Fast writing of soliton waveguides in lithium niobate using low-intensity blue light

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Abstract

We experimentally demonstrate the writing of soliton waveguides in lithium niobate with blue-violet light, at λ=405 nm. This wavelength, obtained from a low-cost laser diode, allows very fast writing of soliton waveguides when comparing with the writing process using green light (532 nm). For the same writing time there is a decrease of ~ 4 orders of magnitude of the light intensity necessary for writing soliton waveguides in blue. The writing process is investigated and characterized by tuning parameters like beam intensity, external field and beam polarization. The IR guiding capability of these soliton waveguides is tested by guiding femtosecond laser pulses at λ=1550 nm.

1 Introduction

Optical spatial solitons (non-diffractive light beams) were demonstrated through different physical mechanisms (Kerr, quadratic, photorefractive) [1, 2]. The prediction of photorefractive (PR) spatial solitons [3] led to their experimental demonstration in different PR materials like strontium barium niobate (SBN) [4-6], bismuth silicon oxide (BSO) [7-9], lithium niobate (LN) [10-14], or liquid crystals [15]. PR spatial solitons may be useful for many applications in integrated optics that imply beam guiding. Routing or switching applications can be developed by using solitons interactions [16-18].

In its evolution from diffracting to spatially confined propagation, the soliton-like beam creates a transversal refractive index distribution along its path in the PR material that acts as a light induced optical waveguide, the soliton waveguide (SWG). The SWG is comparable to a graded index optical guide. After switching-off the beam that generates the SWG, this refractive index distribution remains recorded in the crystal for a time of the order of dielectric relaxation time and can be used to guide other beams at wavelengths outside the PR sensitivity range of the crystal.

It was experimentally demonstrated that bright PR solitons can be used to create 2D soliton waveguides in the volume of the LN crystal [10, 12-14]. LN is a versatile material for creating SWGs, mainly due to the very good crystal reproducibility and low cost. It is being already used in many applications like electro-optic modulators and parametric frequency generation. LN is transparent for infrared (IR) wavelengths. This makes SWGs suitable for integrated optics applications in near IR and telecom wavelengths. The SWGs recorded in the volume of LN crystals show reproducible features, controllable transversal profile of the refractive index, good guiding properties and long lifetime. Also, before permanently fixing the SWG, optical erasure allows multiple writing cycles [12, 14]. The generation of SWGs can be an optical technique alternative to laser direct writing for recording 3D waveguides [19]. The strong PR nonlinearity, for wavelengths in the sensitivity range of the LN crystal, allows the generation of PR quasi-steady-state solitons (beams that are self-trapped during a limited time window only) at low input optical powers, as long as the beam intensity is larger than the dark intensity of the material [20-22]. A challenge is to find a wavelength for which the SWG recording is optimized from the point of view of writing time, input light intensity and availability of low-cost light sources.

In this paper, we experimentally demonstrate that SWGs can be recorded very fast in LN crystals using a low-cost blue-violet laser diode at 405 nm, which is widely used in the Blu-ray technology. We present the results of an experimental study of SWGs writing at this wavelength. We compare the results with the writing process using 532 nm wavelength for the same LN crystal [23-26]. We also show that the recorded SWGs can be used to guide IR femtosecond (fs) pulses (1550 nm) of seven orders of magnitude higher peak power than the writing power.

2 Experiments and data analysis

The experimental setup for SWGs writing is shown in Fig. 1. Setup is similar with that used in [11], where bright 2D spatial solitons in LN were demonstrated for the first time. The sample that we use is a 6x2x10 mm piece of undoped congruent LN crystal. Beam propagation is along the 10 mm direction, which is perpendicular to crystal c-axis. As a light source we used a 405 nm laser diode. The input beam is focused on the input face of the LN crystal (left side in Fig. 1) with the lens L_1 (f = 5 cm). Its polarization is selected with the polarizer P. A CCD beam analyzer collects the images of the input or output faces of the crystal by translating the lens L_2 on the optical axis. These images are magnified ~20 times. A high voltage (HV) is applied on the LN crystal giving an external electric field (E) along the direction of the crystal c-axis. Input beam size is ~8 µm at FWHM and is slightly elliptical, with the long axis parallel to the crystal c-axis. For this beam waist, the crystal length on the propagation direction corresponds to ~12 Rayleigh diffraction lengths. The writing process is monitored by analyzing the output beam profile during the SWG writing. The output profile is compared with the input beam profile. The mirror M is used to couple an IR femtosecond pulsed laser beam to the recorded SWGs in order to test their guiding properties at the wavelength of 1550 nm.

