HIGH POWER TERAHERTZ FEL AT ISIR, OSAKA UNIVERSITY*

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Abstract

The Terahertz FEL is being developed with the L-band electron linac at Osaka University. It is currently operated in the frequency range from 12 down to 2 THz or in the frequency region from 25 to 147 µm at the saturation power level of FEL. The maximum output energy so far obtained is 3.7 mJ in the FEL macropulse at 67 µm. The peak macropulse power up to 1.2 kW is available for user experiments.

INTRODUCTION

We have been developing a Terahertz free electron laser (FEL) based on the 40 MeV, 1.3 GHz L-band electron linac at the Institute of Scientific and Industrial Research, Osaka University. After obtaining the first lasing in 1994 at wavelengths around 32 - 40 µm (9.4 – 7.5 THz) [1], we began modifying the FEL system to make it suitable for user experiments in the Terahertz or far-infrared region and to extend the wavelength region to the longer wavelength side [2]. Finally, the FEL wavelength was extended up to 150 µm (2 THz) in 1988, which was, at that time, the longest wavelength obtained with FELs based on RF linacs [3]. However, we could not achieve power saturation because the macropulse duration is relatively short and the number of amplification is limited to only 50 times. The FEL light could not be used for user experiments, since the unsaturated FEL power was low and unstable.

The linac was extensively remodelled in 2002 - 2004 to realize higher stability and reproducibility of operation. At this opportunity, we added a new operation mode for FEL, in which the pulse duration of the RF power is extended to 8 µs from 4 µs in the normal mode, so that the FEL power can reach saturation. After re-commissioning of the linac, we resumed FEL experiments and observed lasing at the wavelength of 70 µm (4.3 THz) with the high peak power [4]. Next targets of the FEL development are to extend the range of the laser wavelength, to increase the FEL power, and to evaluate characteristics of FEL. In this article, we will report results of recent activities on the Terahertz FEL.

EQUIPMENTS

Accelerator and the FEL System

The L-band linac has the three stage sub-harmonic buncher (SHB) system composed of two 108 MHz cavities and one 216 MHz cavity in order to produce a high-intensity single-bunch beam. The SHB system is also used in FEL experiments to produce the so-called multi-bunch beam. The thermionic electron gun (EIMAC, YU-156) generates a 100 keV electron pulse with a peak current of 600 mA and a macropulse duration of 8 µs, and it is injected into the SHB system, in which the second 108 MHz and the 216 MHz cavities are powered, to make micropulses with a duration of 500 ps and intervals of 9.2 ns. Then the micropulses are bunched to 20 ps with the pre-buncher and the buncher, and the electron beam is accelerated to 12.5 - 21 MeV in the 1.3 GHz accelerating tube. The characteristics of the electron beam are listed in Table 1.

Table 1: Main Parameters of the Electron Beam

Mode	Multi-bunch
Accelerating frequency	1.3 GHz
Repetition rate	≤ 30 pps
Bunch spacing	9.2 ns
Charge / bunch	< 2 nC
Peak current / bunch	< 50 A
Bunch length	20 - 30 ps
Macropulse length	< 8 µs
Typical energy	12.5-20.5 MeV
Normalized emittance	100 - 150π mm mrad

The electron beam is transported through an achromatic bend to the FEL system. The wiggler for the FEL is a strong-focusing wiggler of the planar type based on the edge-focusing scheme [5]. The magnet gap of the wiggler can be varied from 30 to 120 mm, for which K = 0.01 - 1.54. The main parameters of the wiggler are listed in Table 2.

Table 2: Main Parameters of the Wiggler

Magnet	Nd-Fe-B
Total length	1.92 m
Period length	60 mm
Number of periods	32
Magnet gap	30 – 120 mm
K-value	0.01 – 1.54

The optical resonator is a standard concentric resonator composed of two spherical mirrors. Four optical pulses are stored in the 5.531 m long resonator and they are repeatedly amplified by the multi-bunch electron beam. A part of the FEL power stored in the resonator is taken out

