Recording of self-induced waveguides in lithium niobate at 405 nm wavelength by photorefractive – pyroelectric effect

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Abstract

We characterize the process of soliton waveguides recording at 405 nm wavelength using pyroelectric effect in lithium niobate crystals. We experimentally study and discuss the influence of the input irradiance, the polarization of the signal beam, and the crystal temperature change on the waveguide writing time and mode-profile. These characteristics significantly change when changing the recording wavelength. The advantages of recording SWGs in LN by using blue-violet light and pyroelectric field are emphasised. The generation of radiation at 405 nm wavelength by inexpensive laser diodes, the fast recording at this wavelength, and the convenient way to produce a static electric field inside the crystal by heating it with few degrees leads to a next step in the soliton waveguides recording process with applications in 3D integrated optical circuits.

I. INTRODUCTION

The study of spatial solitons in photorefractive media demonstrated the feasibility to generate optical waveguides in the volume of the material using low-power continuous wave (c.w.) visible lasers. Optical waveguides created by generation of bright spatial solitons were proven in many photorefractive materials like strontium barium niobate (SBN) with different compositions[1-8], bismuth silicon oxide (BSO)[9-13], lithium niobate (LN)[14-18], or liquid crystals[19,20]. Using soliton interactions[21-23] and modifying the input parameters, waveguides of different sizes and shapes can be created[24]. LN is a good material for integrated optics mainly due to its many good properties (nonlinear, electro-optic, pyroelectric, acousto-optic etc.). LN crystals are commercially available at a low cost and are grown with very good reproducibility of crystal properties.

To induce bright spatial solitons in LN crystals, an external electric field is required to obtain a self-focusing nonlinearity. This electric field, orthogonal to the light propagation direction, was typically obtained by applying a high voltage on the crystal[13,25-27]. To uniformly apply a high external voltage there are additional experimental difficulties to have good electrodes and a good insulation in order to prevent unwanted electric discharges. Recently the external field was replaced by a temperature generated pyroelectric field, which implies heating the crystal several degrees above the ambient temperature[28]. The use of the temperature change has significant advantages over an external voltage source. First, there is no need to know the direction of the crystal *c*-axis, since pyroelectric field is always along *c*-axis, in one direction for heating and in a reverse direction for cooling. Another advantage is the absence of electrodes on the crystal.

The soliton generation conditions require a good nonlinearity balance that implies precise initial values for the static electric field and signal beam to background irradiance ratio. This process is strongly wavelength dependent due to the wavelength dependence of important parameters that are involved in soliton generation process, like photovoltaic (PV)

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field and photoconductivity. It was recently shown that a significant speedup of the recording process can be obtained when using 405 nm wavelength[29]. From an applicative point of view, it is not so important to respect strictly the steady-state soliton generation conditions. Quasi-steady-state solitons[30], which exist in a particular window of time, can be used to create optical waveguides if the recording process is stopped in their existing time window. Waveguides recorded by quasi-steady-state solitons offer the possibility of 3D integration of optical circuits.

We study the recording process of optical waveguides written by soliton-like beams at 405 nm wavelength using the photorefractive-pyroelectric effect. These waveguides are called, generic, soliton waveguides (SWG) even if they may not be an exact mathematical soliton solution. We stress the importance of the wavelength dependence. There is an important improvement in the recording time when using 405 nm wavelength instead of 532 nm wavelength, which was also observed in the recording using external voltage[29]. We determine the influence of the input optical irradiance (I), temperature change (ΔT), and signal beam polarization on the SWGs writing time and mode-profile**.** The characterization of SWGs writing process allows the optimization of writing process in terms of recording parameters, writing time and desired mode-profile. The estimation of recording time for particular writing conditions is of special importance when writing serially many parallel waveguides[21].

II. EXPERIMENTAL SETUP

The experimental setup for SWGs recording is similar to that in[29] where the external voltage source was replaced by a heating source, as shown in Fig. 1. Experiments were done at 405 nm wavelength using a Blu-ray laser diode and at 532 nm wavelength using a frequency doubled Nd:YAG laser. The LN sample is a piece (4.83 x 9.34 x 2 mm^3) from a *z*-cut commercially available congruent LN wafer. The length on the propagation direction is 4.83 mm. The signal beam is focused on the input face of the LN crystal with the lens L1 (5 cm focal length). The lens L2 (3.5 cm focal length) is used for imaging of the mode-profile on the input and output faces of the crystal, ensuring a magnification of ~ 20X. Images are acquired with a beam analyser. Two polarisers (P1 and P2) are used to set both the power and the polarization of the signal beam. The temperature controller is connected to a Peltier element used to heat the crystal and to a sensor for temperature measurement. The crystal is placed on the Peltier element and has a thermal insulating cover on top for better temperature stabilization. The temperature sensor is put inside an Aluminium support thermally glued above the Peltier element, near the crystal. The temperature increase and stabilization takes 1-2 minutes, depending on the set temperature change, ΔT. The SWG recording process (illuminating the crystal with the signal beam) starts after the temperature stabilization, in order to have along the *c*-axis a constant electric field during the recording.

