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Formation and light guiding properties of dark solitons in one-dimensional waveguide arrays

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We report on the formation of dark discrete solitons in a nonlinear periodic system consisting of evanescently coupled channel waveguides in defocusing lithium niobate. Localized nonlinear dark modes displaying a phase jump in the center that is located either on-channel (mode *A*) or in-between channels (mode *B*) are formed, which is to our knowledge the first experimental observation of mode *B*. By numerical simulations we find that the saturable nature of the nonlinearity is responsible for the improved stability of mode *B*. The ability of the induced refractive index structures to guide light of a low-power probe beam is demonstrated.

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Nonlinear wave propagation in periodic lattices, which occurs in many different systems in nature [1–4], has attracted great interest in recent years. In these systems the dynamics is dominated by interplay of diffraction, i.e., tunneling through adjacent potential wells, and nonlinearity, leading to a large variety of nonlinear effects that have no analog in bulk media. This increasing interest may be attributed to recent progress in the investigation of nonlinear wave propagation in optical periodic media, where the ability to engineer band structures and diffraction as well as a rather easy experimental control of relevant parameters has led to the discovery of many new fundamental features [5–10].

In periodic optical systems including evanescently coupled waveguide arrays [11,12] and photonic lattices and crystals [13], different types of localized bright structures (lattice solitons) have been observed. To name a few, spatial gap solitons [11,14–16], solitons in higher bands [17], and solitons occupying modes of several bands [18] have been experimentally realized. Here we again want to note that the study of these intrinsically localized modes is a universal problem and relevant to many nonoptical systems, such as localized voltage drops in ladders of Josephson junctions [19], localized modes in antiferromagnetic crystals [20], or localization of matter waves in Bose-Einstein condensates using optically induced periodic potentials [21].

For bright discrete solitons in focusing Kerr media it has been shown theoretically that, for a given power, two stationary localized modes may exist [22]: a stable mode *A* centered on a waveguide (on site) and an unstable mode *B* centered between two neighboring waveguides (off site). Recently, we have found that a saturable nonlinearity, for example, by using photorefractive crystals, may support stable propagation of mode *B*, too [23,24]. Similar predictions have been made for other nonlinear media, including cubic-quintic systems [25] and localized surface waves [26]. On the other hand, off-site modes of more complex shape have been observed in Kerr media, for example, bound states of discrete solitons (so-called twisted modes) [27] and off-site vortex solitons in two-dimensional lattices [28,29].

As it is now well understood, bright lattice solitons can exist either in the region of normal diffraction as a result of a self-focusing, or in media exhibiting a self-defocusing nonlinear index change and anomalous diffraction of light in the lattice. Similar to the situation in the bulk [30,31], for dark solitons normal diffraction of a narrow dark notch (a small number of dark elements) on an otherwise homogeneously excited lattice can be balanced by a negative index change. Alternatively, anomalous diffraction in a lattice can be compensated by a positive nonlinearity. In periodic systems, the existence of dark discrete solitons has been investigated theoretically [32], followed by first experimental realizations [16,33]. As has been recognized already in bulk materials, dark solitons are potential candidates for guiding, steering, and switching of light beams in light-induced waveguide channels. Even more interesting, in discrete media like coupled waveguide arrays, a realization of the above mentioned functions would strongly benefit from the inherent multiport structure of the array. Here an increased stability of mode *B* would be beneficial because it simplifies the propagation of solitons across the nonlinear lattice [22,23].

In this Rapid Communication we investigate formation of dark discrete solitons in one-dimensional waveguide arrays exhibiting a saturable self-defocusing nonlinearity. Localized dark modes displaying a phase jump that is located either on channel or in-between two channels are formed, which in the latter case is—to our knowledge—the first experimental observation of mode *B*. Numerical simulations that support our experimental findings show that the saturable nature of the nonlinearity increases stability of mode *B* when compared to the Kerr case. Furthermore, to demonstrate the ability of both types of dark discrete solitons to guide and steer light, waveguiding of probe beams that are launched into the light-induced refractive index structures is demonstrated.

Our waveguide array is fabricated in a Cu-doped lithium niobate crystal, where the saturable defocusing optical nonlinearity arises from the bulk photovoltaic effect. The array that is fabricated by in diffusion of titanium consists of approximately 250 channels with a width of 4.4 μm and a grating period of 8.4 μm [15,34].

