Observation of Spatial Cross-Phase Modulation Effects in a Self-Defocusing Nonlinear Medium

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We report on experimental observations of spatial modifications, induced by the Kerr effect, in the profile of a weak probe beam due to a cross-phase modulation from a strong pump beam. The measurements were performed in a self-defocusing nonlinear medium (semiconductor doped glass) where the observation of induced focusing and spatial modulation instability were made possible. The experimental results are in good agreement with numerical simulations.

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The effects of the Kerr nonlinearity have been well studied through a variety of nonlinear optical processes. Over the years [1-5] considerable attention has been devoted to theoretical and experimental studies in bulk (liquids, solids, or gases) media. Self-focusing, self-defocusing, and self-phase modulation are perhaps the most well studied optical manifestations of the Kerr effect, first reported a few years after the advent of the laser. While self-focusing (or self-defocusing) is related to spatial changes in the beam profile, self-phase modulation describes the spectral changes suffered by a light pulse, both propagating through a so-called Kerr medium. Therefore, a close space-time analogy exists between the propagation of a pulse in a dispersive medium in the presence of self-phase modulation and changes in the transverse beam profile due to diffraction effects in a self-focusing (or self-defocusing) medium. Another effect, the self-bending (or self-deflection) of a beam due to the Kerr effect, first proposed by Kaplan [6], has been recently observed using a cw beam [7]. Self-focusing of optical pulses in optical fibers has been clearly identified [8], and spatial optical solitons have also been reported using nonlinear glass waveguides as the propagating media [9,10].

Although we so far referred to the self-action effects related to the Kerr nonlinearity, whereby a single beam is spatially or spectrally modified due to an intensity-dependent refractive index, two copropagating or counterpropagating beams of different wavelengths can induce spectral and/or spatial modifications on each other. The physical mechanism behind this phenomenon is the cross-phase modulation (XPM), through which the phase of an optical beam is affected by other copropagating beams [11]. XPM has been well studied in the spectrotemporal regime, where the mathematical description between two copropagating beams is provided by a coupled amplitude equation, and several experiments have been reported, particularly in optical fibers [12]. Spatial effects due to XPM are not so common. In recent reports, it has been proposed by Agrawal [13,14], following the space-time analogy, that XPM in the spatial domain should lead to novel transverse instability and focusing effects induced by copropagating beams, with similar predictions for counterpropagating beams [15]. It is the purpose of this Letter to report on the experimental verification of some of those theoretical predictions, which we corroborate with numerical simulations. In particular, we describe observations of spatial XPM from a strong pump beam to a weak probe beam of different wavelength verifying the occurrence of the intriguing effect of induced focusing of the weak beam by the strong beam while both propagate in a self-defocusing medium [13]. An experimental observation of induced focusing was recently reported in an atomic vapor [16].

We also present for the first time measurements of what is described [14] as the equivalent in space of the spectral modulation instability, i.e., spatial frequency sidebands are generated in the probe beam profile induced by the pump beam. Moreover, we demonstrate the possibility of beam deflection control based on the spatial XPM effect.

The experimental scheme used is depicted in Fig. 1. The second harmonic of a Q-switched and mode-locked Nd:YAG laser was used. Each Q-switched burst consists of about 20 pulses of 80-ps duration separated by 10 ns. The available average (peak) power was 120 mW ($\sim$360 kW) and the Q-switch repetition rate was 200 Hz. The laser beam was split through a beam splitter BS1 ($\sim$10% reflection at 532 nm) and the weaker part was used to generate, through the stimulated Raman scattering [17] in a 14-m long monomode fiber, radiation Stokes shifted to longer wavelengths. A filter is employed to separate the wavelength corresponding to the first Stokes at 544 nm, which was used as the weak probe beam. The

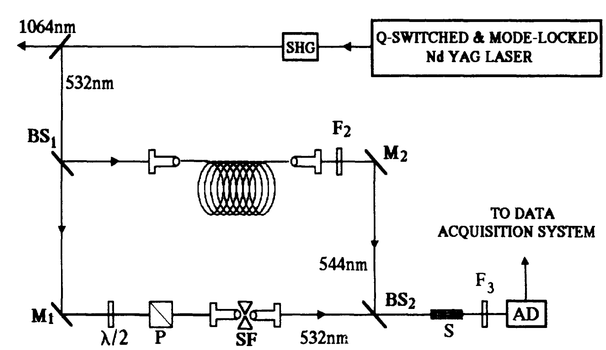

FIG. 1. Experimental setup. S is the nonlinear sample used (Corning CS 3-69). M_1 and M_2 are mirrors. The other symbols are explained in the text.

remaining strong beam at $\lambda_2=532$ nm was spatially filtered and combined, through beam splitter BS2, to copropagate with the probe beam. A careful adjustment of the temporal overlap between the pulses was done. The power of the pump beam was controlled using a $\frac{1}{2}$-wave-plate-polarizer (P) combination before the spatial filter (SF). The beam overlap on the sample was adjusted using the output objectives of the fiber (×40) and the spatial filter (×60). The measured beam waist at the sample position was 90 μm for the pump and 120 μm for the probe beam. The Rayleigh lengths were ~5 and 8 cm, respectively.

