Nonlinear Optical Beam Interactions in Waveguide Arrays

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We report our investigation of Kerr nonlinear beam interactions in discrete systems. The influence of power and the relative phase between two Gaussian shaped beams was investigated in detail by performing numerical simulations of the discrete nonlinear Schrödinger equation and comparing the results with experiments done in AlGaAs waveguide arrays. Good agreement between theory and experiment was obtained.

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The nonlinear interaction between waves is a ubiquitous phenomenon in wave propagation. In continuous media it has led to the production of harmonics in optics, acoustics, plasmas, etc. [1]. An incredibly rich field has been nonlinear optics because nonlinear effects are readily accessible with the powers available from lasers and because the samples and the conditions for experiments can be controlled precisely [2]. As a result, the nonlinear interaction in bulk media (homogeneous in two dimensions) and guiding geometries (homogeneous in one dimension) such as fibers, slab waveguides, etc. are very well understood both experimentally and theoretically [2,3]. Numerous unique nonlinear waves, like solitons, with fascinating properties not available in linear media have also been predicted and observed [4,5]. For 1D Kerr spatial solitons, for example, the local nonlinear refractive index distribution created by a beam of finite width and high intensity (I) in a self-focusing medium ($\Delta n = n_2 I$) leads to a concave shaped phase-front and self-focusing of the beam [4,5]. This effect arrests beam spreading due to diffraction resulting in robust nonlinear eigenmodes, i.e., solitons. This beam localization can occur in space and/or time, or both [4,5].

One- or two-dimensional discreteness in optical media has recently been shown as a way to control both dispersion and diffraction [6]. The equivalent of diffraction has been demonstrated in arrays of weakly coupled channel waveguides. The mechanism is the coupling between two adjacent waveguides due to the evanescent field from one waveguide overlapping in space its neighboring waveguides. Neighboring waveguides are locally excited with a phase shift of $\pi/2$ which leads in certain limits to diffraction phenomena unique to discrete systems. If only a single channel is excited, the resulting "diffraction" pattern is peaked at the extremities and exhibits a minimum in the middle, in sharp contrast to diffraction in homogeneous media where the beam spreads but keeps approximately its "bell" shape [7]. When many discrete channels are excited with the same phase, the diffraction pattern associated with a "continuous" medium is recovered. For intermediate number of channels, the diffraction is intermediate between these two limits, and can appear "square-wave" like, for example.

In arrays made from nonlinear media, this spreading of optical power throughout an array can be arrested by optically changing the local coupling conditions between channels [8]. The propagation constant is higher in the channel with larger intensity which affects the interchannel coupling efficiency via a non-$\pi/2$ relative phase accumulation. Similar to continuous systems, this leads to stable solitons also in discrete systems [5]. This phenomenon was predicted to occur in Kerr, quadratic, and photorefractive media and indeed experimental verifications have recently appeared [8–13]. However, these discrete systems form a nonintegrable system, even in one-dimensional arrays composed of Kerr nonlinear media, and have many different properties when compared to their continuous counterparts [5].

Since diffraction, especially for highly localized beams, is different in arrays than in continuous media, this will change the efficiency and nature of nonlinear interactions. For example, the directional sideways diffraction will increase the interaction between initially separated beams while maintaining a high local intensity. This contrasts with the interaction between initially strongly localized beams in homogeneous media whose peak intensity drops rapidly with distance. To date, although the interaction between waves guided in discrete 1D systems has received limited theoretical attention [5], [14–16], no experiments have been reported. In this Letter we report the first observation of discrete beam nonlinear interactions in any system. Specifically, we have investigated the interaction between two parallel beams and its dependence on the relative phase and input power in a one-dimensional array of channel waveguides exhibiting Kerrlike nonlinearity.