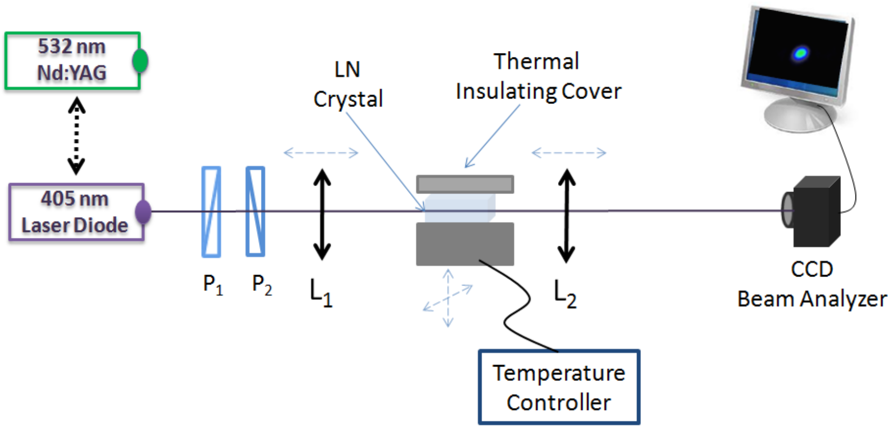

FIG. 1. The experimental setup.

To investigate the pyroelectric field assisted SWGs recording we need to know the pyroelectric coefficient of the LN crystal. Due to the large spread of pyroelectric coefficient values in literature[31-34], we first determined the pyroelectric coefficient for crystals used in SWGs recording experiments. By using an interferometric technique, we measured the pyroelectric field generated by heating the crystal with a different ΔT [35]. The LN crystal is introduced in one of the arms of a Mach-Zehnder interferometer. By heating the crystal, the change of the refractive index induces a phase change which in turn introduces a fringe shift in the interference pattern observed on a CCD camera. The overall change of the refractive index is determined from the fringe shift. The change of the refractive index is due to both thermo-optic and pyroelectric effect. By subtracting the known thermo-optic contribution, the pyroelectric contribution to the refractive index change is determined. Considering the relation of the pyroelectric coefficient to the pyroelectric field,

$$E_{\mathrm{py}} = -p\frac{\Delta T}{\varepsilon_0 \varepsilon_{\mathrm{r}}} \tag{1}$$

where ε_0 is the free space permittivity and ε_{r} is the dielectric permittivity of the material, the pyroelectric coefficient can be determined. For ε_{r} = 28.7[36], the corresponding pyroelectric field is ~ 3.7 kV/cm for a temperature change of 1 K and the corresponding pyroelectric coefficient is p ~ - 95 $\mu\mathrm{C/m^2 \cdot K}$[35]. The details about the experimental setup, the measurement of the pyroelectric field and the corresponding pyroelectric coefficient of congruent LN can be found in[35].

When replacing the external voltage with a temperature change, there are other factors that could affect the writing process in LN crystal. Thermal expansion along the crystal *c*-axis generates a piezoelectric field along this direction. This is the secondary pyroelectric effect[37] and its contribution is included in the pyroelectric coefficient. Thermal expansion along the propagation direction is negligible for small temperature changes[38].

Because of the relative short time of the SWGs recording, ~ 1 minute for typical recording parameters, there is no problem with the pyroelectric field decay which can take several hours[28]. For ΔT higher than ~ 17 K we noticed (by hearing) electric discharges that occur due to a high pyroelectric field. This means that for higher ΔT, the effective pyroelectric field that remains across the crystal could be even lower than for ΔT = 17 K.

The pyroelectric effect has also consequences on optical recording in LN. As a change of the LN temperature of only 1 K induces a pyroelectric field of ~ 3.7 kV/cm, the crystal temperature has to be maintained constant when using LN in optical recording, in order to avoid different results when performing experiments at different temperatures or when laboratory temperature is changing during the experiment.