A commercially available semiconductor doped glass (Corning CS 3-69), 5 cm long, was used as the nonlinear sample. This material, well known for its large resonant nonlinear response $\chi^{(3)}\sim 10^{-8}$ esu, has been well characterized [17-19]. For the wavelengths used in this work $\mathrm{Re}\chi^{(3)}$ is much larger than its imaginary part [20], and the value of n_2 is estimated $\sim 10^{-14}$ cm^2/W.

The beam profiles were analyzed using a linear 1024-photodetector array, whose output was sent to a digital oscilloscope and transferred to a microcomputer. The diode array was placed ~1 cm behind the sample in order to measure the near-field profile of the transmitted beams. The probe beam was weak enough not to be affected by self-defocusing, while the pump beam is strong enough to be self-defocused. The filter F_3 was used to block the pump beam.

The interaction between the two beams in the nonlinear medium can be described solving numerically the following coupled equations [13,14]:

$$\frac{\partial A_1}{\partial z}-\frac{i}{2K}\frac{\partial^2 A_1}{\partial x^2}=\frac{iKn_2}{n_0}(|A_1|^2+2|A_2|^2)A_1, \quad (1)$$

$$\frac{\partial A_2}{\partial z}-\frac{i}{2K}\frac{\partial^2 A_2}{\partial x^2}=\frac{iKn_2}{n_0}(|A_2|^2+2|A_1|^2)A_2, \quad (2)$$

where A_1 and A_2 are the slowly varying envelope amplitude of the pump and probe beams, $K=2\pi n_0/\lambda$, n_2 is the nonlinear refractive index and z and x are the longitudinal and transverse coordinates, respectively. The drawback of this model is that it takes into account only one dimension, which is suitable for geometries like in planar waveguides, but do not allow good quantitative comparison in experiments performed in bulk material [16]. However, very good qualitative agreement is obtained, with the values used in the simulation within the order of magnitude for the relevant experimental quantities. We also assume input Gaussian profiles. The equations were solved using the commonly employed split-step method (see Ref. [14]).

Figure 2(a) shows the measured pump beam profile after propagation through the sample. The presented results, obtained for two incident pump intensities, show a spatial broadening by a factor of 2 due to the negative nonlinear refractive index of the sample. For intermediate powers smaller broadening factors were observed.

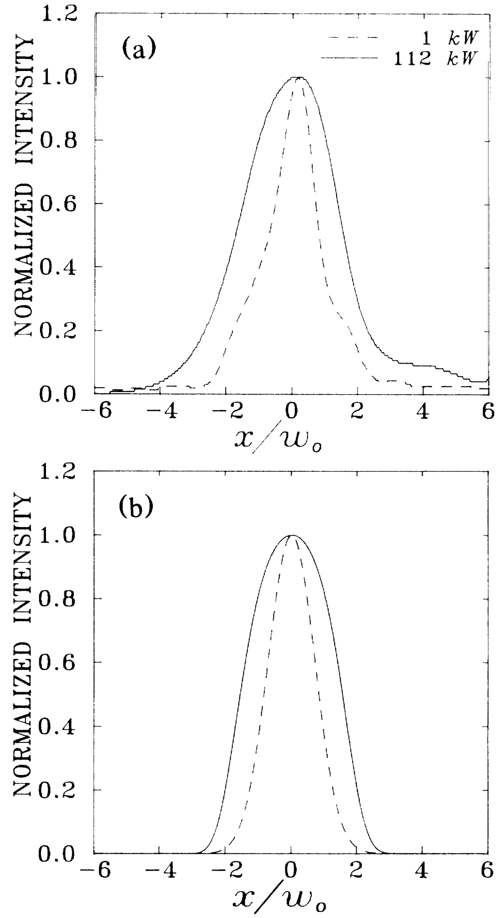

FIG. 2. (a) Experimentally recorded evolution of the pump beam profile exhibiting self-defocusing; (b) calculated evolution of the pump beam profile for the same powers as in (a).

