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Writing single-mode waveguides in lithium niobate by ultra-low intensity solitons

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Abstract

Optical waveguides can be conveniently written in photorefractive materials by using spatial solitons. We have generated bright spatial solitons inside lithium niobate which allow single-mode light propagation. Efficient waveguides have been generated with CW light powers as high as few microwatts. According to the soliton formation, waveguides can be formed with different shapes. Due to the slow response time of the lithium niobate, both for soliton formation and relaxation, the soliton waveguide remains memorised for a long time, of the order of months.

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Keywords: Solitons; Optical waveguides; Photorefractive crystals

1. Introduction

Lithium niobate ($LiNbO_3$) is a widely used material for optoelectronic applications. It has many electrical and optical properties (such as electro-optic, photovoltaic, pyroelectric and piezoelectric activities) that can be used for many purposes, in both bulk and integrated optics. Many research activities on $LiNbO_3$ are devoted to write either planar or channel waveguides, that can be produced either by ion and proton exchange [1] or direct UV writing [2] or by propagating soliton slabs or channels, that leave the material modified for a long time [3]. The last method is especially attractive, since photorefractive solitons [4] can write optimum single-mode waveguides using low-power light. Recently photorefractive "bright solitons" were observed in lithium niobate by applying appropriate external electric fields on the crystals [5,6]. A "bright soliton" is a light beam which

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does not diffract and remains confined within a channel of the order of 10–15 μm. It is originated by a positive change of the material refractive index. In this case the photorefractivity is dominated by a drift transport of electric charges that induces a positive modulation of the refractive index [7,8]. It is opposite to the photovoltaic effect, i.e. induces a negative change of refractive index and generates, consequently, dark solitons, i.e. an undiffracting shadow with a uniform background light [3,9–12]. In this paper we show that bright solitons, induced by CW light beams with powers as low as a few microwatts, generate channels that can be used as mono-mode waveguides after the CW beams are switched off. According to the soliton generation procedure, waveguides with different shapes are formed. We show that single-mode channel waveguides remain active for months after the writing procedure.

2. Experimental

The experimental set-up to generate bright solitons and consequently to write the waveguides is shown in Fig. 1. The lithium niobate crystal is externally biased along its crystallographic Z direction by static field and uniformly illuminated along its Y axis. On the crystal input face, orthogonal to the X axis, a laser beam of $\lambda = 514$ nm is focused to a spot waist of 10 μm, and then propagates inside the material for 5 mm (i.e. about five diffraction lengths). Its polarisation is fixed parallel to the crystallographic Z axis. An imaging system was used to visualise the focused beam by a camera interfaced with a computer.

The signal beam power had a few microwatts, which gave, on the input face of the crystal, an intensity of the order of a few watts per square centimeter. The background beam provided a uniform illumination of the sample, with an intensity 2000 times lower than signal beam. The soliton formation is shown in Fig. 2 for a voltage of 35 kV/cm. The beam is first confined along the vertical direction (i.e. the crystal optical axis direction), becoming of elliptical cross-section 10 min after the voltage is applied, then it is confined in the horizontal direction too (i.e. orthogonally to the optical axis). After 20 min the soliton is completely formed, and is of circular shape. The final beam, and consequently the formed waveguide, has a circular cross-section, constant along the whole propagation, with a full width of 16 μm (calculated using a squared hyperbolic secant function for the soliton beam [13]). The formation dynamics depends on the applied voltage but only slightly on the light intensity. Thus we have ranged the bias voltage between 15 and 40 kV/cm. The dynamics of the two different formation rates, for the two transverse directions, is shown in Fig. 3. The fast direction is confined always within about half an hour, while the slow direction remains large for low voltages (i.e. around 15 kV/cm the beam is elliptical, with the

