Generation of Isolated Soft X-Ray Pulses Around the Carbon *K*-Edge Using CEP-Stabilized Few-Cycle IR Pulses

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Abstract: We demonstrate the generation of a 75-eV-wide continuum in the water window via HHG using CEP-stabilized, few-cycle IR pulses. A pressure dependence of harmonic spectra indicates sub-cycle deformation of IR pulses in the HHG process.
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1. Introduction

Ultrafast spectroscopy using femtosecond optical pulses has been widely exploited in the spectral regions from THz to ultraviolet. Recent advances in the generation of intense few-cycle pulses at 800 nm from Ti:sapphire lasers have triggered many researches in strong-field physics such as high harmonic generation (HHG), attosecond pulse generation, and their spectroscopic applications. However, the maximum photon energy of attosecond pulses has been limited up to 200 eV. To extend the spectral range of attosecond pulses, new light sources with a longer wavelength are required because the cutoff energy of high harmonics (HHs) is approximately proportional to the square of a driver's wavelength. Recent HHG experiments using IR or MIR light sources show the advantage of long-wavelength light sources for producing coherent radiation in a spectral range of up to 1.6 keV [1]. So far, the extension of the HH cutoff has been demonstrated by relatively long IR pulses without controlling the waveform of an electric field. The manipulation of the waveform of few-cycle laser pulses is a crucial point to obtain unprecedented time scales much shorter than the cycle period. Although many IR light sources have been developed so far [2], carrier-envelope phase (CEP)-dependent phenomena have not been observed at energy scales larger than 200 eV. It is because IR sources must meet simultaneously all the requirements such as (i) few-cycle pulse duration, (ii) CEP stabilization, (iii) mJ-class output energy, and (iv) high-repetition rate. We developed an optical parametric chirped pulse amplifier (OPCPA) by use of BiB_3O_6 (BIBO) crystals and Ti:sapphire lasers [3]. This light source is capable of delivering 9.0-fs, 0.55-mJ, CEP-stabilized optical pulses at a central wavelength of 1600 nm and a repetition rate of 1 kHz, satisfying all the requirements above.

In this presentation, we demonstrate CEP-dependent HHG in the water window using the IR light source mentioned above [4]. A collection of HH spectra acquired at different CEPs is well reproduced by simulations based on strong-field approximation. HH spectra possess two peaks with different cutoff energies, which are identified to be half-cycle cutoffs (HCOs) produced by two dominant electron trajectories in a few-cycle pulse driven HHG process [5]. The CEP-dependent spectra as well as the simulation results indicate that the confinement of soft x-ray emission in a single recombination event with a bandwidth of 75 eV around the carbon K edge. The control of HHG by the waveform of few-cycle infrared pulses is a key milestone to extend the spectral range of attosecond spectroscopy from the extreme ultraviolet to the soft x-ray region. We also measure a dependence of HCOs on the gas pressure, which indicates sub-cycle deformation of the waveform of the IR drive pulses in the HHG process.

2. CEP-dependent HHG

The output beam from the OPCPA source was focused by a spherical mirror (f = 375 mm, F/200) into a 1.4-mm-thick gas cell. The backing pressure of the cell was varied up to 1.4 atm. Generated HHs were spectrally dispersed by a soft x-ray spectrometer (SXR-II-1, Hettrick Scientific) and detected by an x-ray CCD camera. We changed the relative CEP value, $\Delta\varphi_{\mathrm{CEP}}$, of the IR pulses by a Dazzler (FASTLITE) in the OPCPA. Figure 1a presents a collection of HH spectra recorded every 0.1π rad of the CEP shift at a backing pressure of 0.6 atm. The two peaks are identified to be different HCOs originated from two electron trajectories in a few-cycle-pulse-driven HHG process. Using a few-cycle Ti:sapphire laser, a similar CEP dependence has been observed in the extreme ultraviolet [6]. The CEP scan measurement shows that the cutoff energies depend significantly on the CEP where the highest cutoff energy reaches ~325 eV. We found good agreement between the experimentally obtained HH spectra (Fig.1a) and SFA-based simulation (Fig.1b) assuming a pulse duration of 10 fs (FWHM of intensity), a peak intensity of 3.8×10^{14} W/cm^2, and a central wavelength of 1600 nm. To estimate the possible duration of the attosecond burst, we selected the spectral component with a 75-eV bandwidth as in Fig.1b (orange arrow). Figure 1c shows the calculated

