Multiple-cone formation during the femtosecond-laser pulse propagation in silica

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Abstract: We numerically show that during its propagation in silica a femtosecond laser pulse whose power is nearly 500 times higher than the self-focusing threshold is split into multiple cones by the interplay of Kerr effect and plasma defocusing.

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Intense femtosecond laser pulses undergo dramatic changes during the propagation in gases and solids due to complex linear and nonlinear effects. Most existing work has been focused on an input power of several times $P_{\rm cr}$, where $P_{\rm cr}$ is the self-focusing threshold (3 GW for air and 2.2 MW for silica at $\lambda_0 = 800$nm), though some work on several tens of times $P_{\rm cr}$ [1, 2] and experimental work on several hundreds of times $P_{\rm cr}$ [3] have recently been done. In this study, by 3D numerical simulations with axial symmetry, we show that the propagation of a pulse with a power several hundreds of times higher than $P_{\rm cr}$ in silica is qualitatively different from lower-power cases. The pulse is split both temporally and spatially to form multiple cones.

We model the pulse propagation with the extended nonlinear Schrödinger equation [1, 2] including the normal and third-order group velocity dispersion, transverse diffraction, the Kerr nonlinearity, plasma defocusing, multi-photon absorption, space-time focusing, and self-steepening. This equation is coupled with an equation describing the evolution of conduction electrons produced through multi-photon band-to-band transitions. We choose a sech^2 laser pulse whose wavelength is $\lambda_0 = 800\,$nm and duration is 130 fs (FWHM). Its lateral profile is gaussian with a FWHM of $235.5\,\mu$m. The geometrical focus is at a propagation distance z of 10.9 mm.

For the case of an input energy of 135μJ ($470P_{\rm cr}$), the pulse energy is, with propagation, concentrated near the beam axis due to self-focusing. As the local intensity increases further, plasma electrons are produced through multi-photon absorption. This leads to defocusing near the trailing edge and results in the formation of an intensity cone. So far the pulse evolution is similar to those for much lower input power. What follows, however, is a spectacular new feature that emerges only when the input power exceeds $P_{\rm cr}$ by orders of magnitude: with further propagation, more and more cones are formed, as is illustrated in Fig. 1.

In Fig. 2 we plot the lateral distribution of intensity and laser-induced refractive index change Δn at $t = 44\,$fs and $z = 3340$ and $3360\ \mu$m. At $z = 3340\,\mu$m, Δn is nearly flat in the range $r = 9 - 12\,\mu$m while the intensity

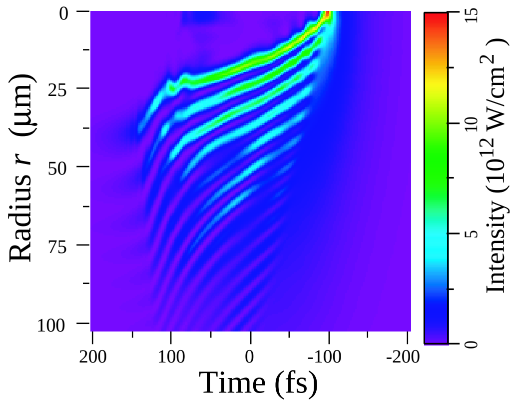

Fig. 1. Spatio-temporal intensity distribution of an initially gaussian pulse with an energy of 135μJ at $z = 5000\mu$m. Note that the pulse is symmetric around the beam axis $r = 0$.

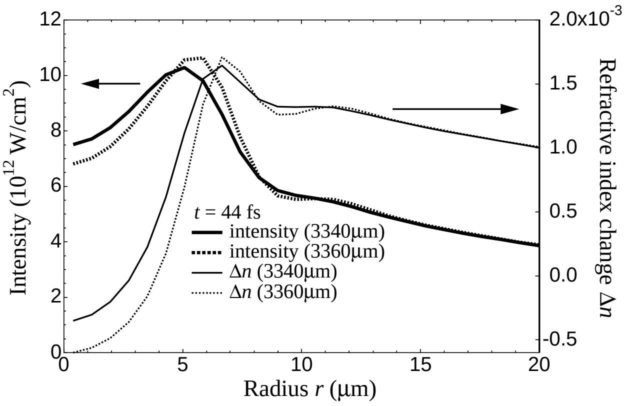

Fig. 2. Radial distribution of intensity (thick lines, left axis) and refractive index change Δn (thin lines, right axis) at $t = 44$ fs. Solid lines are for the propagation distance $z = 3340\,\mu$m, and dotted lines for $z = 3360\,\mu$m.

gradually decreases with increasing r. This is because the electron density is higher for a smaller value of r. By $z = 3360\,\mu$m, the intensity peak takes up much energy from its vicinity due to Kerr effect. Then, a second maximum in Δn is formed around $r = 11.3\,\mu$m. Once the second peak is formed, the self-focusing leads to the grow-up of the second intensity peak. The avalanche of this process leads to the multiple-cone formation.

Figure 3 shows the intensity distribution for a lower incident energy of 15μJ ($52P_{\rm cr}$). The pulse contains a less number of cones than in the higher-energy case (Fig. 1), and they are nearly parallel to the beam axis. This probably corresponds to multiple light filaments in full 3D simulations for air [1].

References

1. M. Mlejnek *et al.*, "Optically turbulent femtosecond light guide in air," Phys. Rev. Lett. **83**, 2938 (1999).
2. S. Tzortzakis *et al.*, "Breakup and fusion of self-guided femtosecond light pulses in air," Phys. Rev. Lett. **86**, 5470 (2001).
3. H. Kumagai *et al.*, "Direct observation of pulse propagation of femtosecond laser in glass with femtosecond time-resolved optical polarigraphy (FTOP)," in CLEO/Pacific Rim 2001, Technical Digest I-310 (2001).

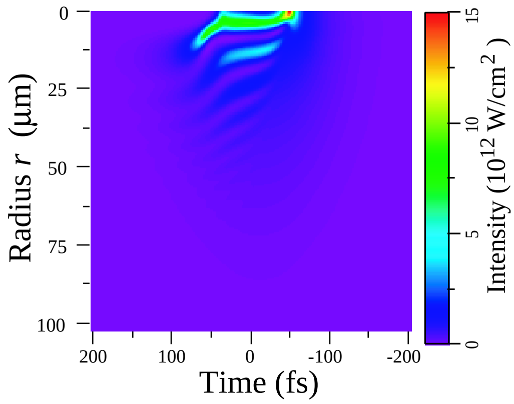

Fig. 3. Spatio-temporal intensity distribution of an initially gaussian pulse with an energy of 15μJ at $z = 7000\mu$m.