III. EXPERIMENTAL DATA AND DISCUSSIONS

A typical evolution of the beam self-confining process is shown in Fig. 2 for a temperature change ΔT = 10 K and an input irradiance I ~ 3 W/cm^2. The input and the output beam diameters are measured from the recorded images of the input and output faces of the crystal. The output beam diameter is normalized to the input beam diameter for the vertical direction (*c*-axis direction) and the horizontal direction. The temporal evolution is better fitted by a compressed exponential function (continuous line) due to a slower initial evolution of the beam confinement process. This is a consequence of the non-uniform (strongly decreasing) irradiance along the propagation path inside the crystal due to the initial large spreading of the signal beam. The oscillations that occur during SWGs recording are usually observed when an external field is used[39]. To have an estimation of the SWG writing time for different writing parameters it is more convenient to use a simple exponential function for time evolution fitting. In this way we can have a consistent estimate of the writing time for all the recorded SWGs.

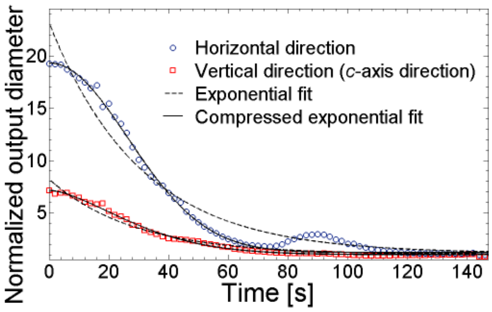

FIG. 2. Temporal evolution of the normalized output diameter during the SWG recording.

We have recorded several SWGs to determine the writing time for different input parameters. The writing time can be considered ~ 5τ, where τ is the time constant of the beam self-confining process.

The output beam diameter normalized to the diameter of the signal beam on the crystal input face is fitted using the equation

$$a \cdot \exp\left(-\frac{t}{\tau}\right) + b \quad . \tag{2}$$

In the equation above, $a+b$ gives the initial value of the output to input diameter ratio and b is the final value in the temporal window of stable confinement. Depending on the recording conditions we can have a confinement process described by output mode-profile larger (b>1), equal ((b=1), or narrower (b<1) than the input mode-profile. The time constant in Eq. (2) is lower for the confinement along the vertical axis (*c*-axis direction) and higher on the horizontal axis. The actual SWGs writing time is considered based on the slower time constant (τ_s) on the horizontal axis.

To analyse the writing time we have made different experiments by varying one input parameter while keeping the others constant. In Fig. 3 (a) the time constant dependence on the input irradiance is showed for a temperature change ΔT = 12 K (corresponding to E_{py} ~ 44 kV/cm) and extraordinary polarization (e-pol) of the signal beam at 405 nm wavelength. The time constant is inverse proportional to the input optical irradiance. For the slow axis, it is given by $\tau_{s,405nm}(I) = 130/I$ s, where I is taken in W/cm^2. For comparison, the corresponding dependence for 532 nm wavelength is $\tau_{s,532nm}(I) \sim 8162/I$ s. At 532 nm wavelength, a higher temperature change, ΔT ~ 17 K, is necessary to obtain good confinement on both transversal directions

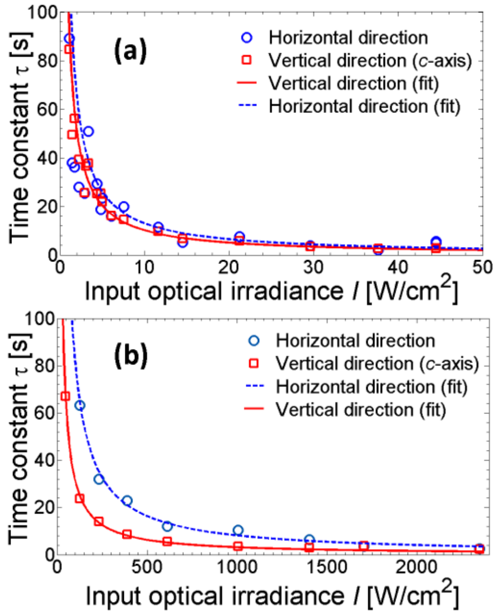

FIG. 3. Time constant for SWGs writing process using e-pol light at: λ = 405 nm and ΔT = 12 K (a); λ = 532 nm and ΔT = 17 K (b).

We can see that the time constant is ~ 3 orders of magnitude lower at 405 nm wavelength compared to that at 532 nm. Note that in this comparison it is important to have nearly the same number of diffraction lengths of light propagating along the crystal. This aspect was considered in our experiments.

