Observation of Discrete Solitons in Optically Induced Real Time Waveguide Arrays

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We report the first experimental observation of discrete solitons in an array of optically induced waveguides. The waveguide lattice is induced in real time by illuminating a photorefractive crystal with a pair of interfering plane waves. We demonstrate two types of bright discrete solitons: in-phase self-localized states and the staggered (π out-of-phase) soliton family. This experiment is the first observation of bright staggered solitons in any physical system. Our scheme paves the way for reconfigurable focusing and defocusing photonic lattices where low-power (mW) discrete solitons can be thoroughly investigated.

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Periodic nonlinear systems are ubiquitous in nature and are known to exhibit behavior that differs fundamentally from that of their homogeneous counterparts. In these periodic nonlinear lattices, the underlying dynamics are dominated by the interplay between linear coupling effects among adjacent potential wells and nonlinearity. Indeed, a balance between these two processes can result in a self-localized state, which can be either a time-periodic breather or a steady-state lattice soliton. Very often, such systems can be represented as a discrete array of coupled nonlinear sites, in which case the associated self-localized states are better known as discrete solitons (DS) [1–4]. Examples occur in abundance, in all branches of science, such as biology [1], nonlinear optics [2], solid-state physics [3], and Bose-Einstein condensates [4]. In the past few years, much progress has been made in attempting to observe discrete solitons in various physical systems. In biological α-helices, time-dependent breather states have been inferred from pump-probe experiments [5]. In (linear) arrays of current-driven Josephson junctions, localized time-periodic rotobreathers (quantum vortex pairs exhibiting counterrotating phases) have been observed [6]. In antiferromagnets, spectral data from resonance experiments have indicated DS states for spin waves [7]. In transition metals, evidence of localization for vibrational states has been reported [8]. However, in all of these systems, direct observations of steady-state discrete solitons (not breathers) remain elusive. In fact, direct observations of DS have been reported only in a 1D array of nonlinear waveguides [9,10], but even that only for self-focusing nonlinearities that restrict the allowed class of soliton solutions. In all of the above, the experiments require specialized materials with fixed geometries that limit their potential application. Here, we demonstrate a new method of creating lattices in photosensitive materials using optical induction and form discrete solitons in the resulting waveguide systems.

Optical waveguide arrays provide a fertile ground for investigating self-localized states in nonlinear periodic systems. In waveguide lattices, wave propagation is associated with a Brillouin zone that significantly alters the collective diffraction behavior. For example, when light propagation is linear, an on-axis beam focused into one waveguide will spread to its neighbors (via discrete diffraction, or tunneling), with the intensity mainly concentrated in the outer lobes [2,9–13]. When the probe beam is injected at an angle $\theta = k_x/k \approx k_x/k_z$ with respect to the array, the corresponding "Bloch momentum" k_x may satisfy Bragg reflection conditions with the lattice wave vectors. For increasing input angles within the Brillouin zone (defined in the range $|k_x D| \leq \pi$, where D is the lattice spacing) excitations in adjacent waveguides will become more out of phase with each other, up to a maximum π phase difference at the zone edge. This region corresponds to a regime of anomalous ("negative") diffraction, allowing for such interesting effects as diffraction management [12]. For nonlinear waveguide arrays with a sufficiently large nonlinearity, a balance between discrete diffraction and nonlinear self-focusing can occur. The resulting discrete self-localized modes or discrete solitons can be located either at the base of the Brillouin zone, forming in-phase solitons [2], or at the edge of the Brillouin zone, leading to staggered solitons [13]. We emphasize that such nonlinear periodic systems exhibit soliton solutions that have no counterparts in homogenous media. These include, for example, dark and bright staggered (π out-of-phase) soliton families [13] that reside at the edge of the Brillouin zone, in self-focusing and defocusing materials, respectively. All experiments carried out so far were in fabricated 1D waveguide arrays with self-focusing nonlinearity, which

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can allow only the observation of certain families of DS (in-phase bright [9] and staggered dark [10]). Furthermore, creating a 2D waveguide array in the bulk through conventional fabrication techniques poses major technological challenges.

