Symmetric and antisymmetric soliton states in two-dimensional photonic lattices

Cibo Lou, Jingjun Xu, Liqin Tang, and Zhigang Chen

Key Laboratory for Weak-Light Nonlinear Photonics Materials, Ministry of Education, and TEDA Applied Physical School, Nankai University, Tianjin 300457, China

P. G. Kevrekidis

Department of Mathematics and Statistics, University of Massachusetts Amherst, Amherst, Massachusetts 01003

Received September 21, 2005; revised November 8, 2005; accepted November 23, 2005; posted December 1, 2005 (Doc. ID 64943)

We study the dynamics of off-site excitation in an optically induced waveguide lattice. A single beam centered between two waveguides leads to an asymmetric beam profile as the nonlinearity reaches a threshold. When two probe beams are launched in parallel into two nearby off-site locations, they form symmetric or antisymmetric (twisted) soliton states, depending on their relative phase. A transition of intensity pattern from on-site to off-site locations is also observed as the lattice is excited by a quasi-one-dimensional plane wave. © 2006 Optical Society of America

OCIS codes: 190.4420, 230.3990.

The dynamics of soliton propagation in coupled optical waveguides, from two coupled waveguides such as dual-core fiber couplers and directional couplers to three coupled waveguides and multiwaveguide arrays, has been studied extensively during the past decades.[1–6] Much of the earlier theoretical work focused on energy switching and stability of solitons in coupled waveguide structures. For instance, it has been shown that, in a dual-core coupler, symmetry breaking typically occurs such that a symmetric soliton becomes unstable when its energy exceeds a threshold value.[2,3]

More recently, closely spaced waveguide arrays (lattices) have attracted considerable attention owing to their strong link with photonic crystals as well as to intriguing phenomena that arise from their collective wave propagation behavior.[7,8] An example is the formation of discrete solitons and bandgap structures, which have been demonstrated in a number of experiments.[9–15] In particular, it has been shown that, in fabricated waveguide lattices with strong coupling, discrete solitons centered in the center of a waveguide (on-site excitation) are stable, while those centered in the middle between waveguides (off-site excitation) are unstable.[14,15] Closely related research with optically induced photonic lattices[16] has shown that an even-mode soliton or an in-phase dipolelike soliton is always unstable.[12,17]

In this Letter we study experimentally off-site excitation in a weakly coupled lattice created by optical induction. When a Gaussian-like probe beam is launched between two lattice sites, its energy switches mainly to the two closest waveguide channels evenly, leading to a symmetric beam profile. However, as the intensity of the probe beam exceeds a threshold value, the probe beam evolves into an asymmetric beam profile, akin to that which results from symmetry breaking in a double-well potential.[2,3] Should the probe beam experience no or only weak nonlinearity, such symmetry breaking in the beam profile would not occur, regardless of the increase in its intensity. When two probe beams are launched in parallel into two off-site locations, they form symmetric or antisymmetric (dipolelike twisted[12,17,18]) soliton states, depending on their relative phase. A transition of the intensity pattern from on-site to off-site locations is also observed as the lattice is excited by a quasi-one-dimensional plane wave, which may be related to excitation of symmetric (first band) and antisymmetric (second band) Bloch states in the lattices.[10,19,20]

The experimental setup for our study is similar to that used for creation of spatial soliton pixels.[16] A partially spatially incoherent beam (488 nm) is generated by use of a rotating diffuser. A biased photorefractive crystal (SBN:60, $6\ \mathrm{mm}\times 8\ \mathrm{mm}\times 5\ \mathrm{mm}$) is employed to provide noninstantaneous saturable self-focusing nonlinearity. To generate a two-dimensional waveguide lattice we use an amplitude mask to spatially modulate the otherwise uniform beam after the diffuser. The mask is then imaged onto the input face of the crystal, thus creating a pixellike input intensity pattern. This lattice beam is ordinarily polarized; thus it induces a nearly linear waveguide array, which remains invariant during propagation.[11–13] An extraordinarily polarized coherent beam (either 488 or 632.8 nm) is used as a probe beam propagating collinearly with the lattice. When required, the probe beam is split by a Mach–Zehnder interferometer to create two beams, which we can make either mutually coherent with a controlled phase relation or mutually incoherent by adjusting a piezoelectric transducer mirror installed in the interferometer.

