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Luminescence-induced photorefractive spatial solitons

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We report the observation of spatial confinement of a pump beam into a photorefractive solitonic channel induced by luminescence [luminescence induced spatial soliton (LISS)]. Trapped beams have been obtained in erbium doped lithium niobate crystals at concentrations as high as 0.7 mol % of erbium. By pumping at 980 nm, erbium ions emit photons at 550 nm by two-step absorption, wavelength which can be absorbed by lithium niobate and originates the photorefractive effect. The luminescence at 550 nm generates at the same time the solitonic channel and the background illumination reaching a steady-state soliton regime. © *2010 American Institute of Physics*. [doi:10.1063/1.3313950]

During the past years soliton optical beams have been realized in electro-optic materials[1,2] by means of photorefractive nonlinearity.[3] In presence of relatively long dielectric relaxations time like in lithium niobate (LNB), solitonic beams write almost permanent waveguides,[4] i.e., channels of self-modified refractive-index, able to confine light waves for long time, even months after the soliton beams have been switched off. Photorefractive nonlinearity requires some soliton light to be absorbed by the host material[3] but no special coherence statistics is required; in fact partially coherent[5] and fully incoherent[6] solitons have been generated as well. Incoherent photons can generate self-trapping also through two-step absorption.[7] Recently, it was demonstrated that non-absorbed wavelengths can be "self-trapped" as well by means of second-harmonic generation.[8]

In the present paper, we demonstrate both numerically and experimentally that photorefractive soliton channels can be written by luminescence. Moreover, luminescence expands almost isotropically, ensuring a background illumination of the whole host crystal around the pump beam. Consequently, luminescence induced spatial solitons (LISS) reach a stable regime in space and time, because luminescence acts at the same time as soliton writer and as stabilizing illumination background.

As an example let us consider a ferroelectric $LiNbO_3$ single crystal, as for example LNB, doped with active erbium ions. When erbium ions are pumped at 980 nm, transitions from $^4I_{15/2}$ (N0) to $^4I_{11/2}$ (N1) levels occur.[9] Either thermal relaxation toward $^4I_{13/2}$ (N2) or further up-transitions toward $^4F_{7/2}$ (N3) may occur depleting N1. This second absorption allows pumping of level $^4S_{3/2}$ (N4) from which luminescence at 550 nm can be produced. The rate equations of the whole process are as follows:

$$\begin{cases} \dfrac{dN_1}{dt} = F_{980}[\sigma_{01}(N_0 - N_1) - \sigma_{13}N_1] - \dfrac{N_1}{\tau_1} \\ \dfrac{dN_2}{dt} = \dfrac{N_1}{\tau_1} - \dfrac{N_2}{\tau_2} \\ \dfrac{dN_S}{dt} = F_{980}\sigma_{13}N_1 - \dfrac{N_S}{\tau_S} \\ \dfrac{dN_4}{dt} = \dfrac{N_S}{\tau_S} - \dfrac{N_4}{\tau_4} \end{cases} \tag{1}$$

where F_{980} represents the pump photon flux at 980 nm, "σ_{ij}" represent the cross sections between levels i and j and "τ_i" are the lifetimes of the ith level. According to such erbium population dynamics, pump light and luminescence at 550 nm intensity evolution along propagation is given by

$$\frac{dF_{980}}{dz} = F_{980}[\sigma_{01}(N_1 - N_0) + \sigma_{13}N_1] \tag{2a}$$

$$\frac{dF_{550}}{dz} = \frac{N_4}{\tau_4} - \sigma^{LN}F_{550}(N_D - N_D^+)_{LN}. \tag{2b}$$

Equation (2b) takes into account that the luminescence photon flux (F_{550}) is reabsorbed by the donor levels N_D (here N_D^+ is the ionized donor concentration) of the host LNB inducing the photorefractive effect (cross sections and numerical coefficients for LNB have been taken from the work by Veasey *et al.*[9]). Thus, a local electric field $\vec{E}$ is generated by the photoexcited charges, according to the Kukhtarev[3] equations. Such local field modulates the refractive index (Δn) by means of the electro-optic effect, affecting the light propagation as well. If a static bias field is applied, its local electric screening induced by the photoexcited charges generates a positive variation in the refractive index in the illuminated region which leads to the light self-confinement.[10,4] Such phenomenon has been simulated by numerically integration[11] of Eqs. (1) and (2) of the erbium, together with the Kukhtarev ones[3] for the host LNB and the following light wave equations for both wavelengths:

