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INFLUENCE OF SHORT-WAVELENGTH RADIATION OF THE VISIBLE RANGE ON THE OPTICAL TRANSMISSION OF PHOTOREFRACTIVE LITHIUM NIOBATE SAMPLES

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Special features of the optical transmission of lithium niobate crystal samples with surface doping by photorefractive impurities at the wavelength of a helium-neon laser under short-wavelength incoherent background illumination are experimentally investigated and discussed. The possibility of optically controlled thermooptical modulation of the coherent light intensity with characteristic time of a few seconds is demonstrated for samples with surface doping by a combination of iron and copper ions.

INTRODUCTION

Electrooptical crystals that provide the basis for elements of control over the light parameters (modulators, deflectors, frequency converters, optical memory elements, etc.) are widely used in laser physics and nonlinear optics. Doping of these materials by specially chosen impurities can essentially modify their physical properties, for example, optical absorption, electrical conductivity, and photorefractive sensitivity [1, 2]. Doping of their subsurface layers by active impurities using the methods of thermal diffusion, ion exchange, and ion implantation opens wide opportunities for a purposeful change in the physical properties of crystal and amorphous materials [3–5]. These methods are also used to form planar and channel waveguide optical elements in amorphous and crystalline materials; therefore, waveguide elements with predicted material properties can be obtained by means of their doping by combinations of active impurities [5]. It should be noted that in many cases, insertion of impurities through the crystal sample surface allows the developers to obtain the impurity concentration in a thin surface layer higher than that obtained by impurity insertion into the crystal while it grows. For example, photorefractive waveguide holographic elements based on lithium niobate ($LiNbO_3$) and strontium-barium niobate ($Sr_xBa_{1-x}Nb_2O_6$ or SBN) crystals are produced exactly by this method. The photorefractive properties allow one to control light by light in these elements using microwatt light beams. The present work studies the opportunity of modulating the optical transmission of lithium niobate samples with surface doping by photorefractive impurities under exposure to short-wavelength radiation of the visible range.

1. EXPERIMENTAL SETUP AND EXAMINED SAMPLES

Figure 1 shows the scheme of experiments on the study of the optical transmission. Here radiation of a He–Ne laser (*1*) with wavelength $\lambda = 633$ nm is transmitted as a parallel or focused light beam through the examined sample in the direction perpendicular to the sample surface. The output laser power is monitored with a beam-splitting cube (*2*) and photo diode (*3*). The probing beam intensity is changed using light filters (*4*). A lens (*5*) with a focal length of 18 cm focuses the probing beam onto the output surface of the $LiNbO_3$ sample (*6*) placed on a table with micrometric positioning. The transmitted light beam power is measured with a lens (*7*) and photodiode (*8*). The area of the sample probed with the

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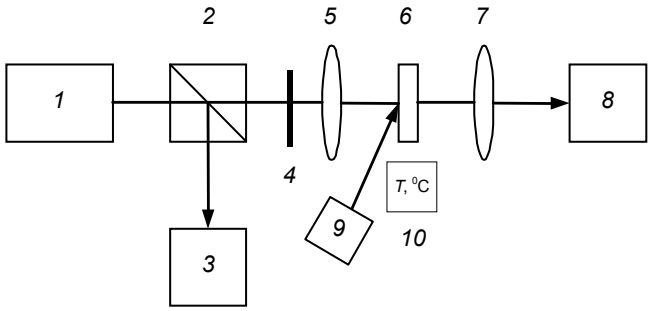

Fig. 1. Scheme of the experiment on the study of the optical transmission of samples comprising He-Ne laser *1*, beam-splitting cube *2*, photo diode *3*, optical filter *4*, focusing lens *5*, examined sample *6*, imaging lens *7*, photodiode *8*, light-emitting diode *9*, and thermometer *10*.

coherent light beam is additionally illuminated by incoherent short-wavelength radiation of a light-emitting diode (*9*) with a wavelength of 470 nm. A thermometer (*10*) measures the temperature near the sample.

