Fast photorefractive self-focusing in InP:Fe semiconductor at infrared wavelengths

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(Received 18 July 2007; accepted 13 December 2007; published online 14 January 2008)

Photorefractive beam self-trapping is investigated in InP:Fe and is shown to occur within tens of microseconds after beam switch on. This fast response time is predicted by an analytical theoretical interpretation based on a simple photorefraction model which suggests buildups in a time range consistent with experiments. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2830989]

Self-trapping of optical beams in photorefractive (PR) materials at telecommunications wavelengths has been studied at steady state in insulators such as SBN (Ref. 1) and in semiconductor InP:Fe (Refs. 2–4) and CdTe.[5] PR self-focusing and soliton interactions in semiconductors find interesting applications in optical communications such as optical routing and interconnections. Moreover, semiconductors exhibit several advantages over insulators: their sensitivity to near-infrared wavelengths and shorter response time. In this letter, we make use of InP:Fe semiconductor and we demonstrate that despite its somewhat low electro-optic coefficient, InP:Fe allows fast infrared (IR) self-focusing. We study both experimentally and theoretically its temporal behavior, showing buildup times of tens of microseconds. Self-trapping of an optical beam is observed in different InP:Fe samples for different beam intensities, beam waists, and two different wavelengths (1.06 and 1.55 μm). To interpret these observations, we develop a theoretical model that describes photorefractivity taking into account the photoexcited holes and the thermally generated electrons.

In our experimental setup, the IR laser beam is focused on an InP:Fe sample, the light propagating along the direction $\bar{1}10$. The quasicircular beam waist is carefully monitored and set on the entrance face of the crystal, with a maximum intensity ranging from 0.2 to 100 W/cm^2. An electric field E_0 of 10 kV/cm is applied to the InP:Fe sample in the 001 direction, perpendicular to the laser beam polarized along 110. The output face of the crystal is directly observed by a charge coupled device camera allowing us to analyze the output beam profile versus intensity and applied electric field. Significant measurements of the output beam profile are shown in Fig. 1 for a beam waist on the entrance face of 25 μm and a maximum intensity of 8.7 W/cm^2. Comparing the obtained images [Figs. 1(b) and 1(c)] to the natural beam diffraction [Fig. 1(a)], self-focusing is observed for E_0 equal to 10 kV/cm and defocusing is obtained for the reverse voltage at steady state regime. These images show that simultaneously with self-focusing or self-defocusing phenomena a deviation of the laser beam or bending is observed as in Chauvet *et al.*[2] On the basis of the performed measurements, we observe, as illustrated in Fig. 2, that for intensities I below 200 mW/cm^2, no change in the beam profile appears. For an intensity of 300 mW/cm^2, the laser beam begins to be slightly self-focused or defocused depending on the sign of the electric field. Increasing the intensity, the process becomes more intense and reaches a maximum for an intensity equal to 8.7 W/cm^2. For intensities larger than 100 W/cm^2, the electric field has no influence on the beam propagation at steady state. The above observations concern the steady-state regime. For quantitative systematic transient regime measurements we also have imaged the output face of the crystal on a position detector to observe simultaneously the influence of both self-focusing and bending (Fig. 3). During the experiment we have always kept the applied field on and modulated the intensity of the beam with an acousto-optic modulator; the time origin (t=0) in Fig. 3(c) is the time when the beam is turned on by the modulator. For 1.55 μm wavelength, we have used input powers ranging from 1 μW to 1 mW, thus yielding maximal input intensities in the range from 1 to 100 W/cm^2, intensity values chosen so that the self-focusing occuring at steady state is maximum. The obtained results have evidenced two time scales: one as fast as tens of microseconds (for the highest intensities used)

