Selective volumetric modification of transparent dielectric media by femtosecond laser radiation

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Abstract. The paper describes the possibility of modifying transparent solid media by ultrashort laser pulses of femtosecond duration. The mechanism of fabricating second- and third-order fiber Bragg gratings in a standard single-mode Corning SMF-28e+ fiber is considered. Examples of multilayer ordered structures formation in a bulk of the glass samples are shown.

1. Introduction
Modification of transparent dielectric media by femtosecond laser radiation have been the subject of much scientific research and innovation over the years. Promising applications have been demonstrated for the formation of three-dimensional optical memories [1, 2] and multicolor images [3], the direct writing of optical waveguides [4, 5], couplers and splitters [6, 7], optical amplifiers [8]. Furthermore, in the recent applied researches, femtosecond lasers have been used as a fabrication tool of photonic crystals [9, 10].

The change in material properties under the action of ultrashort laser pulses (pulse duration $10^{-15}$ s) occurs due to the multiphoton absorption of radiation and has nonlinear nature. The paper presents the results of selective volumetric modification of transparent dielectric media by femtosecond laser radiation: an inscription of fiber Bragg gratings (FBGs) and multilayer volumetric processing.

2. Experimental setup
To solve the tasks of forming optical structures in the transparent dielectric media, a femtosecond laser microprocessing complex was developed (Figure 1), combining a number of required technical components and having a single interface for controlling the component elements of the setup. The core of the system is Yb:KGW femtosecond laser operating at a repetition rate of 10 KHz, 280 fs of pulse duration at 1029 nm wavelength and focused with the aid of high numeric aperture microscope objective Mitutoyo Plan Apo NIR HR (100x, NA = 0.7). Laser radiation passing through the beam attenuation system is attenuated to the required pulse energy level, next passing through a system of turning mirrors reflected from a dichroic mirror and propagated in the direction of the microobjective by which is focused in the region of a sample.

For position adjustment and moving of the sample during inscription high-precision 2-dimensional stage Aerotech ANT130-110-XY and motorized linear translator (Z-axis) Standa 8MT167-25LS were used. Visualization of the results were carried out with the aid of CCD-camera, the focusing positions of the laser and optical systems coincide [11].
Figure 1. Experimental setup for volumetric processing of transparent dielectric media by femtosecond laser radiation: 1 – camera, 2 – portal periscopic system, 3 – variable attenuator, 4 – XYZ-coordinate stages system, 5 – Yb:KGW-laser system, 6 – PC, 7 – joystick.

Drawback of optical structures formation by means of direct femtosecond writing method is changes in the diameter and shape of the laser spot throughout the processing area [12]. This problem is caused by the small size of the laser beam waist region, as well as the inevitable shift of the focus position arising in case of work with samples of complex geometric shapes. For example, fluctuations of diameter in the case of optical fiber that occur during factory manufacturing can reach 5 μm [13], this has a negative impact on the process of focusing laser radiation relative to the fiber core, and, consequently, the quality of the inscribed optical structures.

To sustain a stable position of the focal spot relative to the initially specified level at which the material is modified, a software module has been developed, the principle of which is based on the analysis of images of the modification region captures by the CCD camera in real time. In case of deviations from initially position of focal spot during writing optical structures, the system corrects the position of the sample by shifting relative to the laser beam waist area (Z-axis) which guarantees the invariable diameter of the laser spot over the entire length of processing.

In order to ensure a normal incidence of the laser beam on the plane of the processed area of the transparent sample, an iterative algorithm for correcting the angular deviations of the reference points of the X-Y plane from the focus position of the optical system is used. Compensation of spatial deviations is achieved with the aid of motorized kinematic translator providing two rotational degrees of freedom, and a linear translator designed to correct platform displacement along the height axis (Figure 2).

Figure 2. Schematic view of the angular correction unit.
3. Results of FBG inscription

A promising direction of research related to the formation of optical structures in transparent dielectrics is the modification of quartz glass in an optical fiber under the action of femtosecond laser radiation, which leads to a local change in the refractive index. Such structures are FBGs, which are widely used in various fiber optics devices: as sensitive elements in sensors [14, 15], as spectral filters in fiber lasers [12, 16], etc.