In a recent work [14], we predicted that 1D and 2D optical discrete solitons are possible in biased photorefractive crystals. In that proposition, the photorefractive nonlinearity is utilized to optically induce in real-time waveguide arrays (in either 1D or 2D in the bulk) by interfering pairs of plane waves, and the solitons form when the screening nonlinearity [15] is employed. An advantage of using a dynamic medium such as a biased photorefractive crystal over, say, an array of microfabricated optical fibers is threefold. First, the configuration is *dynamically* adjustable, allowing real-time control of lattice spacing and potential well depth. Second, the material has a strong nonlinear response, allowing soliton formation at very low intensities (mW). And last but not least, the strength and sign of the nonlinearity can be tuned by simply adjusting the magnitude and polarity of the applied field.

In establishing the optically induced waveguide arrays in biased photorefractives, it is essential that the beams *writing* the waveguide lattice remain invariant during propagation. Such diffraction-free periodic patterns can be synthesized easily by appropriately interfering plane-wave pairs under linear conditions [14]. The "signal" soliton-forming beam, on the other hand, must experience the highest possible nonlinearity. To achieve these two, seemingly conflicting, objectives, we chose a photorefractive crystal with a strong electro-optic anisotropy with the interfering waves polarized in a non-electro-optic direction, whereas at the same time the signal beam was polarized in the crystalline orientation that yields the highest possible nonlinearity. In a 1D arrangement, the z evolution of both the lattice waves (V) (periodic along x) and the (soliton-forming) probe (U) can be described by [14]

$$i\frac{\partial U}{\partial z}+\frac{1}{2k_1}\frac{\partial^2 U}{\partial x^2}-\Delta n_e(I)U=0, \tag{1}$$

$$i\frac{\partial V}{\partial z}+\frac{1}{2k_2}\frac{\partial^2 V}{\partial x^2}-\Delta n_o(I)V=0, \tag{2}$$

where $k_1 = k_0 n_e$, $k_2 = k_0 n_o$, the subscripts e and o refer to the extraordinary and ordinary polarizations, Δn is the nonlinear index change, and $I = |U|^2 + |V|^2$ is the total intensity of the two orthogonally polarized fields. It is the *strong anisotropy* of the system that allows the coupled fields to have such markedly different behavior. The periodic structure of the system is implicitly contained in the potential induced by $|V(x)|^2$. In this configuration, the writing wave V evolves almost linearly as $\Delta n_e \gg \Delta n_o$. As a result the system of Eqs. (1) and (2) effectively reduces to a single *nonlinear* partial differential equation for U propagating in the periodic potential induced by V. For example, the 1D field $V = V_0 \cos(\pi x/D)$ (as obtained from the coherent superposition of two plane waves at an angle) propagates invariantly along z while providing a periodic potential (with spatial period D) for the probe field U. In this scenario, the probe (soliton) beam experiences the familiar competition between nonlinearity and nearest-neighbor coupling. Indeed, under suitable conditions, this reduced system of equations can be further simplified [14] into a discrete nonlinear Schrödinger equation, which constitutes the basic model for such phenomena. We emphasize, though, that the nonlinear discretelike behavior of the probe field U arises from a continuous periodic potential. This represents a much more accurate description of many such nonlinear phenomena in periodic lattices (e.g., those occurring in standing-wave traps for atoms in Bose-Einstein condensates) and by itself can have a significant impact on the underlying dynamics of the system. For example, high momentum excitations within the Brillouin zone can lead to radiation modes in higher bands and subsequently to transport anomalies that are not accounted for by a discrete model (or the tight-binding approximation) [14].

