Wavelength extension of the ISIR-FEL toward the longer wavelength region for user experiments

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Abstract

The far infrared FEL based on the L-band linac at ISIR, Osaka University is being modified so that the laser wavelength can be extend to the longer wavelength region. After the wiggler and the bending magnets were remodeled and the vacuum chambers for them were replaced , we have observed laser oscillation at wavelengths from 21 to 126 μm.

1 Introduction

The far infrared free electron laser (FEL) based on the L-band linac is now being developed at the Institute of Scientific and Industrial Research (ISIR), Osaka University [1]. The first lasing was obtained at wavelengths from 32 to 40 μm in 1994 [2, 3]. In the next step, we are modifying the FEL system suitable for user experiments. Since some potential users of the FEL are interested in the longer wavelength region, we plan to extend the wavelength region up to at least 150 μm. This modification will include remodeling of the wiggler and two bending magnets, and replacement of vacuum chambers for the bending magnets and the mirror holders for the optical resonator. As reported previously [4], the wiggler was modified from a fixed magnet gap type to a variable one. Then the vacuum chambers for the two bending magnets have been replaced with new ones with larger cross-sections in order to reduce the diffraction loss in the optical resonator and accordingly magnet gaps of the bending magnets have been widened. After the wiggler and the bending magnets were remodeled, we have been conducting FEL experiments. We have observed laser oscillation at wavelengths from 21 up to 126 μm, which is the longest wavelength so far obtained with FELs based on RF linacs. In this paper, we will report on the FEL and the experiments.

Table 1
Main parameters of the electron beam

Energy	10-19 MeV
Accelerating frequency	1300 MHz
Bunch spacing	9.2 ns
Charge / bunch	2 nC
Peak current / bunch	50 A
Bunch length	20-30 ps
Macropulse length	1.8 μs
Normalized emittance	
Y-646B	80 πmm·mrad
YU-156	300 πmm·mrad

2 Accelerator and the FEL systems

The L-band linac has the sub-harmonic buncher (SHB) system composed of two 12th and one 6th SHBs in order to produce an intense single bunch beam. When FEL experiments are conducted, the electron beam with a peak current of 600 mA is injected from a thermoionic electron gun into the SHB system, and the second 12th and the 6th SHBs are powered to make an electron beam with the macropulse duration of 1.8 μs and micropulse intervals of 9.2 ns. Then micropulses are bunched to 20 - 30 ps with a pre-buncher and a buncher and the electron beam is accelerated to 10 - 19 MeV in an accelerating tube. The characteristics of the electron beam are listed in Table 1.

We used an electron gun with a cathode area of 0.5 cm^2 (EIMAC, Y-646B) for FEL experiments and one with a large cathode area of 20.4 cm^2 (ARCO, Model-12) for usual operation of the linac. Recently the electron gun usually used was changed to one with a smaller cathode area of 3 cm^2 (EIMAC, YU-156), which can provide as much current as the previous one can. We therefore started using the gun YU-156 also for FEL experiments, so that it is not necessary to change the electron guns.

The electron beam is transported through an achromatic bend to the FEL system. The main parameters of the FEL system are listed in Table 2. The wiggler is a planer type. The magnet gap of the wiggler is variable from 30 to 120 mm, for which K = 0.013 - 1.472. By changing the electron energy from 10 to 19 MeV and the magnet gap from 30 to 120 mm, it is possible to cover the wavelength region from 20 to 200 μm with the fundamental peak, and from 6 to 67 μm with the third harmonic peak.

Table 2
Main parameters of the FEL system

Wiggler	
Magnet	Nd-Fe-B
Length	1920 mm
Number of periods	32
Magnet gap	30 - 120 mm
K-value	0.013 - 1.472
Optical resonator	
Cavity length	5532 mm
Radii of mirrors	
M1	3384 mm
M2	2763 mm
Rayleigh range	915 mm
Waist radius	3.4 mm (at 40 μm)

In the wavelength region longer than 100 μm, the diffraction loss due to the vacuum chambers in the optical resonator can not be disregarded. The vacuum chambers in the two bending magnets, which originally determined the diffraction loss, were replaced with new ones with larger vertical sizes and accordingly magnet gaps of the bending magnets were widened to accommodate them so that the calculated diffraction loss due to these parts is less than that due to the vacuum chamber for the wiggler.