A typical temporal evolution of the SWG writing process is shown in Fig. 2, where the output beam diameter is normalized to the input beam diameter. It is somehow difficult to define a precise SWG writing time. As it can be seen from Fig. 2, the self-confinement effect is faster along the crystal c-axis and slower along the orthogonal transversal direction. This leads to a temporal evolution of the transversal beam ellipticity during the process of SWG writing. It can be seen from Fig. 2 that the beam is completely confined on both transversal directions in a particular time interval. The SWGs writing process has to be stopped in that time interval, when quasi-steady-state solitons exist [20, 27]. This requirement is not a critical one. For the experimental conditions mentioned in Fig. 2, this time interval is ~ 1 minute. By stopping the writing process in this time interval the wave-guiding light-induced refractive index distribution is frozen inside the LN crystal. Overreaching that time interval leads to undesired processes like beam filamentation [28].

We should note that the beam propagation may not exhibit an exact mathematical soliton solution when the writing process is stopped. From the practical point of view of writing light-induced waveguides in LN, the conditions for quasi-steady-state solitons are much less restrictive compared to that required for generation of steady-state photorefractive screening solitons [27]. In order to obtain narrow width steady-state solitons, it is necessary to work at signal to dark intensity ratios close to unity or to apply external electric fields much larger than the photovoltaic field [27]. Due to the fact that in LN the dielectric relaxation time is very large [22], it is necessary to work with a large intensity of the input signal beam in order to ensure a fast confinement. In this case, the achievement of signal to dark intensity ratio close to unity requires a strong background illumination of the LN crystal, which can be difficult with low power laser diodes. In our experiments the background illumination is given by the ambient laboratory light, which is five to six orders of magnitude lower than the recording intensity. The signal to background intensity ratio influences the spatial distribution of the space-charge field that gives the refractive index profile. For high ratios the refractive index profile tends to a step-index profile [27]. The use of electric fields applied on the crystal, much larger than the photovoltaic field, imposes additional experimental difficulties to have a good electrical insulation of the crystal. Consequently, from the experimental point of view, the most convenient conditions for the writing of SWGs in LN are those in which quasi-steady-state solitons are generated.

We consider as writing time of the SWGs, the time when the beam spot on the output face reaches the minimum beam size on both transversal directions. To analyze the dependence of writing time on the input parameters, SWGs were recorded at different optical powers, external electric fields and beam polarizations.

The time evolution of the normalized output waist in the SWG recording process follows the time evolution of the space-charge field. The electric space-charge field distribution that produces the light confinement in the process of SWG writing is mainly due to both the static externally applied field and the time dependent photovoltaic field [27]. The defocusing effect of the photovoltaic field distribution generated inside LN by illumination must be exceeded by the opposite effect due to the external applied field in order to have a focusing nonlinearity [27].

Although the time evolution of SWG waist is not perfectly described by a single exponential function [29], in a first approximation we use single exponential functions to fit the experimental data for self-confinement. This is done in order to estimate the time constant for the writing process. In the self-confinement process shown in Fig. 2 the input beam is extraordinary polarized and has the intensity $I \sim 4$ W/cm^2 on the input face of the crystal. The external electric field applied on the crystal is $E \sim 45$ kV/cm. The self-confinement effect along the crystal c-axis is characterized by the time constant $\tau_f \approx 25$ s and along the orthogonal transversal direction by the time constant $\tau_s \approx 33$ s. After a time of five time constants, the normalized output waist is ~1. We consider the writing time $t_w = 5 \cdot \tau_s$, considering the time constant for the slower evolution of the beam waist on the axis orthogonal to crystal c-axis. For the experimental case shown in Fig. 2, the corresponding writing time is ~ 165 s.

From the temporal evolution of the writing process, one can determine the dielectric relaxation time of SWG in dark, T_d, that gives an estimate of the SWG lifetime in dark. The time evolution of SWG waist on c-axis direction is described by the time constant $\tau_f = T_d I_d / I_{tot}$ [11, 27], where T_d is the dielectric relaxation time in dark, I_d is the dark intensity and $I_{tot} = I + I_b + I_d$, where I is the input beam intensity and I_b is the background light intensity, given by the ambient laboratory light in our case. The value of the dark intensity for LN is between $I_d \sim 1$ μW/ cm^2 [30] and $I_d \sim 10$ μW/ cm^2 [22]. For the input beam intensity $I \sim 4$ W/cm^2 >> $I_b + I_d$, T_d is in the interval $(10^7 \div 10^8)$ s, which is roughly between 4 months and 3 years. This value of the SWG lifetime in dark for undoped LN, which has a low intrinsic iron concentration, is consistent with the value of one year reported for dark-storage time of holograms recorded in iron doped LN [30, 31]. One can also observe some oscillations of the beam profile during the SWG recording. This behaviour might appear due to damping oscillations in the temporal evolution of the space-charge field when an external electric field is applied on the crystal [32].