First, we launch a single Gaussian beam (488 nm) as a probe into the middle of two lattice sites located in the vertical direction (illustrated as P_1 in Fig. 1). The choice of vertical rather than horizontal direction is made to prevent possible asymmetry of the beam profile induced by soliton self-bending. When the e-polarized probe beam propagates collinearly with the lattice through the crystal, we observe a transition from a symmetric to an asymmetric beam profile

0146-9592/06/040492-3/$15.00

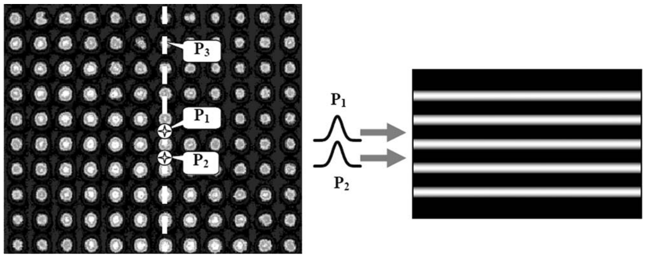

Fig. 1. Illustration of input locations of probe beams in a two-dimensional waveguide lattice.

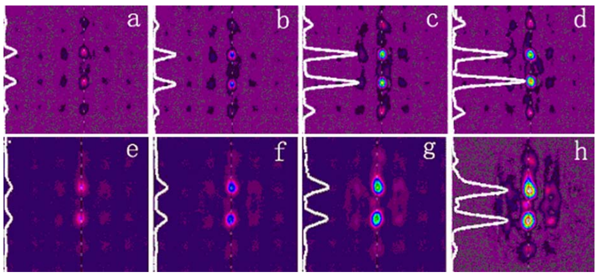

Fig. 2. (Color online) Off-site probing with a single Gaussian beam at 488 (top) and 632.8 (bottom) nm. a–h, Output intensity patterns of the probe beam at intensities (normalized to the lattice intensity) of a, 0.1; b, 0.2; c, 0.4; d, 0.5; e, 0.2; f, 0.4; g, 1.0; h, 2.0.

as the intensity of the probe beam is increased gradually while all other experimental conditions remain unchanged. Typical experimental results are presented in Fig. 2 (top), which were obtained with a lattice of 35 μm spacing (as shown at the left in Fig. 1). When the intensity of the probe beam is low, the energy of the probe tunnels evenly into two waveguides (Figs. 2a–2c). However, above a threshold value of input intensity, the output intensity pattern becomes asymmetric (Fig. 2d). The bifurcation from symmetric to asymmetric output is also clearly visible in the vertical beam profile illustrated at the left in each figure, which we obtained here by changing only the beam intensity without offsetting the beam position. To demonstrate that such a transition was induced by nonlinearity, all experimental conditions were kept unchanged, except that the 488 nm probe was replaced by a 632.8 nm probe. The beam at 632.8 nm experiences much weaker nonlinearity than does the 488 nm beam, simply because the former is at a much less photosensitive wavelength for our crystal. As expected, such a dynamic transition did not occur with the 632.8 nm probe, regardless of the increase in its intensity. In fact, even if the intensity of the probe beam was increased to twice that of the lattice beam, the probe profile remained symmetric, as shown in Fig. 2h.

Next, we split the Gaussian probe beam into two mutually incoherent beams with a Mach–Zehnder interferometer in which one of the mirrors was driven by a piezoelectric transducer at a frequency much faster than the crystal can respond to. When only one of the beams exiting from the interferometer was sent to an off-site position, we adjusted the beam's intensity such that a single beam alone did not lead to an asymmetric beam profile. Adding the other beam at the same location resulted in an overall asymmetric beam profile. When the two beams were sent into two separate off-site locations (P_1 and P_2 in Fig. 1) rather than overlapped, we effectively had a three-well potential for the probe beams in the weak-coupling region. The energy of each probe beam alone tunneled into two adjacent waveguides evenly, as shown in Figs. 3a and 3b. We then opened up both beams and recorded the intensity pattern both immediately and after a new steady state had been reached. From Figs. 3c and 3d, one can see clearly that more energy from the probe beams moved to the central site owing to the noninstantaneous nonlinearity experienced by the probe beams. In fact, when we blocked one beam and quickly recorded the intensity pattern of the other beam, we noted that each beam profile became slightly asymmetric at this new steady state, with the preferred direction of energy tunneling toward the central site. In this case, the asymmetry of the top beam was similar to that shown in Fig. 2d, but the beam profile of the bottom beam had opposite asymmetry simply because the effective waveguide in the central site was stronger. Without the pairing beam, each beam alone will evolve into an asymmetric beam profile such as that in Fig. 2d once its intensity is increased above a threshold value. (The corresponding symmetry-breaking numerical simulation for off-site excitation of a single beam is shown at the right in Fig. 3; the waveguides are centered at $x=-9,-3,3,9$, etc.)

