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OPTICAL WAVES PROPAGATION

Spatial Structure of Femtosecond Laser Radiation during Filamentation in Air

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Abstract—The results of experimental and theoretical studies of the evolution of the small-scale transverse structure of high-power femtosecond laser radiation propagating in air in the multiple filamentation mode are presented. It has been found that the presence of intensity inhomogeneities in the initial transverse profile of the laser beam leads to the formation of spatially isolated light channels due to the Kerr self-focusing effect. When the power in these channels exceeds a certain threshold value (the critical power), radiation filamentation occurs in them. The parameters of these light channels are theoretically estimated on the basis of the diffraction-ray model of single filamentation. It is shown that for a laser beam with a centimeter radius and subterawatt power, the initial radius of intensity inhomogeneities in the transverse profile has a characteristic value of several millimeters.

Keywords: femtosecond laser pulse, air, filamentation, light channels, diffraction-ray tube

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INTRODUCTION

A topical problem in nonlinear optics is filamentation of femtosecond laser pulses. This phenomenon is the decay of a laser beam into a number of spatially isolated light structures characterized by extreme intensity. Examples of the aforementioned structures are light and plasma filaments, as well as light channels observed during the pre- and postfilamentation propagation. For wide-aperture (centimeter) laser beams, the formation of these channels is associated with the presence of inhomogeneities in the initial profile of the laser beam intensity. Postfilamentation channels are formed due to the formation of Bessel–Gaussian light structures in the light filament propagation zone.

When high-power near-IR femtosecond radiation propagates in air, the filaments formed are characterized by a diameter of about 100 μm and a length of up to several tens of meters [1]. In contrast, postfilamentation channels (PFCs) have a low angular divergence (tens of microradians) [2], but persist on longer paths [3–5].

To understand how individual light filaments are formed under multiple filamentation, experimental and theoretical studies of the evolution of intensity inhomogeneities in the initial laser beam profile, i.e., of the so-called small-scale transverse beam structure, are of interest. Their self-focusing results in the formation of light channels before the start of filamentation [6].

This work continues the experimental studies begun in [6] on the detection of prefilamentation light channels. Our studies, in particular, make it possible to ascertain which part of a laser beam is directly involved in the radiation filamentation. For this, not only characteristics of these channels were studied, but also the physical causes of their formation, i.e., small-scale focusing, filamentation and postfilamentation propagation of an individual light inhomogeneity in the initial profile of the laser beam intensity, have been numerically simulated.

The need for an additional theoretical study of the issue of small-scale self-focusing is justified by the fact that the study of this effect has been carried out only qualitatively so far. For example, an approach was used in [7], where the primary fluctuations of the plane wave phase in a cubically nonlinear medium were considered. This increases the amplitude of a plane wave section that stops at some distance due to the balance between self-focusing and diffraction. After that, the wave divides into "threads" of certain sizes with the power equal to the critical power. The use of this model for the interpretation of experimental data on multiple filamentation in air is apparently impossible, since the size of the primary region of high intensity and the power contained in it (which is always constant, both in this model and in others [1]) are uncertain. The description of a change in the size

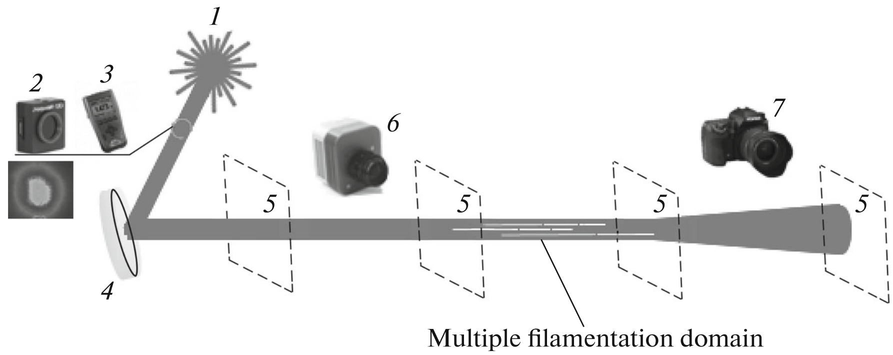

Fig. 1. Experimental design: Ti:Sapphire laser complex (*1*); LBP2-HR-VIS beam profiler (*2*); OPHIR-II pulse energy meter (*3*); rotary mirror (*4*); screen (*5*); ANDOR-Clara E camera (*6*); Pentax K-3 camera (*7*).