The SWG writing time t_w is inverse proportional to the input beam intensity [20, 33]. The writing time dependence on the input beam intensity is shown in Fig. 3, for $E \sim 45$ kV/cm and extraordinary polarization of the input beam. It can be seen in Fig. 3 that SWGs can be recorded in ~ 1 s for $I \sim 700$ W/cm^2 (corresponding to a power of ~ 280 μW) and in ~

1 minute for I ~ 10 W/cm^2 (corresponding to a power of ~ 4 µW). Comparing to the SWG writing in green, at 532 nm, for the same LN crystal, the writing time decreases by 3 orders of magnitude (the writing time is ~ 2800 s in green instead of ~ 1 s in blue, for the same input intensity, I ~ 700 W/cm^2). As the rate of recording (inverse of the recording time constant) is proportional to the photoconductivity σ_{ph} [34, 35], the strong increase of this rate (~ 2800 times) in blue-violet compared to that in green, for the same input intensity, indicates a strong increase in the photoconductivity. One factor that has an influence on the photoconductivity is the crystal absorption [36]. The LN light absorption is increasing when the wavelength decreases from red to blue-violet. For nominally undoped congruent LN with residual concentrations (wt. ppm.) of Fe: 1.10, Cr: 0.06, Ni: <0.01, Cu: < 0.05, the absorption coefficient is increasing from 0.011 cm^{-1} at 532 nm to 0.026 cm^{-1} at 405 nm for extraordinarily polarized (e-pol) light and from 0.015 cm^{-1} to 0.050 cm^{-1} for ordinarily polarized (o-pol) light, respectively [36].

The improvement can also be seen in optical power requirements. To write a SWG in ~ 20 minutes would require 2 kW/cm^2 input intensity in green, but only ~0.6 W/cm^2 in blue (a power of ~ 250 nW). This is a decrease of ~ 4 orders of magnitude of the light intensity necessary for SWGs writing in blue in comparison with green. Such a decrease of the SWG writing time is very important when writing large SWG arrays in the volume of the crystal [18, 23].

In Fig. 4 the dependence of SWG writing time on the external electric field for ~ 6.3 W/cm^2 input intensity and e-pol is shown. The experimental data are fitted by an exponential function, $t_w(E) \sim 7305 \cdot \exp(-0.09 \cdot E)$ where E is in kV/cm and t_w in seconds. The writing time can be reduced ~ 4 times when increasing E from 35 to 50 kV/cm. The maximum refractive index modification, in the center of the SWG transversal profile, is given by the difference between E and the bulk photovoltaic field E_{pv} [37]. The photovoltaic field is inversely proportional to the photoconductivity [34]. As the photoconductivity in blue-violet spectral domain is much larger than in green, the photovoltaic field is much smaller in comparison with that in green. From values of the order of 10 kV/cm [36, 38] in green, the photovoltaic field decreases to 550 V/cm in UV, at 351 nm [39]. On the other hand, as Lüdtke, Waasem, Buse and Sturman recently shown in a study of light-induced charge-transport in undoped LN [35], E_{pv} depends sub-linearly on the incident light intensity. At 532 nm wavelength, it increases from 2kV/cm to 70kV/cm as I^q, with q=0.5-0.6, in the intensity range (30 - 9000) W/cm^2 [35]. The photoconductivity σ_{ph} depends almost linearly on intensity, increasing from 4×10^{-14} to 7×10^{-12} Ω^{-1}cm^{-1} in the same intensity range and for the same wavelength [35]. These dependences of E_{pv} and σ_{ph} on intensity in undoped LN have important consequences on writing SWGs in LN. The faster writing of SWGs requires the increase of input intensity, in order to increase the photoconductivity, but this fact has a detrimental influence on photovoltaic field, that also increases. For a fixed E, the input beam intensity has to be limited to the value for which E_{pv} is close to E. It should be noted that in SWG writing process, the transversal distribution of the signal beam intensity is continuously varying along the propagation path in the crystal. The intensity is increasing from the initial highly divergent free propagation until the SWG is formed and the writing process is stopped. Due to this fact σ_{ph} cannot be considered constant during the SWG recording and its estimation is difficult considering only the signal beam intensity at the input face of the crystal.