The experimental setup is sketched in Fig. 1. Light of a frequency-doubled Nd:YVO_4 laser with wavelength $\lambda = 532$ nm is split into three beams, where two of them

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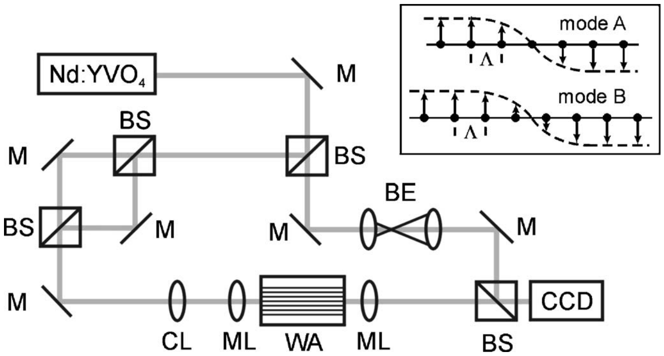

FIG. 1. Experimental setup. M's, mirrors; BS's, beam splitters; CL, cylindrical lens; ML's, microscope lenses; WA, waveguide array; BE, beam expander; CCD, CCD camera. Inset: phase profiles of modes A and B.

(formed by a Michelson interferometer) are partially superimposed under a small angle on the input facet of the waveguide array. In this way a broad beam covering about 25 channels with a small dark notch caused by destructive interference in the overlap region is formed. The center of the input beam experiences a phase jump of π and can be adjusted either on channel to excite mode A, or in-between channels to excite mode B (see inset of Fig. 1). A third beam that is expanded to a plane wave with the help of a beam expander is used to investigate the phase structure of the guided light. For this the plane wave interferes with the outcoupled light of the array on the charge-coupled device (CCD) camera.

In the first experiment we investigate the linear and nonlinear propagation of mode A. The phase discontinuity of the input beam is located on a lattice element, i.e., the central channel is hardly excited. Here the input width [full width at half maximum (FWHM)] of the dark notch is about 25 μm, covering roughly three periods of the lattice and propagating in forward direction (zero transverse wave vector component). The input intensity distribution shown in Fig. 2(a) is measured by imaging the reflected light from the sample's input facet. The response time of the photovoltaic nonlinearity in our sample is about 20 s for the used input power of 100 μW, thus we are able to monitor the buildup of the

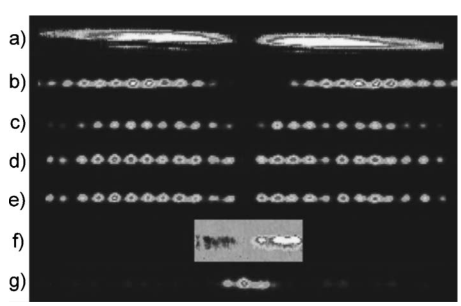

FIG. 2. Propagation of mode A: (a) intensity distribution on the sample's input face, (b) discrete diffraction of mode A at $t=0$ s, (c) nonlinear partial focusing at $t=10$ s, and (d) and (e) dark soliton formation at $t=20$ s and $t=120$ s, respectively, (f) interferogram of the dark soliton shown in part (d), and (g) guiding of a weak probe beam.

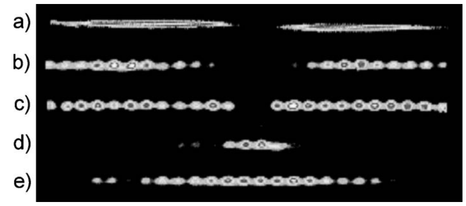

FIG. 3. Propagation of mode B: (a) input intensity distribution, (b) discrete diffraction, (c) dark soliton formation at $t=60$ s, (d) guiding of a probe beam, and (e) diffraction of the probe beam in the linear lattice.

discrete dark soliton as a function of time. Nevertheless, to avoid any nonlinear effects, for investigation of the linear behavior the input power is further decreased to $P_{in}=1$ μW. As can be seen in Fig. 2(b), linear discrete diffraction leads to a broadening of the structure on the homogeneous background, which reaches about 5 channels on the output facet after 15 mm of propagation. When the power is increased back to 100 μW, nonlinear defocusing starts [Fig. 2(c)] and eventually forms a dark soliton in Fig. 2(d) after about 20 s. This structure is stable over times large compared to the buildup time of the nonlinearity, see Fig. 2(e) which is taken after $t=120$ s. For even higher input powers, the width of the dark notch slightly decreases, accompanied by a reduced buildup time of the dark soliton. Furthermore, we have measured the phase profile of the dark soliton by interfering it with a plane wave in Fig. 2(f). Obviously, the resulting trapped state has conserved the phase discontinuity from the input. When the input light is switched off, a low-power probe beam ($P\approx 20$ nW) can be coupled into the central channel. As can be seen in Fig. 2(g), the induced structure forms a single mode waveguide that guides the light of the probe beam.

