FIRST LASING OF MIR-FEL AT KYOTO UNIVERSITY

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Abstract

Laser amplification at a 12 μm mid-infrared free-electron laser (MIR-FEL) was observed at the Institute of Advanced Energy (IAE), Kyoto University in March 2008. A 25 MeV electron beam of 17 A peak current was used for the lasing experiment. FEL gain was estimated to be 16% from the exponential growth of the laser output signal. A beam loading compensation method with an RF amplitude control both in the thermionic RF gun and in the accelerator tube was used to extend the macropulse duration against the backbombardment effect in the gun. We also developed a feedforward RF phase control to stabilize the RF phase shifts which were originated with RF amplitude control. As a result FEL saturation was observed in May 2008. The estimated FEL gain was 33% with the electron beam of 21 A peak current with 5.5 μs macropulse duration.

INTRODUCTION

IR tunable coherent light is a useful tool for the study of molecular dynamics, because such light can excite specific stretching bands[1], e.g., C=N, C=O, and Si-H, which are useful for the production of renewable energy sources, i.e., the production of alcohol or hydrogen and the development of next-generation solar cells. Thus, a mid-infrared free-electron laser facility (KU-FEL) has been constructed at the Institute of Advanced Energy, Kyoto University[2]. The construction of the facility was finished in 2006[3]. We started FEL oscillation experiments in 2007 and succeeded in the first lasing at a wavelength of 12.4 μm in March 2008. An FEL gain saturation has also been achieved in May 2008. In this paper, we will report on the first lasing experiment and the beam conditioning which lead to the FEL gain saturation.

FIRST LASING EXPERIMENT

The KU-FEL system consists of an S-band 4.5-cell thermionic RF gun driven by a 10 MW klystron, a 3 m accelerator tube driven by a 20 MW klystron, a beam transport system, and a Halbach type undulator of 1.6 m. Figure 1 shows a schematic drawing of the KU-FEL system. A LaB6 thermionic cathode of 2 mm diameter was employed to produce a high-brightness electron beam. A transverse magnetic field of about 10 G on the cathode surface was applied to divert backstreaming electrons[4]. The strength of the magnetic field was chosen so that backstreaming electrons with an energy lower than about 300 keV could be diverted well while a transverse kick to the accelerated electron could pass through the 8 mm iris of the RF gun. Although the transverse magnetic field partially minimized the cathode heating effect owing to backstreaming electrons, we observed that cathode surface temperature still increased during the macropulse duration of 2-3 μs. Then we applied amplitude-modulated RF pulses to the RF gun to compensate for the beam loading effect[5]. As a result, the energy degradation in the thermionic RF gun due to backstreaming electrons was dramatically improved and an electron beam pulse of approximately 4 μs long with a 375 mA average current was successfully extracted from the gun.

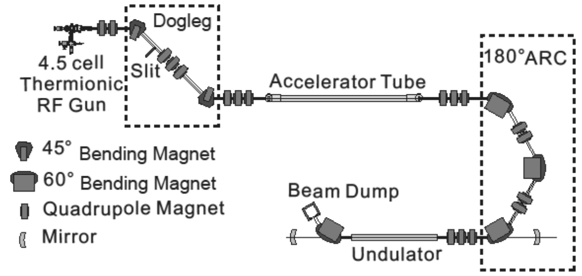

Figure 1: Schematic drawing of KU-FEL.

An achromatic transport system (dogleg section in Fig. 1) consists of a 45° bending magnet and an energy slit, three quadrupole magnets and another dipole magnet, and it serves as an energy analyzer[6]. The energy slit was set to select the electron beam of about 3% energy spread and thus an electron beam of 90 mA was used for the first lasing experiment. An S-band accelerator tube accelerates the electron beam up to 40 MeV using a 20 MW RF power. For the first lasing experiment, we used a 25 MeV electron beam whose parameters were optimized to obtain the maximum FEL gain using a 3D FEL simulation code, GENESIS[7]. It should be noted that the simulation code was modified to treat both the round-trip development of the FEL and the precise geometry of the vacuum chamber of the optical cavity system that defined the optical loss.