In this work, $LiNbO_3$ crystal samples of *X*- and *Y*-cut shaped as plates with thicknesses from 1.5 to 3 mm and optically polished surfaces were investigated. The subsurface layers of different samples were doped by titanium (Ti), iron (Fe), copper (Cu), and Ti + Cu and Fe + Cu combinations. Thermal diffusion of impurities from the films deposited on the sample surface by the method of vacuum sputtering was used for doping. The diffusion occurred in an air or argon atmosphere at temperatures of 900–1000ºC for Cu and 1000ºC for Ti and Fe. The depth of impurity diffusion in different samples was ~3 μm for Ti and ranged from 20 to 50 μm for Fe and from 50 to 200 μm for Cu.

2. EXPERIMENTAL RESULTS

Coherent He–Ne-laser radiation was used in our experiments to measure the optical transmission of the samples determined by the ratio of the transmitted light power P_{tr} to the power of the probing beam. In this case, measurements are influenced by the interference effects caused by light reflection from the input and output planes of the sample as well as by losses on the light absorption. The phase shift between the interfering beams changes with the sample thickness and the refractive index of the material, and the ratio of the beam amplitudes depends on the optical absorption in the volume or in the doped region. In the photorefractive materials, the nonlinear optical effects can contribute to the optical transmission of actual samples. According to [2], the extraordinary refractive index change in the illuminated region of $LiNbO_3$: Fe and $LiNbO_3$: Cu can be as great as 10^{-4}–10^{-3}. In $LiNbO_3$ crystals doped by combinations of photorefractive impurities, the light-induced variations of the optical absorption are also possible [6]. The interference effects allow the sensitivity of experimental methods of investigating these phenomena to be increased significantly.

The results shown in Fig. 2 illustrate the strong spatial dependence of the optical transmission for probing of two samples by an extraordinary polarized light beam with a diameter of 100 μm. The transmitted power P_{tr} for them varied almost periodically owing to slightly nonparallel or nonplanar sample surfaces. In addition, Fig. 2*a* illustrates essential influence of the sample temperature on the local value of the optical transmission. It can be seen that at some points of the sample, the temperature change by ~3°C causes the P_{tr} value to change from maximum to minimum level.

To elucidate a possible influence of the photorefractive effect on the optical transmission, we investigated its spatial dependence under illumination of a local region of the LiNbO3: Fe: Cu sample by the probing laser beam with a diameter of 100 μm and intensity of ~1.3 W/cm^2. The depth of Fe diffusion into the sample was 25 μm, and that of Cu diffusion was 170 μm. Results of these experiments are illustrated by Fig. 3. The sample here was exposed to the probing beam at the point with coordinate z = 2 mm for 60 min. This resulted in a sharp change of the optical transmission near the given point. These optically induced inhomogeneities were stored in crystals within at least several days. Additional investigations demonstrated that the induced optical inhomogeneity was caused by the photorefractive properties of the subsurface regions of the sample, because this effect was not observed in undoped samples even when the exposure time was several hours.

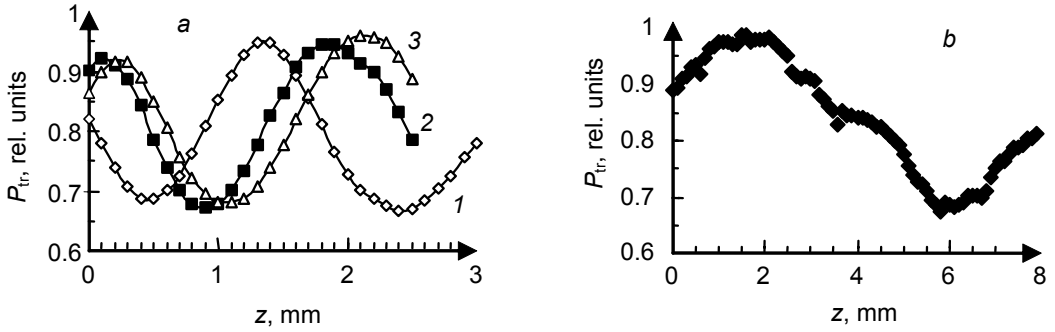

Fig. 2. Dependences of the normalized optical power of the transmitted beam on the spatial coordinate for probing of two samples at different points separated along the optical axis. The sample temperature (Fig. 2*a*) was 18 (curve *1*), 20 (curve *2*), and 21°C (curve *3*).

