DEVELOPMENT OF FREE-ELECTRON LASERS USING TWO "HIGHER ORDERS" WITH THE STORAGE RING NIJI-IV

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Abstract

We developed higher-harmonic free-electron laser (FEL) oscillations with the storage ring NIJI-IV from the visible to near-infrared region. Using another “higher order”, that is, higher-diffraction order of the target wavelength of dielectric multilayer mirrors, we realized a lasing on the highest order in the harmonic FELs. Moreover, the FEL wavelength was shortened to the visible region in the NIJI-IV infrared FEL system. We demonstrated that wavelength regions of FEL oscillations could be selected by changing a condition of the optical cavity in the same conditions of the electron beam and insertion device. Our experimental results will give clues to realize a resonator-type FEL in the extreme ultraviolet and X-ray regions.

INTRODUCTION

A resonator-type free-electron laser (FEL) is superior for its highly coherence and stable lasing wavelength. Because it is necessary for the resonator-type FEL to use an optical cavity, it is thought that a lasing wavelength region of the resonator-type FEL is limited. However, a low-emittance and short-pulse electron beam is designed for an energy-recovery linac recently, so that FEL oscillations will be able to realize with a resonator in the extreme ultraviolet and X-ray regions. Utilization of higher harmonics of a spontaneous emission generated by an insertion device is effective for the resonator-type FEL to enhance a lasing wavelength region. Then, we developed the higher-harmonic FEL oscillations with using an infrared (IR) FEL system in the storage ring NIJI-IV [1]. It was clarified that there were differences between the fundamental harmonic and the higher harmonic FELs in their linewidths and pulse widths. Moreover, we achieved for the first time FEL oscillations with a higher-diffraction order of optical cavity mirrors [2]. Using the two ‘higher orders’ in the NIJI-IV IR-FEL system, we realized a lasing on the seventh harmonic [3], which was the highest order in the higher-harmonic FELs. In this article, we reported detailed characteristics of the higher-harmonic FEL oscillations with the higher-diffraction orders of the optical cavity mirrors.

NIJI-IV IR-FEL SYSTEM

The storage ring NIJI-IV has two 7.25 m straight sections in a circumference of 29.6 m. Short-wavelength FELs were developed with an optical klystron ETLOK-II installed in one of the straight sections in a wavelength region of 595−198 nm [4], which ranges from the visible to the vacuum ultraviolet. A planar optical klystron ETLOK-III, dedicated to development for IR FELs, was installed in another straight section [5]. It has two 1.4 m undulator sections comprised of seven periods and a 72 cm dispersive section. The maximum K value of the ETLOK-III is estimated to be 10.4 at the minimum undulator gap of 36 mm. IR FEL experiments were conducted with electron-beam energy of 310 MeV. Because the RF cavity voltage was low, approximately 20 kV, a natural bunch length was long, 90 ps, and the electron-beam current was less than 6 mA in a single-bunch operation. The relative energy spread of the electron bunch was 4.0×10^{-4} in the FEL experiments. The lasing wavelength region was reported to be from 838 to 1551 nm in the last FEL conference [6].

HIGHER-DIFFRACTION ORDER OF OPTICAL CAVITY MIRRORS

We used dielectric multilayer mirrors in the IR-FEL experiments as optical cavity mirrors. High reflectivity of the dielectric multilayer mirrors arises from constructive interference of lights reflected at consecutive interfaces of a multilayer structure. The designed high-reflectivity wavelength, or target wavelength, is four times the optical thickness of the layers [7]. If the absorptions of the two alternating dielectric materials are negligibly small, the high-reflectivity wavelengths are expected to appear at higher-diffraction orders having a positive odd number. However, the absorption of the dielectric multilayer mirrors at higher-diffraction orders is too large to oscillate storage ring FELs because the conventional target wavelengths are in the visible and ultraviolet regions. Therefore, to develop storage ring FEL oscillations in the middle-IR (MIR) region for the first time, we used niobium pentoxide (Nb_2O_5) and silicon dioxide (SiO_2) dielectric multilayer mirrors (radius of curvature, 8 m) manufactured by LAYERTEC (Germany) [8]. Figure 1 shows a cross-sectional image of the Nb_2O_5/SiO_2 dielectric multilayer mirror observed by field emission scanning electron microscopy (FE-SEM). It has 12 layers of Nb_2O_5 and 11 layers of SiO_2 stacked alternately on a 8.7 mm thick SiO_2 substrate. The thickness of a pair of the Nb_2O_5 and SiO_2 layers was uniform. The measured thickness was 0.75 μm, and the ratio of the thicknesses of the Nb_2O_5 and SiO_2 layers was 2:3. Because the target wavelength of the dielectric multilayer mirror was designed to be 2.56 μm, the refractive indices of Nb_2O_5 and SiO_2 were estimated to be 2.13 and 1.43, respectively, at this wavelength.

