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OPTICAL INSTRUMENTATION

Filamentation of Terawatt Laser Pulses along Hundred-Meter Atmospheric Paths

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Abstract—Results of the experimental study of filamentation of terawatt femtosecond pulses of a Ti:Sapphire laser along an atmospheric path 106 m long using different spatial focusing and pulse power are presented. The control of filamentation region position and length by means of changing the initial laser beam focusing is shown to be highly effective. Dependencies are derived of filamentation region position and length on the initial degree of focusing, pulse power, and the number of filaments along the filamentation region. The obtained data on the filamentation region length and the number of filaments are compared with the results of our previous experiments and data from other authors.

Keywords: laser radiation, filamentation, femtosecond pulse, liquid, spectrum

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INTRODUCTION

Formation of a region of multiple filamentation at a preset distance (hundreds and thousands meters) from a source is an urgent problem for femtosecond atmospheric optics, including both sensing tasks and transmission of light fields of extremely high intensities. To control the filamentation region (FR) position, there are several main methods: variation in the laser pulse power, spatial and temporal focusing, variation in the initial transverse profile of beam intensity, including adaptive control [1].

In this work, we consider results of the experimental study of spatial parameters of a multiple filamentation region along a 100-m path controllable throughout the whole length, when the FR position and length are controlled with the use of variable initial spatial focusing and a change in the pulse energy. The experimental layout is shown in Fig. 1. A mirror Galilean telescope is used as a focusing element.

Figure 1a shows the filamentation of a femtosecond pulse along the path. A glow is in the red spectral range. A black-and-white photograph of rings on the screen at the path end is shown in Fig. 1b. On the screen, the ring color changes from red in the beam center to blue at the beam periphery, which points to the filamentation along the path. Figure 1c shows scorches on the photosensitive paper after the filaments.

FR measurement results are shown in Figs. 2 and 3 for the cases of controlling the distance to the filamentation beginning using the initial spatial focusing (Fig. 2) and pulse energy (Fig. 3). It is seen than an increase in the telescope base within a range of several centimeters (sharper focus) allows moving the filamentation beginning and the FR along the whole 100-m path. Varying the pulse energy and, hence, the power, we can vary the FR position; however, an increase in the source–FR space is accompanied by a significant increase in the number of filaments in this case (Fig. 4). Figure 3 also shows the dependence of the filamentation beginning distance calculated by the Marburger equation [2] for nonlinear focusing:

$$F_n = 0.734 L_R \left[(\eta^{1/2} - 0.852)^2 - 0.0219\right]^{-1/2},$$

where $L_R = \pi r_0^2/\lambda$ is the Rayleigh length, r_0 is the beam radius; $\eta = P_0/P_{cr}$ is the dimensionless pulse power, P_0 is the pulse power, $P_{cr} = 3.77\lambda^2/8\pi n_0 n_2$ is the self-focusing critical power ($P_{cr} = 3.2$ GW for air and $\lambda = 800$ nm), n_0 is the refractive index of the medium, and n_2 is the nonlinear refractive index.

It is seen that experimental and calculated values agree well in the region of low pulse energies (powers), where the number of filaments in a beam is small. As the power increases, that is, under multiple filamentation, the coordinates of filamentation beginning measured are significantly smaller than the calculated ones, i.e., filaments are formed earlier than is forecast

