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Nonlinear beam interactions in 1D discrete Kerr systems

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Abstract: The interaction between parallel beams in one-dimensional discrete Kerr systems has been investigated using arrays of coupled channel waveguides. The experiments were performed in AlGaAs waveguides at 1550 nm which corresponds to photon energies just below one half the semiconductor’s bandgap. The input intensity and relative input phase between the input beams was varied and the output intensity patterns were recorded. Observed was behavior ranging from a linear response, to soliton interactions between moderately and then strongly localized spatial solitons. Finally the influence of multiphoton absorption and asymmetric beam inputs on these interactions was investigated at very high intensities.

OCIS codes: (190.5530) Nonlinear optics, Pulse propagation and solitons

References and links
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1. Introduction

Beam propagation in Kerr material can be affected by several nonlinear processes. Among the most prominent are, self-phase-modulation, when only one beam is present, and in addition for two or more co-propagating beams, cross-phase-modulation and four-wave-mixing [1]. The first two affect the phase fronts and spectra of finite beams and lead to effects such as self- or mutual-focusing/defocusing and beam interactions. Four wave mixing, on the other hand, leads directly to energy exchange between beams that depends on the relative phase between them.

In the last ten years there has been a growing interest in nonlinear optics in discrete systems [2-4]. For 1D, this may for example correspond to a periodic array of channel waveguides which are weakly coupled by the evanescent field overlap between neighboring channels [4, 5]. The field energy is essentially localized in individual channels and light can spread throughout the array via this weak coupling (“discrete” diffraction). The $\pi/2$ phase change inherent to this “hopping” process leads to a unique diffraction pattern for beam widths in which discreteness dominates. For single channel excitation power is primarily transferred in two well-defined lobes at the extremities of the diffraction pattern, leaving progressively less of the power in the central channel. For many channel excitation in which discreteness is small, i.e. the ratio between beam width and channel separation is large, the diffraction pattern resembles that in homogeneous media, i.e. it is “bell”-shaped.

It was predicted that, just as in the homogeneous 1D case, discrete diffraction could be cancelled in channel arrays composed of self-focusing 1D Kerr media, leading to discrete spatial solitons [2]. Although the fields have maxima in each channel and minima between the channels, it is the envelope of the maxima which takes on a soliton shape. The effective width of the soliton can vary from a single channel (highly localized case) to any arbitrary number of channels. Both scalar and vector spatial solitons have been observed in AlGaAs channel arrays, as well as solitons due to the higher order bands that occur in these periodic systems [6-8].

Although spatial solitons in general, exhibit unique particle-like properties, they still interact via the classic mechanisms of cross-phase modulation and four-wave mixing [1]. In bulk media this has resulted in attraction, repulsion and power exchange between solitons, all
depending on the relative phase between the solitons. The nonlinear interactions between discrete solitons also occur due to the same mechanisms [9]. The general characteristics are expected to be the same as for the homogenous case, attraction for in-phase beams, repulsion for out-of-phase beams and energy exchange at other phase angles. The details, however, are expected to be different, both due to the discrete nature of the system and the differences in the diffraction process and its characteristics. To date, only two brief reports on these interactions in Kerr media have been published [10, 11].

We have built a versatile experimental set-up which allows us to record quasi-continuously the output of beam (and soliton) interactions as a function of input power, relative polarization and relative phase at 1550 nm. We have used this apparatus to investigate 1D arrays of weakly coupled channel waveguides (discrete system). This has allowed the output of beam interactions from linear all the way to strongly nonlinear to be recorded. In this paper we discuss these experiments, providing a more complete description of the results for equal co-polarized interactions, and providing new data on cross-polarized collisions involving highly localized solitons, the so called “blocker solitons”.

2. Theory

The equations which govern solitons in discrete 1D systems are by now well-known. Wave propagation in 1-D discrete nonlinear waveguide array is modeled by the Discrete Nonlinear Schrödinger Equation (DNLS) [2, 3],

\[
i \frac{d a_n}{dz} + C(a_{n+1} + a_{n-1}) + \gamma |a_n|^2 a_n = 0.
\] (1)

Here \(a_n\) is the peak amplitude of the modal field in the n’th channel, \(C\) is the coupling coefficient between the nearest neighbor channels \(n+1\) and \(n-1\) due to evanescent coupling, and \(\gamma\) in this case is the self-phase modulation nonlinear coefficient, averaged over the field distribution of an individual channel. Note that for a directional coupler, the distance required for complete energy transfer between the two channels is \(\pi/2C\).