In our case where a photorefractive crystal is employed, the nonlinear index changes are given by $\Delta n_e = k_0 n_e^3 r_{33} E_{sc}/2$ and $\Delta n_o = k_0 n_o^3 r_{13} E_{sc}/2$ where r_{ij} is the appropriate coefficient of the electro-optic tensor and the space charge field E_{sc} is given by [15]

$$E_{sc}=\frac{E_0}{1+\bar{I}(x)}-\frac{K_B T}{e}\frac{\partial \bar{I}/\partial x}{1+\bar{I}(x)}. \tag{3}$$

Here $\bar{I} = I/I_{dark}$, where $I = |U|^2 + |V|^2$ and I_{dark} is the dark irradiance of the crystal, E_0 is the applied bias field, K_B is Boltzmann's constant, T is the temperature, and e the electron charge. The first term in Eq. (3) depends on the applied field E_0 and represents the dominant screening nonlinearity [15]. On the other hand, the second term accounts for the much weaker diffusion field; its contribution is important only at very low applied fields and in nodal regions of the lattice.

In our experiments (Fig. 1), we use a 6 mm long SBN:75 crystal with $r_{33} \approx 1340$ pm/V and $r_{13} \approx 67$ pm/V. The 1D array is created by interfering ordinarily polarized plane waves of wavelength $\lambda = 488$ nm through a Mach-Zehnder configuration. The signal beam is extraordinarily polarized and is coupled into a single waveguide of the periodic array. Voltage applied against the c axis sets the photorefractive screening nonlinearity, which increases (with an intensity dependence) the index contrast, creates the waveguide array, and also leads to localization of the signal beam.

Figures 2–5 show results from our experiments. Figure 2 depicts the transition of the signal beam from discrete diffraction to a discrete soliton for on-axis input as a function of self-focusing nonlinearity (or applied field). The array has a waveguide spacing of 8.8 μm, and the ratio between the peak intensity of the interference

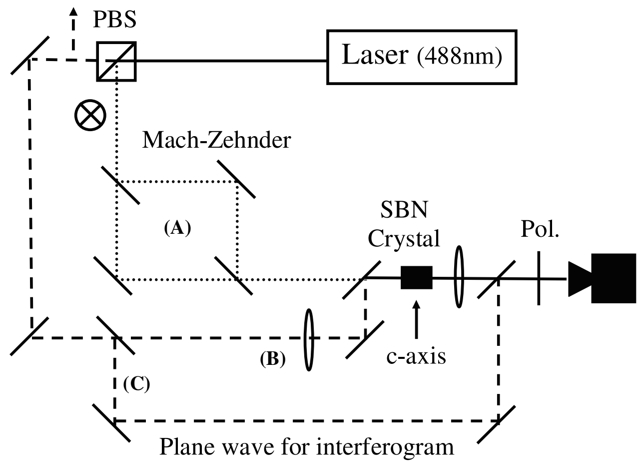

FIG. 1. Experimental setup. Light from a 488 nm laser gets split by a polarizing beam splitter. The ordinarily polarized wave passes through a Mach-Zehnder configuration (A) to create an interference grating on an SBN:75 crystal. The extraordinarily polarized beam is focused into a single waveguide of the array (B). Before focusing, part of the signal is passed through another Mach-Zehnder arm (C) to interfere with the signal output, allowing phase retrieval through interference.

pattern inducing the array and the peak intensity of the signal beam is 5:1. When the nonlinearity is small, the signal beam experiences discrete diffraction. When the signal beam initially excites a single waveguide, two intensity lobes (separated by three waveguides) appear at the output [Figs. 2(a) and 2(b)]. On the other hand, in the strongly nonlinear regime, a highly localized discrete soliton state is formed [Figs. 2(e) and 2(f)] at an applied voltage of 1000 V. Note that in this case, the intensity peaks of these in-phase states reside on the intensity maxima of the writing beam.

Figure 3 depicts the contrast between linear propagation via tunneling and the nonlinear effect of self-focusing. Here the probe is input into a single waveguide of a $D = 7.8\ \mu$m array, and the ratio between the peak intensity of the interference and the peak intensity of the signal beam is 10:1. At high voltages (800 V), an on-axis (in-phase) discrete soliton forms [Figs. 3(a) and 3(b)]. When the signal intensity is lowered by a factor of 8, *at the same voltage*, the self-focusing is weakened and a discrete diffraction pattern results [Figs. 3(c) and 3(d)]. In other words, Fig. 3 proves that the self-trapping process responds to the signal intensity in a nonlinear fashion, and thus what is observed is, in fact, a discrete soliton.

