

PAPER • OPEN ACCESS

## Laser writing of optical structures in quartz glass

To cite this article: E S Oparin *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **525** 012040

View the [article online](#) for updates and enhancements.



**IOP | ebooks™**

Bringing you innovative digital publishing with leading voices  
to create your essential collection of books in STEM research.

Start exploring the **collection** - download the first chapter of  
every title for free.

# Laser writing of optical structures in quartz glass

**E S Oparin, K S Khorkov, D A Kochuev, R V Chkalov and A S Chernikov**

Vladimir State University, Gorky str. 87, Vladimir 600000, Russia

E-mail: oparinvlsu@yandex.ru

**Abstract.** In this paper the interaction of ultrashort laser pulses with a quartz sample are shown. The effect of redistribution of the passing laser radiation intensity after sample treatment in the mode of multiple filamentation is shown. Examples of the formation of ordered structures in bulk transparent solids due to the refractive index modification of the regions exposed to femtosecond laser radiation are given.

## 1. Introduction

The processes of the ultrashort laser pulses interaction with a transparent dielectrics are known and were observing by different groups simultaneously with the appearance of these laser systems [1-5]. Nevertheless, the evolution of processes caused by the interaction of such radiation with the dielectric medium has not been sufficiently studied. Detailed study of the dynamics of changes in spatio-temporal and spectral characteristics of high-intensity light radiation in dielectrics is of great interest because of the wide range of possible applications.

When femtosecond pulses modify the materials, new physical processes and properties are revealed. The modification of transparent materials has been an active area of research for the past four decades. In the case of transparent materials, the absorption of incident laser radiation is nonlinear nature [1,6].

A nonlinear absorption mechanism must deposit laser energy into the material by promoting electrons from the valence band to the conduction band. The main types of nonlinear excitation mechanisms that affect the absorption process are photoionization (multiphoton ionization, tunnel ionization) and avalanche ionization. It should be borne in mind that the probability of multiphoton absorption in the case of ultrashort laser pulses is much higher, compared with pulses of longer duration, which is associated with a greater by several orders intensity of radiation.

When ultrashort laser pulses interact with a medium, in our case with quartz glass, filamentation can be observed. Laser filaments are beams, which are focused by a lens and then, due to high intensity, begin to self-focus into a long light channel. The indispensable conditions for filamentation are high pulse energy and short pulse width. The medium must be optically transparent. In the process of filamentation, annular structures may form around the filament, resulting from the interference of diverging radiation from the filament axis after defocusing and the light field surrounding the filament. Losses in defocusing are extremely small and almost all of the energy is again tightened to the filament axis, and if the power is many times greater than the self-focusing critical power, multiple filamentation can occur with the formation of daughter filaments. The existence of these structures is explained by the phenomenon of self-focusing [7-11].

The physical cause of self-focusing is the cubic optical polarizability of the medium (Kerr nonlinearity), which causes a self-induced increase of the refractive index in areas with high intensity



of radiation and the subsequent compression of the laser beam in the transverse direction. Pulsed radiation, the peak power of which is tens or more times greater than the critical self-focusing power, forms a large number of filaments. This is an inevitable consequence of the spatially modulated instability of an intense light field in a medium with cubic nonlinearity.

It should be noted that during filamentation, the plasma is formed mainly at the front of the pulse, while the back of the pulse is strongly defocused by this plasma, that is, these processes are fundamentally dynamic (non-stationary). The concentration of free electrons in plasma channels, which are formed during the filamentation of collimated or weakly ascending beams, according to estimates carried out in different works, is  $N_e \sim 10^{11} - 10^{17} \text{ cm}^{-3}$ . Such a spread of experimental data (six orders of magnitude or more) is due to the use of various measurement techniques and different experimental conditions.

During the filamentation of laser radiation in a quartz glass sample, the refractive index changes in the region where filamentation occurs. This change is irreversible, even after cessation of filamentation in the medium, the channel remains, which changes the intensity distribution of any radiation passing through the modified region of the sample. Being irradiated with ultraviolet radiation, the modified areas luminesce in the red wavelength range, while a quartz glass (KU-1) is transparent in ultraviolet spectral region. The prevailing plasma-forming processes are multiphoton and tunneling ionization, which do not lead to structural changes in the dielectric [12].

The filamentation of high-power laser radiation over extended paths is often random. This applies primarily to the longitudinal and transverse position of the filament formation point, as well as the number and dynamics of the interaction of multiple filaments in case of a significant excess of peak power. The main factors determining the stochastic nature of the process include inhomogeneities of the initial field distribution in a laser pulse (they can be random, noise-induced or artificially created, for example, in segmented beams), as well as fluctuations in the refractive index of the medium.

