Techniques of surface optical breakdown prevention for low-dephts femtosecond waveguides writing

M A Bukharin\textsuperscript{1,2}, N N Skryabin\textsuperscript{1,2}, D V Ganin\textsuperscript{3,4}, D V Khudyakov\textsuperscript{2,3} and S.K. Vartapetov\textsuperscript{2,3}

\textsuperscript{1}Moscow Institute of Physics and Technology, 9 Institutskiy per., Dolgoprudny, Moscow Region, 141700, Russia
\textsuperscript{2}Optosystems Ltd., Troitsk, Moscow, 142190, Russia
\textsuperscript{3}Physics Instrumentation Center of Prokhorov General Physics Institute RAS, Russian Academy of Sciences, 142190, Troitsk, Moscow, Russia
\textsuperscript{4}National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31 Kashirskoe shosse, 115409 Moscow, Russia

E-mail: mikhail.bukharin@phystech.edu

Abstract. We demonstrated technique of direct femtosecond waveguide writing at record low depth (2-15 µm) under surface of lithium niobate, that play a key role in design of electro-optical modulators with low operating voltage. To prevent optical breakdown of crystal surface we used high numerical aperture objectives for focusing of light and non-thermal regime of inscription in contrast to widespread femtosecond writing technique at depths of tens micrometers or higher. Surface optical breakdown threshold was measured for both x- and z-cut crystals. Inscribed waveguides were examined for intrinsic microstructure. It also reported sharp narrowing of operating pulses energy range with writing depth under the surface of crystal, that should be taken in account when near-surface waveguides design. Novelty of the results consists in reduction of inscription depth under the surface of crystals that broadens applications of direct femtosecond writing technique to full formation of near-surface waveguides and postproduction precise geometry correction of near-surfaces optical integrated circuits produced with proton-exchanged technique.

1. Introduction
Under the influence of tightly focused ultrafast laser pulses refractive index of optical crystals could be permanently changed. Translating the crystal relatively to focus of the lens one can directly inscribe optical waveguide in the bulk crystal [1-3]. This technique is maskless in contrast to standard fabrication techniques of subsurface waveguides formation [4-6]. One of the most important challenges of the technology nowadays is inscription of waveguides at low depth (< 15 µm) under the surface of electro-optical crystals, due to the opportunity to produce fast electro-optical (e.-o.) modulators with low operating voltage.

Such well known and widespread technologies as Ti-diffusion, ion implantation and proton exchange can provide production of subsurface waveguides, but their properties do not meet all requirements of practical applications: mode field diameter of designed waveguides is significantly asymmetric due to diffusion character of the techniques, production process is multistage and...
complex. In addition, Ti-diffused waveguides has high photorefraction [7, 8], and proton exchanged ones maintain only of one linear polarization state [9].

On the other hand, femtosecond waveguide writing could meet the challenge: it provides low optical losses, low influence on waveguide’s core material (there is no observable changes in photorefraction as compared to undoped LiNbO$_3$), and maintenance of all polarization states of propagating light, that is crucial for development of fast electro-optical modulators for laser emission with broad spectrum, based on electro-optical polarization rotation [10, 11]. According to present knowledge, there is no experimentally written waveguides at depths lower than 20 µm [1, 12, 13], which could provide only high operating voltage for e.-o. modulators (>15V compared with <1.5V for modulators, based on Ti-diffused or proton-exchanged waveguides [1]). Thus, actuality of the investigation consists in development of femtosecond writing technique for near surface waveguides production.

![Figure 1](image)

**Figure 1.** Schematic of femtosecond laser written waveguides.

Fundamental problem resolved in the investigation consists in suppression of optical thermomechanical breakdown of surface, that impeding femtosecond inscription of waveguides at low depths. The technique of femtosecond writing proposed in the paper doesn’t eliminate negative factors, described above, but sufficiently decreases its effect.

In this work we experimentally shown femtosecond inscription of waveguides at record low depths (2-15 µm) under the surface of lithium niobate (both z- and x-cut), that could be used with surface electrodes to form electro-optical modulator.

2. Experimental setup

For direct femtosecond waveguide writing we used experiencial setup, represented in Fig.2. Ultrashort laser pulses (340 fs, 1040 nm) from oscillator without additional power amplifier (HighQ femtoTRAIN, 0.1-10 MHz) were focused into lithium niobate sample (both x- and z-cut), which was mounted on precise motorized 3D-translational stage and moved with velocity 10 µm/s to form extended tracks through the full length of the sample (25 mm).
**Figure 2.** Schematic of experimental setup. Dashed elements are designed for alignment of sample regarding to lens focus and placed in the optical path only for the time of adjustment and investigation of surface optical breakdown threshold.

