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NONLINEAR OPTICS

Global Self-Focusing and Features of Multiple Filamentation of Radiation of a Subterawatt Ti:Sapphire Laser with a Centimeter Output Aperture Along a 150-m Path

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Abstract—The formation and propagation of postfilamentation channels along a controllable path 150 m long are studied experimentally for collimated beams of different diameters. During multiple filamentation, a laser beam is compressed into a global focus, after passing which its angular divergence is much greater than the divergence of postfilamentation channels generated during the filamentation. It is shown that the intensity of the postfilamentation channels is sufficient for starting multiple filamentation in optical elements at distances much longer than the filamentation region length.

Keywords: laser radiation, femtosecond pulse, self-focusing, filamentation, postfilamentation light channels, air
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INTRODUCTION

High-power femtosecond laser radiation propagating in optical media is self-focused and filamenting [1]. Generalizing the results of related works [1–4], the physics of the phenomenon in air can be explained as follows. The self-focusing is manifested in compression of a radiation beam, as its peak power attains the critical power P_{cr}, or some beam parts, where the local power P_{loc} exceeds P_{cr}, while the radiation is propagating, which increases the intensity in regions of nonlinear foci. Several scenarios are possible depending on the laser type and initial beam size. The critical power P_{cr} is 3.2 GW at sea level in air for Ti:Sapphire laser radiation. If beam radii are of several millimeters and $P_0 < 10P_{cr}$, then self-focusing develops and results in single filamentation. This means that when the pulse power $P(t)$ becomes higher than P_{cr} during the self-focusing at the distance $z_{loc}^{foc}(t)$ at a time point t, the beam starts collapsing, i.e., its intensity attains extreme values, which results in multiphoton or tunnel ionization of air. The absorption in plasma stops the collapse. A local nonlinear focus or a waveguide structure appears; the latter can include several foci. During path propagation of a pulse, a system of foci and light waveguide structures with nonlinear foci inside is formed. Plasma accumulates in these regions with time, i.e., plasma channels are generated. When a pulse propagates along the path in the lateral direction, the plasma channels glow with the emission spectrum. This elongated glowing region along the path is called a filament.

Wide-spectrum radiation in the Stokes and anti-Stokes regions is formed in the transverse direction, i.e., the so-called supercontinuum, due to the frequency modulation of the pulse because of the Kerr effect and plasma refractive nonlinearity. When the filamentation ceases, this radiation is recorded at a receiver in the form of a localized white spot. Formation of a global focus, i.e., general self-focusing of the beam, is characteristic of single filamentation depending on the beam radius. This means that the main energy of the beam is focused in a region smaller in lateral size that the initial beam diameter.

When $P_0 \gg P_{cr}$, multiple filamentation occurs. Local light structures with plasma channels are formed at the wave front from initial spatial inhomogeneities of the beam amplitude and phase. After the filamentation ceases, cross sections of these structures are recorded by the receiver in the form of a set of white spots. However, far from the filamentation region, channels with the white radiation do not contain plasma. These regions are called postfilamentation channels (PFC) [5].

The question of whether a beam is focused under multiple filamentation has not been studied in experi-