of the primary inhomogeneity after the wave division into "filaments" is also absent. Another point is the number of filaments N_{fil} in a laser beam cross section. This parameter is approximately estimated as the ratio of the initial peak radiation power to the critical self-focusing power. Using this ratio, we can conclude that the number of filaments should attain several hundred for centimeter laser beams of subterawatt femtosecond pulses propagating in air (see, for example, experimental parameters in [4, 8]). At the same time, the experimental value turns out to be one [4] or even two [8] orders of magnitude lower.

In this work, the evolution of the small-scale transverse structure of a centimeter femtosecond laser radiation beam in air is studied on the basis of experiments and numerical simulations. Self-focusing of individual intensity inhomogeneities in the laser beam profile is considered; it leads to the formation of high-intensity light channels before filamentation and individual light filaments along the radiation propagation path. The number and sizes of spatial inhomogeneities in a laser beam cross section are determined, and the features of their evolution along the path are established.

1. EXPERIMENTAL

The experiments were carried out at the femtosecond test bench of the V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences (IAO SB RAS). A Ti:Sapphire femtosecond terawatt system (carrier wavelength 786.8 nm, pulse duration 50 fs, pulse repetition rate 10 Hz, pulse energy up to 40 mJ, beam diameter 2.5 cm (at the energy density level e^{-2})) was used as a source of laser pulses. The experimental design is shown in Fig. 1.

The initial beam profile was recorded using profiler *2*. The accumulation time of the profiler was 100 ms, which, taking into account the pulse repetition rate, made it possible to record the beam profile for one laser pulse. Changes in the laser radiation energy were controlled with meter *3*. The small-scale beam structure was recorded with CCD camera *6* on screen *5* mounted on a movable table. Moving this, we recorded the transverse beam structure along the propagation path. The presence of light filaments was controlled by camera *7*, which recorded a conical emission [8, 9] on screen *5* mounted at the path end. The beginning and end of the multiple filamentation domain (MFD) was determined by burns on light-sensitive paper (TU 6-17-766-76) and with an acoustic sensor. A detailed description of the experimental setup and technique is given in [8].

The path evolution of femtosecond laser radiation with an energy of 40 mJ in air is shown in Fig. 2. One can see that self-focusing of the intensity inhomogeneities in the laser beam profile results in the fact that high-intensity light channels on a millimeter scale were recorded at a distance of 7 m from the source (5 m before the beginning of the filamentation domain). They are shown by bright spatially localized areas in the photographs. Their diameter decreases from several to about one millimeter along the path (Figs. 2b and 2c). Then, at a distance of 12 m (Fig. 2d), plasma filaments are formed inside these channels, which persist up to 23 m. For example, the channels at distances of 13 and 16 m, respectively, are shown in Figs. 2e and 2f). Note that a light filament was not formed in every such channel recorded before the MFD. A qualitative confirmation of the existence of light filaments is the presence of conical emission. After the multiple filamentation ceases at a distance of 23 m from the laser pulse source, the radiation is propagating in the form of a PFC. The characteristic features of this stage have been analyzed and described in detail in [6, 8].