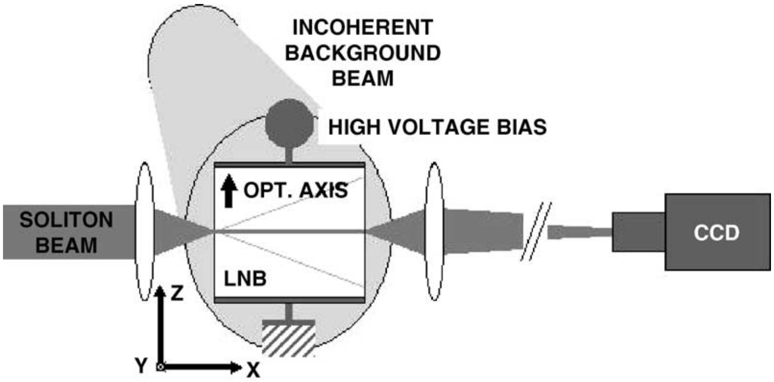

Fig. 1. Soliton generation experimental set-up. An Ar laser beam is focused onto the input face of a lithium niobate crystal, externally biased by a high voltage along the orthogonal Z crystallographic direction. The crystal is illuminated by a second beam, incoherent to the first one. The CCD camera captures the beam shape at the output face of the crystal and consequently monitors and stores the generation in a computer for analysis.

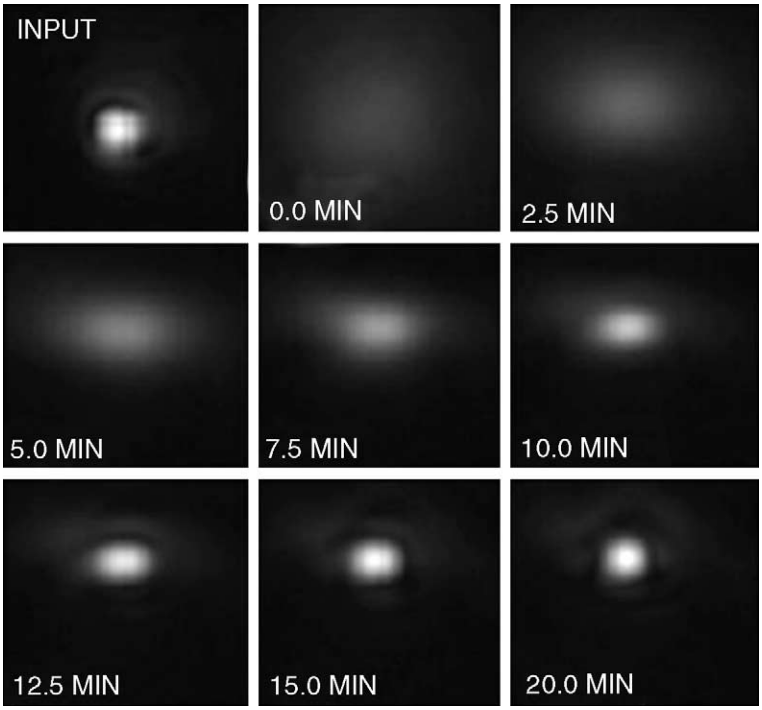

Fig. 2. Dynamics of the soliton formation using an external 35 kV/cm bias. At the input the beam is 10 μm large; at the output face, purely diffracting (0 min), the beam is as large as 55–60 μm. After the soliton is formed, the size of the beam becomes 9.5–10.0 μm.

major axis double than the minor axis). For larger voltages both directions tend to become of the same size, giving rise to circular solitons. Consequently waveguides are formed for biases higher than 20 kV/cm (in this case the screening effect is very efficient and the bright soliton is completely obtained). The characteristic times for soliton formation for the fast (Z) and slow (X) directions show (Fig. 4) that it might be possible to speed up the soliton writing down to hundreds of microseconds with bias fields of the order of hundreds of kilovolts per centimeter, values that can be easily sustained by the material.

3. Discussion

Numerical simulations, with the beam propagation method, confirmed the experimental results and the soliton waveguide formation (Fig. 5). The numerical algorithm considers a change of the refractive index Δn as function of illumination time, beam intensity I uniform background intensity I_b [14]:

$$\begin{aligned}\Delta n = {} & -\frac{1}{2} n_0^3 r_{33} \left(\frac{(E_0 + E_\mathrm{ph}) I}{I_\mathrm{n}} + \frac{1}{I_\mathrm{n}} \left(\frac{k_\mathrm{B} T}{e} \frac{\partial I}{\partial x} \right) \right) \\ & \times \mathrm{e}^{-(I_\mathrm{n}/I_\mathrm{d} T_\mathrm{d}) t} + E_0 \frac{I_\mathrm{b} + I_\mathrm{d}}{I_\mathrm{n}} \\ & - E_\mathrm{ph} \frac{I}{I_\mathrm{n}} - \frac{1}{I_\mathrm{n}} \left(\frac{k_\mathrm{B} T}{e} \frac{\partial I}{\partial x} \right) \end{aligned} \qquad (1)$$