The dependence of E_{pv} on intensity has favourable consequences for SWGs writing with blue-violet light. As it was mentioned previously, the writing of SWGs in ~ 20 minutes would require an intensity of ~ 2000 W/cm^2, at 532 nm, but only 0.6 W/cm^2 at 405 nm. Considering the intensity dependence of E_{pv} at 532 nm from [35], the resulting photovoltaic field at the above intensity is ~ 25kV/cm. Much lower photovoltaic field is expected when writing SWGs at 405 nm considering the same writing time as in green. This is due to the very low intensity required when writing at 405 nm (~ 3000 times lower than in green). For quasi-steady-state solitons, a lower photovoltaic field allows the recording of narrower SWGs for the same externally applied field [27].

When comparing with the SWG recording process in green it is important to comment on the maximum refractive index change attainable at 405 nm wavelength. The refractive index change that can be obtained is given by the relation:

$$\Delta n = 0.5 \cdot r_{eff} n^3 E_{SC} , \qquad (1)$$

where r_{eff} is the effective electro-optic coefficient, n the refractive index of LN and E_{SC} is the space-charge field when the SWG recording is stopped. Δn has a maximum in the centre of the waveguide transversal profile. Due to the wavelength and polarization dependences of LN refractive index and electro-optic coefficient, Δn is also wavelength and polarization dependent. The refractive indices of LN, calculated using Sellmeier equation at T = 293 K, for 405 nm and 532 nm [40], are shown in Table 1. For 405 nm Δn is increased ~1.13 times for e-pol and ~1.15 times for o-pol light. The r_{33} and r_{13} electro-optic coefficients of LN involved in writing of SWGs with e-pol and o-pol are increasing when the wavelength is decreasing from near IR to blue wavelengths [41]. In congruent LN, r_{33}= 31.8 pm/V, r_{13}=10.1 pm/V, measured at 529 nm and r_{33}=34 pm/V, r_{13}=11 pm/V, measured at 458 nm [41]. We expect that the electro-optic coefficients at 405 nm are even higher than those at 458 nm. Taking into account the different values of refractive index (at 405 nm) and electro-optic coefficient (considered at 458 nm), Δn is higher at 405 nm than at 532 nm at least 1.21 times for e-pol and 1.25 times for o-pol.

The polarization of the input beam has an important influence on the writing time of SWGs. It can be seen in Fig. 5 that writing time can double when changing the input polarization from e-pol to o-pol (90º rotation in the Fig. 5) for I ~ 7 W/cm^2 and E ~ 45 kV/cm. In this case the writing time is influenced by a lower photovoltaic current for o-pol with respect to e-pol [42]. Despite the fact that the SWG writing time increases for o-pol, it has an advantage in beam guiding. The photovoltaic field is lower for this polarization and a higher space-charge field can be achieved for the same externally applied electric field [42]. By exciting this space-charge field with an e-pol signal beam, a larger refractive index change can be obtained.

In order to investigate the IR guiding properties of SWGs recorded in blue, we used as light source a fs fiber laser with ~ 200 fs pulse duration, 300 mW average power, at 1550 nm, the central wavelength of the C-band in telecommunications. The probe beam is focused on the input face of the LN crystal. The guiding properties are evaluated monitoring the beam spot size and shape at the crystal output face.

As explained above, a beam is better guided when propagating with an e-pol through a SWG recorded with o-pol. In order to obtain a better waveguide coupling at this wavelength, we used other recording parameters for the SWGs: ~ 20 µm FWHM beam size and o-pol of blue writing beam. In Fig. 6 the guiding properties of the SWGs for λ = 1550 nm are showed. The input profile of the probe beam (Fig. 6a) is compared with the corresponding output profiles in free propagation (Fig. 6b) and in guided propagation with e-pol (Fig. 6c) and o-pol (Fig. 6d). The transversal profile is well fitted by a Gaussian for the input beam (a) and a square hyperbolic secant for the guided beam (c). A better guiding is observed for e-pol probe beam, as expected.

There are different ways to modify the waveguide refractive index profile and obtain different beam shapes. Depending on the input beam size and on the moment when the process of SWG writing is stopped (the input beam and the external electric field are switched off), a different waveguide transversal shape can be obtained [27]. Since the beam mode-profile does not depend on the input intensity for quasi-steady-state solitons [21], the external electric field is an important parameter for controlling the mode-profile ellipticity. Lowering E, while keeping the same input beam waist, would produce an elliptical output profile with the small axis parallel to crystal c-axis. In this way one can create tapered waveguides of different sizes and shapes.

