Highly stabilized femtosecond Ti:sapphire laser designed for beam interaction experiment

Akira Endo*

The Femtosecond Technology Research Association (FESTA) 5-5 Tokodai, Tsukuba 300-2635, Japan

Abstract

Present status of the laser research is described relating with the specified purposes dedicated for beam experiments. A compact and stable UV picosecond laser was developed for photo-cathode RF gun application. An experimental terawatt Ti:sapphire laser is now under development to demonstrate the required performance for the inverse Compton femtosecond X-ray generation at high repetition rate. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Diode-pumped; UV ps laser; Low jitter; Nd:YLF; Adaptive control; Ti:Sapphire; Shack–Hartmann

1. Introduction

Recent rapid progress of the laser-beam interaction research calls for specified lasers depending on dedicated purposes. Commercially available lasers are usually designed for general applications in scientific, medical and industrial fields. The harsh accelerator environment is in general not friendly for conventional commercial lasers to achieve strict requirements specialized in each beam experiment.

Performance of a photo-cathode RF gun injector is mostly determined by reliability and stability of the irradiation laser once the RF gun conditioning is correctly achieved. The required specifications for the lasers are various, namely lower timing jitter to external RF signal, lower fluctuation of pulse energy, positioning, spot size, pulse width and shape. These laser characteristics are fragile to the change of the environmental factors (the ambient temperature and atmospheric pressure change, mechanical vibrations, etc.) together with high level RF and radiation noises in the laboratory. The lasers for inverse Compton experiments are composed of energy amplifiers of long optical path in addition to the initial oscillator and regenerative amplifier stages. Control of the required parameters is generally more challenging in the case of a large scale, high energy short pulse laser.

Femtosecond monochromatic X-ray generation is planned in the FST project (Femtosecond Technology) based on the inverse Compton scattering of a short and intense laser pulse with a focused electron beam [1]. The fundamental requirement is the temporal and spatial control of the laser and the electron beam in 100fs and 10μm precision for highly efficient inverse Compton X-ray source. The laser is to be suited in the whole beam system with compact size. The research group of the FST project has been developing two different types of specified lasers by adopting advanced laser

*Tel.: +81-298-47-5181.
E-mail address: aendo@festa.or.jp (A. Endo).
technologies. One is a compact UV picosecond laser for photocathode RF gun. The other one is a terawatt Ti:sapphire laser at 100 Hz repetition rate for femtosecond X-ray generation. Both lasers have been developed based on a basic research with an experimental Ti:sapphire laser of FESTA and the recent laser technologies like diode pumping and adaptive control to realize compact and stable light sources for dedicated purposes. Detailed technical information is reviewed in the following sections for both lasers.

2. Diode pumped UV picosecond laser for photocathode RF gun

An extensive research has been performed to realize a compact UV picosecond laser [2]. The basic research, which is described in the next session, was also essential in the design and evaluation of the laser. The laser is expected to achieve the strict requirement for stable RF gun operation in the harsh environment of accelerator laboratories. The original developmental goal was set to realize a compact, one box UV picosecond laser synchronized with an external RF signal with fine precision at 100 Hz repetition rate. The recent progress of diode pumping technology seemed promising to realize the general requirement. Laser material was selected as Nd:YLF for better matching to direct diode pumping and for the possibility to operate down to a few picosecond pulse width.

A commercially available “shoe box” picosecond oscillator (LightWave 131) was selected in the breadboard experiment. The oscillator was composed of actively mode-locked Nd:YLF crystal at 1053 nm, with a built-in timing stabilizer to an external 79.3 MHz RF signal. The repetition frequency of 79.3 MHz was selected as 1/36 of the S-band accelerator RF frequency (2856 MHz). The typical output power and pulse width was 100 mW and 20 ps, respectively. An amplifier stage was necessary to increase the seed pulse energy to a few mJ at 100 Hz. The schematic diagram of the breadboard experiment is shown in Fig. 1. A compact regenerative amplifier was designed based on the W-shaped optical arrangement with total optical path length of 1.5 m. The laser beam diameter was designed to be larger at the Pockels Cell and smaller at the amplifier crystal to avoid optical damage and to increase the amplification efficiency. The pulse slicing was performed by the combination with a Pockels Cell, Faraday Rotator, waveplates and polarizers. A nonlinear crystal pair was installed in the last stage of the system to generate UV picosecond laser pulses. Two QCW laser diodes were employed to pump the amplifier Nd:YLF crystal with 0.4 ms pulse width of 70 A peak current at 100 Hz. The timing precision of the electrical components was around 1 ns in the experiment. Fig. 2 shows the arrangement of the breadboard experiment.
The breadboard model was characterized in various specifications relevant to RF gun operations. A single seed pulse was selected at 100 Hz by the Pockels Cell and confined in the cavity of the regenerative amplifier from the repetition pulse train of the picosecond oscillator. The typical single pulse energy was 1 nJ. The confined single pulse was then amplified to the saturation level inside the cavity after several round trips. Amplified pulses were switched out by the Pockels Cell after gain saturation. These behaviors are shown in Fig. 3. The typical output pulse energy was 1 mJ, which was \(10^6\) increase from the oscillator stage. A nonlinear crystal pair was employed to generate UV picosecond pulses at 263 nm. The result was around 50 \(\mu\)J before precise adjustment with 3% pulse to pulse energy fluctuation. The measured fundamental pulsewidth was 20 ps, which was equivalent to the oscillator’s one. The environmental condition control was critically important to achieve a stable operation in terms of pulse energy, pointing and beam shape in the breadboard model.