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The 180° arc in fig. 1 designed for a bunch compressor[6] was tuned to obtain a high peak current of the electron beam. The micropulse length was less than 2 ps, which was measured using a streak camera[8]. Thus, the micropulse peak current was about 17 A. Two triplet quadrupoles located on both sides of the 180° arc worked as a beta-match component between the linac and the undulator. A planar-type undulator, which was used for the first lasing experiment in the collaboration between FELI and the University of Tokyo[9], was used. The undulator length was 1.6 m, the period was 40 mm, the number of periods was 40, and the undulator parameter K-value was varied from 0.99 to 0.17 by changing the gap of the undulator. In the first lasing experiment, we used a 0.99 K-value to maximize the FEL gain in our system.

The parameters of the electron beam, the undulator and the resonator in the KU-FEL are shown in Table I. The horizontal and vertical normalized emittances at the undulator are around 3π mm mrad, which were measured by a tomographic method[10]. The optical resonator consists of a pair of gold-coated Cu mirrors with 99.04% reflectivity, the upstream mirror of which has a coupling hole of 2 mm ϕ.

The FEL signal was measured with an MCT IR detector (HgCdTe, Judson, J15D12). An optical resonator, a monochromator (Digikrom, DK240), and a detector were aligned using a diode laser. The electron beam trajectory and mirror angle were carefully conditioned to maximize the strength of the spontaneous radiation using beam profile monitors and steering magnets. Since the RF frequency was 2856 MHz in the KU-FEL linac, the cavity length was set to 4.516 m using a set of 5-axis mirror manipulators whose scanning resolution in the longitudinal direction was 1 μm. Figure 2 shows the light output signal as well as the electron beam current during lasing. As is shown in Fig. 2, light amplification was clearly observed. We should note that FEL gain saturation was not achieved in this stage. FEL gain was estimated from the exponential growth of laser output signal to be 16% which included a detector response. One can see that the buildup time of the FEL light pulse had only a 1 μs duration, although the macropulse length of the electron beam was 4 μs. This was due to the backbombardment in the thermionic RF gun. As described above, we applied no amplitude-modulated RF pulse to the accelerator tube, but we applied it to the RF gun. Therefore, we observed energy degradation during the macropulse in the undulator section, as shown in Fig. 3, which was due to the beam loading effect in the acceleration section where the beam current increased during the macropulse duration. It should be noted that the phase of the output RF from the klystron should have been shifted significantly during the macropulse because we varied RF amplitude by changing the high voltage of the klystron modulator. We also measured the phase shift and observed a large phase shift of about 40° within 2-3 μs. In this case, the RF phase between the gun and the accelerator tube

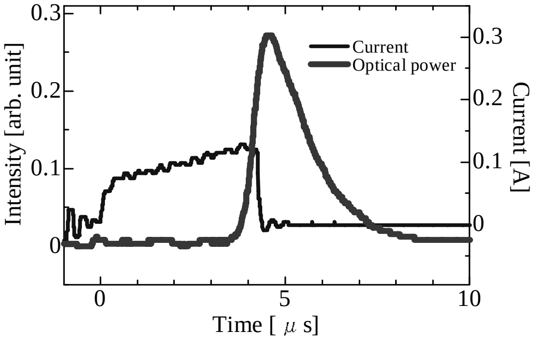

Figure 2: Time evolution of light output signal. The electron beam current is also shown.

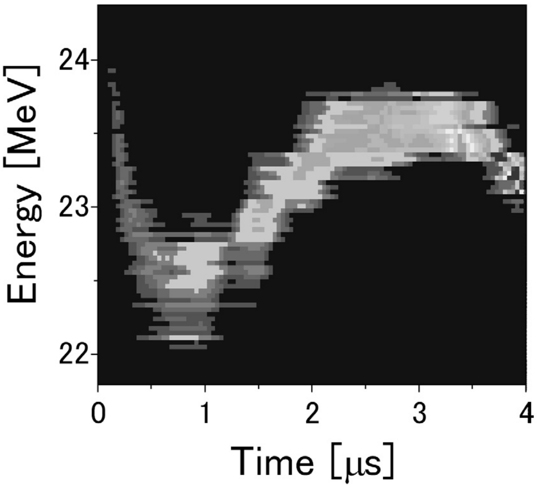

Figure 3: Electron beam energy during macropulse duration.

