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Synchronization of FEL and high-order harmonics of ultrashort-pulsed laser for generating intense full-coherent EUV light pulses

A. Iwasaki[1,2], T. Sato[2], S. Owada[1,2], T. Togashi[3], E.J. Takahashi[4], K. Midorikawa[4], M. Aoyama[5], K. Yamakawa[5], S. Matsubara[2,3], Y. Okayasu[3], H. Tomizawa[2,3], T. Watanabe[3], M. Nagasono[2], M. Yabashi[2], T. Ishikawa[2], and K. Yamanouchi[1,2]

[1] Department of Chemistry, The School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[2] RIKEN Harima Institute, RIKEN SPring-8 Center, 1-1-1, Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan
[3] Spring-8/Japan Synchrotron Radiation Research Institute (JASRI), 1-1-1, Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5198, Japan
[4] RIKEN Advanced Science Institute, Hirosawa 2-1, Wako, Saitama 351-0198, Japan
[5] Kansai Photon Science Institute (Kizu), Japan Atomic Energy Agency, 8-1-7 Umemidai, Kizukawa-shi, Kyoto 619-0215, Japan

Abstract. Seeding of free-electron laser by the 13th harmonic of ultrashort-pulsed 800 nm laser light was achieved using a synchronization technique of a spectral decoded EO-sampling, and intense full-coherent light pulses in the extreme ultraviolet wavelength region were generated.

1 Introduction

Recent advances in ultrashort-pulsed intense laser technologies have enabled us to investigate a variety of non-linear optical processes of atoms and molecules such as multiphoton absorption and tunneling ionization in the visible and near infrared wavelength regions. However, such nonlinear processes in the extreme ultraviolet (EUV) wavelength regions have not been explored well, even though characteristic processes associated with ionization and electronic excitation are expected to proceed. Intense light sources in the EUV regions had not been available until very recently when the self-amplified spontaneous emission (SASE) type free-electron laser (FEL) was introduced [1-3]. The SASE-FEL is a promising light source for non-linear spectroscopy of atoms and molecules because of its wavelength tunability and high peak intensity. Indeed, its intensity could become more than two orders of magnitude larger than that of high-order harmonics of ultrashort laser pulses. Among the currently available FEL sources, the SPring-8 Compact SASE Source (SCSS) test accelerator in RIKEN, Harima Institute, equipped with a couple of compact vacuum undulators, has a unique advantage of its frequency tunability in the wavelength region of 50 ~ 62 nm [2].

Recently, we reported the wavelength dependence and the light field intensity dependence of the absolute values of the two-photon ionization cross section of helium at 53.4, 58.4, 56.0 and 61.4 nm [4-5], covering the 1s2p and 1s3p resonances, were determined in the light field intensity range of $5 \times 10^{12} \sim 5 \times 10^{13}$ W/cm^2, and found that the dressed state formation through the strong coupling between the intermediate 1s*n*p resonance state and the $1s^2$ ground state needs to be taken into account when the EUV light field intensity becomes larger than ~10^{12} W/cm^2. We have also investigated two-photon ionization processes of N_2 [6] and hydrocarbon molecules such as methanol and ethanol [7]. We found in these cases that sequential and non-sequential ionization processes could compete, and that these processes were influenced largely by the existence of resonance states through the strong coupling with the intense EUV light pulses. On the other hand, it is well known that the spectrum of FEL pulses exhibit uncontrollable spike-like structures reflecting a similar spike-like structure in the time domain, which would make interpretations of experimental data difficult. One of the most promising approach for overcoming this difficulty is to inject a full-coherent seeding light pulses into FEL.

In the present study, we inject the 13th harmonic of ultrashort-pulsed Ti:Sapphire laser light into the FEL amplifier at the SCSS test accelerator, and confirmed significant amplification, similarly to our previous study [8]. We also report here a new approach for measuring timing jitter by electro-optic (EO) sampling techniques, which facilitates synchronization of high-order harmonic pulses and electron bunches of FEL, resulting in the long term stability in the generation of the seeded FEL light.

