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Generation of high-flux soft X-ray high harmonics driven by loosely focused TW-class infrared pulses

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Abstract. We develop an experimental strategy for generating high-flux soft x-ray high-order harmonics (HH) driven by loosely focused high-energy infrared femtosecond pulses. Strong soft x-ray HHs are generated in a long Ne medium.

1 Introduction

We previously demonstrated an efficient generation of coherent "water window" x-rays through high-order harmonic generation (HHG) driven by 1.55 μm pulses under a neutral-medium condition [1]. We also reported scalable high-energy high-order harmonics in extreme ultraviolet region using a loose focusing geometry [2]. However, the energy scaling of HHG in the soft x-ray region driven by loosely focused 1.55 μm pulses has not been clarified and is not clear about experimental parameters too.

Hence, this experiment was carried out to evaluate the energy scaling of HHG driven by 1.55 μm pulses. To keep a focus intensity high enough for HHG under a loose focusing geometry, we developed a high-energy 1.55 μm laser system (10 Hz, 80 mJ, 50 fs) [3,4] by using a dual-chirped optical parametric amplification (DC-OPA) scheme [5]. Our DC-OPA laser system generated the highest femtosecond pulse energy ever reported in 1.2-2.4 μm wavelength region. Under the fully optimized phase-matched condition in a 4-cm Ne gas cell, HH intensity at ~250 eV photon energy region is enhanced ~20 times compared with that of HH from a gas jet of which interaction length does not satisfy the absorption limited condition (ALC).

2 Experimental setup

Our laser system starts from a 1 kHz Ti:sapphire laser system which generates compressed pulses and uncompressed pulses. Compressed pulses enter a commercial two stage OPA which generates 1.55 μm seed pulses for DC-OPA. Uncompressed pulses are further amplified to 1 J by a 10 Hz multipass power amplifier, which are utilized as a pump for the DC-OPA system which consists of two stages with Type-II BBO crystals. Pulse duration of the pump is optimized by changing a separation between two gratings inside a compressor.

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Pulse duration of the seed is optimized by an acousto-optic programmable dispersive filter (AOPDF). After the two stage DC-OPA system, the signal pulses are compressed by a prism compressor.

The experimental setup for HHG is shown in Fig. 1. HHs were generated by loosely focusing 1.55 μm pulses into a gas cell using an f = 2000 mm plano-convex lens. To maintain a sufficient vacuum level inside the HHG chamber, the cell consists of a double structure which has four pinholes on each surface of the sides. We can increase the neon gas pressure in the gas-filled region to 1 atm while keeping the outside vacuum better than 10^{-2} torr (Fig. 2).

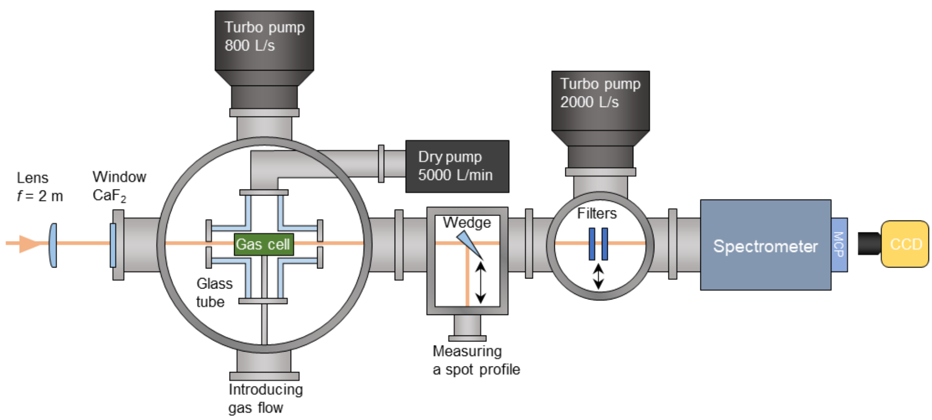

Fig. 1. Experimental setup for HHG driven by loosely focused infrared pulses.

