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Influence of the refractive index gradient on the transmission coefficient in the 1.5-micron range in an electro-optical converter based on lithium niobate

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Abstract. The paper presents the results of a study of the effect of the composition gradient and refractive index on the attenuation of an optical signal at a wavelength of 1.55 microns. The attenuation measurements were carried out by the breakage method and the comparison method, the attenuation by both methods was 0.9 dB/cm when waveguides were formed along the change in the lithium composition in the crystal plate of the composition $Li_{0.94...0.98}Nb_{1.06...1.02}O_{3.12...3.04}$.

Keywords: optical waveguide, optical losses, lithium niobate

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Материалы конференции
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Исследование особенностей влияния градиента показателя преломления на коэффициент пропускания в 1,5 мкм диапазоне в электрооптическом преобразователе на основе ниобата лития

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Аннотация. В статье представлены результаты исследования влияния градиента состава и показателя преломления на затухание оптического сигнала на длине волны 1,55 мкм. Измерения затухания проводились методом обрыва и методом сравнения, затухание по данным обоих методов составило 0,9 дБ/см, когда вдоль изменения содержания лития в кристаллической пластине формировались волноводы состава $Li_{0.94...0.98}Nb_{1.06...1.02}O_{3.12...3.04}$.

Ключевые слова: оптический волновод, оптические потери, ниобат лития

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Introduction

Lithium niobate modulators are one of many optoelectronic modulators developed in recent years. This was facilitated by the needs of the market of fiber-optic telecommunication systems [1]. To date the use of electro-optical modulators is not limited only to telecommunication systems. The advantages of a lithium niobate-based modulator are high modulation frequency, and the ability to work at different wavelengths. One of the disadvantages of electro-optical modulators is their susceptibility to various drift phenomena in the crystal matrix [1].

Important elements of the modulator based on the Mach-Zehnder interferometer are waveguides, the parameters of which affect its characteristics. Reducing optical signal losses in waveguides, increasing stability relative to drift phenomena are important areas for improving the characteristics of the device.

Earlier [2], to increase the temperature stability of optical radiation converters, it was proposed to use the gradient of the composition of the lithium niobate crystal plate. Therefore, the aim of the research was to estimate losses in waveguides in lithium niobate crystals with a gradient of composition.

Materials and Methods

An important part of solving the problem of determining the characteristic features of the formation of periodically polarized structures in the obtained samples of gradient ferroelectrics is the data on the magnitude of the coercive field of the grown gradient crystals. To determine the values characterizing the magnitude of the field required for local reorientation of ferroelectric domains, a processed plate cut from a gradient single crystal of lithium niobate (*z*-slice) was fixed in a high-voltage cell with liquid electrodes. LiCl solution was used as electrodes. A linearly increasing voltage was generated at the output of the digital functional signal generator, which was amplified by a high-voltage controlled power supply. The voltage through the electrolyte falls on the surface of the plate. We recorded current and voltage at the independent oscilloscope inputs CH1 and CH2 simultaneously. The voltage that corresponds to the site of a steep increase in current (with a simultaneous decrease in voltage drop), taking into account the thickness of the crystal, gives the strength of the coercive field.

By measuring the time local dependences of the current and the applied voltage associated with a specific point on the surface of a crystal plate with a thickness of 1.3 mm, the voltage values at which the domains are reoriented at this point of the plate were determined. Then the local value of the coercive field was compared to the lithium crystal composition [3] (Fig. 1).

To estimate losses in waveguide channels in the presence of a gradient distribution of optical properties, a crystal plate cut from gradient lithium niobate was prepared. A lithium niobate crystal with a gradient distribution of the main components was grown by the Czochralski method with liquid recharge [4]. The embedded distribution of the composition gradient was $Li_{0.94...0.98}Nb_{1.06...1.02}O_{3.12...3.04}$, after growing from the crystal along the direction of stretching, a plate with a thickness of 3 mm was cut out and its orientation relative to the *C* axis was performed.

The formation of submerged waveguide layers in a crystal plate with a gradient of composition was carried out in several stages: thermal vacuum deposition of a metal film (masking), photolithography (application and etching of photoresist and film), creation of waveguide layers on the crystal surface (proton-ion exchange), sinking of waveguides into the crystal (post-exchange annealing) [5].

