THIRD HARMONIC LASING IN THE NIJI-IV STORAGE RING FREE-ELECTRON LASERS

N Sei#, K. Yamada, H. Ogawa,
Research Institute of Instrumentation Frontier, National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

Abstract

We report for the first time to our knowledge the experimental achievement of storage ring free-electron laser (FEL) oscillations on the third harmonic in the wide infrared region. The FELs were oscillated in the wavelength regions of 852-881 nm and 1510-1551 nm. The measured linewidth of the third-harmonic FEL was narrower than that of the fundamental FEL owing to the narrower spectral width of the spontaneous emission. The higher harmonic FEL oscillations will be useful for developing an x-ray FEL oscillation with the lower electron-beam energy.

INTRODUCTION

A higher-harmonic FEL oscillation has been studied for obtaining shorter-wavelength coherent light, such as coherent harmonic generation [1], high gain harmonic generation [2] and echo-enable harmonic generation [3]. The higher-harmonic FEL oscillation is superior to these techniques, which generate higher-harmonic spontaneous emissions, in terms of an average power and stability of the wavelength. Limitation of the FEL wavelength owing to cavity mirrors is regarded as a fault of the higher-harmonic FEL oscillation. Recently, however, an x-ray FEL oscillation (X-FELO) was proposed to obtain higher brilliance x-ray compared with the SASE [4]. When the higher-harmonic FEL oscillation is applied to the X-FELO, the electron-beam energy for oscillation in the x-ray region can be decreased.

Pioneer studies of the higher-harmonic FELs have been reported [5, 6], and several groups have been already achieved FEL oscillations on the fifth or lower harmonics [7-9]. Although these studies have contributed to the progress in FEL physics, differences between the higher-harmonic FEL and fundamental FEL have not been observed sufficiently. Thus, we developed an optical klystron ETLOK-III that was aimed at investigating higher-harmonic FEL oscillations [10]. The third-harmonic FEL oscillations have been achieved with it in wide wavelength regions of 852-881 nm and 1510-1551 nm [11]. In this article, the experimental results of the third-harmonic FELs are described in detail.

STORAGE RING NIJI-IV FEL

Although the NIJI-IV dedicated to FEL oscillations is a compact storage ring with a 29.6 m circumference, it has two 7.25 m straight sections [12]. Figure 1 shows the layout of the present NIJI-IV FEL system. The ETLOK-II, a 6.3 m optical klystron, is installed in one of these sections, and we achieved the first FEL oscillations with