For co-polarized interactions, consider two mutually coherent elliptical beams to be focused at normal incidence onto the entrance facet. The input fields can be written as

\[
a_n(z = 0) = \left[ \sqrt{I_{1f}} f(n-n_i) + \sqrt{I_{2f}} f(n+n_i) \exp(i\Delta\phi) \right],
\] (2)

where \(f(n)\) is the envelope function of the individual beams separated by \(n_i + n\) channels and \(\Delta\phi = \phi_1 - \phi_2\) is the initial phase difference between the centers of the beams. Note that the individual envelope functions do not just describe the magnitude of the peak fields in the channels but also the relative phase between adjacent channels at the input.

The total, time independent (cw) field was then propagated through the sample using a variable order Adams-Bashforth-Moulton PECE solver for the DNLS Eq. (1). Shown in Fig. 1 is the evolution with distance of the intensities in the array at 500 W and 1.1 kW, both for 0 and \(\pi\) relative input phase. The simulation parameters used were \(C = 700m^{-1}\) and \(\gamma = 5m^{-1}W^{-1}\). At the lower power level, the two in-phase beams are attracted to each other and coalesce digitally, channel by channel, after 7 nm of propagation. For the out-of-phase case, the intensities primarily remain localized in the channels on which the input is centered. Note also the weak power periodic oscillation with distance between the two strongly excited channels and their adjacent “inner” channels. At 1.1 kW incident power, there is an initial rapid collapse into the two central channels over comparable distances for the two cases. In the case of zero relative phase, power eventually flows towards the center channel of the array by 8 nm of propagation where-as in the out-of-phase case the power remains localized. Note that after the initial collapse, the maxima for the two different relative phases occur at different distances. This could be interesting for phase-dependent switching, a case which will be examined experimentally.
Fig. 1. CW numerical simulation of the propagation along the 8mm sample. Images on the left are for in-phase excitation whereas those on the right are for out-of-phase input beams. The input power is 500 W for simulations (a) and (b) and 1.1 kW for (c) and (d). Note that in this figure the discrete result has been convolved with a Gaussian envelope to mimic the actual waveguide modes.

Fig 2. cw simulations of the waveguide array output versus the total input power for each input beam (assumed Gaussian in shape) at the relative phase angles of (a) $\Delta \phi = 0$, (b) $\Delta \phi = \pi/2$ and (c) $\Delta \phi = \pi$. The simulation parameters are for the 4 mm AlGaAs sample investigated experimentally.

The dependence of the output power distribution on the input power for three different relative phases is examined in Fig. 2. The simulations are for the 4 mm long samples investigated experimentally. There are three distinct regimes, in the first (region I), “low powers”, the output are “scanned as the relative phase is changed, strongly reminiscent of a phase antenna array. At zero relative phase, the output is centered on the central channel, at $\pi/2$ (and $-3/2 \pi$ ) it is scanned to the side as shown, and to the opposite side for $-\pi/2$ and $-3/2 \pi$ (not shown) and there are equal outputs at $\pi$ located symmetrically about the zero channel and displaced outwards from the central launching channel. The output power distributions narrow in (intermediate) region II, essentially become discrete solitons. Finally in region III the outputs become strongly localized solitons, with their high intensity channels localized at the centers of the input beams. These features will all be investigated experimentally here.

For the cross-polarized case (both TE and TM polarizations are present), the inputs are
where \( a_n \), \( b_n \) correspond to the amplitudes in the TE and TM polarization, respectively. In this case we are interested in non-parallel, intersecting beams so that the input fields have a relative phase shift between adjacent channels for the input fields that is included in the envelope functions. The appropriate field equations for the AlGaAs sample geometry of interest can be rewritten as

\[
i \frac{da}{dz} + \beta_n a_n + C_n (a_{n+1} + a_{n-1}) + \gamma |b_n|^2 + \frac{1}{2} a_n^* a_n \exp(2i\Delta\phi) a_n = 0
\]

\[
i \frac{db}{dz} + \beta_n b_n + C_n (b_{n+1} + b_{n-1}) + \gamma |a_n|^2 + |a_n|^2 + \frac{1}{2} b_n^* b_n \exp(-2i\Delta\phi) b_n = 0
\]

The nonlinear terms include self-phase modulation, cross-phase modulation and four-wave mixing (last term). Note that the relative phase \( \Delta\phi \) between the two beams affects the direction of energy flow between the two polarizations.

