STATE-OF-THE-ART RF DISTRIBUTION AND SYNCHRONIZATION TECHNIQUES

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Abstract

In recently constructed FEL accelerators, the temporal stability of an accelerated electron beam is the most crucial problem to achieve stable lasing. The demanded temporal stability is less than several ten femto-seconds (rms) to stably keep an extremely high peak current formed at a bunch compressor, as well as attaining the required temporal resolution of a pump-probe experiment. To realize this stability, an elaborate rf distribution and synchronization system for the accelerator is strongly needed. One of the most promising methods to realize such a system uses a unified instrument involving both laser and electrical technology. Because the system can control the rf phase based on optical wavelength resolution, and it can reduce the effects of environmental perturbations arising from temperature variation, vibration and electrical noise. On the other hand, when designing the system, the selection of optical signal transmission methods using a comb-pulse train or a sinusoidal wave is crucial. Many institutes already employed a unified system comprising necessary instruments, such as optical-fiber signal transmission, in accordance with their own selection. We recently obtained less than 22.7 fs (rms) temporal fluctuation of electron beams at XFEL/SPring-8 "SACLA" by using this kind of system.

INTRODUCTION

Recent sophisticated accelerators, such as an X-ray free-electron laser (XFEL), [1,2,3,4], must have brilliant and very stable electron beams. In the case of the XFEL accelerator, longitudinally and transversely stable electron beams with low emittance, low energy spread, low energy drift/jitter and low temporal jitter should be equipped for stable lasing. For example, bunch compression stability to constantly maintain the electron peak current and width, such as 1 kA and 30 fs (FWHM), of a pulse-compressed beam is directly reflected in the lasing stability of the XFEL [5,6]. One of the key issues to realize stable bunch compression is an elaborated rf and timing distribution system using an ultra-low noise rf signal, as a time reference, to drive cavities, which give an energy chirp along an electron bunch for bunch compression.

On one hand, the elaborated rf and timing distribution is also crucial for an X-ray pump-probe experiment [7] using a Ti:Sapphire laser as a pump with a pulse width of below 100 fs (FWHM) and a 30 fs (FWHM) X-ray laser as a probe with a pulse width of several tens of femto-seconds. Both lasers have to be precisely synchronized by a mode-locked device using an ultra-low noise rf signal. This temporal resolved experiment traces the temporal and structural evolution of a material excited by a pump laser in the X-ray diffraction imaging method. The temporal resolution of this method thus demands the order of a femto-second region for observing the molecule and atom dynamical distribution due to the phase change of the material by photo-excitation [7].

To ensure the temporal stability and resolution in the XFEL, as mentioned above, ultra-low noise and extremely stable (without drift) rf and timing signals should be prepared for an XFEL accelerator and experiments. Furthermore, all of the components, including data acquisition (DAQ) systems related to rf sources, beam monitors and experiments, should be synchronized by one reference rf signal or its harmonics, or sub-harmonics generated by one master oscillator to guarantee temporal stability. This stability is finally reflected in stable lasing and in the quality of the experimental data.

In the case of the XFEL, the machine length including the accelerator, a light source using undulators and an experimental area could be more than 1 km long. Therefore, to distribute the ultra-low noise rf signal and time reference signal, an optical-fiber cable is the best solution to reduce signal transmission loss and to eliminate high-level noise generated by a high-voltage pulser for a klystron, rather than traditional coaxial cables. However, at the individual end stations of the optical fiber cables along the XFEL machine, electrical rf and timing signals must be provided, since the high-power rf sources of the linac, rf control instrument, such as an in-phase and quadrant (IQ) rf control devices, and DAQ system, such as a X-ray charge coupled device (CCD) in an experiment, are electronic equipment. For these reasons, unified rf and timing transmission instruments using laser and electrical technology must be employed for the XFEL.

There are two key methods being commonly employed for signal transmission using optical fiber. These methods should be adaptable to the unified instruments. One is sinusoidal wave transmission; the other is comb-pulse train transmission. When an rf distribution and timing system for synchronization in the XFEL is designed, we must compare the advantages or disadvantages of both methods. The decision for selecting one method from among them is strongly dependent on the features of an accelerator system and an experiment system in accordance with the scientific aim. Furthermore, the most important factor for the selection is how a high signal-to-

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noise (S/N) ratio of the rf and timing signal is guaranteed at the end station. This report is a review article that describes the advantages and disadvantages of both the signal-transmission systems dependent on the accelerator and the experiment, and introduces the details of the signal-transmission systems. As examples, the rf and timing distribution system for SACLA, its instrument performances, electron beam and lasing performances conducted by the system are finally reported.