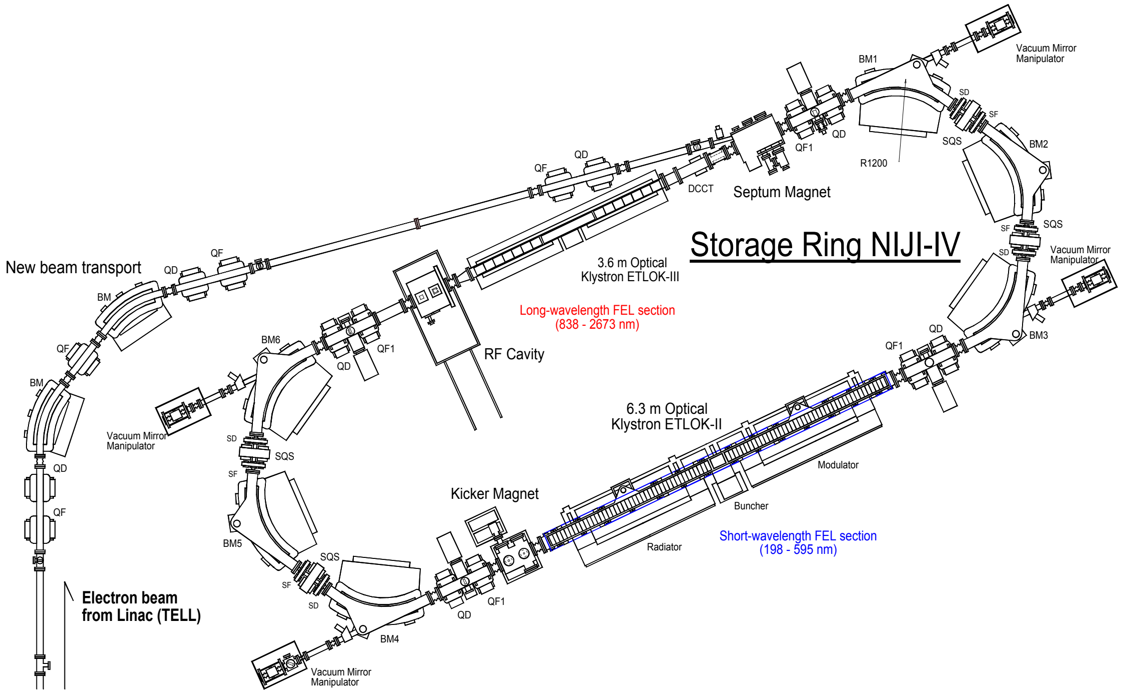

Figure 1: Layout of the NIJI-IV FEL system.

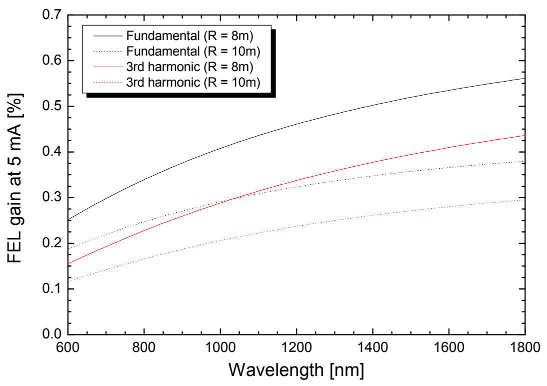

Figure 2: Calculated FEL gains in the case of $g_d = g_u + 17$ for the fundamental and $g_d = g_u + 37$ for the third harmonic. The electron-beam current and energy are 5 mA and 310MeV, respectively. A symbol R denotes radiuses of curvature of the cavity mirrors.

it at wavelengths of approximately 595 nm in 1992 [12]. We attempted to shorten the wavelength of FEL oscillations and achieved lasing at a wavelength of 212 nm, which was the shortest wavelength in FELs in 1998 [13]. The wavelength of the NIJI-IV FEL was shortened down to 197.6 nm in 2003 [14].

These successes suggested that an infrared (IR) FEL could be obtained with the NIJI-IV by developing a new insertion device in another straight section. We planed a new FEL project 'FEL-X' that was aimed at generating x-rays by FEL-Compton backscattering and demonstrating higher-harmonic FEL oscillations. The ETLOK-III, 3.6 m optical klystron, was installed into the straight section in 2004 [15], and new optical-cavity mirror chambers were installed at the end of the IR optical cavity in 2008. An IR FEL was achieved with the ETLOK-III at wavelengths of approximately 1450 nm in 2009 [10]. The IR FEL wavelength region is enhanced in 837.8-2673 nm [16], and energy of the FEL-Compton x-ray is from 0.7 to 2.1 MeV. The NIJI-IV is the first storage ring that has two types of FEL beam line, and the NIJI-IV FELs are oscillated from the mid IR to the vacuum ultraviolet regions.

FEL GAIN

Experiments of higher-harmonic FEL oscillations were conducted at the same electron-beam energy of 310 MeV. When the characteristics of the electron-beam are fixed, an FEL gain on the nth harmonic G_n is given by an FEL gain on the fundamental harmonic G_1 as

$$G_n = \frac{F_n(K_n)\, f_n}{F_1(K_1)\, f_1} n G_1, \tag{1}$$

$$F_n = \frac{4n^2 K_n^2}{\left(2+K_n^2\right)^2}\left[J_{n+\frac{1}{2}}\left(\frac{nK_n^2}{4+2K_n^2}\right) - J_{n-\frac{1}{2}}\left(\frac{nK_n^2}{4+2K_n^2}\right)\right]^2, \tag{2}$$

$$K_n = \sqrt{2\left(\frac{2+K_1^2}{2}n - 1\right)}, \tag{3}$$

where n is a positive odd number [11]. It is assumed that whole higher-harmonic FELs oscillate at the same wavelength. The modulation rate for the nth harmonic f_n is experimentally determined by $(S_+ - S_-)/(S_+ + S_-)$ where S_+ and S_- are the successive maximum and minimum of the amplitude of the spontaneous emission spectrum. It is approximated to $f_{\gamma n}$, which is the most important part of reduction of the modulation rate. This factor represents a contribution of the energy spread of the electron beam without an FEL oscillation, $\sigma_{\gamma 0}/\gamma$, and is given by

$$f_n \cong f_{\gamma n} = \exp\left[-8\pi^2 n^2 \left(N_u + N_d\right)^2 \left(\frac{\sigma_{\gamma 0}}{\gamma}\right)^2\right], \tag{4}$$

where N_u is the number of periods in one undulator section and N_d is the number of periods of the fundamental wavelength passing over an electron in the dispersive section.

