Interactions of discrete solitons with structural defects

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We investigated the interaction of discrete solitons with defect states fabricated in arrays of coupled waveguides. We achieved attractive and repulsive defects by decreasing and increasing, respectively, the spacing of one pair of waveguides in an otherwise uniform array. Linear and nonlinear propagation in the same samples show distinctly different properties. The role of the Peierls–Nabarro potential in the interaction of the soliton with the defect is discussed. © 2003 Optical Society of America

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The study of nonlinear dynamics in discrete systems has recently attracted a great deal of attention. In particular, it was observed that stable energy localization, or discrete solitons, can propagate without broadening, in spite of the tendency of the linear system to spread excitations spatially as they propagate.[1] Discrete optical solitons are examples of such localized states. Christodoulides and Joseph suggested that discrete solitons can be achieved in weakly coupled nonlinear waveguide arrays.[2] Since then, the properties of such waveguides arrays have been studied theoretically and experimentally.

Discrete optical solitons are, in many aspects, similar to continuous solitons. Yet, unlike continuous solitons, they do not have the translation and rotation invariance that is characteristic of continuous systems, a fact that leads to a number of novel dynamic properties. For example, arrays of waveguides support both stable and unstable soliton solutions. The most stable states are solitons that are centered on a waveguide and propagate along the waveguide direction, whereas solitons that are symmetrically centered between waveguides (and hence the two waveguides nearest their center carry the same power) are unstable and tend to shift away from the waveguide direction. The difference in energy between the two kinds of soliton, named the Peierls–Nabarro potential (PNP),[3] accounts for the tendency of discrete solitons to lock to the waveguide direction at high powers, or to acquire transverse momentum and shift sideways.[4] These effects, which have been observed in uniform arrays of waveguides, can be enhanced, or canceled, in nonhomogeneous arrays.

Nonuniform arrays were used in previous studies. For example, the introduction of an (effective) refractive-index gradient across the array results in a motion of the field across the array, which resembles optical Bloch oscillations.[5,6] In another experiment the behavior of a single defect, formed by a narrow waveguide in an otherwise uniform array, was investigated. In the linear regime the defect traps the field, whereas at high input powers the field escapes as phase matching with the neighboring waveguides is achieved.[7]

Theoretical studies have predicted that soliton reflection, transmission, and trapping can be controlled by insertion of suitable defects in an array.[8] In this Letter we study array defects in the form of a local change in the coupling coefficient of a pair of adjacent waveguides. A local increase in the coupling coefficient corresponds to an attractive defect, whereas a decrease in the coupling coefficient corresponds to a repulsive defect. It has been demonstrated that the dynamics of a discrete soliton resembles that of a classical particle in the presence of a potential introduced by the defect. A repulsive defect, corresponding to a local decrease in the effective index, is equivalent to the interaction of the soliton with a potential barrier. In this situation the soliton may be either totally reflected from the defect site (at small transverse velocities, i.e., small input angles) or totally transmitted through it (at high transverse velocities). At intermediate velocities the soliton exhibits an inelastic collision with the defect and is partially transmitted and partially reflected. Trapping of the soliton to the defect site happens only at a specific velocity; however, this trapping is highly unstable owing to the repulsive nature of the potential barrier. An attractive defect, corresponding to a locally higher effective index, is equivalent to an interaction of the soliton with a potential well. For this situation it has been predicted that the soliton will be totally transmitted through the defect at high velocities or reflected from it while it excites a linear guided mode at the defect site at low velocities. At intermediate velocities, however, the soliton may be trapped by the defect, which induces an attractive potential for the soliton.

In this Letter we study the interaction of discrete solitons with structural defects in arrays of AlGaAs waveguides. We fabricated both attractive and repulsive centers by changing the distance between the adjacent waveguides of a single pair in an otherwise uniform array. A local decrease in that distance corresponds to an attractive defect, whereas a repulsive center is created when the distance is increased. We made the measurements described in this Letter by using the same setup employed in previous experiments[4,10] (see Fig. 1). Pulses of 100-fs duration and with a wavelength of 1530 nm were injected into several different arrays. The input power, the number of excited waveguides, and the angle of propagation could all be controlled.

The arrays employed in the experiment contained 41 waveguides etched 0.35 μm deep into the top of a 6-mm-long slab waveguide, which was formed from an $Al_{0.18}Ga_{0.82}As$ core layer sandwiched between two cladding layers, both formed from $Al_{0.24}Ga_{0.76}As$. The upper and lower claddings were 1 and 4 μm thick, respectively, and the core was 1.5 μm thick. The distance, edge to edge, between adjacent waveguides was 5 μm, with the exception of the defect pair, for which the distance decreased to 3 μm for an attractive defect and increased to 7 μm for a repulsive defect.

Red light emitted by the sample near the input facet, which is due to multiphoton absorption and successive fluorescent emission, was collected, and detected by a CCD camera placed above the sample. This allowed the input position and direction of propagation of the injected beam to be determined with respect to the array and defect location. In this experiment we positioned the beam at the center of the two waveguides that formed the defect and performed the measurements at low and at high powers (70 and 800 W, as shown in Figs. 2 and 3, respectively). The input angle varied from −0.85 and +0.85°. We note that, for negative angle, the beam propagates from left to right in the array, whereas positive angles correspond to right-to-left propagation. In each of the four parts of these two figures the horizontal axis stands for the input angle and in the vertical axis a linear gray scale represents the output intensity profile. Figures 2(a) and 2(b) and 3(a) and 3(b) refer to an attractive defect, for which experimental results and two-dimensional beam-propagation method continuous-wave simulations are compared. Similarly, a repulsive defect is shown in Figs. 2(c) and 2(d) and 3(c) and 3(d).

