RECENT PROGRESS IN INFRARED FEL AND COMPTON BACKSCATTERING EXPERIMENT AT THE STORAGE RING NIJI-IV

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Abstract

Recently, an FEL in the near-infrared (IR) region was oscillated at a compact storage ring NIJI-IV. We have been developed a device for the storage ring FEL in the IR region with a 3.6-m optical klystron ETLOK-III, and the first lasing at a wavelength of around 1450 nm was achieved in 2009. The maximum power of the FEL was 0.3 mW per vacuum window and the relative linewidth was $3x10^{-4}$ [1]. Moreover, X-ray/gamma-ray beam was also produced in the long straight section of NIJI-IV by Compton backscattering of the intra-cavity IR FEL and the stored electron beam with an energy of 310 MeV. After the first lasing experiment, we have successfully performed to extend the lasing wavelength region to mid-IR region in this year.

INTRODUCTION

A storage-ring free-electron laser (SRFEL) has been developed with a storage ring NIJI-IV at National Institute of Advanced Industrial Science and Technology (AIST). The NIJI-IV is a compact storage ring with circumference of 29.6m, but it has two 7.25-m long straight sections. A part of the NIJI-IV FEL system is illustrated in Fig. 1, including two optical klystrons. A 6.3-m optical klystron ETLOK-II has been installed in one of the long straight section. It has two 3.0m-undulator sections with 42 magnet periods and the length of dispersive section is 216mm. An FEL in the region of visible to vacuum-ultra violet (VUV) wavelength has been investigated with ETLOK-II [2-6]. FEL lasing has been achieved at wavelength of 198-595 nm. We made use of the deep ultraviolet (DUV) FEL as an excitation source for a photoelectron emission microscopy (PEEM), and real-time observation of chemical reactions on the transition metal surface was performed [7].

On the other hand, we are also trying to extend the lasing wavelength towards IR region. SRFELs have an advantage of a good spectral stability and narrow line width compared with FELs based on linear accelerators. A 3.6-m optical klystron ETLOK-III [8] was installed in the other straight sections, in 2004 [9,10]. The number of magnetic periods in a 1.4-m single undulator section is 7 with the periodic length of 200 mm and the length of dispersive section is 720 mm. The K value can be adjusted from 1.27 to 10.4 and the corresponding range of fundamental wavelength of spontaneous emission is 0.5 – 15 μm at the electron-beam energy of 310 MeV.

The length of optical cavity is 14.8 m which is half of the circumference of NIJI-IV. To stabilize FEL oscillation, we designed a robust optical cavity system. The dielectric multi-layer mirrors were set in the mirror chamber and were remotely manipulated by five-axis stage. The cavity length and tilt angle of mirrors can be adjustable with resolutions of 0.1 μm and 0.4 μrad, respectively. To suppress low frequency vibration, vibration damper was installed between vacuum chamber of the storage ring and the mirror chamber whose stand was the granite base stone with a weight of 1.3 ton.

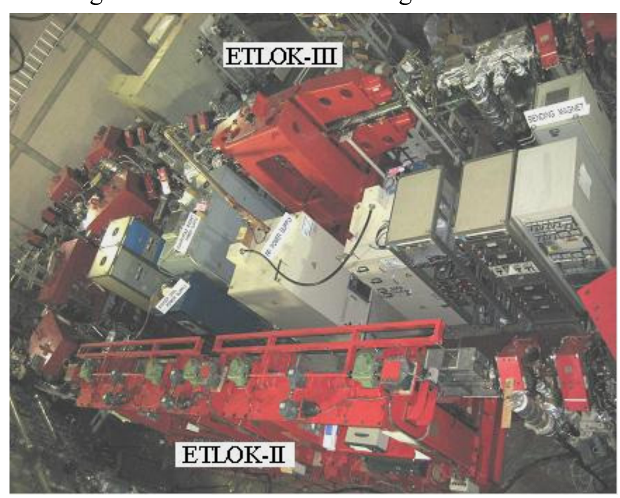

Figure 1: Photograph of storage ring NIJI-IV.

