Spatial localization of a filamentation zone along the propagation path of focused femtosecond laser radiation in air

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Results of experimental study into filamentation of a focused high-power laser beam at its self-focusing are presented. For femtosecond pulses propagating in air, it is shown that the nonlinear focus coordinate has a spatial scale $1/P$ at moderate (for self-focusing) input power P and the focal length of the optical system much shorter than the Rayleigh beam length. It is found that the presence of a liquid fine-droplet aerosol in the region of filamentation introduce no significant features in the transformation of energy characteristics of a laser beam at its strong focusing.

Introduction

The propagation of short and, correspondingly, high-power laser pulses in the atmosphere is accompanied by the effects leading to transformation of spatial and temporal characteristics of a laser beam. Among them, the laser beam filamentation is the most interesting from the viewpoint of atmospheric optics. Filamentation is formation of a high-intensity waveguide channel (filament) in the beam. A filament may have a diameter of 70–100 μm, a peak intensity $I_f = 10^{14}$ W/cm^2, and a length from several centimeters to hundreds of meters depending on the propagation conditions and laser pulse characteristics.

The problem of control for the location of the filamentation zone on the path is quite urgent in this connection. It requires the study of issues associated with the influence of the focal length of an optical system on the process of filamentation under conditions of the focusing effect of the Kerr nonlinearity, caused by nonlinearity of the electronic polarizability with relaxation times of a share of femtosecond,[1] and the defocusing effect of plasma produced upon multiphoton ionization of a medium in a high-power laser beam.

The spatial location of the filamentation zone, in particular, the position of the nonlinear focus (self-focusing length or beginning of the filamentation zone) is studied in numerous theoretical and experimental papers, starting from Ref. 2. In this paper, it was predicted for a high-intensity laser beam, propagating under conditions of the focusing Kerr effect that the focus position of the light beam F_N has the spatial scale $F_N \sim 1/\sqrt{P}$ providing its power P exceeds the critical power for the beam collapse P_{cr}. Here, F_N (nonlinear focus) is always smaller than the geometric focus. Nonlinear focus is the very important characteristic in description of propagation of high-power laser beams in nonlinear media.

Since there is no exact analytical equation for F_N, the problem is solved through numerical simulation. The instability of solution of the nonlinear Schrödinger equation for plane waves at phase self-modulation leads to the dependence $F_N \sim 1/P$, which was noted for the first time in Ref. 3. This result in different versions then served to demonstrate numerically how a small fraction of noise in the input beam, which usually takes place in practice, leads to the collapse and breakdown of the beam into many filaments.

The issues of formation and dynamics of the nonlinear focus upon the transition from single to multiple filamentation were discussed recently in Ref. 4 based on the influence of noise in the input beam on the solution of nonlinear Schrödinger equation, that is, based on the effect first noted in Ref. 3. For the collimated Gaussian beam, the numerical simulation and the experiment (from indication of burns on a movable PVC target) have shown that the position of the nonlinear focus changes from $F_N \sim 1/\sqrt{P}$ to $F_N \sim 1/P$ as a result of transition from single to multiple filamentation and depends on the initial noise in the input beam.

As is well-known, the traditional solution of the nonlinear Schrödinger equation with the Gaussian (in space and time) profile for the slowly varying complex amplitude of the electromagnetic field, which takes into account the frequency dispersion in air, instantaneous and delayed components of the Kerr effect, nonlinear absorption and refraction of radiation at the plasma, produced as a result of multiphoton ionization of a gas, does not lead to beam structure decomposition into multiple filaments[5]: a single filament is formed after the nonlinear focus. In addition, due to instability of obtained solutions and their interpretation in the region of the geometric focus F of the optical system, such problems are

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usually solved for collimated beams or for beams with the Rayleigh length L_R ($L_R = kr_0^2$ where r_0 is the initial beam radius, $k = 2\pi/\lambda$) close to the focal length of the optical system.

