Transverse evolution of a plasma channel in air induced by a femtosecond laser

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We investigate the evolution of filamentation in air by using a longitudinal diffraction method and a plasma fluorescence imaging technique. The diameter of a single filament in which the intensity is clamped increases as the energy of the pump light pulse increases, until multiple filaments appear. © 2006 Optical Society of America

OPTICS LETTERS / Vol. 31, No. 4 / February 15, 2006

The nonlinear propagation of ultrashort laser pulses in the atmosphere has attracted extensive attention recently.1–3 When a femtosecond laser pulse propagates through transparent media (solids, liquids, and gases), high-order nonlinear effects will occur. This leads to Kerr self-focusing balanced by the self-generation of weak plasma, resulting in a filament or plasma channel. When the pump pulse energy is increased, the intensity inside a single filament does not increase because of intensity clamping inside the filament.6–8 What would then happen to the single filament if the input energy increased before multiple filaments set in? In this Letter we report using a sensitive method to measure the evolution of filamentation of a femtosecond Ti:sapphire laser pulse in air from a single to a multiple filament by increasing the input energy. The result shows that intensity clamping and the background energy reservoir force the diameter of the single filament to increase before multiple filaments set in.

The method of longitudinal diffraction measurement has been described in detail elsewhere.9 The laser source is a compact Ti:sapphire chirped-pulse amplification laser system at the Shanghai Institute of Optics and Fine Mechanics. A 25 mJ/pulse, 200 fs, 10 Hz, laser is the laser commonly used. The output beam is split into two parts: 90% as the pump beam and 10% as the probe beam. After a KDP crystal, we obtain the probe pulse at the second-harmonic wavelength of 400 nm (λ). These two pulses propagate collinearly. The focusing lens for the pump pulse has a focal length of 50 cm. The probe pulse after passing through the plasma channel is diffracted and imaged onto a CCD camera with an 8×, f=400 mm imaging lens. After the plasma we eliminate the pump pulse by using a filter; thus, only the probe pulse remains.

Assuming that the original probe beam has a Gaussian profile \( U_0 \approx \exp(-ar^2) \), the phase shift is approximated as a cylindrical phase aperture, \( \phi(r) = \phi \) when \( r < r_c \) or \( \phi(r) = 0 \) when \( r > r_c \) (here \( r_c \) is the radius of the channel). The probe beam experiences phase shift \( \phi(r) \) and will be diffracted. The diffracted field at the CCD plane can be expressed by the Fresnel diffraction integral.10 After simplification, the intensity distribution at the CCD plane can be deduced from the intensity distribution when there is a plasma channel and by subtraction of the intensity distribution when there is no plasma channel; the result reads as

\[
I(r) = -\text{sign}(A_2)C \pi r_c^2 \frac{1}{\sqrt{a^2 + A_1^2}} \exp(-b_0 r^2) \times \frac{J_1(A_2 r_c)}{A_2 r_c} \cos(b_1 r^2 - \phi/2) \sin(\phi/2),
\]

where \( d_0 \) is the distance between the filament and the imaging lens, \( d_1 \) is the distance between the geometrical focus of the imaging lens and the CCD, \( A_1 = (\pi \lambda d_0)[1 - 1/(1 + d_0/d_1 - d_0/f)], \quad A_2 = 2 \pi [(\lambda d_0 + d_1 - d_0 d_1/f)], \quad b_0 = A_2^2 a/4(a^2 + A_1^2), \quad b_1 = A_2^2 A_1/4(a^2 + A_1^2).\]

Fig. 1. Diffraction patterns with a delay of 330 fs for laser powers of (a) 1.0, (b) 2.0, (c) 3.3, (d) 5.3 \( P_r \).
We analyzed the image with the help of Eq. (1) to extract the phase shift and the mean radius of the channel, as is described in Fig. 2. The data in Fig. 2 come from the photographs in Fig. 1, with a laser power of 2 $P_{cr}$. From Fig. 2 we can see that phase shift $\phi=0.65\pi$ and mean radius $r_c=20\ \mu m$ can be extracted simultaneously from a single image.