For a second experiment, the waveguide array is laterally shifted by half a lattice period with respect to the input light, thus mode B is excited with a phase jump in between two channels, as can be seen in Fig. 3(a) (input intensity) and (b) (linear diffraction). For the same input power as for mode A, an even dark discrete soliton is formed with two dark elements in the center [Fig. 3(c)]. This is to our knowledge the first experimental observation of this off-site mode. Again, after switching off the pump light the induced structure can be probed by another weak beam, which in this case covers about four channels on the input face. As can be seen, this probe beam is guided in two parallel waveguide channels shown in Fig. 3(d). When illuminating the sample with intense white light, the induced refractive index structure is erased and finally the probe beam propagates with normal diffraction in the (undisturbed) lattice in Fig. 3(e).

To compare our experimental results with theory, we simulate the light propagation in the array using a nonlinear beam propagation method. For mode A with an input width (FWHM) of 25 μm, in Fig. 4(a) the case of linear diffraction for low input power is shown. A localized dark soliton is obtained in Fig. 4(b) in the nonlinear regime applying a saturable nonlinearity of the form $\Delta n=\Delta n_0 r/(1+r)$, where $\Delta n_0=-1.5\times 10^{-4}$ is the amplitude of nonlinear index change, $r=I/I_d=8$ is the intensity ratio with light intensity I and dark

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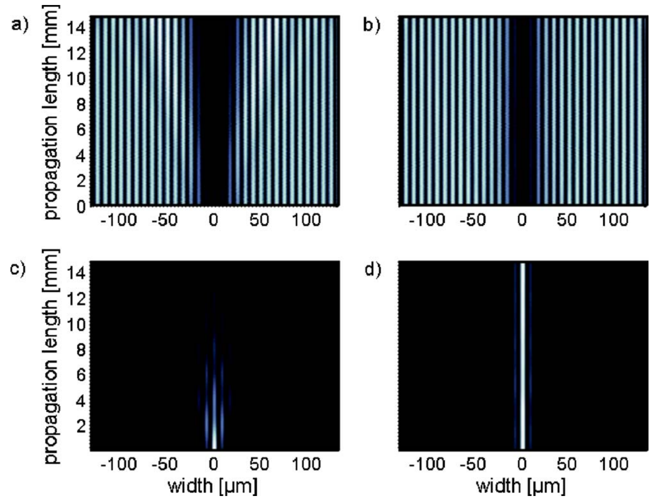

FIG. 4. (Color online) Simulation of mode A: (a) linear diffraction of a dark notch, (b) discrete dark soliton formation, (c) diffraction of a probe beam, and (d) guiding of a probe beam.

irradiance I_d. When the dark soliton is formed, a low-power probe beam that is coupled into the central channel can be guided in the written refractive index distribution of the lattice [Fig. 4(d)]. In the linear case this beam diffracts without guiding [Fig. 4(c)].

For mode B and the same nonlinearity as above, linear diffraction and soliton formation are calculated in Figs. 5(a) and 5(b), in good agreement with the experimental results. For a broad, low-power input probe beam covering about four channels, the resulting refractive index distribution shows guiding in the two induced channels [Fig. 5(d)], whereas this beam diffracts to a broad output beam in the linear case in Fig. 5(c).

Experimentally, stable formation of mode B can be achieved also for small deviations from the exact symmetric input conditions. However, for the Kerr case it has been shown theoretically that mode B experiences instability during propagation [32]. This instability (i.e., conversion of mode B into mode A) may originate from any small deviation from exact symmetry, for example, by a lateral shift of the input light distribution, a small tilt angle of the input beam or a small asymmetry in intensity. On the other hand, our simulation results, using a saturable form of the nonlinearity, show that stability of mode B is significantly improved.