In Ref. 6, the empirical equation, obtained from the results of experimental investigations, allows the coordinate of the nonlinear focus to be determined with acceptable accuracy for collimated beams

$$F_{NC} = \frac{L_R}{2.725\sqrt{\left[(P/P_{cr})^{0.5} - 0.852\right]^2 - 0.022}}. \quad (1)$$

The length of the filamentation zone, in particular, the distance to the nonlinear focus, shortens, as the focusing becomes more strong.[7] For this case, Ref. 6 presents the equation allowing the position of the nonlinear focus to be determined for the focused beam:

$$F_N = \left(\frac{1}{F} + \frac{1}{F_{NC}}\right)^{-1}, \quad (2)$$

where

$$F_{NC} = 2/\left[(P/P_{cr}) - 1\right]^{0.5}.$$

It should be noted that Eq. (2) includes the beam initial power. For collimated beams or beams with $F \sim L_R$ this can provide a satisfactory agreement between theory and experiment. However, the dependence of the Kerr effect on the intensity casts some doubt upon the validity of Eqs. (1) and (2) at strong focusing $F \ll L_R$, because the intensity in this case strongly depends on the longitudinal coordinate. Thus, the question on formation of the nonlinear focus at strong focusing $F \ll L_R$ remains open.

To study the dynamics of the position of the nonlinear focus and the length of the filamentation zone of a laser beam, we used the photoacoustic method,[8] which allows the boundaries of the filamentation zone of a high-power femtosecond laser pulse in air to be determined remotely with an acceptable accuracy.

Experimental setup and measurement method

In the experimental investigations of filamentation of a focused laser beam, the source of laser pulses was represented by a laser system with a Ti:Sa crystal pumped by a Nd–YAG laser. The system generated pulses at $\lambda = 0.8$ μm, $\tau_p = 80$ fs, pulse energy $E < 15$ mJ, and pulse repetition frequency of 10 Hz. The single-pulse mode was used as well. The FWHM of the spectrum for nano- and femtosecond pulses was ~25 nm. The intensity distribution over the beam cross section was close to the Gaussian one, and the width at a level of $0.135 I_{max}$ was 8 mm.

The block diagram of the experimental setup is shown in Fig. 1.

The spatial position and length of the filamentation zone of the laser pulse propagation path, as well as the position of the nonlinear focus were determined from the acoustic response of the laser beam interaction with the propagation medium. The acoustic part of the setup included several measurement channels calibrated for the acoustic pressure with a linear frequency range 20 Hz–100 kHz. No special measures were undertaken for acoustic insulation of measuring microphones against the external noise (operating setup), which achieved acoustic pressures $P_m \sim 0.025$ Pa.