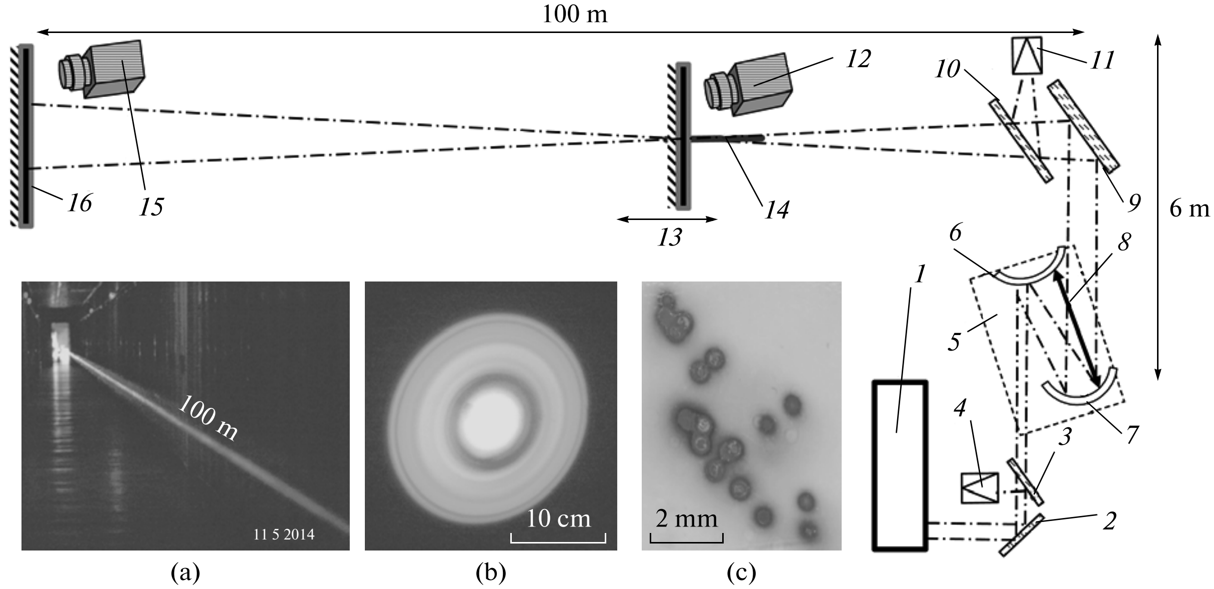

Fig. 1. Experimental layout: Ti:Sapphire laser (*1*) (pulse length $t = 30$ fs, pulse energy $E < 80$ mJ, $P < 2.5$ TW, wavelength $\lambda = 800$ nm, pulse frequency $\nu = 10$ Hz, beam diameter at the level e^{-2} $d = 2.5$ cm (after telescope $d = 5$ cm); rotating plates (*2*, *3*, *9*, and *10*), pulse length meter (*4*) (autocorrelator), Galilean telescope (*5*), defocusing mirror $F_1 = -50$ cm (*6*), focusing mirror $F_2 = 100$ cm (*7*), variable telescope base (inter-mirror space $b = 50$ cm corresponds to a collimated beam) (*8*), OPHIR-II pulse power meter (*11*), CCD arrays, photo cameras, and video cameras (*12* and *15*), movable screen for recording the FR position (*13*), FR (*14*), fixed screen at the path end (*16*); (a) laser beam along the path (filamentation at the beginning of the path); (b) beam structure on the screen at the path end; (c) small-scale beam structure on the movable screen in the FR along the path (in the heterochromatic structure center).

by a model. This might well be connected with the fact that the Marburger equation is not applicable to the whole beam, but for some its regions where a single filament is formed.

Measurements of the number of filaments in a laser beam cross-section have shown that it is inhomogeneous along the FR length. There are several filaments at the beginning of the FR, the number increases up to about two tens to the FR center, and then decreases again (see Fig. 4).

The dependence of the maximal number of filaments on the relative pulse power is shown in Fig. 5. The increase in the number of filaments in a beam observed agrees with our previous data [3, 4] and data from other authors [5–7].

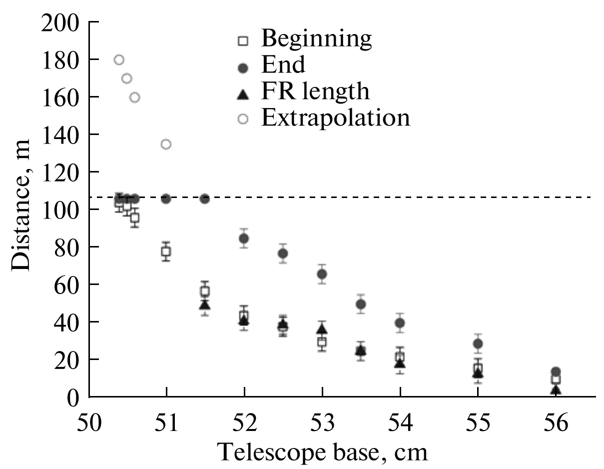

Fig. 2. Coordinates of the FR beginning, end, and length versus the telescope base (telescope focal length).

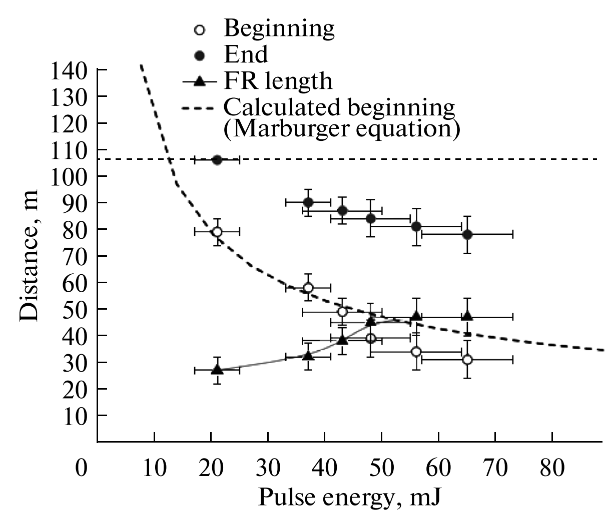

Fig. 3. Coordinates of the FR beginning, end, and length of a collimated beam versus the laser pulse energy.

