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Higher-order Kerr effects improve quantitative modelling of harmonics generation and laser filamentation

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Abstract. The consideration of the higher-order Kerr effect (HOKE) drastically improves the quantitative agreement between measured and simulated harmonic yield, as well as intensity and electron density in laser filaments generated by pulses below a few hundreds of fs. In longer pulses, the plasma defocusing plays a much more important role.

1 Introduction

Laser filamentation [1,2] is due to a dynamic balance between self-focusing by the Kerr effect, and self-defocusing non-linearities of higher orders. While the contribution of the laser-generated plasma to the self-defocusing has been identified more than a decade ago, the contribution of the higher-order Kerr effect (HOKE) [3,4] to self-defocusing is still actively debated.

The first quantitative tests in that regard focused on harmonics generation. We showed that the ratio of the 3rd (corresponding to the third-order susceptibility $\chi^{(3)}$, or to n_2 in terms of HOKE) to the 5th harmonics ($\chi^{(5)}$, or n_4) and its variation with phase matching controlled via the gas pressure can only be reproduced by considering the fifth-order susceptibility [5]. This result was independently reproduced by two other groups [6,7]. It validates the necessity of considering an n_4 HOKE term and confirms its published value [3] not only in the near-infrared (800 nm) but also in the mid-IR (1.5 and 4 μm incident radiation). These findings are however challenged by another experiment [8] and restricted to the fifth-order non-linearity, providing no information on the subsequent nonlinearity orders, including the ninth-order which according to the published values [3] should be the most active defocusing term in typical filament conditions [4]. Furthermore, due to the spectral dispersion of the susceptibilities, these harmonics generation experiments address $\chi^{(k)}(k\omega;\omega,...,\omega)$ and do not strictly apply to filamentation, where the $\chi^{(k)}(\omega;\omega,-\omega,...,\omega)$ tensors are at play.

A similar quantitative approach is harder to perform directly in filaments, where the high intensity within them prevents easy direct in-situ measurements of, e.g., the peak intensity or electron density, and therefore their quantitative comparison with models. In two recent articles [9,10] a quantitative agreement of the plasma-based model with the experimental filament length and the peak electron density, respectively, was obtained at the cost of unrealistic ionization models, overestimating the ionization rates by typically one order of magnitude, as compared with the standard Perelomov, Popov, Terent'ev (PPT) ionization model [1].

Conversely, using the standard PPT ionization model, we found that considering the HOKE [5] is necessary to quantitatively reproduce the published peak intensity [11] and electron density [10,12] in laser filaments. For example, the peak intensity of filaments generated by slightly focused (*f* = 1 m), 42 fs pulses of 1 cm diameter, with energies ranging between 0.2 and 2.5 mJ [12], is reproduced within less than 10% by the full model. The truncated model, in which the HOKE defocusing term is missing and in which the defocusing relies only on the plasma, typically predicts a double intensity as compared with the experimental data.

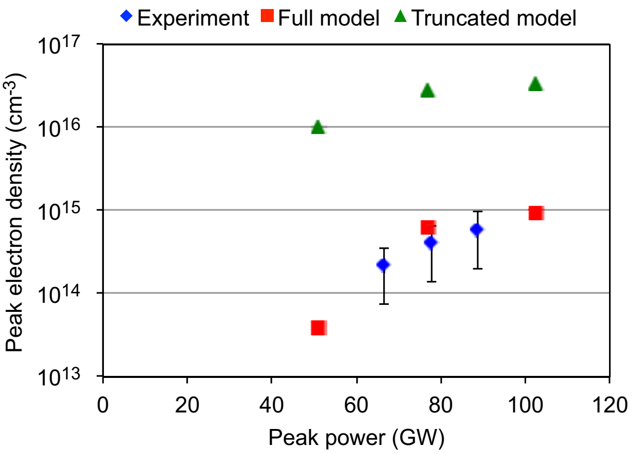

Fig. 1. Experimental [12] and simulated peak intensity as a function of incident power, for a collimated, 45 fs pulse of 8.4 mm initial beam diameter.

This mismatch by a factor of only two may still not be conclusive, owing to the difficulty of the experimental measurements pointed out above. To get more contrast, we considered the electron density, which offers a typical dynamical range of two orders of magnitude. Figure 1 compares the outcome of both the full and the truncated models for the peak electron density in filaments generated by 45 fs pulses with a collimated beam diameter of 8.4 mm as a function of the input power. Only the full model perfectly reproduces the electron density. Similar results are obtained for slightly focused beams, showing that the consideration of the HOKE are necessary to reproduce experimental published by several authors [10,11,12]. Note that this agreement is obtained without any adjustable parameter in the model: Rather, all parameters are taken from the experimental parameters to be reproduced, or experimentally published values of non-linear indices [3] or ionization rates [1].

However, neither the HOKE nor the plasma alone offer the full picture of filamentation. Both experiments and numerical simulations [13] for different pulse durations from shows a transition between a HOKE-driven filamentation regime for pulses below a few hundreds of femtoseconds, and a plasma-driven regime for longer pulses. A similar transition is also expected when sweeping the incident wavelength from the IR to the UV [14].

As a conclusion, by comparing numerical simulations with published experimental data, we have shown that the consideration of the HOKE is necessary to quantitatively model harmonics generation and laser filamentation. This finding confirms that our understanding of laser filamentation has to be updated, which will in particular impact the determination of the optimal conditions for the potential applications [2,15] of laser filamentation, like cloudmaking [16] and lightning control [17].

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