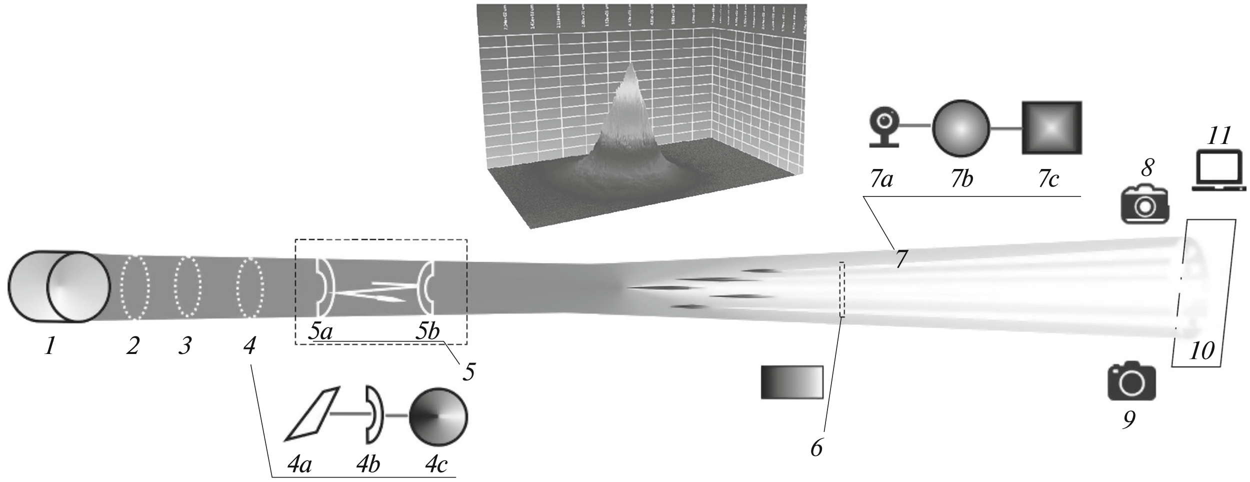

Fig. 1. Experimental layout: Ti:Sapphire laser complex (*1*) (wavelength 800 nm, pulse length 10 fs, beam diameter 2.5 cm at e^{-2} level); autocorrelator (*2*) (pulse length 50 fs); pulse energy meter OPHIR-II (*3*) (up to 30 mJ); beam profiler (*4*): optical wedge Opto-Sigma WSSQ-50C10-20-3 (*4a*), spherical mirror with curvature radius 50 cm (*4b*), beam energy density profiler LBP2-HR-VIS with light filters NS-3, NS-4, NS-8, and NS-10 (*4c*); beam size control unit (*5*) (telescope, output beam diameters d_0 = 1.25, 2.5, 5 cm): spherical mirrors with curvature radius 200 (*5a*) and 100 cm (*5b*); K8 optical glass sample, 10 cm length (*6*); PFC spectrum measurement unit (*7*): aperture (*7a*), integrating sphere Newport 819C-SF-6 (*7b*), Maya2000Pro spectrometer (*7c*); ANDOR-Clara E CCD array with HELIOS-44M 2/58 lens and light filters NS-8 and NS-10 (*8*); Pentax K-3 camera (25 Mp) with Pentax100MacroWR macrolens (*9*); movable screen (*10*); computer (*11*) for recoding the measurements results from (*4*), (*7*), (*8*), and (*9*). The fragment shows the initial laser beam profile.

mental works. In practical point of view, it is important to ascertain a possibility of existence of a global focus of a beam during its multiple filamentation. In addition, it is necessary to analyze the dependence of the global focus coordinate on the initial radiation parameters: pulse radius, peak power, and length. This analysis is required to answer the question about controlling the zone of filamentation of collimated laser radiation.

Another task of practical interest relates to properties of the beam region which contains the above mentioned PFCs. They are narrow spatial zones with the intensity higher as compared to its mean values over the beam cross section and the angular divergence which is an order of magnitude lower than the total beam divergence. Data on the evolution of angular sizes and the spectral composition of these channels is important for the analysis of the prospects of their use for energy transfer through the atmosphere and multifrequency laser sounding of its gaseous and aerosol components. Physical aspects of the manifestation of regularities in the behavior of local high-intensity light structures under multiple filamentation are of interest. This study promotes a more comprehensive realization of the phenomenon of multiple filamentation.

This work is aimed at the experimental study of global self-focusing and properties of multiple filamentation of Ti:Sapphire laser radiation in air. The global self-focusing and multiple filamentation of laser pulses can be used for atmosphere sounding, creation of long ionized channels, and production of a high-intensity laser radiation region at a specified path point [1–3].

EXPERIMENTAL RESULTS

The transverse beam profiles of collimated beams of different centimeter-scale diameters were studied in this work along a ~150-m path. The experimental scheme is shown in Fig. 1. The procedure is described in [6] in detail.

During the experiment, camera *8* imaged a beam. From processing the images [7], different transverse beam structures were detected, i.e., the whole beam, individual PFCs, rings surrounding PFCs, and integral rings. The transverse structure of the central part of a laser beam at different distances from the end of the multiple filamentation region (MFR) for an initial beam diameter (d_0 = 2.5 cm), recorded by camera *8* on screen *10*, is shown in Fig. 2. It is seen that the central part of the beam contains bright, the so-called "hot", points—postfilamentation channels. They are surrounded by a set of rings with the brightness decreasing from the center to periphery, which corresponds to the energy density distribution in a Bessel–Gaussian beam. It is possible that just this configuration of the transverse beam structure formed after the filamentation is the cause of weak divergence of its central part, i.e., PFC.

Beam and PFC radii are shown in Fig. 3 as functions of the propagation distance.