Tunability of the UV pulsewidth is desired in RF gun characterization experiments. A simple optical compressor was developed for this purpose. The experimental setup is indicated in Fig. 4. An optical fiber of 450 m length was installed after the oscillator to introduce frequency chirping to the seed laser pulses. A pair of lens was employed to reshape the spatial mode to introduce the chirped pulse into the regenerative amplifier cavity. A single seed pulse was then amplified up to the saturation level with the chirped structure. Output pulse energy was measured as 0.8 mJ at 100 Hz with 50 mW input power to the fiber from the oscillator. A grating pair was employed to compress the output longer pulse to a 3 ns, 0.4 mJ pulse at fundamental wavelength. The measurement of the pulse-width is shown in Fig. 5.

The breadboard experiment was quite useful to design a commercial one box UV picosecond laser for RF gun application. The critical design parameters are relating with the temperature control of
the Pockels Cell less than 0.1 degree, an invar breadboard for stable optical path control, EMI resistant electrical circuits, etc. The laser oscillator was changed to a passively mode-locked type with a SESAM (Semiconductor Saturable Absorber Mirror) with a reduced pulse width of 10 ps [3]. A built-in timing stabilizer was improved to achieve sub-ps timing jitter. A remote control function was embedded to perform automatic operation in a controlled accelerator laboratory. Fig. 6 shows the outlook of the developed UV picosecond laser together with control boxes (one is for local, the other one is for remote operation). Table 1 shows the general specification of the laser. The laser performs quite stable operation in a several harsh accelerator environments for RF gun operation. The performance of the generated electron bunch was characterized in detail. The generated beam is possibly compressed by magnetic technique down to sub-picosecond pulse width. Five commercial models were fabricated in the last two years with slightly different specifications depending on the applications, namely repetition frequency, output pulse energy and wavelength [4].

An arbitrary laser beam shaping is desirable for better performance of a RF gun. The shaping is possible both in temporal and spatial domain with high efficiency. The temporal shaping is performed by Fourier-transform synthesis of a femtosecond laser pulse [5]. An amplified shaped pulse generation is the new requirement in the technology, which means the combination of a pulse shaper with chirped pulse amplification (CPA). A research group of FST project has started an experimental program to demonstrate the technical possibility of the temporal shaping of the laser pulse for RF gun applications. Fig. 7 shows the general arrangement of the experimental setup. The Ti:sapphire experimental femtosecond laser of FESTA is employed in the experiment. The laser system is composed of a stabilized oscillator and regenerative amplifier, and the details is described in the following section. The main component of the pulse shaper is a liquid crystal spatial light modulator (LC-SLM) and installed between the oscillator and the regenerative amplifier stage and within the pulse stretcher. We can in principle achieve any arbitrary pulse shape around a few ps pulsewidth optimized for RF gun operation. A feedback technique is used to adjust the pulse shape between pulses from the oscillator.
and the amplifier. The result will be reported elsewhere in near future.

3. Stabilized Ti:sapphire laser for femtosecond X-ray generation

A comprehensive research is now undertaken in the FST project to establish the necessary technical background for a highly stable, 100 Hz terawatt Ti:sapphire laser dedicated for inverse Compton femtosecond X-ray generation. The target pulsewidth and energy are moderate 100 fs and 100 mJ for better synchronization with a subpicosecond electron beam pulse. The timing stability of the whole system depends on the mode-locking stability of the master laser oscillator, initially.

The phase noise of mode-locking is well studied in different types of lasers, namely semiconductor, fiber and solid state like Ti:sapphire and Cr:LiSAF. The timing fluctuations are categorized into four species in case of actual solid state lasers. The first one comes from the changes in the gain medium, which is caused by the fluctuation of the pumping source and temperature change inside the medium. All solid state green lasers are usually employed to achieve low noise pumping. The second one is due to the mechanical vibrations of optical components of the laser cavity. The amplitude of the vibration is not large compared to the cavity length, but the fluctuation frequency spans from several Hz to several kHz. A small cavity mirror is adjusted of the position by a piezoelectric transducer (PZT) through a timing stabilizer circuit to compensate the fluctuation. The third one comes from the environmental disturbances like temperature, air flow, atmospheric pressure and floor vibration. The characteristic time of these changes are relatively slow and can be compensated by a motor driven translation stage of a cavity mirror through a timing stabilizer. The remaining timing jitter is the main topics in the laser physics and one is the phase noise due to the quantum noise of the laser material. An analytical work is now in progress and indicating that smaller group delay dispersion (this is determined by material) is better for smaller quantum noise. The typical value of quantum noise is indicated around 10 fs in a Ti:sapphire laser crystal [6]. An experimental laser oscillator was constructed to study these phenomena. The repetition frequency was selected as 119 MHz which is 1/24 of the S-band frequency and matching to the most quiet frequency of a crystal RF oscillator. The experimentally measured jitter was 77 fs in the mode-locked pulses from the laser oscillator [7]. A detailed report is given in this conference by

![Fig. 8. Schematic diagram of the experimental Ti:sapphire femtosecond laser.](image-url)
a separate author on the jitter measurement and stabilization of a mode-locked Ti:sapphire laser oscillator [8].