At the first stage of creating waveguides in lithium niobate a thin metal film was applied to the polished crystal under study. The application of a thin metal film took place in a vacuum installation VUP-5 by thermal evaporation. Metal aluminum was used for spraying, which was placed in the evaporator. During spraying the substrate was heated with a heater, which

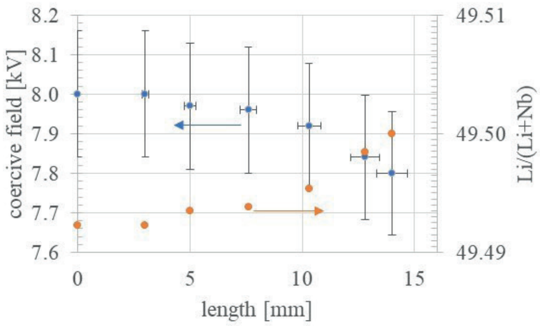

Fig. 1. Radial distribution of the magnitude of the coercive field for a plate cut out in the initial part of the crystal (during the transition from the expansion cone to the cylindrical part)

contributed to the impurities desorption from its surface before spraying, and during deposition created conditions for improving the structure of the growing film. The spraying process took place in three stages: evaporation of the substance, vapor propagation of the evaporated substance, condensation of vapors of the evaporated substance on the substrate and the formation of a film structure.

The next stage of the work was the photolithography process. To estimate optical losses in waveguides in gradient lithium niobate, a photomask was developed in the Autodesk AutoCAD program, shown in Figure 2. The width of the lines is 3–10 microns. The photomask format represented a geometric variety aimed at investigating the possibility of forming waveguide structures of a given geometry in gradient lithium niobate, and included rounding and branching at right angles. The photolithography process used took place in the sequence: the formation of a photoresistive layer, the application of a photoresist and its drying, the formation of a protective relief in the photoresist layer, exposure and manifestation, the creation of a relief image on the substrate, etching of the technological layer of metal and the removal of the photoresist layer.

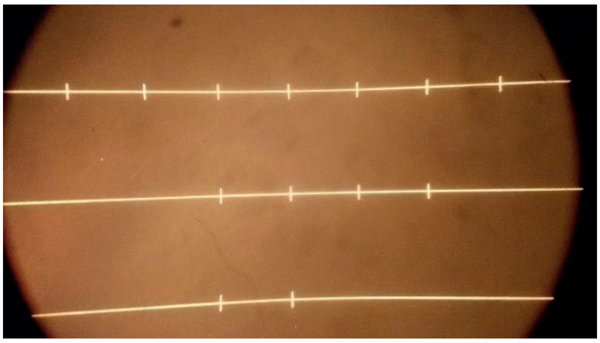

Fig. 2. View of the photomask

One of the ways to estimate losses in the waveguides formed was to provide an additional controllable loss value. Such a controlled quantity was the crosshairs (intersections) in the waveguide channel, and in neighboring waveguide channels, the number of intersections monotonically increases (Fig. 2). When passing a waveguide, the signal must experience attenuation due to scattering in the waveguide channel and due to scattering at intersections. With continuous scanning from a waveguide with fewer intersections to a waveguide with more intersections, a monotonous decrease in signal power at the waveguide output was expected. When estimating the scattering caused by signal attenuation in the waveguide, a large-scale loss estimation coefficient appears associated with losses at the intersection points. With such an estimation of losses in the waveguide channel, there is no need to trim the waveguide channel to estimate attenuation per unit length.

Then, using the [6] proton exchange method, waveguides were formed in a benzoic acid melt in an alundum ceramic crucible in a crystal plate made of gradient lithium niobate. The substrate made of gradient lithium niobate was exposed to temperature in three stages: heating from 24 to 225 °C for 30 minutes, exposure at a temperature of 225 °C for 6 hours, cooling of the crystalline substrate to room temperature. Temperature control was carried out using a K type thermocouple, the signal from which served as a feedback signal for a control system based on a programmable thermostat and a heating element [7]. During the proton-ion exchange the temperature inside the crucible with the melt was in the corridor 2–3 K from the pre-set temperature.

As a result of the application of the described techniques, waveguide layers were obtained on the surface of a lithium niobate crystal with a gradient of composition. After the polishing stage of the ends, the resulting sample was checked with an optical microscope for the presence of optical waveguides.

Fig. 3. Surface optical waveguide

The type of waveguides obtained is shown in Figure 3.

After obtaining the surface waveguide shown in Figure 2, it was sunk into a lithium niobate crystal [8].