Additional complexity is the longitudinal and transverse instabilities of the beam and filaments, associated both with the instabilities of laser systems and with the fundamental stochasticity of the propagation process. For pulses whose power is hundreds of times greater than the critical self-focusing power, methods of forming an ordered array of a large number of filaments are investigated. It was experimentally and numerically shown that periodic intensity modulation can suppress the stochastic nature of filamentation caused by random fluctuations [13].

## 2. Optical structures in bulk transparent glass

### 2.1. Formation of optical channels in quartz glass

For inscription optical channels femtosecond Yb:KGW-laser system was used. The parameters of laser system: wavelength  $\lambda=1029 \text{ nm}$ , pulse width  $\tau=280 \text{ fs}$ , pulse repetition rate of  $10 \text{ kHz}$ , pulse energy  $E_{\text{max}}=150 \text{ }\mu\text{J}$  [14-15]. The laser radiation was focused in the quartz glass sample by single lens with a focal length of  $150 \text{ mm}$ . The beam diameter in the focusing region was about  $50 \text{ }\mu\text{m}$ . The focused laser beam passed into the bulk of the quartz parallelepiped with dimension  $5 \text{ mm} \times 5 \text{ mm} \times 20 \text{ mm}$ . The sample is mounted on a two-axis translation stage.

Directly next to the sample two devices have been installed – a CCD-camera and a system for analyzing the cross section profile of the beam. With the aid of CCD-camera formed filaments were visualized, their geometrical dimensions relative to the exposure time and laser power were registered.

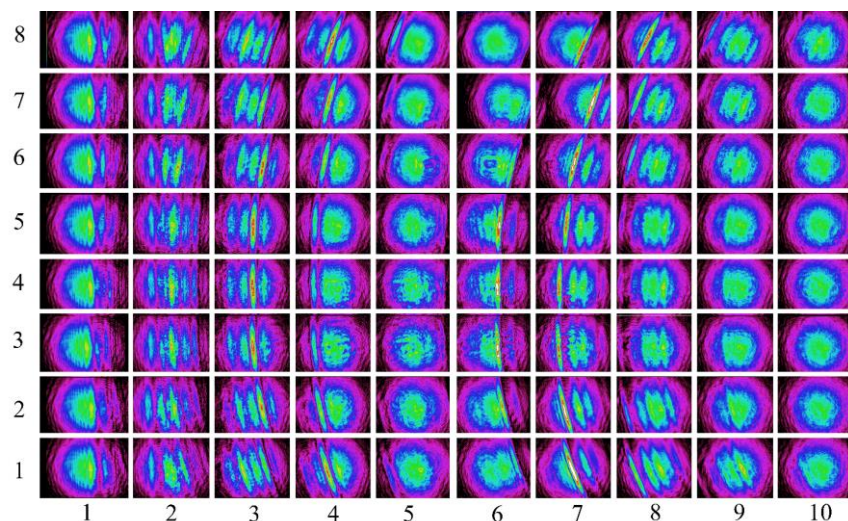
The filamentation of laser radiation in a quartz glass sample leads to a change in the refractive index of the exposure area. In this case, the intensity distribution in the transmitted beam also changes. Registration of the transverse profile of the distribution of laser radiation was carried out using the BeamStar system. A change in the beam profile as a function of power of laser radiation was registered.

At the beginning of the experiment, the area of the sample in which the beam intensity distribution corresponds to the Gaussian was chosen. As a source of transmitted laser radiation a DPSS-system

with a wavelength of 532 nm was used. The radiation passing through the sample with inscribed structures thereby redistributing its intensity.

With the aid of laser beam analysis system the images of the intensity distribution at each point of the sample were obtained and then combined using a graphical editor into a panorama corresponding to the actual size of the sample (figure 1). Due to the small coverage of the camera, it was impossible to cover the entire sample in one continuous image, therefore this method of fixing data was applied: the images were combined according to a measurement matrix having 10 columns and 8 rows, each 5 millimeters in width across the sample.

