Beam interactions with a blocker soliton in one-dimensional arrays

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We investigate experimentally and numerically the interaction of a highly localized, single-channel discrete soliton (blocker) with a wide, tilted beam in a one-dimensional AlGaAs array. In agreement with theory the blocker is observed to discretely shift its position by multiple channels, depending on the intensity and relative phase of the tilted beam. © 2005 Optical Society of America

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Light propagation in arrays of identical weakly coupled channel waveguides exhibits many unique features owing to discreteness.[1] In such systems light diffracts in a discrete manner through tunneling (coupling) effects between nearest-neighbor waveguides.[2] In general, energy transfer among waveguides occurs with propagation distance and is most efficient provided that all the sites exhibit the same propagation wave vector. There are three important repercussions to this weak coupling process. First, it leads to dispersion relations that are periodic with the transverse wave vector. This in turn results in angular regions of normal and anomalous diffraction and allows a direction for which diffraction is effectively zero. Second, the light is spatially localized (or digitized) in discrete sites; i.e., the intensity is a maximum in individual channels. Third, it is possible to excite discrete spatial solitons in such periodic systems. This is possible through nonlinear processes, such as the Kerr effect, that locally perturb the propagation wave vector and hence detune the coupling between neighboring channels.[3–7] Of particular interest are highly localized solitons in which the light is confined to essentially a single channel with only weak tails in the nearest neighbors.

Recently it was demonstrated that optical switching networks may be possible based on the unique properties of two-dimensional (2D) waveguide arrays.[8] The concept utilizes the transverse motion of a wide signal soliton, or a weak nondiffracting beam, whose routing is controlled by a sequence of highly localized or blocker solitons at junction points inside a 2D array. In such systems it is often required that a blocker soliton be able to deflect a weaker signal beam into a different path within the network. Or, if transmission along already blocked paths is desirable, then perhaps interaction with a weak control beam could be used to remove the blocker solitons from the path.[8] For coherent interactions these blocker functions are dependent on the relative phase between the interacting beams.[9,10] Here we investigate experimentally for the first time to our knowledge the coherent interaction between a blocker and

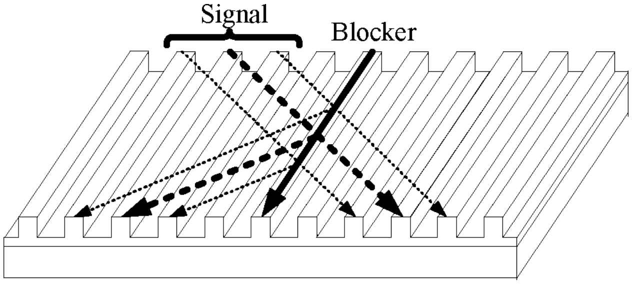

Fig. 1. Geometry for the interaction between a blocker beam essentially localized to a single channel and a signal beam a few channels wide crossing the array at the zero-diffraction angle.

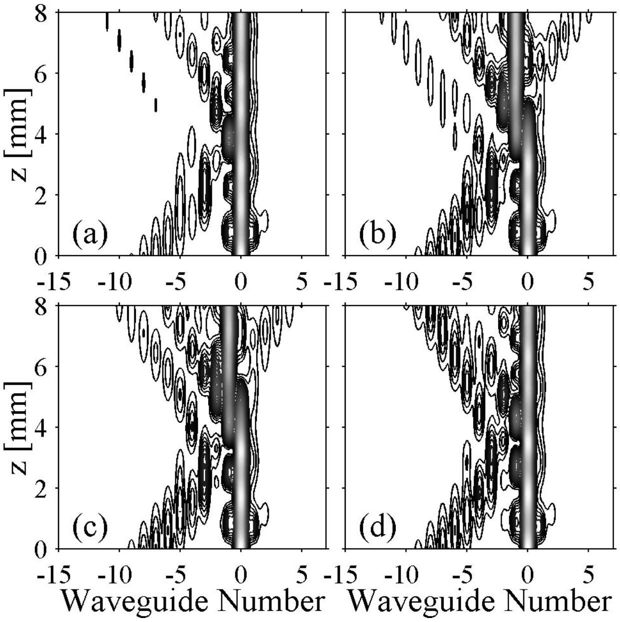

Fig. 2. Beam intensities (signal and blocker) versus propagation distance calculated under cw conditions for different power levels and relative phase. The highly localized soliton is excited with 1 kW, the signal beam with (a) 150 W and (b)–(d) 300 W. The relative phases between the two beams are (a) 0, (b) 0, (c) 0.25π, and (d) 0.5π.

a signal beam traversing the array. The sample and interaction geometry is shown in Fig. 1. In our case the signal beam is always assumed to propagate along the diffraction-free direction of the array, thus facilitating interactions even at low input power levels. The experiments were performed in a one-dimensional nonlinear AlGaAs array. In agreement with theory[9] the blocker was observed to shift its position by multiple channels, depending on the intensity and relative phase of the tilted beam.