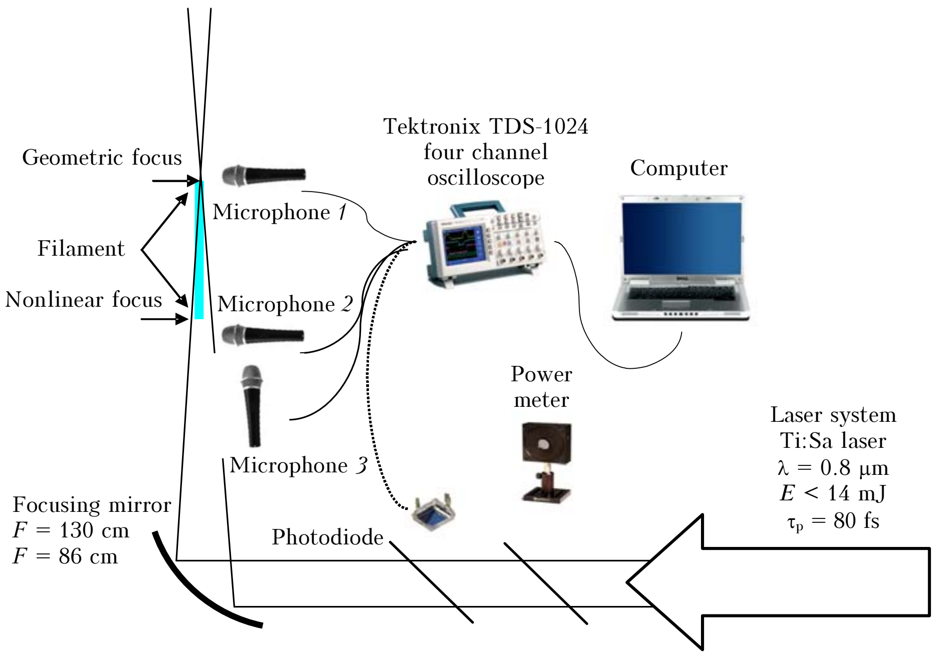

Fig. 1. Block diagram of the experiment.

For processing of weak acoustic responses with acoustic pressures lower than ~0.05 Pa, we used the software including extended tools for optimal processing of photoacoustic digital data: the compensation of frequency and phase distortions of measurement channels; the optimal band-pass filtering of useful signals against the background of acoustic noise and instrumental interference; the compensation of nonlinear, diffractive, and dissipative distortions of recorded photoacoustic signals.

Two techniques were used in the measurements. The first one assumed the use of a focusing mirror with $F = 86$ cm and the single-pulse operating mode of the laser source. It consisted in recording of an acoustic signal in the direction longitudinal relative to the filamentation zone. For this purpose, microphone *3* was set in alignment with the laser beam at a distance of 61 cm from the focusing mirror and 2 cm from the laser beam. In this case, the time scan of the acoustic signal was formed through the consecutive recording of length of signals, generated by elements of the filamentation volume, starting from the beginning of the area (nonlinear focus) to its end farthest from microphone *3* (geometric focus). The similar technique was described in Ref. 9 and used for recording of electric discharges in water.

A typical oscillogram processed by a bandpass filter is shown in Fig. 2.

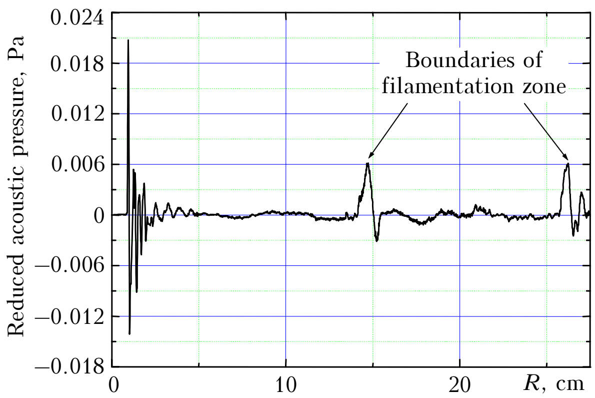

Fig. 2. Time scan of the acoustic signal generated by a laser beam and measured in the longitudinal direction. The acoustic pressure is reduced to a distance of 1 m: $P_{ac.red} = P_{ac.m}R$.

Similar oscillograms were obtained in Ref. 8, but they had a qualitative character not relating the filament length to the laser pulse energy. The first peak of the signal corresponded to the acoustic pulse generated by the laser beam just near the microphone (d = 2 cm) due to dissipation of laser energy into air thermal energy.[8] The second signal corresponded to the filament beginning, that is, to its nearest boundary to the laser source. The third peak corresponded to the filament far boundary, that is, to the filament decay region. The distance from the focusing mirror to the close and far boundaries of the filament is $R_f = 61 + tc_s$, where t is the time from the triggering the synchronizing pulse to the second or third peaks on the oscillogram; c_s is the sound speed in air.

It should be noted that according to Ref. 9, a cylindrical source of an acoustic signal (filament) emits in the direction of the cylinder base two unipolar acoustic pulses, corresponding to the near and far bases of the cylinder with respect to the detector. The first pulse is positive (compression phase), while the second one is negative (depression phase). In our case, acoustic signals of the same polarity are recorded, which is partly connected with the bandpass filtering of signals during their processing. In this case, the spatial position of the signal corresponding to the cylinder far base is stably localized near the geometric focus.