Without permanent fixing, waveguide lifetime is several months [23] when writing with green light (532 nm) and keeping the crystal in laboratory ambient light. For the SWGs recorded with blue light (405 nm), we have also observed no change in guiding properties in more than four months after the recording, which is consistent with T_d determined previously. Propagating light outside the PR sensitivity range of the crystal does not affect the lifetime of the SWGs. We used this as an advantage to guide IR beams of much higher optical intensities comparing with SWG writing intensity (seven orders of magnitude higher for fs pulses at 1550 nm).

When guiding ultrashort near infrared light pulses, the dispersion properties of LN and of SWGs written in it have to be taken into account. Due to the transversal profile and the low light-induced-change of the refractive index in SWG writing process, the dispersion components introduced by the waveguide have been estimated as negligible in comparison with the material dispersion of LN [43]. The material dispersion of LN at 1550 nm is ~ 1 fs/(cm·nm), which is ~ 2 orders of magnitude lower than for visible wavelengths (~50 fs/(cm·nm) at 532 nm) [43]. The low dispersion and low absorption at near infrared wavelengths ($\alpha<0.0015$ cm^{-1} at λ=1064 nm) [44] are important advantages of SWGs written in LN in applications involving the guiding of ultrashort light pulses in this spectral region.

3 Conclusions

We have experimentally demonstrated the very fast writing of soliton waveguides in the volume of LN crystals using blue-violet (405 nm) c.w. light from a low-cost laser diode. We analyzed the writing process in terms of the writing time dependence on the input parameters (light intensity, external electric field and beam polarization). A strong decrease can be seen for the writing time (three orders of magnitude) and also for the power requirements when comparing with the writing process using green light at 532 nm. SWGs recorded at 405 nm can be used to guide beams at 1550 nm and are robust to the propagation of IR powers even seven orders of magnitude higher than the writing power. The presented results show the possibility to use SWGs recorded in the volume of LN for photonic integrated applications.

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Table 1. Refractive indices for LN at 532 nm and 405 nm.

λ [nm]	n_e	n_o
532	2.232	2.321
405	2.323	2.428

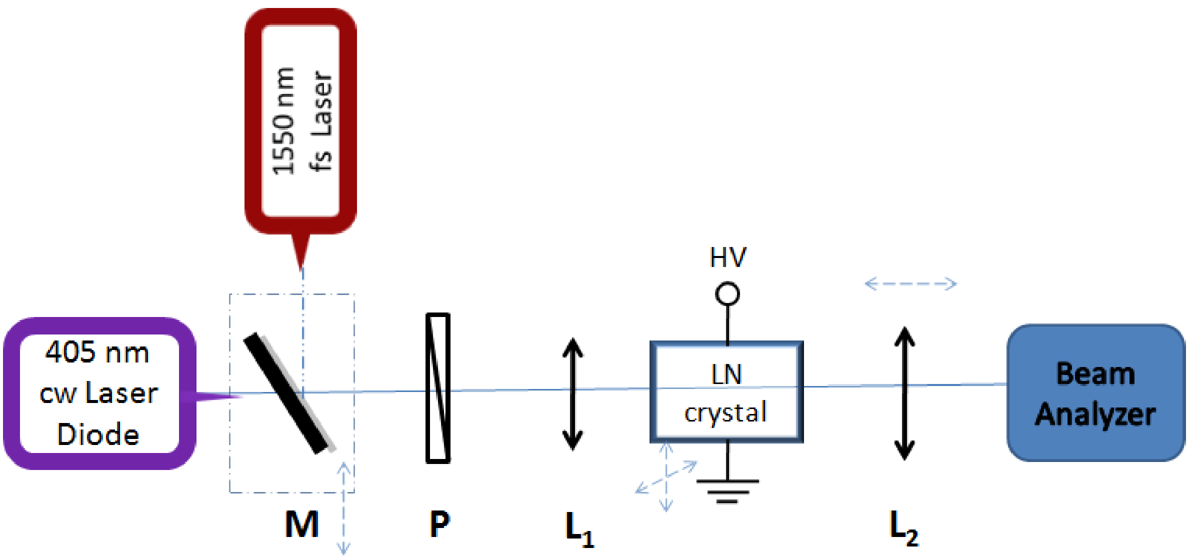

Fig. 1. Experimental setup for SWG writing and testing.