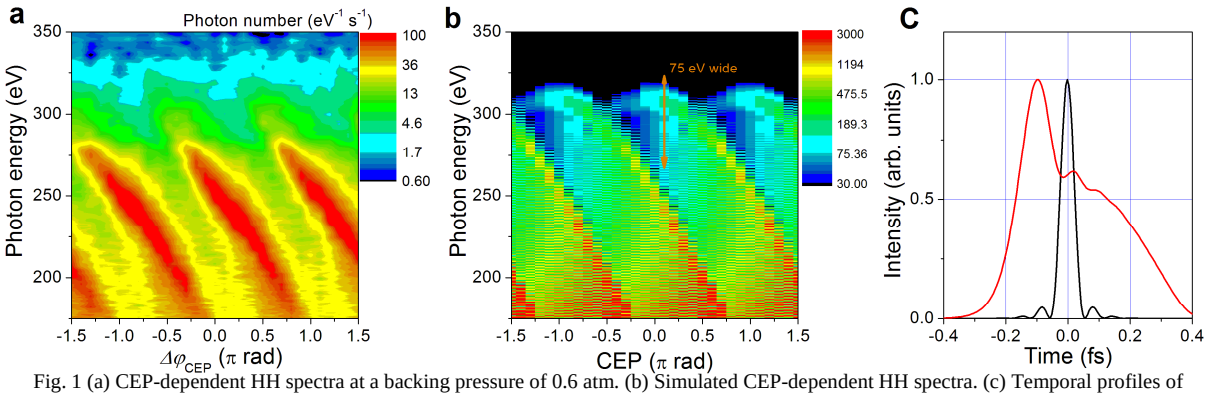

Fig. 1 (a) CEP-dependent HH spectra at a backing pressure of 0.6 atm. (b) Simulated CEP-dependent HH spectra. (c) Temporal profiles of an soft X-ray burst with chirp (red line) predicted by the simulation and without chirp (black line).

temporal profile assuming a single atomic response. The isolated pulse assuming potential attochirp from the simulation (Fig. 1c red line) would have a duration of about 300 as, which could be compressed down to 60 attoseconds as shown by the black line in Fig. 1c.

3. Pressure dependence of HH spectra

We also investigated a dependence of the HCOs on the target gas pressure. Figure 2a shows CEP-dependent soft x-ray spectra measured at a backing pressure of 1.0 atm. This CEP-dependence shows a similarity to that observed with a backing pressure of 0.6 atm as in Fig. 1a. However, the spectral widths of the half-cycle bursts were broadened and their locations were shifted horizontally by -(0.3-0.5)π rad depending on the photon energies. We scanned the backing pressure from 0.2 to 1.4 atm with a fixed CEP ($\Delta\varphi_{CEP}$ = -0.3π rad) as shown in Fig. 2b. By increasing the pressure from 0.2 to 0.4 atm, the on-axis intensity of HHs rapidly increased, which indicates the onset of self-guiding of the IR pulses [1]. The HH spectrum at 0.6 atm in Fig. 2b contains two HCOs located at approximately 180 and 280 eV. These two HCOs were shifted downward with different slopes when the gas pressure was increased. The lower-energy peak downshifts with a slope of -280 eV/atm (black dashed line in Fig. 2b), whereas the higher-energy peak with -130 eV/atm (black solid line in Fig. 2b). The down-shifts of HCOs indicate up-shift of the instantaneous frequency of the drive field in a half cycle. The difference in the slope for different half cycles reveals that the waveform of the IR pulses is affected by sub-cycle phase modulation by nonlinear processes such as self-phase modulation, self-focusing, and plasma effects. The peak power of the IR pulses was 38 GW, which is about two times more than a critical power of 21 GW for self-focusing when the pressure of neon is set at 1.0 atm [6]. In our method, gas pressure- and CEP-dependent HH spectra can be used to retrieve sub-cycle waveform deformation of drive pulses in the HHG process after more detailed analysis.

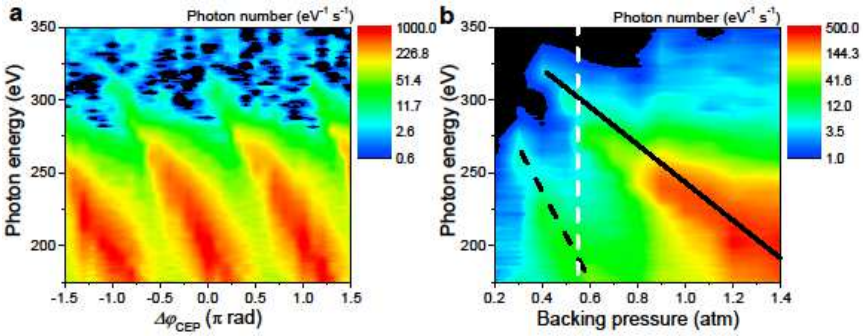

Fig. 2**a,** HH spectra recorded at a backing pressure of 1.0 atm. **b**, Pressure dependence of HH spectra. The black solid and dashed lines are drawn along the spectral peaks that originate from different HCOs. The white dashed line is drawn at the gas pressure of the self-focusing threshold (0.55 atm) when the critical power is identical to the peak power of the IR pulses (38 GW).

4. References

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