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Macroscopic model of formation of the domain of multiple filamentation in glass and water

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ABSTRACT

The results of natural experiments of the propagation of powerful femtosecond laser radiation in glass and water, accompanied by multiple filamentation, and the results of numerical simulation of the process are presented. Based on the diffusive equations for density of the number of filament estimates of the positions of maxima in the number of filaments were obtained. Sufficient criterion of macroscopic refocusing for density of the number of filaments was established.

Keywords: multiple filamentation, femtosecond laser radiation

1. INTRODUCTION

The results of natural experiments of the propagation of powerful femtosecond laser radiation in glass and water, accompanied by multiple filamentation, and the results of numerical simulation of the process are presented. The purpose of these experiments was to find regularities of multiple filaments along a propagation path. These experimental results are the basis for refinement and development of our theoretical models of multiple filamentation. The first comparison of the results of natural experiment with the results of numerical simulation indicates only the possibility of accordance. However, because of the ambiguity of the theoretical values of the parameters of nonlinearity of the medium, it is necessary to vary these parameters in order to approach the experimental results, and it is shown in this work. Thus, when numerical simulations of the process provide qualitative results, we propose a simple semi-empirical model of the process, which has a simple physical meaning and allows reproducing the experimental results with enough precision at substantially lower expenses.

2. EXPERIMENTAL RESULTS

Multiple filamentation is the process of contraction of a laser beam into filaments distributed in the transverse and longitudinal cross section of the beam during propagation and self-focusing of laser radiation in a medium with cubic nonlinearity, when the power of a pulse is significantly higher (~ 10^3-10^5) than the critical power of self-focusing P_{cr}[1,2]. Researching of this phenomenon on atmospheric paths is heavy because it is difficult to visualize individual channels (they are thin ~ 0.1 mm and long ~ 10 m) in the air. Moreover, multiterawatt laser sources are not yet a common experimental tool. Thus, experiments to study multiple filamentation of powerful laser pulses of the basic harmonic of Ti:Sapphire laser in a medium with a strong Kerr nonlinearity in the glass and water were conducted. The critical power of self-focusing in water $P_{cr} \sim 10^6$ W is power in water is three orders of magnitude lower than in air. The purpose of the experiments was to establish qualitative patterns in the evolution of the spatial characteristics of the domain of multiple filamentation (DMF) depending on the laser pulse parameters and to obtain quantitative relationships between the characteristics of the DMF (coordinate of the start, length, number of filaments, the distribution of filaments along the DMF, size of filaments) and the characteristics of the laser pulse (energy, power, diameter of the beam).

Figures 1 and 2 show qualitative pictures of filamentation of laser radiation. It is seen that with increasing the initial power of laser pulse the DMF approaches to the source and the number of filaments increases. When the power of laser pulse reaches ~ 10^{11} W, the DMF takes the form of a hollow cone, the vertex of which is directed to the source of laser radiation. This circumstance is clearly seen in Fig.2, where the beam was restricted to a vertical slot. Figure 2 also illustrates that the second peak of filamentation can be realized after the first peak of filamentation in achieving specific value of energy. Figure 1 shows that the filamentation in water and filamentation in the glass have the same a qualitative character.

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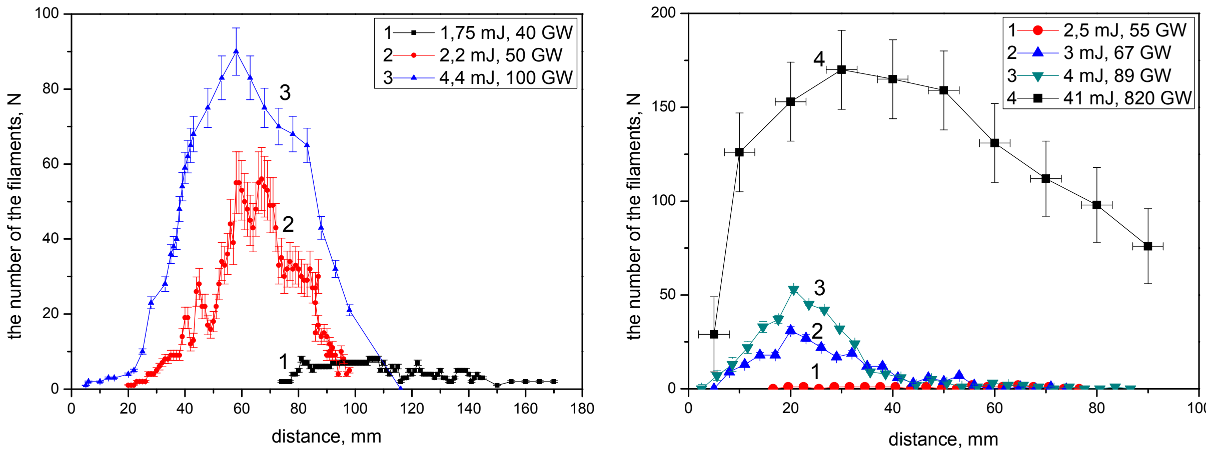

a) b)

Fig.1. Distribution of the number of the filaments inside of filamentation domain in water (a) and in glass (b).

