TUNABILITY AND POWER CHARACTERISTICS OF THE LEBRA INFRARED FEL

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Abstract

The use of the infrared (IR) Free-Electron Laser (FEL) in medical science and material science started in October 2003 at the Laboratory for Electron Beam Research and Application (LEBRA) of Nihon University. The FEL resonator which consists of silver-coated copper mirrors has demonstrated a wavelength tunability ranging from 0.9 to 6.5 μm as a function of the electron energy and the undulator *K*-value. The wavelength dependence of the FEL output power has been measured in terms of different electron energies and different undulator *K*-values. At about 2 μm, an FEL energy of roughly 25 mJ/macropulse has been obtained at the FEL monitor port, which corresponds to the peak power of 1 to 2 MW, provided that the FEL pulse length is less than 0.5 ps that resulted from the measurement by the autocorrelation method. A power decrease observed in the long-wavelength range has resulted from the wavelength dependence of the coupling coefficient of the FEL resonator mirror and the transport efficiency of the FEL guiding optics.

INTRODUCTION

Since the first lasing at 1.5 μm by the LEBRA FEL system in 2001 [1], efforts have been made to achieve the saturation of the FEL power, and to stabilize the pulse-to-pulse power level.

In the early lasing experiment in the infrared region, the FEL resonator consisted of dielectric multilayer mirrors optimised for lasing at a narrow wavelength range of around 1.5 μm. The mirrors were easily damaged by a high optical power. However, this suggested that the property of the LEBRA FEL system including the electron beam is sufficient for intense lasing.

The resonator mirrors were changed to silver-coated copper mirrors in August 2003, which was intended to bring about an early beginning of user's experiments by a wide-range variability of the FEL wavelength and a high mirror tolerance for an intense FEL power. The FEL beam has been extracted from the mirror placed upstream from the undulator through a small coupling hole, and the FEL beam has been successfully transported to user's experimental rooms by the optical guiding system. The user's experiments in medical science and material science began in October 2003.

This paper reports on the improvement of the LEBRA FEL system, the result of the experiments on the wavelength variability and the power characteristics. The current specifications and arrangement of the FEL system are expressed elsewhere [2].

IMPROVEMENT OF THE FEL SYSTEM

Lasing by dielectric multilayer mirrors

Improvement of the FEL power stability has been an important problem for user's experiments. The uniformity of the electron beam energy and current in macropulse duration was improved by the reduction of the phase fluctuation of the accelerating rf in the linac [3]. Although it contributed to the increase of the FEL power, the improvement did not show a significant effect on the stability. Use of the dielectric multilayer mirrors with insufficient tolerance for high power FEL resulted in damage to the mirrors by the FEL before its saturation, which led to difficulty in the investigation of the stability.

In a series of lasing experiments using the dielectric mirrors, the 1.5 μm FEL was observed by detecting the light transmitted through one of the mirrors, where only a fraction of the light beam stored in the resonator was detected using the transmission property of the mirrors.

Vibration and drift of the mirrors

Besides the tolerance for the optical power, there were problems of the vibration of the mirrors and the drift of the mirror separation, which was found from the observation of the interference pattern by the alignment laser lights that reflected on the two mirrors in the resonator [4]. The drift of the mirror separation resulted from a change in room temperature. However, the behaviour of the temperature dependence has not yet been well understood. The slow drift of the mirror separation has been compensated for by adjusting a piezo device manually. The vibration of the mirrors resulted from the vibration of the mirror chambers, which was caused by the water flow for cooling of the bending magnets in the beam transport line, which suggested a lack of flexural rigidity of the mirror chamber's frame bases. The amplitude of the vibration in the bases, measured with a laser displacement gauge, was suppressed from several hundred nm to within 20 nm (limit of measurement) by the reinforcement of the frames, which was made with 6-mm thick steel plates attached to the side faces of the bases.

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Lasing by silver-coated copper mirrors

The FEL guiding optics system for user's experiments was constructed in June 2003. This system was designed to use an external-coupling mirror which has a small coupling hole. Since August 2003 the silver-coated copper mirrors have been used for the lasing experiments corresponding to the new optical guiding system. The nominal reflectance for the mirrors is greater than 99.3 % in the wavelength range longer than 0.9 μm. The FEL has been extracted from the mirror placed upstream from the undulator through a coupling hole of 0.15 mm in radius.

The silver-coated copper mirrors demonstrated a high performance. The saturation of the FEL power has been observed for the wavelength range from 0.9 to 6.5 μm. There has been no evidence of damage so far by the saturated FEL power.