Consider two co-polarized elliptical beams to be focused at normal incidence onto the entrance facet. Assuming that there is no coupling to leaky modes in the underlying film or the radiation fields in the substrate,

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the propagation of radiation in the 1D nonlinear waveguide array can be modeled by the discrete nonlinear Schrödinger equation (DNLS) [5,8].

$$i\frac{da_n}{dz} + C(a_{n+1} + a_{n-1}) + \gamma|a_n|^2 a_n = 0. \qquad (1)$$

Here, a_n is the peak amplitude of the field in the nth channel, C is the coupling coefficient between the nearest neighbor channels $n+1$ and $n-1$, and γ is the self-phase modulation nonlinear coefficient, averaged over the field distribution of an individual channel. The distance required for complete transfer between two adjacent isolated channels due to evanescent field overlap is $\pi/2C$. The initial field is written as

$$a_n(z=0) = I_0[f(n-n_l) + f(n+n_r)\exp(i\Delta\phi)], \qquad (2)$$

where $f(n)$ is the envelope function of the individual beam, $n_l + n_r$ is the separation of the beams, the center of the array is the $n = 0$ channel, and $\Delta\phi$ is the initial phase difference between the beams.

Equation (1) was numerically evaluated for the conditions of our experimental setup. We assumed a Gaussian shaped excitation field with $n_r = n_l = 2$ and a full width at half maximum (FWHM) of 1.6 channels. Continuous wave (cw) input beams were assumed. The array itself consists of sets of 101 identical, parallel, AlGaAs channel waveguides. Such arrays have been used previously to demonstrate scalar discrete bright solitons for near normal incidence and self-defocusing near the edge of this periodic structure's Brillouin zone [9,17]. The array sample was 4.0 mm long, with a channel separation $D = 10\ \mu$m and a coupling constant $C = 715\ \mathrm{m}^{-1}$, corresponding to an effective sample length of 1.9 coupling lengths. The propagation losses were measured to be 1.5 dB/cm. The nonlinearity n_2 has been measured previously to be self-focusing Kerr ($n_2 > 0$) for photon energies just below one half the semiconducting band gap with small multiphoton absorption [18]. From the nonlinear refractive index and the effective mode area, a nonlinear coefficient $\gamma = 5\ \mathrm{m}^{-1}\mathrm{W}^{-1}$ is found.

The variation at the output with input power, shown at three phase angles in Fig. 1, exhibits three distinct regimes. The linear regime (I) is dominated by discrete diffraction which depends on the relative phase between the input beams, similar to interference in homogeneous media. Discrete self-focusing occurs over a narrow power range (region II), producing one or two narrow beams, depending on the relative phase. In region III, at high powers, the two input beams become self-trapped primarily in their center excitation channels.

These predictions were tested experimentally. The relevant details of the experimental geometry are shown in Fig. 2. The light source was a Spectra Physics OPA-800CP which produced 1.1 ps FWHM pulses at a 1 kHz repetition rate. The signal beam from the OPA was split into two beams and shaped using cylindrical lenses to form two elliptical spots at the input surface of the sample. Translation and rotation of mirror M allowed adjusting the position and angle of the second beam relative to the first. The input power distribution for the incident beams is shown in the inset of Fig. 2. The inputs had a center-to-center separation of 40 μm (corresponding to four channels), and a measured FWHM of 16.5 μm (hence, only three channels were significantly excited). The spatial intensity distribution at the sample output was observed using a highly sensitive InGaAs line camera and a vidicon camera. The InGaAs camera allowed observation over a large dynamic range on a single shot basis while the 2D vidicon camera was necessary for alignment purposes. The input power of one beam and the total output power was monitored using germanium photodiodes. The power of the second beam was adjusted to have the same throughput as the first beam. The temporal overlap of the pulses could be adjusted with a delay line in either beam path and the relative phase between the beams was varied using a piezoelectric actuator. The partial overlap of the two beams resulted in about 3% intensity modulation at the sample output.

The experimental outputs for intermediate and high powers are shown in Figs. 3(a)–3(d) as a function of phase difference. The results are striking. At intermediate powers [Figs. 3(a) and 3(b)], the output is localized to a few channels whose position varies linearly with the phase difference and repeats every 2π. At zero phase