3. Samples

The wafers for the Al\(_{x}\)Ga\(_{1-x}\)As samples were grown by MBE at the University of Arkansas. The semiconductor Al\(_{x}\)Ga\(_{1-x}\)As has a bandgap which can be tuned by varying the Al concentration. The samples prior to waveguide etching consisted of a 1.5 \( \mu \)m thick guiding layer of Al\(_{0.18}\)Ga\(_{0.82}\)As, a 4 \( \mu \)m thick lower cladding region of Al\(_{0.24}\)Ga\(_{0.76}\)As, and a 1.5 \( \mu \)m thick upper cladding region of Al\(_{0.24}\)Ga\(_{0.76}\)As, both with a lower refractive index than the core region. Since the bandgap of the core material lies around 750 nm, the operating wavelength of 1540 nm lies below half the bandgap. These layers were deposited by MBE onto a GaAs substrate whose index is higher than that of the core waveguide at 1550 nm. This necessitated that the lower cladding layer to be thick enough to isolate the core region from the substrate. The GaAs substrate’s [0,0,1] axis was normal to the propagation plane for beam propagation along the [1,-1,0] axis. In our system, the slow axis \( (n_x) \) is associated with the TE polarization (parallel to the guiding film interfaces). On the other hand, the TM polarization sees an effective refractive index \( n_y \) that is smaller than \( n_x \) (fast axis).

![Sample cross-section and top-view image](image)

Fig. 4. (a) Sample cross-section; (b) Top-view image of an array (waveguide width \( w = 4 \mu m \), etch depth \( e = 0.2...1.0 \mu m \), waveguide pitch \( d = 6...11 \mu m \))

Such waveguides have been characterized extensively in previous work [12, 13]. The measured loss coefficient was about 1.5dB/cm and previous measurements of the nonlinearity in similar samples yielded \( n_L = 1.5 \times 10^{-13} \text{cm}^2 \text{W}^{-1} \) and \( \gamma = 5 \text{ m}^2 \text{W}^{-1} \), approximately equal for both TE and TM polarizations. Even though the excitation photon energy at 1550 nm was less than one-half the bandgap energy of the core, there is the equivalent of the Urbach linear absorption tail that also occurs for two photon absorption (2PA) so that there is always some
2PA present. Of course three photon absorption (3PA) is also present. The value of the
multiphoton absorption coefficients depends on the number of defects, the exact wavelength
relative to one-half the bandgap wavelength etc. In our samples this was deduced to be
\(7 \times 10^{-5} \text{ m}^{-1} \text{W}^{-2}\) by fitting it to the experimental data.

Selected slab waveguides required further processing by etching at the University of
Glasgow to form arrays of closely spaced rib waveguides. The coupling strength is
determined by the etch-depth \(e\) and the center-to-center separation \(d\) shown in Fig. 4.
Samples with coupling constants between 400 and 4000 mm\(^{-1}\) were manufactured by
varying both \(d\) and \(e\). Each sample consists of blocks of 5 arrays with either 101 waveguides
with separations ranging from 6 to 11 \(\mu\)m. The sample length varied between 2 and 10 mm. In
our samples the effective core area of each waveguide is \(19 \mu m^2\); the effective nonlinear
coefficient \(\gamma\) for these multi-core arrays was estimated to be \(5 \text{ m}^{-1} \text{W}^{-1}\). The linear
birefringence in every channel is estimated to be \(n_x - n_y = 1.8 \times 10^{-4}\).

4. Experimental apparatus

The experimental apparatus is shown in Fig. 5. It was built to be able to both vary the relative
phase between two input beams and their power under computer control. The source was a
tunable Spectra Physics OPG/OPA pumped by a amplified Ti:Sapphire laser. The system
produced pulses between 1300 and 3000nm of 1 ps at a 1 kHz rate with individual pulses
having energies up to 30 \(\mu\)J around 1500 nm.

![Experimental apparatus](image)

Fig. 5. Experimental apparatus. Inset: Input beam distributions used for the collinear
interactions (thick blue line) and waveguide modes (dotted line).

The individual pulses were split by a beamsplitter cube into two independent paths, each
of which forming an independent input beam into the sample. One path contains a delay line
to ensure overlap of the pulses at the sample. The second path contains a polarization rotator
(when needed) and piezoelectrically controlled mirror which allows the phase of this beam to
be adjusted with respect to the first path. By ramping the piezoelectric actuator in time, data
can be acquired over the full range of relative phase (0...2\(\pi\)). Each beam is transmitted
through a lens train so that an elliptical beam with a planar wavefront in both dimensions is
formed at the input facet of the waveguide or array. The excitation beams had a width of
16.5 \(\mu\)m (FWHM) and the sample a channel separation of \(D = 10 \mu m\), hence only three
channels were significantly excited. The two input beams had a center to center separation of
40 \(\mu\)m.
The radiation transmitted from the output facet of the sample was collected by a 20X microscope objective and split into three parts. The camera provides a real time output invaluable in lining up the system. The total energy transmitted is also measured for comparison with the input energy. The InGaAs linear array provides a very sensitive array detector with which even the outputs from a single pulse can be measured. It is nevertheless used in an averaging mode to provide the data shown later. The data is accumulated and manipulated on a computer.