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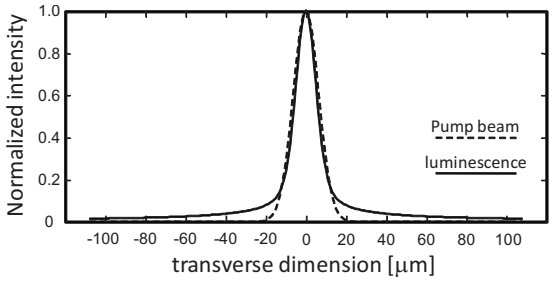

FIG. 1. Normalized transverse profiles of the pump beam at 980 nm (dotted line) and of the induced luminescence at 550 nm (continuous line).

$$\frac{\partial}{\partial z}A_{980/550}(x,z) = i\left(\frac{1}{2k}\frac{\partial^2}{\partial x^2} + \frac{2\pi}{\lambda}\Delta n\right)A_{980/550}(x,z), \qquad (3)$$

where A_{980} and A_{550} are the optical field amplitude of the pump and signal, respectively. At the input face, luminescence gets almost the same profile of the pump beam, as shown in Fig. 1. The presence of extended tails for the luminescence plays the role of the background illumination.

If a static bias as high as 40 kV/cm is externally applied along c-axis, such luminescence modifies the refractive index of LNB by screening effect, writing a guiding channel inside which the pump beam will enter as well (Fig. 2). The recursive luminescence-writing and pump-confinement processes give rise to a stable solitonic state (LISS). Beam bending may occur when photorefractive solitons are generated without background illumination.[12]

Here instead a background is automatically generated by luminescence: because of its isotropic emission, luminescence expands radially with a decreasing intensity which scales almost as 1/r as observed in Fig. 1. It is important to point out one more time from Fig. 1 that the luminescence core has almost the same shape as the pumping beam, due to its quadratic profile.

Experiments were performed using LNB crystals doped in volume by erbium at a nominal concentration in the starting melt composition of 0.7 mol %.[13] Such high concentration ($\sim 1.3\times 10^{20}$ cm^{-3}) was chosen to produce enough luminescence. Samples were grown by the Czochralski method, at a pulling rate of 3 mm/h and at a rotation rate close to 30 rpm.[14] The obtained boules were poled after growth by applying a constant current density of about 3 mA/cm^2 while they were cooled from the paraelectric to the ferroelectric phase, in order to achieve a single domain state through the whole sample volume. By x-ray diffraction, they were oriented and cut in slices with the major surface

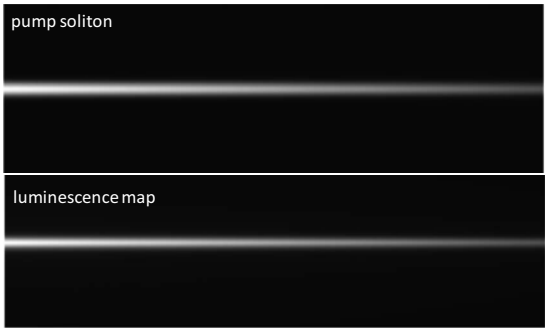

FIG. 2. Numerical calculation of the luminescence and of the pump beam intensity during propagation.

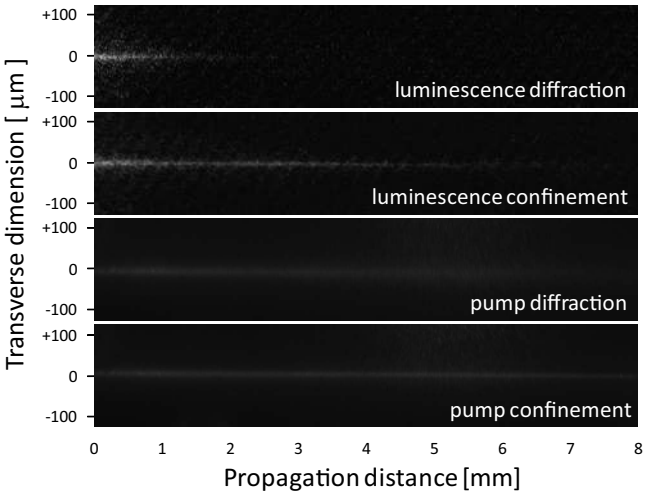

FIG. 3. Images of the pump beam and luminescence light along propagation in the diffraction and self-trapping regimes.

perpendicular to the $\hat{c}$ direction. Finally slices were annealed in air for 6 h at 950 °C and optically polished using a Logitech PM5 lapping machine with standard techniques. The final used crystals were 8 mm along $\hat{a}$, 6 mm along $\hat{b}$, and 1 mm along $\hat{c}$. The electro-optic properties of samples have been measured,[15] showing a good response to the photorefractive screening effect with respect to the photovoltaic one.