FIRST LASING OF INFRARED FEL AT NIJI-IV

We performed the FEL experiment at a wavelength of around 1450 nm. The cavity loss of the mirror optimized at a wavelength of 1450 nm was evaluated to be smaller than 0.18 %. The maximum FEL gain was expected to be about 0.5% at a beam current of 5 mA, so that it would be possible to realize FEL oscillation even if in low electron beam current. During the IR FEL experiments, both the optical transverse mode and cavity length were precisely adjusted by observing the third harmonic. Then, we achieved the first lasing of near-IR FEL at a wavelength of around 1450 nm on February 12, 2009 [1]. Figure 2 shows the FEL spectrum measured using a spectrometer with a resolution of 1.1 nm. The relative line width was evaluated to be only $3x10^{-4}$. This value is much smaller than the typical relative linewidth of 10^{-3}–10^{-2} in the

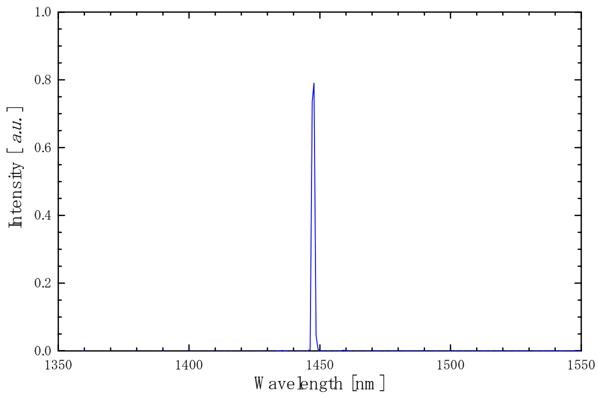

Figure 2: FEL spectrum observed in the near-IR region.

Linac FELs. The FEL oscillated in the wavelength region of 1392–1502 nm by adjusting the undulator gap. Figure 3 shows the dependence of the measured FEL power through the upstream vacuum CaF_2 window on the electron-beam current. We observed the FEL oscillations at an electron-beam current less than 5.2 mA in this experiment, so that the maximum power of the FEL was evaluated to be 0.3 mW per vacuum window.

After the first lasing experiment, we carried out FEL experiments in the near and mid-IR region to extend the lasing wavelength region. As for the near-IR region, the lasing was achieved down to a wavelength of 0.84 μm by changing the optical cavity mirrors. Moreover, efforts have been made to achieve mid-IR FEL oscillations using ETLOK-III. A system of high efficiency spectrometer in the mid-IR region was developed to observe low-power spectra, and we could confirm the lasing at a wavelength of 2.63 μm on January 19, 2010. The oscillation of mid-IR FEL was achieved up to 2.65 μm. The detail will be reported elsewhere.

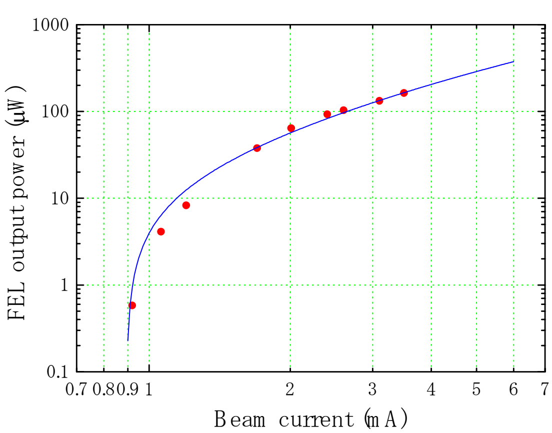

Figure 3: Dependence of the average FEL power on the electron-beam current

FEL-COMPTON SCATTERING EXPERIMENT

The IR FELs were applied to FEL-Compton scattering experiments [11-13]. We have proposed production of tunable and quasimonochromatic hard X-rays including energy range of 0.3 – 1 MeV where conventional light sources cannot provide the sufficient amounts of photons [4,8,14].

The energy of the backscattered photon, E_γ, for a head-on collision in the laboratory frame is given by

$$E_\gamma = \frac{(1+\beta)E_L}{1-\beta+(2E_L/m_e c^2)\sqrt{1-\beta^2}}, \quad (1)$$

where β is the ratio of the electron and light velocities and E_L is photon energy of FEL, and $m_e c^2$ is the electron energy at rest ($m_e c^2 = 0.511$MeV). In Fig. 4, E_γ is plotted as a function of FEL wavelength. At present, the lasing range of fundamental wavelength using ETLOK-III is 0.84 – 2.65 μm, so that the corresponding range of E_γ is 0.7 – 2.2 MeV with an electron beam energy of 310 MeV.

