DEVELOPMENT OF A 770 NM PUMP-PROBE LASER DIRECTLY TRIGGERED BY A 1540 NM OPTICAL MASTER OSCILLATOR AT XFEL/SPRING-8

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Abstract

A pump-probe experiment at XFEL/SPring-8 is one of the most prominent parts to extract the future of a coherent short-pulse X-ray laser. A commercial Ti:Sapphire mode-locked laser is presently being used as a pump laser, while a probe laser is the XFEL. However, the time jitter of the commercial mode-locked laser, which is caused by the noise of an electrical mode-locking circuit, is around several hundred femto-seconds. This jitter value is not sufficient for temporal resolution demand for our pump-probe experiment with a laser pulse width of several ten femto-seconds. To improve this time jitter, a method using a 770 nm Ti:Sapphire laser amplifiers directly triggered by 1540 nm laser light generated with a optical master oscillator as a time reference signal source for an XFEL linac was devised. This method could eliminate the noise caused by an electrical mode-locking circuit. The basic principle of this method was proved by a preliminary experiment with laser pulse manipulation employing an E/O crystal shutter with a several ten pico-seconds pulse response. The results of a preliminary experiment, such as comb laser pulse train culling from a high repetition-cycle of 5712 MHz to a low repetition-cycle of 10Hz and laser wavelength converting from 1540 nm to 770 nm, show a great possibility to develop a pump laser system using our devised method.

INTRODUCTION

The crucial experiment of an X-ray free-electron laser (XFEL) [1] is a pump-probe experiment using characteristics, such as a laser pulse width of several ten femto-seconds. [2] This temporal resolved experiment traces the temporal and structural evolution of a material excited with a pump laser in the X-ray diffraction imaging method using a probe laser. In this experiment, an X-ray laser is a probe laser, which has a pulse width of several ten femto-seconds, and an ordinal Ti:Sapphire laser is a pump-laser. The temporal resoluon of this method demands the order of a femto-second region for observing a molecule and atom dynamical distribution due to the phase change of material by photo-excitation. In the case of the pump-probe experiment of XFEL/SPring-8, an X-ray with a pulse width of about 30 fs is used as a probe laser, while a Ti:Sapphire laser with a pulse width below 100 fs is used as a pump laser; both lasers have to be precisely synchronized. Figure 1 shows configuration of the experimental instruments of an XFEL machine based on the present plan of the pump-probe experiment. The frequency of a time reference signal for synchronization between the pump laser and the probe laser is a sub-harmonics 79.3 MHz of the 5712 MHz acceleration frequency for an XFEL linear accelerator (LINAC). Since the present plan of the pump-probe experiment employs a commercial Ti:Sapphire laser as a pump laser, this time reference signal of 79.3 MHz corresponds to the mode-locked frequency of the pump laser. This synchronization technique uses a 79.3 MHz electrical sinusoidal wave filtered from comb pulses generated with the mode-locked laser. In order to detect the comb pulse for making an electrical sinusoidal wave, a pin-photo diode and a band-pass filter are used. The phase difference between a time reference sinusoidal wave and the filtered wave is detected with a phase detector, and the detected phase difference signal is fed into a piezo actuator in order to control the length of a laser cavity for mode-locking feedback control. In the case of the electrical mode-locking circuit, as previously mentioned, the time jitter of the comb pulse train generated with the mode-locked laser cannot be suppressed below 55 fs (RMS, see http://www.coherent.com/downloads/SynchrolockAP_DS_3.pdf), since there is thermal, shot and external noise in the mode-locking circuit and the pin-photo diode. For this reason, a commercial mode-locked Ti:Sapphire laser is not suitable for the pump-probe experiment of the XFEL, if we consider the 30 fs pulse width of the XFEL. To date, we should use a commercial laser based on the present technology with a several hundred femto-seconds time jitter. However, this kind apparatus is not sufficient for realizing a temporal accuracy of several femto-seconds, which is demanded for the XFEL experiments. Therefore, we must develop a method having a femto-seconds temporal accuracy for the pump-laser, and have thus devised a Ti:Sapphire regenerative amplifier driving system by only optical component without any electrical circuits. In the SCSS test accelerator, the time jitter between a 5712 MHz time reference signal and accelerated electron beams is achieved up to about 46 fs. [3] Furthermore, an optical fiber time reference signal transmission system, which only increases noise corresponding to a time jitter of 7fs, was already developed. [4] From this fact, if a Ti:Sapphire

