Dark and bright blocker soliton interaction in defocusing waveguide arrays

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Abstract: We experimentally demonstrate the interaction of an optical probe beam with both bright and dark blocker solitons formed with low optical light power in a saturable defocusing waveguide array in photorefractive lithium niobate. A phase insensitive interaction of the beams is achieved by means of counterpropagating light waves. Partial and full reflection (blocking) of the probe beam on the positive or negative light-induced defect is obtained, respectively, in good agreement with numerical simulations.

OCIS codes: (190.0190) Nonlinear optics, (190.5330) Photorefractive nonlinear optics, (190.5330) Pulse propagation and solitons.

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30. For $r < 1.1$ only partial focusing of the narrow input beam is achieved. Nevertheless for such small intensity ratios (i.e. in the Kerr regime) bright solitons may still be obtained using larger soliton (input) widths.

1. Introduction

The investigation of light propagation in periodic optical media has attracted a great deal of attention in the last years [1-4]. A relatively simple realization of optical materials with periodically varying refractive index is an arrangement of parallel, evanescently coupled waveguide channels, which form a one-dimensional (1D) photonic crystal [5-7]. As a direct consequence of the inherent discreteness, light propagation in such waveguide arrays displays many attractive features like discrete diffraction [1,2] or the possibility to tailor diffraction properties [5,8]. Even more interesting, in nonlinear waveguide arrays, self-trapped optical beams — so-called discrete solitons — may be obtained, and a wide spectrum of nonlinear effects offer huge potential for future applications [9-13].

Among the most interesting properties of spatial optical solitons is the nonlinear interaction that takes place when solitons intersect or propagate close enough to each other within the nonlinear material [14-16]. Therefore, solitons are potential candidates for all-optical elements that are used to guide, steer, and switch light beams [17]. Especially in discrete media like coupled waveguide arrays, a realization of the above functions would strongly benefit from the inherent multi-port structure of the array [18,19]. Experimentally, interaction of solitons in 1D periodic media has been investigated so far mainly in semiconductor waveguide arrays exhibiting a self-focusing Kerr nonlinearity. Here both attraction and repelling of two initially parallel beams has been observed [20,21]. In the same material, interaction of bright solitons with coherent and incoherent probe beams has been demonstrated, too [22,23]. However, from bulk media it is well

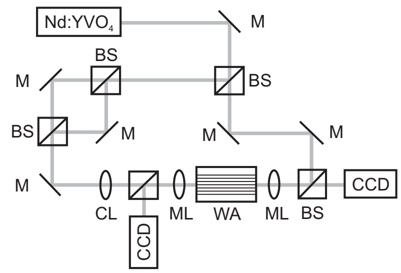

Fig. 1. Scheme of the experimental setup: M's, mirrors; BS's, beam splitters; CL, cylindrical lens; ML's, 20× microscope lenses; WA, waveguide array; CCD's, CCD cameras.

known, that for saturable nonlinearities an even richer spectrum of interaction scenarios of solitons is possible: Saturation may lead to fusion and annihilation of solitons [24,25], or nonlinear effects like the break up of extended waves into trains of solitons (modulation instability) may be completely suppressed for high degrees of saturation [26]. For discrete saturable media new effects., e.g. a cascade mechanism of saturation [13] or the existence of off-channel dark modes [27] have been found. Recently, we have reported first experimental results on interaction of collinearly propagating solitons in waveguide arrays exhibiting a saturable nonlinearity [28]. In that work, two parallel in-phase solitary beams may fuse together at low input power, while independent propagation is observed for higher power.