The wave dynamics of the total electric field amplitude within a discrete waveguide array is known to obey the following discrete nonlinear Schrödinger equation[3]:

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

where a_n represents the mode-field amplitude of a single isolated channel at the nth waveguide site, C is the coupling coefficient between adjacent waveguides, and γ is a measure of the strength of the Kerr nonlinearity in the system; i.e., $\gamma \propto n_2$. In the interaction geometry shown in Fig. 1 the input field is assumed to have the form

$$a_n(0)=g_n\exp(in\theta)\exp(i\phi)+s_n, \qquad (2)$$

where g_n is a Gaussian-like discrete envelope of the tilted signal beam and s_n represents the contribution from the blocking soliton. In this study the propagation angle of the signal beam g_n was always taken to be along the diffraction-free direction[5]; i.e., the phase difference between adjacent channels is $\theta=\pi/2$. We note that along this direction the beam is essentially free of modulational instability.[11,12] Furthermore, we assume that the blocking soliton contribution s_n is mostly localized in channel m; that is, $s_n \propto \delta_{nm}$. In Eq. (2), ϕ stands for the initial phase difference between the two fields. The two field components are separated by N waveguide sites at the input facet with the broad beam input centered at the $m-N$ site. Similar settings have been previously analyzed theoretically for both coherent[9] and incoherent[8] interactions. According to predictions, a low-power signal beam is expected to be partially deflected by the blocker soliton, whereas at higher levels the same beam should be able to drag the blocker (toward the signal beam) in discrete steps. This process is illustrated in Fig. 2 after numerically solving Eq. (1) for two different input signal power levels.

The experimental apparatus is shown in Fig. 3. A 1550-nm beam from a pulsed optical parametric amplifier (1-ps-long pulses) was attenuated with a variable filter and split into two parts. One beam was used to generate the highly localized soliton and was shaped to excite only one channel in the array (8 μm by 2 μm). The power in this beam was increased until localization in essentially one waveguide site was obtained at an input power of 2.5 kW, which was used for all our observations. The second beam was shaped by a lens combination to be elliptical with a cross section of 40 μm by 2 μm. This signal beam was wide enough to excite seven waveguides of the array with an initial center-to-center separation of nine waveguides from the highly localized blocker soliton at the input. The signal was launched at the zero-diffraction angle of the array toward the blocking soliton. A piezoelectric actuator was used to vary the phase of this beam relative to the soliton. The output of the waveguide array was then imaged on a conventional vidicon camera and a highly sensitive InGaAs detector array for different power levels of the tilted beam. The AlGaAs array was 8 mm long, had a coupling constant C of 0.9 mm^{-1}, and consisted of 101 waveguides. Effective nonlinear coefficient γ was estimated to be 5 $\mathrm{m}^{-1}\,\mathrm{W}^{-1}$. Waveguide spacing D for this array was 9 μm.

In Fig. 4 we show the output intensity distribution for three peak powers of the tilted beam. The two images on the left of each figure show the location of the two beams at the input, whereas the two images on the right show the intensity at the end of the sample if only one of the beams is present. As can be seen, the tilted beam crosses the path of the highly local-

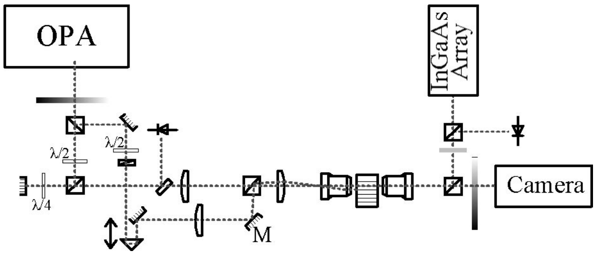

Fig. 3. Experimental apparatus: OPA, optical parametric amplifier; M, mirror; λ/2, half-wave plate; λ/4, quarter-wave plate.