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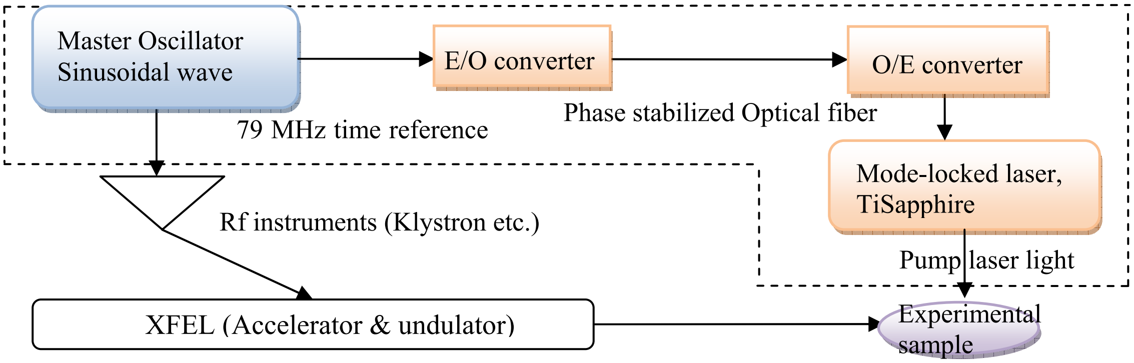

Figure 1: Present XFEL pump-probe experimental set-up using a commercial Ti:Sapphire laser system. The inside of the dotted line is an improved part at this time.

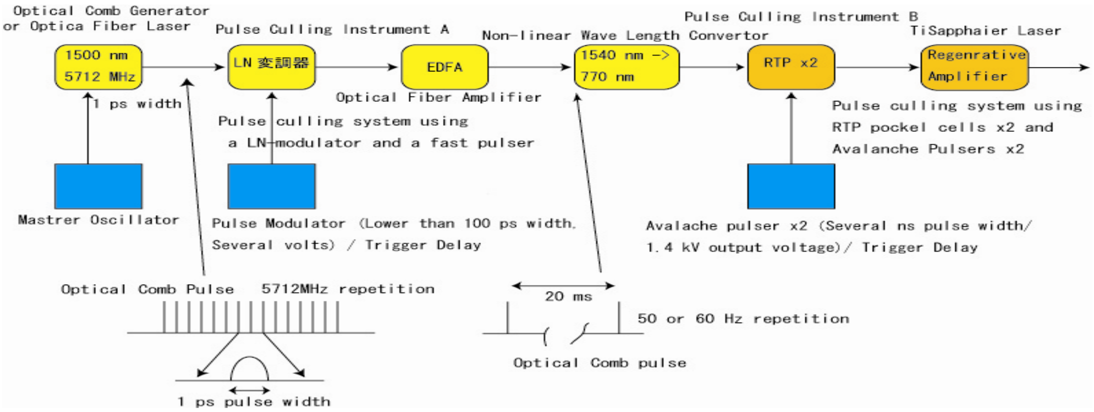

Figure 2: Direct triggering of a 770 nm pump-laser by a 1540 nm comb-laser for an XFEL time reference signal.

regenerative amplifier driving system using only optical components utilizing the time reference signal transmission system is developed, realizing below a 50 fs time jitter of a pump-laser can be strongly expected. Date's immediate goal of development for this laser system focuses on proof of principle. In this paper, we report on its idea, the results and the setup of a preliminary experiment for the proof of principle of our devised method.

METHOD TO GENERATE A 770 NM PUMP-LASER DRIVEN BY A 1540 NM TIME REFERENCE LASER SIGANL

System Outline

The temporal resolution of a Ti:Sapphire laser using an electrical mode-locking circuit, which is synchronized by a linac time reference signal of 5712 MHz, is limited up to 55 fs (RMS), because of using a commercial mode-locked laser in the present plan. In order to improve this temporal resolution, employing a mode-locking method only using optical instruments without any electrical circuit is crucial. For this purpose, we devised a direct triggering method to a Ti:Sapphire regenerave amplifier, as shown in Fig. 2, which improves a function in the dotted line part of Fig. 1. (A similar idea was presented in the Ref. [5].) In this method, at first, an optical comb-pulse train which is accurately synchronized to a 5712 MHz reference signal being the acceleration frequency of an XFEL linac is generated with an optical comb-generator [6] or an optical fiber mode-locked laser. [7] This optical comb-pulse train with a 1ps pulse width and a 5712 MHz pulse repetition cycle has a wavelength of 1540 nm. Since laser devices with a 1500 nm band are widely and commercially available products for information technology (IT), these devices are very helpful to decrease costs in order to develop our laser system using the method as mentioned above. In the next stage, the optical intensity of the pulse train is amplified with an erbium-doped fiber amplifier (EDFA) [8], and then this signal is transmitted with phase-stabilized optical fiber cables [9] to the instruments for the XFEL, such as an experimental apparatus. For example, at an instrument point, like a pump-probe experiment station, this pulse train is thinned out from a repetition cycle of 5712 MHz to a lower repetition cycle, such as 60 Hz, which corresponds to the operation repetition-frequency of the XFEL linac. An optical-shutter using a Lithium-niobate (LN) modulator [8], being an electrical-optical (EO) crystal (we call this method A.), thins out the pulse train. After this manipulation, the culled optical pulses are amplified again with the EDFA for generating the second harmonics of 1540 nm by using periodically poled lithium niobate (PPLN) being a non-linear crystal, for which it is a second harmonic generator. This wavelength of 770 nm, which is the second harmonic, is close to that of a standard Ti:Sapphire laser. This 770 nm light is injected into two pockels cells [10] driven by fast avalanche pulsers having an output pulse with a several ns width, and two polarizers in order to increase the extinction ratio between the pulsed parts and non-pulsed part of the optical pulse train (we call this method B.). This optical manipulation is used to reject any unnecessary DC bias part of the optical pulse train. The details of these optical pulse manipulations are explained in the next section. This trimmed optical pulse train is finally injected into the regenerative amplifier of a high-power Ti:Sapphire laser system. After passing through several stages of the laser amplifiers, it becomes the pump laser light in order to activate an experimental sample. Figure 3 shows a photo of the developed optical comb pulse culling system using the previously mentioned method in order to perform a preliminary experiment for proof and principle. In the following sections we explain the details of the optical pulse culling methods.