Table 1: Parameters of electron beam, undulator and resonator of the KU-FEL

Electron beam (measured at undulator section)	
Energy (MeV)	25
σ_E/E (%) (last 1 μs)	0.5
Bunch length (ps in rms)	2
Macropulse length (μs)	4
Average current (mA)	90
Peak current (A)	17*
*estimated from GENESIS calculation	
Undulator	
K-value	0.99
Number of periods	40
Period (mm)	40
Gap (mm)	25
Optical Resonator	
Mirror curvature (m)	
upstream	3.03
downstream	1.87
Reflectivity of mirrors at 10 μm (%)	99.04
Hole diameter (mm ϕ)	2
Cavity length (m)	4.516

was also shifted, resulting in a fluctuation in beam energy in the undulator section. Because of the small FEL gain and the short buildup time, the FEL output amplitude was only about 50 times as high as that of spontaneous light. A GENESIS calculation showed a good agreement with the experimental observations in terms of FEL gain and output power with the peak current of 17 A.

The wavelength of the FEL light, 12.4 μm, was measured with a monochromator. As has already been described above, the FEL gain was too small to obtain a stable FEL oscillation. Therefore, the bandwidth of the FEL light was too peaky and could not defined clearly. However, since the spontaneous emission had a bandwidth of 470 nm in FWHM, we clearly observed the spectral narrowing in KU-FEL.

BEAM CONDITIONING

To achieve an FEL gain saturation, it was obvious that the amplitude modulated RF power also installed in the accelerator tube in combination with a phase stabilization control both for the gun and the accelerator tube. Figure 4 shows the time dependent energy spectrum of the electron beam at the undulator section. The energy spread was 0.8% which was 6% at the first lasing We installed a feedforward phase control system (Fig. 4). A 2-channel function generator (Tektroxis, AFG3022B) whose waveforms were controlled by the signals from phase detectors via a personal computer("PC" in Fig. 4) drove fast phase shifters (R&K, PS-3-2856MHz). The phase shift during the macropulse was stabilized from 40° to 2° in the gun and from 14° to 2° in the accelerator tube, respectively. We also developed frequency detuned method in RF gun[11]. The quality of the electron beam has been improved (Table.2).

We made a lasing experiment with the improved electron beam. Figure 6 shows the output signal from a fast MCT detector (Vigo, PVMI-2TE) whose rising time was about 10 ns. A -60 dB filter was inserted in front of the detector. We observed an FEL power saturation. The electron beam current was not constant during the macropulse, the laser output was increase even at the saturation region. The gain was evaluated to be 22% and the optical loss was evaluated to be 11%. Therefore, the total FEL gain was deduced to be 33%. The laser energy of 4.6 mJ was measured with a power meter. The peak power was expected to be about 2 MW assuming the pulse duration of 1 ps. Figure 7 shows the output power as a function of detuning length. It should be noted that the detuning length was relative value to the position where the maximum output power was observed with detector. About 1 wavelength detuning length was observed. Figure 8 shows the spectrum of the FEL light at the maximum output condition. The center wavelength of 13.4 μm and the width of 240 nm in FWHM (bandwidth of about 1% in rms) were observed. We summarised the measured FEL parameters in Table.3.

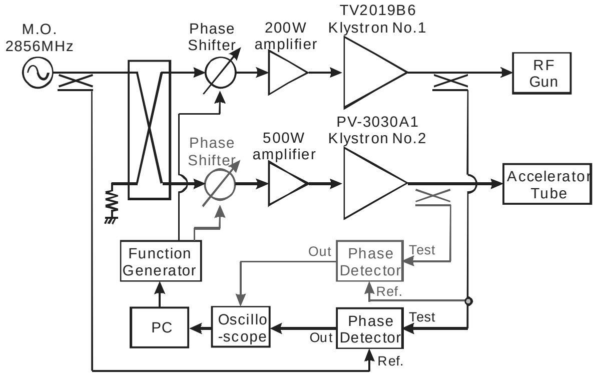

Figure 4: Feedforward phase control system.

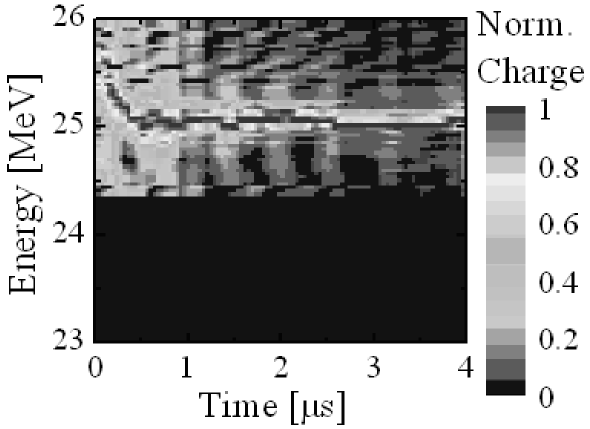

Figure 5: Electron beam energy during macropulse duration.