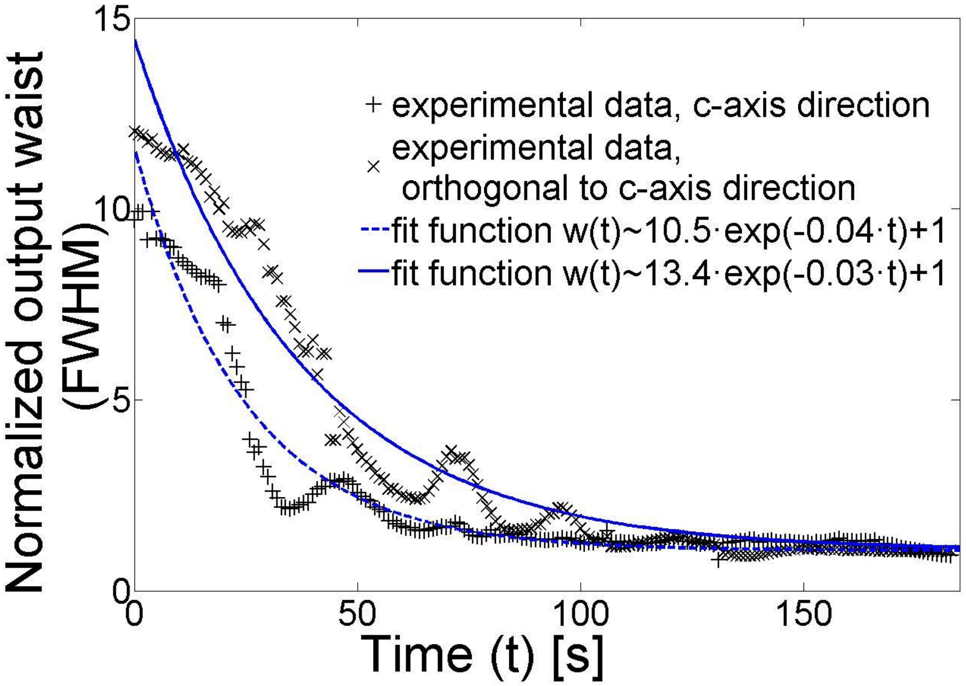

Fig. 2. SWG writing process for input beam intensity of ~ 4 W/cm^2 and external field of ~ 45 kV/cm.

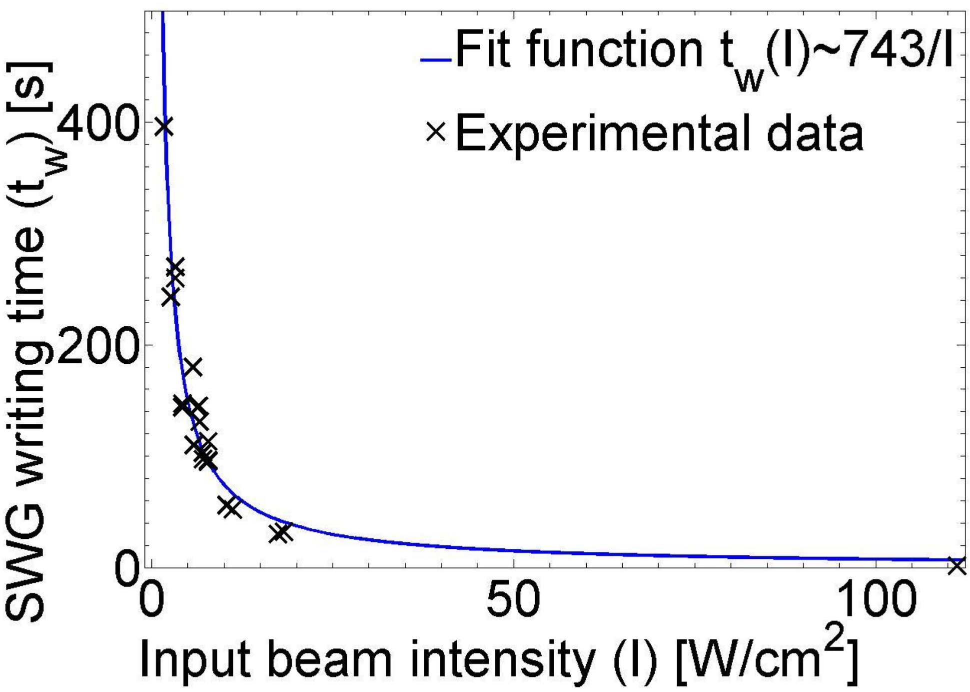

Fig. 3. SWG writing time dependence on input light intensity.