The results imply that the PFC angular divergence is 42 μrad at an initial beam diameter of 1.25 cm (Fig. 3a),

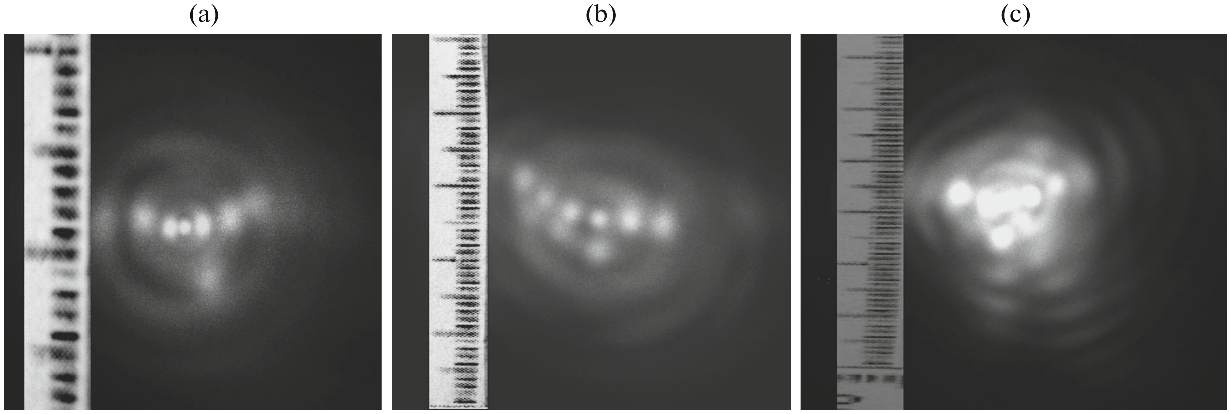

Fig. 2. Lateral structure of a laser beam with an initial diameter of 2.5 cm at a distance of (a) 45 m from the sources (3 m from the end of MFR), (b) 105 m from the source (65 m from the end of MFR), and (c) 138 m from the source (98 m from the end of MFR).

