FREE ELECTRON LASER PULSE CONTROL BY ACOUSTO- OPTIC MODULATORS

Taizou Kanai*, Sachiko Yoshihashi-Suzuki, Kunio Awazu, Institute of Free Electron Laser, Graduate School of Engineering, Osaka University, Japan

Abstract

The free electron laser (FEL) at Osaka University can be continuously varied over a range from 5.0 to 20.0 µm when using the 30 MeV electron beam. The FEL has a double pulse structure. The structure consists of a train of macropulses with a pulse width of 15 µs, and each macropulse contains a train of 330 micropulses with a pulse width of 5 ps. The FEL's tunability and short pulse make possible new medical applications, such as investigating protein dynamics and ablating soft tissues. Precise control of the micropulse train is essential for FEL medical applications because macropulses of long pulse duration lead to undesirable thermal effects. An FEL pulse control system, using an acousto-optic modulator (AOM), was developed to investigate the non-thermal effects of FEL on living tissues. This system provides efficiency (~ 65%) and a fast switching speed (> 200 ns), and we predict that FEL will serve as a novel tool in many new applications.

INTRODUCTION

The free electron laser (FEL) at Osaka University is a pulsed, tunable infrared source. It is designed to work in the region from 5 to 20 µm at an average power of up to 50 mW. The FEL applications research is broadly interdisciplinary, including measurements of investigation of protein dynamics, the ablation of soft tissues and narrow band-gap materials [1-4].

An electron beam of 30 MeV energy is the laser gain medium for the FEL. It is accelerated with a linear, pulsed RF accelerator. This leads to the pulsed beam current and complex temporal intensity profile of the emitted IR light as shown in Fig.1. The accelerated electron pulses have up to 20 µs duration and each of them generates one optical "macropulse" have duration of 15 µs. The mode locked pulse or "micropulse" have duration of approximately 5 ps with 44.8 ns spacing between pulses. For many FEL application 15 µs duration of the macropulse leads to undesirable thermal effects or obscures signals from fast optical process. The FEL user community has identified the need for selecting the number of micropulse. The switching device to achieve this should have the following properties;

(1) Operating wavelength of 5 to 12 µm;
(2) Variable pulse duration between 500 nanoseconds and the full macropulse length, with fast rise and fall times;
(3) High efficiency;
(4) Easy pulse duration adjustment; and
(5) Portability between different experimental stations.

An acousto-optic modulator (AOM) has therefore been chosen as the best solution for the Osaka University FEL system. Section 2 describes the principles of AOMs and pulse control systems. Section 3 details the performance evaluations of the pulse control system, and Section 4 reports the results of these evaluations.

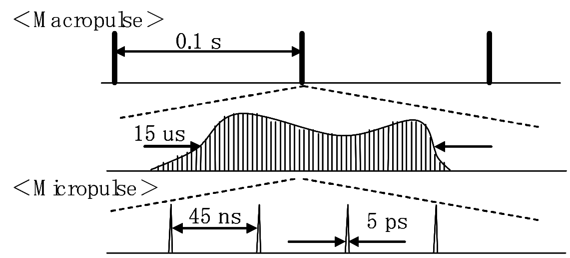

Figure 1: Pulse structure of FEL.

MATERIALS AND METHODS

The principle of an Acousto Optic Modulator

An AOM is a device that allows control of the power, frequency, or spatial direction of a laser beam using an electrical drive signal. It is based on the acousto-optic effect, i.e., refractive index modification by the oscillating mechanical pressure of a sound wave. The geometry of the input and output laser beams relative to the acoustic column is shown in Figure 2. An AOM's key element is a transparent crystal (or a piece of glass) through which the light propagates. A piezoelectric transducer attached to the crystal is used to excite a high-frequency sound wave. Light can then be diffracted at the periodic refractive index grating generated by the sound wave. The scattered beam has a slightly modified optical frequency (increased or decreased by the frequency of the sound wave) and a slightly different direction. The frequency and direction of the scattered beam can be controlled via the frequency of the sound wave, while the acoustic power allows control of the optical power. For sufficiently high acoustic power and to align the input laser beam for a true Bragg input angle, more than 70% of the optical power can be diffracted as the first order beam. When a supersonic wave intercepts the incident beam, the AOM generates a first order beam. Therefore, the rise time of first order beam depends on the diameter of the incident beam and the speed of the supersonic wave. The rise time of the first order beam is given by equation (1). The following

* kanai@fel.eng.osaka-u.ac.jp

equation describes the time required before the primary light output rises from 10% to 90% [5].

$$TR = S/\,(v*1.56), \qquad (1)$$

where:

TR = Rise time of first order beam,
S = Diameter of incident beam,
V = Speed of supersonic wave,
1.56 = correction factor.

