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Modeling extreme ultraviolet attosecond pulses in modulated waveguides

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Abstract. We explore via numerical modeling the generation of very short photon wavelengths in hollow core waveguides (HCW) filled with He gas at high pressures. Propagation of femtosecond driving pulses is first solved using a split-step method and tested against other methods. The propagation along the HCW reveals mode beating seen in quasi-periodic oscillations of the field intensity and phase which in turn will determine the single atom response to the field. We explore both cylindrical and conical HCW in which the guide diameter varies along the propagation direction. This second configuration generates very high harmonic orders in a regime of quasi-phase matching. We found three spectral ranges which show amplification, at 3.5, 7.6, and 11-13 nm, which are of great interest given their practical applications in spectroscopy, XUV metrology and photolithography.

1 Introduction

Despite the low efficiency, high order harmonics generation (HHG) in (mainly noble) gases remains the main method to obtain extreme ultraviolet or soft X-ray attosecond pulses [1] because they can be obtained at large repetition rates and do not need very high laser intensities. The gas medium is usually supplied in a jet or in a static cell but using dielectric structures to host the gas and to guide the ultrafast beam is of practical interest. Dielectric hollow core waveguides (HCW) allow gas confinement at high pressures and keep high laser intensity over longer interaction lengths, leading to a significant chance to increase the HHG yield [2].

2 Building and testing the model

The model was built in three main parts. First, the field configuration inside the HCW was calculated by solving the propagation equation in frequency domain [3] and taking into account the refractive index contributions of the gas (dispersion by neutrals, optical Kerr and electron plasma contribution). For propagation in the HCW we used the split-step method as described in [4]. Second, the propagated solution $E_1(r,z,t)$ is then used to calculate the single atom polarization $P_{nl}(r,z,t)$ in the strong field approximation [5] over the whole interaction region. This is the most computationally demanding step. Finally third, we solve the propagation equation for the harmonic field $E_h(r,z,t)$, which have the same form as for the driving field, but having atomic polarization as source. Testing the model against experimental data was a necessary step in the model development. Here we have to mention that a very good agreement was found between experimental data reporting dependence along the propagation direction of Ar fluorescence [6], and the total electron density obtained from simulations [4]. In addition we used two different methods to validate the split-step method, one solving propagation equation using finite-difference time-domain (FDTD), the other using normal mode decomposition in frequency domain, both methods being available in Lumerical software [7]. The results obtained using the FDTD method are in good agreement with those obtained with the split step method, as seen in fig 1.

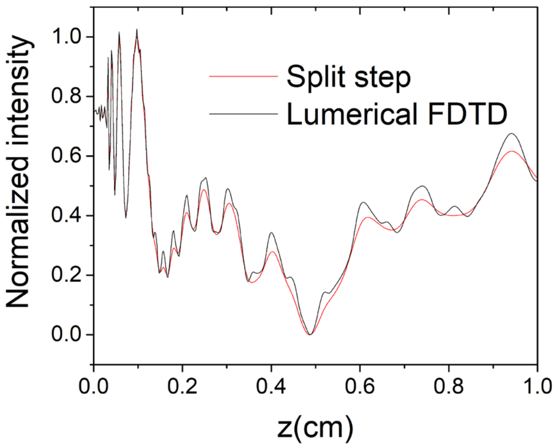

Figure 1. On-axis intensity along a 1 mm waveguide with 30 μm diameter for a 25 fs pulse at 800 nm central wavelength

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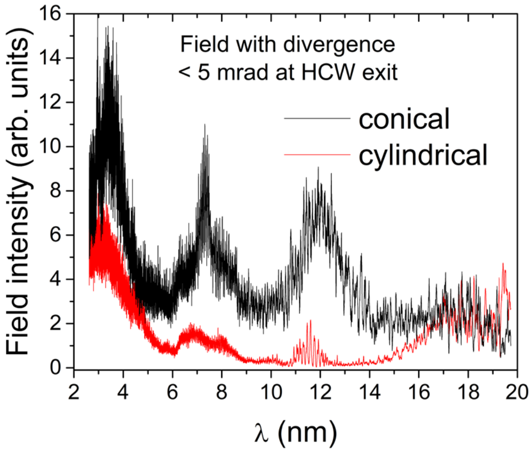

Figure 2. Harmonic field intensity exiting from the waveguides with a divergence smaller than 5 mrad

3 Results and discussion

The HHG model yields the harmonic field $E_H(r, z, \omega)$ inside the HCW and other useful quantities like the total harmonic power generated at a specific frequency, total power spectrum at exit or at user specified axial positions, as well as far field reaching a specific position relevant for the experiment.

The results presented here are for a driving field of 2000 nm central wavelength and 25 fs pulse duration, injected as a gaussian in an 8 mm long waveguide of 70 μm diameter, filled with He at 10 bar pressure. A pressure profile similar to that reported in [2] as well as best coupling conditions were assumed. We consider in the following two cases of cylindrical and conical waveguides, the first one with a constant diameter of 70 μm, the second having a linearly variable diameter starting from 70 μm at beam input and ending after 8 mm with a diameter of 50 μm.

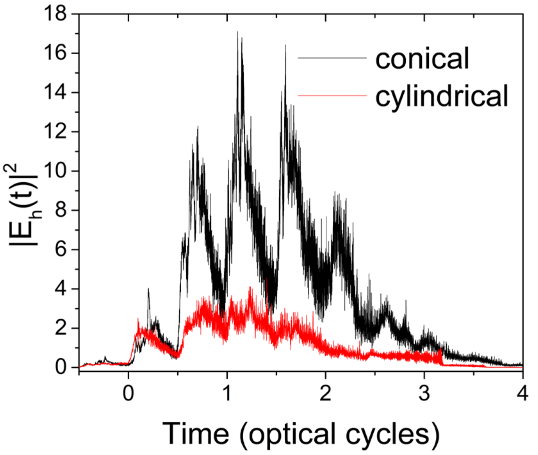

Figure 3. Attosecond pulse train corresponding to the spectra shown in fig. 2

Propagation of the driving pulse is dominated by the mode beating, having local maxima and minima as one can see also in fig 1, but maintains the positions of maxima and minima at all pressures from 1 to 10 bar. The pulse energy loss is also dependent on pressure being around 30% for 1 bar and 50% for 10 bar peak pressure.

The harmonic field intensity which comes out from the waveguide having a divergence under a specific threshold is of particular interest because the result is independent on the far field configuration which may be less known or can change from on experiment to other. This quantity is shown in fig 2 for both cylindrical and conical waveguide and demonstrate the advantage of using a conical waveguide for the HHG. For this last case one can distinguish three spectral regions with a good amplification, around 3.5, 7.6, and 11-14 nm, which are of great interest given their practical applications in spectroscopy, XUV metrology and photolithography.

We analyzed in detail the field generation along the 8 mm of propagation and showed that a quasi-phase matching is responsible for this amplification. The spatial distribution of the single atom polarization for a specific range of frequencies is in close dependence on the spatial distribution of laser field intensity which in turn is governed by the mode beating inside the waveguide. The pressure or better the distribution of pressure influences the strength of the polarization but less the driving field intensity. The HHG process is dependent on the single dipole polarization which is the source for the harmonic field and exhibits regions of strong intensity (corresponding to the maxima of the driving field) alternating with regions of weaker source (corresponding to the driving field minima).

The time counter-part of the data in fig 2 is shown in fig.3 and show that the attosecond pulse train generated by the conical configuration has a better resolved time structure and a much higher intensity. In conclusion this geometry show promising results and is also suitable to further optimization and control of the HHG process.

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