Dynamics of Discrete Solitons in Optical Waveguide Arrays

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By using a nonlinear waveguide array we experimentally demonstrate dynamic features of solitons in discrete systems. Spatial solitons do not exhibit these properties in continuous systems. We experimentally recorded nonlinearly induced locking of an initially moving soliton at a single waveguide. We also show that discrete solitons can acquire transverse momentum and propagate at an angle with respect to the waveguide direction, when the initial excitation is not centered on a waveguide. This is to our knowledge the first time that the effect of the Peierls-Nabarro potential has been observed in a macroscopic system.

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Within the past few decades, there has been a constant interest in nonlinear discrete systems. This is due to the fact that matter itself is discrete, i.e., it consists of many single elementary units. If the spatial scale of an excitation approaches the size of its individual constituents, a continuous approach fails to give an accurate picture and the discreteness of the system must be taken into account. For example, energy transport phenomena through polarons, excitons, and defects in polymers [1] relies on the fact that the excitation is hopping from molecule to molecule and depends critically on the internal structure. The analytical descriptions of several macroscopic systems also result in an effective discretization.

Many discrete systems of a quite different origin can be depicted by the same set of evolution equations. The energy transport on molecular chains [1], the motion of localized waves on discrete electrical lattices [2], and optical field propagation in waveguide arrays [3] are all described by the discrete nonlinear Schrödinger equation (DNLSE), even though the size of these systems differs by many orders of magnitude. Those similarities allow the identification of basic principles and effects of discreteness, which are much more general than the model from which they are derived.

One important feature of the DNLSE is its localized solitonlike solution. We recently reported the first experimental realization of discrete solitons in nonlinear waveguide arrays [3]. In the low power limit, the optical field spreads over the whole array due to the evanescent coupling between nearest neighbor waveguides. When the power is increased, a narrowing of the output field distribution is observed until a discrete soliton is formed. Here we report experimental investigations of the dynamics of these discrete solitons. In particular, we are interested in the differences between discrete solitons and spatial solitons propagating in slab waveguides [4]. When a discrete soliton spans many individual waveguides, it can be formally shown to be equivalent to its continuous counterpart [5]. However, many differences are expected when the soliton is confined in just a few waveguides. The differences with the continuous case become obvious if such a soliton is forced to move across the array. There is no Galilean invariance in the waveguide array and the discrete soliton tends to propagate along the waveguides [6] giving rise to a characteristic dynamical behavior.

In addition to this fundamental interest, the practical importance of waveguide arrays should be mentioned as well. They are regarded as promising candidates for all-optical signal switching, routing, and steering applications. The individual waveguides are compatible with fibers and other waveguide devices, simplifying input and output into such elements. In what follows we demonstrate that nonlinear effects can be effectively employed in order to guide signals into desired output channels [6].

In the idealized case (no losses, continuous wave excitation) the evolution of the field amplitude a_n of the nth element of an infinite waveguide array is described by a DNLSE as

$$i\frac{da_n}{dz} + C(a_{n-1} + a_{n+1}) + \gamma|a_n|^2 a_n = 0\,, \qquad (1)$$

where C is the coupling coefficient and γ is the nonlinear parameter [5]. The total power P and the Hamiltonian H, defined as

$$P = \sum_n |a_n|^2, \qquad H = \sum_n \left[C|a_n - a_{n-1}|^2 - \frac{\gamma}{2}|a_n|^4 \right], \qquad (2)$$

are conserved during propagation [6]. It should be noted that in quantum mechanical systems those quantities have a different meaning. P accounts for the norm of the wave function and H denotes the energy containing the kinetic part $C|a_n - a_{n-1}|^2$.

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We first discuss stationary solutions localized on a few waveguides. For each power level we find one solution centered on a single waveguide and one centered in between two waveguides (see Fig. 1). Only the first one is stable and represents a minimum of the Hamiltonian. If a soliton is forced to move sideways, it has to jump from waveguide to waveguide, passing from a stable to an unstable configuration. The difference between the Hamiltonians in the respective cases—the so-called Peierls-Nabarro potential (PNP)—accounts for the resistance that the soliton has to overcome during transverse propagation [7]. For increasing power levels, the PNP increases (see Fig. 1) resulting in a strong localization of the soliton, mainly in a single waveguide which is effectively decoupled from the rest of the array. As proposed recently, this might be the basis of a power dependent steering [6]. We note that in the respective continuous system—spatial solitons in a slab waveguide—every phase gradient imposed onto the initial beam results in a corresponding tilt of the soliton motion [8].