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ISBN 978-3-95450-123-6

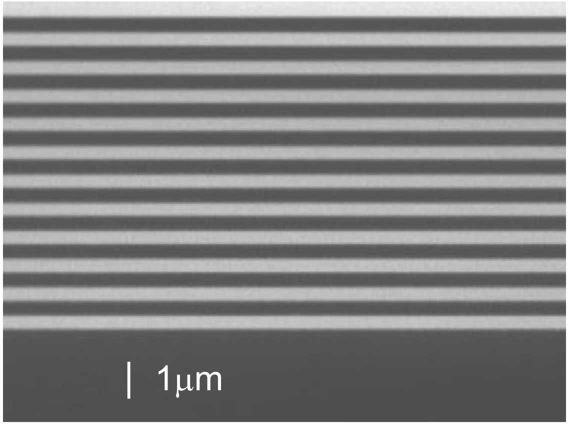

Figure 1: FE-SEM cross-sectional image of the Nb_2O_5/SiO_2 dielectric multilayer mirror. Bright gray and black images are Nb_2O_5 and SiO_2 layers, respectively.

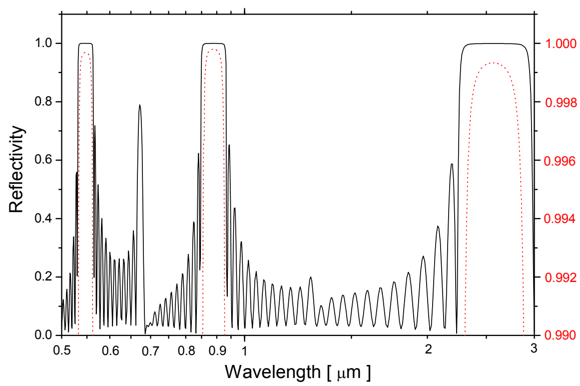

Figure 2: Calculated reflectivity of the Nb_2O_5/SiO_2 dielectric multilayer mirror (solid line). Reflectivity in the high-reflectivity wavelength region is expressed by dotted line (right vertical axis).

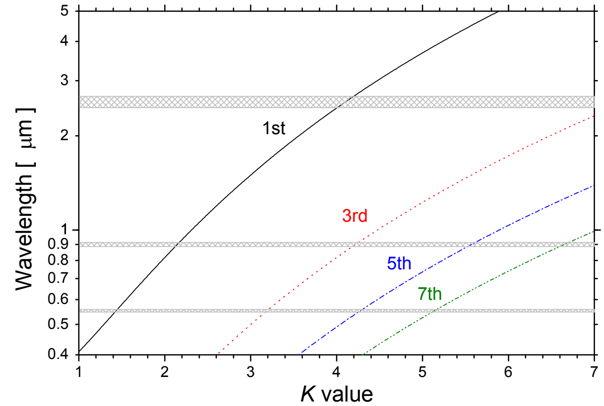

Figure 3: Relationship between the K value of the ETLOK-III and the wavelengths of the higher-harmonic FEL oscillations. Gray-mesh zones are high-reflectivity regions of the Nb_2O_5/SiO_2 dielectric multilayer mirror (> 99.9%).

