INTERACTION OF LASER RADIATION WITH MATTER. LASER PLASMA

PACS numbers: 52.58. – r; 42.65.Re; 42.79.Bh
DOI: 10.1070/QE2005v035n11ABEH013031

Formation of extended plasma channels in a condensed medium upon axicon focusing of a femtosecond laser pulse

O.G. Kosareva, A.V. Grigor'evskii, V.P. Kandidov

Abstract. **The formation of plasma channels of a femtosecond laser pulse in the bulk of fused silica is studied by numerical simulation, and the advantages of using a conical lens (axicon) over conventional parabolic lenses are shown. It is found that the length of the plasma channel formed with the help of an axicon exceeds the length of the channel formed upon lens focusing.**

Keywords: *axicon, filamentation, femtosecond pulses.*

1. Femtosecond laser pulses with a high peak power offer a promising means of developing microoptics elements in the bulk of a transparent medium [1 – 4]. When a pulse of energy 0.1 – 10 mJ and duration 50 – 100 fs is focused into the sample, the peak intensity achieves $10^{12} - 10^{13}$ W cm^{-2}, which leads to a multiphoton transition of electrons from the valence band to the conduction band. After the passage of the pulse, the electrons return to the valence band, causing local heating and optical modification of the material [2].

The possibility of developing optical waveguides in the bulk of fused silica with the help of femtosecond laser pulses was shown in [1]. The authors of [3] found that the key factor in waveguide recording is the radiation focusing condition in the sample. After the passage of a pulse focused by a long-focus lens, the molten material in the region of the laser plasma self-induced by the pulse passes into the solid state, forming a region with a uniformly increased refractive index ($\Delta n \approx 10^{-4} - 10^{-2}$) of transverse size 1 – 2 μm and a length of several millimetres. The use of a short-focus lens leads to an increase in the number of free electrons in the bulk of the sample, to a local destruction of the material during plasma relaxation, and to a deterioration of the waveguide quality. Thus, the geometry of the experiment is one of the decisive factors facilitating the modification of the material in a preset form.

An increase in the length of optical waveguides in the bulk of transparent solids is provided by displacing the sample at a laser pulse repetition rate of 1 kHz. The recording time can be shortened by increasing the length of the channel formed in a single laser pulse.

O.G. Kosareva, A.V. Grigor'evskii, V.P. Kandidov Department of Physics, M.V. Lomonosov Moscow State University, Vorob'evy gory, 119992 Moscow, Russia; e-mail: alexandergrig@mail.ru

Received 29 September 2005
Kvantovaya Elektronika **35** (11) 1013 – 1014 (2005)
Translated by Ram Wadhwa

An axicon was used in the experimental work [4] for increasing the length of the nonlinear optical interaction while focusing femtosecond subterawatt radiation into a transparent dielectric target. It can be expected that the length of the plasma channel in a single pulse will increase upon axicon focusing, and hence the rate and quality of recording of optical waveguides will also improve.

This study aims at an analysis of the control over a femtosecond laser pulse channel in fused silica by varying the wavefront of the input beam with the help of lenses of various focal lengths and an axicon. Investigations were carried out by numerical simulation.

2. Numerical simulation is based on the quasi-optics equation for a slowly varying electric field amplitude:

$$2ik\frac{\partial E(z,r,t)}{\partial z} = \Delta_{\perp}E - kk''_{\omega}\frac{\partial^2 E}{\partial \tau^2} + \frac{2k^2}{n_0}(\Delta n_k + \Delta n_{\rm p})E - ik\alpha E, \qquad (1)$$

where

$$\Delta n_k = \frac{1}{2}n_2|E|^2;$$

$$\Delta n_{\rm p} = -\frac{\omega_{\rm p}^2}{2n_0(\omega_{\rm las}^2 + v_{\rm c}^2)}\left(1 + {\rm i}\frac{v_{\rm c}}{\omega_{\rm las}}\frac{\omega_{\rm p}^2}{\omega_{\rm las}^2 + v_{\rm c}^2}\right); \qquad (2)$$

$$\omega_{\rm p}^2 = \frac{4\pi e^2 N_{\rm e}}{m\omega^2}.$$

The first and second terms on the right-hand side of Eqn (1) describe the diffraction and dispersion of input radiation in fused silica respectively ($\tau = t - z/v_{\rm gr}$ is the running time), while the third term described the Kerr self-focusing and defocusing in self-induced laser plasma. The fourth term accounts for the loss of energy due to multiphoton transition of electrons from the valence band to the conduction band. Here, α is the attenuation factor associated with ionisation, $\omega_{\rm p}$ is the plasma frequency, $v_{\rm c}$ is the frequency of elastic collisions of electrons with atoms, and $\omega_{\rm las}$ is the laser frequency corresponding to a wavelength $\lambda = 800$ nm. The rate of increase in the number of free electrons in fused silica can be described by the equation

$$\frac{\partial N_{\rm e}}{\partial t} = R\big(|E|^2\big)(N_0 - N_{\rm e}) + v_{\rm i}N_{\rm e} - \beta N_{\rm e}^2. \qquad (3)$$

The first term on the right-hand side of this equation describes multiphoton ionisation according to the Keldysh model, the second terms describes the impact ionisation, while the third term corresponds to recombination of electrons in triple collisions; $N_0 = 2.1 \times 10^{22}$ cm^{-3} is the density of neutral molecules before the passage of a pulse. The impact ionisation frequency is defined as [5]

$$\nu_{\rm i} = \frac{1}{W_{\rm g}} \frac{e^2E^2}{2m(\omega_{\rm las}^2 + \nu_{\rm c}^2)}\,\nu, \tag{4}$$

where $W_{\rm g} = 9$ eV is the band gap in silica.