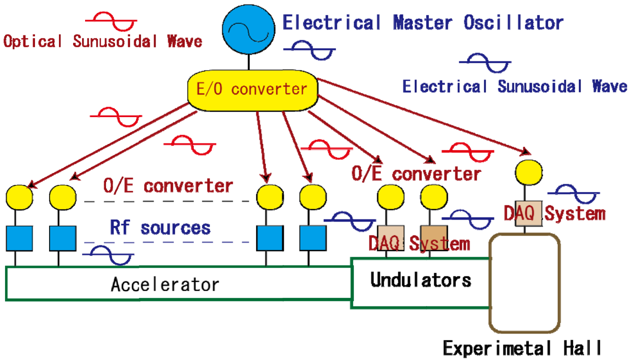

Figure 1: Sinusoidal wave rf and timing distribution.

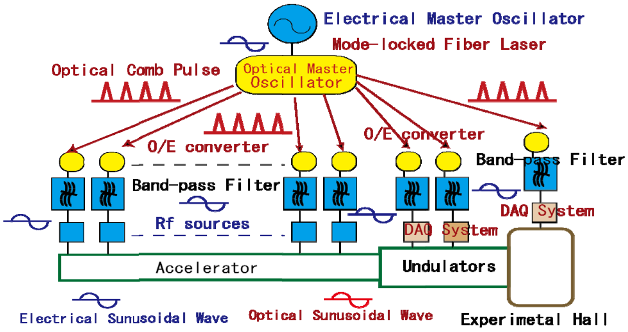

Figure 2: Comb pulse rf and timing distribution system.

FUNDAMENTAL DESIGN CONCEPT OF RF AND TIMING DISTRIBUTION

Sinusoidal Wave Transmission Method

A reference rf signal transmission with a sinusoidal wave is commonly used in a traditional linear accelerator (linac) using a normal conducting acceleration cavity; even a linac for XFEL, such as LCLS at SLAC, FERMI at Elettra and SACLA at SPring-8, uses it [8,9,10,11]. Figure 1 illustrates a schematic diagram of the basic configuration of the sinusoidal wave transmission. One of the reasons to use it is that this method is easily adaptable to rf transmission using a coaxial cable. Even through this technique is very old fashion; this transmission method is still easily extended to fiber-optic signal transmission as state-of-the-art-technology. Therefore, this method also easily adapts to the electrical instruments for the XFEL. The configuration of the system using sinusoidal-wave transmission is as follows. A time reference rf signal, which is for an acceleration rf signal and/or a timing signal, is generated with a master oscillator (MOSC) with ultra-low noise. This reference rf signal is transmitted by optical fiber cables after electric-optical (E/O) conversion to the end terminals nearby high-power rf sources, such as a klystron, and/or a data-acquisition (DAQ) system. At the end station, the optical signal is again converted into an electrical signal by an optical-electrical (O/E) conversion to drive the rf source and the DAQ system.

Comb-pulse Train Transmission Method

In the latest laser technology, a mode-locked laser oscillator [12] generates a comb-pulse train in principle. This type of laser oscillator is one of the candidates to make an ultra-low noise oscillator as a MOSC. Of course, it is also necessary to lock the laser oscillator light in the output signal of a time reference electrical sinusoidal oscillator with ultra-low noise. This pulse structure can also be applied to time reference signal transmission for an accelerator. Especially, the accelerator using super-conducting cavities, such as FLASH and Euro-XFEL [3], usually employs this method. Figure 2 depicts the system structure of the timing distribution using a comb-pulse train. Generated comb pulses are distributed from a central optical master oscillator to the end station, like the klystron part along the accelerator. At the end station, there is a local oscillator (LOC-OSC) used to drive a local rf source for the super-conducting cavity. This LOC-OSC refers to and locks in the one-frequency component of the optical comb-pulse, which is the acceleration frequency. In the case of using the super-conducting cavity, the LOC-OSC system is embedded into a local phase locked loop (PLL), including the super-conducting cavity with an ultra-high quality (Q) factor, such as 100,000, on the loop. The phase reference for this PLL is the one frequency component of the comb-pulse train. The super-conducting cavity acts as an ultra-narrow band filter to purify the impurity like noise of the signal generated by the phase-locked loop. This means that this PLL behaves as a very low-noise and narrow-band rf oscillator, because of the high Q factor of the cavity.

Frequency Choice for a Time Reference Signal

We can fundamentally choose any frequency signal different from the acceleration frequency for a time reference rf or a comb-pulse train, if there are individual LOC-OSCs, frequency multipliers or frequency dividers near high-power rf sources and DAQ systems. For example, the LOC-OSC is locked by a PLL using a 10 MHz time reference signal. This kind of PLL occasionally has a fast phase jump in a frequency region above the corner frequency (-3 dB point) on a PLL bode diagram. In the case of an XFEL accelerator, many LOC-OSCs should be provided, because of many high-power rf sources. The individual LOC-OSCs have a possibility to independently change their characteristics by independent surrounding temperature changes. The frequency multiplier and divider also have the same possibility.

