First-principle modeling of overcritical plasma formation by ultrashort pulses: Towards high-intensity nanoplasmonics

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Abstract

We investighate tightly-focused short pulse propagation in fused silica with intensities above 100 TW/cm^2, which leads to the formation of the photoionized plasma and the backreflection of the pump beam. For the modeling of this process we formulate a comprehensive material response model which is coupled to the finite-difference time-domain numerical approach. We discuss the spatiotemporal patterns of the electric field and the plasma density, as well as the possibility to enhance the pump field by excitation of localized plasmons.

The intense light propagation in solid materials is of high importance in many fields such as material modification, investigation of the material properties, small-scale modeling of the large-scale matter-radiation interactions, and studies of pulse propagation dynamics. Ionization of a transparent dielectric material by a tightly focused femtosecond laser pulse results in a rapid energy deposition inside a microscopic material volume. The extreme pressure conditions that follow lead to the formation of new super-dense material phases. For the high-intensity cases the plasma density can reach and overcome the critical value leading to the nontransparent, reflective plasma regions inside of the solid state. These situations are notoriously difficult to model as paraxial or unidirectional approaches are not suitable. For the simulation of this process we developed a comprehensive material response model and coupled it to the (3+1)D FDTD Maxwell solver, as discussed in this contribution.

For the numerical simulation of the above process we have developed a numerical model based on the finite-difference time-domain approach. The ionization is described by the advanced model which takes into account both the instantaneous value of the electric field and the time-averaged light intensity. The dynamics of the created electron cloud is influenced both by the electric field and by the electron scattering, which is accounted for by considering both the average electron velocity and the temperature of the electron cloud. Exemplary results of the simulation are shown in Fig. 1. The 8-fs pulse at 800 nm central wavelength is focused to a spot with a radius of 0.8 micrometer, with focal intensity of 325 TW/cm^2. One can see in (b) that the pump field creates a region with relative plasma density above critical value of 0.16 (black contour), which leads to lightbackreflection. The back-reflected light results in a high-intensity interference pattern (c) with the incoming rear part of the pump pulse, which creates periodic spots of high-plasma density before the focus. During this process, the light energy is deposited in the lattice by both electron ionization and electron and lattice heating. The deposited energy density is sufficiently high to melt and even evaporate the fused silica.

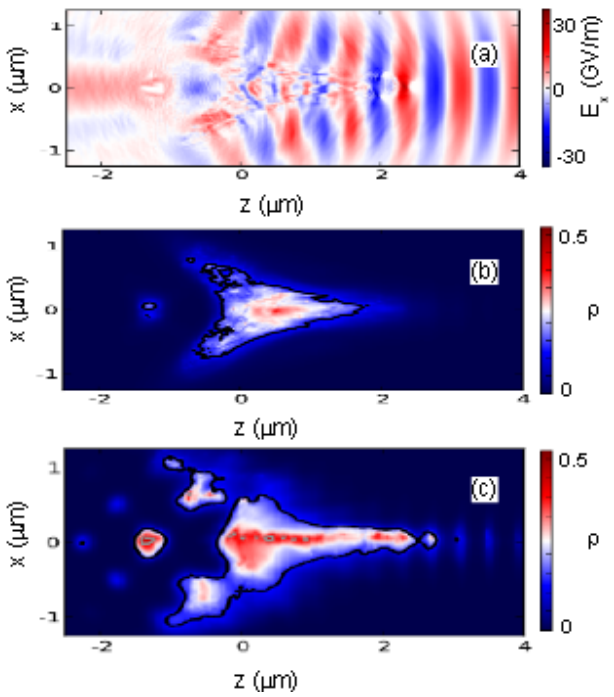

Fig. 1. The field distribution (a) and the relative plasma density (b),(c) for the pulse focused in fused silica. The spot radius is 0.8 micrometer, the maximum intensity is 350 TW/cm^2. Pulse duration is 8 fs (a),(b) and 16 fs (c). Plasma density is normalized by concentation of SiO_2 molecules.

In addition, a detailed analysis of the spatiotemporal field profile allowed us to identify a spherical region of high plasma density with localized field oscillations around this region. The possibilities to excite and optimize such excitation by tailoring the pulse shape and focusing are discussed, with the aim to enhance the electric field and increase the deposited energy density.

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