Experimental study of the filamentation phenomenon and measurement of filaments parameters

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Abstract. The article experimentally investigated the phenomenon of filamentation in the propagation of femtosecond laser radiation in transparent solid media. The experimental scheme for measuring the parameters of filaments using spherical and cylindrical optics was developed and assembled. A series of experiments on the spatial ordering of filaments was carried out. The sample was structured in the filamentation mode with a predetermined distribution of laser radiation intensity. The spatial redistribution of laser radiation passing through the formed structures in the quartz glass sample is also investigated.

1. Introduction
The phenomenon of filamentation of femtosecond laser radiation consists in the spatiotemporal localization of energy in a high-power laser femtosecond pulse under the action of self-focusing in a medium and nonlinearity in a self-induced laser plasma [1]. Unique possibilities of filamentation open new possibilities for using femtosecond laser technologies in micro-optics, material modification, atmospheric optics and other applications [2]. The necessary condition for the development of filamentation is the excess of the critical power of self-focusing. In the process of filamentation, the intensity increase in the self-focusing of femtosecond radiation is limited by the nonstationary defocusing of radiation in a self-induced laser plasma, which occurs when the intensity of the photoionization threshold of the medium is exceeded [3]. The change in the refractive index of the medium associated with the induced plasma can be regarded as the appearance of a defocusing lens [4]. With increasing intensity, multiphoton absorption begins to play an increasing role. Multiphoton absorption is a nonlinear process in which a material simultaneously absorbs several photons to excite an electron. The result of ionization of the medium passing through filamentation with laser radiation is the formation of a narrow plasma channel, the filament. Pulsed radiation, the peak power of which is tens or more times higher than the critical power of self-focusing, forms a multitude of filaments.

2. Description of the experimental scheme
The ytterbium femtosecond laser TETA-10 was used as a source of laser radiation. The laser has the following parameters: the wavelength $\lambda = 1033$ nm, the radiation pulse duration $\tau = 280$ fs, the pulse repetition rate $f = 10$ kHz, the pulse energy $E_{\text{max}} = 150$ µJ. Polarization of laser radiation is linear.

As a sample, KU-1 quartz glass with geometric dimensions of $5 \times 5 \times 20$ mm was used. KU-1 is the optical quartz glass that is transparent in the ultraviolet and visible regions of the spectrum, without absorption bands in the wavelength range of 170-250 nm, with absorption bands in the wavelength ranges of 2100-2300 nm and 2600-2800 nm, non-luminescent, radiation-optically stable [5].
A series of experiments was carried out to measure the filaments parameters, namely the length and intensity distribution in the transverse profile of the beam [6]. The scheme of the experiment is shown in Figure 1.

![Figure 1](image)

**Figure 1.** Scheme for measuring the parameters of filaments: 1 - laser system; 2 - polarization attenuator; 3 - laser radiation (LJ); 4 - spherical lens; 5 - optical wedge; 6 - camera and micro lens; 7 - sample; 8 - photodiode sensor, 9 - frequency converter unit (514 nm, 257 nm); 10 - the mirror; 11 - measuring device of the transverse profile of the laser radiation intensity distribution.

A spherical lens with a focal length of 150 mm was used to focus the laser radiation. The sample was fixed on a precision moving table x-y-z, which allowed to move it relative to the focus. In our case, the focus was located behind the back of the sample to prevent its destruction. Photo-registration of the filamentation zone was carried out with the help of a camera and a micro lens. They were placed on a three-coordinate precision table above the sample.

### 3. Measurement of filament parameters

The parameters of filaments were measured, namely: the length of the filament, the dependence of the length on the power, the critical value of the power of the beginning of filamentation, as well as the power necessary for the beginning of the multiple filamentation effect. Images of the filamentation zone at different power values are shown in Figure 2. As the radiation power values increase, the length of the filament increases.