For comparison, Fig. 2(b) shows the calculated beam profile for 1 kW (dashed line) and 112 kW (continuous line) peak power, corresponding to the experimental value and $n_2=10^{-14}$ cm^{2}W^{-1}.

To examine the XPM effect imposed on the probe beam by the strong beam, we analyzed the probe beam profile as a function of the pump intensity and as a function of the spatial overlap between both beams. The two beams were aligned to copropagate along the sample. A careful adjustment of the beam overlap allowed us to move the pump laser across the profile of the probe beam, such as to either properly overlap, or to overlap only in the wings of the beam profile. Figure 3(a) shows the probe beam profile when the beams are overlapping partially. As can be observed, a profile "compression" (focusing) of the probe beam by a factor of 2 occurs and a shift of $0.5W_0$ was measured. This behavior was discussed in Refs. [13,16] for the case of partial overlap between the beams. The focusing of the probe beam occurs as a result of the XPM induced phase shift imposed on the probe by the pump. It is important to notice that, for the same conditions, the pump beam exhibits self-

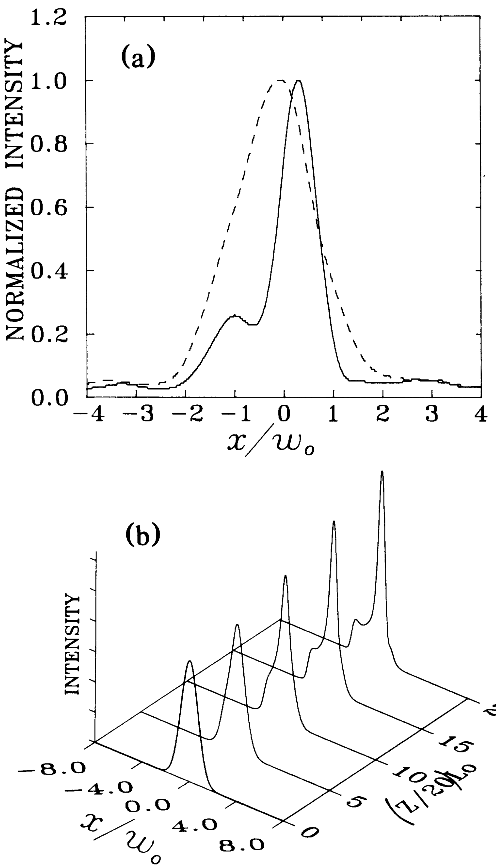

FIG. 3. (a) Transverse probe beam profile after propagation through the nonlinear medium without the pump beam (dashed line) and with the pump beam (solid line). The beams copropagate along the sample and the overlap occurs only in the wings of the beams profile. (b) Evolution of the probe beam profile as calculated using the set of coupled equations [Eqs. (1) and (2)] using $n_2 I = 10^{-4}$ and normalized to L_0, the length of the Kerr medium.

defocusing as illustrated in Fig. 2. Qualitatively the induced focusing effect and beam shift are explained considering that a portion of the probe beam is contained in the region where the pump-beam phase front becomes negative. This effect is related in nature to the self-bending effect [6,7] because they arise from the Kerr nonlinearity. Notice, however, that in our case the underlying physical mechanism exploits the XPM between two beams rather than a self-action process. The oscillatory wing in Fig. 3 is the spatial analog of optical wave breaking [16]. Figure 3(b) shows the calculated probe beam profile evolution, normalized to the beam waist, where the shape at the output closely resembles the experimental one. Figure 4 shows the weak beam profile when it is exactly overlapped with the strong beam. Notice that when the pump beam is present the probe spreads, but unlike in Fig. 2 symmetrically displaced lateral spatial lobes at $\pm 0.5 W_0$ are observed when the pump beam power is 112 kW. This is, to our knowledge,

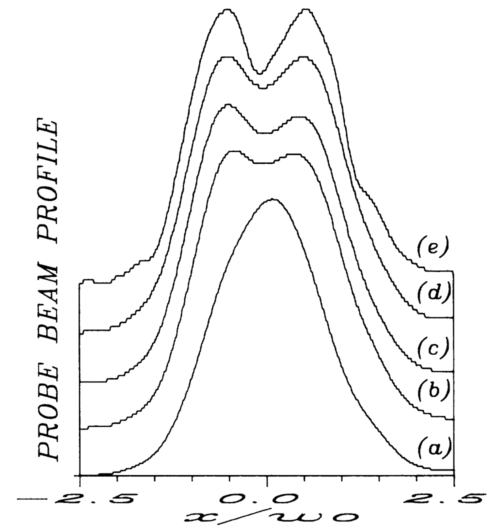

FIG. 4. Transverse probe beam profile after propagation through the sample in the presence of the pump beam. The centers of the two copropagating beams are coincident. Pump peak powers: (a) 0; (b) 28 kW; (c) 56 kW; (d) 84 kW; (e) 112 kW.

the first observation of such an effect. Detection of larger peak separation was limited by the available power. Also in this situation the probe is too weak and does not influence the pump beam in a significant way. We corroborate again our measurements with calculations based on Eq. (1). This is shown in Fig. 5, where the probe profile evolution is calculated as a function of pump power using values approximately equal (within 10%) to the experimental ones. A very good qualitative agreement is observed.