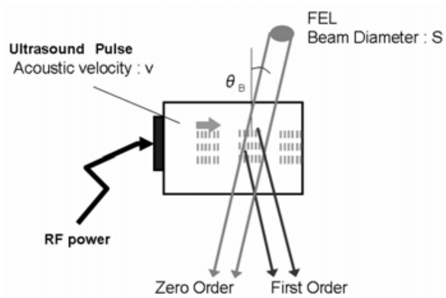

Figure 2: Principles of an AOM.

Pulse control system design

The diameter of the original FEL is about 50 mm Φ. To control the high efficiency/high speed pulse, it is necessary to incident para-parallel/diameter of very small beam into AOM. A schematic diagram of an FEL pulse control system is shown in Figure 4. The FEL beam (50 mm Φ) diameter was reduced in size to 1.5 mm Φ by two mirrors with either long (radius of curvature = 385 mm) or short (radius of curvature =50.0 mm) focal lengths. Table 1 shows the specifications of a standard AOM (AGM-402A1, IntraAction Corp).

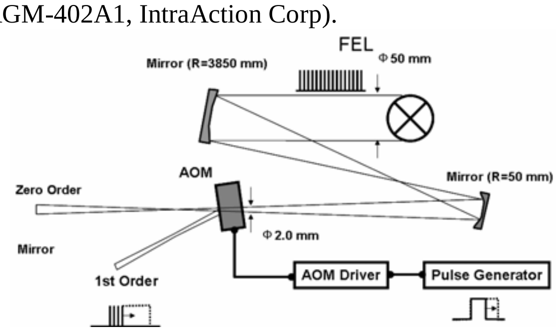

Figure 3: Experimental setup for pulse control.

Table 1: Specifications of Ge-AOM

Optical Wavelength	@10.6 µm
Acousto-optic Material	Single Crystal Germanium
Acoustic Velocity	5.5 mm/µsec
RF Center Frequency *	40 MHz
Optical Insertion Loss	<7 %
Optical Power Capability	25 Watts
Laser Polarization	Parallel to Base
Rise Time (diameter)	116 nsec (1 mm)
Bragg Angle	38.5 mrad
Beam Separation	77 mrad
Diffraction Efficiency	<70 %

*Other frequency available

PERFORMANCE EVALUATIONS

The laser damage threshold for Ge was determined empirically for the FEL. Surface damage occurred at 20 mW of average power, less than 1.5 mm Φ beam diameter, and 6.3 µm wavelength. The absorption by Ge does not change significantly between 6 and 12 µm. Our experimental setup is shown in Figure 5. The FEL enters the AOM at a diameter of 1.5 mm Φ and the pulse duration is controlled by adding a supersonic wave pulse to the AOM. First order beam is detected by infrared detector (MCT; VIGO Systems, R005). MCT signal is recorded by an oscilloscope (LeCroy, WaveMaster 8000).

RESULTS 1

Wavelength-dependence of pulse control system

The wavelength dependence of the pulse control system is shown in Figure 4, Input/picked FEL average power vs. wavelength in the range from 5.4 to 12 µm.

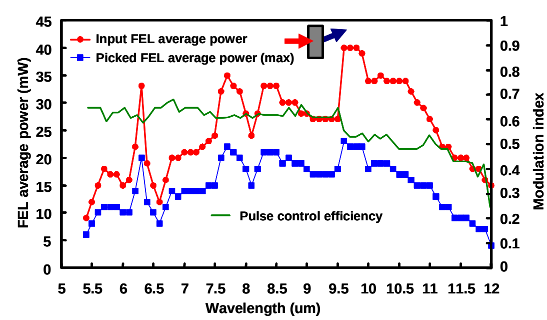

Figure 4:Wavelength-dependance of pulse control system.