where n_0 is the extraordinary refractive index, r_{33} the electro-optic coefficient, E_0 the applied field, E_ph the photovoltaic field, k_B the Bolzmann constant, T the crystal temperature, e the electron charge, T_d the dielectric response time of the medium in the dark, I_d the equivalent dark irradiance and $I_\mathrm{n} = I + I_\mathrm{b} + I_\mathrm{d}$. For $I_\mathrm{d} \ll I_\mathrm{b} = 1$ mW cm^{-2}, $I_\mathrm{max}/I_\mathrm{b} = 1500$, $r_{33} = 32$ pm/V, $n_0 = 2.2$, $k_\mathrm{b}T/e = 25$ mV, the calculated value E_ph of our sample is −24.5 kV/cm, when 35 kV/cm of bias is applied, using just one free fitting parameter, ($I_\mathrm{d}T_\mathrm{d}$), equal to 750 W cm^{-2} s.

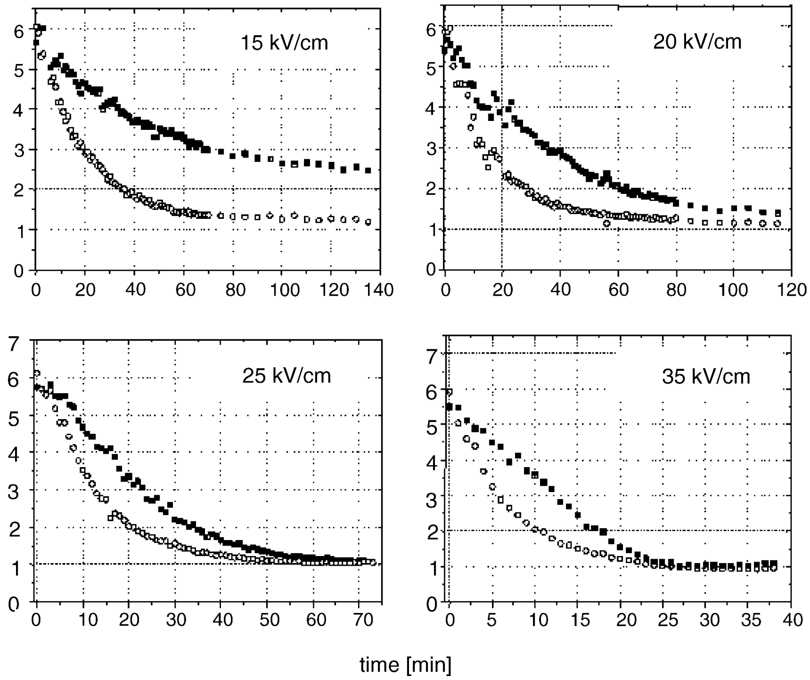

Fig. 3. Soliton formation dynamics along the vertical direction, parallel to the *Z* crystallographic axis, and the horizontal direction, parallel to the *X* crystallographic axis.

The whole procedure suggested that different writing protocols give either cylindrical or conical waveguides, with circular or elliptical cross-sections.

At low biases, up to 20 kV/cm, see Fig. 3, the beam focuses down to different dimensions along the fast and slow axes, thus conical waveguides with elliptical profiles are created. By increasing the external bias, the waveguide becomes cylindrical, reaching circular sections at biases of about 25 kV/cm after 1 h of light exposure. However we have noted that by applying bias fields higher than 40 kV/cm the process becomes faster, but instabilities may occur which destroy the waveguide quality.