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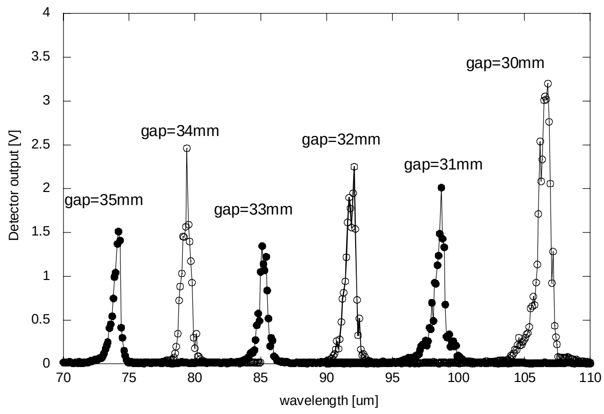

Figure 1: Wavelength spectra of FEL measured at wiggler gaps from 30 to 35 mm.

through a coupling hole of 3 mm in diameter at the center of the upstream mirror. The coupling coefficient of the output hole is estimated to be 3 % at a 60 µm wavelength. The main parameters of the optical resonator are listed in Table 3.

Table 3: Main Parameters of the Optical Resonator

Cavity length	5.531 m
Mirror diameter	80 mm
Radii of mirrors	
M1 (upstream)	3.385 m
M2 (downstream)	2.877 m
Rayleigh range	1 m

The optical resonator is a standard concentric resonator composed of two spherical mirrors. Four optical pulses are stored in the 5.531 m long resonator and they are repeatedly amplified by the multi-bunch electron beam. A part of the FEL power stored in the resonator is taken out through a coupling hole of 3 mm in diameter at the center of the upstream mirror. The coupling coefficient of the output hole is estimated to be 3 % at a 60 µm wavelength.

FEL light is led from the linac room to the measurement room through an evacuated optical transport system using plane and concave mirrors coated with gold. A lower vacuum in the transport system is separated from a higher vacuum in the FEL beam line with a synthesized diamond window of 20 mm in diameter and 0.2 mm thick, which has constant transmittance of approximately 70 % in all the spectral regions longer than the ultraviolet except for small absorption around 5 µm. A concave mirror in the transport system focuses the light onto the entrance slit of the spectrometer, which is connected to the optical transport system with no window.

Measurement System

The far-infrared spectrometer used to analyze laser light is a cross Czerny-Turner type monochromator with a plane reflective grating with 7.9 grooves / mm (Milton Roy). It can be used in the wavelength region from 60 µm beyond 150 µm with the grating. Spectral resolution is dependent on the measured wavelength and the slit width, and it is less than 1.5 µm for the slit width of 6 mm. The monochromatized light is taken out through another diamond window to the air.

The laser light is detected with a Ge:Ga photo conductive detector (QMC) cooled with liquid helium or a pyroelectric detector (JASCO Corp., DLATGS). The Ge:Ga detector has the highest sensitivity around 105 µm and the sensitivity drops steeply as the wavelength increases. It has a short wavelength cut-off filter at 50 µm. The measured time resolution of the Ge:Ga detector is 10 ns (FWHM). We use the detector for measuring the time evolution of FEL light. On the other hand, the pyroelectric detector has the wider range of sensitivity and works at room temperature without cooling, though the response speed is slow. The detector is used for measuring FEL spectra. Teflon blocks are inserted in front of the detector as an attenuator to avoid saturation of the detector when necessary.

FEL PROPERTIES

Wavelength Tunability

Since the wavelength of FEL light is dependent on the electron energy and the K-value of the wiggler, it can be varied by changing either the wiggler gap or the electron energy. Figure 1 shows FEL wavelength spectra measured at six wiggler gaps from 30 to 35 mm in 1 mm steps. The beam energy is fixed approximately at 16 MeV. The peak wavelength can be varied continuously from 107 to 74 µm. This peak wavelength is in agreement with the resonance wavelength calculated with the electron energy and the K value. Since the wiggler gap can be moved in a few seconds by 1mm, the wavelength can be swept in a short time. The change of the electron energy is, on the other hand, used for changing the wavelength largely as it