For this purpose, post-exchange annealing was used under the following conditions: heating from 25 to 300 °C in 45 minutes, exposure at 300 °C for 3 hours, cooling of the crystal to room temperature. During post-exchange annealing, the surface layer changed the refractive index due to diffusion of lithium ions, which corresponded to the movement of the waveguide deep into the crystalline substrate of lithium niobate. Also during the formation of the buried waveguides, the waveguide took a rounded shape.

Results and Discussion

To measure the optical losses in the resulting submerged waveguides in a substrate of gradient lithium niobate, an optical circuit was created, shown in Figure 4.

In this scheme, a semiconductor laser with a fiber output operating at 1550 and 630 nm wavelengths was used as a source of coherent optical radiation, a red laser was used to adjust the optical circuit, and lasers with a wavelength of 1550 nm radiation were used directly for measurements. Holders for the fiber laser output patch cord and a collecting lens with a focal length of 30 mm were also used in a pair to focus the input radiation on the end of the plate under study, where the received waveguides are located [9].

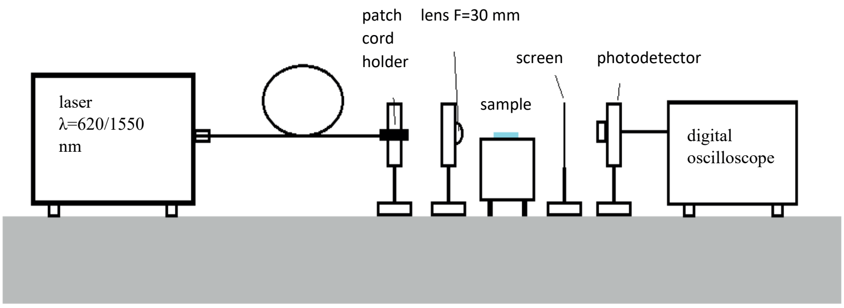

Fig. 4. Optical loss measurement scheme in waveguides

To position the manufactured waveguides relative to the axis of the input radiation a three axis microposition platform was used, the adjustments of which were used to achieve the input of focused optical radiation into the end of the waveguide. A collecting lens with such a focal length was selected so that the focused beam corresponded to the intended aperture of the resulting waveguide.

After the optical radiation passed through the waveguides in the substrate, an opaque screen with a horizontal slot of about 2 mm was installed on the path of the optical axis. This was done to cut off reflections and reflexes from the surface of the plate, which is located on the microposition table. Thus, the photodetector located last in this optical measuring circuit receives only radiation that has passed only through the end of the plate and the main part of this radiation passes through waveguides running along the propagation path of the reference radiation.

After setting up the optical circuit, the plate was moved only in the horizontal plane of the table, thereby the radiation fell into the end of the waveguide or simply into the end of the plate without a waveguide structure.

To measure losses in waveguides, the classical breakage method was chosen as a reference, when losses in a full-length waveguide are measured, then the waveguide is shortened by 2 times and the measurements are repeated. This technique makes it possible to eliminate losses and scattering at the input and output from the waveguide and to obtain relative values of losses in the resulting waveguides. This technique was applied to waveguides without formed intersections (Fig. 3).

By feeding optical radiation through the fiber output to the end of the crystal and adjusting the position of the positional table in 3 directions, we ensure that the optical radiation is introduced into the waveguide. The optical fiber from the output of the laser emitter is fed through a patch cord to the sample under study. Immediately before insertion into the end of the crystal, the fiber is cleaved on a fiber cleaver so that the edge of the fiber is flat and even. This makes it possible to concentrate optical radiation in a beam with a diameter of about 10–15 mm, which is comparable to the size of the waveguide on the crystal surface. The optical fiber is brought as close as possible to the end (Fig. 6), but not in contact with it, being a continuation of the waveguide, which is located in the figure in the horizontal plane.

To measure the relative optical losses, a 25 mm long waveguide and its half (after the segment), 12.5 mm, were used. Based on the measurements, the optical losses in the waveguide at a wavelength of 1.55 microns amounted to 0.9 dB/cm.