Naturally, one wonders what would happen if the two probe beams were made mutually coherent with a different phase relation. By controlling the dc voltage applied to the piezoelectric transducer mirror, we made the two beams exiting the interferometer either in phase or out of phase with each other. Keeping all other experimental conditions unchanged, we obtained quite different steady states between in-phase and out-of-phase excitation, as illustrated in Fig. 4. In the in-phase case, most of the energy flows into the central lattice site (Fig. 4a), whereas in the out-of-phase case the energy flows mainly into the two lateral sites in the vertical direction (Fig. 4b). Radiation to other nearby lattice sites owing to waveguide coupling is also visible. Intuitively, one may consider these new steady states to be a result of constructive and destructive interference, but they correspond to symmetric (in-phase) and antisymmetric

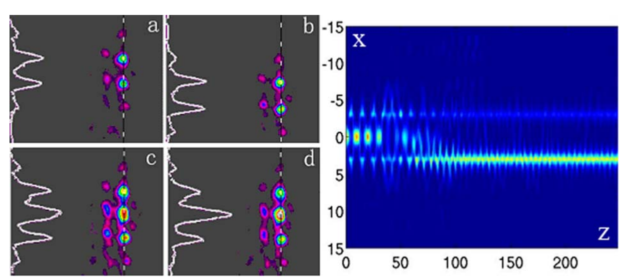

Fig. 3. (Color online) Left, off-site probing with two mutually incoherent beams. a, b, Output of a beam alone; c, d, output of two combined beams at 1 and 30 s, respectively. Right, numerical simulation of a single probe beam launched initially in the middle of two lattice sites located at $x=-3.0$ and $x=3.0$ for 250 spatial steps of evolution (corresponding to ~50 cm propagation distance).

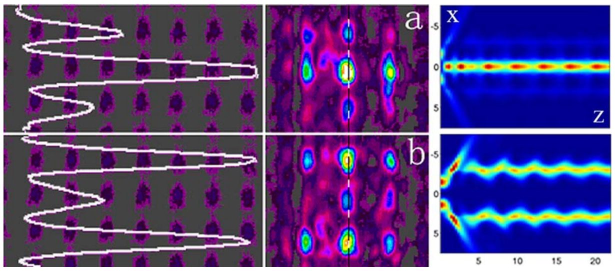

Fig. 4. (Color online) Off-site probing with two mutually coherent beams. Shown are the combined output beam profile (left) and the intensity pattern (middle) for, a, in-phase and, b, out-of-phase excitation. Right, simulation of dynamic evolution of two in-phase and out-of-phase beams launched at two off-site locations ($x=-1.5$ and $x=1.5$).

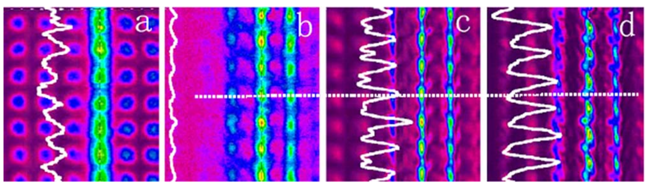

Fig. 5. (Color online) Probing with a stripe beam: a, combined input of lattice and stripe beams; b–d, output of the stripe beam at normalized intensities of b, 0.2 and 0.8 after c, 1 s and, d, 30 s.

(twisted) soliton states as defined for lattice solitons.[17,18] Here the solitons are excited in an effectively three-well potential as embedded in a weakly coupled waveguide lattice. In fact, we theoretically investigated this issue, using a continuum model based on saturable photorefractive nonlinearity with an effective three-well potential. We found that in this setting any state with multiple in-phase beams (all centered on site) is always unstable. However, both symmetric states (corresponding to a single beam on site) and antisymmetric states (corresponding to two out-of-phase beams on two different sites) can be linearly stable. Typical results from simulations are included in Fig. 4 (right), where the top figure shows the evolution of two Gaussian beams launched at $x=-1.5$ and $x=1.5$ (while the three waveguides are centered at $x=-3,0,3$). It can be seen that the two beams (although they are excited at off-site locations) evolve quickly into either a single beam (for the in-phase case) at the central site or two beams (for the out-of-phase case) at the two lateral sites.