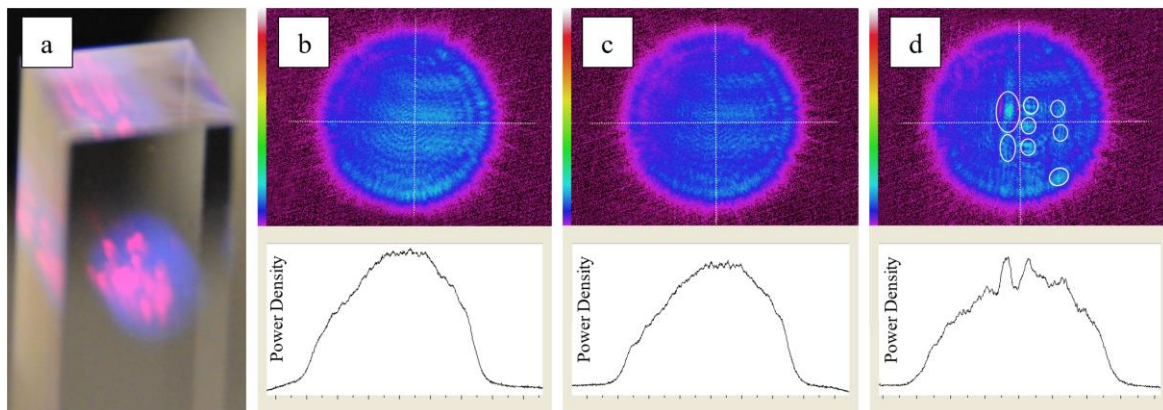
Structural changes causing redistribution of the transmitted laser radiation are observed on obtained image. The green circles are normal Gaussian distribution; in these zones there is no modification. Red vertical arcs in columns 3 and 7 indicate increased intensity; the absence of color in column 6 in lines 2-6 indicates the absence of intense radiation in this zone. Both of these effects are caused by the redistribution of energy through the plasma channels created previously in the sample using filamentation.



**Figure 1.** Panoramic image combined from images of the intensity distribution in various places of the modified quartz glass sample.

The formation of local maxima of laser radiation, in the presence of such kind of structures in the medium, occurs on the formed tracks. The propagation of laser radiation through the structures formed is independent of the power of the laser radiation. With a significant decrease in the intensity of laser radiation below the filamentation threshold, laser radiation retains the distribution structure characteristic of structures inscribed in the bulk of the medium. Thus, this property can be successfully used to form a given distribution profile of laser radiation in accordance with the requirements of material processing tasks.

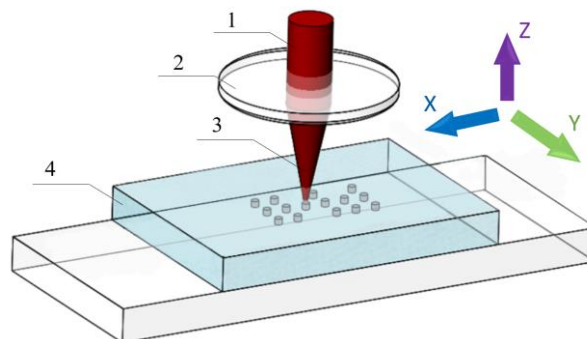
To confirm this fact, the following experiment was conducted. A sample of KU-1 glass containing previously modified regions was irradiated with ultraviolet laser radiation with a wavelength of 257 nm. This spectral range was used for clarity of the experiment. By using a laser radiation with other wavelength, the nature of the propagation of laser radiation in the structure of the material is similar. The convenience of using ultraviolet laser radiation lies in the convenience of detecting the region of transmitted laser radiation (parallel beam) through the sample (figure 2).



**Figure 2.** Registration of the laser radiation spatial distribution: a – the sample containing written structures; b – beam distribution at the exit of the laser system; c – laser beam passing through the unprocessed quartz sample; d – the formation of local radiation maxima in the beam cross section (outlined by ellipses).

### 2.2. Laser writing of information in transparent bulk samples

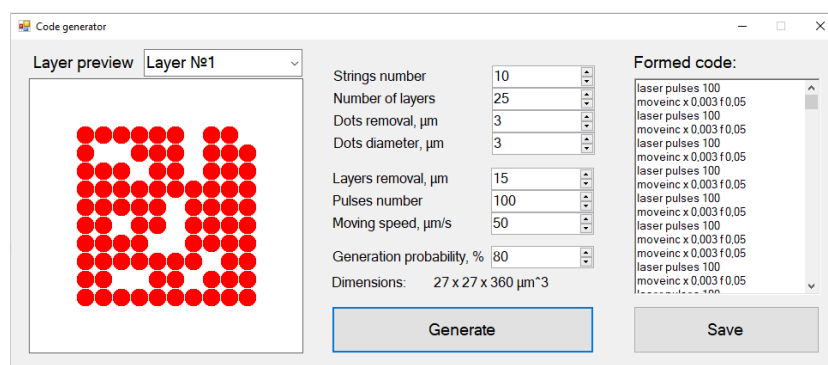
Another promising area of application of the presented laser method is controlled formation of structures in the volume of transparent medias. The scheme of the experiment is shown in figure 3. Structures were obtained using a 100x micro objective with a NA of 0.72, an average laser radiation power was 4 mW. Selective formation of structural entities was carried out by moving the sample relative to a stationary beam in coordination with the laser activation.