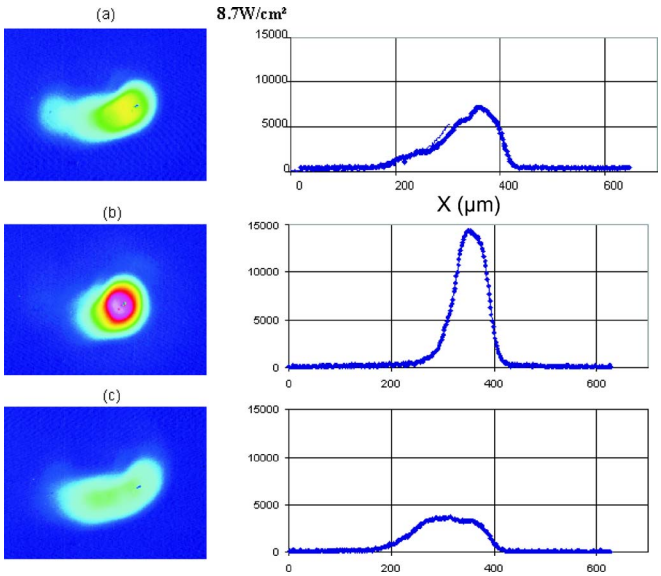

FIG. 1. (Color online) Steady-state transversal (left) and horizontal (right) beam profiles (a) without any applied electric field (b) for E_0=+10 kV/cm (c) for E_0=−10 kV/cm.

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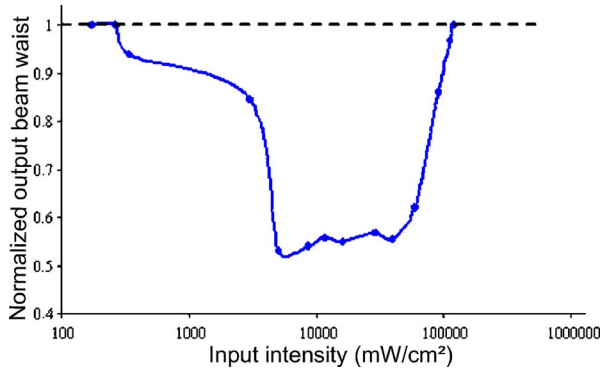

FIG. 2. (Color online) Output beam waist as a function of the input beam peak intensity, normalized to the linearly diffracted beam waist: $w=25\ \mu$m. The solid line shows nondiffracting beam.

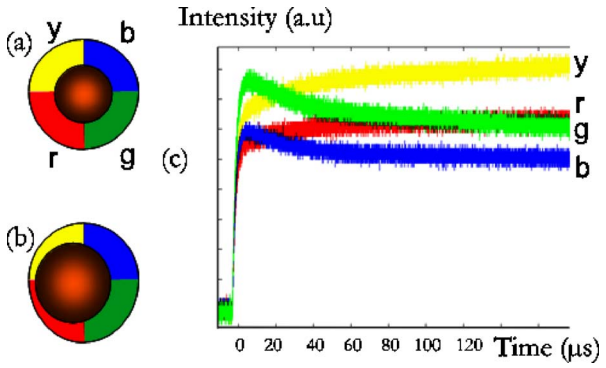

FIG. 3. (Color online) Beam asymmetry measured with a four quadrants position detector [(a)–(b)] and temporal evolution of the intensity received by each quadrant when an electric field is applied (c) (beam self-focused and deflected).

which can be seen in Fig. 3(c) as the first peak produced by "b" and "g" curves, the other one on the scale of milliseconds [corresponding to the steady state, not yet reached in Fig. 3(c) after 150 μs]. Our experimental results show that PR associated phenomena (bending and self focusing) are taking place in InP:Fe as fast as tens of microseconds for intensities of the order of 10 W/cm^2 at 1.55 μm. Part of these observations can be explained by previous theoretical developments[2–4] but not the temporal buildup of the self-focusing phenomenon. We propose in the following to interpret both temporal and steady state photorefractive phenomenon using a simple model of photorefraction in a semiconductor material.