At the NIJI-IV FEL, there are magnet-free collision points of FEL pulse and electron bunch, because the length of ETLOK-III is less than half of the long straight section. This enables us to make an intense X-ray/gamma-ray beam production. The storage ring was operated with a two or three electron-bunch beam and the collision points were selected by choosing the beam-filling pattern. The X-ray/gamma-ray beam was generated outside ETLOK-III in a magnetic field-free region and detected by using $LaBr_3$(Ce) scintillation detector after passing through a lead collimator as illustrated in Fig. 5.

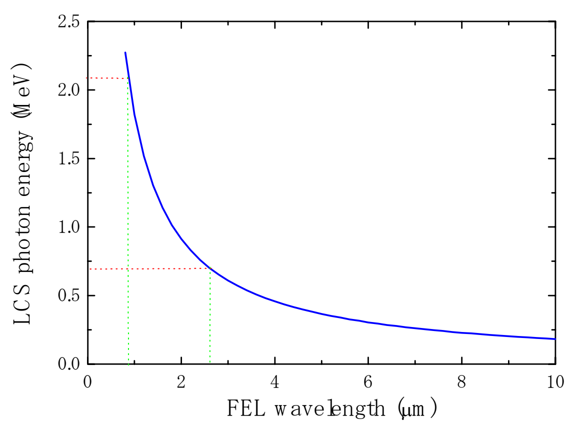

Figure 4: Energy of Compton backscattering photon as a function of an FEL wavelength with an electron energy of 310MeV

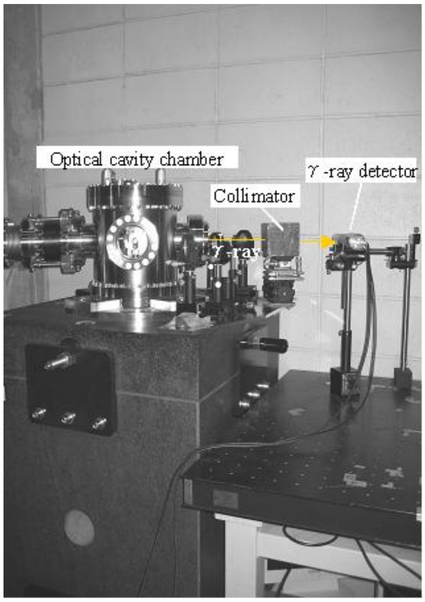

Figure 5: Experimental setup for FEL Compton backscattering measurement.

Figure 6 shows an observed spectrum of 1.2-MeV gamma-ray beam produced by Compton backscattering of FEL at 1.5 μm and an electron beam at 310 MeV. The gamma-ray beam is nearly monochromatic, and the signal in the low energy region is gamma-ray event without full-energy deposition in the detector due to the detector response.

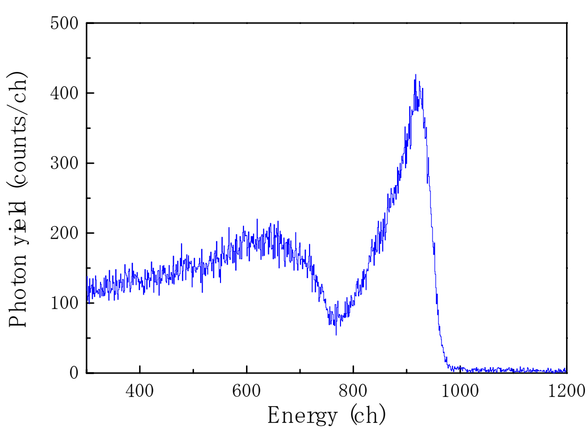

Figure 6: Typical measured energy spectrum of gamma-ray generated by FEL-Compton scattering

By tuning wavelength of near-IR FEL, study of generation of gamma-ray beam was carried out and we obtained the maximum energy of gamma-ray beam as 2.1 MeV using ETLOK-III. Moreover, we tried to produce low energy gamma-ray beam less than 1 MeV by using mid-IR FEL, and successfully performed to generate 0.7-MeV photon beam in February 2010.

SUMMARY

SRFELs are being developed at wavelengths ranging from the IR to VUV, based on the compact storage ring NIJI-IV. In this study, we carried out lasing experiments in the near and mid IR region using the optical klystron ETLOK-III. FEL lasing was achieved at a wavelength region of 0.84 – 2.65 μm. In addition, FEL-Compton backscattering experiment was performed using the IR FEL, production of X-ray/gamma-ray beam with an energy of 0.7 – 2.1 MeV was observed.

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