After the writing beams are switched off, the soliton waveguides remain written for long time even

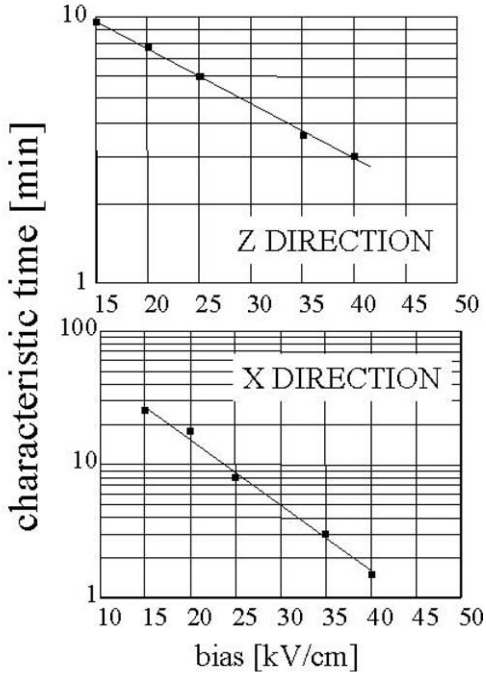

Fig. 4. Soliton formation characteristic times for biases in the range 15–40 kV/cm.

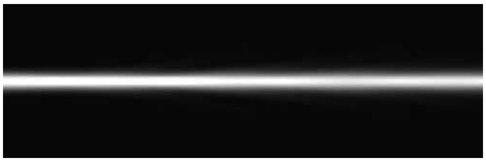

Fig. 5. 2D plot of the numerical simulation for the soliton propagation.

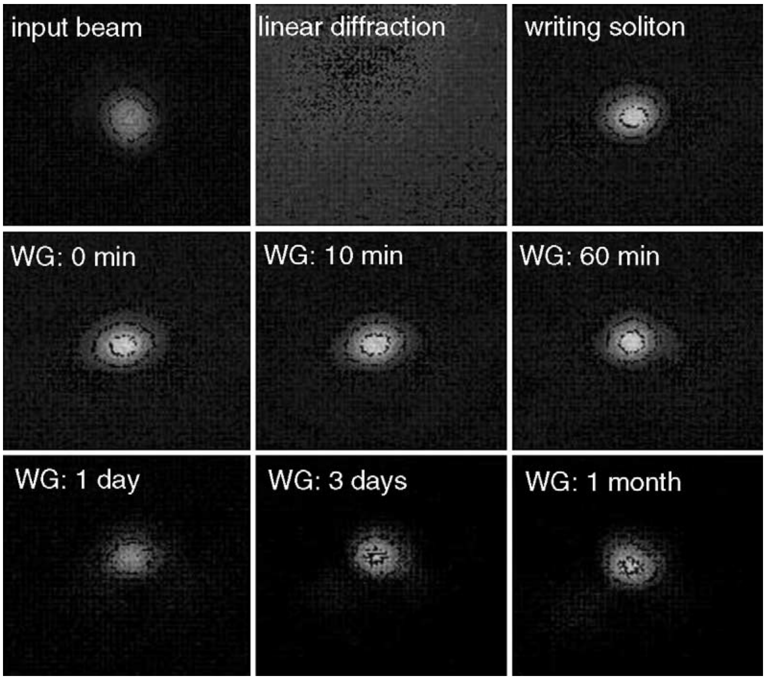

Fig. 6. Picture of the long term stability for the soliton waveguides. The upper images show the cross-sections of the soliton during the waveguide writing process. When the soliton is formed, the solitonic channel remains written in the material and can be used later on as a single-mode waveguide (WG), as large as 10 μm. The propagating mode has exactly the same cross-section of the writing soliton even after 1 month since the waveguide is written.

without any fixation, see Fig. 6. We have tested the temporal stability of the waveguide by injecting signals with different polarisation, for a few months after the writing. Injecting a signal with a polarisation parallel to the Z axis, the waveguide is rapidly erased, due to a strong photovoltaic field developed by the signal. Injecting a signal with a polarisation orthogonal to the Z axis, the waveguide remains stable and with a single-mode for more than 2 months.

The quality of the waveguides is so good that by injecting laser pulses as long as 75 fs, they stretch only a few femtoseconds more that the time stretching in the pure bulk material, passing from a dispersion on 9.9 to only 10.5 fs/mm inside the waveguide.

4. Conclusions

In conclusion we have demonstrated in this work a new procedure to write single-mode waveguides in lithium niobate using ultra-low intensity bright soliton beams. The technique is simple, relatively economic and reliable.

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