Numerical simulation was performed under conditions close to the experiment [3], where a pulse of duration 43 fs and energy 2 μJ was focused at fused silica. The ratio of the peak power $P_{\rm peak}$ to the critical power $P_{\rm cr} = 2.6$ MW in fused silica was found to be ~ 17. The initial Gaussian beam of radius 3.4 mm was focused by the axicon with an apex angle of 174.28°. Fig. 1a shows the distributions of free electron density in the plane $[r = (x^2 + y^2)^{1/2},\ z]$ immediately after the passage of a pulse. The formation of a 2-mm-long plasma channel in which the electron density is $(4-8)\times 10^{-3}N_0$ can be seen clearly. For comparison, Figs 1b and 1c show the electron density in channels formed upon focusing by lenses with $F = 6$ and 21 cm. In this case, the geometrical focus lies in the bulk of the sample at a distance of 1 mm from its surface. Plasma channels obtained as a result of numerical simulation match qualitatively the experimentally recorded zones of local increase in the refractive index which were recorded experimentally with the help of a microscope [3] for different focal lengths of the lenses.

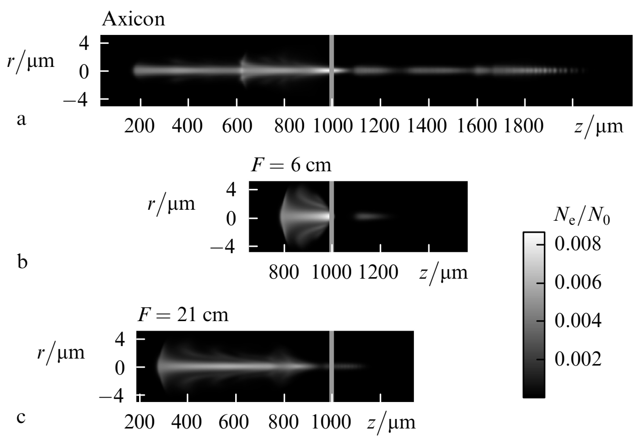

Figure 1. Spatial distribution of free electron density after the passage of a femtosecond pulse in the bulk of fused silica. The pulse propagates from left to right, $z = 0$ corresponds to the input surface of the sample, the vertical line shows the position of the geometrical focus (Fig. 1a corresponds to an axicon with a base angle 2.86°, Figs 1b and c correspond to lenses with focal lengths 6 and 21 cm, respectively).

An increase in the focal length of a lens leads to an increase in the length of the plasma channel and a decrease in the region of transverse plasma distribution. However, the longest and narrowest plasma channel was obtained as a result of focusing by the axicon. Figure 2 shows the lengths of plasma channels formed by focusing with the help of different lenses and the axicon. It should be observed that a further increase in the focal length of a conventional lens leads to a refocusing of radiation and a nonuniform distribution of electron densities in the channel.

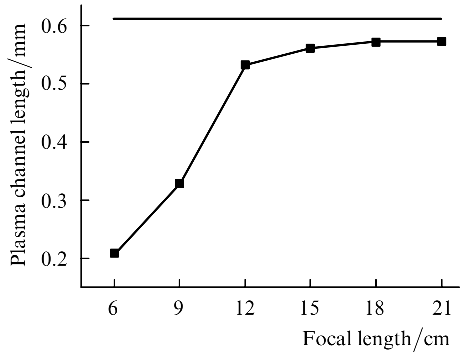

Figure 2. Dependence of the plasma channel length (recorded at a level 20 % of the highest electron density in the sample) on the focal length of the lens. The horizontal line in the figure shows the length of the most homogeneous region of the axicon channel ($z < 1050$ μm) in Fig. 1a.

Thus, the fact that the axicon channel is the longest and the narrowest suggests that the conic lens is a promising tool for recording of optical waveguides.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 03-02-16939) and European Research Office of the US Army under Contract No. W911NF-05-1-0553.

References

1. Davis K.M., Miura K., Sugimoto N., Hiaro K. *Opt. Lett.*, **21**, 1729 (1996).
2. Kasaai M.R., Lagace S., Boudreau D., Förster E., Muller B., Chin S.L. *J. Non-Cryst. Sol.*, **292**, 202 (2001).
3. Nguyen N.T., Saliminia A., Liu W., Chin S.L., Vallee R. *Opt. Lett.*, **28**, 1591 (2003).
4. Babin A.A., Kiselev A.M., Pravdenko K.I., Sergeev A.M., Stepanov A.N., Khazanov E.A. *Usp. Fiz. Nauk*, **169**, 80 (1999).
5. Raizer Yu.P. *Gas Discharge Physics* (New York: Springer-Verlag, 1997; Moscow: Nauka, 1992).