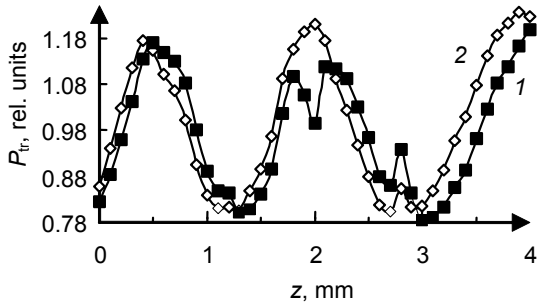

Fig. 3. Spatial dependences of the normalized optical power transmitted through the $LiNbO_3$: Fe: Cu sample before (curve *1*) and after exposure to the probing beam (curve *2*).

When a nonlinear lens is induced in the doped layer, the phase change of the probing light beam is determined by the expression $\Delta\varphi = -4\pi \cdot \Delta n \cdot L / \lambda$, where Δn specifies changes in the refractive index, and L is the effective thickness of the lens. Setting $\Delta n = 10^{-4}$, $\lambda = 0.63$ μm, and $L = 150$ μm we obtain $\Delta\varphi \approx \pi/10$. This phase change is essential for interference of the light beams. To exclude the influence of the photorefractive effect in our experiments, we used probing beams with lower intensity, and the exposure time did not exceed 5 s for each individual measurement.

It is well known that nonlinear bleaching effects in LiNbO3: Fe: Cu crystals are observed under exposure to short-wavelength radiation [7]. This is of great interest for optical fixing of photorefractive holographic gratings to provide the opportunity of their nondestractive readout [8]. We experimentally investigated the influence of incoherent radiation with wavelength $\lambda = 470$ nm (commercially available light-emitting diodes with luminous intensity of about 20 cd) on the optical transmission of the $LiNbO_3$: Fe: Cu, $LiNbO_3$: Ti: Cu, and $LiNbO_3$: Ti samples. The light intensity in the probing beam was ~0.3 W/cm^2, and the average intensity of incoherent background illumination was ~3 mW/cm^2.

Figure 4 shows time dependences of the normalized transmitted optical power for two points of the $LiNbO_3$: Fe: Cu sample when the background illumination was switched on and off. The diffusion depths for Fe and Cu in this sample were 50 μm. The points probed lie at different slopes of the $P_{tr}(z)$ dependence shown in Fig. 2*b*. Measurements were carried out with a period of 10 s. It can be seen that the maximum rate of transmission change is observed at the initial moments of time after switching on incoherent background illumination. The relaxation of the induced optical inhomogeneity occurs within 20–40 s. Investigations at different points of the sample demonstrated that the induced optical inhomogeneities affect the radiation phase, and their time dependences allow the photorefractive effect to be excluded from the possible mechanisms responsible for the observed phenomena. It was revealed that the background illumination affects the optical transmission only for samples doped by Cu, and the rate of response change depends on the concentration and depth of Cu diffusion.

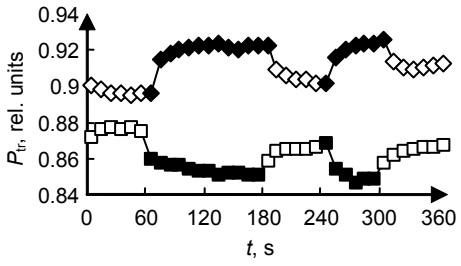

Fig. 4

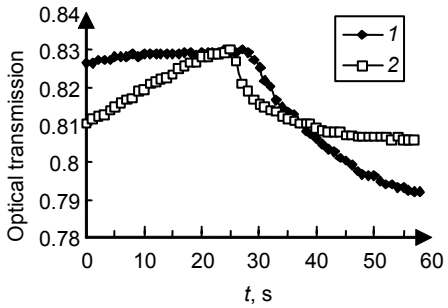

Fig. 5

Fig. 4. Time dependences of normalized transmitted optical power at different points of the $LiNbO_3$: Fe: Cu sample upon exposure to background illumination (black symbols illustrate the period over which the background illumination was switched on).

