TECHNOLOGY OF THREE-DIMENSIONAL FEMTOSECOND WRITING FOR CREATING INTEGRATED OPTICS ELEMENTS

A permanent change in the refractive index affected by femtosecond laser pulses at a small depth (2–15 μm) under the surface of a lithium niobate crystal has been studied. Based on the technology of femtosecond writing, solutions for the problems of industrial electro-optical modulators are proposed. For interference schemes obtained by lithographic methods, a correction track with a reduced refractive index (Δn = −3 ∙ 10–3) was writing to reduce the coupling between the channels of the splitter and to increase its temperature stability. Apart from the above, a possibility of a fully femtosecond writing of a depressed cladding waveguide with a core diameter of 12 μm at small depths below the surface of a lithium niobate crystal has been demonstrated to create a noninterference electro-optical modulator based on the effect of electrooptic rotation of polarization.

Keywords: femtosecond writing, lithium niobate, refractive index, electro-optical modulator, waveguide, integrated optics.

Introduction

An electro-optical modulator (EOM) based on a lithium niobate crystal (LiNbO₃) is one of the most common components in optoelectronic devices [1]. Nowadays, the most commonly used technologies for creating optical circuits in lithium niobate based on planar and channel waveguides are titanium diffusion and proton exchange. However, it is known that each of these methods has its own advantages and disadvantages. The Ti-diffusion method allows obtaining single-mode waveguides with the maintenance of all states of polarization of the spreading radiation. However, it leads to an increase in material photorefraction and, therefore, does not allow modulating high-performance laser signals [2, 3]. The proton exchange method, on the contrary, ensures low photorefraction, although it allows creating only waveguides supporting the linear polarization state [4]. Both above-mentioned methods enable manufacturing of waveguides with low but significant asymmetry in the mode field due to the diffuse nature of these production methods, which leads to high losses on the connection with optical fibers at 3 dB [5]. These processes are complex and multi-stage; they lead to the high sensitivity of optical waveguide parameters to the quality of the crystal surface due to the fact that the surface acts as an upper reflective waveguide boundary. In addition, industrial production of multifunctional integrated optical elements (MIOEs) using Υ-splitters on channel waveguides is occasionally accompanied by spurious spectral selectivity because of the excessive refractive index (r/i) in the Υ-splitting area as a consequence of technological instabilities in the implementation of photolithography and proton exchange processes [4]. It was also found that such MIOEs are exposed to vibration energy exchange between output branches of the Υ-splitter when changing the temperature, which is intolerable for the practical use of MIOEs [4]. An MIOE performs the polarization of optical radiation, division into two channels and phase modulation of the optical radiation. An MIOE consists of a Υ-splitter and two electro-optical phase modulators based on channel waveguides in the lithium niobate crystals.

This paper proposes a solution to the problem of the excessive increase in r/i in the area of Υ-splitting using direct femtosecond writing technology. Namely, it has been proposed to adjust the profile of the r/i splitter and thereby reduce the coupling parameter between splitter channels. The essence of this technology is a permanent change in r/i of transparent dielectrics under the action of focused ultrashort laser pulses that induce several nonlinear processes in the focal area. Depending on the writing conditions and processed material, both increase and decrease in r/i can be observed in the processed area [6].
In addition to fine-tuning of r/i, this technology makes it possible to fully record long structures with modified r/i in glasses and crystals [7]. They become the basis for such integrated optical devices as power splitters [8], directional couplers [9], waveguide lasers [10], amplifiers [11] and fiber Bragg gratings [12]. Structures with high r/i can serve as a core of recordable waveguides, structures with low r/i – as a clad that keeps optical radiation in the waveguide under the effects of total internal reflection. A mixed effect is often observed, where increased r/i manifests itself in the center of the focal area and a ring with low r/i appears in its periphery. In this case, one can also write a fully depressed waveguide clad (with low r/i) as shown in [13]. Waveguides with a written depressed clad unlike waveguides with a written core possess a number of advantages, such as reduced losses during propagation of radiation, high mode symmetry, and support for the distribution of orthogonal polarizations with closely approximated characteristics [14]. This feature is crucial for the development of electro-optical modulators of laser radiation with low operating voltage (< 3 V) and wide spectrum (> 100 nm) due to the possibility of using crossed polarizers (based on the effect of electro-optical rotation polarization) instead of the interference modulation scheme (integrated Mach-Zender interferometer) that is sensitive to the wavelength and spectrum width of the modulated radiation. In this article, the authors present the latest results of research on femtosecond writing near the surface of a lithium niobate crystal, adjusting of Y-splitters, and writing of single-mode waveguides.

Materials and methods
Experiments were carried out near the surface of LiNbO₃ crystals for optical MIOE chips with sizes of 30×15 mm and 30×3.5 mm (Fig. 1).

