INTRODUCTION

A high-power femtosecond laser pulse transforms in a complicated spatio–temporal way while propagating in the atmosphere; in this case, the energy is localized in its axial area, forming a filament. The filamentation occurs at a peak pulse power exceeding the critical power of the Kerr self-focusing of the laser radiation in the air. The increase in the energy intensity and density in a filament on the pulse axis due to Kerr self-focusing is restricted by defocusing in the laser-induced plasma caused by photoionization of the nitrogen and oxygen molecules of air. The dynamic balance between the Kerr self-focusing and defocusing in the laser-induced plasma results in formation of fine (about 100 μm) long (up to 100 m) filaments with highly concentrated laser energy and plasma channels in the atmosphere. In the filamentation, a spatial mode close to the Townes one, being a stationary solution of the beam self-focusing equation [1, 2], is evolved in the axial area of the focusing time layers of the pulse.

A long filament exists due to an background energy reservoir [3]. A permanent energy exchange occurs in the plane of its cross-section between the axial area with a high intensity and the periphery with a low density of power. Refocusing occurs in pulses with a power 5–10 times higher than the critical power of the self-focusing. In this case, the plasma-defocused radiation again collapses to the axis due to the Kerr self-focusing in the time layers at the tail of the pulse, and the Townes mode is re-evolved. As a result, the fluence on the pulse axis grows, and the deficiency in energy is dynamically compensated in the filament.

Filamentation is accompanied by a number of effects, which are of applied relevance in atmospheric optics systems. Wideband radiation of the supercontinuum generated in nonlinear pulse transformation is used in femtosecond lidars for air sensing [4, 5]. The high intensity and fluence on the filament axis allows one to obtain optical breakdown plasma and fluorescence signal on targets at distance of up to kilometers [6].

The atmosphere is a complex multicomponent medium, the properties of which can substantially affect the character of the laser pulse filamentation when propagating in air. Turbulence results in fluctuations of the refractive index disturbing the phase of the light field of the pulse and initiating multiple filamentation.

Experimental and numerical investigations of filament interactions with individual aerosol particles [7–9] have shown that a droplet that overlaps the axial area of a laser pulse does not fatally prevent the occurrence of a filament. The radiation at the periphery of the pulse cross-section misses the droplet, and the energy flows to the pulse axis, thus maintaining the filament recovery after the droplet.

Filament attenuation in a medium with a high concentration of aerosol droplets (10^5 cm^-3) was studied experimentally in [7, 10, 11]. Theoretical models, representing a medium with scattering particles as a cloud of absorbing discs [11] or a linearly absorbing layer, describe the decrement in the filament energy in an aerosol in comparison with propagation in an unclouded medium.
Accounting for amplitude-phase perturbations due to scattering shows that the scattering by aerosol particles results in not only a decrease in the pulse power but also in the origination of intensity fluctuations initiating the multiple filamentation, which can predominate over the attenuation [13]. The substitution of a scattering nonlinear medium for a solid one with an attenuation coefficient matching the aerosol parameters is not equivalent for studying filament transformation into a disperse medium and after it [14].

In this work, the refocusing of a high-power femtosecond laser pulse after filamentation in a layer of atmospheric aerosol is numerically studied. The influence of scattering on this nonlinear effect accompanying the filamentation has not been previously considered in the literature.

STATEMENT OF THE PROBLEM

Consider a high-power femtosecond laser pulse incident on an aqueous aerosol layer, where the formation of a filament is completed. The filament originates on the femtosecond laser pulse axis without any initial perturbations of the light field on the laser system exit aperture in an unclouded air medium without turbulence. A growth of fluence in the filament, which is maximal at its start point, changes to its decrement caused by radiation defocusing in the laser-induced plasma. The process of energy redistribution in the pulse cross-section during the filamentation occurs under conditions of multiple scattering of the light field by aerosol particles. Radiation attenuation and amplitude-phase perturbations of the light field caused by scattering in the aerosol layer influence the pulse refocusing. The pulse energy decreases significantly, but pulse refocusing occurs after the aerosol layer at a certain range of the parameters (Fig. 1).

Let the femtosecond laser pulse be of the Gaussian shape, the cross-section intensity distribution be Gaussian, and the wave front be planar. The central wavelength of a laser pulse \( \lambda = 0.8 \, \mu m \); the \( e^{-1} \)-width is \( \tau_p = 280 \, fs \); the radius of the initial beam \( a_0 = 1.5 \, mm \); the energy \( W_0 = 5 \, mJ \); and the peak intensity \( I_0 = 2.8 \times 10^{11} \, W/cm^2 \), which corresponds to a peak power of \( P_0 = 20 \, GW \). The peak power \( P_0 = 5P_{cr} \) at the critical power of self-focusing in air \( P_{cr} = 4 \, GW \).

We considered an aerosol layer of the fixed height \( L_a = 0.5 \, m \); the water particle concentration varies within the interval \( N_a = 1600–3500 \, cm^{-3} \). We suppose the aerosol to be monodisperse with a particle radius \( R_a = 10 \, \mu m \).

FORMULATION OF THE PROBLEM

The analysis was carried out using the slowly varying amplitude method, which is valid for pulses of several periods of optical vibrations in duration [15]. The model does not consider group velocity dispersion. As has been shown by estimation, the dispersion length in air is significantly longer for the considered pulse than the self-action length [16]. According to the accepted approximation, the stochastic equation for the complex field amplitude \( E(x, y, z, t) \) is written as

\[
2ik\frac{\partial E}{\partial z} = \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{2k^2}{n_0} \Delta n E - ik\alpha_{ion}E + \hat{D}_a E,
\]

where \( k \) is the wave number corresponding to the wavelength \( \lambda = 800 \, nm \), \( n_0 \) is the refractive index of air, and \( \hat{D}_a \) is the functional describing the light field stochasticization due to the coherent scattering by aerosol particles and is set to be zero out of the layer. The increment of refractive index \( \Delta n \) is defined by the Kerr nonlinearity \( \Delta n_{kerr} \) and the contribution of the laser-induced plasma \( \Delta n_{pl} \):

\[
\Delta n = \Delta n_{kerr} + \Delta n_{pl},
\]

\[
\Delta n_{kerr} = \frac{1}{2}n_2|E|^2; \quad \Delta n_{pl} = \frac{e^2N_e(x, y, z, t)}{\varepsilon_0m_e\omega^2},
\]

where \( n_2 \) is the coefficient of the Kerr nonlinearity of gas components of the air medium; \( m_e \) and \( e \) are the electron mass and charge, respectively; \( N_e(x, y, z, t) \) is the electron concentration, and \( \omega \) is the central pulse frequency.

Equation (10) does not take into account the influence of the nonlinear response delay caused by the stimulated scattering on the rotational transitions of nitrogen and oxygen molecules. This delay results in an increasing distance to the filament start for the initial filamentation stage, which can be accounted for by introducing the effective nonlinearity factor \( n_{2eff} \) [17].

The coefficient \( \alpha_{ion} \) describes the loss at multiphoton ionization:

\[
\alpha_{ion} = \frac{m\hbar\omega}{I(x, y, z; t)} \frac{\partial N_e(x, y, z; t)}{\partial t}.
\]

Here \( I(x, y, z; t) = \frac{c_0n_2\varepsilon_0}{2}|E(x, y, z, t)|^2 \) is the radiation intensity and \( \varepsilon_0 \) is the electric constant. The numbers \( m = 8 \) for oxygen and \( m = 10 \) for nitrogen determine