

Planar proton-exchange waveguides in reduced lithium niobate

© A.V. Sosunov¹, A.V. Shipitsyn¹, A.A. Mololkin², M.A. Bazalevsky², A.P. Borovikhin³,
A.R. Kornilicyn¹, I.V. Petukhov¹

¹ Perm State University, Perm, Russia

² National University of Science and Technology MISiS, Moscow, Russia

³ St. Petersburg State Electrotechnical University „LETI“, St. Petersburg, Russia

e-mail: avsosunov@psu.ru

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Photonics and microelectronics are promising fields for the development of various devices for telecommunications, navigation, and sensing. New optical materials enable the production of devices with improved performance. This work demonstrates the possibility of fabricating and operating planar proton-exchange waveguides in reduced lithium niobate with the pyroelectric effect eliminated. The main parameters (refractive index and depth) of the planar waveguides are determined. It is shown that post-exchange annealing leads to complete restoration of the lithium niobate crystal lattice under specific modification regimes. The obtained results are promising for the creation of integrated optical circuits based on lithium niobate with enhanced temporal and thermal stability of characteristics.

Keywords: reduced lithium niobate, pyroelectric effect, waveguide, refractive index, profile.

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Introduction

Lithium niobate (LN) is a segnetoelectric and a pyroelectric. It means it has spontaneous polarization, i.e. nonzero electric dipole moment in absence of an external electric field. The general neutrality of LN is implemented by compensation of charges on the surface of LN with charges in the crystal volume. However, when temperature changes, the charge compensation is easily disturbed, and when pins are connected to the faces of the sample, current will flow in the external electric circuit. Such phenomenon is called a pyroelectric effect. The relationship between the speed of pyroelectric temperature change speed and current value passing in the external electric circuit connected to the faces of the sample is described using of the following equation [1]:

$$I = Ap(T) \frac{dT}{dt}, \quad (1)$$

where I — current, $p(T)$ — pyroelectric coefficient, A — sample area, T — temperature, t — time. This effect may bring both positive and negative results. In particular, LNs are widely used in the manufacturing of radiation phase and amplitude modulators [2], and also in the field of sensorics [3,4] for various purposes of optical instrument engineering. When these integrated optical devices are designed on the basis of LN, their high temperature stability is required, i.e. absence of pyroelectric effect [5–7]. Elimination of the pyroelectric effect is achieved by various process routes, for example, closure of crystal faces or application of a conducting paste on them [8,9]. However, such approaches have certain technical and economical limitations.

Another option to reduce the pyroelectric effect is use of the reduced (black) LN. Change of the crystal color is related to appearance of color centers in connection with evaporation of O_2 and Li_2O and formation of defects Nb_{Li} and 4 electrons produced from the break of the covalent bond between Nb and O ions [10–12]. There are different methods of LN recovery: vacuum annealing [13], doping with Fe [14], annealing in hydrogen or nitrogen environment [15,16].

The reduced LN with the eliminated pyroelectric effect is a promising material for integrated and nonlinear photonics in those applications where the pyroelectric effect is one of the key negative factors that impacts the final characteristics of the devices [17,18]. Integrated optical circuits based on LN for the applications of navigation, telecommunications and sensorics function with the use of optical waveguides obtained by the method of proton exchange with the post-exchange annealing [18]. Therefore it becomes necessary to study the functioning of planar proton-exchange waveguides in the reduced LN by the assessment of their main parameters (increment of the refractive index, waveguide profile, waveguide depth, crystalline lattice deformations) or the design of integrated optical circuits.

Materials and methods

The materials studied were samples of congruous LN of Z-cut by Fomos-Materials (Russia) with size of $10 \times 15 \times 1$ mm, reduced using the vacuum annealing at temperatures 550°C for 1 h and pressure of residual gases of not more than 10^{-3} Pa.

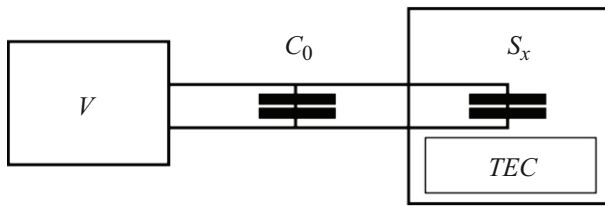


Figure 1. Design for measurement of pyroelectric effect by quasistatic method.

Planar waveguides were formed by proton exchange (PE) in a closed zirconium reactor in benzoic acid melt at temperature of 190 °C for 2 h with subsequent annealing on air at temperature of 370 °C for 5 h. PE mode was selected so that 3–4 modes existed at wavelength 0.63 μm for the possibility to restore the profile of the refractive index using the reverse Wentzel–Kramers–Brillouin method [19]. Samples for comparative analysis were also available: the virgin LN and the virgin LN with PE and annealing.

