Formation of channels with changed refractive index at the filamentation of femtosecond laser radiation in quartz glass

M A Tarasova, K S Khorkov, D A Kochuev, A V Ivaschenko and V G Prokoshev
Vladimir State University, 87 Gorky str., Vladimir, 600000, Russia
trsvmargarita@gmail.com

Abstract. The paper considers the phenomenon of filamentation during the propagation of femtosecond laser radiation in transparent solid media as a tool for structuring quartz glasses, contributing to the formation of channels with a modified refractive index. This approach allows changing the intensity distribution in the transverse profile of the laser beam as it passes through the sample. The spatial intensity distribution is determined by the geometry of the formed channels. The use of high-intensity femtosecond laser radiation contributes to the formation of intensity distribution channels.

1. Introduction
During the propagation of high-power laser radiation with femtosecond duration in transparent medium energy localization occurs with the formation of thin extended filaments [1]. The high intensity of the light field in the filament leads to photoionization of the medium, and after the laser pulse, plasma channels with a relatively high concentration of free electrons are formed.

A prerequisite for the development of filamentation is that the critical self-focusing power is exceeded. In the process of filamentation, the increase in intensity during self-focusing of femtosecond radiation is limited to non-stationary defocusing of radiation in a self-induced laser plasma that occurs when the intensity of the photoionization medium exceeds the intensity, which can be viewed as the appearance of a defocusing lens [2-4].

When creating conditions for the formation of filaments, the energy is redistributed and an extended channel is formed in the volume of a transparent medium. The change in the refractive index is associated with the melting of sections of the medium during the passage of high-intensity laser radiation through the sample. The mode of influence is chosen in such a way that a split of the medium does not occur, and the change in the refractive index is associated with a local melting of the medium.

Forming extended areas with a different refractive index from the main medium, the energy is redistributed in accordance with the geometry of the location of the formed channels.

The change in the intensity distribution in the transverse profile of the laser beam is of great interest for applications in various fields of laser technology. For example, when using multibeam laser technological operations, when a redistribution of intensity is required, which will meet the necessary requirements of laser processing modes.

2. Description of the experimental scheme
The ytterbium femtosecond laser TETA-10 was used as a source of laser radiation, which has the following parameters: radiation wavelength $\lambda = 1033$ nm, pulse duration $\tau = 280$ fs, repetition
frequency $f = 10$ kHz, pulse energy $\varepsilon_{\text{max}} = 150$ $\mu$J. The polarization of laser radiation is linear. A quartz glass sample of KU-1 type with geometric dimensions of $5 \times 5 \times 20$ mm was used as a sample [5].

A series of experiments was carried out to measure the parameters of the filaments, namely, the length and intensity distribution in the transverse beam profile. The filament length was recorded along the length of the plasma channel. The scheme of the experiment is shown in Fig. 1.

![Figure 1. The scheme of the experimental setup: 1 - laser system; 2 - polarization attenuator; 3 - laser radiation; 4 - spherical lens; 5 - optical wedge; 6 - camera and micro lens; 7 - quartz sample; 8 - laser power meter; 9 - cross-section intensity profile meter (Nova BeamStar).](image)

A spherical lens with a focal length of 150 mm was used to focus the laser radiation. The sample was located on a precision movable table XYZ (Aerotech, Standa), which made it possible to move it relative to the focus. In our case, the focus was located behind the rear edge of the sample, which was necessary to prevent its destruction. A polarizing attenuator is necessary to regulate the values of the radiation power. Photo-registration of the filamentation zone was performed using a CCD camera and a micro-lens located on a three-coordinate precision table above the sample.

3. Measurement of filament parameters

The filament parameters, i.e., the filament length, the power dependence of the length, the critical power of the filamentation onset, and the power necessary for the multiple filamentation onset, were measured. When using the focusing lens, the beam diameter at the focus was 50 $\mu$m which corresponds to the pulsed power density of $\sim 10^{13}$ W/cm$^2$ at the pulse energy of 150 $\mu$J. Images of the filamentation zone at various values of intensity are shown in Fig. 2.

![Figure 2. Filamentation in fused quartz KU-1.](image)

The critical intensity value was experimentally determined, which amounted to $2.6 \cdot 10^6$ W/m$^2$. Registration of individual filaments was carried out by photofixation of the formed plasma channels. When the value reached $1.9 \cdot 10^7$ W/m$^2$, the effect of the formation of multiple filamentation was observed. During filamentation, the intensity is redistributed in the transverse beam profile. The passage of high-intensity radiation through the sample forms areas with a modified refractive index in places of self-localization of laser radiation. In the future, the formation of filaments occurs on the modified areas. Fig. 3 shows the intensity distribution in the transverse beam profile at various radiation intensities, obtained using a BeamStar, i.e., a device measuring the transverse profile of the intensity distribution of laser radiation.
Figure 3. Distribution of the transverse intensity profile of the laser beam with an intensity:
(a) $3.6 \times 10^5$ W/m$^2$ without sample with a focusing lens; (b) $3.6 \times 10^5$ W/m$^2$ with a sample;
(c) $2.1 \times 10^6$ W/m$^2$; d) $4.6 \times 10^6$ W/m$^2$.