In the case of SACLA, to prevent the independent motions of the distributed LOC-OSCs, multipliers or dividers, we employ a method in which an acceleration frequency signal of rf and a time reference are directly transmitted from the central MOSC to the distributed rf sources. However, this method usually uses higher frequency signal transmission than that of the case using the LOC-OSCs and multipliers. In our case, a 5712 MHz rf and time reference is distributed. When using this method, much care to eliminate the rf phase and amplitude shifts at individual rf components should be given, because of the high frequency.

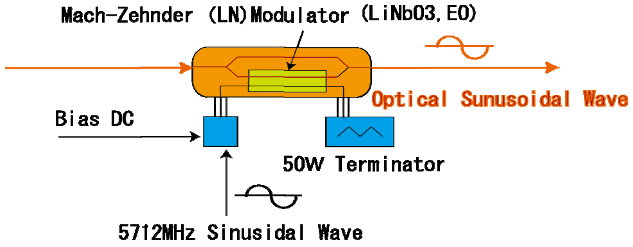

Figure 3: Mach-Zehnder interferometer (LN modulator).

Choice of a Transmission Cable, a Laser Source and an RF and Timing Modulation Method

An optical fiber cable can only be used to handle to transmit signals for a long distance of more than 1 km without the low-frequency signal transmission case of below 10 MHz; otherwise, a high-power and continuous wave (CW) rf amplifier, which usually causes rf phase and amplitude movements, is necessary to transmit a signal by a long-distance coaxial cable.

Concerning the choice of rf and timing laser modulation, there are basically two categories corresponding to the sinusoidal wave and comb pulse train transmissions. For sinusoidal-wave transmission, rf laser modulation is achieved by using a distributed-feedback (DFB) laser diode directly driven by an rf signal, and by using an optical modulation device, such as a Mach-Zehnder interferometer [13], as shown in Fig. 3. The wavelength of the laser is a 1500 nm band, because of low-cost optical devices, since information technology uses this laser wavelength.

In the case of comb pulse transmission, an optical comb-generator [14] or a mode-lock fiber laser [15,16,17], as mentioned in the details given below, are used with a low-time jitter. Even through either the comb-generator or the fiber laser is chosen, a solid-state laser for pumping is still needed. An ordinary laser cavity oscillator with a gain material, such as Cr and Yb, on the optical pass between mirrors can also be employed. However, the XFEL institutes do not presently employ this type of cavity oscillator, since this method does not easily fit to optical-fiber technology using the 1500 nm band. Therefore, this paper dose not cover further details. The optical comb-generator, as depicted in Fig. 4, has an electro-optic (E/O, LN) crystal inserted on an optical pass into an optical Fabry-Periot cavity. If an rf signal is added to the LN crystal, this optical cavity forms an optical comb pulse train with rf frequency repetition. This type of generator is suitable to generate a comb pulse with a higher repetition rate than 1 GHz; even 10 GHz repetition can be generated.

The mode-locked fiber laser, as shown in Fig. 5, used to generate a comb pulse train with a 1.3 GHz or lower repletion, as an example, comprises an Erbium (Er) or Ytterbium (Yb) -doped optical fiber as a laser gain material and an anomalous dispersive optical fiber for pulse-width shortening. Both the optical fibers and a mode-locked device, such as an optical fiber stretcher, are sequentially connected on a loop. This laser is pumped by a pump laser, such as a laser diode with a wavelength of 980 nm or 1480nm.

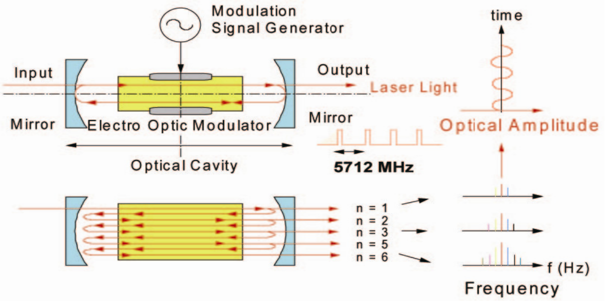

Figure 4: Optical comb generator. An electro-optic (E/O, LN) crystal is inserted into an optical Fabriot-Periot cavity.

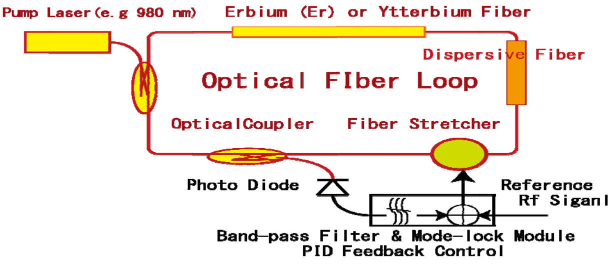

Figure 5: Mode-lock fiber laser. For example, a pump laser with 980 nm pumps it.