Pyroelectric coefficients were determined using the supply of constant thermal flux to the samples and detection of the obtained pyroresponse (Fig. 1).

The studied samples S_x were placed into a measurement cell with a thermoelectric cooler (TEC). Using the thermoelectric cooler, the samples were heated (heating temperature was measured with a four-probe method). Non compensated electric charges on the surface of the samples were detected using a voltmeter (V). A reference capacitor $C_0 = 1 \mu\text{F}$ was also present in the circuit to stabilize the total electric capacity. Electroconductive contacts on the surface of the samples were made of silver paste L100.

Pyroelectric coefficient p is expressed as the change in polarization with the change in temperature ($p = dP/dT$), and for flat parallel samples the change in polarization may be expressed via the change in the charge in a certain area ($dP = dq/S$), therefore (with account of $q = CU$) you can obtain the following equation:

$$p = \frac{C_0}{S} \frac{\partial U}{\partial T}. \quad (2)$$

X-ray studies of the samples were carried out using a two-crystal spectrometer. A monochromator was a single crystal of dislocation-free silicon installed in a position corresponding to reflection of K_β -line of cobalt emission ($\lambda = 1.62075 \text{ \AA}$) from the crystallographic plane (111). Crystallographic plane of reflection for LN of Z-cut — (006). Relative deformations of the LN crystalline lattice after the proton exchange were calculated using the change in the interplanar spacing d from Bragg's-condition:

$$d = \frac{\lambda}{2 \sin \theta}, \quad (3)$$

where θ — Bragg's angle of reflection.

Main parameters of planar waveguides (increment of the refractive index, depth and profile) were determined

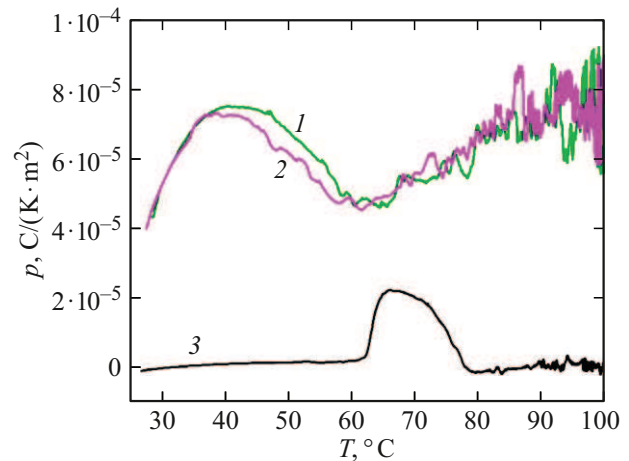


Figure 2. Temperature dependence of pyroelectric coefficient of LN: 1 — virgin sample, 2 — PE waveguide in the virgin LN, 3 — PE waveguide in the reduced LN.

using the prism coupling method. For this purpose, first the number and distribution of modes N_m of optical waveguide at wavelength $\lambda_{\text{HeNe}} = 632 \text{ nm}$ were determined. Then on the basis of the obtained values N_m the profile of the waveguide layer was reconstructed by the inverse Wentzel–Kramers–Brillouin method [19]. For this method the accuracy of measurement of the refractive index is ± 0.0002 .

Results and discussion

The results of measurements of temperature dependences of pyroelectric coefficients are shown in Fig. 2. Comparing the virgin 1 and protonated 2 samples, one may conclude that PE and annealing of samples practically do not influence the pyroelectric coefficient $p = 4 \cdot 10^{-5} \text{ C/(K} \cdot \text{m}^2)$ [1]. Samples 1 and 2 have practically matching results in the entire temperature range. Besides, the reduced LN demonstrates the decrease of the pyroelectric coefficient down to two orders $p = 6 \cdot 10^{-7} \text{ C/(K} \cdot \text{m}^2)$, which practically results in its elimination. There is a certain abnormality in the range from 60 to 80 °C, which requires further research.

As for the „rattling“ nature of temperature dependences of pyrocoefficients in the right part of the figure, they are explained by the fact that when the constant thermal flux is supplied to the samples, the system gradually arrives into the thermal equilibrium, and the heating speed decreased. Accordingly, the value of the pyroelectric response decreased, and the influence of noise in the calculation of the pyroelectric coefficient became more noticeable.