We discuss the linear case first (Fig. 2). At low power, a broad linear mode propagates along the attractive defect, as shown in the experiment [Fig. 2(a)] and reproduced by the simulation [Fig. 2(b)]. The center of the localization, which corresponds to the bright white area in the figure, moves between the two waveguides of the pair that generates the defect, which suggests weak trapping of the linear mode by the defect site. The repulsive defect [Figs. 2(c) and 2(d)], however, behaves differently: The beam smoothly crosses the defect, and no trapping or slowing down occurs. Only a slight decrease in the field intensity about the defect is noted.

The nature of the attractive and repulsive defects becomes more pronounced when the power is increased (Fig. 3). In the former case, a narrow soliton locks firmly around the defect (the soliton is trapped by the defect for input angles as high as 0.4°). Locking caused by the PNP[11] also occurs in a uniform array, and soliton escape occurs at an angle of 0.2° for the same initial conditions. Hence the presence of an attractive center adds to the PNP and increases its effect. In the case of a repulsive defect, we clearly observe the opposite behavior. A very sharp instability appears when the soliton crosses the pair of waveguides that forms the defect, and the soliton flips abruptly from one side of the defect to the other. This effect clearly saturates and cancels the trapping effect of the PNP. We also note the excellent qualitative agreement between experimental results and the simulation, in spite of the fact that a continuous-wave picture was used for the numerical calculations. The fact that linear and nonlinear absorption, together with material dispersion, were not taken in account merely resulted in an underestimation by a factor of ~2 of the power required for generating the soliton (simulations predicted a value of 400 W instead of the 800-W peak power that was actually injected into the waveguides).

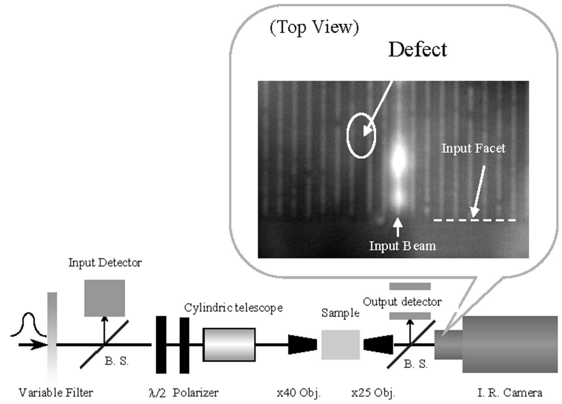

Fig. 1. Experimental setup and top view of the sample. (N.B.: in the experiment we centered the beam on the defect; in the picture above we intentionally positioned the beam three waveguides aside from the defect, which is now visible.) B.S.'s, beam splitters.

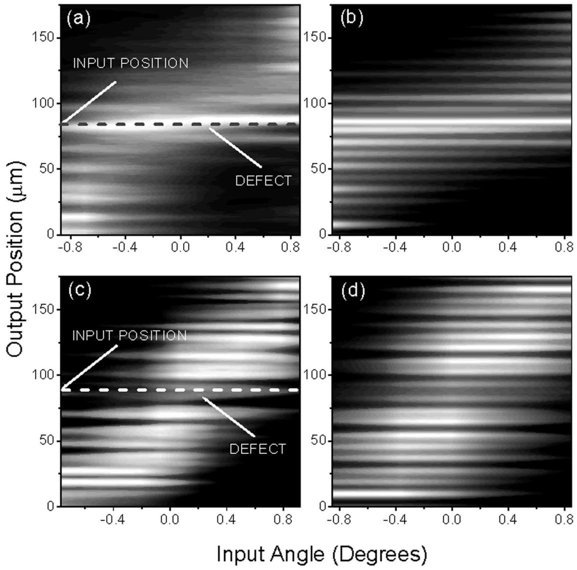

Fig. 2. Interaction of a low-power beam with defects. The light is injected at the defect site (dashed lines). (a), (b) Attractive defect, experimental result and simulations; (c), (d) repulsive defect, experimental results and simulations, respectively.

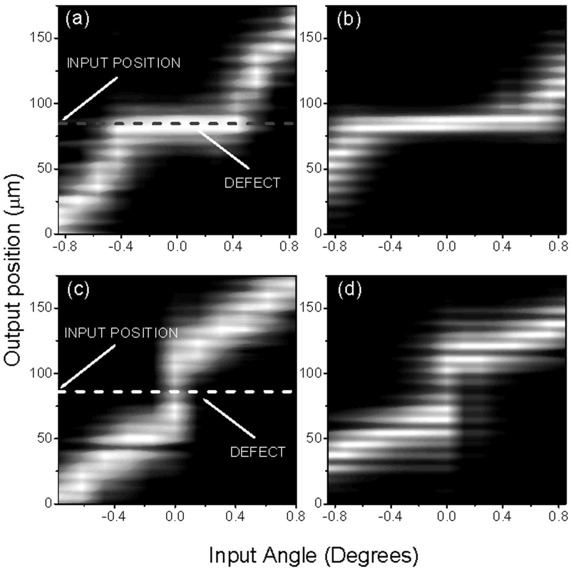

Fig. 3. Interaction of a discrete soliton with defects. As in Fig. 2, the soliton is injected exactly into the defect, represented by a dashed line. (a), (b), Attractive case, experimental results and simulations; (c), (d), repulsive defect, experimental results and simulations.

In conclusion, we have shown experimentally how engineered structural defects in arrays affect the motion of discrete solitons, leading to a significant difference between soliton and linear propagation through the same structures. We note that in certain cases we obtained quite dramatic changes of the output positions for relatively small changes of the input conditions. As an example we cited the sudden switch of the soliton across a narrow repulsive defect [Fig. 2(c)]. Such changes could be potentially useful for various all-optical operations.

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