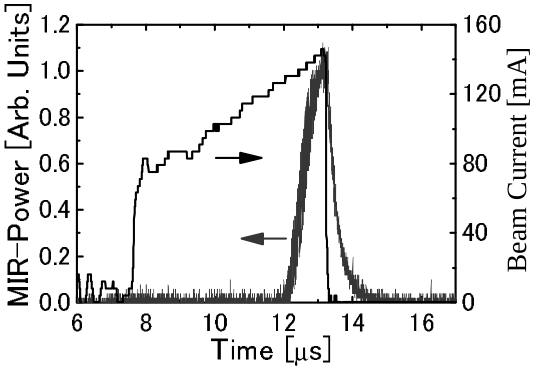

Fig. 6: Time evolution of light output signal. The electron beam current is also shown.

Table 2: Electron Beam Parameters in the saturation experiment

Energy (MeV)	24
σ_E/E (%)	0.8
Bunch length (ps in rms)	2
Macropulse length (μs)	5.5
Average current (mA)	115
Peak current (A)	21*

* estimated from GENESIS calculation

Table 3: Parameters of the FEL light at saturation

Wavelength (μm)	13.4
σ_λ/λ (%)	1
Average Power (mW)	4.6
Peak Power (MW)	2*

*assumed 1 ps pulse duration

CONCLUSION

We have succeeded in lasing at 12 μm MIR FEL in the KU-FEL, which is dedicated for research on renewable energy sources in IAE, Kyoto University. A laser output with an intensity 50 times as high as the spontaneous emission intensity was observed with a 1 μs buildup duration. The FEL gain estimated from the exponential growth of the laser output signal was 16%. The FEL gain obtained from the simulation showed a good agreement with that observed.

An amplitude-modulated RF power was applied in an acceleration field to compensate for the backbombardment effect in the thermionic RF gun. As a result, an electron beam pulse of 4 μs length was successfully extracted from the RF gun. However, beam loading compensation was not applied in the accelerator tube, and the energy of the electron beam markedly changed during the macropulse duration. Moreover, a large phase shift caused by the amplitude modulation of RF power was also observed. Consequently, the duration of the electron beam with constant energy, which is useful for FEL oscillation, was only 1 μs. A beam loading compensation system and a phase stabilization system in both the thermionic RF gun and the accelerator tube were developed in the KU-FEL. As a result the energy spread of the electron beam has been improved to be 0.8% during the macropulse duration of 5.5 μs. By using this electron beam, we made an experiment to achieve FEL power saturation. A saturated FEL light of 4.6 mJ pulse energy at 13.4 μm in wavelength with 1% bandwidth was successfully observed. In the present stage, the FEL output is unstable and further improvement of the electron beam is required for user experiments.

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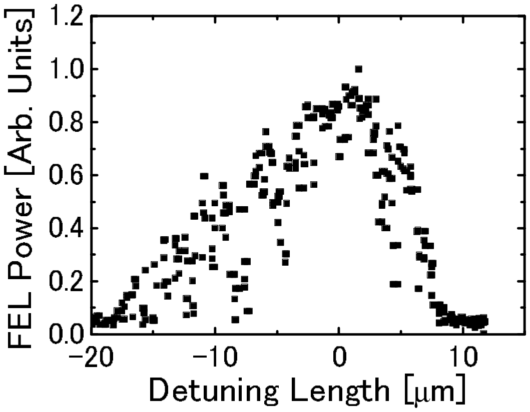

Figure 7: Relationship between FEL power and detuning length.

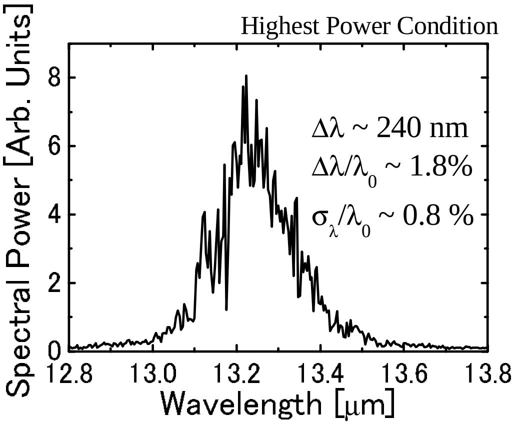

Figure 8: FEL Spectrum at the saturated condition.

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