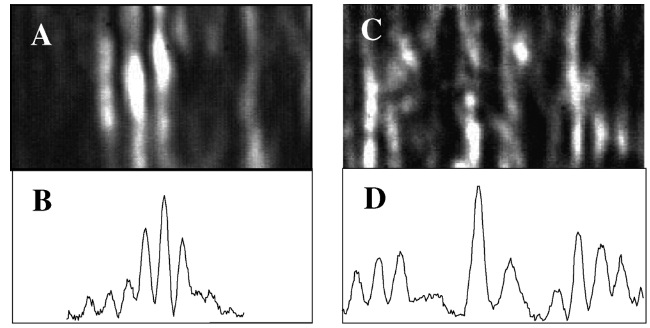

FIG. 3. Effect of nonlinearity on soliton formation in an array of 7.8 μm channel spacing. When the intensity of the grating beams to the probe beam is 10:1, a discrete soliton is formed (A),(B). When the probe intensity is reduced to an intensity ratio of 80:1, self-focusing is too weak to overcome tunneling, and discrete diffraction results (C),(D).

Figure 4 shows discrete soliton formation when the signal beam is incident at an angle of 0.57° with respect to the crystal, with its Bloch momentum being very close to the edge of the Brillouin zone ($\sim 0.62°$). Here the waveguide spacing is $D = 9.3\ \mu$m, and the ratio between the peak intensity of the interference and the peak intensity of the signal beam is 10:1. In this regime of anomalous diffraction, we reverse the applied bias to create a self-defocusing nonlinearity. As predicted in

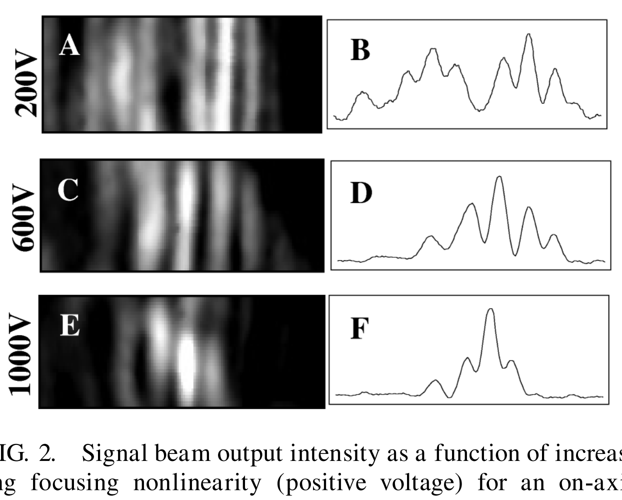

FIG. 2. Signal beam output intensity as a function of increasing focusing nonlinearity (positive voltage) for an on-axis beam coupled into a single waveguide in an array with 8.8 μm channel spacing. (A),(B) show discrete diffraction, (C),(D) show intermediate self-focusing, and (E),(F) depict an on-axis (in-phase) discrete soliton.

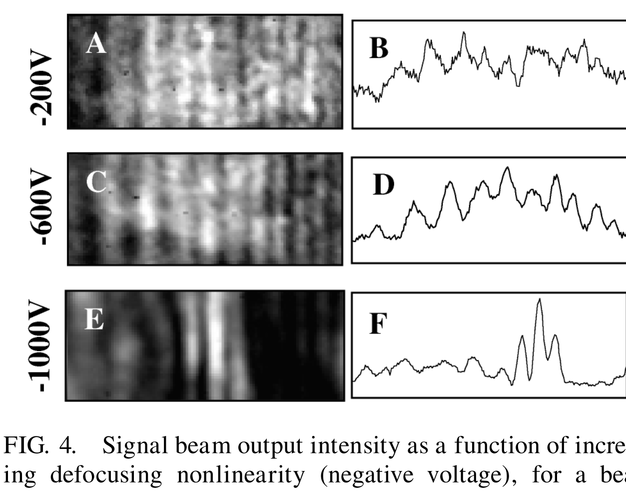

FIG. 4. Signal beam output intensity as a function of increasing defocusing nonlinearity (negative voltage), for a beam launched at 0.57° (close to the edge of the Brillouin zone) in an array of 9.3 μm channel spacing. (A),(B) show discrete diffraction, (C),(D) show intermediate collapse, and (E),(F) depict a staggered discrete soliton.