In the case of the NIJI-IV FEL system, the energy spread is 4.0×10^{-4} at the electron-beam energy of 310 MeV [10]. Therefore, the optimum value of $n(N_u + N_d)$ for the FEL gain is evaluated to be approximately 200. However, there is a lower limitation in the value of $n(N_u + N_d)$ due to a variable space of the dispersive section of the ETLOK-III. A gap of the dispersive section g_d is limited as

$$42 \le g_d \le g_u + 38, \tag{5}$$

where g_u is a gap of the undulator section [17]. The ratio of the FEL gain for the third harmonic to that for the fundamental harmonic becomes small in the shorter-wavelength region due to the large $n(N_u + N_d)$. However, the gain for the third harmonic is expected to be approximately two thirds of that for the fundamental harmonic in the IR region as shown in Fig. 2. Using high-reflectivity mirrors for the optical cavity, it is possible to oscillate the third-harmonic FEL with the NIJI-IV FEL system in the IR region.

THIRD HARMONIC FEL OSCILLATION

Dielectric multilayer mirrors, which were deposited with Ta_2O_5 and SiO_2 alternately, were prepared as cavity mirrors for the FEL experiments at wavelengths of 870 and 1530 nm. The radiuses of curvature of the mirrors were 10 m for the 870 nm wavelength and 8 m for the 1530 nm wavelength. A cavity loss l_c was evaluated by measuring the pulse shape of the resonant light transmitted from the cavity mirror with a streak camera while detuning the cavity length [11]. Figure 3 shows the dependence of the cavity loss on the wavelength of approximately 870 nm. It was noted that an initial cavity loss was minimized at a wavelength of 860 nm and the optimum wavelength changed to 880 nm due to the exposure of the klystron radiation to the cavity mirrors. Because the cavity-mirror degradation quickly saturated at the optimum wavelength, the cavity loss was estimated to be approximately 0.10%. Then, threshold currents were estimated to be 1.9 and 3.0 mA for the FEL oscillations on the fundamental and third harmonics, respectively. Although a cavity loss for the 1530 nm mirrors could not

ISBN 978-3-95450-117-5

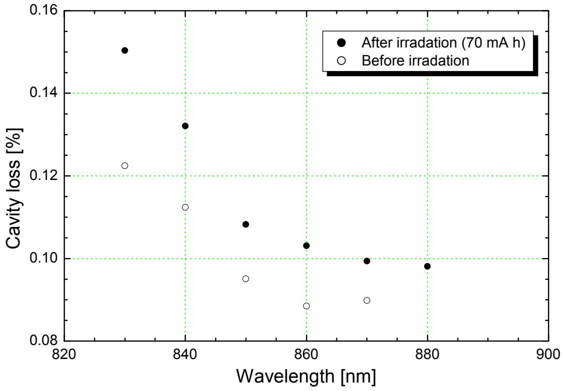

Figure 3: Measured cavity losses at the wavelengths of around 870 nm before (open circle) and after (solid circle) exposure of the klystron radiation.

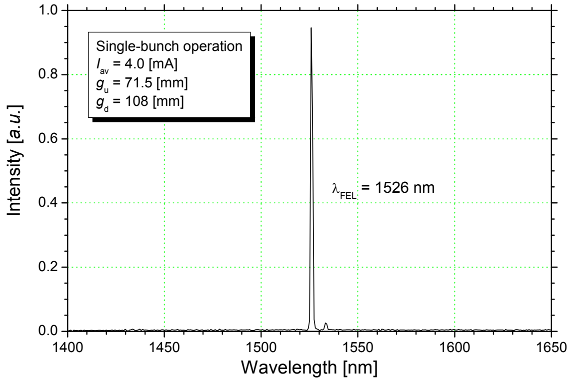

Figure 4: Observed spectrum of the third-harmonic FEL at a wavelength of around 1530 nm for the undulator gap of 71.5 mm and the dispersive gap of 108 mm.

be measured due to poor sensitivity of the streak camera, it was supposed to be approximately 0.10% because the both mirrors were made of the same material and were made by the same manufacturing method.