Method of Optical Fiber Length Control

The thermal optical length change of a fiber for a long distance of more than 1 km is not ignorable. For example, even through an optical fiber cable with a thermal optical length coefficient of 2 ppm/K is installed in a temperature-stabilized environment within 0.1 K, the optical-length change of the fiber is 1.2 ps. Therefore, employing optical fiber length control, which could control its length up to one-tenth of an optical wavelength, is crucial in order to realize femto-seconds temporal accuracy. The basic concept of fiber optical length control using Michelson interferometry was introduced from technology developed for the astronomical radio telescope array of ALMA [18]. Several institutes related to XFEL are already employing fiber length control by three methods [8,9,10,18,19,20], which use sinusoidal optical waves (e.g. Fig. 6) and optical-comb pulses. The detector used to measure the fiber length change is a waveform mixer using diodes or Gilbert cells [21], as a phase detector. The detailed configuration of the optical fiber length control system is described later, as one example.

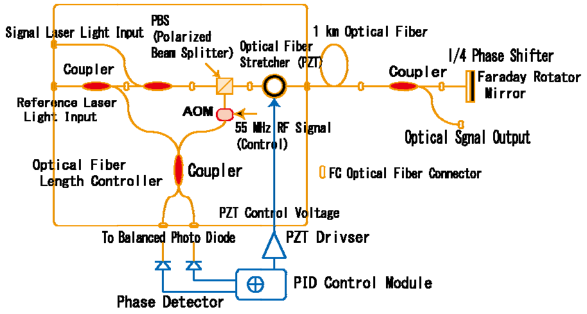

Figure 6: Fiber optical length control.

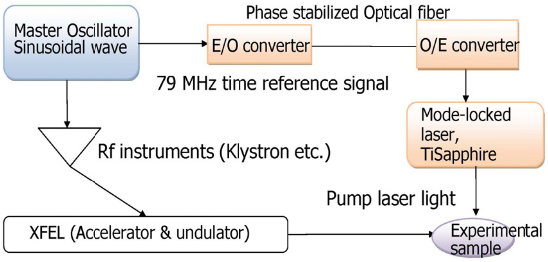

Figure 7: XFEL pump-probe experiment set-up.

Pump-laser Synchronizing System

For a present pump-probe experiment for XFEL [7,22], as shown in Fig. 7, a commercial Ti:Sapphire laser as a pump laser is used. An electrical sinusoidal rf signal of around 80 MHz is necessary to make the optical cavity mode-lock of a commercial laser, because a laser vendor only provides an electrical mode-locking signal input. The mode lock means adjusting the laser cavity length by using a phase comparison signal between a laser monitor being an rf (sinusoidal wave) signal with which unnecessary components is filtered out from a comb-pulse train with a band-pass filter, and a reference rf signal. The laser monitor signal is detected with a photo diode. Therefore, the above-mentioned rf and timing distribution system must provide the electrical reference signal for the mode lock. The synchronization accuracy of the mode lock to the reference rf signal is about 100 fs (rms, time jitter) in the case of the commercial laser. The requirement of synchronization accuracy is, of course, dependent on the experiment and 100 fs accuracy is sufficient for some experiments. However, other experiments demand further temporal accuracy of the synchronization over several femto-seconds to an X-ray laser with a ~20 fs pulse width, because of the science aim. For this reason, we are developing a further low-temporal jitter Ti:Sapphire laser using a thin mirror attached at a cavity length actuator, which is very helpful to expand the frequency band width of the mode lock servo-control [23], and a method to directly activate a regenerative amplifier of a Ti:Sapphire laser by wavelength-converted laser light form 1540 nm to 770 nm [22]. A schematic diagram of this wavelength conversion method is illustrated in Fig. 8. The 1540 nm laser light is provided by the above mentioned comb generator or fiber laser. Figure 9 shows the result of a preliminary experiment to convert the wavelength from 1540 nm to 770 nm by a periodically poled lithium niobate (PPLN) crystal, and the pulse wave forms culled from a 5712 Hz repletion comb pulse generated with the comb generator to 10 Hz by using a LN modulator and Pockels cells with polarizers.

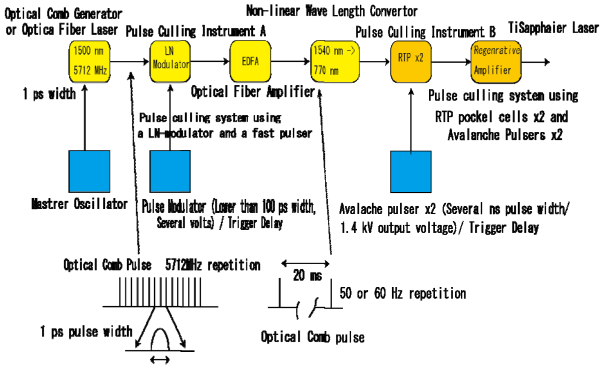

Figure 8: Direct triggering of a 770 nm pump-laser by a 1540 nm comb-laser for an XFEL time reference signal.

