Self-Guiding of IR femtosecond laser pulses in air: Experiments versus Simulations

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Abstract: Experimental data characterizing the atmospheric propagation of femtosecond laser pulses with power above the self-focusing threshold are shown to support the comparison with realistic numerical simulations including group-velocity dispersion and retarded optical Kerr effect.

OCIS codes: 190.5530 Pulse propagation and Solitons, 320 7110 Ultrafast nonlinear optics

1 Introduction

There is presently a considerable interest in understanding the propagation of intense femtosecond laser pulses through the atmosphere. Self-guided infra-red (IR) laser beams with high peak power forming an intense filament over long distances have been reported by several groups [1, 2, 3]. On the other hand, various attempts in modeling this phenomenon have been proposed, either by solving numerically nonlinear Schrödingerlike systems or by using more analytical approaches [4, 5, 6]. However, although there is a wide consensus on the physical effects sustaining this unusual propagation, controversies still remain about the detailed explanation of the observed features. They partly originate from the fact that experiments are usually realized with pulses having an input transverse power exceeding by far the critical power, P_{cr}, for self-focusing, whereas the simulations are mostly limited to powers close to P_{cr}, which require considerably less computational time.

We present a systematic study of the propagation of femtosecond IR pulses exhibiting a single transverse mode within a well-defined geometry, with pulse peak powers above critical. Emphasis is laid on precise measurements of the length of the self-guided filament and its inner energy, the power spectrum and the density of electrons liberated in the trail of the pulse. These data are compared in detail with results from a numerical code, which involves the main ingredients for describing ultra-short pulse propagation in air.

2 Experimental procedure and numerical modeling

The laser source is a Ti:Sapphire oscillator-amplifier operating at kHz rate and at the wavelength $\lambda_0 = 800$ nm. It delivers pulses of 40 fs duration with an energy of up to 8 mJ per pulse. The pulse time profile is measured accurately by cross-phase modulation or by the SPIDER technique. The pulse diameter is first reduced by an inverted telescope and then launched through the atmosphere in the form of a converging beam with different focal distances varying from $f = 2$ m to infinity. The following measurements are performed as a function of the propagation distance for different incident pulse powers: beam diameter, energy and spectrum of the self-guided pulse, air conductivity, and lifetime of the created plasma.

A detailed numerical analysis of the same pulses is developed from a three-dimensional code with axial symmetry. This code encompasses the effects of diffraction, the nonlinear optical Kerr response of the medium, with both instantaneous and retarded components in a ratio $\frac{1}{2}$ fixed by experimental evidence, together with

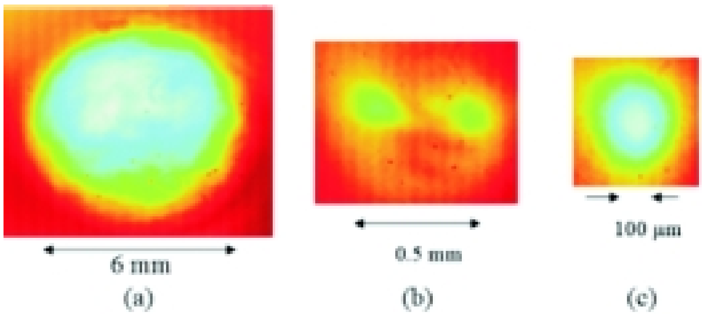

Fig. 1. (a) input beam (5 mJ). (b) ring structure, $z = 163$ cm. (c) self-guided filament, $z = 313$ cm.

the air ionization by multiphoton transitions. It resolves the slowly-varying envelope of the laser electric field $\mathcal{E}(r, z, t)$, which is governed by the nonlinear Schrödinger equation

$$2i\frac{\partial \mathcal{E}}{\partial z} + \frac{1}{k_0}\Delta_\perp \mathcal{E} - k''\frac{\partial^2 \mathcal{E}}{\partial t^2} + k_0 n_2\{|\mathcal{E}|^2 + \int_{-\infty}^{+\infty} \mathrm{e}^{-(t-t')/\tau_K}|\mathcal{E}(t')|^2 dt'\}\mathcal{E} - k_0\frac{\omega_{pe}^2(\rho)}{\omega_0^2}\mathcal{E} = 0, \quad (1)$$

coupled with the density ρ of the electron plasma created by ionization such as $\partial\rho/\partial t = \sigma|\mathcal{E}|^{2K}(\rho_{at} - \rho)$, where $\rho_{at} = 2.7 \times 10^{19}$ cm^{-3} is the density of neutral atoms. The input pulses exhibit transverse waists from $w_0 = 3$ mm and beyond, and they are either collimated, or focused by various lenses of different focal lengths. At atmospheric pressure, the appropriate parameters are $n_2 = 3.2 \times 10^{-19}$ cm^2/W, $K = 10$, $\sigma = 1.38 \times 10^{-128}$ W^{-10}s^{-1} and the critical power for self-focusing is $P_{\text{cr}} \simeq 3.18$ GW.

3 Results

A self-guided filament is observed to form when the input energy lies at least above 1.5 mJ. In this situation, the wave grows up, excites an electron plasma by ionization, from which a steady-state filament results. This point has been detailed for incident pulses being narrow in space [$w_0 = 3$ mm, Fig. 1(a)] and having an input energy increased from $E_{in} = 1$ mJ to $E_{in} = 5$ mJ, which corresponds to input powers belonging to the range $6 \leq P_{\text{in}}/P_{\text{cr}} \leq 30$. The experiments together with the numerical results show that, for these powers and with a lens $f = 2$ m, the pulse forms a self-focused beam, then decays into spatial rings from a nonlinear focus [Fig. 1(b)] and finally relaxes to a robust filament [Fig. 1(c)], which is able to propagate over several Rayleigh lengths $z_f \sim 11.3$ cm. For z far above the focal point, this filament is observed to reach diameters of about 100 μm with energies around 10% of the input pulse energy. These results appear to be generic, even when the focal length and incident waist vary. We have indeed also studied the influence of a lens with larger $f = 4$ m at fixed input energy and waist, and the influence of a larger incident waist $w_0 = 5$ mm at fixed energy. On the one hand, using a large focal length displays evidence that the resulting filament forms just after a sharp self-focusing regime promoting the generation of a continuum. On the other hand, using a larger waist favors the development of optical turbulence, which degrades the homogeneity of the energy distribution inside the self-guided structure. The characteristic length, energy and propagation domain of the filament measured experimentally are found to be qualitatively well restored by the numerical simulations.

References

1. A. Braun, G. Korn, X. Liu, D.Du, J. Squier and G. Mourou, *Opt. Lett.* **20**, 73 (1995).
2. E.T.J. Nibbering, P.F. Curley, G. Grillon, B.S. Prade, M.A. Franco, F. Salin, and A. Mysyrowicz, *Opt. Lett.* **21**, 62 (1996).
3. B. La Fontaine, F. Vidal, Z. Jiang, C. Y. Chien, D. Comtois, A. Desparois, T.W. Johnston, J.-C. Kieffer, H. Pépin, and H.P. Mercure, *Phys. Plasmas* **6**, 1615 (1999).
4. M. Mlejnek, E.M. Wright and J.V. Moloney, *Opt. Lett.* **23**, 5 (1998).
5. A. Chiron, B. Lamouroux, R. Lange, J.-F. Ripoche, M. Franco, B. Prade, G. Bonnaud, G. Riazuelo, and A. Mysyrowicz, *Eur. Phys. J. D* **6**, 383 (1999).
6. A. Couairon and L. Bergé, *Phys. Plasmas*, to appear (2000).