In Fig. 4 (a) the time constant of SWGs writing is determined as a function of the temperature change, for I ~ 3 W/cm^2 and e-pol, at 405 nm wavelength. For ΔT higher than ~ 12 K, there is no significant improvement in the time constant. For ΔT > 17 K (corresponding to E_{py} > 63 KV/cm) there is an increase in the time constant that indicates a decrease of the pyroelectric field due to electric discharges on the crystal faces. The occurrence of these discharges can be even heard. The same behaviour can be seen in the dependence of the minimum mode profile diameter on ΔT, in Fig.4 (b). The mode profile FWHM should decrease if the electric field is higher, which means a higher self-focusing nonlinearity. However, we observe an increase of this parameter as ΔT becomes higher than ~ 17 K in Fig. 4 (b) that suggests a lower electric field, due to pyroelectric field decrease. We can also conclude from this data that there is an optimal recording at ΔT ~ 12 K at 405 nm wavelength. For higher ΔT there is no significant improvement in both writing time and minimum mode-profile diameter. For recording at 532 nm or higher wavelengths, the temperature change higher than ~ 17 K, eventually needed for the best confinement, might not be reached due to the electric discharges that can also alter the sample quality. Taking into account these considerations, it is better to write SWGs at blue-violet wavelengths.

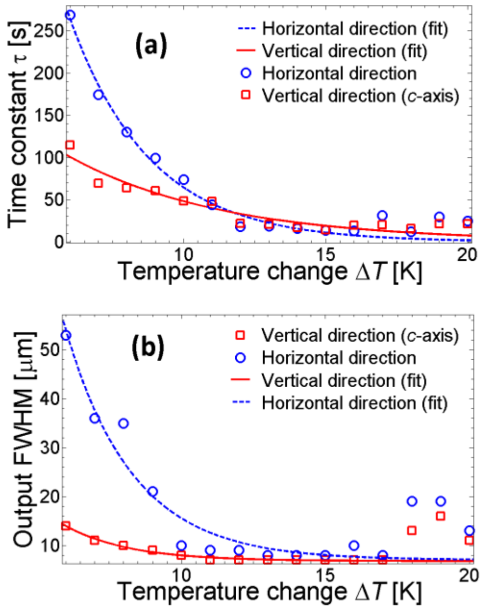

FIG. 4. Time constant (a) and output FWHM (b) dependence on the temperature change for I ~ 3 W/cm^2 and e-pol of the input beam at λ = 405 nm.

The refractive index change Δn that creates the SWG is directly related to the electro-optic effect by

$$\Delta n = -\frac{1}{2} n^3 r_{\mathrm{eff}} E_{\mathrm{SC}} \quad , \tag{3}$$

where n is the LN refractive index, E_{sc} is the space-charge field created by illumination and by temperature change, and r_{eff} is the effective electro-optic coefficient, which is polarization dependent. For e-pol, r_{eff} is r_{33} = 32.2 pm/V and for ordinary polarization (o-pol), r_{eff} is r_{13} = 10 pm/V, at 633 nm[40]. This has consequences in the dependence of the writing time constant on the signal beam polarization. In Fig. 5 (a) the dependence of the time constant on the angle between the polarization direction of the signal beam and crystal c-axis is shown for ΔT ~ 12 K and I ~ 3 W/cm^2, at λ = 405 nm. For lower wavelengths the values of electro-optic coefficients are higher[41]. This is one of the factors that increase the speed of the SWGs recording in blue-violet, compared to recording in green.

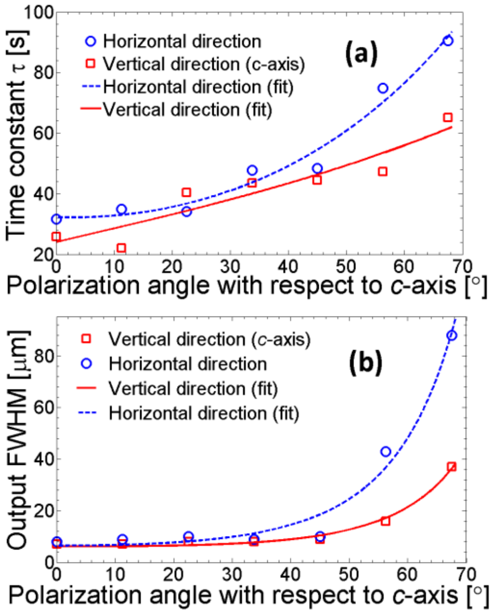

FIG. 5. Time constant (a) and output FWHM (b) dependence on the input beam polarization for $\Delta T \sim 12$ K and $I \sim 3$ W/cm^2 at $\lambda = 405$ nm.