EXAMPLE OF AN ACTUAL RF AND TIMING DISTRIBUTION SYSTEM

Choice of the Comb Pulse or the Sinusoidal Wave

We checked the advantages and disadvantages of both the comb pulse train and the sinusoidal signal transmission systems to design the SACLA rf and timing distribution system [10,24]. A decision was made to employ the sinusoidal signal transmission system due to the fact of a signal-to-noise (S/N) ratio, when these optical signals are converted to electrical signals with an optical-to-electric (O/E) converter using a Pin photo diode. In the case of a sinusoidal wave, this sinusoidal optical wave ideally has one fundamental frequency component, and a large part of the laser power is converted to an electrical rf signal having one frequency component (e.g. an acceleration frequency for XFEL). Of course, we should take account of the quantum efficiency (e.g. 0.5~1 A/W at 800 nm) of the photo diode. However, in the case of the comb pulse, an optical power of less than 1% of all Fourier components (dependent on the pulse width) could be converted to an electrical sinusoidal wave with a bans-pass filter to obtain a driving rf signal for XFEL high-power rf sources, since the comb pulse comprises many frequency components and one frequency component of it is used.

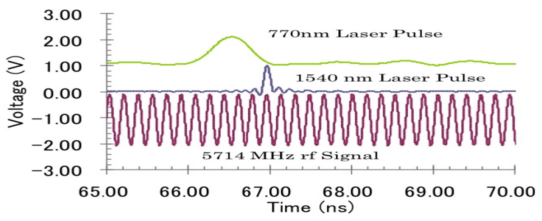

Figure 9: Laser pulse culling and wavelength converting results by the PPLN crystal. The 5712 MHz time reference rf signal (below, red), the 1540 nm thinned out a 10 Hz laser pulse (middle, blue), and the 770 nm thinned out and converted laser pulse (upper, green) are shown in the figure.

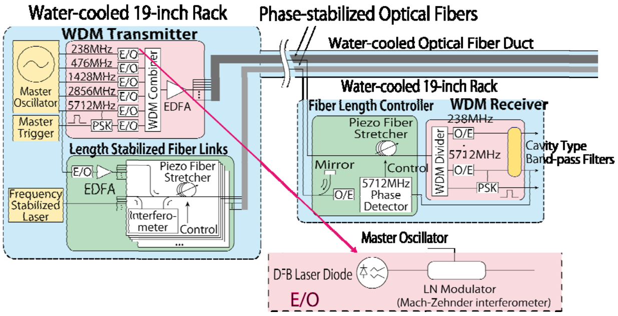

Figure 10: Rf and timing distribution system for SACLA.

Rf and Timing Distribution System for SACLA

From these design choices ,as mentioned above, we have made a decision, designed and constructed an rf and timing distribution system for XFEL "SACLA" at SPring-8. I mainly introduce our system, as an example, since I do not have much detailed information about the rf and timing distribution systems of other institutes, and limited space is allowed in this paper.

The optical rf and timing distribution system for SACLA is shown in Fig. 10. It comprises a master oscillator (MOSC), a master trigger module (MTU), optical transmitters (OPT-TX), an optical fiber signal transmission system using a wavelength division multiplex (WDM) and optical receivers (OPT-RX). At first, we considered two methods for the OPT-TX (E/O). One is an optical comb generator (OPT-COMB), and the other is a Mach-Zehnder interferometer, a called lithium niobate (LN) modulator, which was finally chosen for our system. These LN modulators installed in the OPT-TX are connected to the MOSC generating sinusoidal rf waves and DFB laser diodes. After modulating the different wavelength lasers generated at the diodes with the LN modulators, a wavelength division multiplex (WDM) signal-transmission system is connected. The WDM transmitting system merges the optical signals being the lasers modulated by the rf signals and the timing pulses. The merged optical and timing signals are then amplified with an erbium doped fiber amplifier (EDFA). After amplification, the optical signals are transmitted through long phase-stabilized optical fiber (PSOF) cables [25] installed in a water-cooled and temperature-stabilized duct along the 800 m SACLA building [26]. At 80 individual end points of the optical fibers along SACLA, the OPT-RXs including WDM receiving modules and optical dividers distribute the individual optical rf and timing signals. The individual optical signals are inputted into O/E converters using Pin photo diodes that convert the laser light to electrical rf signals. Cavity-type band-pass filters with very narrow bandwidths of 15 MHz at 5712 MHz and 2 MHz at 238 MHz reduce noise after the O/E. This low-loss and narrow band of the filter is indispensable to reduce noise. The rf signals are again distributed to drive the high-power klystrons (e.g. 50 MW S-band and C-band klystrons) through an IQ modulator and a 500 W klystron driver amplifier. In the following sections, the details of individual rf and timing distribution components are explained.