Laser Pulse Culling Method A

In the method A, a 1540 nm laser pulse train with a repetition cycle of lower than several ten GHz is injected into the laser pulse culling system of method A, as shown in Fig.4, and thinned out to a very low repetition pulse train, such as 60 Hz. In order to thin out from the 5712 MHz optical comb pulse with a 1ps width to the 60 Hz pulse train, the LN modulator is used as a fast temporal response optical shutter at the first stage in Fig. 2. This modulator is a mach-zehnder interferometer [11] using a crystal of $LiNbO_3$, and is driven with a first pulser (Picosecond Pulse lab, 3500D, 65 ps output pulse width) having an output pulse with a 100 ps width (FWHM). This pulse width allows the opening time of the optical shutter for which one pulse in the comb-pulse train only passes.

Laser Pulse Culling Method B

Figure 5 shows another laser pulse culling system of method B for the second stage optical shutter in Fig. 2. This system adapts to thin out from 770 nm comb-laser pulses of a several hundred MHz repetition with about a 1 ps pulse width to a very-low pulse repetition cycle, such as 10 Hz. Furthermore, it is also for increasing the extinction ratio between the pulsed parts and the non-pulsed part of the optical comb-pulse train. This method uses two pockels cells using RTPs being EO crystals and two optical polarizers. These pockels cells are driven with high-voltage fast avalanche pulsers. These pulsers generate 1.3 kV peak voltages with several nano-second pulse widths (FWHM) and a pulse rise time of less than 1 ns. The function of this optical shutter is as follows. At first, the incident laser pulse train to the method B system is injected into the first pockels cell in Fig. 5 in order to control the optical polarization of the incident laser.

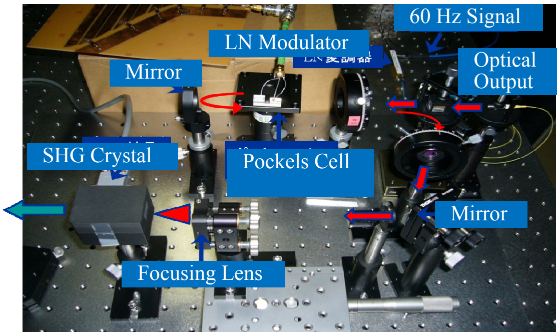

Figure 3: Laser comb-pulse train culling system for the preliminary experiment.

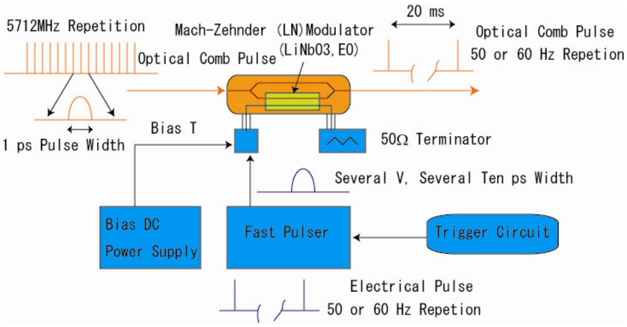

Figure 4: Laser pulse culling system (method A) using an LN modulator.

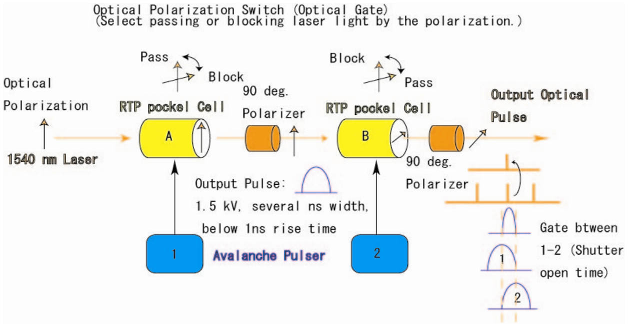

Figure 5: Laser pulse culling system using RTP Pockels cells as optical shutters (method B).