![Figure 2](image)

**Figure 2.** Filamentation in fused quartz KU-1.

![Figure 3](image)

**Figure 3.** Growth of the filament: (a) at the beginning; (b) after 5 minutes; (c) after 10 minutes.

The critical power value was determined experimentally, which was 5.18 mW. When the value of 38.5 mW was reached, the effect of the formation of multiple filamentation was observed.
Also in the course of the experiment, luminescence of the impact area was observed, which indicates structural changes in the environment. The growth of the filament has been observed over time, which is clearly shown in Figure 3.

During filamentation, the intensity is redistributed in the transverse profile of the beam. When high-intensity radiation passes through the sample, areas with a changed refractive index are formed in the places of self-localization of radiation. And in the future, the formation of filaments occurs on modified areas. Figure 4 shows the intensity distribution in the transverse profile of the beams at different values of the radiation power.

![Figure 4. Distribution of the transverse intensity profile of the laser beam: (a) initial beam; (b) power 4.2 mW; (c) power 9 mW.](image)

Thus, using the phenomenon of filamentation, it is possible to obtain the redistribution of intensity, forming several local maxima.

4. Control of the spatial arrangement of filaments

Multiple filamentation of powerful femtosecond laser pulses is inevitable and stochastic. It is therefore of interest to examine the question of control of filamentation. The use of focusing, for example, cylindrical or axial optics, is one of the simplest ways to control the parameters of laser filaments and their plasma channels [7].

A series of experiments using cylindrical optics was carried out [8]. The use of cylindrical optics in experiments allows the formation of filaments arrays propagating in one plane [9]. In this case, the intensity redistribution in the transverse profile of the beam, shown in Figure 5.

![Figure 5. Intensity distribution in the transverse beam profile at different laser radiation power values using cylindrical optics.](image)

![Figure 6. The development of filamentation in the volume of medium at a power of 1.5 W](image)

Figure 6 shows the distribution of filaments in the sample at a laser radiation power of 1.5 W. The distribution of filaments occurs in one plane.

An experiment was carried out to modify the sample using the phenomenon of multiple filamentation, when the cylindrical lens was rotated several times around the radiation axis. When the
cylindrical lens rotated around the radiation axis, the spatial position of the focus changed. To visualize the structures formed, the sample was illuminated by ultraviolet radiation with a wavelength of 257 nm, according to the scheme shown in Figure 1. Ultraviolet radiation, getting into the sample of quartz glass, caused a pronounced luminescence of the formed structures.

![Figure 7](image1.png)

**Figure 7.** The structure formed in the process of filamentation.

Figure 7 shows the structure recorded in the sample during filamentation using cylindrical optics. Formation of the ring structure achieved the rotation of the cylindrical lens, in this experiment, it rotated 10 times around the axis of the laser radiation.

![Figure 8](image2.png)

**Figure 8.** The intensity distribution in the beam: (a) when passing through a clean sample (b) when passing through a modified sample located along the laser radiation (c) as it passes through a modified sample perpendicular to the laser radiation.

Figure 8 shows the intensity distribution of the laser radiation passing through the modified sample (Figures 8(b), 8(c)). It can be seen that structures have formed, and there is also a redistribution of intensity. Laser radiation is propagated by the modified area.

To create more equal structures, the laser power must be stable and the sample must be rotated, not the lens. This requires special technical equipment and a computer program that will carry out the automated movement of the sample along a specified trajectory.

5. **Conclusion**

Thus, the parameters of the filaments were measured. The processes occurring during the interaction of femtosecond laser radiation with a dielectric transparent medium are studied. A series of experiments using cylindrical optics was carried out, which makes it possible to obtain an ordered arrangement of filaments in one of the planes. The control of the spatial location of the filaments is of great interest, since it can be used for the modification and structuring of the surface of materials.

In the course of the experiments, the formation of structural changes in the medium in the places of laser radiation passage was recorded, which directly affects the further spatial distribution of filaments. Thus, controlling the spatial arrangement of the filaments, we obtain the intensity
distribution with a given geometry. The sample was modified using the phenomenon of filamentation and cylindrical optics. The transverse profile of laser radiation distribution was measured. This phenomenon can have a wide range of practical applications, for example, in the precision processing of materials and various laser processing operations.

Further optimization of the experimental scheme for sample structuring and obtaining a specified laser beam intensity distribution is planned.

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