![Graph showing intensity vs. waveguide number](image)

**Fig. 6.** Comparison of the measured discrete diffraction pattern (continuous line) with the best-fit prediction of the discrete wave equation.

The inter-channel coupling length in the array was evaluated by measuring the linear diffraction pattern obtained for single channel excitation. A typical diffraction pattern is shown in Fig. 6 and its analysis gave a coupling length of \( C = 715m^{-1} \).

5. **Nonlinear beam collisions in discrete arrays: co-polarized parallel beams**

The two input beams were input into the discrete array waveguides. The outputs observed are shown for two different sample lengths in Fig. 7. In both cases, the outputs of the two beams are shown to the far right when they are excited separately. The output pattern at each power level consists of a collage of many outputs obtained by scanning the relative phase between the two input beams. The successive figures in the movies contain such patterns at a number of progressively increasing power levels.

![Movies showing the measured array output intensity distribution](image)

**Fig. 7.** Movies showing the measured array output intensity distribution from (a) the 4mm sample and (b) the 8 mm sample as a function of phase difference between the two input beams. Power is increased from frame to frame and can be found in the upper left-hand-corner. Shown in the strips at the left-hand sides are the outputs when the individual beams are excited separately (no interaction).

At low input powers for which diffraction dominates, the output from the 4 mm long sample depends on the relative phase between the two beams in a fashion reminiscent of a phased array antenna, as discussed previously. The radiation at zero relative phase is maximum halfway between the centroids of the two input beams. For phase differences increasing from zero to \( \pi \), the center of the output radiation is deflected downwards. As \( \pi \) is approached, a small fraction of the output appears on the upper side and grows until at \( \pi \) the...
output is equally split on both sides of the center. Beyond \( \pi \) the signal on the upward side grows and is deflected downwards until at \( 2\pi \) phase difference only an output along the centroid of the input beams occurs. The only difference between the two samples is that the net deflection in the 8 mm sample is approximately twice that of the 4 mm sample, simply because the propagation distance and hence the diffraction is doubled.

As the input powers are (equally) increased, the outputs become progressively more localized to progressively fewer channels, especially for relatively phase near even (0, 2, 4 etc.) multiples of \( \pi \), but remain linear in the relative phase. The output becomes progressively more localized in the centroids of the input channels and the switching which occurs at odd multiples (1, 3, 5 etc.) of \( \pi \) becomes sharper. Further increase in input power increases further the power localized in these centroid channels (located at \( \pm 20 \) microns). In excess of 90% of the input power now appears localized in the two channels as highly localized solitons.

![Fig. 8](639 kB) Movie showing the theoretical (calculated) array output intensity distribution (cw assumed) from the 4mm sample as a function of phase difference between the two input beams. Power is increased from frame to frame and can be found in the upper right-hand-corner. No absorption effects were included in the simulations.

Around 1.2 kW the individual beams start to broaden again at the output. The key to this behavior is shown in Fig. 9. It is evident that multi-photon absorption begins to decrease the channel throughputs and flatten the peak intensities. As a result, the fraction of power in between the strongly localized solitons starts to increase again. By about 1.5 kW peak power input, the two interacting beams start to break into filaments. This persists to the highest input powers used.

![Fig. 9](150 kB) The total throughput power from the array as a function of increasing input power

The behavior for the longer sample, 8 mm, is quite similar, especially from low input powers up to the soliton threshold. However, the localization into the initially excited waveguides occurs only for excitation with out-of-phase beams. For in-phase excitation, the
two beams continue to collapse into one waveguide, with the position of the waveguide varying with relative phase. This observation is consistent with the simulations shown in Fig. 1.

6. Nonlinear collisions between orthogonally polarized blocker solitons and beams

Collisions were also investigated between “blocker” solitons and a signal beam. The blocker solitons are essentially high power solitons whose power is localized essentially to a single channel. The signal beam direction coincided with diffraction-less propagation across the array, including the blocker channel. It has been predicted that such interactions could be useful for 3D reconfigurable interconnects [14, 15]. The key operations are the “dragging” of the blocker beam channel by channel, and the partial reflection of the signal by the blocker, see Fig. 10. In fact, the interaction between co-polarized blockers and signals has been reported elsewhere [11]. Here experiments with orthogonally polarized beams were performed. These allow new features of this interaction like the effects of four-wave mixing and polarization instabilities to be isolated and investigated.