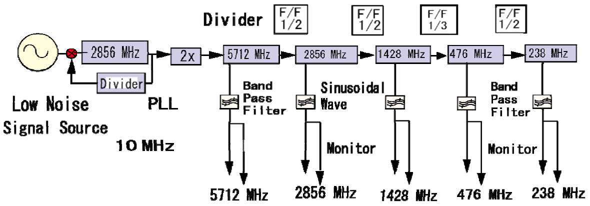

Figure 11: Master oscillator for SACLA.

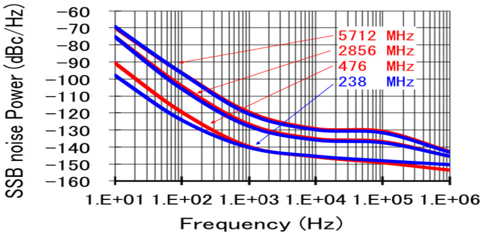

Figure 12: SSB noise of the master oscillator at 5712 MHz.

Master Oscillator

The MOSC [10,24], which generates 238, 476, 1428 2856, and 5712 MHz stable RF signals, is a time-reference rf source. The configuration of the MOSC is shown in Fig. 11. It comprises a very stable reference generator with a frequency stability of 10^{-11} at 10 MHz and a low-noise characteristic in the frequency region below 1 kHz, measured from 10 MHz, a 2856 MHz signal generator having a low noise characteristic in the frequency region over 1 kHz measured from 2856 MHz, a frequency-doubler instrument to generate 5712 MHz from 2856 MHz and frequency dividers to produce the above-mentioned frequency signals. Both of the low-noise signal generators are connected by a PLL circuit to make very low single side band (SSB) phase noise over the whole frequency range, as shown in Fig. 12. The noise level is -140 dBc/Hz at 1 MHz, measured from a career frequency of 5712 MHz. The most important feature is that the

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signal source uses the frequency-dividing method, a power supply with a very low-noise of -150 dBV/√Hz, and the above-mentioned PLL connection. The noise levels at individual frequencies proportionally decrease with the frequency-dividing ratio of the divider.

Optical Comb Generator

The OPT-COMB [10] for SACLA was developed. It generates an optical bomb pulse train with a pulse width of 1ps (FWHM) and a repetition of 5712 MHz, when the 5712 MHz signal generated with the MOSC is added to the LN crystal. Figures 13 -a and b show the output waveform of the optical pulse train and its frequency spectrum envelope. The comparison between the noise spectra of the comb generator output after 500 m single-mode optical fiber transmission and of the master oscillator output is shown in Fig. 14. There is an increase in the noise over a frequency range of 1MHz.

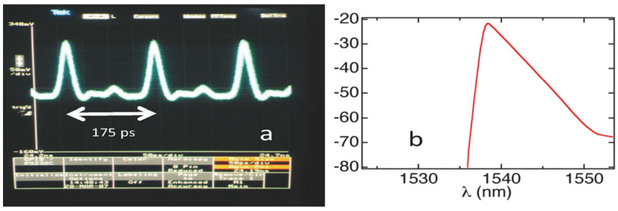

Figure 13: Output wave form of the comb generator (about 1 ps pulse width, 175 ps period) and its spectrum envelope.

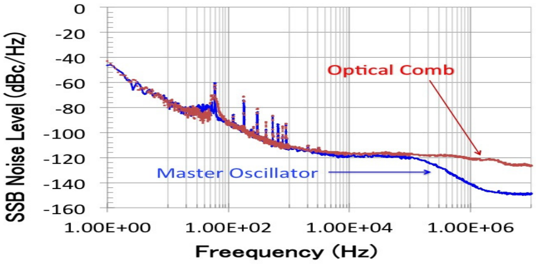

Figure 14: Comparison between the noise spectra of the comb generator output after 500 m optical fiber transmission and of the master oscillator output.

Optical Sinusoidal Wave Transmitter

The OPT-TX was designed and fabricated for the SACLA rf and timing distribution. This transmitter comprises 1500 nm band DFB laser diodes with different wavelengths, which correspond to 238, 476, 1428, 2856 and 5712 MHz rf signals generated with the MOSC and Mach-Zehnder interferometers, a called LN-modulator using a crystal of $LiNbO_3$, [27], as E/O rf converters, a WDM optical power combiner to merge the different wavelength signals, an EDFA and an optical power divider. This transmitter also has a trigger pulse transmission function using the phase-switch keying (PSK) technique, which modulates a 5712 MHz carrier signal by a pulse-shaped phase change of +/-180 deg. on both the rise and fall sides of the pulse edges, respectively. This modulation is achieved with an IQ modulator.