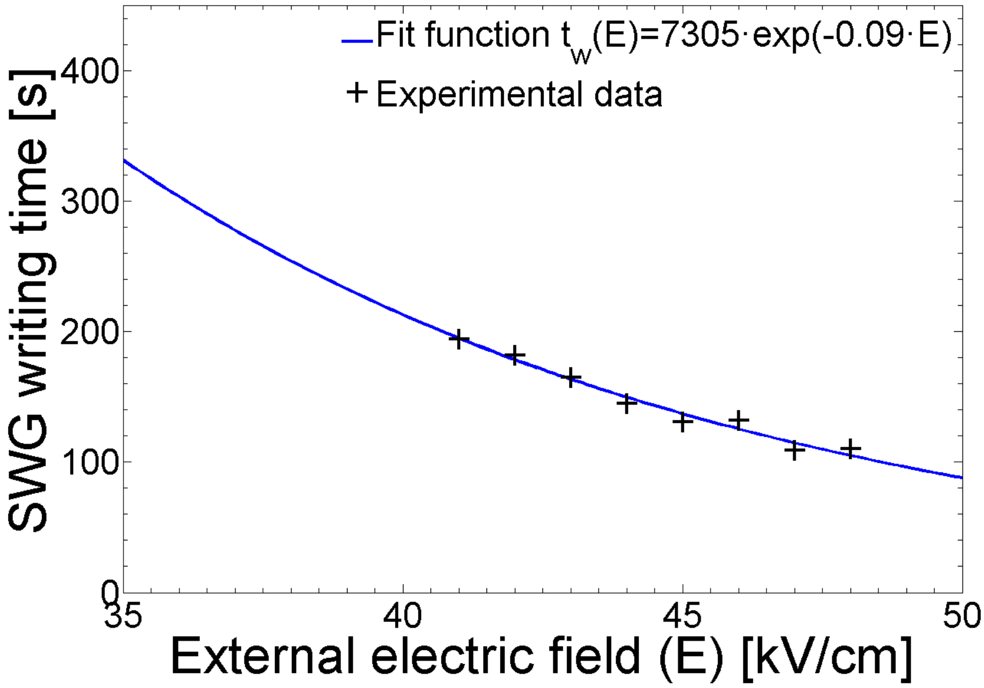

Fig. 4 SWG writing time dependence on external electric field.

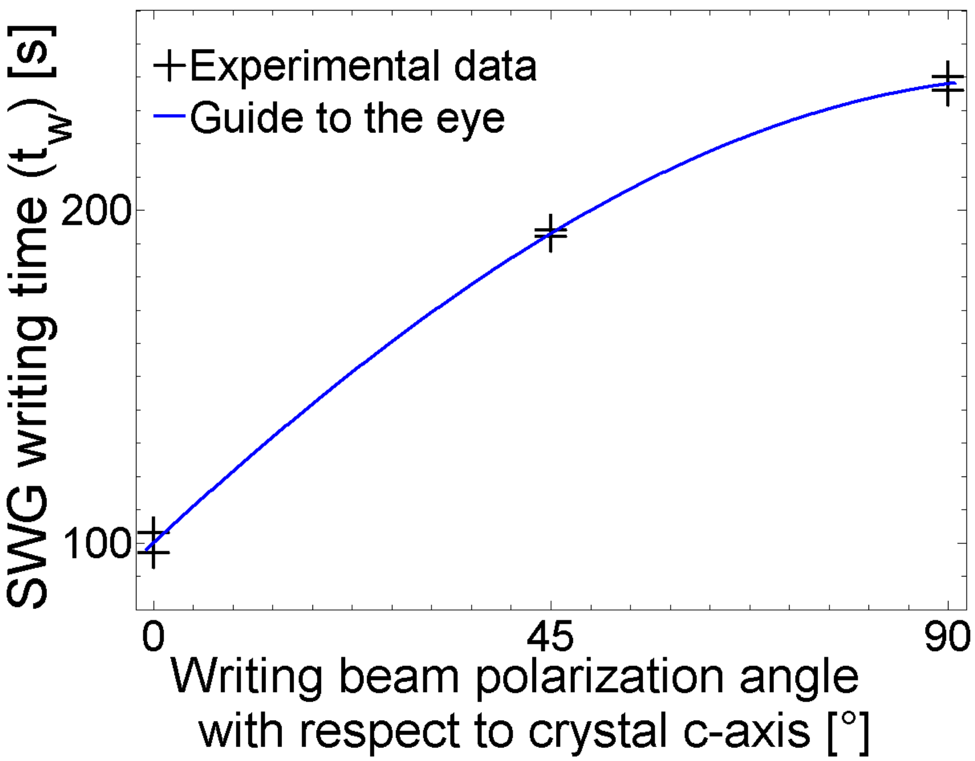

Fig. 5. SWG writing time dependence on the beam polarization.