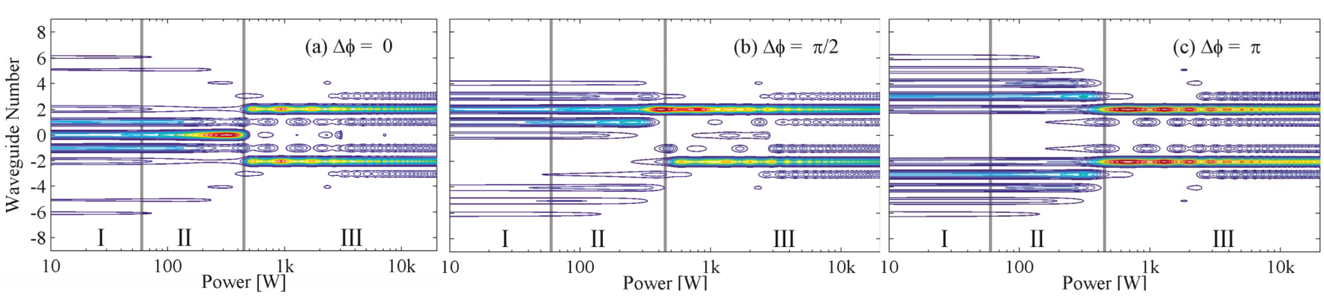

FIG. 1 (color online). cw calculations of the waveguide array output versus the total power for each input beam (assumed Gaussian) at the relative phase angles of (a) $\Delta\phi = 0$, (b) $\Delta\phi = \pi/2$, and (c) $\Delta\phi = \pi$. The powers are for the AlGaAs samples investigated.

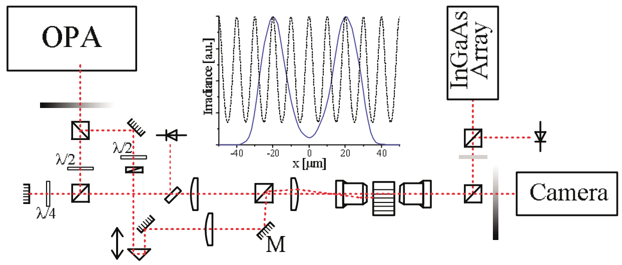

FIG. 2 (color online). Experimental apparatus. Inset: Input beam distributions (thick line) and waveguide modes (dotted line).

difference, the input beams self-focus into a spot on the zero channel ($n = 0$), similar to the slab waveguide case [19,20]. As the phase angle is increased or decreased, the spot moves in one direction ($n > 0$) or the other ($n < 0$), respectively. In the slab case, there is a similar imbalance for the interaction of two output solitons, but a significant fraction of the input power always appears on the "weak" side [20]. As $|\Delta\phi|$ is increased, at around $\pi/2$ and $3\pi/2$ phase difference, a small fraction of the energy begins to appear on the opposite side of the strong beam. At $\Delta\phi = \pi$ the calculated output is split equally between two wide beams displaced symmetrically about the zero channel, again similar to the slab case. This unidirectionality of the output is potentially useful as a beam scanner. As the power is increased, the beams become progressively more localized, the fraction of input energy on the "other" side of the zero channel decreases, and the focusing into primarily a single channel at the output extends to larger $|\Delta\phi|$. Here the central few channels correspond to spatial solitons and are strongly localized. Increasing the input power extends the range over which discrete solitons are observed. In these regimes, the beam output position is linear in the phase difference. These pulsed laser results are in excellent agreement with the cw simulation shown in Fig. 4(a).

The situation changes dramatically when the incident intensity is increased yet again into response region III, Fig. 3(c) and 3(d). The "scanning" behavior disappears and the output is strongly localized as discrete solitons in each of the center channels of the initial excitation. Changing the relative phase through multiples of π results in a periodic energy transfer from one localization channel (for example, n_r) to the other (n_l). The surprising aspect is that there is essentially very little energy in other channels, especially the ones intermediate to the two discrete soliton channels. These results are in excellent agreement with the simulation shown in Fig. 4(b), despite the pulsed versus cw nature of the experiment and simulations, respectively. Experiments at even higher input powers exhibited strong multiphoton absorption.