In this work we investigate the interaction of a probe beam with both bright and dark solitons. The solitons are formed with very low optical power using the saturable photorefractive nonlinearity in waveguide arrays fabricated in a lithium niobate crystal. To enable a phase insensitive interaction of the two light beams, we make use of the anisotropic nature of the photorefractive nonlinearity in $LiNbO_3$. The transverse electrically (TE), extraordinarily polarized narrow soliton beam and broader probe beam are mutually coherent but are propagating in opposite directions in the array, thus forming an interference pattern with a grating vector directed along the propagation direction (y axis). As a consequence, a modulated space charge electric field builds up, however, no appropriate electrooptic tensor element (here $r_{eff} = r_{32} = 0$) exists for crystals with point symmetry 3m, and the resulting nonlinear index change is zero. In this way we achieve an almost complete, phase-insensitive reflection (blocking) of the probe beam on either positive or negative light-induced defects formed by bright and dark (blocker) solitons, respectively. Numerical simulations based on a nonlinear beam propagation method (BPM) are in fairly good agreement with our measurements and show the suitability of this nonlinear process for the realization of beam splitters with adjustable splitting ratios.

2. Experimental methods

Experiments are performed in a 25 mm long x-cut lithium niobate crystal where permanent channel waveguides are fabricated by Ti indiffusion. A Ti layer with a thickness of 10 nm is lithographically patterned and the resulting stripes are in-diffused for 2 hours at a temperature $T = 1040\,^{\circ}$C. To enhance the photorefractive nonlinearity additional doping with Fe is realized by in-diffusion of a 5.6 nm Fe layer that is annealed for 24 hours at $T = 1060\,^{\circ}$C. The final waveguide array has a pitch of 8.4 μm with a distance of 4.4 μm between adjacent channels.

The experimental setup is shown schematically in Fig. 1. We use a frequency-doubled $Nd{:}YVO_4$ laser with a wavelength $\lambda = 532$ nm. The light is split into three beams, where two of them are formed by a Michelson interferometer. For the excitation of bright solitons one of these two beams is blocked, while the other remaining beam is focused onto the left hand input facet of the sample. On the other hand, dark solitons may be formed by partially superimposing both beams of the interferometer (having a phase difference of π) under a small angle on the input facet of the 1D waveguide array. In this way a broad beam covering about 15 channels with a small dark notch caused by destructive interference in the overlap region is formed. A third beam that enters the sample from the right hand side (rear facet) under a small angle is used to form the counterpropagating probe beam. This beam is launched at half the Bragg angle of the array (transverse wave vector $k_z = \pi/2\Lambda$), thus it experiences almost zero diffraction during propagation. Input and output light intensities can be monitored by two CCD cameras. For the imaging of input light distributions reflection from the polished input facet is used.

3. Experimental results and discussion

The linear propagation of both types of blocker solitons as well as the counterpropagating probe beam is monitored in Fig. 2. For the formation of a narrow bright staggered soliton a single channel is excited on the input facet in Fig. 2(a), which diffracts after 25 mm of propagation to about 13 channels [29]. The input light intensity as well as linear diffraction of the dark soliton beam are shown in Fig. 2(b). Here the phase discontinuity of the input light pattern is located on a lattice element, i.e. the central channel is hardly excited [27]. The corresponding input width (FWHM) of the dark notch is about $\Delta z = 25\,\mu$m, covering roughly 3 channels of the lattice, i.e. it is slightly broader then the input for the bright soliton beam. Finally, in part (c) the evolution of the probe beam (propagating from top to bottom with transverse wave vector $k_z = \pi/2\Lambda$) is given. The probe beam covers about 5 channels and shows only negligible diffraction. As can be seen, in all three cases a rather good agreement of experiment and numerical simulation is