### 2.1. Technique of femtosecond writing

To write tracks with induced refractive index at record low depth under surface of crystal we proposed technique of negative factors reduction that eliminates optical and thermomechanical breakdown of the surface. To prevent optical breakdown we used high numerical aperture aspheric lenses for focusing of light (NA=0.6). As a development of our previous investigation [14], we have shown that to write near-surface waveguides there is no need in expensive high numerical aperture objectives (NA>0.8). Moreover, for the purpose under consideration utilization of oil-immersed objectives is prohibited due to low breakdown threshold of immersion oil.

Varying pulse repetition rate from 0.1 MHz up to 10 MHz we experimentally shown, that widely used heat accumulation regime of femtosecond writing is unsuitable for inscription of waveguides at low depth due to formation of steep temperature gradients [15], which could break up crystal surface even at pulse energies lower than required for refractive index induction. According to estimation described in details in [16], critical repetition rate for transition to thermal cumulative regime equals

\[ f_{\text{critical}} = \frac{D}{w_0^2} = 1.4 \text{MHz}, \]

where \( D = 1.9 \times 10^{-6} \text{ m}^2/\text{s} \) - thermal diffusivity and \( w_0 = 1.3 \mu\text{m} \) - focal spot radius. Experiments confirm the estimation: at repetition rate higher than 2 MHz written tracks with induced refractive index were not observed under surface breakdown threshold at depths lower than 15 \( \mu\text{m} \) (thermomechanical breakdown of the surface occurred at lower pulse energies). To prevent the negative thermal accumulation effect we proposed to write the structures in non-thermal regime in spite of lower achievable induced refractive index value compared to the thermal cumulative one. In the investigation laser pulse energy in focal region was 40-60 nJ and pulse repetition rate was \( f_{\text{PRR}}=0.1 \text{ MHz} \).

Under the influence of tightly focused femtosecond laser emission refractive index of lithium niobate permanently changes due to several photochemical processes and formation of macroscopic defects that depend on number of laser pulses, accumulated in the interaction volume. Thus, to compensate reduced number of accumulated pulses per focal spot due to low repetition rate and to increase achievable value of induced refractive index, writing exposition was proportionally increased by reducing of translational velocity down to 10 \( \mu\text{m}/\text{s} \). As a result, induced refractive index was of the order of \( 3 \times 10^{-3} \), which is sufficient for formation of waveguide’s cladding. The value of induced refractive index was measured on the base of widely used quantitative phase microscopy technique, described in details in [16-19].
2.2. Surface optical breakdown threshold

Before writing of waveguides the crystal should be precisely aligned in relation to focus of the lens. One of the most practical and precise techniques consists in analyzing of back-reflected operating emission from the surface of treated crystal, as shown in Fig.2 (dashed elements).

![Image](76x495 to 519x665)

**Figure 3.** Reduction of back-reflection signal due to local ablation of x-cut (A) and z-cut (B) lithium niobate crystal surface at high pulse energies while z-scanning around focusing point at surface (near 15 µm coordinate).

The alignment setup also provides an opportunity to estimate surface optical breakdown threshold by reduction of back-reflection signal due to local ablation in the focal spot even at low pulse energies, as shown in Fig.3. Each experimental graph was fitted with theoretical z-scan curve, representing part of back-reflected light in the presence of central ablated (non-reflected) region for Gaussian beam profile. It was found that critical peak energy density for x-cut LiNbO$_3$ was nearly twice higher than the one for z-cut LiNbO$_3$ ($I_{\text{critical}}^{\text{x-cut}} \approx 2 \cdot I_{\text{critical}}^{\text{z-cut}}$) and under experimental focusing conditions achieved at 56 nJ pulse energy. The relation strongly depends on surface polishing quality. In the experiments we used LiNbO$_3$ wafer (Crystal Technology Inc.) with surface quality scratch #10, dig #5.

