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Estimation of the coupling efficiency of optically induced waveguides in a lithium niobate crystal

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Abstract. The paper presents the results of an experimental study of the efficiency of coupling of waveguide structures formed in a lithium niobate crystal by the optical induction method. The waveguides were produced by soliton laser beams with wavelengths of 532 and 457 nm at different optical powers. Estimation of the efficiency of coupling of the obtained structures for infrared radiation with a wavelength of 850 nm was more than 70%.

Keywords: lithium niobate, optical waveguide, photorefractive effect, pyroelectric effect, coupling efficiency.

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Оценка эффективности оптически индуцированных волноводов в кристалле ниобата лития

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Аннотация. В работе приведены результаты экспериментального исследования эффективности связи волноводных структур, сформированных в кристалле ниобата лития методом оптического индуцирования. Волноводы были получены солитонными лазерными пучками с длинами волн 532 и 457 нм при разных оптических мощностях. Оценка эффективности связи полученных структур для инфракрасного излучения с длиной волны 850 нм составила более 70 %.

Ключевые слова: ниобат лития, оптический волновод, фоторефрактивный эффект, пироэлектрический эффект, эффективность связи.

Финансирование: Работа в части разработки экспериментальной установки выполнена при поддержке Министерства науки и высшего образования Российской Федерации в рамках Государственного задания № 122041500075-5. Исследование по оценке эффективности связи волноводов выполнено при поддержке Министерства науки и высшего образования Российской Федерации в рамках Государственного задания № FEWM-2022-0004.

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Introduction

The rapid development of fiber-optic technologies stimulates the need for further improvement of the component base based on the use of elements and devices of integrated optics and photonic integrated circuits (PIC), and the possibility of optical nonlinearity in some crystalline materials is of practical interest from the point of view of their application in these areas.

Some crystalline materials have pronounced piezoelectric, pyroelectric, electro-optical and ferroelectric properties, which makes it possible to modulate the parameters of light waves by external fields. In such nonlinear optical media, it is possible to form optical inhomogeneities that can play the role of waveguide elements. One of these materials is a lithium niobate crystal ($LiNbO_3$), which is the base for creating many different optical devices [1, 2].

To create waveguide circuits in lithium niobate, the methods of diffusion [3], ion implantation [4], and proton exchange [5] are successfully applied. There is also a method of optical induction, the essence of which is to modulate the refractive index by known physical phenomena - photorefractive and pyroelectric effects, the combination of which achieves a soliton mode of propagation of narrow monochromatic light beams by compensating for their linear and nonlinear diffractions. This technique is used both in bulk [6, 7] and thin-film materials [8].

The method of formation of structures is implemented due to the electro-optical effect, which causes a change in the refractive index of a substance under the action of an electric field. The photorefractive effect is due to the appearance of an electric field from light entering the ferroelectric medium, which, in turn, causes a redistribution of charges that affect the refractive index of the illuminated area. Laser beams passing through the crystal undergo diffraction divergence caused by a drop in the refractive index. The pyroelectric effect causes a change in the refractive index under the influence of a pyroelectric field arising from a change in temperature. But, unlike the photovoltaic one, the pyroelectric field arising from heating has the opposite direction. Since the two fields are opposite to each other, there is no change in the refractive index in the region of their interaction. In the unlight of the heated region, the refractive index decreases due to the self-defocusing nonlinearity of $LiNbO_3$. As a result, a structure is formed that is capable of channeling light due to the induced difference in the refractive indices. In the previously illuminated region, the refractive index is higher than that in the unilluminated region, which is the main condition for the existence of an optical waveguide.

For the practical application of waveguide elements in integrated optics, it is necessary to solve the problem of efficient light transmission and optical connection of waveguides with each other and with optical fibers. The solution of this problem involves the choice of a technique for creating optical waveguides and the optimal matching of various waveguide structures. A large number of works have been devoted to this problem, but the number of publications on this issue continues to grow, and this shows that the problem of creating efficient waveguide structures and their matching, including various types, still needs to be solved.

This paper presents an experimental study of the coupling efficiency of waveguide structures formed by optical induction in a lithium niobate crystal.

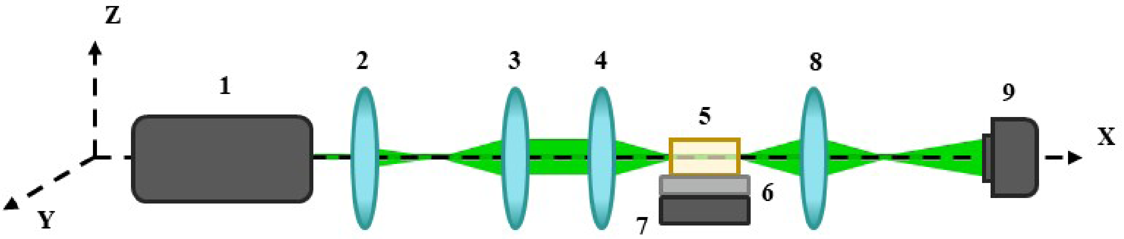

Fig. 1. Scheme of the experimental setup for the formation of optical waveguides: source of laser radiation *1*; focusing lenses *2*, *3*, *4*; $LiNbO_3$ crystal sample *5*; Peltier element *6*; linear translator *7*; imaging lens *8*; laser beam analyzer *9*

Experimental setups and conditions

An undoped $LiNbO_3$ Z-cut sample was used in the experiments. The sample dimensions were $20\times7\times1$ mm^3 along the X, Y, Z axes, respectively. The light beam forming the waveguide propagated in the sample in the direction of the X axis, and its polarization corresponded to an extraordinary wave in the crystal.