One could think that it is always better to record SWGs with e-pol, due to a higher recording speed. However, an important difference between propagation through SWGs recorded with e-pol and o-pol beams exists, which was observed when guiding IR beams[25,29]. SWGs recorded with o-pol have a higher refractive index contrast with respect to SWGs recorded with e-pol due to a lower PV field for o-pol. To benefit on the largest refractive index contrast one should record SWGs with o-pol and propagate signal beams with e-pol[25].

An important advantage of the SWGs recording at 405 nm wavelengths, can be seen from the dependence of the output mode-profile on the input irradiance, shown in Fig. 6. For $\lambda = 532$ nm (Fig. 6 (b)), by increasing the input irradiance in order to make the recording speed comparable with that at 405 nm, the confinement is worse. Due to the poor confinement the horizontal output beam diameter significantly increases when the input irradiance is increasing and the output mode profile becomes strongly elliptic. This is a consequence of higher PV field, which increases with $\sim I^{0.6}$ in the interval 30 ÷ 9000 W/cm^2 at 532 nm wavelength[42]. For lower signal beam irradiance, as used in the recording of SWGs at 405 nm, no significant change in the output mode-profile can be observed (Fig. 6 (a)). This suggests that the PV field is nearly constant for I in the range 0.3 ÷ 30 W/cm^2 at 405 nm. To record SWGs very fast at 532 nm, with a small mode-profile, a large irradiance and a very strong static electric field (to compensate for the large PV field) are required. The strong static field would require a very good electric insulation of the sample that is difficult to achieve experimentally. For $\lambda = 405$ nm, SWGs can be recorded very fast at significantly lower irradiance that results in a lower PV field.

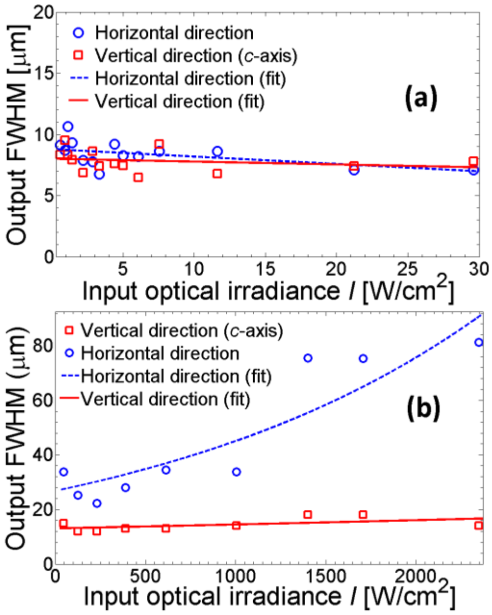

FIG. 6. Dependence of the output FWHM on the irradiance at the input face, for the recording process at λ = 405 nm (a), and λ = 532 nm (b).

The writing process of SWGs in LN by using pyroelectric effect to generate electric field on the crystal is in principle faster than applying an external electric field of the same strength. In Ref. 42 it was experimentally shown a pronounced decrease of the PV field when temperature increases, for temperatures in the range 20 – 130°C and for a large range of light intensities (210 W/cm^2 - 7300 W/cm^2), at 532 nm wavelength. The Arrhenius temperature dependence of PV field is related to the corresponding increase of the photoconductivity in LN. As the recording time constant is inversely proportional to the photoconductivity[42,43], a larger LN photoconductivity speeds up the writing process in the heated crystal, for the same irradiance. Alternatively, for the same recording time it is possible to have lower signal beam irradiance when using pyroelectric effect to bias the crystal, due to the lower PV field.

IV. CONCLUSIONS

We have done a complex characterization of the SWGs recording process in LN at 405 nm wavelength by photorefractive - pyroelectric effect. We analyzed the influence of different recording parameters (optical irradiance, temperature change, and beam polarization) on the writing process. We showed that the photorefractive - pyroelectric recording of SWGs in LN at this wavelength is significantly faster than the recording at 532 nm, for the same optical power. Alternatively, much weaker irradiance is necessary at 405 nm to ensure the same writing time as at 532 nm. Also a lower photovoltaic field at shorter wavelengths results in a lower pyroelectric field requirement. Lower heating decreases the potential risk of crystal damage produced by electric discharges. The writing of SWGs by using pyroelectric field instead of an externally applied field benefits from the increase of the photoconductivity and the decrease of the photovoltaic field in the heated crystal. The characterization of the SWGs recording process by photorefractive-pyroelectric effect reported here is important for the writing of channel SWGs in the volume of lithium niobate crystals with applications in 3D optical circuits.

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