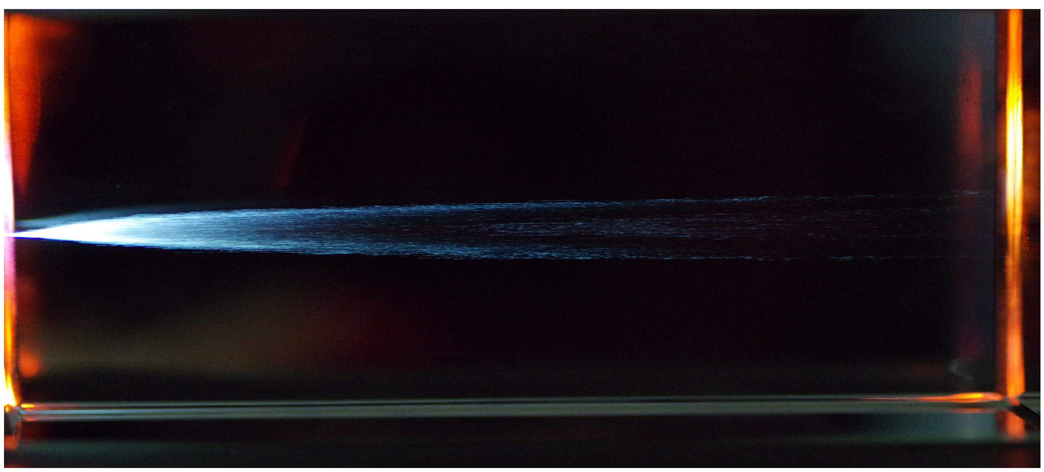

Fig.2. Dependence of the number of filaments in the cross section of the plasma channel at different distances from the laser source in glass.

Modeling filamentation based on direct numerical solution of non-stationary nonlinear Schrödinger equation can provide a qualitative assessment of situation with a relatively small number of filaments (10-100) and beam size of the order of 1-2 mm. Transition to an effective stationary scheme[3,4] will significantly reduce restrictions on the size of the beam and its power. It should be noted that within this description it is not possible to reproduce the V-shaped structure observed in the experiment. Our numerical experiments show that for reproduce of the structure, it is necessary, for example, to increase several times the absorption coefficient.

The set of the problems arising in numerical simulations does especially important the development of analytical methods based on the macroscopic approach suggested by the authors[3,4]. This approach assists to explain the observed experimental data.

3. MACROSCOPIC DESCRIPTION OF FILAMENTATION

For qualitative analysis, we write the equation for the density of the number of filaments in the approximation of a given macroscopic field of intensity:

$$\frac{\partial}{\partial z} n_f(\boldsymbol{r}_\perp, z) = -\Gamma n_f + C(\bar{I}) n_f^{\,3/2} - B n_f^{\,2} + F_{out}(z)\,. \qquad (1)$$

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Here Γ - "speed" of disintegration of filament, i.e. an inverse value to length of filament, leaving about 4-6 m for air; $C(\overline{I}) = C_0 + C_1\overline{I}$ - the coefficient which is responsible for reproduction of filament at the expense of an interference of rings from filament including at the expense of an interference with a background field (coefficient $C_1\overline{I}$); and at last the coefficient B is providing existence of final decisions (1) for any $\overline{I}$ and corresponding to effects of saturation[4]; the non-uniform composed $F_{out}(z)$ is responsible for external mechanisms of excitement of system, such as: entry conditions and turbulence of the environment.

Let us make a comment about the relaxation coefficient $\Gamma \sim 1/l_f$. Numerical simulations show that filamentation length increases with increasing radius of the disturbance from which it has developed[5].

In the first approximation, this dependence can be expressed as:

$$l_f = \sqrt{l_0 + l_1 \cdot \rho}\,.$$

According to the instability theory of Bespalov and Talanov, the most effective developing mode has the scale:

$$\rho(R) = \sqrt{\frac{P_f}{\pi \overline{I}_0(R)}}\,.$$

This mechanism is one possible reason determining the dependence of Γ on R, giving the experimental V-shaped structure. Another possible mechanism that leads to this result is the dependence of Γ on n_f and on the degree of coherence of the light field. It should be noted also that V-shaped structure can be formed due to deformation of the macroscopic profile of intensity. In either event, the true mechanism of the formation of this structure will only be determined later. The dependence of Γ on R can be extrapolated by function $\Gamma = \Gamma_0(1+\Gamma_1 \cdot R^2)^{-1}$. The value Γ_0 and Γ_1 are selected to be equal to $2\cdot 10^2 m^{-1}$ and $1.6\cdot 10^5 m^{-2}$.