In order to investigate the dynamical behavior of discrete solitons, we used the same experimental setup as in Ref. [3]. The sample under investigation was a 6 mm long array consisting of 41 rib waveguides of 4 μm width and with a uniform spacing of 5 μm between each of them. The array was etched 0.95 μm on top of an AlGaAs slab waveguide composed by a guiding layer of $Al_{0.18}Ga_{0.82}As$, 1.5 μm thick, sandwiched between two layers of $Al_{0.24}Ga_{0.76}As$. These upper and lower claddings were 1.5 and 4.0 μm thick, respectively. The sample was mounted on top of a piezoelectrically driven translator to control the spatial position of the excitation. We launched 180 fs long pulses with a maximum peak power of 1.5 kW into the central waveguide at a wavelength of 1.53 μm, which is below half the band gap of the AlGaAs, resulting in the suppression of two-photon absorption. In order to avoid damage of the input facet and to increase the coupling efficiency we used an elliptically shaped input beam with a height of 3 μm and a width of 9 μm. The image of the optical field at the output facet was recorded with an infrared camera. Note that since the width of the incident beam is about the same as the array period, the excitation is effective even when it is not centered on a waveguide. In particular, when the beam is scanned across the input facet, the change in the coupling efficiency is less than 5%.

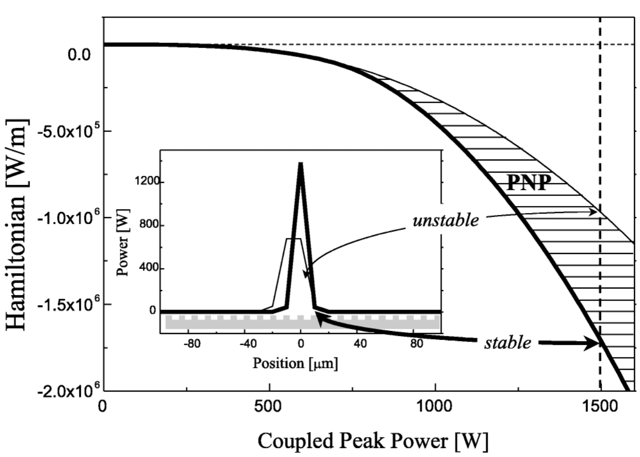

FIG. 1. Peierls-Nabarro potential Hamiltonian versus guided power for solitons centered on a waveguide and in between two waveguides. Inset: field shapes of the two types of solitons for a peak power of 1500 W (vertical dashed line).

To interpret the experimental results, we modeled the pulse dynamics with the following set of equations [6]:

$$i\,\frac{da_n}{dz} - \frac{D}{2}\,\frac{\partial^2 a_n}{\partial t^2} + i\,\frac{\alpha_1}{n}\,a_n + \beta a_n + C(a_{n-1} + a_{n+1}) + \gamma|a_n|^2 a_n + i\alpha_3|a_n|^4 a_n = 0\,. \quad (3)$$

This equation adds to the idealized DNLSE [Eq. (1)], the temporal effect of pulsed excitation, the reduction of power due to linear absorption, and nonlinear three-photon absorption. In our model, the Kerr nonlinearity amounted to $\gamma = 3.6\ \mathrm{m}^{-1}\,\mathrm{W}^{-1}$ for the TE polarization, the coupling constant was $C = 0.82\ \mathrm{mm}^{-1}$, the linear absorption coefficient was $\alpha_1 = 0.9\ \mathrm{cm}^{-1}$, and the three photon absorption coefficient was $\alpha_3 = 10^{-4}\ \mathrm{m}^{-1}\,\mathrm{W}^{-1}$. Although the dispersive effects are weak (for 180 fs pulses and $D = 1350\ \frac{\mathrm{ps}^2}{\mathrm{km}}$, a linear pulse only broadens by a factor of 1.2), we have to take into account that the coupled power varies along the temporal profile continuously between zero and an upper value of about 1.5 kW. Therefore we expect to see a certain average of different soliton shapes, but still a clear demonstration of the effects envisaged.

In fact we found the results obtained for an averaged model on the basis of Eq. (1) not to differ too much from those following from a more involved simulation based on Eq. (3). Although the influence of dispersion is amplified by the nonlinearity and the high power pulse is broadened by a factor of about 2 [see inset in Fig. 2(a)] the pulse profile around the center remains flat. In our experimental situation the transient behavior results mainly in an effective damping. Effects as predicted from simplified theories based on Eq. (1) still occur, but with slight variations and for different power levels. However, we would like to note that in other cases, such as in longer arrays or for anomalous dispersion, the temporal behavior can affect the steering properties of the array [9].