In this connection, it is worth supposing that this signal corresponds to the acoustic response from the optical breakdown plasma, formed in the geometric focus of the mirror at any initial laser pulse energy realized in this experiment due to the beam part, whose intensity is insufficient for Kerr self-focusing. A small shift of the signal position toward the source at the pulse energy increase is connected with the fact that the threshold intensity of optical breakdown determined mostly by multiphoton ionization is achieved in the larger diameter of the laser beam, that is, closer to the source.

When focusing laser radiation by a mirror with $F = 130$ cm, another technique was used to determine the filamentation zone length. The laser pulse repetition frequency was 10 Hz. Microphones *1* and *2* (see Fig. 1) were mounted perpendicularly to the laser beam at a distance of 1.5 cm from it in the areas roughly corresponding to the filament start and decay. The microphones were scanned equidistantly to the laser beam axis. The points of the filament beginning and end were determined from the sharp decrease (nearly halved) of the acoustic signal observed on the oscilloscope display, as the microphone has left the filamentation zone.

The character of changes in the acoustic response amplitude upon the transition into the filamentation zone is illustrated in Fig. 3, which was obtained for a focusing mirror with $F = 130$ cm and the laser source operating in the single-pulse mode.

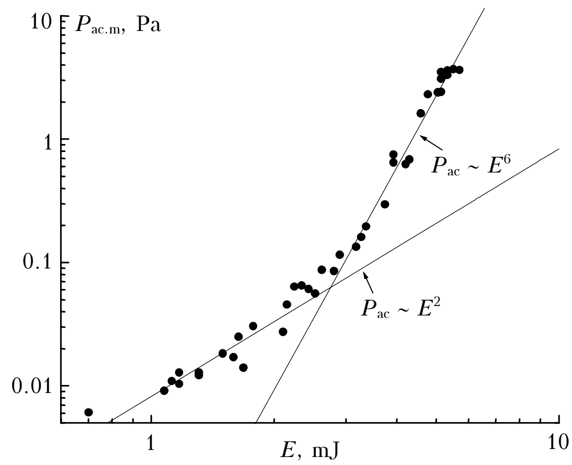

Fig. 3. Peak acoustic pressure as a function of the laser pulse energy.

Microphone *2* was 118 cm far from the focusing mirror and 1.5 cm far from the laser beam axis. One can see that as the laser pulse achieves the energy $E \sim 3$ mJ, that is, the filamentation zone achieves the place, where the microphone is installed, the dependence of the peak acoustic pressure in the received signal alternated the form from the square, characteristic of the rotational mechanism of laser energy dissipation into the internal kinetic energy of a medium,[10] to the power one with the exponent 6 characteristic of air multiphoton ionization. It should be noted that the threshold energy of the filament formation at the geometric focus in our experiment was ~ 1 mJ.

Experimental results and discussion

The distances from the focusing mirror to the filament beginning and end R_f as functions of the input beam energy E obtained with the use of the first measurement technique are shown in Fig. 4 as curves *3* and *4*, respectively.

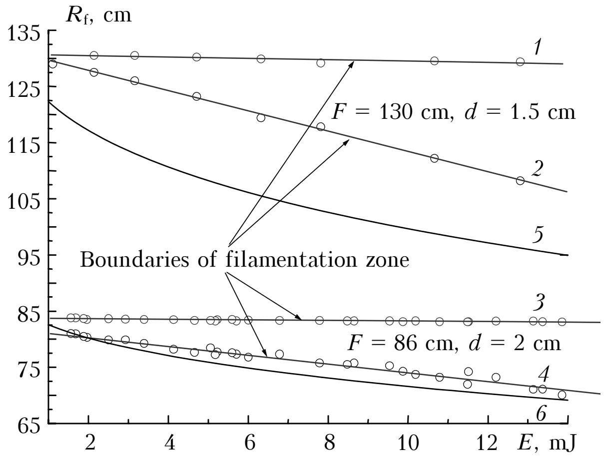

Fig. 4. Positions of the beginning (*2, 4*) and end (*1, 3*) of the filamentation zone for two focusing mirrors as functions of the input beam energy; (*5, 6*) theoretical dependences.

