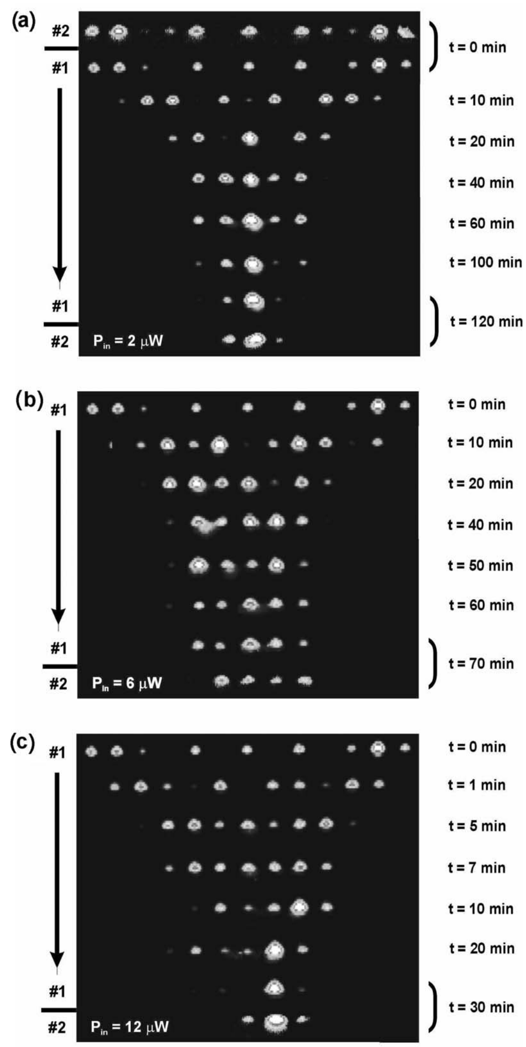

Fig. 3. Interaction of forward- (#1) and backward- (#2) propagating discrete solitons for input powers (a) $P_{in}=2\ \mu$W, (b) $P_{in}=6\ \mu$W, and (c) $P_{in}=12\ \mu$W.

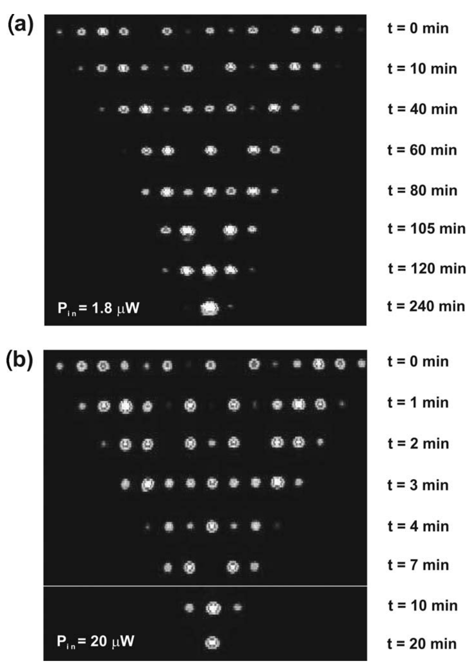

Fig. 2. Temporal evolution of discrete soliton formation for two different input powers, (a) $P_{in}=1.8\ \mu$W, (b) $P_{in}=20\ \mu$W of beam #1.

To compare our experimental results with theoretical modeling, we numerically solve the coupled nonlinear paraxial wave equations for electric fields $E_{1,2}$ propagating along the $\pm y$ direction in an index grating with modulation $n(z)=0.005\cos^2(\pi z/\Lambda)$:

$$i\frac{\partial E_1}{\partial y}+\frac{1}{2k}\frac{\partial^2 E_1}{\partial z^2}+k\frac{n(z)+\Delta n}{n_e}E_1=0,$$

$$-i\frac{\partial E_2}{\partial y}+\frac{1}{2k}\frac{\partial^2 E_2}{\partial z^2}+k\frac{n(z)+\Delta n}{n_e}E_2=0, \tag{1}$$

where coupling is due to the saturable defocusing nonlinearity of the form

$$\Delta n = \Delta n_0 \frac{I_1 + I_2}{I_1 + I_2 + I_d} = \Delta n_0 \frac{2r}{2r+1}. \quad (2)$$

Here n_e is the extraordinary substrate refractive index, $r = I/I_d$, where I_d is the so-called dark irradiance and $I = I_1 = I_2$ is the input light intensity. The interaction is modeled using a nonlinear beam propagation and calculating time steps τ/N with buildup time constant τ and $N \gg 1$ and assuming a temporal buildup of the nonlinear index change, $\Delta n_0(t) = \Delta n_0[1 - \exp(-t/\tau)]$. Each tiny time step consists of first launching beam #1 and then recording a corresponding nonlinear index change. Then beam #2 is launched in the opposite direction, while the index change that is due to beam #1 is held constant. In this way artificial symmetry-breaking effects due to the numerical procedure can be minimized.

In the simulation results depicted in Fig. 4, the refractive index change is fixed to $|\Delta n_0| = 4 \times 10^{-4}$, and the total calculated time is set to 10τ with $N = 20$ (200 time steps). As can be seen, for a small intensity ratio of $r = 0.75$ the two solitons propagate stably with only weak interaction, whereas for a higher ratio of $r = 2.5$ instability grows and soliton formation is partly suppressed. For an intensity ratio of $r = 5$ the two formed discrete solitons are displaced by one channel to the left. Numerically, if the intensity ratio is further increased to values of $r > 7$, no steady-state solution can be obtained anymore: The output intensity on both facets starts to fluctuate rapidly also for recording times $t \gg \tau$, similar to the results described in Ref. 20. As already discussed in Ref. 17 for bulk media, when the propagation length L is increased to $L > 25$ mm, instability thresholds are shifted to lower intensity ratios r, and vice versa.