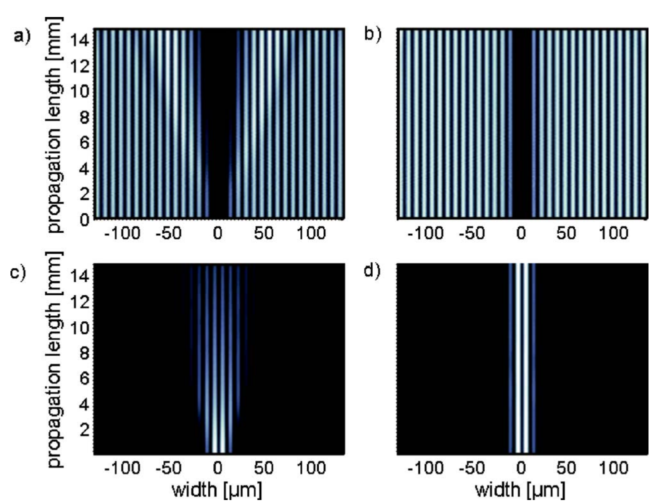

FIG. 5. (Color online) Simulation of mode B: (a) discrete diffraction of a linear beam, (b) discrete dark soliton formation, (c) diffraction of a probe beam, and (d) guiding of a probe beam.

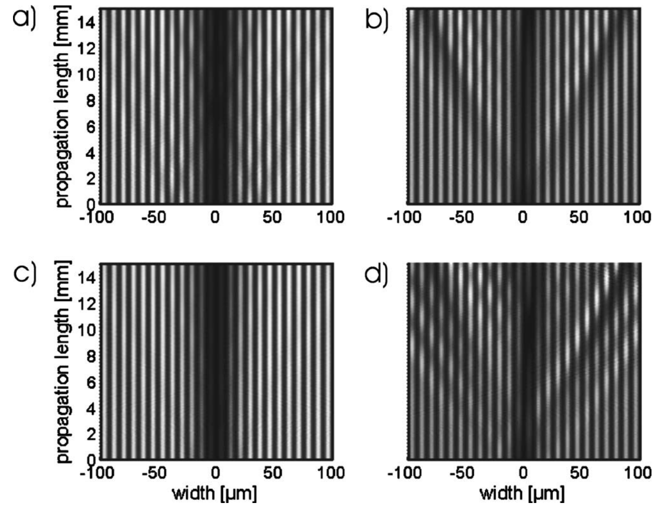

FIG. 6. Comparison of stability of mode B for saturable and Kerr-type nonlinearity. Tilt angle $\delta\alpha = 0.003°$ of the input phase front for (a) saturable and (b) Kerr case, and asymmetry $P_{in,r}/P_{in,l} = 1.03$ of power of right and left half of the input beam for (c) saturable and (d) Kerr case.

Two numerical examples demonstrating this improved stability are given in Fig. 6, where deviations from exact symmetric input conditions comparable with typical experimental ones have been chosen. In the upper part [Figs. 6(a) and 6(b)] we have added a small tilt angle $\delta\alpha = 0.003°$ of the input phase front, with all other parameters being the same as in Fig. 5. This tilt angle is about 1% of the Bragg angle of our lattice. As can be seen, for a saturable nonlinearity [Fig. 6(a)] almost stable propagation of mode B is obtained, while for purely Kerr-type nonlinearity [Fig. 6(b)] the input mode experiences instability and is converted into mode A. In the second example in Figs. 6(c) and 6(d), the right-hand side of the input intensity is increased by 3% relative to that on the left-hand side. This asymmetry leads to destabilization of mode B in the Kerr case [Fig. 6(d)], while the same input intensity propagates stable in a saturable nonlinear lattice in Fig. 6(c). In a very recently submitted theoretical paper [35] the increased stability of off-site dark modes in saturable nonlinear lattices has been investigated in detail. It has been concluded that this effect is mainly due to weaker instability growth rates when compared to the Kerr case, rather then to a true stability of these modes that may be related to a reduction (or vanishing) of the Peierls-Nabarro potential as formerly described in Ref. [23].

To summarize, we have experimentally investigated dark soliton formation in a nonlinear waveguide array with defocusing saturable nonlinearity. With the general limitation of using a crystal of finite length stable propagation of localized dark beams centered either on site or in-between two channels has been observed experimentally, and our findings are well supported by numerical simulations. It has been shown that the saturable character of the nonlinearity leads to increased stability (i.e., smaller growth rates of distortions) of mode B when compared to a purely Kerr-type nonlinearity. The ability of the induced refractive index patterns to guide light of low-power probe beams has been demonstrated, which is of great practical interest for the realization of all-optical devices such as routers and switches.

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