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Microsecond infrared beam bending in photorefractive iron doped indium phosphide

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A time resolved study of the behavior of a single beam in photorefractive iron doped indium phosphide is provided down to the microsecond range, showing that infrared beam bending does occur on the microsecond time scale for moderate beam intensities. Two distinct time scales are evidenced, the behavior of which are the sign of two different photorefractive mechanisms.

1. Introduction

Self-focusing of a laser beam in a photorefractive (PR) material is a process that leads to the formation of waveguides in bulk crystals. Under the right conditions, such a self-focused beam can propagate as a spatial soliton [1,2]. Since their first observation [3,4], the PR solitons have been modeled and the models found their experimental validations. As such, their properties are well known in typical PR materials (such as SBN, $Bi_{12}TiO_{20}$ and $BaTiO_3$ [5–8]), in which the PR effect is due mainly to only one type of charge carriers and occurs at visible wavelengths: the dynamics of self-focusing and soliton formation have been studied and characterized at steady state [9–12] as well as in transient regime [13,14].

However, all the materials that obey this *one carrier* model have somewhat slow dynamics: the fastest of them, tin hypothiodiphosphate ($Sn_2P_2S_6$) has time reactions above 10 ms for intensities above 100 W/cm^2 [15]. Obtaining a photorefractive self-focused beam in a shorter time requires either going to really high beam intensities (MW/cm^2) [16] or change the material type towards semi-conductors such as iron doped Indium Phosphide [17] where microsecond response times can be obtained for intensities as low as a W/cm^2, paving the way for information all-optical routing in telecommunication networks.

Indeed, as was shown previously [18], two self-focused beams can interact with each other in a nonlinear way, literally colliding with each other. Therefore, if fast enough build-up is achieved, an all optical beam steering device can be based upon the collision of a rapidly modulated signal beam and a control beam. The resulting device would be transparent to high frequency signal modulation and would allow beam steering with no moving part.

This particular light configuration, consisting of two distinct beams on a dark background is essentially nonperiodic and high contrast, while two-carrier-photorefractivity has been studied and understood two decades ago [19–22] in the framework of periodic illumination only. Its behavior under low nonperiodic illumination has been inferred from the previous works [23]. However, its precise behavior under high contrast nonperiodic illumination still remains to be fully understood, building on a partial previous model [24], full 3D numerical simulations [25] and steady-state experiments [26].

In this paper, a time resolved experimental analysis of a single beam bending behavior in a biased photorefractive InP:Fe sample is proposed for two different wavelengths. One beam, of wavelength either 1.06 or 1.55 μm, is shone on an iron doped indium phosphide sample and its behavior is analyzed in a time resolved fashion below the microsecond range. The best solution for this analysis would be to make a movie imaging the beam on the crystal output face, using an infrared high speed camera. However, as we aim to a time resolution below the microsecond, this solution is very expensive. We have thus devised a cheaper, yet insightful, method based on a position detector. In the following sections, the experimental apparatus will be detailed, followed by measures as functions of beam intensity, background homogeneous intensity and temperature, for the two wavelengths whenever possible.

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2. Experimental setup

The experimental setup we used is similar to one that was previously published [26]: a Gaussian free space laser beam either issued from a 1064 nm CW Nd:YAG laser or from a Continuous Wave (CW) 1.55 μm free space collimated Laser Diode is spatially filtered and switched on and off using an acousto-optic modulator. Two different acousto-optic modulators were used for the two wavelengths, both have a rise time of 500 ns. The laser beam is focused down to a 25 μm waist on the entrance face of a 10^{17} doped InP:Fe sample, as measured from Secondary Ion Mass Spectroscopy. As in a previous experiment [26], the InP sample has dimensions $10 \times 5 \times 5$ mm^3 along the axes $\langle \bar{1}10 \rangle \times \langle 110 \rangle \times \langle 001 \rangle$ respectively. As was also suggested previously [24,25,27,28], the beam propagates along $\langle \bar{1}10 \rangle$ axis and is polarized along $\langle 110 \rangle$ axis. The crystal is thermally stabilized with a Peltier cell. Finally, a steady 10 kV/cm external electric field is applied along the $\langle 001 \rangle$ axis: during all the experiments, the electric field is kept on and the laser beam is switched on and off using the acousto-optic modulator.

The goal of this experiment is to get an insight on the temporal behavior of the laser beam on the output face of the sample from the time the laser is switched on, without using an expensive high speed camera. To this aim, the acousto-optic modulator is modulated around the Hertz; thus, the beam is on for 500 ms and off for the next 500 ms. The frequency is not of importance as long as the period (here around a second) is long enough so that the crystal has the time to reach its steady state after turning the beam on. Also, the frequency is low enough that the crystal has the time to fully relax in between two consecutive pulses.