In these MIOEs, channel waveguides were used (channel width W = 6 μm), single-mode at wavelengths ≥ 1480 nm and having low optical losses in the range of 1500–1580 nm. One of the most theoretically promising schemes was used for the practical implementation of MIOEs based on the Y-splitter [4]. This scheme is a combination of a Y-splitter with a complex shape, which includes horn transition (additional spread-out area) and smooth area (cos-curve) of channel waveguides splitting far (320 μm) from each other. The application of this scheme allowed for a division ratio values close to 50:50% and resistant to unavoidable small deviations of technological parameters during the production of the integrated-optical element [1]. The deviation of the distribution of optical power from 50:50% depends in a complex manner on the small but almost inevitable asymmetry of channel waveguides that generate output MIOE shoulders (sections II and III in Fig. 2) [4]. The use of the chosen scheme unlike a number of other schemes allows adjusting the optimal value of the division ratio of optical power using the technological operation of additional low-temperature annealing.

An MIOE contains a Y-splitter with a standard cosine geometry of smooth waveguides splitting (Fig. 2) described by equation

\[ y(x) = y_s + \frac{y_c - y_s}{2} \left(1 - \cos \frac{\pi x}{x_e}\right). \]

Figure 1. Photos of LiNbO₃ industrial samples for the PSEEL optical chips (LLC RPC Optolink, Zelenograd)

Рисунок 2. Рисунок 2. Figure 2. Diagram of the Y-splitter power divider: Θ – branch angle; W = 2y – the width of the channel waveguide; xe – branch length (area II); ye – the output channel's indent from the input channel's center. Areas I and III consist of straight single-mode channel waveguides.

Figure 3. Branch area topology: L – the broadening length; Let and 2w – the length and width of the section with additional broadening. Dotted lines show the Y-splitter without additional
Technologies and production

The effective splitting angle $\Theta = 1.9^\circ$. In order to suppress spurious spectral selectivity, a horn transition $L_{et} = 100 \mu m$ was added (Fig. 3) [4].

The standard orthogonal layout has been used for femtosecond writing (Fig. 4) [7]. The radiation source was the HighQ FemtoTRAIN laser with a wavelength of 1040 nm, pulse width 360 fs, energy up to 350 nJ, frequency 0.1 MHz.

In order to reduce high radiation intensity at the surface of the material and prevent ablation, an immersion focusing microlens with a large numerical aperture ($N_A = 1.25$) has been used with distilled water ($n = 1.32$) instead of immersion oil ($n = 1.51$). This replacement is associated with a low breakdown threshold of immersion oil, which could lead to the powerful heating of the output plane of a lens and its deformation. In contrast to immersion oil, water does not form combustion products in case of exceeding a breakdown threshold and evaporates without contaminating the lens and causing no significant heating. To create three-dimensional structures, the sample was moving relative to the focus of the radiation through a 2D angular piezo-actuator (Newport AG-M100N).

Results and discussion

The described method allowed writing a number of 100 $\mu m$ tracks with an induced refractive index at extremely shallow depths (2–17 $\mu m$) under the surface of the pure lithium niobate crystal of X-cut with different pulse energies (35–80 nJ) at a rate of 10 $\mu m/s$. An energy diagram was obtained for writing near the surface of lithium niobate (Fig. 5).

The minimum writing depth reached 2 $\mu m$. Each induced track had characteristic cross-section dimensions from 1×2.5 to 1.5×4 $\mu m$ and an induced refractive index to $-3 \times 10^{-3}$. The impossibility to write tracks with modified r/i at lesser depths (<2 $\mu m$) is conditioned by the low optical breakdown threshold of the surface relative to the breakdown threshold of the material volume, as well as high temperature gradients causing significant mechanical tensions inside the focal plane. Therefore, the destruction of the sample surface is observed on lesser writing depths.

Adjustment of $Y$-splitters

It has been experimentally determined that small changes in the input of optical radiation in the input channel of the $Y$-splitter having an excessive increment of r/i cause significant changes in the ratio of optical power between the output shoulders of the splitter in the output channels of MIOEs. So, a small lateral shift (0.5–2.5 $\mu m$) of the fiber transferring radiation into MIOEs from the center of the input channel in the $Y$ direction (Fig. 2) leads to the «pumping» of optical power between the outputs channels of the MIOEs having parasite spectral selectivity. Similar «pumping» was observed in the case of temperature change, when the position of the fiber optic was fixed with glue. These results clearly indicate the presence of inter-mode interactions in the $Y$-splitting area with the excessive increment of r/i [4, 5].

To address the problem of the excess increase in r/i in the area of $Y$-splitting, the technology of direct femtosecond writing was used that allows adjusting the r/i profile of the splitter, i.e. reducing the r/i increment in the central area of $Y$-splitting between channels of the splitter.