Provided that the FEL in the resonator is a Gaussian beam, the coupling coefficient κ of the coupling hole is given by [5]

$$\kappa = 1 - \exp(-2a^2 / w^2)\,, \tag{1}$$

where a is the radius of the coupling hole, w the FEL beam radius on the surface of the resonator mirror that is given as a function of the FEL wavelength λ_L, the Rayleigh length L_R in the resonator and the separation D between the two resonator mirrors by

$$w = \sqrt{\frac{\lambda_L L_R}{\pi}\{1 + (D/2L_R)^2\}}\,. \tag{2}$$

Using the parameters for the LEBRA FEL system, D = 6.718 m and L_R = 1.47 m, the wavelength dependence of the coupling coefficient is approximated as

$$\kappa = 0.687 \frac{a^2}{\lambda_L}\,, \tag{3}$$

where the units of a and λ_L are mm and μm, respectively. For instance the coupling coefficient of the 1.5 μm FEL is 0.0103.

The divergent FEL beam extracted from the resonator through the coupling hole has been converted to a parallel beam in the expander system which consists of an ellipsoidal mirror and the parabolic mirrors. Then, the optical size of the collimated beam is determined by the diffraction pattern on the surface of the ellipsoidal mirror.

EXPERIMENTAL SETUP

Fig. 1 shows a schematic layout of the FEL system and the guiding optics system from the accelerator room to the large experimental hall. Also, the experimental setup is shown in Fig. 1. All the measuring devices for monitoring of the FEL have been installed in the large experimental hall.

The macropulse waveform of the FEL and the spontaneous emission were observed with an LN_2-cooled InSb detector in combination with a focusing lens or neutral density filters depending on the intensity of the light. The light was picked up with a CaF_2 beam sampler or an aluminium total reflection mirror in the first FEL monitor chamber.

The light picked up from the second FEL monitor chamber can be divided into the infrared components and the visible components with a cold mirror as shown in Fig. 1. A simultaneous measurement is possible for the spectra of the higher harmonics in the near infrared to the visible region and the fundamental FEL power, if the FEL wavelength lies in the range where the absorption of the fundamental FEL in the cold mirror is negligibly small.

The optical power of the FEL in a wavelength range longer than 2 μm was measured by placing the power meter on the upstream side of the cold mirror. Then, the FEL power and the spectra of the higher harmonics were measured alternately. The FEL power was measured as an integrated energy over the macropulse duration of 20 μs by using a pyroelectric element.

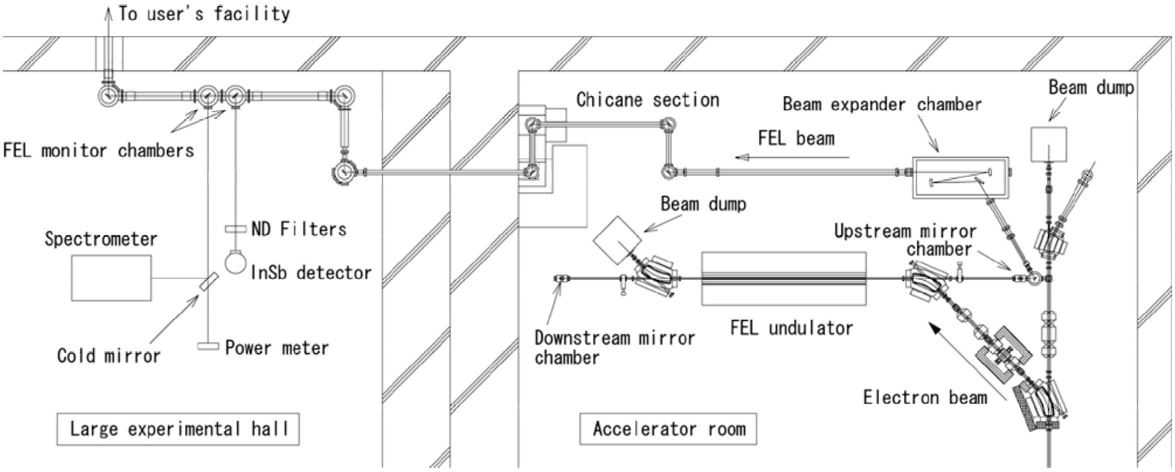

Fig. 1. Schematic layout of the FEL system, the FEL guiding optics system, and the experimental setup. The macropulse waveform, the power and the spectrum of the FEL have been measured in the large experimental hall in order to monitor the FEL during user's experiment. The intense FEL has been picked up with a CaF_2 beam sampler in each FEL monitor chamber.

