X-rays from quasi-phase-matched high-harmonic generation

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Abstract: Extension of high-order harmonic cutoff in quasi-phase-matched environment is proposed, using low-intensity, counterpropagating pulses in the NIR and MIR regime. We calculate the optimal field parameters, bandwidth and possible cutoff extension of the generated radiation.

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1. Introduction

High-order harmonic generation in noble gases by infrared laser sources allows researchers the production of coherent x-rays and attosecond pulses. These provide the tools to study the structure and time evolution of molecular compounds and even the electronic transitions in individual atoms. To reach high spatial and temporal resolution in pump-probe studies, broadband and coherent XUV or x-ray light sources are needed, and their development is in focus of a large number of experimental and theoretical research groups.

The efficient generation of high-energy harmonic photons is limited by macroscopic processes during the generation, as increasing the laser intensity generates high ionization rate, producing unfavorable phase-matching conditions and severely limiting the generation efficiency [1]. The optimal phase-matching conditions of harmonics generated in a waveguide or with loose focusing (in the plane-wave limit) only depends on the ionization rate, pressure, and refractive index at the generating and harmonic wavelengths [2].

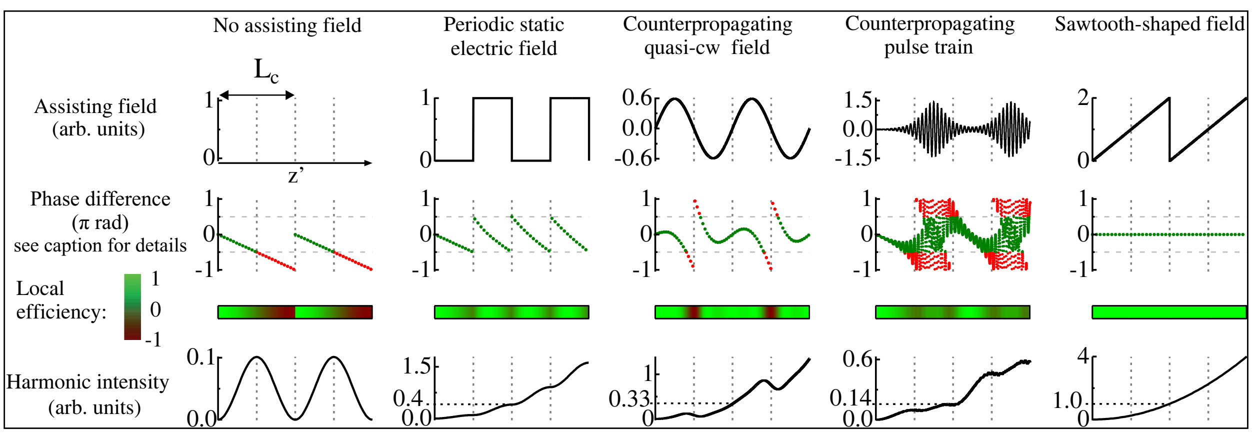

Fig. 1. (a) Under phase-mismatch with no assisting field the phase slip between generated and propagated fields increases along the propagation axis z causing destructive interference and an oscillating harmonic intensity. (b)-(e) Schematic presentation of QPM methods employing periodic assisting fields. Top row: illustration of the assisting field distribution. Second row: phase difference (modulo 2π) between the generated and propagated fields and local efficiencies shown in color scale. Bottom row: Harmonic intensities, whose value at L_c also shows the overall efficiency of the process.

Phase-matching models showed that there is a critical ionization rate (for each type of gas) above which phase-matching is not possible in these geometries. A way to increase the efficiency of the process under phase-mismatch is the use of quasi-phase-matching schemes, that use some type of periodic modulation in the generating medium to affect the microscopic efficiency or phase of the generated harmonics [2]. The electrons contributing to HHG – being driven by the electric field of the laser and acquiring hundreds of radians of phase during the process – are very sensitive to the presence of other fields. As a result relatively weak static, perpendicularly- or counter-propagating fields can be used to control these phases (see Fig 1).

2. Results

In this contribution we discuss QPM schemes employing low-intensity assisting fields, and present numerical results indicating to experiments on the intensities of the secondary field required to induce QPM, depending on the parameters of the driving field. We calculate the phase-modulation induced by fields with the same wavelength as the driver, and also correction factors to be applied when using different wavelength assisting fields.

Using these, QPM efficiencies and optimal conditions can be calculated for different QPM schemes, applying static fields [3], counterpropagating quasi-cw fields [4], or pulse trains [5]. We discuss the bandwidth of the QPM processes in question and show analytical expression to calculate it. Using one dimensional phase-matching models we predict the parameter space of efficient QPM generation for different wavelength NIR and MIR driver pulses, and show possibilities to increase the harmonic cutoff, that is limited by the critical ionization rate under traditional phase-matching conditions.

Fig. 2 shows the regions of efficient QPM generation for the first three QPM orders, under loose focusing, with 10 fs 800 nm and 25 fs 2400 nm driver pulses using counterpropagating quasi-cw fields. In case of 800 nm driver 10 μm assisting field is assumed, and Fig 2.a shows that, for example 198 eV photons can be phase-matched at 1 bar pressure. This is a result of a 9.3×10^{14} W/cm^2 laser field producing 16.8% ionization at the pulse peak, and having a cutoff at 198 eV, well above the $\approx$130 eV phase-matching limit that is set by a 1% critical ionization rate in neon.

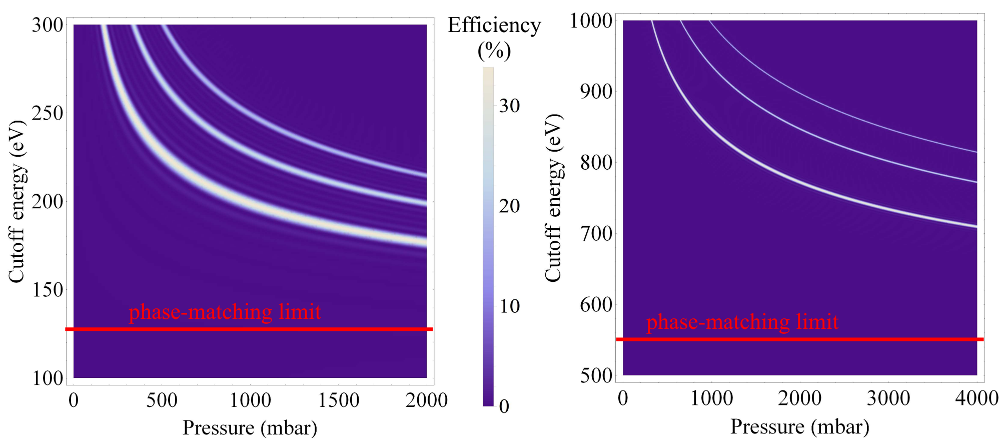

Fig. 2. Predicted highest photon energies achievable in neon with (a) 800 nm 10 fs driver and 10μm assisting fields, and (b) 2.4μm driver and assisting field. The cutoff is set by the driver intensity producing the optimal ionization rate needed for efficient QPM at a given pressure.

Similarly, in the MIR regime, we show that 2.4 μm fields used both as driver and assisting fields can generate photon energies at 2 bar pressure up to 770 eV. In this case 4.4×10^{14} W/cm^2 intensity produces the optimal 1% ionization for QPM at this photon energy, which is, again, well above the 550 eV phase-matching limit achieved at $\approx$0.1% critical ionization rate at this driver wavelength.

References

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