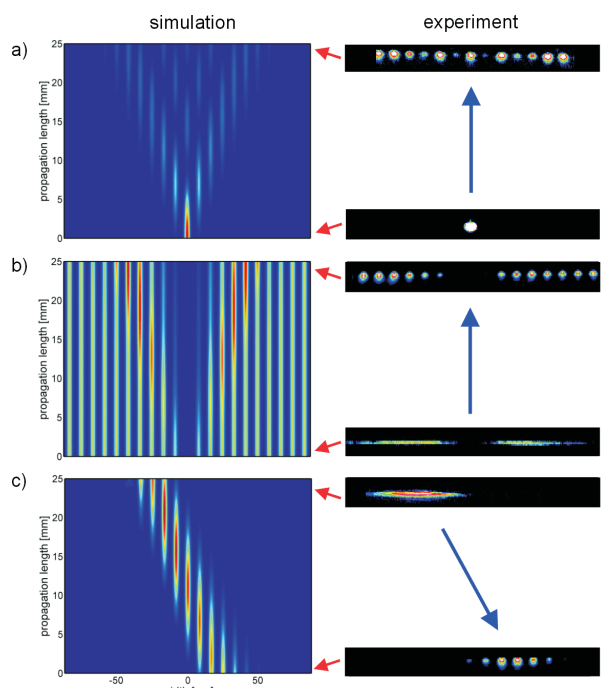

Fig. 2. Linear propagation of blocker and probe beams: comparison of simulation (left hand side) and experiment (right hand side). a) Discrete diffraction for (bright) single-channel excitation; b) discrete diffraction of a dark notch covering about 3 channels; and c) propagation of a broader probe beam in the array.

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achieved.

The response time of our waveguide array that is determined by the sample's photoconductivity is in the range of several minutes, thus we are able to observe the intensity distributions on both sample facets as they evolve in time. Consequently, we monitor the linear propagation of the input beams through the waveguide by measuring the intensity distribution at the sample's output facets immediately after switching on the light, and then continuously monitor the time evolution of the nonlinear interaction.

To compare the obtained experimental results with theoretical modelling, we solve the nonlinear paraxial wave equation numerically by using a nonlinear BPM. For doing this we use the parameters of our waveguide array and a saturable defocusing nonlinearity of the form $\Delta n_{nl} = \Delta n_0 I/(I + I_d)$, with fixed amplitude $\Delta n_0 = -2 \times 10^{-4}$ and an intensity ratio $r = I/I_d$, where I_d is the so-called dark irradiance and I is amplitude of the input light intensity.

In Fig. 3 we show the reflection of the weak probe beam by a defect state with negative nonlinear index change (see the corresponding diagram in Fig. 5(a) induced by a bright blocker soliton. Here the narrow gap soliton displayed in part b) that is excited with an input power of $P = 6\,\mu$W covers mainly one channel of the array, with a build-up time of about 60 minutes. The input power of the probe beam is chosen to be very low ($P_{in} = 10\,$nW), therefore nonlinear index changes induced by the probe beam itself can be ruled out. As can be seen in (a), during the build-up of the defect state an increasing part of the incident probe beam is reflected to the reverse side of the array, with almost total energy reflection in steady-state. Because of the low power of the probe beam no lateral shift of the bright gap soliton is observed here, as has been recently reported for Kerr media [23]. For the corresponding waveguide array and nonlinear parameters, the numerical simulations in (c) and (d) show good agreement with the experimental situation in steady-state. When the input power of the blocker soliton is decreased, still almost full reflection of the probe beam is achieved, however the probe beam's intensity is predominantly trapped closer to the defect channel. As an example, for a soliton input power