In the experimental set-up for LISS demonstration a static bias of 40 kV/cm was applied along $\hat{c}$. A pump beam at 980 nm (10 mW of continuous power) was focused onto the input face with a 9.0 ± 0.5 μm waist (giving an intensity of about 4.0 ± 0.5 kW/cm^2). We estimated the green luminescence intensity to be about 60 ± 20 W/cm^2. Due to the pronounced luminescence and re-emission at the pump wavelength, it was possible to image transversally the pump beam as well as the luminescence trace during propagation inside the crystal, as shown in Fig. 3. Initially the pump beam diffracts and induces a weak luminescence at 550 nm. However, as soon as this luminescence is absorbed by the LNB matrix, the photorefractive nonlinearity starts to grow up, inducing the confinement of the pump beam that consequently increases the two-step luminescence all along propagation. The process continues to evolve until this recursive process induces an efficient confinement of the 980 nm pump beam. Luminescence acts contemporarily as channel writer and bending stabilizer because of its natural expansion over the whole sample that act as a background illumination beam. To illustrate this behavior we have reported the output beam as a function of time in Fig. 4. We can see that the self-confined beam is stable and does not show significant bending as expected since a background illumination is used to control the nonlinearity.[14] The final beam has a near circular transverse mode. It should be pointed out here that due to this very special geometry of self-confinement, the ratio between the background illumination and the luminescence channel remains constant along the whole propagation, ensuring as a consequence a very high stability in space. The output spot images have been fitted by a "2D-Gaussian best-fit algorithm," which overlaps the best two-dimensional Gaussian surfaces to the experimental images. The fitting results are reported in Fig. 5. The beam center position shows a slight movement of the center position of a few microns, mainly

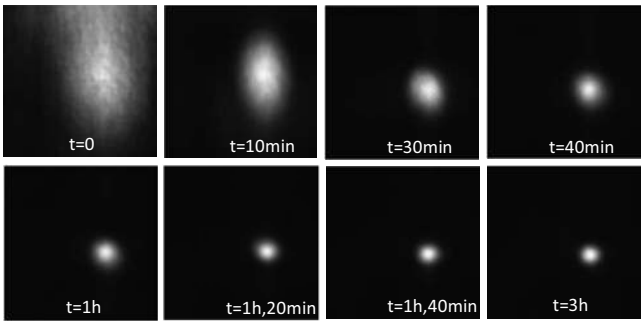

FIG. 4. Images at the output face as a function of the formation time. The beam does not bend thanks to the presence of the background illumination due to the luminescence.

along $\hat{c}$. It is due to the space charge field component produced by charge diffusion. This component cannot be removed. The complete self-confinement occurred within one hour, and for the two following hours the beam remained completely stable, as formed.

In conclusion, we have generated stable LISS in erbium doped LNB crystals. We have shown numerically that the isotropic luminescence emission from the pump beam acts at the same time as writer of photorefractivity and as stabilizer through a background illumination. The luminescence channel gets the shape of the pump beam which, as a consequence, is perfectly self-confined inside it, reaching the soliton regime. The very special geometry of the experiment

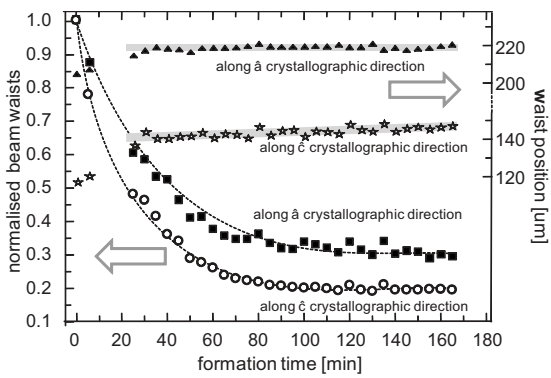

FIG. 5. Fitting parameters. The closed marks refer to the fitting parameters along the $\hat{c}$ direction while the open marks refer to the fitting parameters along the $\hat{a}$ direction.

ensures a very high stability, almost eliminating the spurious large bending that may arise for photorefractive solitons in presence of charge saturation.[12]

We envisage that LISS solitons will find important applications for optical amplifiers and lasers integrated inside soliton waveguides, a perspective for active devices that can be now perfectly integrated in the volume of the active host medium, experiencing ultralow losses and very clean transverse modes.

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