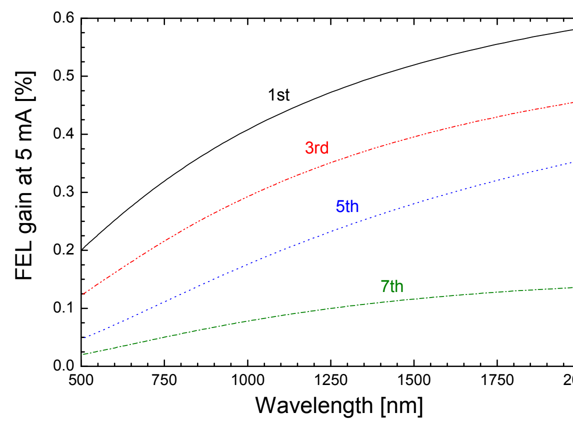

Figure 4: Calculated FEL gains at the beam current of 5 mA in the case of $g_d = g_u + 17$ for the fundamental harmonic and $g_d = g_u + 37$ for the higher (third, fifth and seventh) harmonics.

The reflectivity of a dielectric multilayer mirror can be calculated by the transfer matrix method [9]. Using dependences of refractive indices of Nb_2O_5 and SiO_2 on a wavelength in a reference [10], it is found that there are three high-reflectivity wavelength regions as shown in Fig. 2. Two high-reflectivity regions appear at wavelengths of around 0.89 and 0.55 μm, which correspond to odd number diffraction orders of the target wavelength. It is expected that near-IR and visible FELs can be obtained by using a pair of the dielectric multilayer mirrors that are optimized in the MIR region.

FEL GAIN

Adjusting the electron beam orbit to pass on the axis of the ETLOK-III, the K value of the ETLOK-III was limited in the single-bunch operation. FEL experiments in the IR region were conducted with the K value from 2 to 7 [3]. Figure 3 shows a relationship between the K value and the wavelength of the FEL oscillation. It is noted that an FEL can oscillate with using higher harmonics up to seventh order at a wavelength of around 890 nm and more than third order at a wavelength of around 550 nm. However, the dispersive section of the ETLOK-III cannot be opened more than 38 mm wider than the gap of the undulator sections. Then, the gap of the dispersive section can not be adjusted to an optimum value of N_d, which is the number of periods of the fundamental wavelength passing over an electron in the dispersive section, for the FEL gain in the higher-harmonic FEL experiments. Figure 4 shows a relationship between higher-harmonic FEL gains and a wavelength of the FEL oscillation. The higher-harmonic FEL gain considerably decreases in the visible region. Therefore, we conducted FEL experiments with using the higher harmonics up to seventh order at a wavelength of around 890 nm and third order at a wavelength of around 550 nm.

ISBN 978-3-95450-123-6

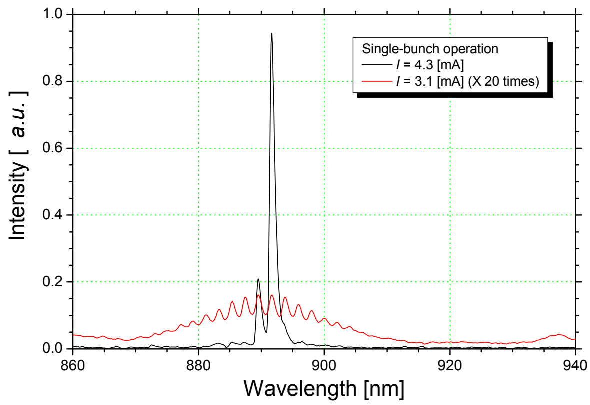

Figure 5: Measured spectra of the seventh-harmonic FEL oscillation (black line) and spontaneous emission (red line) at g_u = 62.7 mm. The red line is 20 times as large as the seventh-harmonic spontaneous emission.

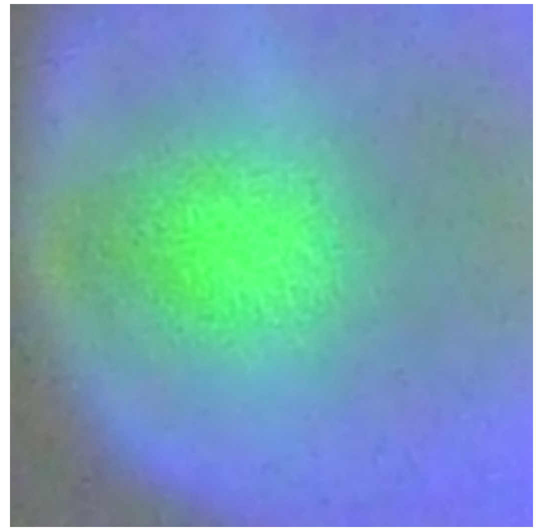

Figure 6: Photograph of the third-harmonic FEL oscillation at a wavelength of 552 nm. Electron- beam current was 3.0 mA.