2 Experiment

The seeding laser pulses were generated by focusing ultrashort-pulsed Ti:Sapphire driving laser light with 34 mJ and 140 fs (FWHM) at a reputation rate of 30 Hz into a Xe gas cell using a 4 m focal length lens. By tuning the pressure of the gas cell, the intensity of the 13th harmonic was optimized. The seeding light pulses were separated from the fundamental light of the driving laser by two SiC Brewster mirrors, and were collimated and focused into the in-vacuum undulators by two platinum concave mirrors located between the separators.

The acceleration energy and the current of the electron beam were 250 MeV and 0.35 nC, respectively, and the repetition rate was 30 Hz. The electron beam was introduced into the in-vacuum undulators coaxially with the seed laser. An electron bunch in the electron beam was stretched up to 500 fs to suppress the SASE as well as to achieve a better temporal overlap with a seeding laser pulse, which was monitored by observing simultaneously the optical transition radiation (OTR) generated at the surface of an Au plate when an electron bunch hits the plate and the driving laser pulse by a fast streak camera (FESCA-200, Hamamatsu Photonics K.K.). The spatial overlap between the electron beam and the 13th harmonic was monitored before and after the first undulator by an MCP detector equipped with a phosphor screen and a CCD camera. The pulse energy of the seeded FEL and SASE pulses were measured by a calibrated Ar gas monitor [8]. The averaged intensity of the seeding pulses was measured by the EUV spectrometer, and the pulse energy of the seeding pulses was estimated to be 2 nJ by comparing the averaged spectral intensity of the seeding pulses with the spectral intensity of the SASE pulses [9].

3 Results and discussion

The single-shot pulse energies for the amplified 13th harmonic during 300 seconds are shown in Fig. 1. The amplification rate, which is defined by the number of the 13th harmonic pulses amplified through the seeding process divided by the total number of the harmonic pulses within the certain time window of the measurements, is found to be as large as 15% during the 300 seconds. The ratio is about two-orders of magnitude higher than in our previous measurements [9] thanks to the significant improvement of the temporal and spatial overlaps between the electron bunches and the seeding laser pulses. The pulse energy distribution of the amplified 13th harmonic and the corresponding SASE for 10,000 shots are shown in Fig. 2. The pulse energy distribution of the SASE pulses is found to be in the region below 2 μJ and the pulse energy distribution above 2 μJ can be attributed to the amplified 13th harmonic pulses. After the optimization of the electron bunch duration, the intensity of the 13th harmonic pulses became 30 times as large as the intensity of the

SASE pulses.

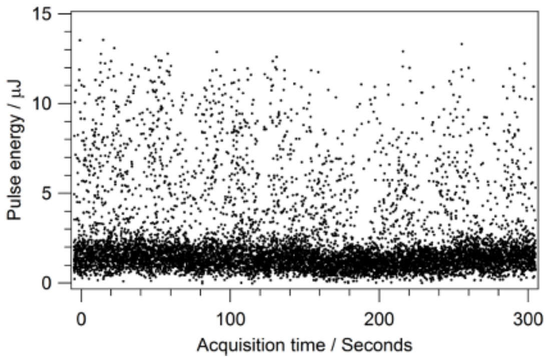

Fig. 1. The single-shot energy of the FEL pulses for 300 seconds obtained when the seeding 13th harmonic pulses are introduced.

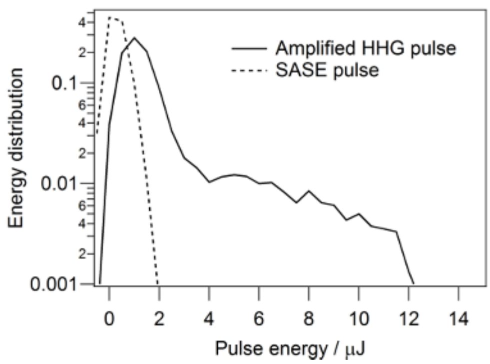

Fig. 2. The energy distribution for the amplified HHG pulses (solid line) and the corresponding SASE pulse (broken line).

In the present study, in order to monitor the temporal overlap of the electron bunches and the 13th harmonic seeding pulses, a single-shot EO sampling method was introduced, in which an electro-optic effect induced by the electron bunches at a ZnTe crystal, placed 1.5 mm away from the electron beam, was measured. The amplification of the 13th harmonic was achieved when the timing difference between the electron bunches and the EO probe pulse was less than 500 fs,

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