The second shutter using the same instruments also works with the same function. Both polarizers after the pockels cells determine passing or blocking the incident laser light due to its light polarization, respectively, which is manipulated with the pockels cells. Both the polarizers and pockels cells work as optical shutters. The pockels cells alternatively change the incident laser light's polarization. When the one optical shutter using the combination of the polarizer and pockels cell is opened for passing through the laser pulse, then another optical shutter is shut behind the open timing of the pervious shutter for blocking the pulse. In this operation, control of the shutter to manipulate the laser pulses width is realized. Even through, the control pulse width outputted with the high-voltage pulser is longer than the open time of the shutter, this method can thin out the laser pulse train having a time interval between the pulses, which is shorter than the output pulse width of the high-voltage pulser, by adjusting the activation timing of both pulsers. The temporal overlap time between the output pulses generated with the pulsers, as shown in the lower right part of Fig. 5, corresponds to the open time of this shutters system. By this method, we can cull fast comb-laser pulses with the 4 ns time interval of a 238 MHz repetition cycle to a low-repetition comb pulses, such as 60 Hz, by a 7 ns high-voltage pulse width.

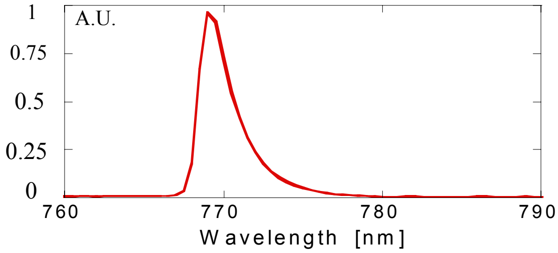

Figure 6: Laser pulse converted from a wavelength of 1540 nm to 770 nm with a PPLN crystal.

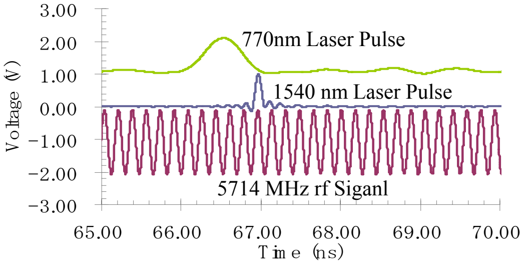

Figure 7: Laser pulse culling and wavelength converting results by the PPLN crystal, and methods A and B. The 5712 MHz time reference rf signal (below, red), the 1540 nm thinned out a 10 Hz laser pulse (middle, blue), and the 770 nm thinned out and converted laser pulse (upper, green) are shown in the figure.

EXPERIMENTS AND ITS RESULTS FOR WAVE LANGTH CONVERSION AND PULSE THINNING

To prove the principle of the above-mentioned idea for comb-laser pulses culling and wavelength converting, a preliminary experiment was carried out. A test system, as shown in Fig. 2, was built for the experiment. In this experiment, 1540 nm laser comb pulses with a 5712 MHz repetition and about a 1ps pulse width, were generated with the optical comb generator, which was driven by the electrical master oscillator and synchronized to the 5712 MHz rf output signal for the XFEL linac. This laser comb pulse train was added to the test system in order to convert from the 1540 nm comb laser pulses to 770 nm comb laser pulses, and in order to cull the 5712 MHz repetition cycle pulses to 60 Hz repetition pulses by methods A and B. The results of the wavelength converting and pulse-culling experiment are shown in Fig. 6 and Fig. 7, respectively. The spectral data of Fig. 6 was measured by a spectrometer (Ocean Optics, USB2000). This wavelength conversion and pulse culling system worked well. Unfortunately, the pulse response of a photo diode for 770 nm laser light is slow. Therefore, the pulse width of the converted light observed with the diode does not show a proper pulse width, as shown in Fig. 7. However, we can recognize that the 5712 MHz comb pulses is properly thinned out to 10 Hz comb pulses (the graph does not show the 10 Hz pulses, because, the horizontal time span on the graph is too narrow to show the 10 Hz pulses.).

SUMMARY

We obtained furutiful results of a priliminary experiment to prove the principle of laser wave length converting from 1540 nm to 770 nm by using a PPLN second-harmonic generator and pulse culling using a LN-modulator, RTP pockels cells, and optical polarizers. The proof of principle for our devised methods was successfully finishied. As a next step, the development of a pracitical laser pulse culling and wavelength converting system can be started based on our sucessful present results. We thank the members of the XFEL/SPring-8 group of RIKEN for their great help.

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