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Integrated-optical properties of waveguides in reduced lithium niobate crystals

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The structure and electro-optical properties of waveguides in reduced lithium niobate are being studied to improve the manufacturability and stability of integrated optical circuits. Optical loss is increase due to increased material defects during thermal annealing. Electro-optical coefficient r_{33} is 13.6 % decrease to compared congruent lithium niobate samples. Finding a compromise between the electro-optical and pyroelectric properties of reduced lithium niobate for its effective use in integrated photonics and optoelectronics is a key future challenge.

Keywords: reduced lithium niobate, waveguide, electro-optical sensitivity, optical losses.

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Lithium niobate (LN) is a pyro-, piezo,- and ferroelectric material that is used widely for the fabrication of substrates in integrated photonics and optoelectronics. LN is used in the production of radiation phase and amplitude modulators [1,2], electrical voltage sensors [3], and navigation systems [4]. Thin LN films also have enormous application potential [5].

Integrated optical circuits based on LN have a significant drawback associated with operating point drift [3,4,6–10]. A solution to this problem is highly sought after in photonic computing, quantum communications, and sensorics [11–13]. The operating point drift is caused primarily by electrical inhomogeneities in the surface layer of an LN crystal that are associated with its pyroelectric properties [6].

One of the ways to suppress the pyroelectric effect in LN is reduction annealing [10]. Therefore, the aim of the present study is to analyze the structure and electro-optical properties of reduced LN for evaluation of its applicability in integrated optical devices.

The studied materials were X-cut LN plates $10 \times 15 \times 1$ mm in size produced by JSC „Fomos Materials" (Russia). These plates were polished on both sides. Reduction annealing was carried out in a vacuum furnace at a temperature of 700 °C for 2 h. The electrical resistance of samples was measured with a V7E-42 multipurpose electrometric voltmeter with a resistance measurement range extending to $10^{18}\,\Omega$. Copper pressure plates were used as electrodes. The top electrode had a rectangular shape with a size of 10×2 mm, and the bottom one had a circular shape with a diameter of 11 mm. The examined sample was placed between these two electrodes, and electrical resistance R was measured. The obtained value was then converted into resistivity ρ:

$$\rho = \frac{RS}{l}, \tag{1}$$

where S is the top electrode area and l is the sample thickness.

The sample structure was studied via diffraction analysis at wavelength $\lambda = 1.62075$ Å(the K_β cobalt emission line). The crystallographic reflection plane for X-cut LN is (110).