As mentioned above, the experiments of higher-harmonic FEL oscillations were conducted at the energy of 310 MeV in a single-bunch operation. For the mirrors optimized at 860 nm, the fundamental FEL achieved lasing at g_u of around 123 mm and the third-harmonic FEL achieved lasing at g_u of around 87 mm. The threshold currents for the fundamental and third harmonics were 2.3 and 3.5 mA, respectively. They were roughly in agreement with the threshold currents estimated from the cavity loss. Average FEL power transmitted from a vacuum window of the upstream cavity-mirror chamber was measured by using a calibrated power detector (COHERENT, USA). The FEL power for the fundamental and third harmonics at the electron-beam current of 5.9 mA was 39.9 and 8.1 μW, respectively. The FEL power per electron-beam current was roughly in proportional to Ln(G_n/l_c)/ $n(N_u + N_d)$ [14].

For the mirrors optimized at 1530 nm, the fundamental FEL achieved lasing at g_u of around 103 mm and the

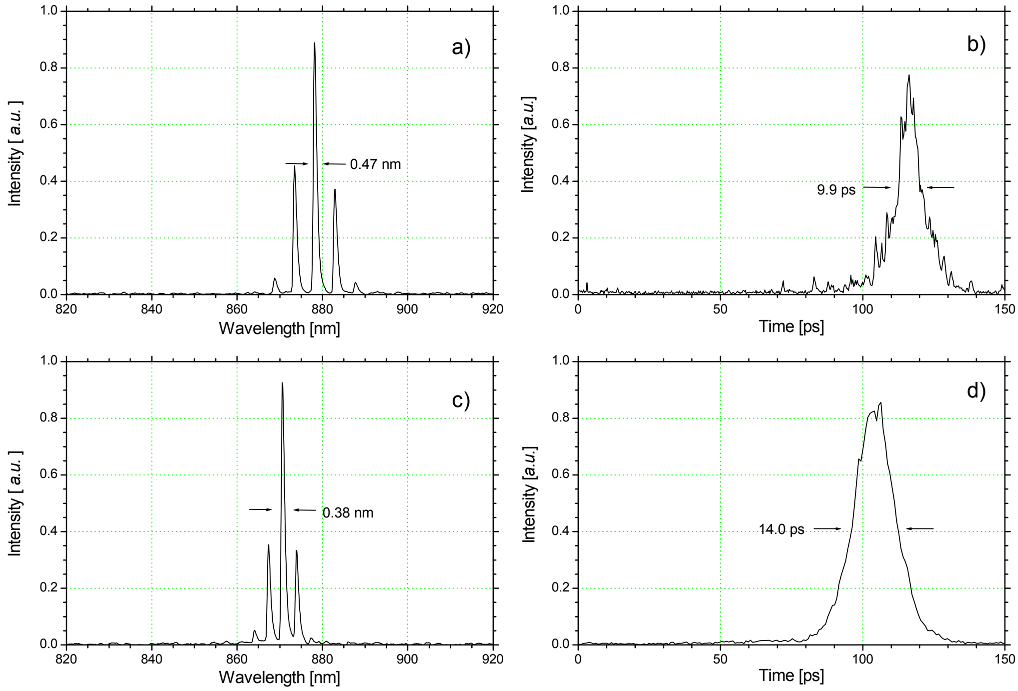

Figure 5: Measured spectrum (a) and pulse shape (b) for the fundamental FEL oscillation and measured spectrum (c) and pulse shape (d) for the third-harmonic FEL oscillation. The electron-beam currents were 3.4 (a), 3.1 (b), 5.0 (c) and 4.6 (d) mA, respectively.

ISBN 978-3-95450-117-5

third-harmonic FEL achieved lasing at g_u of around 71.5 mm. Figure 4 shows an example of a spectrum of the third-harmonic FEL oscillation at the current of 4.0 mA in the single-bunch operation. The threshold currents for the fundamental and third harmonics were 1.0 and 1.6 mA, respectively. The cavity loss of the 1530 nm mirrors was estimated to be 0.13% from the threshold current of the fundamental FEL. The average FEL power for the fundamental and third harmonics at the electron-beam current of 3.0 mA was 120 and 30 μW, respectively. The FEL power at the wavelength of 1530 nm was higher than that at the wavelength of 870 nm because of the higher FEL gain and higher transmission of the cavity mirrors. We obtained the fundamental FEL power more than 1.5mW at the wavelength of around 1530 nm in a three-electron-bunch operation for the FEL-Compton experiment.