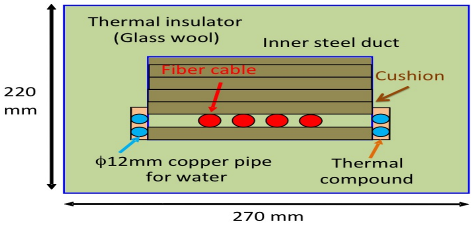

Figure 15: Water-cooled and temperature-stabilized optical-fiber duct.

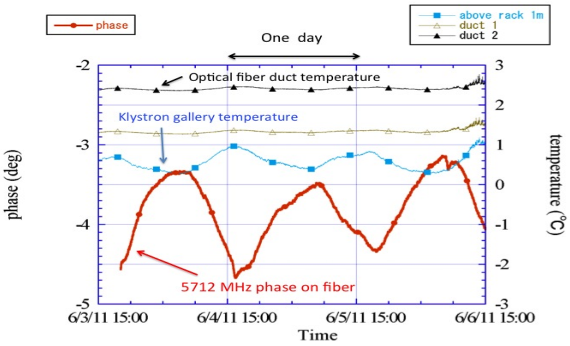

Figure 16: Water-cooled and temperature-stabilized optical-fiber duct and a 5712 MHz phase-shift by the duct temperature change.

Optical-fiber Cable with Optical Length Control

The PSOF usually has a temperature coefficient of 2 ppm/K in optical length. Therefore, the optical length of the fiber changes 1.6 m/K for a length of 800 m. This value corresponds to a phase shift of about 8 deg./K and 4 ps/K at 5712 MHz. This fact is not acceptable to employ this method for SACLA. The methods used to reduce the thermal optical length change around the PSOF are indispensable. One is temperature control around the PSOF cable; the other is optical length control for the PSOF.

Temperature stabilization around optical fiber cables: In order to moderate a change in the ambient temperature around the PSOF cable, the cables are installed in a dedicated and temperature-stabilized duct, as shown in Fig. 15. This water-cooled and temperature stabilized duct comprises double rectangular steel ducts; also, four copper water pipes are tightly attached on both sides of the outer surface of the inner duct with a thermal compound material. This inner duct makes an isothermal distribution plane. The PSOF cables are installed between cushions in the inner duct to reduce any vibration caused by the cooling water. Figure 16 shows the measured temperature changes of the duct inside in the klystron gallery of SACLA. Then, the temperature of the gallery was about 26.0 ± 1 K (p-p), but the PSOF temperature was controlled to within 26.0 ± 0.08 K (p-p) by temperature-stabilized cooling water within a temperature of 26.0 ± 0.1 K (p-p). The temperature change in the duct is moderated to be about one fifth lower than that of the gallery.

Optical fiber length control using Michelson interferometer: To obtain further precise temporal resolution, we developed a Michelson interferometer to observe the optical length of the fiber cable for SACLA. An optical length change is reduced by feedback-control using data measured by the interferometer. A block diagram of the fiber optical length control system is shown in Fig. 6. The system comprises a DFB laser diode locked to an acetylene absorption line, a fiber stretcher to change the fiber optical length, an acoustic optical modulator (AOM) module placed at the start point of the optical fber to modulate the laser light by a 55 MHz signal for rf phase detection (optical length detection), a Faraday rotation mirror at the fiber end point to reflect laser light and to distinguish backward and forward lasers, a phase detector to measure the fiber displacement and a displacement feedback control circuit to drive the fiber stretcher. The displacement signal outputted from the feedback control circuit is proportional to the filber optical length change. The data of the optical fiber length control are shown in Fig. 17 [10]. They were taken by using the existing 2 km PSOF along the circumference of the SPring-8 ring accelerator. It is apparent that the optical length control for the fiber worked well, and decreased the displacement to less than several micron-meters of its optical length in a frequency range of under 50 Hz. This system is unfortunately not installed in SACLA, because of a budget shortage. However, by taking into account the performance of the water-cooling duct for the optical fiber, the optical fiber length control is indispensable.

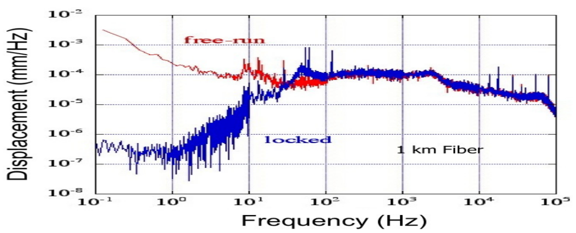

Figure 17: Performance of the optical-fiber length control using the 1 km fiber of SPring-8 ring accelerator.