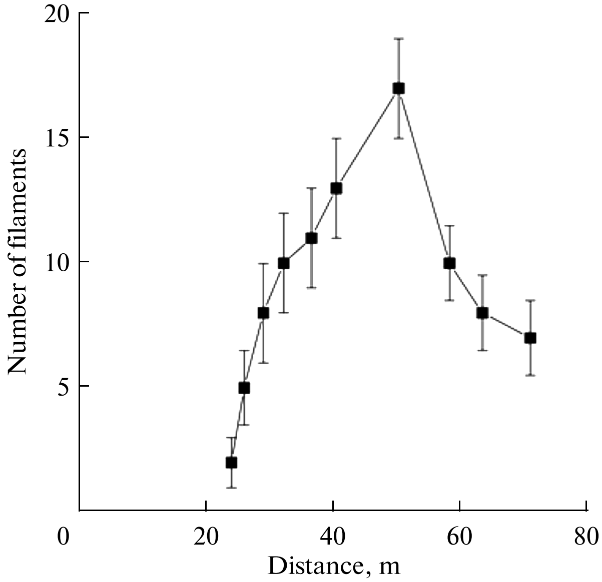

Fig. 4. Number of filaments in a beam cross-section along the atmospheric path for a collimated beam with pulse energy of 82 mJ.

Analyzing the results of this work and our previous data [8–11] on the FR length, one can see (Fig. 6) that sharper focusing results in FR shortening. An increase in the pulse power at a preset numerical aperture of the beam ($NA = r_0/F$, where F is the length of the geometrical beam) results in an increase in the FR length.

Thus, the results of the experiments performed show the efficiency of the control of the position of a multiple filamentation region several tens of meters long when using the initial spatial beam focusing along 100-m atmospheric paths with tens of filaments in a beam cross-section, localized at centimeter areas.

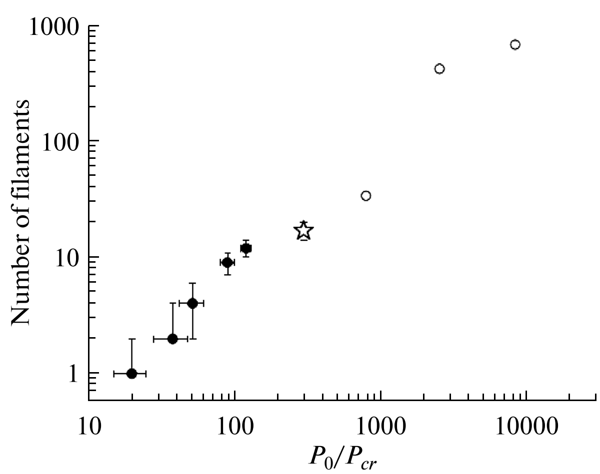

Fig. 5. Number of filaments versus the relative pulse power. Dots correspond to data [3, 4], empty circles, to data [5–7], and the asterisk shows data of this work.

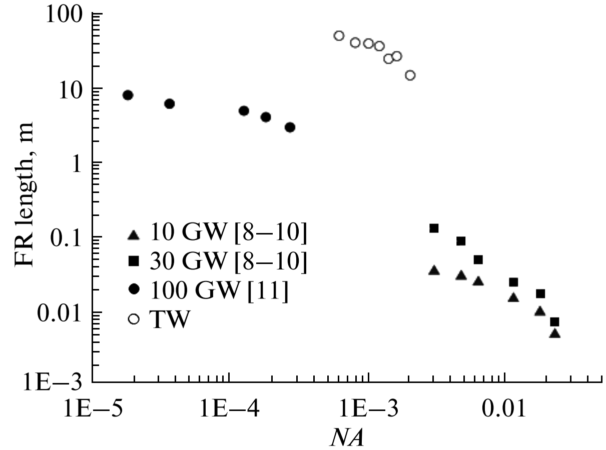

Fig. 6. Experimental data from works [8–11] and this work (empty circles) on the length of the multiple filamentation region in air versus the numerical beam aperture for different pulse power.

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