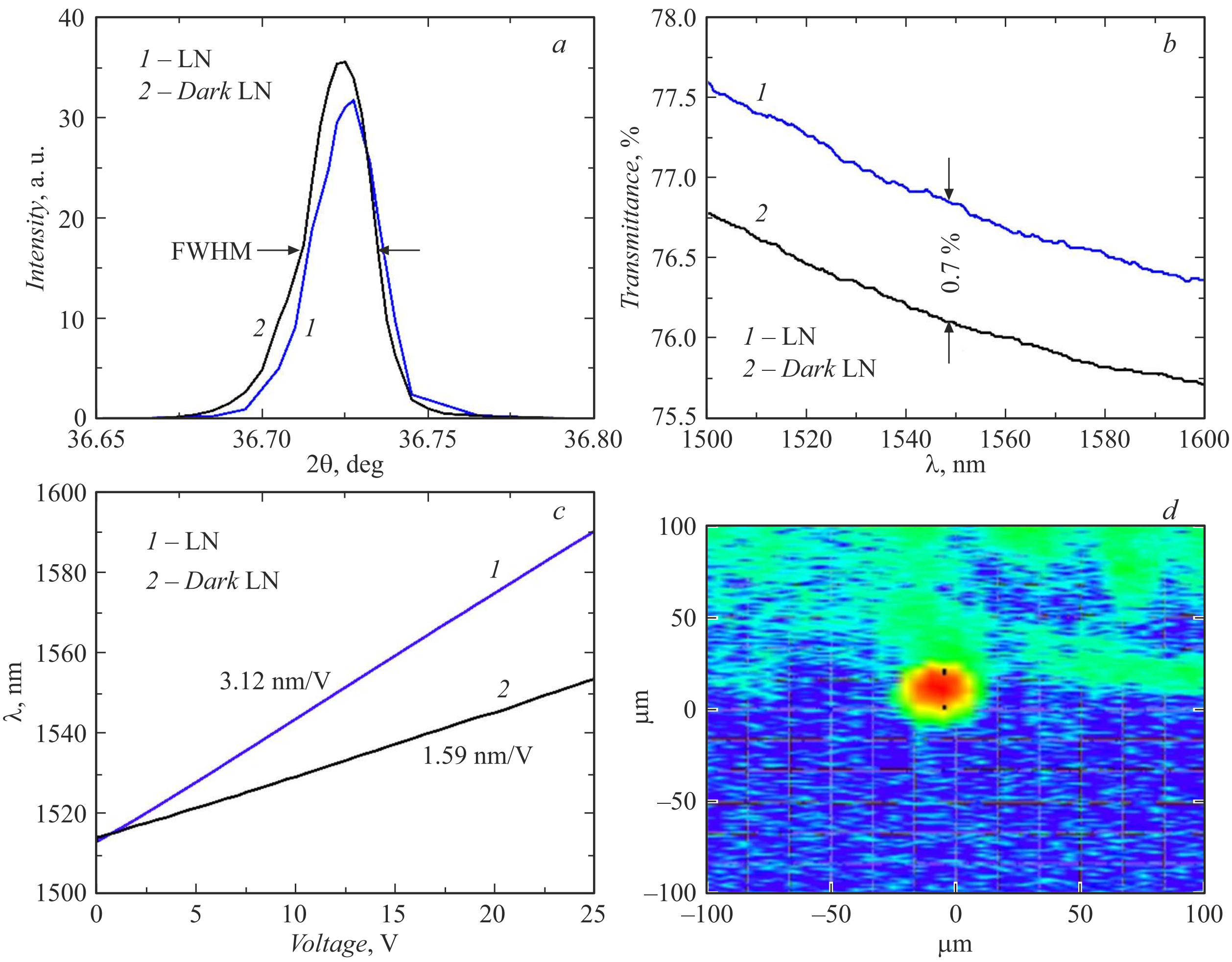
The transmission spectrum of the studied samples within the wavelength range of 1500−1600 nm was estimated using a Spectrum Two (PerkinElmer) IR Fourier spectrometer with a resolution of 1.0 cm^{-1} in the direction of crystallophysical axis X.

One of the most important parameters of integrated optical devices is insertion optical loss α in waveguides, which is specified by the exponential law of attenuation of radiation power

$$P(z) = P_0 e^{-\alpha z}, \tag{2}$$

where $P(z)$ is the optical power at distance z, P_0 is the initial optical power, and α is the insertion optical loss coefficient. This refers to proton-exchange waveguides. The insertion optical loss depends on the concentration of defects in the bulk of a waveguide layer and the transmission coefficient. Diffraction analysis is used widely to assess the structural changes in a crystal after processing. The full width at half maximum (FWHM) of the diffraction maximum provides an estimate of the degree of imperfection of the crystal lattice of a material.

The insertion optical loss was estimated in single-mode channel waveguides using the fiber-to-fiber method at a wavelength of 1550 nm with a PM2000 (FiberPro, Inc.) multi-channel optical power meter. Details on the process of channel waveguide fabrication, photolithography, and crystal−fiber coupling are omitted in this brief report.



Comparative analysis of the properties of reduced and standard LN. *a* — Broadening of the diffraction maximum; *b* — transmission spectrum within the 1500–1600 nm range; *c* — electro-optical sensitivity; *d* — fundamental mode at a wavelength of 1550 nm for a waveguide formed in a reduced LN crystal.

The electro-optical effect is characterized by a linear variation of refraction index Δn_z when external electric field E_z is applied along polar axis Z of a crystal (Pockels effect):

$$\Delta n_z = -\frac{1}{2} n_e^3 r_{33} E_z, \quad (3)$$

where n_e is the extraordinary refraction index and r_{33} is the maximum electro-optical coefficient.