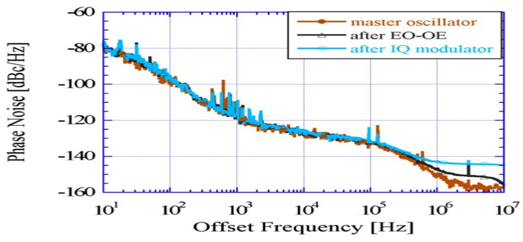

Figure 18: Comparison among the noises of the MOSC, after 400 m signal transmission, and of the IQ-modulator output.

EXAMPLE OF RF AND TIMING DISTRIBUTION PERFORMANCE

RF Amplitude/Phase Stability and Noise

The performance of the rf and timing distribution system for SACLA was verified, when beam commissioning was proceeded. Figure 18 shows the noises increased by the above-mentioned signal transmission using a 400 m optical fiber and also a noise increase at the output of an IQ modulator to be connected after the 400 m optical signal transmission. The amounts of these noise increases are about 10 fs each. The drift of the phase of 5712 MHz rf signal transmitted for about 400 m along the SACLA klystron gallery by using the above-mentioned optical system is shown in Fig. 16. Even through, the PSOF cable is installed in the water-cooled and temperature stabilized duct, the temperature of which is regulated to within +/-0.08, the rf phase drift is 1.5 deg. (P-P) for 3 days. This phase drift is consistent with a calculated result using the thermal optical length coefficient with 2 ppm/K of the PSOF and the temperature variation of the duct.

Accelerated Beam and Lasing Performance by using the Developed Optical rf and Timing Distribution System

The accelerated electron beam performance, such as beam energy and temporal stabilities, of the SACLA accelerator indirectly shows the performance of the above-mentioned rf and timing system. The energy jitter and stability for 7 GeV at the accelerator end were 1.4 x 10^{-4} in STD of the shot-by-shot data and 1.0 x 10^{-4} in P-P of 100 points moving averages for 6 hours, respectively. The shot-by-shot temporal fluctuation of the beam arrival times at the accelerator middle position (C-band accelerator of a number 07) was about 400 fs in P-P, and its drift was 700fs in p-p. This arrival time was observed with a cavity-type beam position monitor (BPM, a 4760 MHz, TM010 mode reference cavity for the BPM), and by comparing the phase between the reference rf signal and the beam-induced signal at the BPM [10]. The trend of the arrival time was unfortunately correlated with the optical length drift of the PSOF cable dependent on the fiber duct temperature change in the klystron gallery. The time jitter of the accelerated electron beam measured by an rf deflector system for observing a beam bunch length is shown in Fig. 19. The beam time jitter is 22.7 fs in STD. We finally obtained continuous lasing at a wavelength of 0.12 nm with a power of 30 mJ on average for 12 hours by using our rf and timing distribution system.

Comparison Between the Comb Pulse and Sinusoidal Wave Transmission

We can compare the SSB noise performances of both the optical comb-pulse signal transmission and the sinusoidal optical signal transmission at 5712 MHz, as shown in Figs. 14 and 18. The noise level of the comb-pulse transmission is slightly larger than that of the sinusoidal-wave transmission in the frequency region over 100 kHz.

This noise increase is not very large, but is still not easily made negligible. Unfortunately, the measurement apparatus noise level in the case of Fig. 14 is slightly larger than that of Fig. 18. We cannot directly and easily compare both of the data, because of the instrument noise.

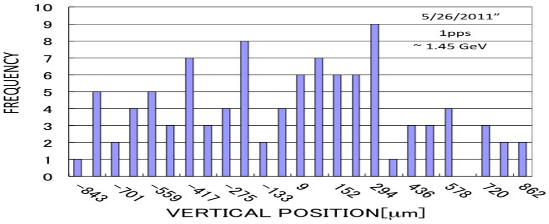

Figure 19: Beam time jitter observed by the rf deflector. The beam time jitter is 22.7 fs in STD.

SUMMARY

The tempral accuracy and stability of the state-of-the-art rf and timing distribution system, which is supported by combined technology of a laser and a microwave, have already achieved up to a femto-second region. This technology of the system strongly supports the lasing of an XFEL, like LCLS and SACLA. The temporal stabilities of an accelerated electron beam and X-ray lasing indirectly prove the ultra-stable temporal stability of our develoed rf and timing distribution system for the XFEL. On the other hand, the noise level of sinusoidal siganl transimission is samller than that of comb-pulse signal transmission in the case of SACLA. Empolying the sinusoidal siganal transmission for SACLA could be more advategious than the comb-pulse transmission.

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