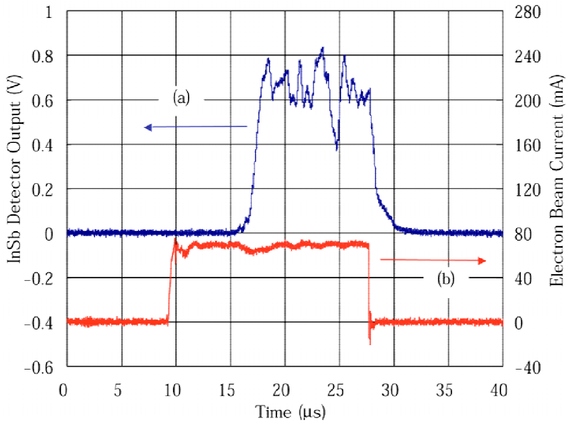

Fig. 2. An example of the macropulse waveform of the FEL lased at 5.75 μm (a). Also shown is the electron beam macropulse current (b).

Fig. 2 shows an example of the macropulse waveform of the FEL measured at a wavelength of 5.75 μm, where the FEL power was saturated in 8 μs from the beginning of the electron beam injection into the FEL system.

The macropulse energy of the FEL was measured using a pyroelectric element with an injection window of 24×24 mm^2, where no focusing device was placed in front of the element. In the experiment, the measured macropulse energy was calibrated only to the fraction contained in above square region in the FEL monitor chamber. It is assumed that the optical beam profile at the pyroelectric element has approximately the same size and shape as in the FEL monitor chamber. Then, the macropulse energy of 2 mJ for the case of Fig.2 was deduced from the measurement.

The electron beam from the linac has been bunched every period of the 2856 MHz RF. From the FWHM of the FEL macropulse in Fig.2, the average energy in each saturated FEL micropulse is estimated to be 0.064 μJ. An FEL micropulse length was deduced to be less than 0.5 ps for the wavelength of 1.5 μm from a measurement with the autocorrelation method [6]. As a result, the micropulse energy of 0.064 μJ corresponds to a peak power greater than 0.1 MW. The maximum FEL energy obtained in the lasing experiment was 25 mJ at a wavelength around 2 μm, which corresponds to the micropulse peak power of nearly 2 MW.

TUNABILITY OF THE WAVELENGTH

The result of the experiment on the FEL wavelength tunability is shown in Fig. 3, where the rhombus-shaped data points show the wavelengths measured in terms of the various undulator gap widths for the fixed electron energy E_e. The 2D analytical expression for the fundamental sinusoidal component of the undulator peak field B_0 is given as [7]

$$B_0 = 2B_r\{1-\exp(-2\pi h/\lambda_U)\} \times \exp(-2\pi g/\lambda_U)\frac{\sin(\pi/4)}{\pi/4}, \qquad (4)$$

where B_r (= 1.2 T) is the remanent field of the permanent magnet, λ_U (= 48 mm) the undulator period, g the undulator half gap width, h (= 35 mm) the block height of the magnet [7]. The dependence of the wavelength on the undulator gap width was calculated from the magnetic field given by Eq. (4) as shown by the curves in Fig. 3. The electron energy has an ambiguity within ±1 % due to the momentum acceptance of the electron beam analysing system. Therefore, the curves were fitted to the experimental results by a small correction for the electron energy. The good agreement with the experimental result suggests that the undulator magnetic field is well described by Eq. (4).

The FEL lasing is possible over the range of g from 12 to 18 mm, which makes change of the K-value from 1.99 to 0.91. Thus, the FEL wavelength can be varied continuously to 1/2 of the wavelength at the minimum gap width for fixed electron energy.

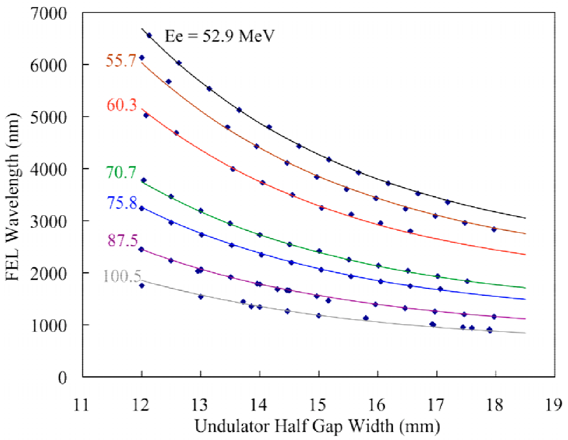

Fig. 3. The FEL wavelength measured as a function of the undulator half-gap width for fixed electron energies. The curved lines show predicted wavelength dependences on the gap width.

POWER AT THE FEL MONITOR PORT

Fig. 4 shows the dependence of relative FEL power on the electron energy and the FEL wavelength, which was measured as the macropulse energy using the pyroelectric element. The wavelength was changed by the adjustment of the undulator gap width with the electron energy fixed.