As mentioned above, for a single beam excitation in waveguide lattices, the odd solitons (centered on a lattice site) are stable but the even ones (centered between two lattice sites) are not.[12,14,15] Symmetry breaking in double-well potentials is well known,[2,3] but in a fully periodic potential it may no longer be possible. Instead, an even-symmetry mode is indeed unstable, but it can be transformed into an odd-symmetry mode through an asymmetric beam profile.[14,15] Such a transition is what we observed in our experiment (Fig. 2). In addition, twisted- (or dipole-) mode solitons (centered between two lattice sites but with an out-of-phase relation) were indeed predicted and found to be stable.[12,17,18] Here we observed such antisymmetric solitons by off-site excitation of two probe beams simultaneously.

Finally, we launched a stripe beam (akin to a quasi-1D plane wave) to cover many lattice sites in the vertical directioin (shown in Fig. 5a and as P3 in Fig. 1). When the intensity of the probe beam was increased, we observed a shifting of its intensity peaks from on-site (Figs. 5b and 5c) to off-site (Fig. 5d) locations as the beam experienced higher nonlinear self-action and bending. This may be related to excitation of different Bloch states in the lattices.[10,19,20]

This work was supported by National Natural Science Foundation (60328406, 10334010) and Ministry of Education (704012, PCSIRT) of China and by the U.S. National Science Foundation, Air Force Office of Scientific Research, and Petroleum Research Fund. We thank. D. Frantzeskakis, D. Neshev, T. Kapitula, and J. Yang for discussions. Z. Chen is also with San Francisco State University, San Francisco, California. Z. Chen's email is zchen@stars.sfsu.edu.

References

1. D. N. Christodoulides and R. I. Joseph, Opt. Lett. **13**, 794 (1988).
2. E. M. Wright, G. I. Stegeman, and S. Wabnitz, Phys. Rev. A **40**, 4455 (1989).
3. M. Romangoli, S. Trillo, and S. Wabnitz, Opt. Quantum Electron. **24**, S1237 (1992).
4. N. N. Akhmediev and A. V. Buryak, J. Opt. Soc. Am. B **11**, 804 (1994).
5. A. B. Aceves, M. Santagiustina, and C. Angelis, J. Opt. Soc. Am. B **14**, 1807 (1997).
6. P. G. Kevrekidis, K. O. Rasmussen, and A. R. Bishop, Int. J. Mod. Phys. B **15**, 2833 (2001).
7. D. N. Christodoulides, F. Lederer, and Y. Silberberg, Nature **424**, 817 (2003).
8. D. Campbell, S. Flach, and Y. S. Kivshar, Phys. Today **57**, 43 (January 2004).
9. H. S. Eisenberg, Y. Silberberg, R. Morandotti, A. R. Boyd, and J. S. Aitchison, Phys. Rev. Lett. **81**, 3383 (1998).
10. D. Mandelik, H. S. Eisenberg, Y. Silberberg, R. Morandotti, and J. S. Aitchison, Phys. Rev. Lett. **90**, 053902 (2003).
11. J. W. Fleischer, M. Segev, N. K. Efremidis, and D. N. Christodoulides, Nature **422**, 147 (2003).
12. D. Neshev, E. Ostrovskaya, Y. Kivshar, and W. Krolikowski, Opt. Lett. **28**, 710 (2003).
13. H. Martin, E. D. Eugenieva, Z. Chen, and D. N. Christodoulides, Phys. Rev. Lett. **92**, 123902 (2004).
14. R. Morandotti, U. Peschel, J. S. Aitchison, H. S. Eisenberg, and Y. Silberberg, Phys. Rev. Lett. **83**, 2726 (1999).
15. U. Peschel, R. Morandotti, J. M. Arnold, J. S. Aitchison, H. S. Eisenberg, Y. Silberberg, T. Pertsch, and F. Lederer, J. Opt. Soc. Am. B **19**, 2637 (2002).
16. Z. Chen and K. McCarthy, Opt. Lett. **27**, 2019 (2002).
17. J. Yang, I. Makasyuk, A. Bezryadina, and Z. Chen, Opt. Lett. **29**, 1662 (2004).
18. S. Darmanyan, A. Kobyakov, and F. Lederer, JETP **86**, 682 (1998).
19. A. A. Sukhorukov, D. Neshev, W. Krolikowski, and Y. S. Kivshar, Phys. Rev. Lett. **92**, 093901 (2004).
20. F. Fedele, J. Yang, and Z. Chen, Stud. Appl. Math. **115**, 279 (2005).