7TH-HARMONIC FEL OSCILLATION

At first, we carried out the FEL experiments at wavelengths of around 890 nm, which correspond to the third diffraction of the target wavelength. The fundamental and third harmonic FEL oscillated until the electron-beam current decreased to 0.55 and 0.90 mA in the single-bunch operation, respectively. The measured threshold current showed good agreement with the calculated value. By increasing K value to 5.52 and 6.62, the FEL oscillations for the fifth and seventh harmonics were achieved at the wavelengths of approximately 890 nm [3]. Figure 5 shows the spectrum of the seventh-harmonic FEL oscillation, which is the highest achieved order in the higher-harmonic FEL oscillations. The measured threshold currents for the fifth and seventh harmonics were 1.5 and 3.8 mA, respectively, and they showed good agreement with the calculated values.

SHORTENING FEL WAVELENGTH

It is important to demonstrate that the higher harmonic can be used effectively to shorten the FEL wavelength. In the NIJI-IV IR-FEL system, no FEL had been developed in the visible region. Therefore, we planned experiments for the third-harmonic FEL oscillations using a pair of Nb_2O_5/SiO_2 dielectric-multilayer mirrors at wavelengths of around 550 nm, which corresponded to the fifth-diffraction order of their target wavelength of 2560 nm. We conducted the experiments of the third-harmonic FEL at a K value of 3.19, and we achieved FEL oscillations at wavelengths of 549.4–553.8 nm [11]. The FEL oscillation continued until the electron-beam current reached 2.3 mA. The minimum cavity loss was evaluated to be 0.07% from the threshold current at a wavelength of 552 nm. Figure 6 shows a photograph of the green FEL at a position 3.07 m away from the downstream cavity mirror. The FEL profile was almost a perfect TEM_{00} mode.

SELECTION OF THE FEL-WAVELENGT REGIONS

As reported in references [6, 11], we achieved FEL oscillations at wavelengths of 1510–1551 nm for a K value of 5.56–5.62. On the other hand, we achieved fifth-harmonic FEL oscillations at wavelengths of around 890 nm for a K value of 5.47–5.57. Therefore, the K value for the third-harmonic FEL at wavelengths of around 1520 nm partially overlapped with that for the fifth-harmonic FEL at wavelengths of around 890 nm. We demonstrated that wavelength regions of storage ring FELs could be selected by changing a condition of the optical cavity in the same conditions of the electron beam and insertion device. Even if the effective FEL gain was fixed, influence which an FEL oscillation gave to the electron beam was different for a higher-harmonic. For example, cavity-length detuning curves for the third and fifth harmonic FEL were different at the same effective FEL gain. We will report the differences in detail at another article.

CONCLUSIONS

We realized higher-harmonic FEL oscillations with using higher diffraction orders of a target wavelength of dielectric multilayer mirrors in the NIJI-IV IR-FEL system. Nb_2O_5/SiO_2 dielectric multilayer mirrors had three high-reflectivity wavelength regions from the MIR to the visible. Two high-reflectivity regions appear at wavelengths of around 0.89 and 0.55 μm, which correspond to the third and fifth diffraction orders of the target wavelength. FEL oscillations for the seventh harmonic, which was the highest order in the higher-harmonic FELs, were achieved at wavelengths of around 0.89 μm. The third-harmonic FEL oscillation was achieved at wavelengths of around 0.55 μm, which was

ISBN 978-3-95450-123-6

the shortest wavelength in the NIJI-IV IR-FEL system. Then, we demonstrated that the higher harmonic could be effectively used to shorten the FEL wavelength.

ACKNOWLEDGEMENTS

This work was supported by the Budget for Nuclear Research of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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ISBN 978-3-95450-123-6