A power spectral analysis method is usually applied in the evaluation for the jitter characteristics of high repetition rate laser pulses [9]. A single-shot jitter measurement is necessary to evaluate and control the timing of the amplified pulses at 100 Hz. A compact regenerative amplifier was constructed for the research and development of the single-shot jitter measurement architecture. The general arrangement is shown in Fig. 8, which is composed of the timing stabilized oscillator stage with Millennia pumping laser, a stretcher/compressor stage, the regenerative amplifier stage and the jitter measurement system. The regenerative amplifier is equipped with Evolution all solid state pulsed green laser and a temperature stabilized (by a Pertier cooler) Pockels Cell. The regenerative amplifier was operated at 1 kHz with 0.4 mJ output pulse energy and 100 fs pulsewidth after compression. A FROG measurement is shown in Fig. 9, and indicates a transform-limited behavior of the amplification. The strict temperature control was quite useful for stable operation of the Pockels Cell. The resulting pulse-to-pulse energy was stabilized less than 0.4% rms with the temperature of the Pockels Cell controlled within less than 0.1 degree. The fluctuation of the spectrum was also within the measurement limit. The regenerative amplifier is one of the most stable system ever reported. An extensive research is now in progress to measure the timing jitter of the amplified low repetition rate pulse relative to the stabilized standard light pulse of the oscillator [10]. The basic approach of the measurement is indicated in Fig. 10.

The experimental efforts are also contributing to the improvement of the picosecond UV laser operation in terms of lower timing jitter and measurement. The experimental setup of the FESTA Ti:sapphire laser is shown in Fig. 11. The laboratory is carefully controlled of the temperature, vibration, humidity, dust and air-stream.

A significant heat accumulation is the phenomenon in high repetition rate amplifiers, which may
cause the degradation of the beam focusability due to thermal lensing. Nonlinear effects inside the amplifier is also responsible for the decrease of the beam quality. An experiment was performed to evaluate the effect of the wave front distortion due to thermal lensing by a Shack–Hartmann wave front sensor. The test amplifier was a 20 mm diameter, 12 mm thick Ti:sapphire crystal doped at 0.15wt.% with AR coating on both surfaces. The crystal was pumped by a frequency-doubled Q-switched Nd:YAG laser (Quanta-Ray PRP-290-50) with 500 mJ, 12 ns pulses at 50 Hz repetition rate. The pump beam was separated into two by a beam splitter, and the pump beam profile was imaged onto the crystal surfaces with 7.5 mm diameter. The amplified beam diameter was designed as 6 mm to obtain higher extraction efficiency above 80% by 4-pass amplification. The near filed beam profile was measured by a laser beam profiler with a relatively inhomogeneous distribution. The thermal lensing was evaluated by measuring the optical path difference (OPD). The measured radial dependence of the OPD was almost quadratic in the pumping region despite the fairly inhomogeneous pumping. The effective focal length was estimated as 8 m by extrapolation from the present data for the 50 W pumping of our design. The thermal relaxation time was around 0.5 s in our case. The thermal lens was concluded as not affecting the pointing stability even in an inhomogeneous pumping. A He–Ne laser beam was probed in the pumped amplifier with 10 μrad pointing stability [11].

The remaining problem is the inhomogeneous spatial gain distribution due to inhomogeneous pumping. This may cause wave-front distortion during the amplification. An experiment is planned.
to evaluate the effect by synchronizing the pumping and measurement of the Shack–Hartmann sensor. An experimental prototype is now prepared to study the whole performance of the stable terawatt system. Fig. 12 shows the general outlook of the laser with various adaptive feedback controls. The system operation will be performed after the confirmation of these stabilizing technologies.

4. Conclusion

Two different types of lasers were described, which were specially developed for laser-beam experiments. One is a UV picosecond laser, mainly for RF gun applications. This laser may be also useful for various experiments where strict control of timing and position is required. The other one is a high repetition rate terawatt Ti:sapphire laser for femtosecond X-ray generation. Both lasers were designed to achieve sub-picosecond timing jitter to realize a good spatial and temporal synchronization with short electron beam pulses.

The author would like to greatly thank all people who are contributing to the research work. Some people are mentioned in the reference of this report. This work was performed under the management of the Femtosecond Technology Project Association supported by New Energy and Industrial Technology Development Organization (NEDO).

References