The most uncertain element in this structure is to define a source function. It is possible to construct this function in an explicit form on the following assumptions: all disturbances develop independently and have a gaussian appearance, and, accordingly, they will develop only if they have power exceeding the critical power of self-focusing. According to these assumptions, the source function takes the form:

$$F_{out}(z,R) = \frac{\partial}{\partial z}\int_s \theta(z - z_m(s,\overline{I}(R)))\overline{I}(R)w(s)ds / P_f = w(\overline{s}_m(I(R),z))\overline{I}(R)/P_f\ , \tag{2}$$

where $w(s)$ is a function of the distribution scale (squares) disturbances have been given to the example of the Rayleigh distribution; $P_f \approx 2\pi \cdot P_{cr}$ - is power in one filament[2].

Then we look for a solution in the form

$$n_f = n_f{}^0 + \delta n_f\,, \tag{3}$$

where the nonlinear correction is considered:

$$\delta n_f << n_f^0\,,$$

and $n_f{}^0$ is the solution of the equation $\frac{\partial}{\partial z} n_f{}^0(\boldsymbol{r}_\perp, z) = -\Gamma n_f{}^0 + F_{out}(z,\boldsymbol{r}_\perp)$. That is:

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$$n_f{}^0 = \int_0^z e^{-\Gamma(z-z')} F_{out}(z', \boldsymbol{r}_\perp) dz' \,. \tag{4}$$

We find the nonlinear correction

$$\frac{\partial}{\partial z}\delta n_f(\boldsymbol{r}_\perp, z) = \left(-\Gamma + \frac{3}{2}C(\overline{I})\sqrt{n_f{}^0} - 2Bn_f{}^0\right)\delta n_f + C(\overline{I})\left(n_f{}^0\right)^{3/2} - B(n_f{}^0)^2 \,.$$

Suppose that the following conditions are performed:

$$\Gamma > (\frac{3}{2}C(\overline{I})\sqrt{n_f{}^0} - 2Bn_f{}^0); \quad \frac{3}{2}C(\overline{I})\sqrt{n_f{}^0} >> 2Bn_f{}^0 \,.$$

Find finally:

$$\delta n_f = \int_0^z e^{-\int_{z'}^{z}\Gamma_c(t)dt} C(\overline{I})\left(n_f{}^0\right)^{3/2} dz'$$

where Γ_C is the coefficient of relaxation, taking into account of corrections for the effect of reproduction.

$$\Gamma_C = \Gamma - \frac{3}{2}C(\overline{I})\sqrt{n_f{}^0} \,.$$

The last relationship shows that maximum δn_f should be moved along the propagation distance as compared with the maximum $n_f{}^0$. Function C includes two phenomenological constants C_0 and C_1, and they will determine the form of the deformation function of the coordinates of the filamentation maximum. In particular, the experimental results for two observed maximums may be reproduced at certain combinations of the values of these constants. Figure 3 illustrates implementation of the first nonlinear correction.

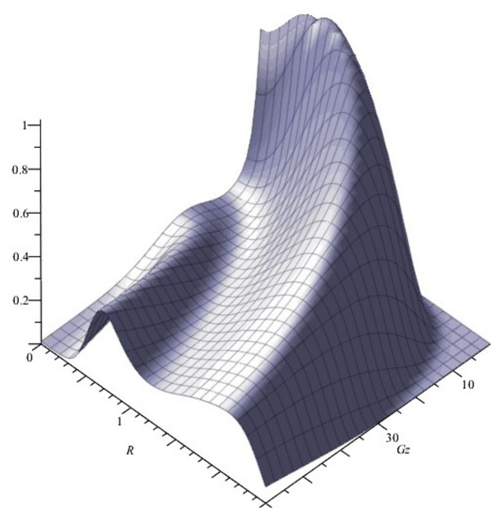

Fig.3. Normalized to its maximum value the distribution of density of the number of filaments along the dimensionless distance and the beam radius.

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4. CONCLUSION

The standard model of plasma in condensed matter poorly reproduces the high-energy regime of filamentation. The increase in the absorption coefficient allows to correct the situation. A simple phenomenological model based on the macroscopic description of the process of filamentary with using the assumption of the decisive factor of the initial perturbations in the formation of the picture, allows to reproduce qualitatively the experimental results. It is shown that consideration of the effect of interaction allows to describe the experiment results (in contrast to the situation without considering this effect) even if the source of initial perturbations is spatially uniform. This property is observed in the experiment with water, refers to the implementation of the effect of propagation of the filaments in a condensed medium upon reaching sufficient power of laser radiation.

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REFERENCES

[1] Kasparian, J., Wolf, J.-P. “Physics and applications of atmospheric nonlinear optics and filamentation,” Optics Express, 16(1), 466–493, (2001).
[2] Boyd, R. W., Lukishova, S. G., Shen, Y. R. [Self-focusing: Past and Present], Springer, New York, 605, (2009).
[3] Bulygin, A. D. “The density number of filaments in the state of the weak and optical turbulence,” arXiv:1208.3916, (2012).
[4] Bulygin, A. D. “The kinetic equation for filament density, formed during propagation of femtosecond laser radiation, in the approximation of self-consistent field,” arXiv:1306.5329v3, (2014).
[5] Geints, Yu. E., Zemlyanov, A. A. “Filamentation of high-power ulta-short laser radiation. Size factor of light beam,” Atmospheric and oceanic optics, 26(1), 11-17, (2013).

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