Solitons in Optically Induced Nonlinear Photonic Lattices

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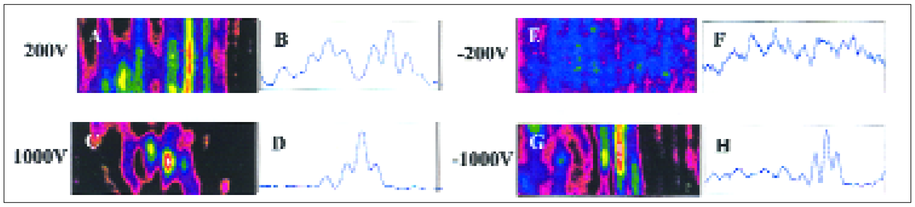

Figure 1. Propagation behavior through a 9.3-μm waveguide array for an input beam coupled into a single waveguide. (a–d), on-axis propagation. For low voltage (linear regime) (a, b), a discrete diffraction pattern occurs, whereas a discrete soliton is observed (c, d) at higher nonlinearity. (e–h), staggered behavior for an input beam launched at an angle of 0.57° with respect to the normal to the input plane. In this case, the Bloch momentum of the beam lies in the vicinity of the first Brillouin zone edge in a regime of anomalous diffraction. For low voltages (e, f), a diffuse pattern occurs, whereas a staggered (π out-of-phase) bright soliton is observed (g, h) at higher nonlinearity.

Wave propagation in nonlinear periodic lattices is associated with a host of exciting phenomena that have no counterpart in bulk media. In such systems, the dynamics are dominated by the interplay between linear coupling or tunneling effects among successive lattice points and on-site nonlinearity. In principle, these two competing processes can balance each other and form a self-localized state: a discrete soliton.[1] Examples occur in abundance in all branches of science, as well as in nonlinear optics,[1,2] in which discrete solitons of the nonlinear Schrödinger type were first observed. In general, the dynamic behavior of nonlinear periodic systems differs substantially from that of their continuous analogs. For example, in an optical case, a periodic array of waveguides is associated with a Brillouin zone that significantly alters its collective diffraction properties. This leads to fundamentally different behavior, such as anomalous (or negative) diffraction, and to in-phase[1] and out-of-phase[3] soliton solutions.

Thus far, all discrete soliton experiments were carried out in epitaxially grown one-dimensional (1D) AlGaAs waveguide arrays. These structures exhibit a self-focusing nonlinearity and, as a result, allow observation of only certain families of discrete solitons (in-phase bright and staggered dark). It would be interesting to explore discrete solitons in 2D topologies, which allow a much greater range of dynamics, with the potential for new applications. However, establishing 2D waveguide arrays in bulk through conventional fabrication techniques poses major technological challenges.

In a recent theoretical paper, Efremidis *et al.*[4] predicted that nonlinear photonic lattices can be optically induced in highly anisotropic, biased, photorefractive crystals, allowing for the observation of both 1D and 2D optical discrete solitons. Such waveguide arrays can be induced in real time by interfering pairs of plane waves; the solitons form when photorefractive screening nonlinearity is employed. To keep the waveguides as uniform as possible, the interfering plane waves should be polarized in a non-electro-optic direction, allowing them to propagate almost linearly. The probe beam, on the other hand, should be polarized in a direction that gives rise to a large electro-optic effect, so that it experiences both a periodic potential and a significant (screening) nonlinearity. This method allows for dynamic, reconfigurable arrays of any Bravais class.

We followed up with experimental observation of discrete diffraction and discrete solitons in such an array of optically induced waveguides.[5] Because our system is optically induced, it offers complete control over all its linear and nonlinear parameters. For example, the array pattern and periodicity are determined by the interference structure of the induction beams, whereas we can tune the nature of the nonlinearity and its magnitude by adjusting the external bias field. We demonstrated two types of bright discrete soliton: the in-phase and the staggered (out-of-phase) states. To the best of our knowledge, our results represent the first observation of discrete staggered solitons in any system in nature.

Figure 1 depicts the formation of on-axis and staggered discrete solitons in a 1D periodic (9.3- μm) system. The extraordinarily polarized input probe (soliton-forming) beam is coupled into a single waveguide and has an intensity that is five times smaller than the average intensity of the interference pattern (inducing the waveguide array). Figures 1 (a–d) show the behavior of on-axis input: low voltage (linear regime) results in a discrete diffraction pattern (a,b), whereas a lattice soliton forms at higher nonlinearity (c,d). Figures 1 (e–h) show results when the input beam is launched at an angle of 0.57° with respect to the normal. Here, the Bloch momentum of the probe lies in the vicinity of the first Brillouin zone edge (~0.62°) in a region of anomalous diffraction. At low voltages [Figs. 1 (e) and (f)], a diffuse diffraction pattern occurs, while a staggered (out-of-phase) bright soliton is observed [Figs. 1 (g) and (h)] at higher nonlinearity. The distinctive gap between waveguide excitations suggests that the lobes are out of phase with the central peak, a relationship confirmed by interference experiments.

Our results demonstrate the exciting prospect of reversing both diffraction and nonlinearity, whereas the technique of optical lattice induction allows for reconfigurable arrays of almost any geometry (including defect states and 3D structures). Moreover, this experiment paves the way for controlling beam transport across photonic lattices by use of solitons as both signal carriers and routers. Finally, note that we recently experimentally demonstrated both square and hexagonal lattices of 2D waveguides, and our current experimental effort is focused on generating 2D discrete solitons in these structures.

Acknowledgments

This research was supported by the U.S. ARO MURI program on solitons and the Israeli Science Foundation.

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