Deformations of PE waveguides were assessed by the broadening of the diffraction curves at FWHM (Fig. 3). The studied samples yield practically identical results at the specified regime of waveguide formation, which means complete recovery of the LN crystalline lattice in process

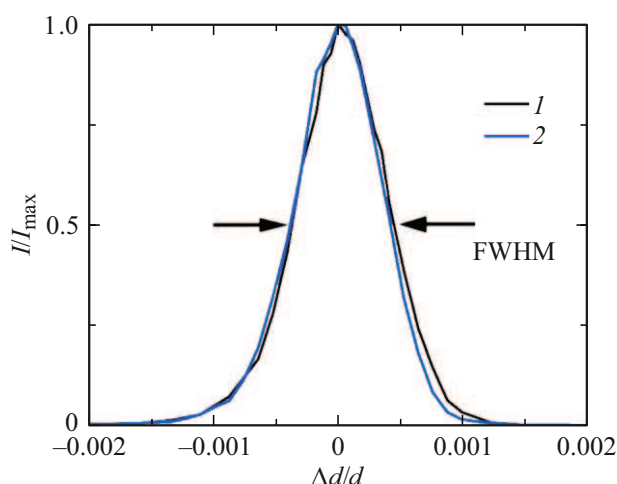


Figure 3. Normalized curves of relative change in the interplanar spacing (deformations) $\Delta d/d$ of samples: 1 — PE waveguide in the virgin LN, 2 — PE waveguide in the reduced LN.

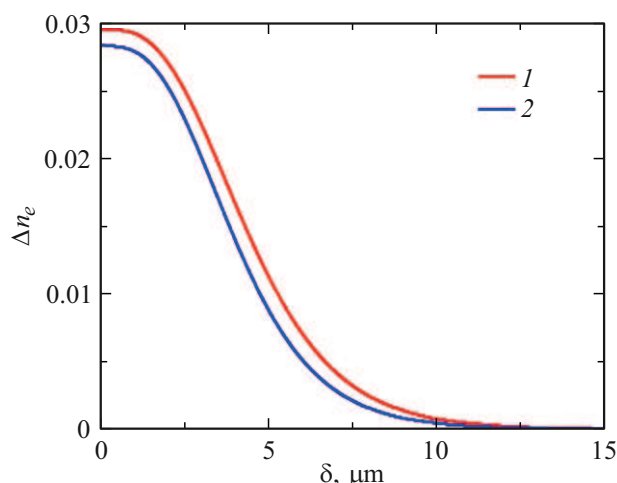


Figure 4. Profiles of PE waveguides: 1 — PE waveguide in the virgin LN, 2 — PE waveguide in the reduced LN.

Parameters of PE waveguides

Sample	Profile view	Δn_e	$\delta, \mu\text{m}$
1	Gradient	0.0292 ± 0.0002	5.0
2	Gradient	0.0283 ± 0.0002	4.6

of the post-exchange annealing for the functioning of waveguides in the mode of stable α -phase [18].

Profile, depth δ and increment of the extraordinary refractive index Δn_e were determined for the formed PE waveguides. Results of measurements are presented in Fig. 4 and in the table. PE waveguides are formed in the recovered LN with smaller depth and increment of the refractive index. Waveguide profiles are gradient. The obtained results demonstrate that no peculiarities are observed in

the diffusion of protons. The process is quite stable. The obtained parameters are quite close, but there is a decrease in the growth of the refractive index and depth of the waveguide. The smaller area under the curve 2 compared to curve 1 indicates a smaller concentration of protons in the layer, which is a favorable factor for the creation of the stable waveguides. However, when channel waveguides are created, the additional selection of the proton exchange regime is necessary to provide for the required depth, mode composition and optical losses for the specific mode of LN sample modification and planned use.

Conclusion

For the first time not only the possibility of creation, but also functioning of planar proton exchange waveguides in the reduced LN was shown. The absence of the pyroelectric properties is maintained practically in the entire temperature range regardless of the process of proton exchange and post-exchange annealing. A certain abnormality of properties is observed in the temperature range of 60–80 °C. This requires additional studies. However, the mode of operation of integrated optical circuits is usually limited on top of 60 °C, which quite satisfies the technical conditions.

The main integrated optical properties of planar proton exchange waveguides in the reduced LN were defined. The results are comparable to the data for the standard LN samples without any processing. From the practical point of view the obtained results are important for the development and design of integrated optical circuits based on LN with the eliminated pyroelectric effect for the sensors and systems of navigation. Further it is necessary to search for the optimal mode of formation of the waveguide layer depending on the degree of LN wafers modification, and also to assemble and test the pilot samples of integrated optical circuits for the specific applications.

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Conflict of interest

The authors declare no conflict of interest.

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