Enhancement of high-order harmonics radiations around 13.5 nm by a long-interaction gas tube and its application to photoresist materials

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The generation of high-order harmonics (HH) in the interaction between an ultrashort optical laser pulse and rare gases has attracted lots of attention in the last two decades. In addition, their photon energies have been extended to keV region, and the pulse duration of a several tens attosecond has been achieved so far. The HH radiations, therefore, have pave the way to explore the electron dynamics in atoms and molecule with an adequate time resolution. The current issues are: (1) higher HH generation by using long wavelength drive laser, (2) single attosecond pulse, which provide readily understandable information on the X-ray and atom interaction, (3) increase of the HH photon number, especially, 13.5 nm (~59th order at 800-nm drive laser), where the HH can contribute to fundamental technology of efficient extreme ultraviolet (EUV) lithography. Among these, we have focused on the method, that is, X-ray parametric amplification (XPA) to much increase the HH intensity and demonstrated significant increase of HH signals [1-5]. In this study, we employed different approach to enhance the HH intensity, in which the drive laser traveled in 20 mm or 40 mm gas tube. Consequently, we have succeeded in drastically increasing the photon number around 13.5 nm HH lights.

The experiment was carried out at QST Kansai. The specification of an optical drive laser was Ti:S laser (center wavelength: 800 nm, pulse duration: 40 fs, beam diameter: 20 mm, maximum pulse energy: 40 mJ). The laser was focused onto the gas target with a focal length of 4 m (Rayleigh length: 40 mm). The gas targets were Mo tube of 20, 40 and 80 mm in length and their diameter was

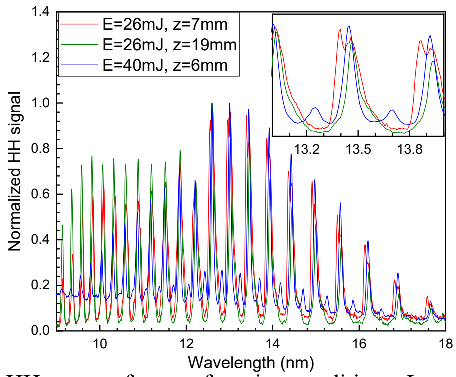

FIG.1 HH spectra for two focusing conditions. Laser pulse energies on target were 26 mJ or 40 mJ.

2.9 mm. The gas was supplied by a fast solenoid valve with various backing pressures. The valve opening time of ~5 ms contributed to suppress the HH absorption due to the gas. The HH spectra was measured with a grazing incident spectrometer with a spherical mirror, enabling us to estimate the beam divergence. Fundamental laser light was blocked by a thin Zr filter.

Figure 1 shows the HH spectra for 26 mJ at two laser focusing positions and for 40 mJ at z=6 mm measured relative to the best focal position. For 26 mJ laser energy, the low order HHs shift to shorter wavelength side (blue shift), while for higher orders they are almost at the same wavelengths or slightly red shifted. This indicates the present of the XPA contribution [6]. On the other hand, surprisingly, above 12 nm, the even order HHs appear.

Figure 2 shows the dependence of each HH signal on the gas valve pressures. With increasing gas pressure, HHs intensity around 63rd drastically increased between 0.2 and 0.25 bars. Both, pressure induced phase matching and XPA can be explanations. We perform numerical simulations including propagation effects for deeper understanding.

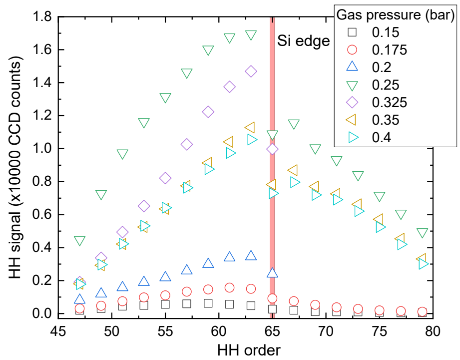

FIG.2 HH signal observed under various valve gas pressures.

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