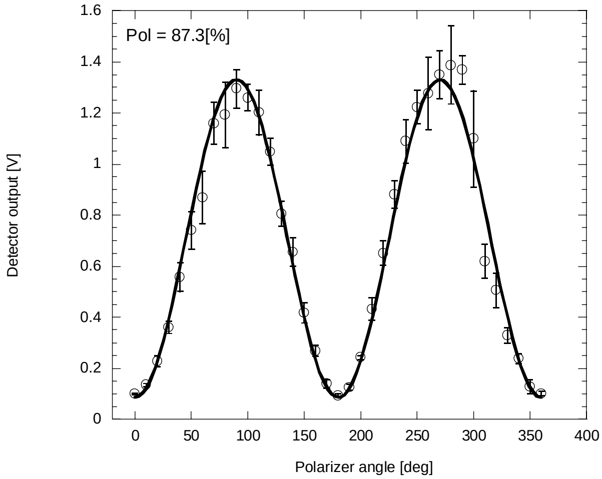

Figure 2: Light intensity measured with a wire-grid polarizer as a function of its rotation angle in ten-degree steps. The solid line is a fit of the sine function to the data points, and the degree of polarization is evaluated to be 87.3%.

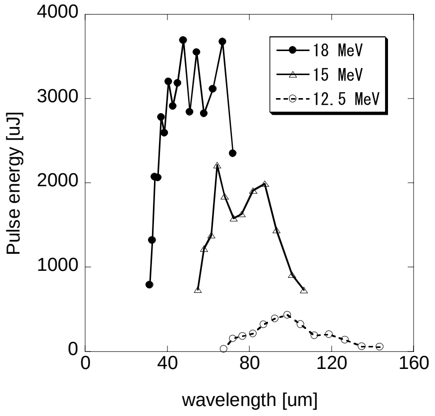

Figure 3: Output energy of the FEL light in the macropulse measured with an energy sensor for three different electron energies.

takes time to do so. By changing the electron energy from 12.5 to 20.5 MeV, it is possible to cover the wavelength region from 25 to 147 µm (12 – 2 THz) with the fundamental peak.

Polarization

Since the FEL light is amplified by the electron beam oscillating horizontally in the wiggler, it is polarized horizontally. Since all the mirrors in the optical transport line, the spectrometer, and the detector are arranged on the same horizontal plane, the horizontal polarization of the FEL light is preserved to the position of the detector. Figure 2 shows the light intensity measured with a wire-grid polarizer (wire diameter 10 µm and wire interval 25 µm) as a function of its rotation angle in 10-degree steps. The sine curve was fitted to the measurement points, and the degree of polarization is evaluated to be 87.3% from the maximum and the minimum values of the curve.

FEL Output Power and Extraction Efficiency

A part of the beam energy is converted into laser light by the FEL interaction. We measured the FEL power with an energy sensor for the laser (Coherent, J-25MB-LE). Although the sensor has high sensitivity in the wavelength region longer than 100 µm, the calibration data is given up to the wavelength of CO_2 laser. The calibration coefficient at the CO_2 laser is, therefore, used to convert the sensor signal into the pulse energy. Figure 3 shows the output energy of the FEL in the macropulse measured with the energy sensor as a function of the wavelength for three electron energies of 12.5, 15, and 18 MeV. The wavelength is varied from 32 to 144 µm by changing the electron energy and the wiggler gap. The maximum energy so far obtained is 3.7 mJ at 67 µm for 18 MeV, though the FEL energy in macropulse considerably changes with the wavelength. Since it is known that sensitivity decreases on the longer wavelength side, the actual pulse energy is expected larger.

The macropulse duration of the FEL light measured with the Ge:Ga detector is approximately 3 µs. As a result, the peak power in the macropulse is estimated to be 1.2 kW or higher. The macropulse consists of a train of micropulses at 9.2 ns intervals, and the micropulse duration is roughly equal to temporal width of the electron bunch, 20 ps. Thus, the micropulse peak power is estimated to be 0.5 MW. Moreover, considering the transmittance of the two vacuum windows and the coupling coefficient of the hole, the peak power of the optical pulse accumulated in the optical resonator becomes 30 MW. Since the electron beam energy is 18 MeV in this experiment and the peak current is estimated to be 50 A, the electron beam power is roughly estimated to be 900 MW. The FEL extraction efficiency from the electron beam power to the optical one is evaluated to be approximately 3 %.

SUMMARY

The Terahertz FEL based on the L-band electron linac at ISIR, Osaka University was commissioned and the power saturation was achieved. Characteristics of FEL were evaluated, including wavelength tunability, the degree of polarization, the saturation power, and the extraction efficiency. The FEL system is ready to provide the high power Terahertz radiation for users experiments.

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