3 Light detection system

Laser light was taken out from the optical resonator through a hole of 3 mm in diameter in the front mirror, and led from the vacuum chamber to the air through a window, which is either a KRS-5 plate 5 mm thick or a single crystal quartz plate 2 mm thick, and transported in the air to the measurement room using plane and concave mirrors coated with gold. The laser light was detected with a Ge:Be or Ge:Ga detector cooled with liquid helium. Teflon sheets were inserted in front of the detector as an attenuator to avoid saturation of the output signal when necessary. In some experiments, a grating type monochromator was used, which can monochromatize light with a wavelength shorter than 90 μm. The Ge:Be detector has the highest sensitivity around 40 $\sim$ 45 μm and the sensitivity drops rapidly as the wavelength becomes longer, while it has a cut-off filter for light with a wavelength shorter than 20 μm. The spectral sensitivity of the detector extends from 20 up to 52 μm. On the other hand, the Ge:Ga detector has the highest sensitivity around 105 μm and the sensitivity drops steeply as the wave length increases. It has a cut-off filter for light with a wavelength shorter than 50 μm. The sensitivity of the Ge:Ga detector ranges from 50 to 130 μm. For each kind of detector, we used two detectors; one is a so-called slow detector which has the high detection sensitivity but has the slow time response, and the other is a fast detector for measuring the time evolution of FEL light. We have measured the time resolution of the fast Ge:Be detector to be 170 ns (FWHM) [3], but has not yet measured that of the fast Ge:Ga detector. We expect the time resolution to be approximately 100 ns. The transmission of light through the KRS-5 plate decreases very much above 45 $\sim$ 50 μm, while the transmission through the single crystal quartz plate rises around 50 μm and is high in the longer wavelength region. Therefore we used the KRS-5 window for measurement below 50 μm and the quartz window above 50 μm.

4 Experimental results and discussions

4.1 Oscillation experiments below 50 μm

We conducted experiments at an electron energy of 18.3 MeV. We used Y-646B as an electron gun. Laser light coming through the KRS-5 window was directly detected with the Ge:Be detector. The wavelength of laser light was determined from the electron energy and

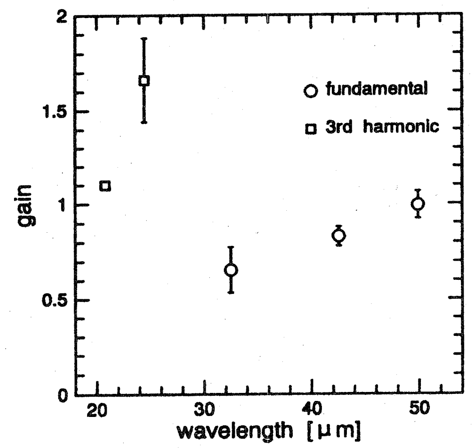

Fig. 1 FEL gain as a function of the wavelength below 50 μm. The data points denoted by the circles and the squares are assigned to the fundamental oscillation and third harmonic oscillation, respectively. See text for details.

the K-value of the wiggler. Fig. 1 shows the gain as a function of the wavelength which was derived from the time evolution of laser light measured with the fast Ge:Be detector [3]. The light wavelength was varied by changing the wiggler gap. Since the transmission of light through the KRS-5 window rapidly decreases above 45 $\sim$ 50 μm and the sensitivity of the detector is practically zero above 60 μm, we have assigned laser light corresponding to wavelengths longer than 50 μm with fundamental peak are due to the third harmonic peak. Laser oscillation thus assigned to the fundamental peak and to third harmonic peak are denoted by the circles and the squares, respectively, in Fig. 1. The shortest wavelength obtained in the experiments is 21 μm with the third harmonic oscillation.