The experiment for the same electron energy was run in one machine shift, therefore the relative change of the power dependent on the wavelength was obtained with approximately the same electron beam condition. On the other hand, the relative power between the different electron energies involves the difference of the electron beam condition due to the difference of the beam emittance, the energy spread, and the beam focusing

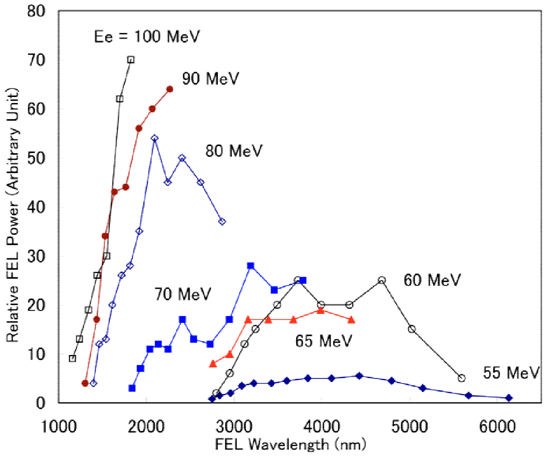

Fig. 4. Relative FEL power obtained with different electron beam energies.

parameters. Also, the absolute value and stability of the FEL macropulse energy has been strongly dependent on the beam handling and the alignment of the resonator mirror. However, the result shown in Fig. 4 gives a good indication of the power available at the user's port.

ESTIMATION OF THE POWER IN THE RESONATOR

The macropulse energy measured at the FEL monitor port represents the energy contained in the power meter injection window area of 24×24 mm^2. By a simple assumption that the profile of the parallel beam obtained at the output of the expander system is conserved at the FEL monitor chamber, the detection efficiency ε_d of the power meter for the total extracted energy is given by [8]

$$\varepsilon_{\mathrm{d}} = 1 - J_0^2(2\pi aA/d\lambda_{\mathrm{L}}) - J_1^2(2\pi aA/d\lambda_{\mathrm{L}}), \quad (5)$$

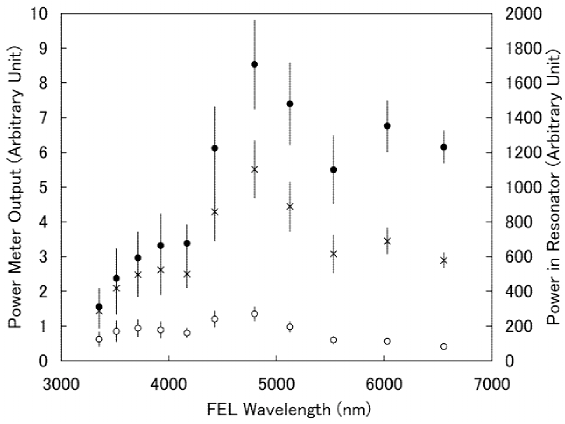

Fig. 5. The FEL power obtained at E_e = 52 MeV. Open circles: raw data divided by T_M, stars: corrected for ε_d, black circles: corrected for ε_d and κ. The error bars represent the fluctuation of the macropulse energy and the macropulse length in the experiment.

where d (= 2.5 m) is the distance between the coupling hole in the resonator mirror and the ellipsoidal mirror in the expander system, and the area of the power injection window was approximated by a circle with the radius A (= 13.5 mm).

From Eqs. (3) and (5), the micropulse peak FEL power in the resonator can be estimated by applying a factor

$$k = \frac{1}{\varepsilon_{\mathrm{d}}\kappa\tau_{\mathrm{L}}}\frac{T_{\mathrm{RF}}}{T_{\mathrm{M}}} \quad (6)$$

to the macropulse energy measured at the FEL monitor port, where τ_L is the FEL micropulse length, T_{RF} the period of the micropulse, T_M the FEL macropulse length.

The effect of corrections for ε_d and κ on the FEL power measured at E_e = 52 MeV is shown in Fig. 5, where the open circles are the raw data divided by T_M, the stars corrected for ε_d (the same vertical scale as raw data), the black circles corrected for ε_d and κ(corresponding to the power in the resonator). The FEL macropulse length was measured for each wavelength. Fig. 4 shows a decrease of the power in the wavelength region longer than 3 μm at the FEL monitor port. However, the result of corrections for ε_d and κ suggests that the power in the resonator was not necessarily decreased in this region.

SUMMARY

Saturation of the FEL power was achieved in the wavelength range from 1.0 to 6.5 μm by use of silver-coated copper mirrors in the FEL resonator. The property of the wavelength variability is in agreement with the theoretical prediction. The FEL power measured at the FEL monitor port has shown a decrease of saturated power in the wavelength region longer than 3 μm. However, the power in the FEL resonator has not been necessarily decreased, considering the detection efficiency and the coupling coefficient of the external-coupling mirror.

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