For recording FBG, a standard single-mode fiber Corning SMF-28e+ (core diameter 8.2 μm) with an acrylate protective coating was used. The fiber was mounted on a two-axis air bearing stage in such a way that the FBG with given desired parameters can be fabricated by translating the fiber regarding to the focused laser beam. For position adjustment of the Z-axis a motorized linear stage was used, flatness position of the fiber was established by the tilt corrector system [17], it is necessary for uniform recording throughout the entire length of the FBG.

To overcome the limitation of inscription associated with the influence of the fiber geometry on the focusing of the laser beam, the optical fiber was set between two glasses. The space between glasses was filled with an index-matching immersion liquid (glycerin) with a refractive index close to the refractive index of optical fiber. FBGs were inscribed without removing the polymer coating of the fiber. Schematic drawing of the processing area shown in Figure 3.

![Figure 3](image)

**Figure 3.** Schematic drawing of the processing area: 1 – femtosecond laser radiation, 2 – focusing optics, 3 – focused laser beam, 4 – optical fiber sample.

FBGs were fabricated using line-by-line technique of inscription with a pulse energy of 150 nJ, the fiber was translated at a velocity of 80 μm/second during exposure of laser radiation and 200 μm/second without exposure laser radiation, the length of the line being 30 μm. The period of FBGs was chosen taking into account the second and third diffraction order, this was done on the basis of the linear dimensions of the inscribed structures.

Images of inscribed second order (period Λ = 1.07 μm) and third order (period Λ = 1.605 μm) FBGs with the estimated central wavelength at 1550 nm is shown in Figure 4. Diameter of each inscribed line (cylinder) is nearly 800 nm.
In Figure 4 c, d, it can be seen that, at an energy 150 nJ, the modification region extends to a depth of 10 µm and completely intersects the core of the fiber (8.2 µm), that in turn fulfilled the necessary requirements.

4. Multilayer volumetric processing

Another promising area of application of the presented laser system is the formation of structures in the volume of transparent medias. The scheme of the experiment is shown in Figure 5. Structures were obtained using a 100x micro objective with a NA of 0.7, average pulse energy of laser radiation was 150 nJ. Selective formation of structural entities was carried out by moving the sample relative to a stationary beam in coordination with the laser activation.

The multilayer volumetric processing is based on sequential exposure by femtosecond laser pulse trains on a given area of a transparent solid medium with subsequent sample displacement in the X-Y plane, or along the Z axis. The structures are written layer-by-layer from bottom to top. To provide additional protection for the encoded information, the algorithm can be extended by the data masking...
methods. Figure 6 illustrates an example of information encoded in the bulk glass in a form of dots array. The images obtained at different focus position.

![Figure 6](image)

**Figure 6.** Dots array formed in a volume of the quartz sample.

The formed structures have a close to spherical shape that represents a hollow region in the volume of quartz glass. The minimum size of the formed dots can achieve up to 0.8 μm depending on the laser radiation power. The method allows for layer-by-layer direct writing and reading of structures in the sample volume. The optimal interlayer distance for the presented recording parameters was 15 μm.

The method can be modified for cylindrical transparent samples processing. Geometric features allow coding and writing of information in a form of lines of various lengths formed in the bulk of material (Figure 7). Variation of the writing period and the width of the lines allows to achieve optimal processing parameters.

![Figure 7](image)

**Figure 7.** Volumetric processing of transparent cylindrical samples.

5. Conclusion

The results of inscription of second order and third order FBGs in standard single mode fiber through the acrylate polymer coating using a femtosecond laser line-by-line technique are presented. The approach used makes it possible to record FBGs of the second, and higher diffraction orders, thus inscribed gratings that can be used as sensitive elements of fiber-optic sensors.

The results of the multilayer bulk modification of transparent materials are demonstrated. This type of processing can be used as a method of originality authentication for substances packaged in thin-walled glass ampoules. This approach of formation of coded data in the volume of glass along with other methods of protection based on laser processing, such as recording of 3D-holographic images on a photosensitive emulsion, also meets the requirements for operation speed, cost and reproducibility of process.
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