At $2.1 \times 10^6$ W/m$^2$, there is a redistribution to several local intensity maxima, which are not very pronounced. Achieving an intensity of $2.6 \times 10^6$ W/m$^2$ allows you to register a filament with a camera. At an intensity of $4.6 \times 10^6$ W/m$^2$, two pronounced isolated maxima are observed. Thus, using the filamentation phenomenon, it is possible to obtain a redistribution of intensity, forming several local maxima. Fig. 4 shows the results of recording the spatial distribution of laser radiation.

Figure 4. Registration of the spatial distribution of laser radiation: (a) a laser beam at the exit of the laser system; (b) - a beam of laser radiation passing through the sample without recorded structures; (c) the formation of maxima of laser radiation in the beam cross section in the region of the recorded tracks (indicated by ellipses).

Multiple filamentation of femtosecond laser pulses inevitably develops and has a stochastic character. Using focusing, such as cylindrical or axicon optics, is one of the simplest ways to control the parameters of laser filaments and their plasma channels [6].

A series of experiments were carried out using a cylindrical lens. The use of cylindrical optics in experiments allows the formation of arrays of filaments propagating in the same plane [7]. Fig. 5 shows the dynamics of intensity distribution in the transverse beam profile at filamentation with the use of cylindrical optics in a volume of medium at a laser radiation power of 1.5 W [8].

Figure 5. The development of filamentation in the volume of medium at a power of 1.5 W.

The redistribution of intensity in the transverse beam profile using cylindrical optics is presented in Fig. 6.
Figure 6. Intensity distribution in the transverse beam profile at different laser radiation power values using cylindrical optics.

The region formed as a result of the interaction of focused laser radiation with the medium undergoes structural transformations associated with changes in the refractive index. During self-focusing of laser radiation in the glass structure, a channel is formed with a refractive index different from the base material. Further propagation of laser radiation is carried out on the channel formed. Even with a slight displacement of the laser beam relative to the area of impact, the laser radiation continues to propagate through the channel formed.

4. Formation the given geometry channels with modified refractive index

By controlling the spatial distribution of local structural changes in the sample, it is possible to achieve the production of a specifically specified intensity distribution in the transverse beam profile. An experiment was conducted to record the structures in the sample. The radiation passed through the portal-perisopic system, scheme of the experiment is given in article [9].

The sample trajectory was set using a computer program. Structures were recorded longitudinally. The radiation power was 600 mW, the velocity of beam displacement over the sample was 50 μm/s. To visualize the formed structures, the sample was illuminated by ultraviolet radiation with a wavelength of 257 nm.

UV radiation arriving at the quartz glass sample caused pronounced luminescence of formed structures. Figure 7 shows the optical structures under UV illumination.

Figure 7. Optical structures under UV illumination.

Fig. 8 shows the redistribution of intensity when laser radiation (with a wavelength of 1030 nm) passes through the entire volume of the modified sample, according to the scheme in Figure 1, but without using a focusing lens. The diameter of the laser beam was about 4 mm.
Figure 8. Intensity redistribution: (a) before sample modification; (b) a modified sample, the radiation passes along the beam; (c) a modified sample, radiation perpendicular to the course of the beam.

Moving the beam along the surface of the sample from a given trajectory forms structures that provide a redistribution of intensity. The geometry of the intensity distribution is determined by the spatial arrangement of the structures formed.

5. Conclusion

Thus, in this paper, the process of filamentation of femtosecond laser radiation and the formation of channels with a modified refractive index, which provide a redistribution of intensity in the transverse beam profile, was investigated.

A series of experiments were carried out using cylindrical optics, which allows one to obtain an ordered arrangement of filaments in one of the planes. By controlling the spatial location of the channels, it is possible to realize the intensity distribution according to a given law, since the redistribution of intensity is determined by the spatial location of the channels with a modified refractive index. The control of the spatial position of the filaments is of great interest, since it can be used in modifying and structuring the surface of materials, as well as when using various laser technological operations.

References

[1] Dergachev A A, Ionin A A et al. 2013 Quantum Electronics 43 (1) 29-36
[2] Kandidov V P, Shlenov S A, Silaeva E P, Dergachev A A, 2010 Optics of the atmosphere and ocean 23 (10) 873-884
[3] Chekalin S V, Kandidov V P, 2013 Successes of physical sciences 183 (2) 133-152.
[4] Kandidov V P, Fedorov V Yu, Tverskoi O V, Kosareva O G, Chin S L, 2011 Quantum Electronics 41 (4) 382–386
[5] Zverev V A, Krivopustova E V, Tochilin T V, 2013 Optical materials. Part 2. (St. Petersburg ITMO) p 248
[6] Theberge F, Liu W, Simard P.T. et al, 2006 Physics Review E. 74 036406
[7] J–Ph. Bérubé, R Valléè, et. al., Optics Express. 18 (3), 1801 (2010)
[8] Khorkov K S, Kochuev D A, Chkalov R V et al. 2018 International Conference Laser Optics (ICLO). – IEEE 357-357
[9] Tarasova M A, Khorkov K S, Kochuev D A et al. 2018 Bulletin of the Lebedev Physics Institute 45 (8) 246–250