Through curve fitting in Fig. 1 with the help of Eq. (1), in Fig. 3 we present the relationship between the diameter of the plasma channel and the laser power: Before multiple filaments appear, the diameter increases as the power increases. The diameter of the plasma channel changes from 20 to 80 $\mu m$ when the power of the pump pulse increases from 1.5 to 4 $P_{cr}$.

To corroborate these results, we used the fluorescence imaging technique to measure the plasma column’s diameter as a function of the laser power. In Fig. 4 the experimental results of the plasma column diameter as a function of the propagation position are shown for four pump powers. The 50 cm focal-length lens was positioned at propagation distance $z=0\ cm$, and its geometrical focus was at position $z=50\ cm$. The results obtained by using the ICCD imaging system are similar to those obtained with the longitudinal diffraction technique (Fig. 3). The average diameter of the plasma channel along the filament increases from $\sim 50$ to 85 $\mu m$ when the laser power increases from 1.0 to 3.0 $P_{cr}$. Furthermore, similarly to previous observations, we find that the filament length increases as the power increases.

The phenomenon that the diameter varies as the pump pulse changes is presented here for the first time as far as we know. Here, the focusing length in our experiment is 50 cm, and the filament is formed through the balance among geometrical focusing, Kerr self-focusing, and defocusing by plasma and diffraction. The plasma generation balances the self-focusing effect and leads to a limited peak intensity. This is known as intensity clamping. When the pulse energy is increased, the intensity inside a single filament will not increase for the sake of intensity clamping. Thus it is intensity clamping that forces the diameter of a single filament to increase before multiple filaments form.

During the filamentation, the core of the filament is fed by the surrounding energy reservoir, which can

![Fig. 2](image-url)  
Fig. 2. Phase shift $\phi=0.65\pi$ and radius of the channel $r_c=20\ \mu m$ extracted by fitting of the experimental data with the calculated curve through Eq. (1).

![Fig. 3](image-url)  
Fig. 3. Diameter of the plasma channel as a function of the power of the incident pump pulse.
contain as much as 90% of the total energy.\textsuperscript{16–18} For a collimated laser beam, it has been shown that the diameter of the energy reservoir interacting with the filament core is approximately 5–10 times larger than the filament's diameter.\textsuperscript{18} In this case the intensity of the energy reservoir is not high enough to induce ionization. However, during the filamentation of an initially convergent laser beam, the energy reservoir surrounding the filament core is confined to a smaller volume, thus increasing its intensity. The part of the energy reservoir next to the filament core could contribute to the generation of plasma. In such a situation the increase of the input energy has an important effect on the volume of ionization during the propagation of the laser pulse, as one can observe from Figs. 3 and 4. The increase of the plasma columns' diameter with increasing laser energy is due mainly to the geometrical focusing that restrains the laser energy reservoir inside a smaller volume than in the case of free propagation. For laser power higher than $P_{cr}$, the maximum plasma density remains almost constant inside the plasma channel and thus the peak intensity of the laser pulse does also.\textsuperscript{15}

In conclusion, using the longitudinal diffraction method and the fluorescence imaging technique, we have investigated the transverse evolution of a plasma channel in air induced by a femtosecond laser with a 50 cm focal-length lens. Our experimental result clearly indicates that the length and the diameter of the plasma channel increase with pulse energy.

This study is supported partially by a Major Basic Research project of the Shanghai Commission of Science and Technology, the Chinese Academy of Sciences, the Chinese Ministry of Science and Technology, and the Natural Science Foundation of China. F. Théberge and S. L. Chin acknowledge support in part by Natural Sciences and Engineering Research Council of Canada, Defence R&D Canada–Valcartier, Le Fonds Québécois de la Recherche sur la Nature et les Technologies, Canada Research Chairs, the Canada Foundation for Innovation, and the Canadian Institute for Photonic Innovations. Y. P. Deng's e-mail address is ypdeng@mail.siom.ac.cn.

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