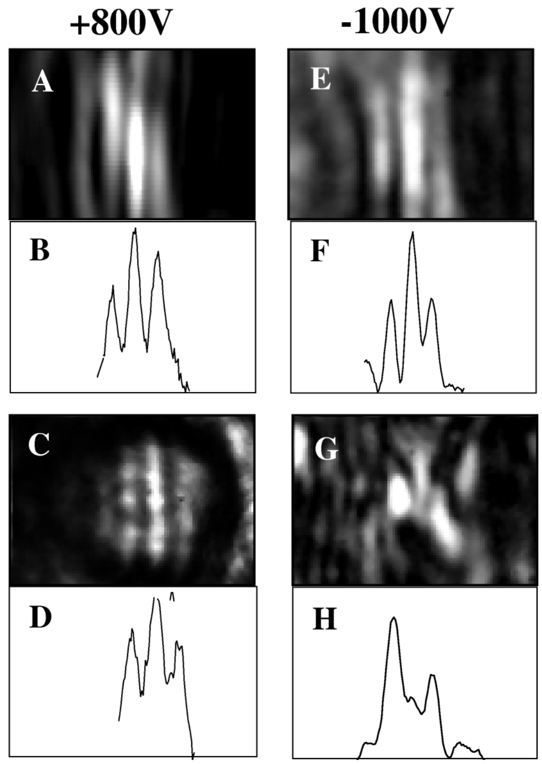

FIG. 5. On-axis and staggered solitons through a 7.8 μm waveguide array. Crystal output and intensity profile for on-axis soliton at $+800$ V (A),(B) and staggered soliton at -1000 V (E),(F). Interferograms for the respective cases, showing in-phase behavior for the on-axis input (C),(D) and out-of-phase behavior at the edge of the first Brillouin zone (G),(H).

[13], a staggered (π out-of-phase) bright soliton is observed [Figs. 4(e) and 4(f)]. *This is the first observation of bright staggered solitons in any physical system.* Unlike the case of in-phase discrete solitons, the intensity peaks of staggered states are located on the intensity minima of the writing beam V.

Figure 5 shows relative phase information for on-axis and staggered bright solitons for a grating spacing of 7.8 μm. Figures 5(a) and 5(b) show a discrete soliton created on-axis (in-phase), as in Fig. 3, while Figs. 5(c) and 5(d) depict the corresponding interferogram (created via interference with a copropagating plane wave) showing that all the lobes are in phase with each other. On the other hand, Figs. 5(e) and 5(f) show a staggered discrete soliton produced at the edge of the Brillouin zone, while its corresponding interferogram [Figs. 5(g) and 5(h)] shows that the central lobe is out of phase with its neighbors (destructive interference in the center and constructive interference at the outer lobes). The two interferograms confirm again that the two self-localized states observed in our experiments are indeed of the in-phase and staggered type.

In conclusion, we have reported the first experimental observation of discrete solitons in a 1D array of optically induced waveguides. We have demonstrated two types of bright discrete solitons: in-phase self-localized states and the staggered (π out-of-phase) soliton family—with the latter never having been observed before. Our work paves the way for the first experimental observation of 2D discrete solitons and opens up the possibility of inducing, in real-time, photonic lattices of various kinds where the diffraction properties can be controlled and the nonlinearity can be tuned in real time. These ideas can be readily extended to other nonlinear wave systems and specifically to the formation of discrete solitons in 2D optically induced periodic potentials in Bose-Einstein condensates. More specifically, the exciting feature of reversing both diffraction and nonlinearity, which is offered by the photorefractive nonlinearity (by reversing the applied field), can also be accomplished in Bose-Einstein condensates, where the nonlinearity can be controlled and reversed with a magnetic field [16] and the periodic potential can be induced by light [17].

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