The experimental setup was identical to the one used previously but the polarization was adjusted to excite the TE modes for the blocker soliton and the TM modes for the signal beam with a wider beam. The power in either polarization was monitored at the input and output of the sample. To be able to take pictures of the two beams separately, a polarizing filter with 1:500 extinction ratio was placed before the InGaAs camera. Images have then been taken separately for both the TE and TM polarization. The two input beams are shown in Fig. 11. The TM beam has been placed close to the TE beam and then clipped on the left side by a razor blade (at the focus after the first lens in the beam-shaping setup) to avoid spatial overlap between the two beams. The grey line in Fig. 11 indicates the modes of the waveguide array used. For this experiment an 8 mm long array with 10 µm pitch and a coupling constant of $C = 715$ $m^{-1}$ was used.

The relative phase between the two beams was scanned by a piezo-electric actuator in one beam path. Images showing the outcome of the interaction and its dependence on the relative phase are shown in Fig. 12(a) (TE polarization) and 12b (TM polarization). The small images on the left side of the frame show the two input beams for both polarizations. Those on the right depict the output beams in the absence of the second polarization. The results of the interactions are shown in the central images. These pictures represent the output intensity distribution as a function of the beams’ relative phase angle at the input, and successive frames have been taken for increasing signal power. Note that the images for the two polarizations have been taken sequentially. Although the voltage on the piezo used to scan the phase difference is always set to the same values, hysteresis in the piezo and random changes in the setup introduce a small random phase-shift between the two images.
Fig. 11. Shape of the two input beams for orthogonally polarized blocker experiments. The grey line indicates the modes of the array.

At the lowest power level of 49 W for the signal beam, it was impossible to drag the blocker soliton. One can see that a part of the signal was reflected off the blocker and showed up on the input side of the signal. The most striking effect in this case was however the sudden appearance of energy at the blocker location in the TM polarization. This is an effect of FWM which gives rise to an amplification of the TM signal when the blocker and signal beam spatially overlap and is observable for all signal powers lower than the blocker power. This is also related to the polarization instability of a soliton in the presence of FWM effects [8,16].

For a signal power of 460 W the blocker was dragged towards the signal for some phase angles. Doubling the signal power showed blocker dragging by one waveguide site for all phase angles. Further increase of the signal power to 1.5 kW and 3 kW resulted in phase-dependent dragging of up to two and four waveguide sites, respectively. Note that even for a shift of four waveguides the blocker soliton maintains a tightly confined shape.

Fig. 12. (840kB) Movie of the experimentally observed output beams for the TE (left) and TM (right) polarizations. The narrow images on the far left show the input beams, the narrow images on the far right depict the output beams when only one beam is present. The two images in the center show the output beams for TE (left) and TM (right) polarization when their relative phase is varied.

The power exchange due to FWM is shown for two examples in Fig. 13. The black line shows the linear interference between the two beams at the input as the relative phase is ramped. For this curve the polarizer in front of the InGaAs camera was set to 45º and the input beams were spatially overlapped. The red and blue curves show data taken at the output of the
sample for the interaction geometry when the input TM power was 3.06 and 0.83 kW respectively. Note again that this data has been taken sequentially and the actual absolute phase-relation could be shifted by a small amount. The periodic energy exchange between the two polarizations is clearly visible. This energy exchange happens at twice the frequency of the linear interference, a signature of FWM.

Fig. 13. Power Exchange due to FWM. Black: linear interference. Blue: TE and TM beam power for a signal power of 873 W. Red: TE and TM beam power for a signal power of 3.06 kW

7. Summary

The interaction between high power beams in 1D arrays of channel waveguides have been investigated for two beam geometries. When the two input beams were injected for parallel propagation, three regimes of response were observed. At low powers, the output beam center was scanned across the array when the relative phase was varied, with two distinct beams occurring at π phase difference. As the input power was increased, the scanned beams became progressively more localized. Finally, at high power levels, two parallel localized discrete solitons were generated, centered on the input channels with maximum input intensity.

The second geometry studied involved the collision of a blocker soliton with an orthogonally polarized signal beam traversing the array in the direction associated with zero diffraction. The theoretically predicted behavior, namely the dragging of the blocker by an integer number of channels and the partial reflection of the signal beam were both observed and their variation with relative phase between the two beams was measured.

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