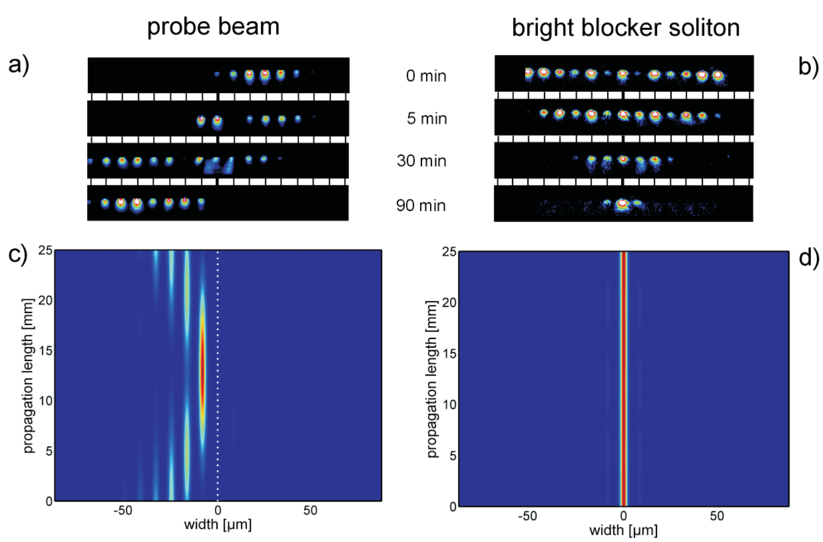

Fig. 3. Reflection of the probe beam by a bright blocker soliton. a), b) Temporal evolution of the intensity on the output facet for probe ($P_{in} = 10\,$nW) and bright soliton beam ($P_{in} = 6\,\mu$W), respectively; c), d) Simulation of propagation of probe beam ($r = 0.01$, propagation from top to bottom) and bright soliton ($r = 6$, propagation from bottom to top), respectively, in steady-state.

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of $P = 1\,\mu$W nearly 60 % of the probe beam intensity is guided in the channel adjacent to the defect state, and for slightly lower input power partial trapping of the probe beam's intensity inside the soliton channel is observed.

Interaction of the probe beam with a dark blocker soliton is shown in Fig. 4. Here, similar to the case of the bright blocker soliton, reflection of the probe beam on the created defect in the array is observed. Here the main difference is the formation of a nonlinear index change by the blocker soliton that effectively acts as a positive defect. As an example, in Fig. 5(b) the resulting shape of this positive defect state is shown. The total power of the input beam in this experiment is again $P_{in} = 6\,\mu$W, however this power is now distributed among roughly 12 input channels. Consequently, the resulting intensity ratio is $r \approx 0.5$. In steady-state, only partial reflection of the probe beam's intensity is achieved, which may be attributed to the different cross-section of the defect and in particular to the lower input power (per channel) of the used dark soliton when compared to the situation of the bright blocker beam. Again, a good agreement of numerical simulations with the experimental situation os obtained. Furthermore, in a recent submission [27] we have demonstrated the formation of localized nonlinear dark modes displaying a phase jump that is located in-between two channels (mode B). For such off-channel dark solitons reflection of a probe beam is observed in a similar manner as for the on-channel case discussed before.

To investigate the reflection properties of the light induced defects in more detail, we have calculated the ratio of reflected and total transmitted power for both, bright and dark blocker soliton, as a function of the soliton input power in Figure 6. Here the reflected light power is defined as the sum of all channels on the left hand side of the central channel $n = 0$. For the simulation we used again the corresponding input profiles (narrow single-channel bright beam and three-channel dark input beam) of the experiments from Figs. 3 and 4. As can be seen, for both cases and higher input power, reflected light intensities saturate at a reflectivity of almost 90 percent. Note that here narrow bright solitons only exist for input power ratios $r > 1.1$ [30], whereas dark solitons can be excited also at significantly lower input power. In the low input

