Plastic Deformation as Nature of Femtosecond Laser Writing of Waveguides in YAG crystals

S.S. Fedotov[1], **L.N. Butvina**[2], **A.G. Okhrimchuk**[1,2,*]

[1]*Mendeleev University of Chemical Technology of Russia, Moscow*
[2]*Prokhorov General Physics Institute of Russian Academy of Sciences, Dianov Fiber Optics Research Center, Moscow,*

[*]*E-mail: okhrim@fo.gpi.ru*

Direct femtosecond laser writing in the bulk of transparent glasses and crystals has proved itself as a quick and flexible method of forming waveguides and waveguide circuits in a 3D format. This technique allows to structure refractive index with micron- and sub-micron resolutions. Admittedly the mechanism and nature of the refractive index change in glass is basically clear. As opposed to glass the mechanism of refractive index change in crystals, which is suitable for low loss waveguide writing, is not clarified yet. Forming of voids and phase transformation are examples of the extreme impact of ultrashort laser pulses on a crystal, and such mode obviously isn't suitable for writing of low loss waveguides [1,2]. Meanwhile, knowledge of the state of the matter obtained as a result of moderate modification in crystals is important for discovering ways improving uniformity of the modification tracks composing waveguide, as this knowledge opens the way to reduce propagation loss.

Here we focused on the study of longitudinal nonuniformity of tracks and the statistics of transmitted pulse energy in the course of track writing in the YAG:Nd single crystal and silica glass, and these findings allowed us to draw a conclusion about nature of modification in broad ranges of sample translation speeds and laser pulse energies, starting from modification threshold, that is, for energy range, where most smooth tracks are formed, which are suitable for writing of waveguides with low propagation loss.

We measured the relative standard deviation of the laser pulse transmittance (RSDT) under laser writing conditions, and longitudinal inhomogeneity of the written tracks R. We presented the results as plots against the number of laser pulses that overlap with each other in the modification region $P=D/(f*V)$, where D is the diameter of the laser beam waist, f is the laser pulse repetition rate, V is the translation speed of the beam waist (the scanning direction is perpendicular to the laser beam) (Fig.1). Longitudinal inhomogeneity of a track R in the YAG:Nd was investigated with Fourier analysis of their phase images obtained by the quantitative phase microscopy (QPm) (Fig.1c). We have revealed the surges in the plots of RSDT and the longitudinal inhomogeneity at P=11-15 for the crystal, and further monotonic growth of these parameters with overlap increase. No surges of RSDT are observed for silica glass (Fig.1b). Instead of this, RSDT decreases at large overlaps.

We believe that the modification of the YAG:Nd crystal under the impact of femtosecond pulses is a plastic deformation in a microvolume. The plastic deformation is accompanied by generation of vacancies, their fusion into vacancy disks, and the subsequent generation of dislocations on them. The decrease in the refractive index in the modification region is the result of the crystal density decrease during the plastic tension under impact of the internal pressure arising in the region of the electron plasma. The decrease in crystal density is associated with the generation of vacancy disks and agglomeration of dislocations. We have identified three modes of plastic deformation relevant to direct laser writing. The first mode is characterized by an easy glide of dislocation (P<9), the second is the hardening mode (P>15), at which dislocation of different sleep systems are generated, and the third mode is an intermediate one with self-organization in dislocation system (P=9-15), which appeared as modulation of refractive index with period of 1.2 μm [3]. The mode of plastic deformation is defined by two independent parameters, that are laser pulse energy E_p and overlap of exposed areas by laser pulse sequences P.

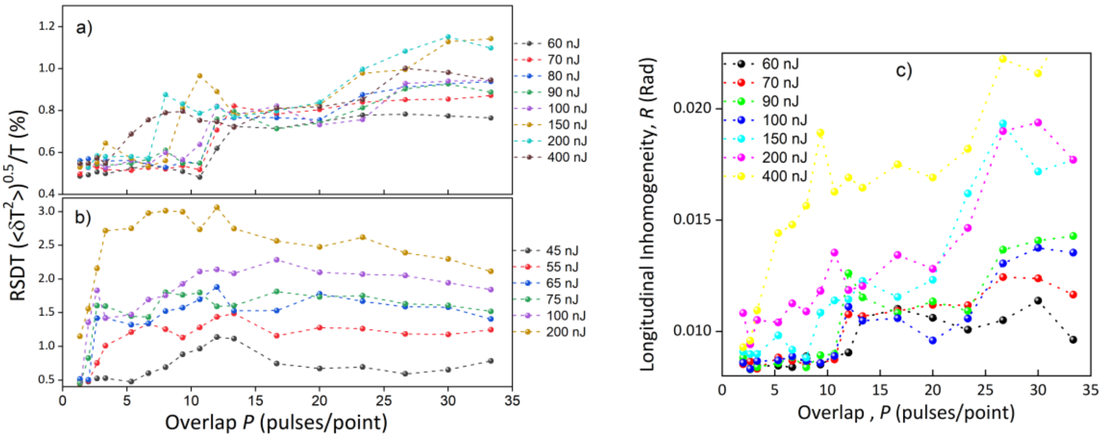

Fig.1. Plots of RSDT for YAG (a) and silica glass (b), and track roughness in YAG (c) upon overlap.

We presume that the surges in the dependences of the longitudinal inhomogeneity and RSDT on the overlap in the crystal are connected with the change from the plastic deformation mode with easy glide of dislocations to the hardening mode. The qualitatively different dependence of RSDT for YAG and silica glass is explained by the fundamentally different nature of plastic deformation in crystals and glass. In crystals, it is the generation and slipping of dislocations that have long-range fields. In glass, rearrangement of the short-range order is only possible; therefore, the hardening in glass is not observed.

Plastic deformation mode with easy glide of dislocations has to be provided for direct laser writing of waveguides with low scattering loss. In order to get this mode, it is necessary to set the laser pulse overlap in the range of 3-7. We expect that the proposed model of laser writing can be expanded on other crystals and open a new approach in the study of direct femtosecond laser writing in crystals.

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