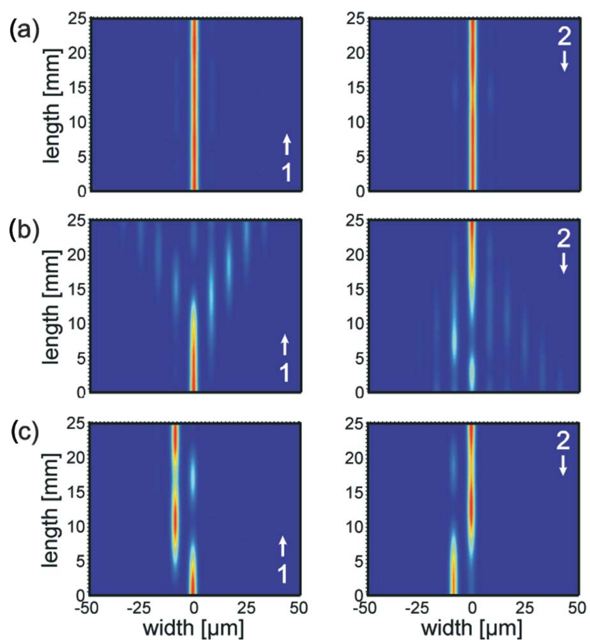

Fig. 4. (Color online) Simulation of the interaction of counterpropagating discrete solitons (left-hand side, beam #1; right-hand side, beam #2) for three different intensity ratios, (a) $r = 1$, (b) $r = 2.5$, and (c) $r = 5$ in steady state ($t = 10\tau$).

To summarize, we have experimentally and numerically investigated the interaction of counterpropagating discrete solitons in a 1D $LiNbO_3$ waveguide array. For small input powers or intensity ratios, respectively, interaction is weak and almost independent propagation of the two discrete solitons in the same channel is achieved. When the input power (intensity ratio) is increased soliton instability occurs, and for sufficiently high values spontaneous symmetry breaking with discrete lateral displacement of the two solitons is observed. A further increase of power leads to temporally irregular propagation with spatial fluctuations that are fast compared with the buildup time τ.

We gratefully acknowledge financial support from the German Federal Ministry of Education and Research (DIP-E6.1) and the Deutsche Forschungsgemeinschaft (KI482/8-1 and 436RUS17/26/06). D. Kip's e-mail address is detlef.kip@tu-clausthal.de.

References

1. A. W. Snyder and A. P. Sheppard, Opt. Lett. **18**, 482 (1993).
2. G. Stegeman and M. Segev, Science **286**, 1518 (1999).
3. Yu. S. Kivshar and G. P. Agrawal, *Optical Solitons: From Fibers to Photonic Crystals* (Academic, 2003).
4. J. P. Gordon, Opt. Lett. **8**, 596 (1983).
5. H. Meng, G. Salamo, M. Shih, and M. Segev, Opt. Lett. **22**, 448 (1997).
6. D. Kip, M. Wesner, C. Herden, and V. Shandarov, Appl. Phys. B **68**, 971 (1999).
7. D. N. Christodoulides and R. I. Joseph, Opt. Lett. **13**, 794 (1988).
8. H. Eisenberg, Y. Silberberg, R. Morandotti, A. R. Boyd, and J. S. Aitchison, Phys. Rev. Lett. **81**, 3383 (1998).
9. J. W. Fleischer, G. Bartal, O. Cohen, T. Schwartz, O. Manela, B. Freedman, M. Segev, H. Buljan, and N. K. Efremidis, Opt. Express **13**, 1780 (2005).
10. F. Chen, M. Stepić, C. E. Rüter, D. Runde, D. Kip, V. Shandarov, O. Manela, and M. Segev, Opt. Express **13**, 4314 (2005).
11. J. Meier, G. I. Stegeman, Y. Silberberg, R. Morandotti, and J. S. Aitchison, Phys. Rev. Lett. **93**, 093903 (2004).
12. M. Stepić, E. Smirnov, C. E. Rüter, L. Prönneke, V. Shandarov, and D. Kip, Phys. Rev. E **74**, 046614 (2006).
13. J. Meier, G. I. Stegeman, D. N. Christodoulides, Y. Silberberg, H. Yang, G. Salamo, M. Sorel, and J. S. Aitchison, Opt. Lett. **30**, 1027 (2005).
14. E. Smirnov, C. E. Rüter, M. Stepić, V. Shandarov, and D. Kip, Opt. Express **14**, 11248 (2006).
15. O. Cohen, R. Uzdin, T. Carmon, J. W. Fleischer, M. Segev, and S. Odoulov, Phys. Rev. Lett. **89**, 133901 (2002).
16. M. Belić, Ph. Jander, A. Strinić, A. Desyatnikov, and C. Denz, Phys. Rev. E **68**, R025601 (2003).
17. M. Petrović, D. Jović, M. Belić, J. Schröder, Ph. Jander, and C. Denz, Phys. Rev. Lett. **95**, 053901 (2005).
18. K. Motzek, Ph. Jander, A. Desyatnikov, M. Belić, C. Denz, and F. Kaiser, Phys. Rev. E **68**, 066611 (2003).
19. M. Belić, D. Jović, S. Prvanović, D. Arsenović, and M. Petrović, Opt. Express **14**, 794 (2006).
20. M. Belić, Ph. Jander, K. Motzek, A. Desyatnikov, D. Jović, A. Strinić, M. Petrović, C. Denz, and F. Kaiser, J. Opt. B: Quantum Semiclassical Opt. **6**, 190 (2004).