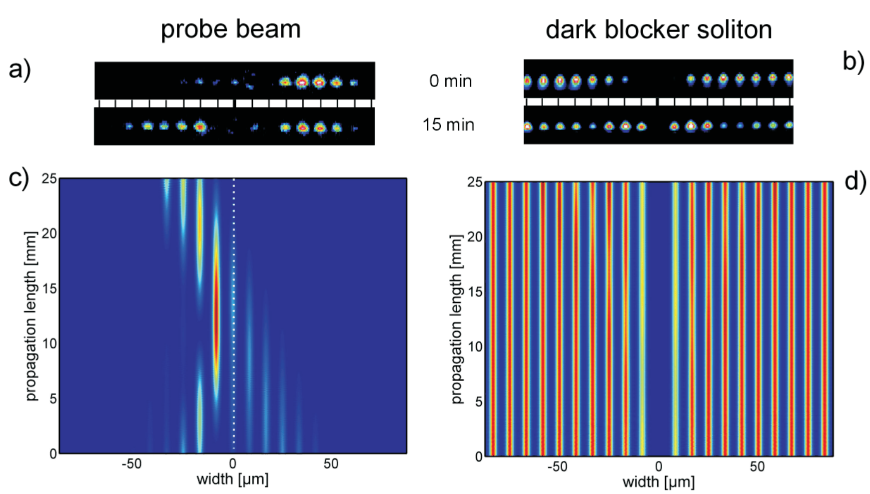

Fig. 4. Reflection of the probe beam by a dark blocker soliton. a) and b): Linear output ($t = 0$) and nonlinear steady-state ($t = 15$ min) intensity distribution on the output face for probe and dark soliton beam, respectively; c) and d): Simulation of propagation of probe beam ($r = 0.01$, propagation from top to bottom) and dark soliton ($r = 0.4$, propagation from bottom to top), respectively, in steady-state.

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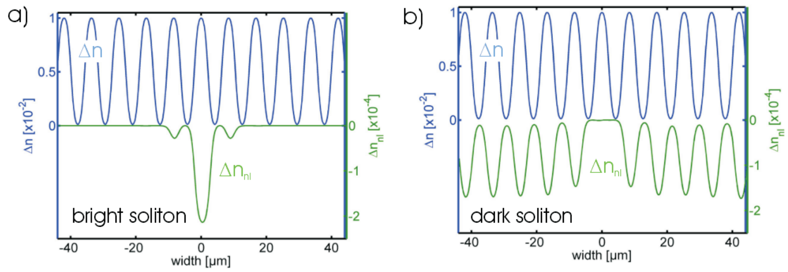

Fig. 5. Linear and nonlinear refractive index profiles of the waveguide array: permanent periodic refractive index modulation (blue solid line, left hand scale) and nonlinear light-induced refractive index changes (green solid line, right hand scale) for a) bright blocker soliton ($r = 6$) and b) dark blocker soliton ($r = 2$).

power region (small ratios r) reflection by the dark soliton is more effective when compared to the bright case, which may be attributed to the larger spatial extension of the induced (positive) defect state. Again, the experimentally obtained reflection of about 50 % for the dark blocker soliton with $r = 0.5$ is in reasonable agreement with our simulations.

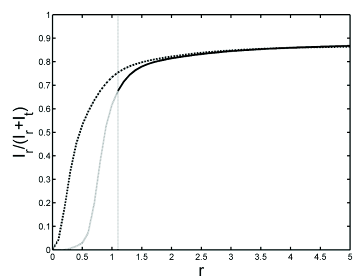

Fig. 6. Ratio $I_r/(I_r+I_t)$ of reflected and total transmitted intensity as a function of intensity ratio r for bright blocker soliton (solid line) and dark blocker soliton (dotted line), respectively. A bright soliton only exists for input power ratios $r > 1.1$ (vertical dotted line).

4. Summary

To summarize, we have used a counterpropagating scheme to experimentally investigate the reflection of a weak probe beam by both bright and dark blocker solitons. The interaction takes place in a 1D waveguide array fabricated in lithium niobate, which displays a saturable defocusing (negative) nonlinearity that is due to the photovoltaic effect. A phase-insensitive reflection of the probe beam is achieved because of the anisotropic nature of the photorefractive nonlinearity in our sample. For narrow bright blocker solitons almost complete reflection of the probe beam is achieved already for microwatt optical input powers. Similar reflection efficiencies can be obtained for dark blocker solitons for the same input power per waveguide channel. Nevertheless, by properly adjusting the soliton input power all-optical beam splitters with tailored splitting ratios may be realized. To conclude, we have experimentally shown the ability of discrete solitons in defocusing waveguide arrays to split and steer other light beams, which offers attractive potential for future applications in all-optical networks.

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