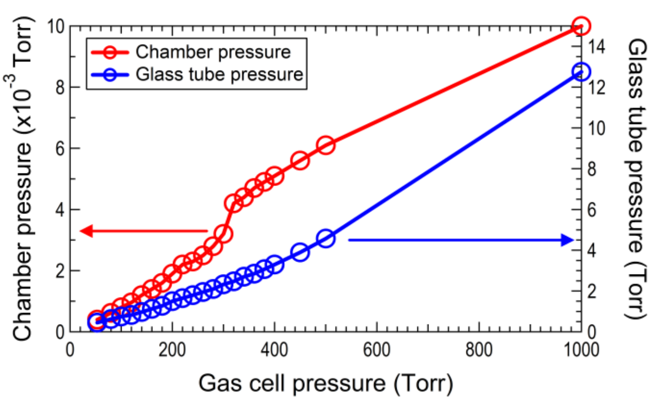

Fig. 2. Neon gas pressure in HHG chamber.

3 Results and Discussions

Figure 3 (a) shows the harmonic spectra from a 4-cm-long (red line) Ne gas cell. We also generate HH from a gas jet of which interaction length is approximately 4 mm (blue line). By changing Ne gas pressure, we optimize the condition of HHG. The HH intensity from a 4-cm gas cell is approximately 20 times stronger than that from a gas jet at 240 eV. The spectral shape of the HHs from a gas jet is flat, while that from the gas cell shows the absorption feature of the medium. These results indicate that an interaction length of 4 cm can satisfy the ALC.

Figure 3 (b) shows the HH intensity at 240 eV as a function of a pressure in a gas cell. Both HH intensity of a 4-cm cell increases quadratically as increasing a gas pressure. The yields of HHs from a 4-cm cell reaches its peak at 220 Torr. This result shows that the phase-matched condition is satisfied at 240 eV with a gas pressure of 220 Torr. The phase matching condition of HHG can be simply written as

$$\Delta k_{\mathrm{N}}(p) + \Delta k_{\mathrm{Gouy}}(\pi\omega^2) + \Delta k_{\mathrm{Plasma}}(p,\eta) = 0 \qquad (1)$$

Here Δk_{N}, Δk_{Gouy} and $\Delta k_{\mathrm{Plasma}}$ are the phase mismatch contributed from neutral dispersion, geometric dispersion and plasma dispersion, respectively, p is the pressure, ω is the focal spot radius and η is the ionization level. When the focal spot radius is measured value of 115 μm and the ionization level is 0.1-0.15%, the optimum Ne pressure for HHs at 245 eV is calculated as 201-343 Torr. This value is in good agreement with the optimized pressure shown in the Fig. 3 (b). Note that the absorption length of 220-Torr Ne gas is 2.5 mm at 240 eV.

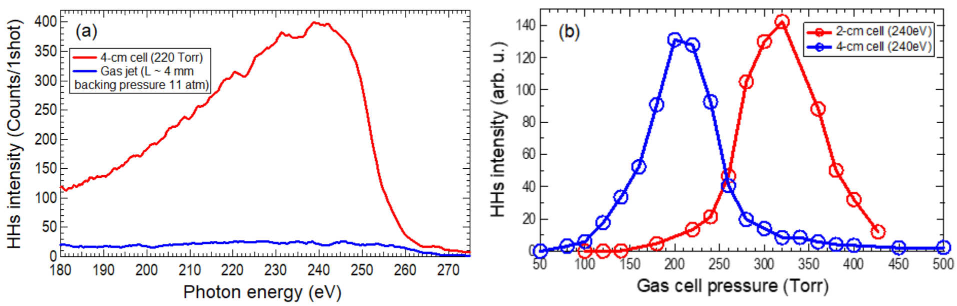

Fig. 3. HH spectra from neon (a). Dependence of a HH intensity at 240 eV as a function of a pressure in a gas cell (b).

4 Conclusions

We have generated high-flux soft x-ray HHs in a 4-cm-long Ne cell which is ~20 times stronger than that from a 4-mm-long gas jet. Our results proved that utilizing a loosely focusing method [2] for energy scaling of HHG is universally applicable to HHG, which is independent of a driving laser wavelength. In the next experiment, by loosely focusing our TW-class infrared femtosecond pulse at 1.65 μm into a long Ne medium, we expect to obtain a HH pulse in the "water window" region with ~10 nJ/order/shot as estimated based on our previous experiment [1].

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