LINEWIDTH AND PULSEWIDTH

Linewidths of the FELs at the wavelengths of around 870 nm were measured by a polychromator with a resolution of 0.83 nm. Moreover, pulse widths of the FELs at the wavelengths of around 870 nm were measured by a dual-sweep streak camera with a resolution of 2 ps [11]. Figure 5 shows spectra and pulse shapes of the FEL oscillations for the fundamental and third harmonic. In order to compare the characteristics of the third-harmonic FEL with those of the fundamental FEL, the effective FEL gain for the third harmonic was set to be equal to that for the fundamental harmonic in the measurements. The linewidths calculated by considering the resolution of the detector for the fundamental and third harmonic FELs, denoted by $\Delta\lambda_{F1}$ and $\Delta\lambda_{F3}$, were 0.47 and 0.38 nm in full width at half maximum, respectively. It is noted that the linewidth of the third-harmonic FEL was narrower than that of the fundamental FEL. The reason is that peak interval of the spontaneous emission spectrum for the third harmonic ($\Delta\lambda_{P3}$ = 3.3 nm) is narrower than that for the fundamental harmonic ($\Delta\lambda_{P1}$ = 4.6 nm) due to the higher $n(N_u + N_d)$. In the recent experiments using an improved spectroscopic system with a higher resolution, a ratio $\Delta\lambda_{F3}/\Delta\lambda_{F1}$ was almost equal to $\Delta\lambda_{P3}/\Delta\lambda_{P1}$. The pulse widths calculated by considering the resolution of the detector for the fundamental and third harmonic FELs, denoted by Δt_1 and Δt_3, were 9.9 and 14.0 ps in full width at half maximum, respectively. It was noted that a ratio $\Delta t_3/\Delta t_1$ was almost equal to the reciprocal of $\Delta\lambda_{P3}/\Delta\lambda_{P1}$. This fact suggests that the linewidth and pulse width can be changed by selecting the order of higher harmonic in the FEL oscillations.

CONCLUSIONS

We achieved storage ring FEL oscillations on the third harmonic in the wide IR region. The measured FEL gain for the third-harmonic FEL oscillation was agreement with that calculated by the one-dimensional FEL theory. The higher-harmonic FEL was demonstrated to be useful for controlling characteristics of the FEL.

The technique of the higher-harmonic FEL oscillation is useful to realize a resonator-type FEL with lower electron-beam energy in the EUV and x-ray regions. We expect that our results will lead to develop such the high-power short-wavelength FEL.

ACKNOWLEDGMENTS

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

REFERENCES

[1] J. M. Ortega *et al*, IEEE J. Quantum. Electron. **21** (1985) 909.
[2] G. De Ninno *et al*, Phys. Rev. Lett. **100** (2008) 104801.
[3] G. Stupakov, Phys. Rev. Lett. **102** (2009) 074801.
[4] K. J. Kim *et al*, Phys. Rev. Lett. **100** (2008) 244802.
[5] W. B. Colson, IEEE J. Quantum. Electron. **17** (1981) 1417.
[6] E. Jerby and A. Gover, Nucl. Inst. and Meth. A **250** (1986) 192.
[7] S. V. Benson and J. M. J. Meday, Phys. Rev. A **39** (1989) 1579.
[8] R. W. Warren *et al*, Nucl. Inst. and Meth. A **296** (1990) 84.
[9] G. R. Neil *et al*, Phys. Rev. Lett. **87** (2001) 084081.
[10] N. Sei *et al*, Opt. Lett. **34** (2009) 1843.
[11] N. Sei *et al*, J. Phys. Soc. Jpn. **79** (2010) 093501.
[12] T. Yamazaki *et al*, Nucl. Inst. and Meth. A **331** (1993) 27.
[13] K. Yamada *et al*, Nucl. Inst. and Meth. A **445** (2000) 173.
[14] K. Yamada *et al*, Nucl. Inst. and Meth. A **528** (2004) 268.
[15] N. Sei *et al*, Jpn. J. Appl. Phys. **41** (2002) 1595.
[16] N. Sei *et al*, "Lasing of middle-infrared free electron lasers using the storage ring NIJI-IV", Opt. Lett. ID:148319, *in press*.
[17] N. Sei *et al*, Infrared Phys. Technol. **51** (2008) 375.

ISBN 978-3-95450-117-5