Femtosecond-laser microstructuring in transparent materials

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Abstract. Femtosecond laser microstructuring is a hot topic in fabrication of optical elements in transparent dielectrics. This work is devoted to direct femtosecond laser writing of surface nanostructures on calcium fluorite surface. The dependence of the period of nanostructures on the parameters of laser radiation and their optical properties were studied.

1. Introduction
In recent decades, the possibility of structuring in dielectrics on the surface of a substance has been actively studied. The main direction of this topic has become - microstructuring of the material surface, during which periodic nanostructures can form on the surface [1,2]. The resulting structures can be used as diffractive elements. These operations are performed using femtosecond lasers, since transient processes in matter occur with a longer time than a single laser action. The type of the resulting structure is directly related to the polarization of the laser radiation [3,4]. In order to obtain elongated structures, the polarization must be linear with the scanning direction. It is also possible to obtain two components - linear and perpendicular, for this it is necessary to use circular polarization.

In this paper, we consider the dependence of the parameters of the resulting lattice on the surface of calcium fluoride single crystals on the wavelength of laser radiation. Including the optical properties of the resulting structures.

2. Experimental
In the course of this work, using ultrashort laser pulses at various polarizations on the surface of transparent materials, microstructures (Fig.1) were recorded in the form of arrays of parallel microlines (with linear polarization) and perpendicular microlines. The polarization was changed using half-wave plates, which were rotated at an angle of 45°.

In this work, the Satsuma femtosecond laser system was used [5], using a harmonic generator to obtain wavelengths of 515 nm and 1030 nm. The pulse duration is 300 femtoseconds. Laser radiation was focused on the surface using an objective with a numerical aperture NA = 0.65. The polarization is linear to the scanning direction.

A motorized three-axis movement was used to record the structures. The number of pulses per point was varied by the ratio of the frequency of laser pulses (100-250 kHz) and the speed of movement of the slide (20-100 μm/s). The optimal number of pulses per point is about N = 10000. The high pulse repetition rate allows for a more uniform structure. Were recorded arrays of microstructures 100x100 μm for far optical

Figure 1. Schematic of surface modification of a calcium fluoride crystal by focused laser radiation (the polarization is along the scanning direction)
characterization. Arrays of periodic nanostructures were recorded on the surface of the material depending on the number of pulses and the energy per pulse (64 nJ).

3. Results and discussion

Nanostructures are formed with tight focusing on the surface due to the interference of the incident and reflected waves. The period ($\Lambda$) of the structures is consistent with the laser wavelength and refractive index as $\Lambda = \lambda / 2n$ (where $n$ is the refractive index) [6].

The images of the surface nanostructures were obtained with JEOL SEM. Since CaF$_2$ is a dielectric, its surface can be charged, so there are two ways to view the sample surface. In the first case, a thin film layer, such as gold or silver, is deposited on the surface of the sample by magnetron sputtering. This process is difficult to control (it is possible to partially dust the structures). The second and more convenient way is the BSE SEM mode, which reduces the surface charge.

As can be seen in the SEM images, at the wavelength of 515 nm, the period of nanostructures (Fig. 2A) is 200-250 nm. At a wavelength of 1030 nm, the period of the nanostructures (Fig. 2B) is 400-450 nm. Oscillations in the period of nanostructures can be associated with the appearance of a crater on the surface of the material and the redistribution of energy in the volume. A significant problem is tight focusing on the sample surface; it is rather difficult to position and move the sample in one plane.

The transmission and reflection spectra (Fig. 3) of the structures were measured using a LOMO spectrophotometer. The light source used was a halogen lamp, which possessed unpolarized light. As can be seen in the spectra, these structures have optical bleaching in the red area. The drop in transmission is
associated with the arising inhomogeneities during processing. As can be seen from the spectra at wavelengths of 450, 520 and 800 nm, modulation occurs which is associated with Bragg diffraction on the resulting gratings, which is proportional to the wavelength [7].

4. Conclusion
In this work, we investigated the possibility of creating structures that can have optical effects during direct femtosecond laser recording of arrays with a microline, taking into account possible self-organized nanostructures. It is shown in the work that the period of nanostructures depends on the wavelength of laser radiation, which is confirmed by SEM images. The resulting period of the nanostructures corresponds to the Bragg diffraction of light for different periods of the nanostructures.

5. Acknowledgments
Experiments and spectral studies were carried out with the support of RFBR grant No. 19-52-54003. This article was published with the support of RFBR No. 20-02-22038

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