Figures 2a–2c show that the mutual arrangement of high-intensity light channels formed from intensity inhomogeneities in the laser beam profile remain constant in the beam cross section during the initial stage of radiation propagation (before the formation of filaments) within the measurement error. This testifies to their independent propagation. The radiation intensity in the channels and the number of channels recorded in the laser beam cross section increase with the distance from the beginning of the path. This is

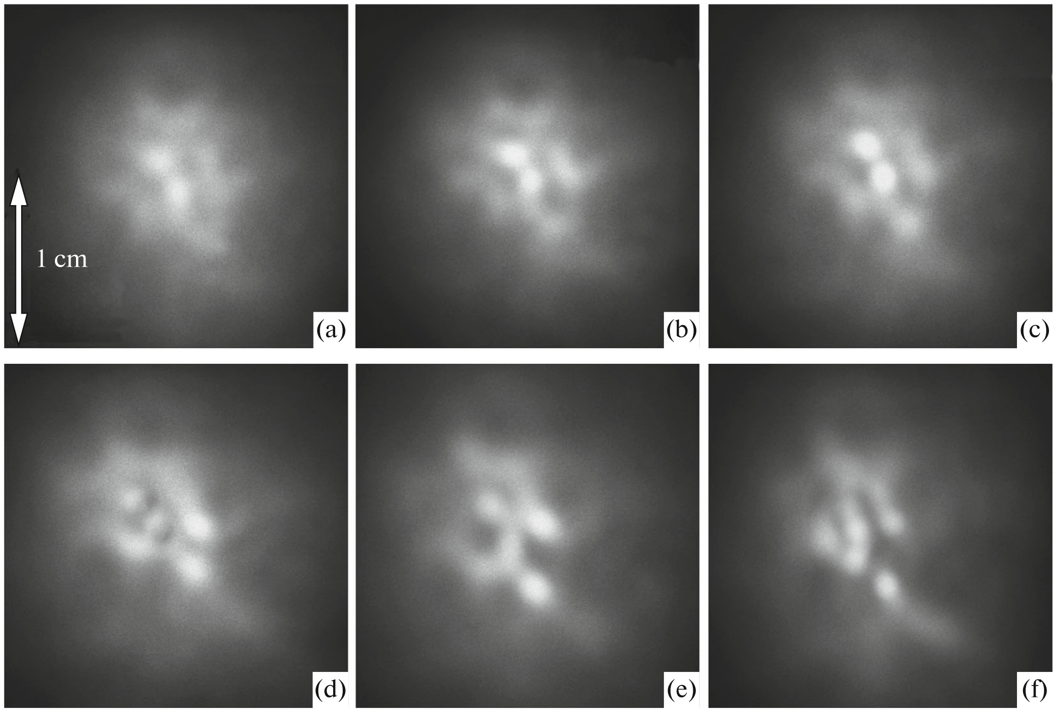

Fig. 2. Images of high-intensity channels in the cross-section of a beam with $E = 40$ mJ at a distance of (a) 7; (b) 9; (c) 10; (d) 12; (e) 13, and (f) 16 m from the radiation source.

due to the self-focusing of inhomogeneities with a lower power and/or with a large initial radius. When approaching the filamentation domain (Fig. 2d), the mutual arrangement of the channels does not significantly change, which is consistent with the results [10]. The intensity in the channels and their number remain approximately constant during this propagation stage.

In the experiments, no changes were found in the qualitative nature of the above-described features with a change in the laser pulse energy. For laser pulses with lower energy, fewer channels are formed at the same distance from the radiation source.

Figure 3 shows the diameter d of high-intensity light channels formed during self-focusing of intensity inhomogeneities in the transverse laser beam profile along the propagation path z measured in the experiments. As is seen, the size of high-intensity light channels in the transverse laser beam profile remains almost constant along the propagation path during the filamentation for pulses with E = 20–40 mJ. The diameter of these channels, recorded before the beginning of MFD, decreases along the propagation path from a few to approximately 1 mm. As the pulse energy decreases, the distance at which high-intensity light channels are recorded increases.