The dependences $R_f(E)$ represented by curves *1* and *2* in Fig. 4 were obtained with the use of the dependence $P_{ac.m}(E)$ shown in Fig. 3 and the second measurement technique.

It follows from Fig. 4 that as the pulse energy increases, starting from $E \sim 1$ mJ, the beginning of the filament approaches the focusing mirror (moves off from the mirror linear focus), that is, with the increase of radiation energy or intensity, the nonlinear focusing of radiation begins to contribute significantly. In this case, the position of the far (with respect to the mirror) boundary of the filament remains nearly unchanged. The near (with respect to the focusing mirror) boundary of the filament in the energy range $E = 1$–14 mJ becomes closer to the mirror with F = 130 cm roughly by 24 cm and to the mirror with F = 86 cm roughly by 11 cm.

Figure 4 shows that in the energy range of the laser pulse, starting from the threshold energy for filamentation to the maximal value of 14 mJ, achieved in the experiment, the filament length increases linearly for focusing mirrors with $F = 86$ and 130 cm. Curves *5* and *6* in Fig. 4 were calculated according to Eq. (1).

The experimental investigations of the femtosecond laser pulse propagation in water aerosol[8] have shown that the attenuation of the pulse energy by an aerosol layer is close to the Bouguer law with almost linear extinction coefficient and that the aerosol medium is capable not only to decrease the energy of a femtosecond pulse, but also to increase its length due to dispersion in water particles. The pulse power decreases, and according to Eq. (1) this should affect the regime of self-focusing and the length of the filamentation zone.

To study the effect of these mechanisms, the specialized experiment with monodisperse water aerosol was conducted. Particles of a radius of 2.5 μm and the particle number concentration $N \sim 10^5$–10^7 cm^{-3} in the form of a flow of 1.3 cm thick were injected in the laser beam between the focusing mirror and the filamentation zone. The comparison of the obtained dependence of the length of the filamentation zone on the aerosol number concentration (signs in Fig. 5) with the dependence (curves) calculated taking into account the energy extinction of radiation,[8] as well as the dependences of the filament length shown in Fig. 4, allows us to make the following conclusion. For conditions of the experiment, distortions introduced by the water aerosol into the temporal and spatial characteristics of the laser pulse are insignificant or absent, because they do not lead to changes in the filamentation process.

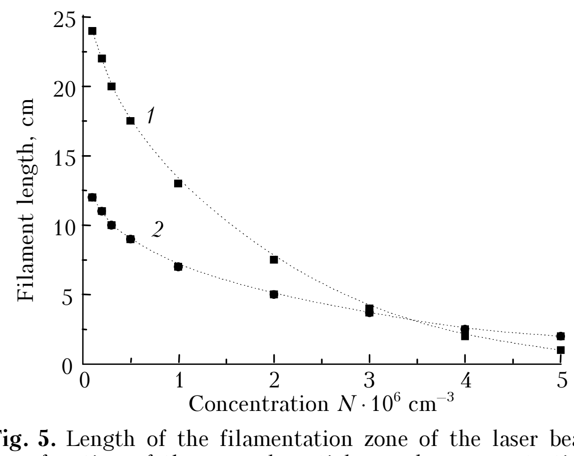

Fig. 5. Length of the filamentation zone of the laser beam as a function of the aerosol particle number concentration: (curves) calculation from the data on energy extinction[8] and curves *1–4* in Fig. 4 at the pulse energy E = 15 mJ; F = 130 cm (*1*) and 86 cm (*2*).

Conclusions

It has been shown experimentally that at the strong focusing of a laser pulse of the femtosecond length the increase in the initial pulse energy leads to the nonlinear focus shift from the geometric focus toward the source in direct proportion to the increase in the initial pulse energy. Monodisperse water aerosol introduces no significant features into transformation of the laser beam at its spatial focusing, which allows us to recommend to use this aerosol as a linear neutral attenuator when controlling the position of the nonlinear focus and the spatial position of the filamentation zone.

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