Thus, measurements of electro-optical interferometer sensitivity N

$$\Delta\lambda = N\Delta V, \quad (4)$$

where $\Delta\lambda$ is the wavelength change and ΔV is the applied voltage change, allow one to calculate electro-optical coefficient r_{33} of reduced LN.

In the present study, electro-optical coefficient r_{33} of reduced LN was calculated using an electro-optical interferometer by measuring its electro-optical sensitivity within the wavelength range of 1500–1600 nm with a constant voltage ranging from 0 to 25 V (in 0.5 V steps) applied to a system of capacitive control titanium–gold electrodes. The interferometer spectrum was recorded by a YOKOGAWA AQ6370D spectrum analyzer.

The results of measurement of the structural and electro-optical properties of reduced LN are presented in the figure.

Reduction annealing of LN suppresses the pyroelectric effect due to an increase in conductivity of the material [11]. The resistivity of samples decreases from 10^{14} to $10^8\ \Omega \cdot$ cm depending on annealing time or temperature. In the present study, ρ was $1.2 \cdot 10^{14}\ \Omega \cdot$ cm for the initial LN plate and $5.7 \cdot 10^{11}\ \Omega \cdot$ cm for the reduced LN sample. The process of LN reduction is characterized by the formation of color centers (black LN) due to the removal of molecular O_2 and Li_2O with the formation of Nb_{Li} defects and four electrons, which are produced when the covalent bond between Nb and O ions breaks [11]. The formation of Nb_{Li} defects is characterized by broadening of the diffraction maximum (see panel *a* in the figure), which leads to an increase in optical losses (from 10 to 20 dB). At the same time, the transmission spectra within the range of 1500–1600 nm are virtually identical (the difference is smaller than 1 %; see panel *b* in the figure), which is completely consistent with the results reported in [14]. This means that the main contribution to optical losses is produced by defects. The fundamental mode field of the waveguide is shown in panel *d* in the figure.

The electro-optical properties of LN depend directly on the valence state of Nb. The electro-optical response of LN is maximized when Nb^{5+} is predominant and decreases with the emergence of Nb^{4+}/Nb^{3+}, which is associated with defects and the non-ideal structure of a crystal [11].

In the present study, electro-optical coefficient r_{33} of reduced LN was calculated in order to evaluate this dependence. The calculation relied on the method of finding half-wave voltage V_π of the LN-based electro-optical interferometer. The following formula relating electro-optical properties to geometric parameters of the device [15] was used to determine r_{33}:

$$r_{33} = \frac{\lambda d}{2n_e^3 \Gamma L V_\pi}, \quad (5)$$

where λ — operating wavelength, d — interelectrode distance, n_e — LN refraction index [2], L — length of the active region of waveguides, and Γ — overlap integral. Special calculations of the values of the overlap integral were not performed, since it is determined exclusively by the geometry of the electro-optical interferometer. Interferometers fabricated here based on standard unprocessed LN plates and reduced LN had identical geometries (i. e., the same overlap integral values). The primary difference between the materials is in their electronic structure and is caused by a partial change in the valence of Nb, which has little effect on the overlap integral of optical and electric fields.

The calculated value of electro-optical coefficient r_{33} was 26.7 pm/V. This result is 13.6 % lower than the value of $r_{33} = 30.9$ pm/V, which is the reference one for unprocessed congruent LN [2]. The difference is manifested clearly in the reduction in electro-optical sensitivity of the interferometer fabricated based on reduced LN (see panel *c* in the figure). These results are consistent with the findings reported in other studies. Specifically, it was found that the percentage of Nb^{4+} increases in the course of reduction annealing when the oxygen concentration in the crystal decreases. The electro-optical coefficient and nonlinear optical characteristics of LN also go down in the process [16,17]. The observed electro-optical coefficient reduction is not critical, and the search for optimal balance between optical losses, electro-optical properties, and operational stability of integrated optical devices is a key task for further research.

Despite the deterioration of its key electro-optical properties, reduced LN has great application potential in fabrication of integrated optical devices with increased stability of characteristics. Prototype samples of an electric voltage sensor are planned to be designed and tested in the future.

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Conflict of interest

The authors declare that they have no conflict of interest.

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