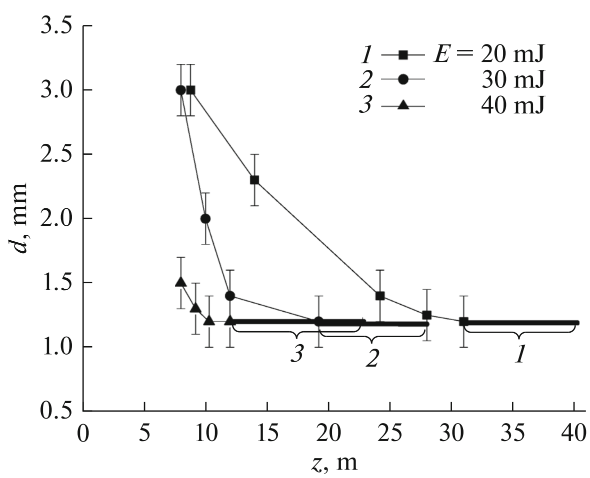

Fig. 3. Diameter of high-intensity light channels as a function of the propagation distance for different pulse energies; braces show the MFD.

2. INTERPRETATION OF EXPERIMENTAL DATA WITH THE DIFFRACTION-RAY TUBE APPROACH

Based on experimental results (Section 1) and conclusions [10], it can be concluded that, upon the formation of MFD of laser pulses, cyclic refocusing of single filaments occurs; they weakly interact with others or do not depend on them. The independent formation of filaments is confirmed by the experiments where PFCs in air [3, 8] and multiple filamentation of femtosecond laser pulses in glass [11] were detected. This makes it possible to use the data obtained for a single filamentation for estimation of the characteristics of multiple filamentation.

Let us consider the diffraction-beam model [12] as a model of single filamentation. Within this model, a laser beam is divided into a set of nested diffraction-ray tubes (DRT) [13]. These tubes do not intersect in space and do not exchange energy with each other; therefore, variations in their parameters along the path make it possible to estimate the effect of physical processes accompanying the radiation propagation in the medium. Considering each DRT as a single light structure, it is possible to describe all the characteristic stages of filamentation, including the initial stage of propagation before the formation of filaments and postfilamentation channeling.

Let us consider Fig. 4 as an example of applying the diffraction-ray model of single filamentation of femtosecond laser pulses to the interpretation of experimental data on multiple filamentation in air. Figure 4 shows the results of numerical simulation self-focusing and filamentation of Ti:Sapphire laser pulses with length t_p = 100 fs for an intensity inhomogeneity in the initial laser beam profile with radius r_0 = 3.5 mm in the case where the initial peak pulse power P_0 exceeds by six times the critical self-focusing power P_{cr}, i.e., where the relative peak power $\eta = P_0/P_{cr} = 6$. The P_{cr} = 3.2 GW in air, according to [1, 8]. The complete mathematical formulation of the problem is given in [12].

The bold curve in Fig. 4 shows the energetically replenishing DRT. It is selected from the set of DRTs as an external tube the closest to the curve which corresponds to the energy density at the level e^{-1} from the maximum in the beam paraxial region (dashed curve) during the postfilamentation propagation stage (z > 60 m). This approach to the choice of the energetically replenishing tube is based on the fact that just this parameter (energy density at the level e^{-1}) is used to estimate the PFC parameters in experimental studies (for example, [2]). If we consider the initial stage of radiation propagation (Fig. 4), it can be seen that the indicated tube also corresponds to the high-intensity light channels (squares) described in Section 1. In Fig. 4, experimental data (squares) correspond to curve *1* shown in Fig. 3 for a laser beam with r_0 = 1.25 cm and E = 20 mJ. For convenience of comparison between the experimental data with numerical simulation results, the radii of the light structures under study are shown.

The analysis of Fig. 4 confirms that the coordinate of the start of filamentation of femtosecond laser pulses, determined from the numerical simulation for the inhomogeneity with r_0 = 3.5 mm (bold curve), coincides with the corresponding coordinate found in experimental studies for laser beams with the radius R_0 = 1.25 cm. This fact confirms that the MFD of a subterawatt centimeter laser beam, consisting of individual filaments, is formed upon self-focusing and filamentation of individual millimeter-size intensity inhomogeneities in the light field with $P_0 < 10P_{cr}$. In the case under study, the inhomogeneity radius is 3.5 mm, and the power (in view of P_{cr} = 3.2 GW) is ~19 GW.