These experimental and numerical results corroborate the calculations presented in Ref. [14] which predicted

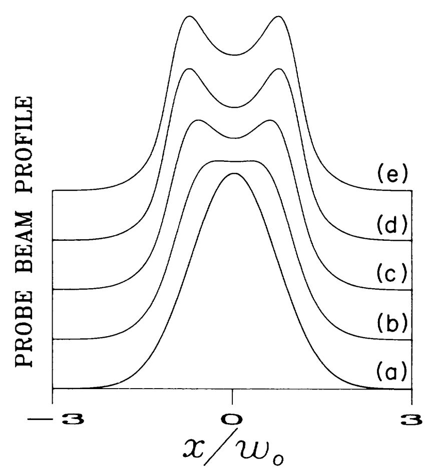

FIG. 5. Numerically simulated results corresponding to the experimental data of Fig. 4. Relevant quantities used for the fitting are $n_2 = 10^{-14}$ cm^2/W, interaction length 5 cm, and peak power as in Fig. 4.

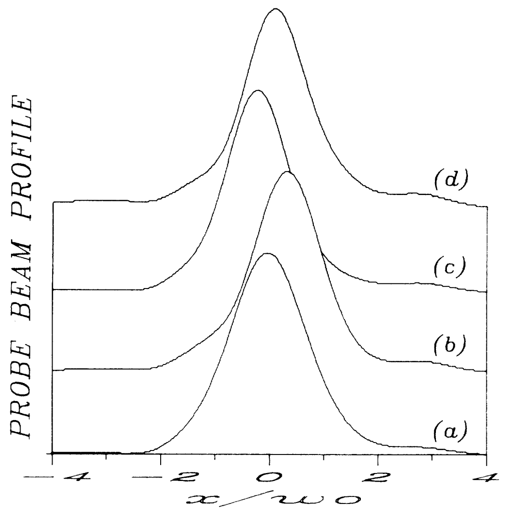

FIG. 6. Probe beam deflection modulation. In (a) only the probe beam is present. For (b) and (c) the overlap between the probe and pump beams is occurring either in the right or the left wings of the probe; and in (d) the probe beam returns to its original direction when the right and left pump beams are simultaneously present.

that when the two copropagating beams are exactly overlapped in a self-defocusing medium, the weak beam indeed spreads out but new spatial frequencies are generated, which finds similarities with the modulation instability in the spectral regime.

Figure 6 shows the results of a further experiment performed to demonstrate the potential of the herein reported effects to applications of spatial beam deflection modulation. The results presented show the occurrence of spatial deviation of the probe beam due to the presence of two strong beams overlapping with the probe in its right and left wings, respectively. In this experiment the two strong beams at 532 nm were obtained splitting the original pump in two beams having equal intensities. Figure 6(a) shows the transmitted probe profile in the absence of the pump beams. No self-action occurs because the probe beam intensity is kept as small as in the other experiments. Figures 6(b) and 6(c) illustrate the probe spatial shift induced by each pump beam when the other is blocked. Notice the spatial shift of $\sim \pm 0.25 W_0$ for the right and left of the original probe direction obtained with a peak power of 30 kW in each pump beam. In Fig. 6(d) we show that it is possible to compensate for either deviation when the two pump beams are simultaneously present. Since the pump beams have equal intensities the probe is not shifted from its original direction exhibiting a small compression. In fact, the two pump beams induce an optical waveguide to the probe beam through XPM. We stress that it all occurs in a self-defocusing medium.

In conclusion, we have verified the novel phenomena of induced focusing and spatial modulation instability and induced optical waveguide occurring in a self-defocusing medium due to the XPM effect. The phenomena are quite general and can be observed in any material medium exhibiting a large Kerr nonlinearity. The possibility of spatial light modulation in the picosecond regime was also demonstrated. The reported effects can be further exploited for studies of ultrafast phenomena such as optical bistability and logic operations for optical computing. Numerical simulations supported the experimental results.

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