4.2 Oscillation experiments above 50 μm

Experiments were conducted at electron energies of 14.0 and 14.4 MeV in order to make the wavelength long. We used not only Y-646B but also YU-156 as an electron gun in these experiments. Laser light coming through the quartz window was detected directly or through the monochromator with the Ge:Ga detector. With the combination of the quartz window and the Ge:Ga detector, the detectable range of light was from 50 to 130 μm. Fig. 2 shows the gain as a function of the wavelength which was also derived from the time evolution of laser light measured with the Ge:Ga detector. The wavelengths of the data points denoted by the diamonds were measured with the monochromator and those of the other points were derived from the electron energy and the K-value of the wiggler. The electron energy and the K-value were calibrated with the wavelengths measured with the monochromator. The gain values denoted by the circles were obtained with the electron gun YU-156, which is usually used in operation of the linac and those denoted by the squares and the diamonds were obtained with Y-646B. Values of the normalized emittance of the

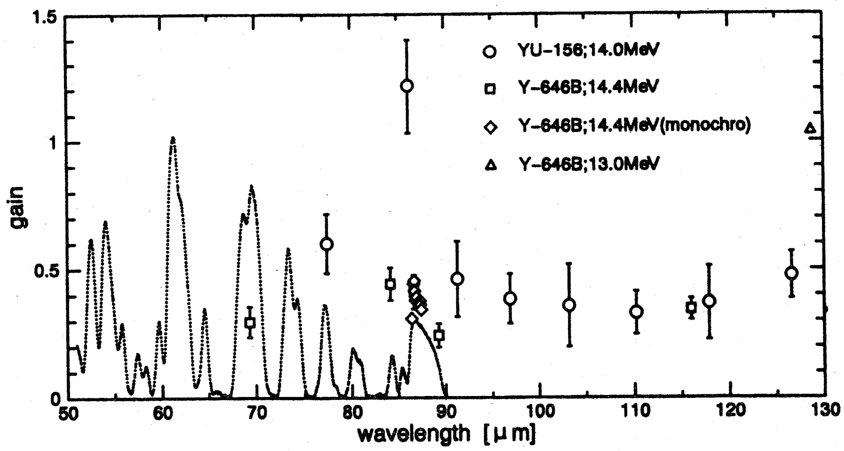

Fig. 2 FEL gain as a function of the wavelength above 50 μm. The gain values denoted by the circles were obtained at an electron energy 14.0 MeV using the electron gun YU-156 and the other points were obtained at respective energies using the electron gun Y-646B. The wavelengths of the data points denoted by the diamonds were measured with the monochromator. The dotted line is the spectrum of the black body radiation measured in the air with the monochromator and the Ge:Ga detector. See text for details.

electron beams from YU-156 and Y-646B were measured to be 300 and 80 πmm·mrad, respectively, as shown in Table 1. Although they are appreciably different, the measured values of the gain are not very much different in both cases except for the gain value at 86.3 μm. The dotted line in Fig. 2 shows the spectrum of light emitted by a black body radiator at 1300 K which was measured up to 90 μm wavelength with the same monochromator and the detector. The vertical scale for the spectrum is arbitrary units. The spectral shape is mostly determined by absorption of light by the water vapor in the air though it also includes smooth wavelength dependences of efficiency of the detector and that of the monochromator. It is apparent from the figure that FEL light we can measure in this wavelength region is considerably limited due to the absorption of light in the transport line by water vapor in the air. At the end of these experiments, we decreased the electron energy down to 13 MeV and observed lasing at wavelengths of 129 $\sim$ 131 μm. The gain and the time spectrum at 129 μm are shown by the triangle in Fig. 2 and in Fig. 3, respectively.

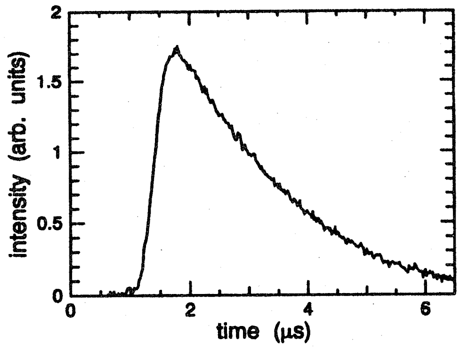

Fig. 3 The time spectrum of the laser light from the FEL operated at the wavelength 129 μm measured with the fast Ge:Ga detector.

5 Conclusion

In the experiments after the remodeling of the wiggler, the following results were obtained. We obtained lasing from 32 beyond 126 μm with the fundamental oscillation and from 21 to 25 μm with the third harmonic oscillation. The FEL gain was measured to be $\sim$ 120 % at maximum with the fundamental oscillation and to be $\sim$ 160 % with the third harmonic oscillation. In the wavelength region above 50 μm, the measured gain was almost constant independently of the wavelength and the beam emittance. We plan to confirm these experimental results in following experiments.

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