Measurement of first order FEL

The MCT signal of the FEL first order beam is shown in Figure5. This pulse control system can control the FEL pulse width in the range of 10 micropulses (>200 ns) to the full macropulse (15 µs). A 630 ns first order FEL is produced by a control signal of 500 ns, a 360 ns first order FEL is produced by a control signal of 200 ns. Based on these results, the rise/fall time of this pulse control system is about 100 ns. This result aligns closely with the theoretical value derived from equation (1).

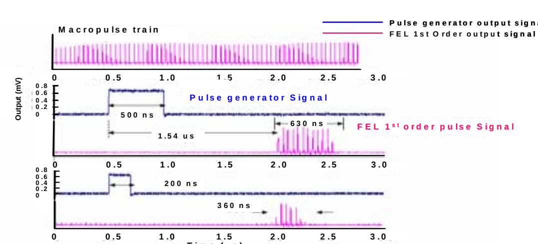

Figure 5: The pulse structure of the picked FEL.

EXPEREMENT

In case of FEL irradiation to gelatin, interaction arrives at depth of 2mm, at the maximum. However, Photo penetration depth = 3 µm. Interaction extends to much deeper from the region where light can arrive at. It is thought that this reaction depends on a shock wave.

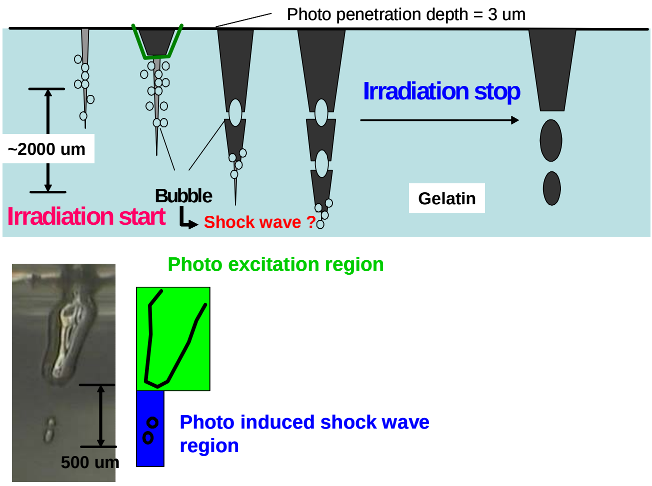

Figure 6: The process of gratin cut.

Experiment setup

Experiment setup for proof experiment of pulse control effect is shown in Fig 7. In this experiment, change of a shock wave is estimated by an image analysis and wave pattern analysis.

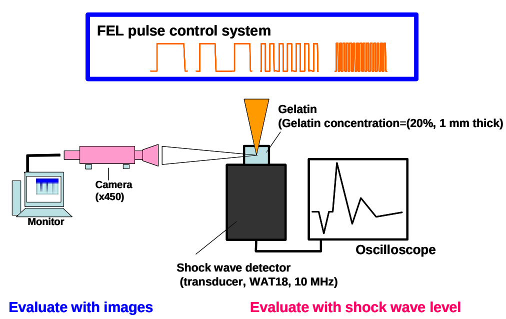

Figure 7: Experiment setup for proof experiment of pulse control effect.

RESULTS 2

A difference of a level of shock wave by a difference of pulse structure is shown in Figure8. Figure 9 illustrates the maximum shock wave level (peak to peak)/ maximum shock wave arrival depth (image analysis) vs. FEL pulse width. From these results, the same tendency was seen in an analysis result by an image and an analysis result by a wave pattern. A shock wave grows up to 1-2 µs and reaches saturation afterwards.

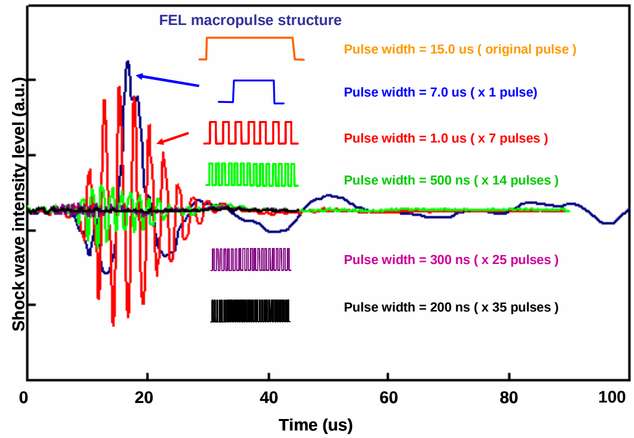

Figure 8: A difference of a level of shock wave by a difference of pulse structure.