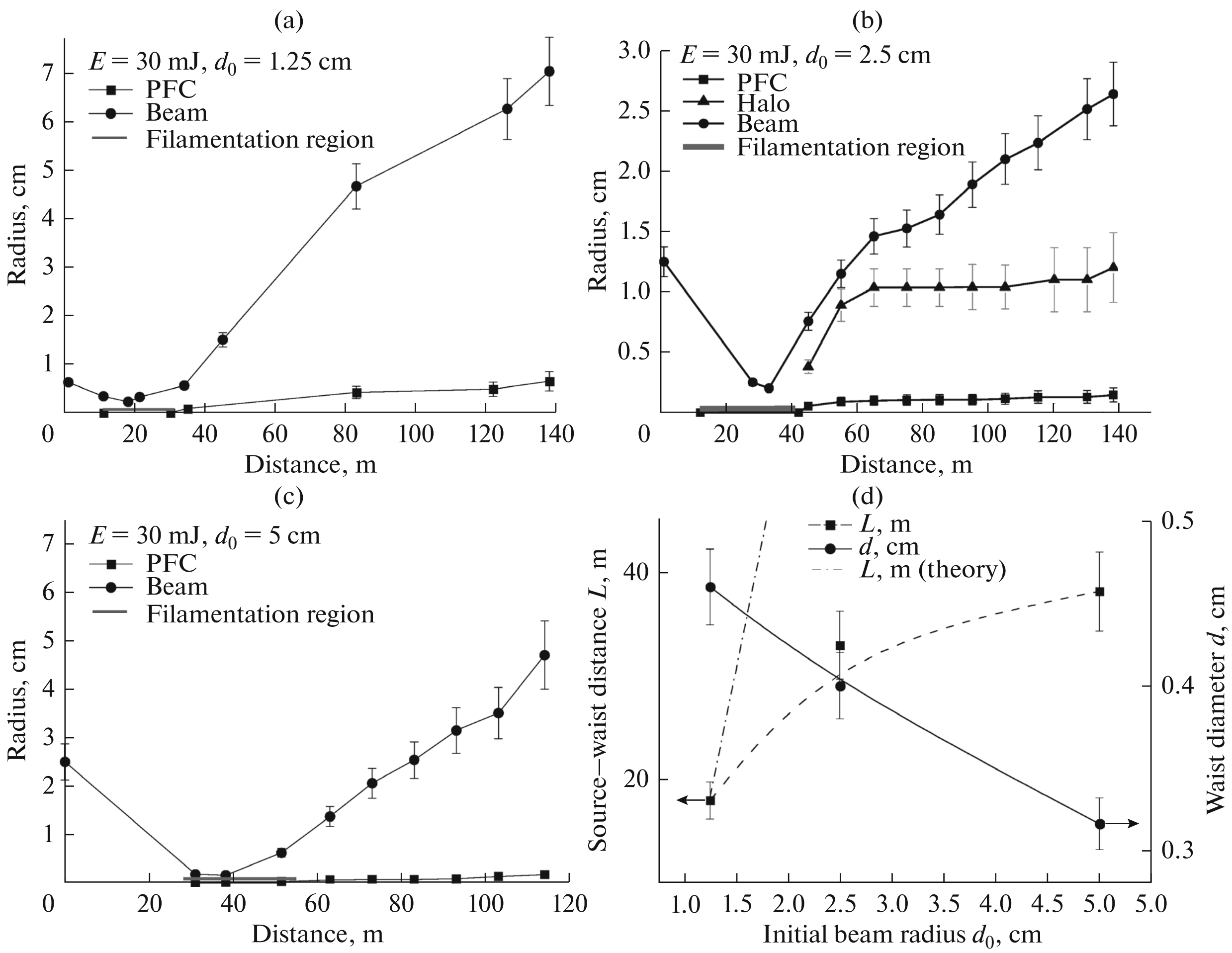

Fig. 3. Radii of beam and PFC versus the pulse propagation distance for an initial beam diameter of (a) 1.25, (b) 2.5, and (c) 5 cm; (d) beam waist diameter and distance between the start of the beam waist and the source versus the initial beam diameter.

5 μrad at a diameter of 2.5 cm (Fig. 3b), and 22 μrad at a diameter of 5 cm. The divergence of the whole beam (d_0 = 1.25; 2.5; 5 cm) is 0.6; 0.2; 0.65 mrad, respectively, after passing the global focus (including the cone-shape emission from the filamentation region, that is, a system of color rings). Abnormally weak divergence of PFC for a beam with an initial diameter of 2.5 cm might well be explained by the fact that the

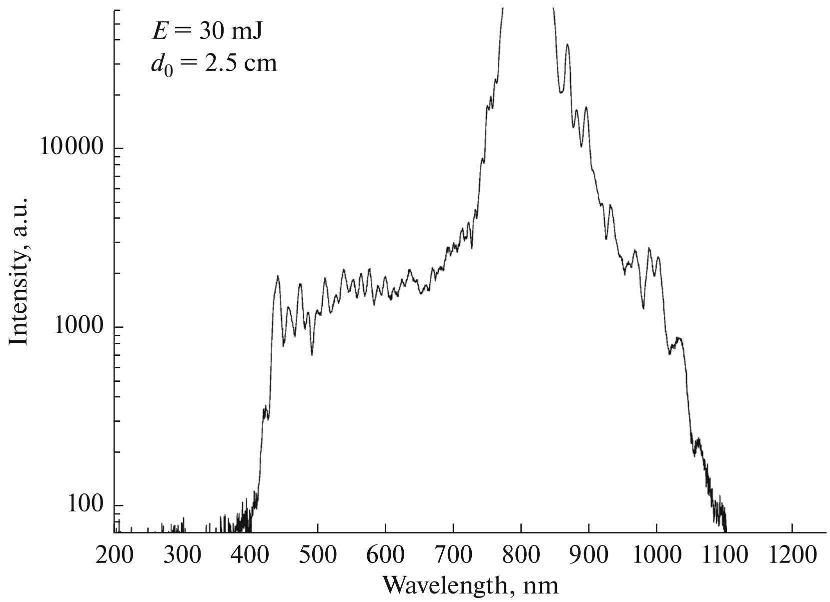

Fig. 4. Spectrum of a single PFC at a distance of 100 m from MFR.

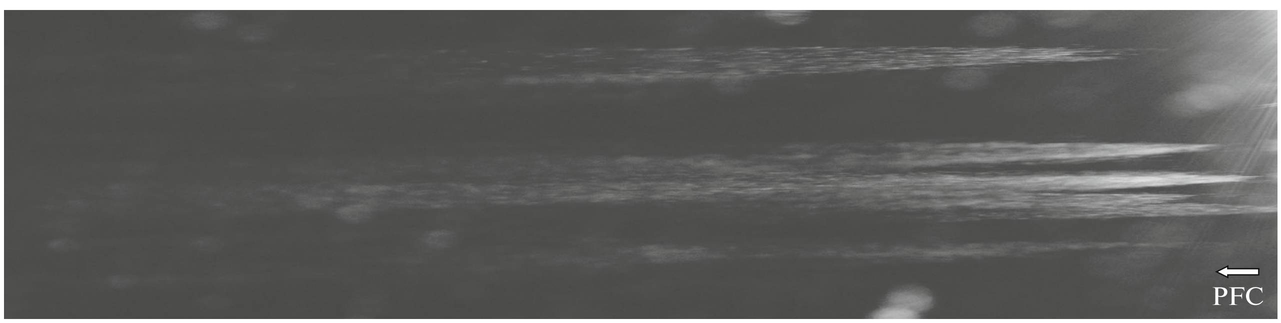

Fig. 5. Multiple filamentation in K8 glass under the action of PFCs at a distance of 90 m from the end of the filamentation region.

ring structure surrounding a PFC packet is the most pronounced just for this beam, which is not distorted during two-fold decrease or increase in the beam diameter by telescope *5* (see Fig. 1).