The lateral motion of the solitons was induced by a very small tilt of the input beam of $0.4 \pm 0.1°$, corresponding to a phase difference of $\sim 0.08^*\pi$ between adjacent waveguides. The output intensity distribution as a function of input power is shown in Fig. 2(b). At low power we observed the field maximum at the output to shift by about eight waveguides away from the input waveguide. This

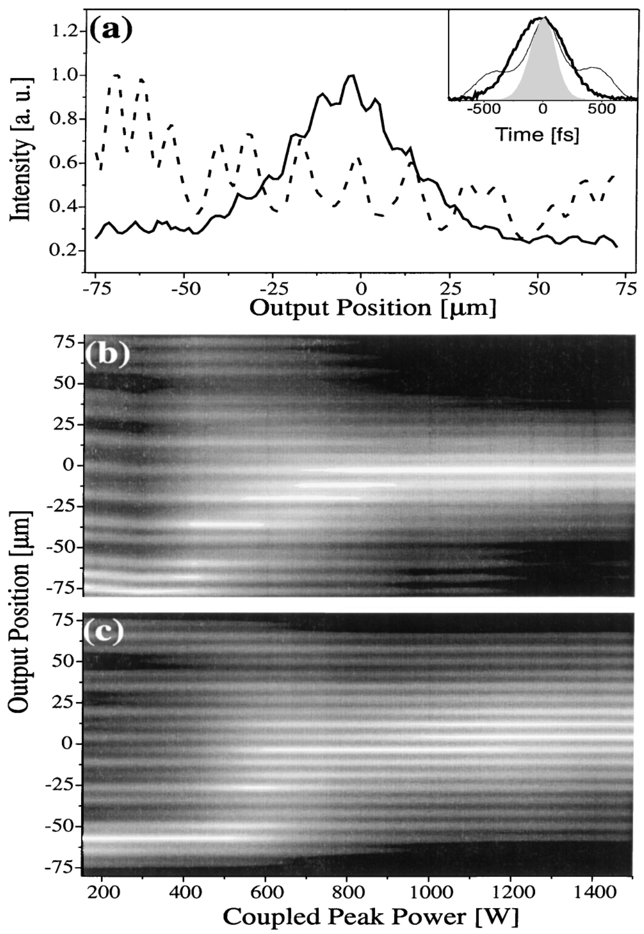

FIG. 2. Power dependent soliton steering by an externally induced velocity. Output field distribution for an initial tilt of the beam of $0.4 \pm 0.1°$. (a) Experimentally recorded power distributions for high (solid line) and low (dashed line) power. Inset: autocorrelations measured at high (1500 W) power; gray area: input pulse; bold line: output pulse in the center of the beam; thin line: output pulse in the wings of the beam. (b) Experimentally recorded field distribution at the output for varying power levels. (c) Simulation of (b) according to Eq. (3).

corresponds to an overall distance of 72 μm. In a slab waveguide the same tilt would yield a shift in the output field distribution of only 14 μm. This enhanced sensitivity of the array to phase tilts is mainly due to the different nature of discrete diffraction. When a single waveguide is excited, much more power is transferred to the wings of the field distribution compared with the continuous case. As the power is increased, a soliton is formed. The soliton transverse velocity becomes lower and lower. The peak of the output field moves closer to the input waveguide, until it finally locks to it at about 1 kW of input peak power. The simulation using Eq. (3), shown in Fig. 2(c), reproduces most of the details observed in the experiments. This example is a clear demonstration that the Galilean invariance of the continuous system ceases to hold when discreteness starts to play a role.

In additional experiments we also investigated less confined solitons, which were created by much wider beams of smaller power (beam width $\sim$20 μm, peak power $\sim$500 W). As predicted in [6] their ability to move across the array was considerably increased and almost no difference to the continuous case was observed.

While in the situation described above an initial sideways motion is damped and finally suppressed completely with increasing soliton power, we demonstrate that discreteness can also induce an acceleration of the soliton. For that purpose we make use of the fact that the overall coupling efficiency is practically independent from the spatial position of the excitation. In a different experiment, we fixed the power at its maximum value, scanned 14 μm across the input facet, and recorded the resulting field pattern at the output facet, as shown in Fig. 3(a). The scanning spanned the distance between almost three waveguide centers, so that in the middle of the image (corresponding to the vertical solid line) the field is precisely centered on a waveguide. The good agreement between experimental and numerical results based on Eq. (3) [see Figs. 3(b) and 3(c), respectively] suggests that the observed effects can be still understood using coupled mode theory. For all input conditions [see, e.g., the two field distributions displayed in Fig. 3(a)] the output distributions are much more localized than in those obtained in the linear case, and the amount of radiation emitted is very low. Simulations suggest that for high induced velocities the energy loss for the soliton is about 10%. Therefore, we conclude that the entire beam always behaves like a soliton. We note that the displacement of the field at the output facet is up to 10 times larger than the initial shift of the input beam. The soliton has gained a considerable transverse momentum, although no initial phase tilt was introduced. It should be pointed out that the input beam, which is wide enough to excite more than one waveguide, is uniform in phase. Deviations from normal incidence are not bigger than $\pm 0.1°$. The transverse soliton motion is not explained by the structure of the input beam.