Fig. 1 shows a scheme of an experimental setup for the formation of optical waveguides. Radiation sources *1* in the experiments were YAG:Nd^{3+} lasers with a wavelength of 532 nm and KLM-457/50 with a wavelength of 457 nm, both with linear light polarization. The photorefractive sensitivity of $LiNbO_3$ is maximum in the blue-green region of the visible spectrum [9, 10], so optical induction of photonic elements is most effective at these wavelengths. The system of lenses *2*, *3*, *4* set the diameter of the laser beam and focused it on the input face of the crystal. Imaging lens *8* was used to scale the intensity distribution patterns on the front (input) and rear (output) surfaces of the sample, which were studied using a laser beam analyzer *9* coupled to a personal computer.

In the experiments, the diameter of the light beam at the input face of the crystal was ~10 **μ**m at full width at half maximum (FWHM). Sample *5* was able to move in the transverse direction relative to the laser beam using a linear translator *7* with micrometric positioning accuracy. The $LiNbO_3$ crystal was fixed on a Peltier element *6*, which uniformly heated the sample. During the experiments, the sample was heated to the required temperature, which was monitored and controlled by an electronic sensor.

To evaluate the efficiency of optical waveguides, the setup was reduced to the form shown in Fig. 2. Tapered fiber LEN-T-1-Y(47/56-90-SMF28) *2*, which focused infrared (IR) radiation with a wavelength of 850 nm, was fed to the entrance of the structures formed in the crystal *3*. At the output, as close as possible to the sample, an optical power meter *4* was installed, which recorded the parameters of the output radiation. Based on the data obtained, the coupling efficiency was calculated.

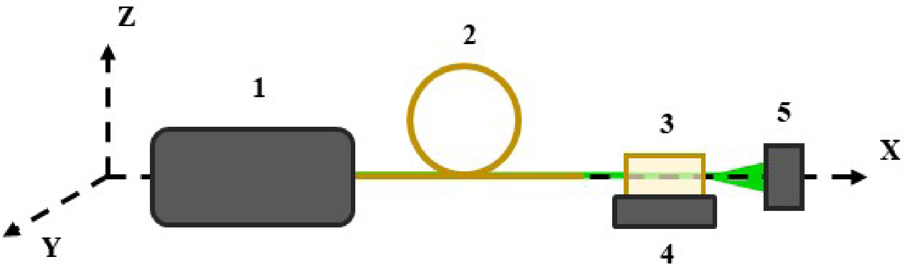

Fig. 2. Scheme of the experimental setup for evaluating the efficiency of optical waveguides: source of IR radiation *1*; conical fiber *2*; $LiNbO_3$ crystal sample *3*; linear translator *4*; optical power meter *5*

Experimental results and discussions

To evaluate the coupling efficiency, groups of waveguides were first recorded at different wavelengths and at different optical powers. Studies comparing recording with blue and green laser radiation already exist [8, 9]. Of these, it is known that $LiNbO_3$ has a greater sensitivity to the blue optical range, because waveguide structures are recorded faster at a wavelength of 457 nm than at 532 nm and require less radiation power. Based on this, for recording a wavelength of 532 nm, the powers were 0.1, 0.5 and 1 mW; and for a wavelength of 457 nm 0.05, 0.1 and 0.2 mW. For both wavelengths, the diameter of the laser radiation focused on the input face of the crystal was reduced to a size of 10 μm. The temperature of the recording sample was raised by $\Delta T = 10$ °C, for all the cases taken, it was sufficient to compensate for linear and nonlinear diffractions. Further, IR radiation (a wavelength of 850 nm) was introduced into the structures formed by us, and its optical power was measured at the output. The power of IR radiation at the input was 2.87 μW.

The coupling efficiency of the formed waveguide structures was calculated from the ratio of the input power of the IR radiation coming out of the cone-shaped fiber and focused on the input face of the crystal into the recorded structures, and the output power of the radiation transmitted through the waveguides. Losses due to Fresnel reflections were not considered. According to the calculations obtained, tables 1 and 2 were compiled.

From the results, it can be seen that the radiation power equal to 0.1 mW for both wavelengths showed the best communication efficiency, therefore, for the formation of waveguide structures, this optical power can be considered optimal in our case.

From the coupling efficiencies obtained, it can be seen that waveguides recorded at 457 nm have slightly better results than waveguides recorded at 532 nm.

This result is probably due to the fact that a lower photoelectric field at shorter wavelengths leads to lower requirements for the pyroelectric field [9]. A smaller photoelectric field, in turn, makes it possible to detect narrower laser beams in a crystalline medium [10], and, together with a lower field applied for compensation, contributes to a finer and clearer formation of the structure.

Conclusion

Thus, we experimentally studied the coupling efficiency in waveguide structures formed by optical induction in a lithium niobate crystal. It has been experimentally found that structures formed at a wavelength of 457 nm have a better coupling efficiency than at a wavelength of 532 nm.

Table 1

Coupling efficiency of waveguides recorded at wavelength 532 nm

Recording power, P (mW)	Output IR power, P_{out} (μW)	Coupling efficiency, T (%)
0.1	2.12	73.9
0.5	2.118	73.8
1	2.09	72.8

Table 2

Coupling efficiency of waveguides recorded at wavelength 457 nm

Recording power, P (mW)	Output IR power, P_{out} (μW)	Coupling efficiency, T (%)
0.05	2.137	74.5
0.1	2.158	75.2
0.2	2.133	74.3

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