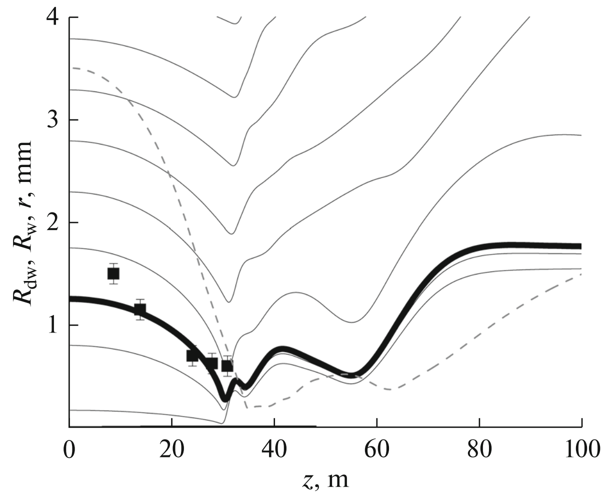

Fig. 4. Path dependence of DRT radii R_{dw} (solid curves) for an inhomogeneity of the intensity profile with r_0 = 3.5 mm and η = 6: the dotted curve corresponds to the energy density at the level e^{-1} from the maximum R_w; the bold curve shows energetically replenishing DRT, and squares correspond to experimental data for a pulse with E = 20 mJ shown in Fig. 3.

Taking into account the ratio of the radius of an individual inhomogeneity and the beam as a whole, we can also estimate the possible number of inhomogeneities formed in a laser beam and capable of self-focusing and filamenting. If we consider this problem in radial symmetry and assume the inhomogeneities to be at the same distance from each other, equal to the inhomogeneity radius, then the number of inhomogeneities turns out to be five in the simplest case. Taking into account that the maximal number of light channels formed from intensity inhomogeneities in the laser beam profile is four [6, 8] (it is equal to three at the beginning of MFD and then it increases to four), we can conclude that the approach suggested provides for a quite accurate estimate. It should be noted that the number of channels, and hence, inhomogeneities, attains five during filamentation of a laser beam with the transverse structure shown in Fig. 2, the same radius as in [8], but with higher energy. These estimates of the number of inhomogeneities, as well as the experimental results presented in Fig. 2 and in [6, 8, 14], are important for numerical simulation of multiple filamentation of femtosecond laser pulses in air.

All this, as well as the results of experimental studies of multiple filamentation [8, 10, 11, 14], indicate that laser beam intensity inhomogeneities have different initial parameters (radius and power). These parameters determine the coordinate of the start of filamentation and the plasma region length for each such inhomogeneity. In this regard, the positions of inho-

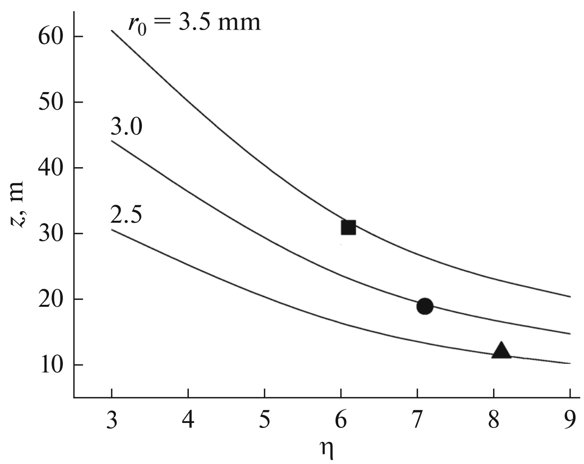

Fig. 5. Coordinate of the filamentation start as a function of the relative peak power in inhomogeneities with different initial radii; symbols correspond to experimentally found coordinates from Fig. 3.

mogeneities in a beam and their parameters require additional study.