In order to understand these results, we first note that for symmetry reasons the light will propagate along the waveguide direction when a symmetric excitation field is either centered exactly on a waveguide (solid line in Fig. 3) or in the middle between two waveguides [dashed line in Figs. 3(b) and 3(c)]. In the later case, an unstable soliton is excited [7]. In all other cases, the asymmetry between the power levels in the input waveguides induces a phase difference through the action of the Kerr nonlinearity. This phase tilt steers the field towards the waveguide with high power, thereby amplifying the initial deviation from the balanced state. This is precisely the source of the instability of the soliton with the higher PNP, which is steered away by any small power imbalance. Indeed, we observe in Fig. 3 that when the excitation is in between waveguides (dashed lines at ± 4.5 μm), the output position changes very rapidly.

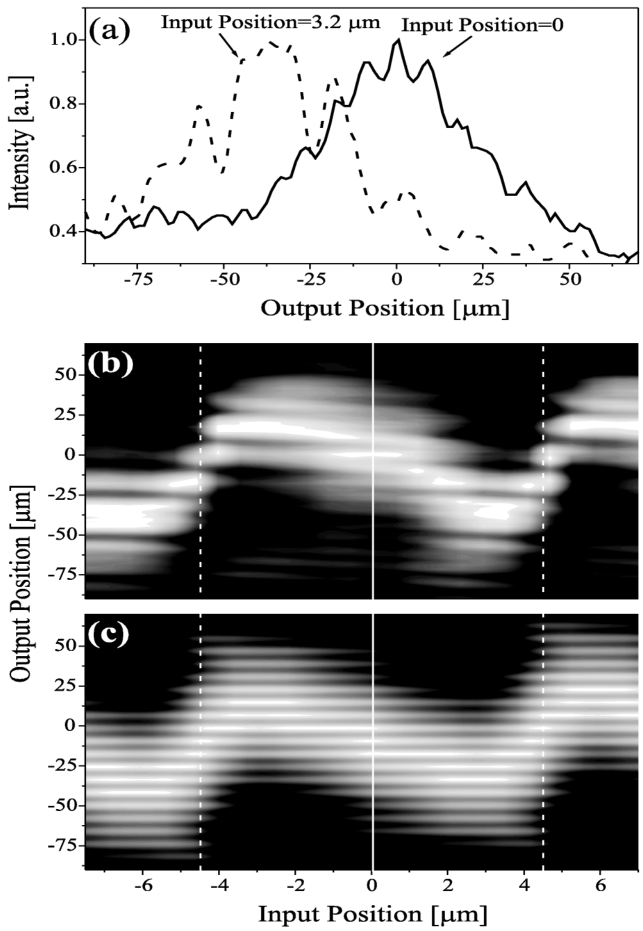

FIG. 3. Soliton steering by internally induced velocity. Output field distribution for fixed input peak power of ~1500 W as a function of the input beam position. (a) Experimentally recorded power distributions for two input positions relative to the central guide, (b) output field distributions for various positions of the initial excitation (solid line: beam centered on a waveguide; dashed lines: input beam centered in between two waveguides), (c) simulation of (b).

Even small changes of the input beam position caused the output field to sweep from -25 to $+25$ μm. This behavior is due to the fact that the soliton has to preserve both its total power and its Hamiltonian. The excess Hamiltonian of the unstable initial state is transferred into kinetic energy causing the soliton to move across the array. A similar mechanism does not exist in continuous systems because momentum conservation does not allow a resting solution to speed up without emitting radiation. From the point of view of applications, the latter feature can be interpreted as a highly efficient power dependent steering. Again it has to be emphasized that the last result is strongly related to the discrete nature of the excitation. We repeated this experiment using a wider input beam (20 μm at FWHM) of about 500 W peak power, which created a much less confined soliton, the PNP of which was almost zero (see Fig. 1). In this case, the output distribution was practically invariant under translation of the input.

In conclusion, we have shown that the dynamical nonlinear properties of discrete systems differ considerably from those of continuous systems. We experimentally demonstrated that initially moving solitons are captured at the initial waveguide if a certain power level is reached. On the other hand, the decay of unstable solitons, centered between two waveguides, may result in a considerable lateral motion across the array. We found that a small displacement of the input beam can be amplified at the output facet by up to a factor of 10. All these dynamical properties are power dependent and may therefore be employed for all-optical switching and routing applications.

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