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

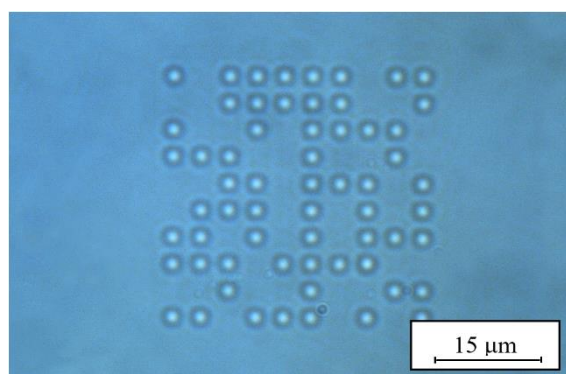
For the layer-by-layer formation of the topological pattern of the structures, specialized software was developed, allowing to set the parameters of sample processing and generate the executable command code for the laser complex (figure 4). Such a processing procedure involves the sequential impact 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 4.** Interface of the software for the formation of the optical structures topology in transparent solid media.

Figure 5 illustrates an example of information encoded in the bulk glass in a form of dots array in accordance with the configuration of the generating program.



**Figure 5.** 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  $0.8\ \mu\text{m}$  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  $15\ \mu\text{m}$ .

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.

### 3. Conclusion

The dependence of the formation of optical structures in bulk transparent samples on the intensity of laser radiation and the focal length of the optical system is studied. Lengthened optical channels were formed due to filamentation of femtosecond laser radiation. The program of forming dots arrays is described and the results of processing in accordance with the specified parameters are presented.

### Acknowledgements

This work was performed as a part of Vladimir State University's State Task 3.5531.2017/8.9 GB-1106/17.

## References

- [1] Schaffer C B, Brodeur A, Mazur E 2001 Laser-induced breakdown and damage in bulk transparent materials induced by tightly focused femtosecond laser pulses *Meas Sci Technol* 12(11):1784-1794
- [2] Anisimov S I and Luk'yanchuk B S 2002 Selected problems of laser ablation theory *Uspekhi Fiz Nauk* 45(3):293-324
- [3] Mao S S, Quéré F, Guizard S, et al 2004 Dynamics of femtosecond laser interactions with dielectrics *Appl Phys A* 79(7):1695-1709
- [4] Kondo T, Yamasaki K, Juodkazis S, Matsuo S, Mizeikis V, Misawa H 2004 Three-dimensional microfabrication by femtosecond pulses in dielectrics *Thin Solid Films* 453-454:550-556
- [5] Shugaev M V, Wu C, Armbruster O, et al 2016 Fundamentals of ultrafast laser–material interaction *MRS Bull* 41(12):960-968
- [6] Delone N Band Krainov V P 1998 Tunneling and barrier-suppression ionization of atoms and ions in a laser radiation field *Physics-Uspekhi* 41(5):469-485
- [7] Apeksimov D V, Bukin O A, Bykova E E, et al 2013 Filamentation of the focused Ti: Sapphire laser pulse in air at two harmonics *Plasma Phys Reports* 39(13):1074-1081
- [8] Couairon A and Mysyrowicz A 2007 Femtosecond filamentation in transparent media *Phys Rep* 441(2-4):47-189
- [9] Kandidov V P, Shlenov S A, Kosareva O G 2009 Filamentation of high-power femtosecond laser radiation *Quantum Electron* 39(3):205-228
- [10] Tarasova M A, Khorkov K S, Kochuev D A, Ivaschenko A V 2018 Study of the Filamentation Phenomenon of Femtosecond Laser Radiation *Bull Lebedev Phys Inst* 45(8):246-250
- [11] Khorkov K S, Kochuev D A, Chkalov R V, et al 2018 Experimental study of the filaments parameters at the focusing with cylindrical lens *International Conference Laser Optics (ICLO) IEEE* 357
- [12] Vislobokov N Yu 2014 Numerical simulation of the influence of dispersion on spectral continuatio powerful femtosecond pulses in silica glass *Journal of VDU* 2(80):23-24
- [13] Kandidov V P, Akozbek N, Scalora M, et al 2004 A method for spatial regularisation of a bunch of filaments in a femtosecond laser pulse *Quantum Electron* 34(10):879-880
- [14] Chkalov R V., Khorkov K S, Kochuev D A, et al 2018 Computerized laser complex for monitoring and controlling of the precision micromachining processes *Proceedings of the International Conferences on WWW/INTERNET 2018 and APPLIED COMPUTING 2018. - Budapest: IADIS* 395-399
- [15] Chkalov R V, Khorkov K S, Kochuev D A, et al 2018 Thin film elements design: software and possibilities of femtosecond laser techniques *J Phys Conf Ser* 1109:012029