The coincidence of the experimental data and the numerical calculation results in Fig. 4 also allows estimating the radius of these inhomogeneities and the power in them. According to Fig. 5, it turns out that the initial inhomogeneity radius $r_0 \approx 3.5$ mm under the condition of the fixed relative peak power in the inhomogeneity $\eta = 6$ for the experiments from Section 1 (curve *1* in Fig. 3) and work [6]. This value is an order of magnitude larger than the characteristic transverse dimensions of filaments formed for near-IR radiation [1, 15, 16] and is comparable to the transverse dimensions of a high-intensity light channel observed before the beginning of MFD [6] and PFC [6, 8]. If $\eta = 3$ or 9, for example, then the radius of this inhomogeneity also changes, but retains the millimeter scale (~4.5 and 2.5 mm, respectively). If using experimental data on the coordinate of the start of filamentation of femtosecond laser pulses with higher energy (curves *2* and *3* in Fig. 3) and at fixed $\eta = 6$, then $r_0 = 2.8$ and 2.3 mm, respectively. In other words, the radius of inhomogeneities capable of self-focusing and filamentation decreases as the pulse energy increases, which is confirmed by the results [17].

To estimate the power of intensity inhomogeneities in the laser beam initial profile, we use the dependence of the filamentation start coordinate normalized to the Rayleigh length, equal to half the diffraction length, on the relative peak power for laser beams of millimeter radius derived in [18] by the DRT method (curves in Fig. 5). For comparison with experimental data, the filamentation start coordinate in Fig. 5 is given in dimensional values. The symbols correspond to the coordinates of the beginning of MFD in Fig. 3; their type corresponds to pulse energies in Fig. 3.

According to Fig. 5, filaments are formed at a greater distance from the beginning of the path because of larger initial radii and lower power of inhomogeneities. The results also correspond to the qualitative conclusions drawn in [9]. In the experiments on the femtosecond laser pulse propagation in air, the filamentation domain forms due to millimeter-scale intensity inhomogeneities (2.5–3.5 mm radius) in the initial profile of a centimeter laser beam. The power in these inhomogeneities varies from 19 to 26 GW. Moreover, it was shown in [17], where a large volume of experimental data on laser pulse filamentation in air, including along atmospheric paths up to several hundred meters long, was analyzed, that the power in inhomogeneities generally varies from several units to tens of gigawatts (9–26 GW).

The analysis of experimental data from [4, 8] also showed that the filamentation domain length and the number of filaments in a beam cross section increase with the laser pulse peak power.

CONCLUSIONS

The results of experimental studies of the propagation of collimated beams of a Ti:Sapphire laser along a controlled air path are presented. The laser beam diameter was 2.5 cm, and the pulse energy varied from 20 to 40 mJ. The small-scale transverse structure of femtosecond laser radiation under multiple filamentation, which is implemented due to self-focusing of intensity inhomogeneities in its transverse profile, is considered. It is shown that the transverse size of high-intensity light channels in a laser beam remains approximately constant and weakly depends on the pulse energy in the optical path section, where multiple filamentation occurs. It is found that a filament, which is a spatially localized light structure associated with plasma formation and conical emission, does not always arise during propagation of such a channel.

To assess the parameters of an MFD formed along an air path, a diffraction-ray model of a single filamentation of femtosecond laser pulses was used. The application of this approach is based on the experimental data, which have shown cyclic refocusing of single filaments during the formation of an MFD. Considering DRT as a single light structure makes it possible to describe all the characteristic stages of filamentation. Estimates made with this approach show that the radius of small-scale intensity inhomogeneities in the profile of a centimeter laser beam, which form the MFD of subterawatt laser pulses, varies within 2.5–3.5 mm in the experiments performed. The radiation power characteristic of these inhomogeneities varies from 19 to 26 GW.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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