Our model is based on a band transport model[6] for two different types of carriers (both electrons and holes), considering one spatial dimension along x. We start with the standard set of equations,[7]

$$\frac{\partial E}{\partial x}=\frac{e}{\epsilon}(N_D-N_A+p-n-n_T), \tag{1a}$$

$$j_n=e\mu_n nE+\mu_n k_B T\frac{\partial n}{\partial x}, \tag{1b}$$

$$j_p=e\mu_p pE-\mu_p k_B T\frac{\partial p}{\partial x}, \tag{1c}$$

$$\frac{\partial n}{\partial t}=e_n n_T-c_n n p_T+\frac{1}{e}\frac{\partial j_n}{\partial x}, \tag{1d}$$

$$\frac{\partial p}{\partial t}=e_p p_T-c_p p n_T-\frac{1}{e}\frac{\partial j_p}{\partial x}, \tag{1e}$$

$$\frac{\partial n_T}{\partial t}=e_p p_T-e_n n_T-c_p p n_T+c_n n p_T, \tag{1f}$$

$$N_T=n_T+p_T, \tag{1g}$$

where N_D, N_A, n, p, n_T, and p_T represent, respectively, the densities of donors, acceptors, electrons, holes, filled, and ionized Fe traps; ρ, j_n, and j_p define the charge and electrons or holes current densities, E is the electric field, and I is the beam local intensity. These variables are functions of time and space. μ_n and μ_p represent, respectively, the electron and hole mobilities; k_B is the Boltzmann constant, T is the temperature, e is the elementary charge of electron and c_n and c_p are the recombination constants for electrons and holes, respectively. e_n and e_p describe the excitation coefficients for electrons and holes and are defined as $e_n=e_n^{\text{th}}+\sigma_n^0 I(x)$ and $e_n=e_p^{\text{th}}+\sigma_p^0 I(x)$ with e_n^{th} and e_p^{th} as the thermal emission rates, σ_n^0 and σ_p^0 as the photoionization cross sections. In InP:Fe, at room temperature, we can consider that electrons are excited thermally and holes optically:[7] $e_n\simeq e_n^{\text{th}}$ and $e_p\simeq\sigma_p^0 I(x)$. We describe here an analytical method of deriving the space charge field E as a function of the laser beam intensity I, time, and space. Assuming that (i) the diffusion is neglected in comparison to the drift effect, the evolution equation for E is deduced from the boundary conditions and system (1),[8]

$$\frac{\partial E}{\partial t}=\frac{-e}{\epsilon}[(\mu_n n+\mu_p p)E-(\mu_n n_0+\mu_p p_0)E_0], \tag{2}$$

where E_0 is the applied field and n_0 and p_0 are the equilibrium charge carrier densities in the dark. To solve the system yielded by Eqs. (2) and (1d)–(1g), further hypotheses have to be considered. (ii) The density of free carriers remain small with respect to the density of dopant: n, $p\ll n_T$, p_T; (iii) the electric field varies slowly with space, thus the term $\partial E/\partial x$ [when deriving $(1/e)\partial j_{n,p}/\partial x$] is neglected in Eqs. (1d) and (1e) in comparison with other terms. This assumption is valid provided that $\partial E/\partial x\ll(e_n^{\text{th}}N_T)/(\mu_n n_0)$; (iv) the relaxation times of n and p being very short in the nanosecond range, the adiabatic approximation writes as $\partial n/\partial t=\partial p/\partial t=0$, from which we deduce, using Eqs. (1) and assumption (iii), that $\partial n_T/\partial t=0$. From assumption (ii) we see that n_T remains equal to its value n_{T0} in the dark. Hence, from Eqs. (1d) and (1e), we get

$$n=\frac{e_n n_{T0}}{c_n p_{T0}},\quad p=\frac{e_p p_{T0}}{c_p n_{T0}}, \tag{3}$$

with $p_{T0}=(N_T-n_{T0})$. Reporting Eq. (3) into Eq. (2), the latter is straightforwardly solved to give the expression of the space charge field as

$$E=\frac{E_0}{I_d+I(x)}\left[I_d+I(x)\exp\left(\frac{-[I_d+I(x)t]}{\Sigma}\right)\right], \tag{4}$$

where Σ represents an energy density depending on the crystal parameters,

$$\Sigma=\frac{e}{\varepsilon}\frac{c_p c_n n_{T0}p_{T0}}{\mu_p\sigma_p^0 c_n p_{T0}^2+\mu_n\sigma_n^0 c_p n_{T0}^2} \tag{5}$$