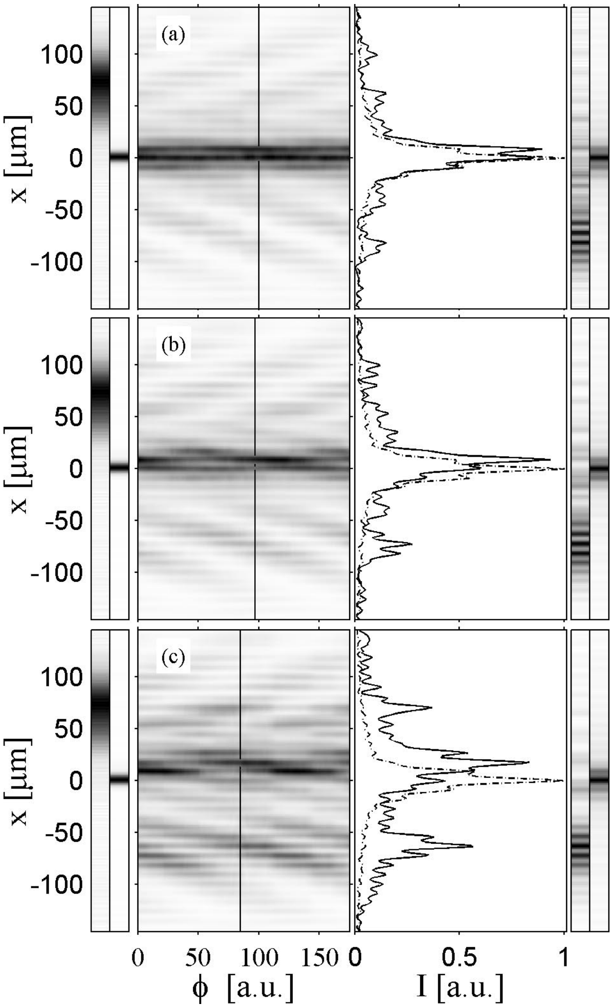

Fig. 4. Experimentally measured intensities of the output beams for three different pulsed input signal beams of different intensities crossing a pulsed blocker soliton as a function of relative phase between the beams. The intensity profiles show the blocker soliton in the absence of the tilted beam (dashed curve) and the observed output intensity during the interaction (solid curve) for a phase angle indicated by the vertical line in the left central part. Peak powers of (a) 350 W, (b) 780 W, and (c) 1.4 kW were used for the signal beams.

ized soliton. As expected, it essentially maintains its initial width on propagation, even though some small third-order diffraction effects are noticeable in the output images.

The interaction dynamics of the two beams (intensity at the output of the array) are shown in the central parts of Fig. 4 as a function of relative phase angle ϕ on the left and an example intensity profile on the right. At the lowest shown power of 350 W the blocker is split to cover two waveguides. Increasing the power of the tilted beam to 780 W results in the dragging of the blocker by one waveguide site for some phase angles as shown in the intensity profile. For the highest shown power of 1.4 kW [Fig. 4(c)] the blocker is dragged by two waveguide sites toward the incoming signal. As for all the interactions, the outcome of the interaction is phase sensitive. Note that, even though the whole process is phase sensitive as expected for a coherent interaction, the deflection of the blocker soliton is always toward the incoming weak beam. For a power of 1.4 kW the tilted beam drags the soliton up to two sites to the side, again depending on relative phase. For some phase angles the interaction leads to splitting of the blocker beam. Before closing we would like to note that the agreement between the modeling and the experiment is primarily qualitative. This is because the simulations were carried out under cw conditions, whereas in our experiment we used picosecond pulses.

In summary, we have experimentally observed, for the first time to our knowledge, the interaction of highly localized discrete (blocker) solitons with a signal beam propagating at the zero-diffraction angle.

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References

1. D. N. Christodoulides, F. Lederer, and Y. Silberberg, Nature **424**, 817 (2003).
2. S. Somekh, E. Garmire, A. Yariv, H. L. Garvin, and R. G. Hunsperger, Appl. Phys. Lett. **22**, 46 (1973).
3. D. N. Christodoulides and R. I. Joseph, Opt. Lett. **13**, 794 (1988).
4. H. S. Eisenberg, Y. Silberberg, R. Morandotti, A. R. Boyd, and J. S. Aitchison, Phys. Rev. Lett. **81**, 3383 (1998).
5. R. Morandotti, H. S. Eisenberg, Y. Silberberg, M. Sorel, and J. S. Aitchison, Phys. Rev. Lett. **86**, 3296 (2001).
6. R. Iwanow, R. Schiek, G. I. Stegeman, T. Pertsch, F. Lederer, Y. Min, and W. Sohler, Phys. Rev. Lett. **93**, 113902 (2004).
7. J. W. Fleischer, M. Segev, N. K. Efremidis, and D. N. Christodoulides, Nature **422**, 147 (2003).
8. D. N. Christodoulides and E. D. Eugenieva, Phys. Rev. Lett. **87**, 233901 (2001).
9. O. Bang and P. D. Miller, Opt. Lett. **21**, 1105 (1996).
10. J. Meier, G. I. Stegeman, Y. Silberberg, R. Morandotti, and J. S. Aitchison, Phys. Rev. Lett. **93**, 093903 (2004).
11. Y. S. Kivshar and M. Peyrard, Phys. Rev. A **46**, 3198 (1992).
12. J. Meier, G. I. Stegeman, D. N. Christodoulides, Y. Silberberg, R. Morandotti, H. Yang, G. Salamo, M. Sorel, and J. S. Aitchison, Phys. Rev. Lett. **92**, 163902 (2004).