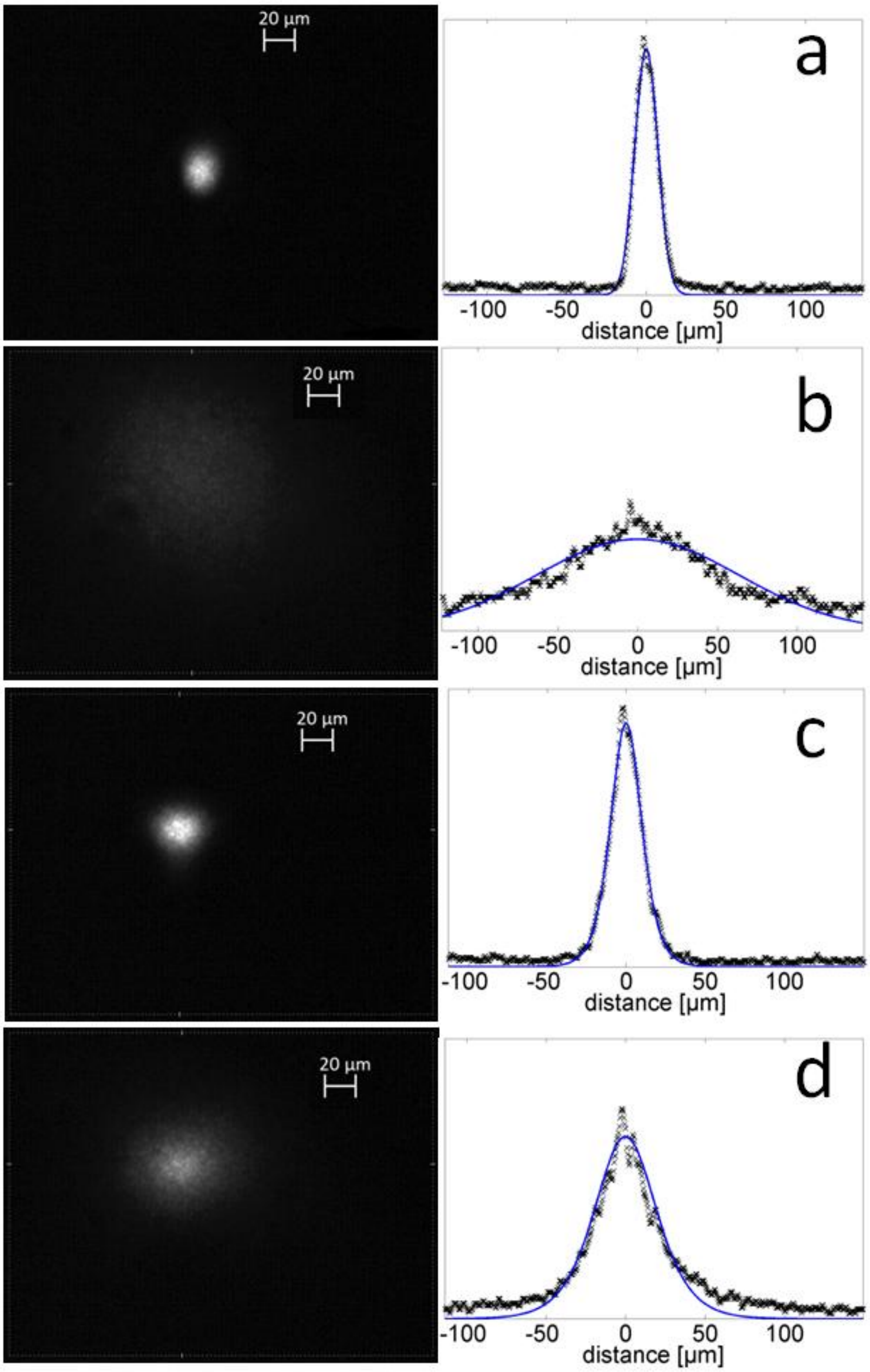

Fig. 6. Propagating fs pulses in SWGs at λ=1550nm: a) Input beam, b) Output in free propagation, c) Guided output with extraordinary polarization, d) Guided output with ordinary polarization.