Figure 3d shows the dependences of the radiation source–beam waist distance (global nonlinear focus, GNF) and the waist diameter d on the initial beam diameter. The GNF–initial beam diameter curve rise does not contradict qualitatively the response of the nonlinear focusing diameter to an increase in the beam aperture while maintaining constant its initial peak power P_0. However, the behavior of this dependence quantitatively strongly differs from the forecasted quadratic dependence on the beam radius. The estimate of the distance to the GNF by the formula written in [1] for stationary self-focusing and single filamentation satisfactorily agrees with the value measured only for the minimal beam diameter (1.25 mm, see Fig. 3d). As the initial aperture increases, the divergence between the calculated and measured values increases significantly.

Spectrum measuring unit *7* (see Fig. 1) records the spectrum of an individual PFC (Fig. 4). Figure 4 implies that the radiation spectral width accumulated in the PFC expands to 1100 nm. This allows the use of even individual PFC for multifrequency laser sounding of the atmosphere.

The intensity in the PFC at a distance of about 100 m from the MFR can be estimated based on experiment results shown in Fig. 5. An optical glass sample was placed in the PFC region, where hollow-cone-shaped multiple filamentation was observed at sites of PFC action. This MFR structure was observed earlier in [8] only after the mean intensity in a pulse with Gaussian distribution attained values of 10^{11}–10^{12} W/cm^2.

Thus, the results of experimental study of features of PFC propagation along a controlled path 150 m long for collimated beams of different diameters showed the following. The PFC divergence is tens of microradians. The whole beam is self-focused during multiple filamentation; its lateral size is minimal at a distance that corresponds to the maximal number of filaments in the MFR. The angular divergence of a beam after the global focus is an order of magnitude larger that the divergence of PFCs. A ring structure surrounding the filamentation region provides for abnormally low divergence of the PFC packet. The PFCs have a Gaussian distribution of the energy density over the cross section at distances from the end of the filamentation region much longer than the filamentation region length, and their intensity is the maximum possible for multiple filamentation formation in dense optical media for ionization-free propagation. The high intensity of weakly diverging PFCs makes it possible to use them for long-range laser energy transfer. A wide spectrum of PFC allows multifrequency remote sounding of the atmosphere.

CONCLUSIONS

The effect of global self-focusing of femtosecond radiation of a Ti:Sapphire laser under multiple filamentation in air was first ascertained in the experiments. After reaching a global focus, the laser beam starts diverging. This pattern is qualitatively similar to the behavior of a laser beam in a nonlinear medium after its focusing. It was shown earlier [9, 10] that an initially focused laser beam diverges after self-focusing and its angular divergence exceeds its value in the linear case.

Hence, after self-focusing of collimated and focused laser beams, the angle of divergence of a beam always exceeds its initial diffraction divergence. It should be noted that this property is not distinctive only for centimeter-size beams. Calculations for millimeter and submillimeter beams also confirm a conclusion about nonlinear focal divergence. However, this concerns only the qualitative dependence of the occurrence of global angular divergence when the laser beam reaches the nonlinear focus. All other conclusions about the regularities of multiple filamentation derived from numerical calculations for millimeter-radius beams do not provide for quantitative and even (sometimes) qualitative forecast of the propagation. First, this is connected with the fact that the behavior of light structures that are generated inside a beam under multiple filamentation differs for beams with different initial beam radii.

Numerical experiments for millimeter beams do not show formation of ring light structures with the divergence much weaker than the divergence of the whole beam after the global focus. Such structures include plasma and postfilamentation channels. The experimental results of this work show a possibility of formation of structures supporting long-term existence of long PFCs in a beam with the initial diameter 2.5 cm. It is also shown that the macroring structure is not formed for all beams. It is evident that favorable conditions can be artificially produced by means of selecting optimal spatial amplitude and phase distributions of the light field at the exit from a laser system.

The experiments carried out have shown that if the conditions in a beam provide for abnormally weak angular divergence of PFCs, high mean radiation intensities are attained in the PFCs comparable in magnitude with the intensities in condensed optical media under filamentation.

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