In summary, we have reported the first investigation of nonlinear optical interactions between two beams guided in discrete waveguide arrays. For excitation of just a few

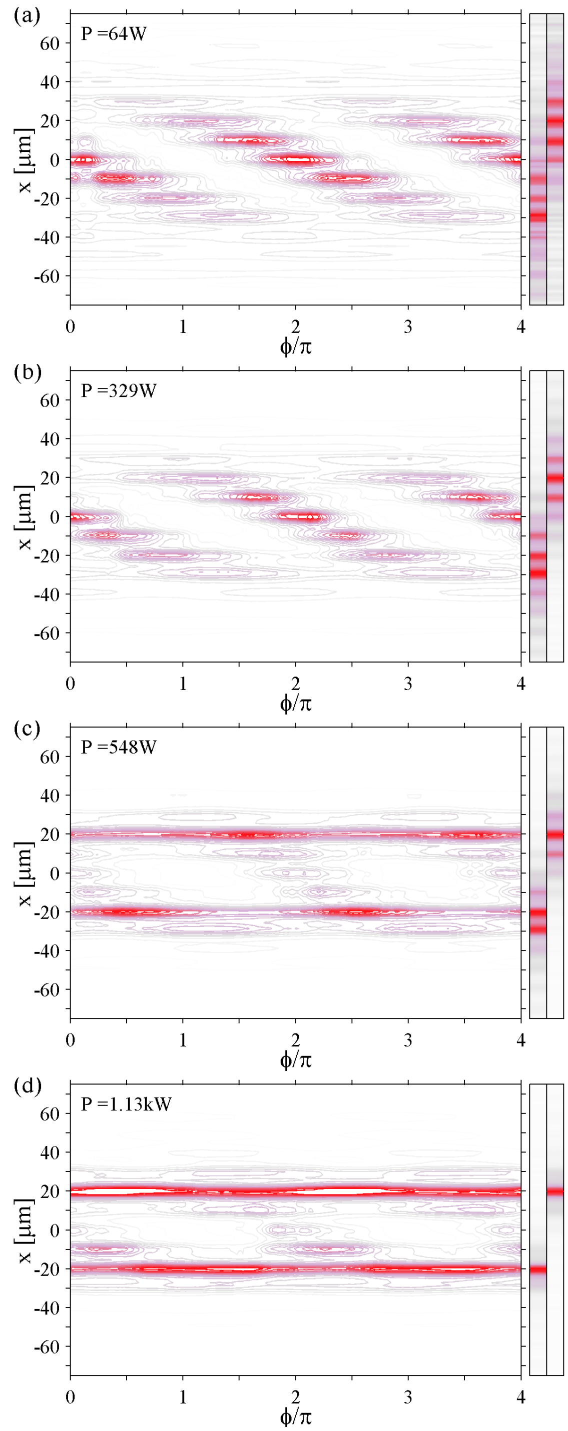

FIG. 3 (color online). Array output versus relative phase at four different peak input channel powers. (a) and (b) are in the intermediate power region II. (c) and (d) are in the high power region III. Shown on the right is the output energy distribution for each beam alone.

channels, the nonlinear effects are manifest at relatively low input intensities. The output, including the formation of single discrete solitons, varies strongly with the relative phase of the interacting beams. New phase-

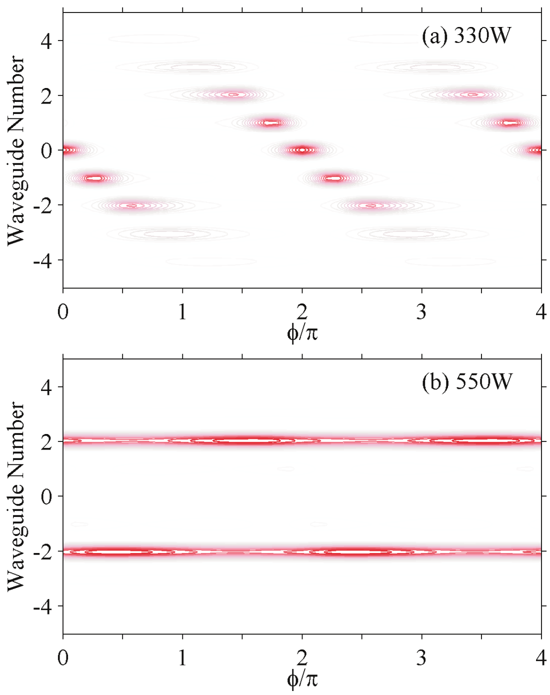

FIG. 4 (color online). cw simulations for cases (b) and (c) shown in Fig. 3.

controlled effects such as the scanning of strongly localized beams across the array and switching between well-separated channels containing discrete solitons were observed.

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