and

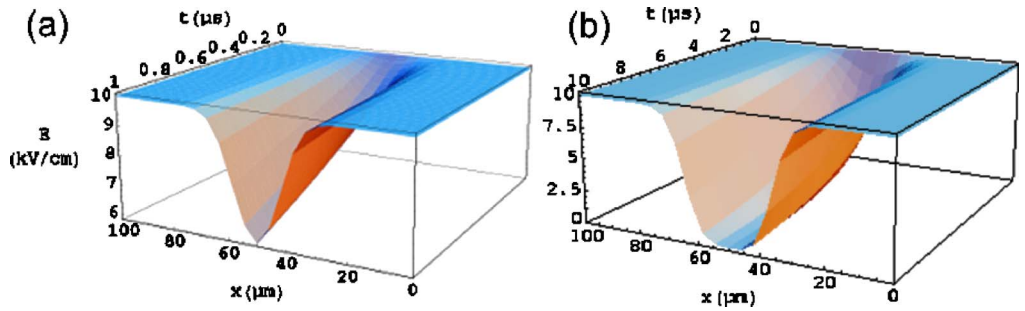

FIG. 4. (Color online) Space-charge field buildup for a duration of 1 μs (a) and for a duration of 10 μs (b) as a function of time and space.

$$I_d = \frac{e_n^{\text{th}} \mu_n c_p n_{T0}^2}{\sigma_p^0 \mu_p c_n p_{T0}^2}. \tag{6}$$

Notice that at steady state, the electric field is

$$E = \frac{I_d}{I_d + I(x)} E_0. \tag{7}$$

It is important to notice that the theoretical expression (4) of the space charge field has the same form as in insulators[9] changing the value of I_d and Σ only as functions of n and p. At steady state, the experimental evolution of the normalized output beam versus intensity is reproduced qualitatively by Eq. (7): this curve reaches a minimum corresponding to a maximum self-focusing[9] at $I(x)=3I_d$. Our measurements presented in Fig. 2 allow us to determine the dark irradiance of our sample $I_d=3$ W/cm^2: this value is consistent with an independent measurement of the dark intensity done by measuring the photocurrent generated by a uniform illumination yielding $I_d=2$ W/cm^2. Figure 4 shows the simulations obtained using Eq. (4): the temporal behavior of the space charge field versus time and one spatial dimension parallel to the electric field applied is calculated at the entrance face of the crystal for a Gaussian 25 μm laser beam.

For the calculation, the parameters concerning InP:Fe were taken in the literature.[7,10] As illustrated on Fig. 4(a), for a waist $w=25$ μm and an intensity equal to 1 W/cm^2, the space charge field decreases from 10 to 6 kV/cm at 1.55 μm wavelength. If the applied electric field has the correct direction, this corresponds to an increasing index and therefore to a self trapping of the beam. This variation can be expected to be more important for larger exposure times, paving the way for obtaining short time self-focusing (several microseconds). The space charge field presented in Fig. 4(b) decreases to 0, owing to its total masking, showing saturation for 1 W/cm^2 of illumination reached in a very short time. The space-charge field decreases progressively from the initial uniform value $E_0=10$ kV/cm to 0 in about 10 μs. It shows a waveguide, corresponding to self-focusing, which builds up in a very short time, less than 10 μs. This simple analytical model reproduces qualitatively the self-focusing behavior versus intensity observed in our InP:Fe samples (Fig. 2) at steady state[8] and concerning the transient regime. It confirms qualitatively the possibility for a waveguide to be self-induced in InP:Fe in tens of microseconds. For reaching a quantitative agreement, a numerical model taking into account additional physical mechanisms such as possibly the non parabolic lens effect that occurs when accounting for the additional transverse dimension,[11] the diffusion of charge carriers and the electron-hole resonance intensity, the role of which is the subject of future studies.

To conclude, we report, both experimentally and theoretically, on PR self-focusing of an infrared laser beam in a time faster than tens of microseconds. The presented analytical model reproduces qualitatively the observed self-focusing behavior as a function of incident intensity, allowing us to determine the dark intensity of InP:Fe crystals.

The authors thank the Lorraine region for their financial support.

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