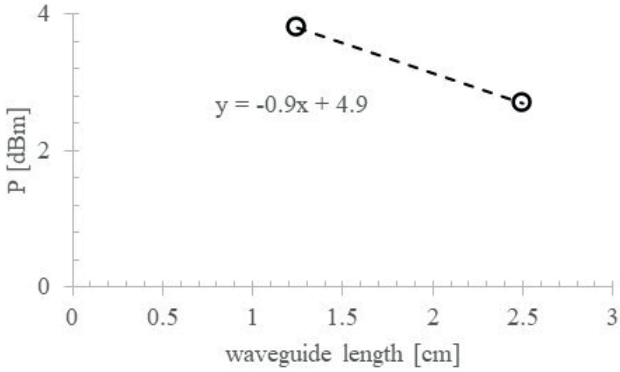

Fig. 5. Dependence of the output signal at a wavelength of 1.55 microns on the length of the waveguide

The scheme of another technique (similar to the insertion loss technique) used to estimate optical losses in a waveguide in gradient lithium niobate is shown in Figure 6. The technique includes measurement of losses in full-length waveguides. The waveguide loss component will remain constant, and the component from the intersections will be added depending on their number. With the same total length of the waveguide *L*, the same length of the waveguide between the intersections *x*0 and *a* different number of intersections n in the waveguides (Fig. 2), the recorded signal will decrease with increasing losses at each intersection. Taking into account some constant component of losses at each intersection of the waveguide, the total number of losses due to intersections is $n \cdot \alpha_1$, where α_1 is the loss in Db at one intersection. Then, the signal recorded by the photodetector when scanning along waveguides with different numbers of intersections will have a constant component associated with attenuation in the waveguide and a component of attenuation at intersections:

$$\lg(P) = \lg(P_0) + 0.1 \cdot \alpha \cdot L + 0.1 \cdot n \cdot \alpha_1, \tag{1}$$

where α is the loss in the waveguide.

Putting $\lg(P)$ values on the chart (Fig. 7) on the ordinate axis, and *n* values on the abscissa axis, we obtain a series of points by approximating them with a straight line of the form

$$\lg(P) = A - n \cdot \alpha_1, \tag{2}$$

so, we determine the attenuation value at one intersection. Then, knowing the fixed distance between the intersections *x*0, we represent the recorded power by the photodetector as:

$$\lg(P) = \lg(P_0) + 0.1 \cdot \alpha \cdot (x1 + x2) + 0.1 \cdot (n-1) \cdot \alpha \cdot x0 + 0.1 \cdot n \cdot \alpha_1, \tag{3}$$

where *x*1, *x*2 are the edge sections of the waveguide from the ends of the plate to the first and last intersection.

Approximating the lg (*P*) values by the expression:

$$\lg(P) = B + 0.1\cdot(n-1)\cdot\alpha\cdot x0 + 0.1\cdot n\cdot\alpha_1, \tag{4}$$

we find the parameters *B* and α.

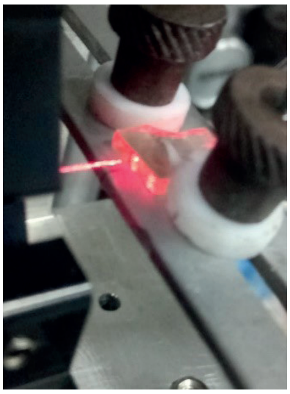

Fig. 6. General view of the measurement scheme

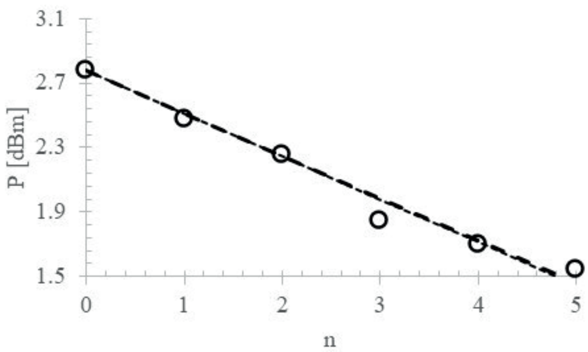

Fig. 7. Dependence of the output radiation power on the number of intersections and its approximation

Based on the data obtained, the losses at intersections amounted to 2.6 dB, the losses in the waveguide determined by this method amounted to 0.9 dB/cm, which correlates with the measurement data given in [6], where losses in non-annealed lithium niobate waveguides from 0.5 to 1 dB/cm are estimated.

Conclusion

Thus, the formation of waveguides in gradient lithium niobate with a composition $Li_{0.94...0.98}Nb_{1.06...1.02}O_{3.12...3.04}$ was carried out when heated to a temperature of 300 °C for 45 minutes and held at a temperature of 300 °C for 3 hours. To measure attenuation in the formed gradient waveguides, the breakage methods and the insertion method were used, by forming regular additional losses at the intersections of waveguides. The results of the attenuation measurement in the formed gradient waveguides obtained by both methods were 0.9 dB/cm.

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