3. Results

Using the proposed technique of femtosecond inscription, we have produced a number of parallel tracks (from 34 to 50, see Fig.4) with induced refractive index ($\Delta n=3\cdot10^{-3}$), that form a waveguides with mode field diameter from 8 µm up to 13 µm at record low depths (2-15 µm) under the surface of LiNbO$_3$ crystal (both x- and z-cut). Each track has cross sectional dimensions of 1.1 µm×6.0 µm. In comparison to previous published results [14], that were written with higher NA=0.8, aspect ratio of the tracks significantly increased from the value of 2.5 up to 5.5. It connected with 1.8 times higher Rayleigh length in current investigation and higher writing pulse energy, that increases plasma defocusing in the focal region and also increases aspect ratio of written structures. Typical microscopic images of single near-surface tracks are shown in Fig.4a and 4b. Cross section of designed waveguide and corresponding modelling trajectory are shown in Fig.4c and 4d. It should be noted, that there is no negative macroscopic cracks that are typically appear in widespread high energy and low numerical aperture technique of femtosecond writing.

In series of experiments it was shown that operating pulse energy range strongly depend on writing depth under the surface of crystal (see Fig.5). While the lower boundary of the range do not changed with writing depth (with amount nearly 50 nJ), the upper boundary rapidly decreases from more than 110 nJ at 8 µm down to 60 nJ at 2 µm depth. Thus, operating range rapidly narrows and complicates process of near-surface waveguide formation due to necessity of dynamic adjustment of operating energy.
Figure 4. (A, B) Microscopic images of written near-surface tracks with induced refractive index; (C) facet view of inscribed waveguide with mode field diameter 10 µm at low depth under the surface of crystal, white pointers indicates top and bottom borders of waveguide’s core; (D) schematic of written cladding of waveguide from Fig. 4c.

Figure 5. Narrowing of operating pulses energy range with writing depth under the surface of crystal.

4. Discussion
Waveguides produced by the proposed technique possess both advantages of low optical losses and maintaining of all polarization states of propagation light [14]. Taking into account the opportunity to use commercially available aspheric lens to directly write three-dimensional near-surface waveguides instead of costly multilens objectives with high NA or multistep lithographic techniques, it provides a new avenue in production of fast electro-optical modulators with non-interferometric architectures, based on electro-optical polarization rotation, that is crucial for fast modulation of femtosecond laser emission in fully integral schemes.
On the one hand, increased aspect ratio of written tracks (5.5 instead of 2.5 for high NA femtosecond writing) negatively effect on written waveguide’s properties, increasing its asymmetry and impels to compensate it with more complex multilayer cladding, as shown in Fig.4d. But on the other hand, narrow and tall (1µm×6µm in cross-section) tracks with induced refractive index provides a new application of proposed femtosecond writing technology. Using single tracks with such geometry one can carry out postproduction precise geometry correction of near-surfaces optical integrated circuits (Y-branching power dividers, for instance), produced with proton-exchanged technique [20]. Proton exchanged waveguides have longitudinal dimension (in depth) of the same 6 µm. Thus, femtosecond written tracks could cover all of its cross-section in single path. This result provides an opportunity to reduce thermal sensitivity of proton-exchanged Y-branching power divider (Fig.6a) due to reduction of mode coupling in the transitional region of branching without increasing of optical losses (as in the case of correction with optical breakdown, shown in Fig.6b), but only with increasing of refractive index contrast between waveguide’s core and cladding, as shown in Fig.6c.

![Microphotographs of proton-exchanged Y-branching power divider (A) with mode coupling via optical breakdown (B) and femtosecond induced track (C).](image)

**Figure 6.** Microphotographs of proton-exchanged Y-branching power divider (A) with mode coupling via optical breakdown (B) and femtosecond induced track (C).

### 5. Conclusion

In the paper we have reported an advanced technique of direct femtosecond inscription of near-surface waveguides at record low depth in lithium niobate (both x- and z-cut). Using high-NA focusing lens and non-thermal regime of femtosecond writing with increased exposure for optical and thermomechanical surface breakdown prevention it was experimentally shown the opportunity to write full cladding of single-mode waveguide in depth range 2-15 µm. The result opens a new opportunities in fabrication of fast electro-optical modulators with low operating voltage and postproduction precise geometry correction of near-surfaces optical integrated circuits produced with proton-exchanged technique. As compared to previous investigations in the field of waveguide writing in LiNbO₃ for the purposes of modulators development (structures at depths more than 50 µm with buried electrodes [1]), the obtained waveguides could be used with easy-to-produce on-surface electrodes.

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