The output face of the crystal sample is imaged on a high speed position detector, which is in fact, as shown in Fig. 1, a set of four photodiodes carefully adjusted to allow beam position tracking: by comparing the powers received on the four diodes, the beam center of gravity can be located. Furthermore, if an off-center beam focuses, the four powers measured by the position detector will change. Therefore, this setup allows us to monitor the self-bending and self-focusing of a beam. Only a centered focusing beam cannot be monitored. However, this last case is not likely, as previously found [25].

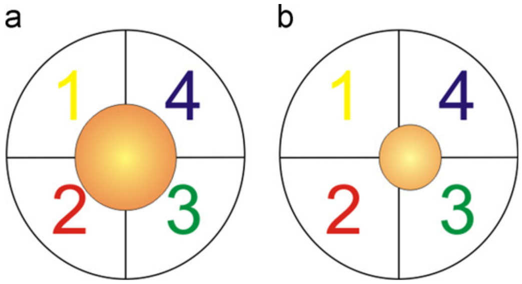

Fig. 1. The position detector four quadrants. When the electric field is off, the beam is centered (a). When the field is switched on, the beam is no longer centered, because of beam-bending, and can be self-focused (b). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

A typical measurement is shown in Fig. 2 where a beam deviates to the right, as shown in Fig. 1(b). Fig. 2(a) is a plot of the detector four signals without applied field. The measured powers are nearly equal and constant with time: the beam is centered on the detector and does not move. This measure serves as a reference. The fact that the four measured powers cannot be made equal by centering the beam more precisely on the detector is due to imperfections in the InP:Fe crystal, which alter slightly the Gaussian shape of the beam during propagation. A motion of the beam as the one that is shown in Fig. 1(b) leads to the four detected signals shown in Fig. 2(b).

In order to make systematic measurements of the beam motion on the detector, we considered the fact, given from previous theoretical and experimental literature [24–28], that the beam bends mainly in the direction parallel to the externally applied electric field—direction which corresponds to the horizontal direction in Fig. 1. We have therefore defined the *asymmetry* α as

$$\alpha = 1 - \frac{I_1 + I_2}{I_3 + I_4}, \tag{1}$$

where I_n is the optical power received on the photodiode numbered n in Fig. 1.

Thus, from the camera observation of steady state and the measurements issued from the detector, a time resolved measurement of the asymmetry can be deduced: for instance, the measurements shown in Fig. 2(b) lead to the asymmetry shown in Fig. 3. As such, any variation of the asymmetry is due to a combination of beam bending and focusing.

Finally and to conclude this description of the experimental setup, let us mention that measurements with a homogeneous *background intensity* are also included in this analysis, to complete previous steady state measurements [26]. As has been shown before [14], the background intensity needs to be of the same order of magnitude as the signal beam peak intensity, implying the use of a laser source much more intense for the background intensity than for the signal. For this reason, these measurements will only be presented for the 1.55 μm wavelength, the background intensity being provided by our 1064 Nd:YAG laser, expanded to shine on the whole sample.

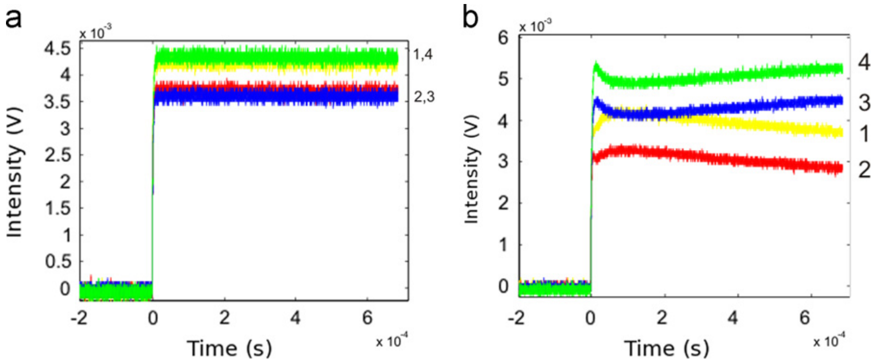

Fig. 2. Typical measurement output from the position detector. Each curve shows the intensity measured by the quadrant of the same number and color as in Fig. 1, in the same conditions: (a) centered beam, (b) off-centered beam as in Fig. 1. The wavelength here is 1064 nm. The temperature is 20 °C and the beam intensity is 10 W/cm^2. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)