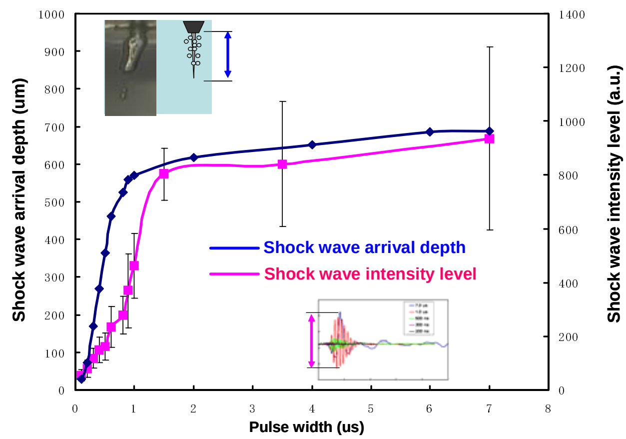

Figure 9: A difference of shock wave by a difference of pulse structure.

CONCLUSIONS

FEL pulse control system using an AOM was developed in order to investigate of non-thermal effect between the FEL and living tissue. With a time scale of 200 ns ~ 15 µs, this system provides the efficiency of ~65 % and a fast switching speed.

From results of pulse control effect proof experiment, the same tendency was seen in an analysis result by an image and an analysis result by a wave pattern. A shock wave grows up to 1-2 µs and reaches saturation afterwards. This system made it possible to control a shock wave by controlling a thing of pulse structure.

Picking out a single micropulse is impossible using this device with a time scale from 200 ns to 15 µs; it is, however, a very successful pulse control technique.

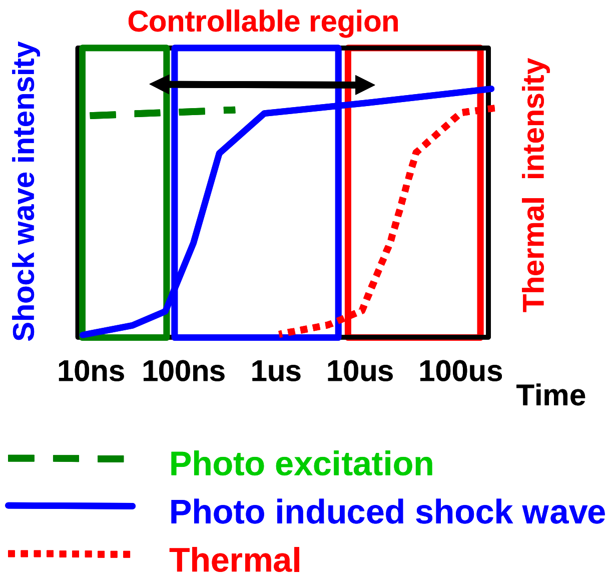

Figure 10: Controllable region by pulse control system.

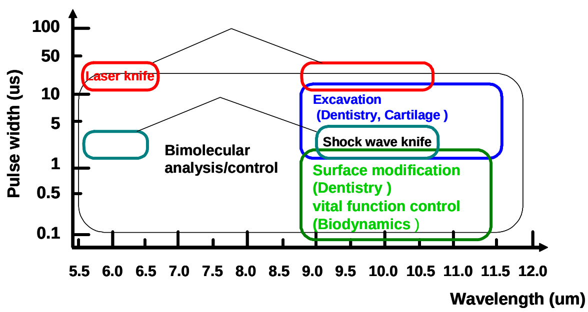

Figure 11: New regions that FEL can apply.

DISCUSSIONS

Using this system, the pulse width becomes the third parameter of the FEL system, in addition to the two conventional irradiation parameters of wavelength and power density. This system allows more precise FEL-biomolecular interactions, and was thereby able to produce a new irradiation effect of FEL that was not previously available (Figure 11). Improvement of the pulse control system (higher speed, higher power density) affords more selective excitation of biomolecules on a pico- and nanosecond time scale. In addition, by using FEL as the excitation light, we can introduce the picosecond time resolution vibration minute light method to the field of chemistry and biology.

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