The correction on the reduction of r/i in the area of MIOE $Y$-splitting was performed basing on the obtained energy calibration of direct FS writing (Fig. 5). The correction was made in the form of tracks with a width $d = 1 \mu m$, length $L_{cor} = L_1 + L_2$, where $L_1$ lies within the expansion plot and reduces connection between splitting waveguides, and its continuation $L_2$ suppresses connection in further dissemination, as shown in Fig. 6.

The tracks lay at 2 to 6 $\mu m$ depth and covered a large part of the waveguide proton-exchange channel with a depth of 6 $\mu m$. $L_1$ ranged from 40 to 60 $\mu m$ (60 $\mu m$ is the maximum value of the correction track within the additional extension plot with a length = 100 $\mu m$), and $L_2$ – from 10 to 40 $\mu m$ (40 $\mu m$ is the sufficient length for correcting the r/i in the area of MIOE Y-splitting.
splitting waveguides to be at a sufficient distance. Thus, the correction tracks were of varying lengths (from 50 to 100 μm) and were written at different energies (40, 43 and 46 nJ). The photos of the corrected Y-splitters are shown in Fig. 7.

MIOEs (i.e. Y-splitters) were tested for temperature stability before and after the femtosecond correction. Correction was made for MIOEs possessing a big temperature drift of optical power division ratio: from 64:36% to 36:64% in the range from 0 to +60 °C, at room temperature 48.5:51.5%, which is slightly different from the projected value 50:50% for an ideal Y-splitter. It has been experimentally revealed that laser-induced structures of 70 μm length significantly reduce the thermal sensitivity of the Y-splitter in a manner that the division ratio remains unchanged throughout the whole temperature range with an accuracy of 0.1%. The FS-correction of Y-splitters in MIOEs slightly increases the total optical loss of MIOEs from 0.1 to 1.3 dB. Such MIOEs containing corrected Y-splitters and possessing a high temperature stability of the division ratio at small optical losses are undoubtedly interesting for application in fiber-optic gyroscopes of middle and high accuracy [15].

Waveguide for a non-interference EOM

Fully femtosecond writing of waveguides was proposed as an alternative to electro-optical modulators on the Y-splitter obtained through proton exchange. For the pilot testing of this feature, clean X-cut lithium niobate samples with a size of 36.5×13 mm were written with single-mode waveguides with a depressed clad 12 mm in diameter, which consisted of several rows of parallel tracks as shown in Fig. 8.

The waveguide was located at 2 to 20 μm depths (the location of core boundaries from 5 to 17 μm). Such waveguide supported any linear polarization state, and the magnitude of losses on dissemination stood at 1.5 dB/cm for the horizontal polarization and 1.8 dB/cm for the vertical polarization. The difference in dissemination losses at the level 0.3 dB compared with more than 1 dB in [16, 17] indicates a high level of homogeneity of waveguide clads and their possible use for non-interference electro-optical modulators based on the effect of electro-optical polarization rotation. Shallow depth of femtosecond-written waveguides obtained for the first time in this work allows their use with surface-coated electrodes in contrast to the previously used buried electrodes for femtosecond-written waveguides at deep depths beneath the crystal surface (more than 15 μm) [18].

Figure 5. Performance range for recording on lithium niobate surface. The square dots mark the upper limit of the performance range with a permanent change in the semiconductor, round dots – the lower one. Optical breakdown of the material volume occurs above the upper horizontal dotted line with destruction near the surface at high energies.

Figure 6. Correction scheme of the Y-splitter: the track recorded by the FS-laser is shaded in the figure, its left part (L₁) lies inside the additional section of the extension Lₑₑ, the right part (L₂) – outside

Figure 7. Micro photo of corrected Y-splitters: the arrow indicates tracks recorded by the FS-laser with following lengths: L₁ = 60 μm, L₂ = 10 and 7 μm
The possibility of femtosecond track writing near the surface of a lithium niobate crystal has been studied. This allowed developing a new manufacturing technology for channel waveguides. The minimum writing depth of 2 μm has been achieved. A direct single-mode waveguide with a depressed clad with a core diameter of 12 mm and length of 36.5 mm, which can become a basis for the non-interference EOM based on polarization rotation, has been written. In addition, a correction of Y-splitters has been performed, which increases the thermal stability of integrated optical devices using such splitters (e.g. multifunction integrated optical elements in fiber optic gyroscopes [4]).

Thus, femtosecond writing of tracks with induced r/i and waveguides on their basis is a promising technology for integrated optics and has the following advantages:

- This is single-stage and maskless technology, which allows creating wave-guiding structures with random geometry defined by the trajectory of the sample motion relative to the laser system focus.
- It allows creating waveguides that support any polarization state of optical radiation propagation, which provides high mode field symmetry and insensitivity of optical characteristics of waveguides to the quality of the crystal surface due to writing of the upper boundary of the waveguide clad.

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