Transverse selective-zoning method of quasi-phase-matching for ion-based high-harmonic generation operated from water window to keV X-ray

YAO-LI LIU [1], JYHPYNG WANG [2,3,4], HSU-HSIN CHU [3,4]
[1] Institute of Space and Plasma Sciences, National Cheng Kung University, [2] Institute of Atomic and Molecular Sciences, Academia Sinica, [3] Department of Physics, National Central University, [4] Center for High Energy and High Field Physics, National Central University
e-mail (speaker): yaoliliu@gs.ncku.edu.tw

Gas-based high-harmonic generation (HHG) driven by ultrashort intense laser pulses has been demonstrated as a reliable coherent light source from extreme-ultraviolet (EUV) to x-ray [1]. It is generated through the processes of ionization, acceleration, and then recombination of bound electrons in neutral atoms [2]. The cut-off photon energy is determined by $\mathrm{E}_{\mathrm{cutoff}} = I_p + 3.17U_p$, where I_p is the ionization potential of the bound electron and U_p is the ponderomotive potential of the driving laser field. Using the long-wave infrared (LWIR) as the driving pulse to increase U_p, the HHG spectrum has been demonstrated to reach the keV range [3]. However, limited by the small recombination probability under long pumping wavelengths and the strict phase-matching condition at a low ionization ratio, the overall conversion efficiency is quite low. On the other hand, ion-based HHG driven by near-infrared (NIR) has been demonstrated to generate harmonic orders higher than that from neutral gases [4]. Since the bound electrons in ions possess higher I_p, which can only be ionized at a higher driving laser intensity and thus a higher U_p, both effects result in a higher cut-off photon energy. Nevertheless, in a highly ionized plasma, the dispersion of the plasma cannot be balanced by neutral atoms. Direct phase matching is not possible. Therefore, generating HHG at short wavelengths with high efficiency is an outstanding challenge. To overcome the phase-matching problem, quasi-phase-matching (QPM) is a promising solution.

In this paper, we propose a QPM scheme of high-harmonic generation from NIR-driven He^{1+} ions [5]. It can be applied to a wide spectral range from water window to keV x-ray. By using an intense NIR (810 nm) pulse focused into a helium-filled capillary waveguide, the NIR pulse ionizes the first electron of He atom at its front edge, and then generates keV/water window harmonics from the He second electron at its peak. QPM is done by employing a transverse disruptive pulse to eliminate the HHG emission at the location of wrong phase. Based on the "selective-zoning mechanism'' the phase of the driving NIR field is disturbed by the transverse pulse, resulting in the destruction of coherent generation of high harmonics at the irradiated locations [6]. The mechanism is originally demonstrated using counter-propagating pulses, but also verified recently with a transverse pulse [7]. Therefore, by using a spatial light modulator to control the transverse pulse beam profile, QPM can be achieved with hundreds of zones of adjustable lengths, matching the required several-tens-micrometer coherent length of keV/water window harmonics. The interplay between the longitudinal driving pulse and the patterned transverse pulse is shown in Fig. 1. Based on our calculation, the 675th-order HHG of 1-keV photon energy can be generated efficiently with a 40-mJ, 30-fs, 810-nm driving pulse, and a 125-mJ, 33-ps, 810-nm transverse pulse interacting in a capillary waveguide with 50 µm radius, 10 mm length, and $1\times10^{16}\,\mathrm{cm}^{-3}$ helium density. The conversion efficiency reaches 15\% of the perfect phase-matching condition, as shown in Fig. 2.

The proposed method is wavelength tunable. With the same driving pulse, capillary waveguide, and helium density, the 337th-order HHG in water window can be generated efficiently with a 350-mJ transverse pulse and the optimized QPM pattern. The conversion efficiency reaches about 14\% of the perfect phase-matching condition. These two examples of calculation show the promise of this QPM scheme in the water-window to keV wavelength range.

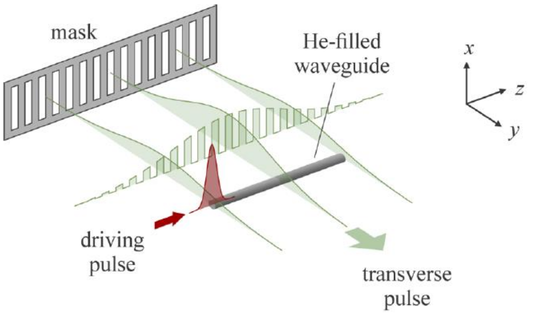

Figure 1. The scheme of QPM-HHG.

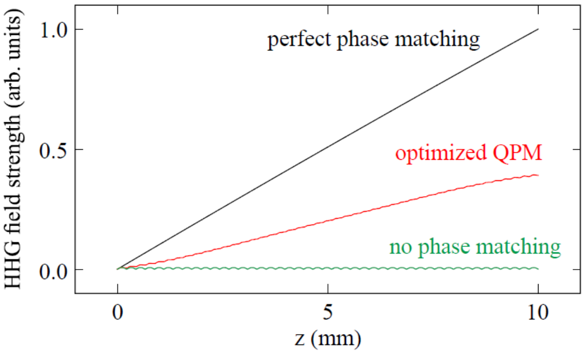

Figure 2. The calculation result of QPM-HHG.

References

[1] T. Brabec and F. Krausz, Rev. Mod. Phys. 72(2), 545–591 (2000).
[2] P. B. Corkum, Phys. Rev. Lett. 71(13), 1994–1997 (1993).
[3] T. Popmintchev et. al, Science 336(6086), 1287–1291 (2012).
[4] E. A. Gibson, et. al, Phys. Rev. Lett. 92(3), 033001 (2004).
[5] Yao-Li Liu, et. al, Opt. Express, 30, 1365 (2022)
[6] J. Peatross, et. al, Opt. Express 1(5), 114–125 (1997).
[7] Yao-Li Liu, et. al, Phys. Rev. A, 104, 023112 (2021)