Fig. 5. Time dependences of transmission of the $LiNbO_3$: Fe: Cu samples. Here curve *1* is for the sample with diffusion depths of 25 and 170 μm for Fe and Cu, respectively (background illumination at $t > 28$ s) and curve *2* is for the sample with diffusion depths of 50 μm for Fe and Cu, respectively (background illumination at $t > 25$ s).

Thus, Fig. 5 shows the time dependence of optical transmission for two $LiNbO_3$: Fe: Cu samples under incoherent background illumination. Curve *1* here is for the sample with diffusion depths of 25 μm for Fe and 170 μm for Cu (background illumination was switched on at $t = 28$ s). Curve *2* characterizes the sample with diffusion depths of 50 μm for Fe and 50 μm for Cu (background illumination was switched on at $t = 25$ s). It can be seen that the maximum rate of response change is observed for the sample with Cu diffusion depth of 50 μm, and the characteristic time of its change is 3–4 s. We explain the response variations in curve *2* before switching on the background illumination by the influence of the ambient temperature because samples were not thermally stabilized in our experiment.

The results of our investigations allow us to conclude that the basic mechanism of variations of the optical transmission for the photorefractive samples under short-wavelength background illumination is the thermooptical effect in the doped region. It is well known that incorporation of Cu results in a significant increase in the $LiNbO_3$ optical absorption in the short-wavelength region of the visible spectrum [1]. The temperature of the illuminated region increases under exposure to radiation with $\lambda = 470$ nm, and the thermooptical effect changes the refractive index in the doped layer. According to [9], the temperature gradient of the $LiNbO_3$ extraordinary refractive index is $dn_e/dT \approx -7 \cdot 10^{-5}$ 1/ºC; therefore, the temperature change by a few fractions of a degree in the layer with a thickness of several tens of micrometers results in a noticeable variation of the intensity of light transmitted through the sample.

The conclusion about the dominant contribution of the thermooptical effect is also confirmed by experiments in which the examined samples were illuminated during several tens of minutes. The results obtained in one of the experiments are shown in Fig. 6. In this case, the coherent beam probed the $LiNbO_3$: Fe: Cu sample at the point with a maximum transmission. Within 10 min after switching on the background illumination ($t = 600$ s), the transmission reached its minimum value; then it increased again. Analogous results were obtained for all examined $LiNbO_3$: Fe: Cu samples. The observed variations of the optical transmission resulted from continuous heating of the doped region of the sample due to partial absorption of background illumination and the heat exchange between this region and the sample volume in which the optical absorption was much lower.

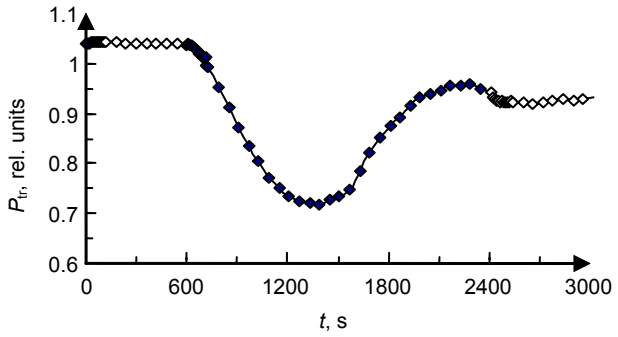

Fig. 6. Time dependence of normalized transmitted optical power for the $LiNbO_3$: Fe: Cu sample with Fe and Cu diffusion depths of 50 μm under continuous background illumination. Illumination was switched on at t = 600 s and switched off at t = 2400 s.

CONCLUSIONS

We have experimentally established that upon incoherent short-wavelength irradiation, the optical transmission of the $LiNbO_3$ samples with surface doping by Cu ions can change up to 30% of its maximum value. The basic mechanism of the observed effect is the thermooptical effect in the doped region resulted from the absorption of radiation with a wavelength of 470 nm. The characteristic time of response change is units of seconds for a background illumination intensity of 3 mW/cm^2. This effect can be used in optically controlled modulators of laser radiation intensity after optimization of the doped layer parameters and increase in the controlling radiation intensity.

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