DEVELOPMENT OF THE OPTICAL TIMING AND RF DISTRIBUTION SYSTEM FOR XFEL/SPRING-8

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Abstract

We describe the design and development of an optical timing and rf distribution system for the X-ray free electron laser (XFEL) facility at the RIKEN SPring-8 campus. A timing and rf phase accuracy of less than ten femto-seconds is required for the timing system of an XFEL accelerator. We have developed an optical timing and rf transmission system that can transmit several signals in one optical fiber, an optical comb generator to provide short pulses synchronized with the accelerator and a fiber length stabilization system to suppress any fluctuation of the propagation delay. The phase noise of the optical rf transmission system was measured to be sufficiently small. The optical comb generator appropriately generates a pulse train with a 1 ps width and a 5712 MHz repetition. The fiber length stabilization technique was applied to an existing 2 km-long fiber laid along the SPring-8 storage ring, and the length fluctuation was reduced to the 1 μm level. Thus, the performance of each technology was confirmed.

INTRODUCTION

The accelerator components of an XFEL facility must be precisely synchronized with each other. The tolerance of the timing fluctuation is at the femtosecond level. To satisfy this demand, we have been developing an optical timing and rf distribution system for the Japanese XFEL facility being constructed at the RIKEN SPring-8 campus.

The XFEL facility at SPring-8 [1] is designed to generate an X-ray laser in a wavelength region of around 0.1 nm. The electron beam energy is 8 GeV and the total length is about 700 m. A thermionic electron gun generates an electron beam. The bunch length is shortened by 238 MHz and 476 MHz cavities with a velocity bunching process. Subsequently, an L-band (1428 MHz) with additional continuous velocity bunching, S-band (2856 MHz) and C-band (5712 MHz) accelerators boost the beam energy. In the way of acceleration, a longitudinal bunch profile is compressed by three bunch compressors. The bunch length after all the bunch compressors is estimated to be 30 fs in FWHM and the peak current is expected to be more than 3 kA. Finally, the beam goes through in-vacuum undulators, and coherent X-rays are generated by a self-amplified spontaneous emission (SASE) process.

Considering the accelerator configuration mentioned above, the requirements for the timing system of the XFEL accelerator are summarized below:

- The signal must be transmitted over a long distance of up to 1 km.
- The time precision is less than 10 fs, because the bunch length finally becomes 30 fs [1].
- In total, six signals are needed: 238 MHz, 476 MHz, 1428 MHz, 2856 MHz and 5712 MHz rf signals and a trigger signal.

To satisfy these requirements, we employed an optical system having a wavelength of around 1550 nm. Since the attenuation of an optical fiber is lowest around this wavelength region, and much lower than the attenuation of a conventional metal cable, a signal is easily transferred for a distance of 1 km. Furthermore, many commercial devices, such as light sources, optical amplifiers and passive devices, are available. To achieve a femtosecond stability of the propagation delay, we use an optical fiber with a small thermal coefficient of expansion and we regulate the temperature of the fiber. Furthermore, the path length of the fiber is actively stabilized. The fiber length is monitored with sub-micron resolution by using optical interference, and is regulated with a variable delay line, such as a fiber stretcher. To transmit many signals, all of the signals are combined into one fiber by a wavelength division multiplexing (WDM) method. The WDM method reduces the cost of the optical fibers, optical amplifiers and fiber length regulation systems. In addition, we developed an optical comb generator that provides a short-pulse signal to obtain precise trigger timing.

In this paper, we present the design and performance of a WDM signal distribution system, a fiber length stabilization system and an optical comb generator.

DESIGN OF OPTICAL TIMING AND RF DISTRIBUTION SYSTEM

We describe the design of the optical timing and rf distribution system in detail. A schematic diagram of the optical system is shown in Fig. 1. The WDM transmitter converts five rf signals and a trigger signal into optical signals and merges them into one fiber. The merged signal is amplified and distributed to various accelerator components. In addition to the WDM line, length-stabilized fiber links are also equipped. The fiber length of this link is measured with a Michelson interferometer, and regulated with a Piezo-electric fiber stretcher. This link transfers a frequency-stabilized laser as a length standard and a 5712 MHz rf signal as a time reference. The length of the WDM line is monitored by using the rf

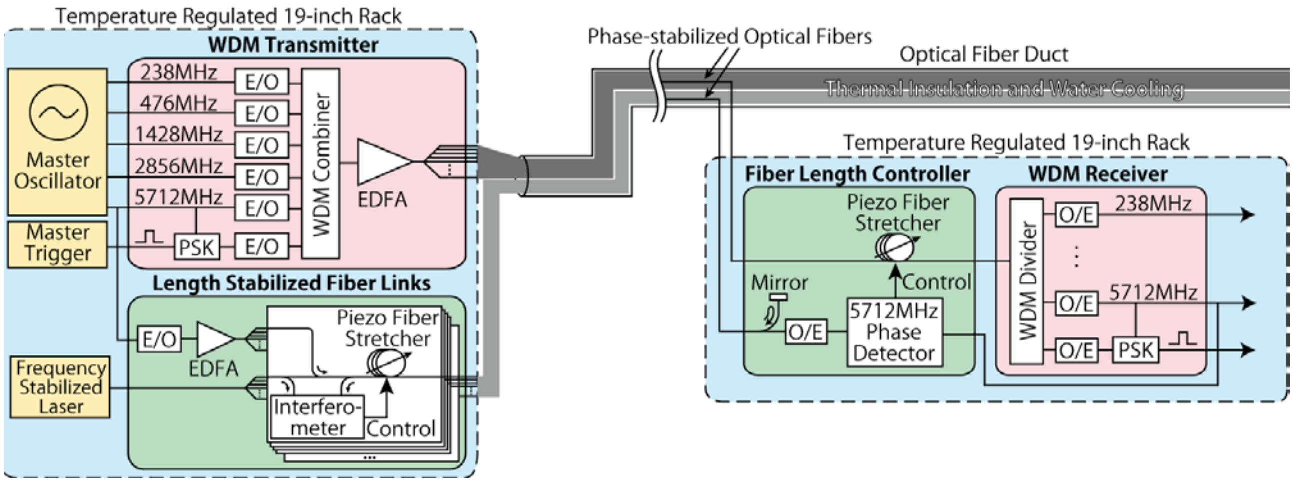

Figure 1: Schematic diagram of the optical timing and rf distribution system.

phase of the 5712 MHz signal, and is controlled with a fiber stretcher on the receiver side.

In the following subsections, detailed descriptions of these components are provided.

WDM Transmitter and Receiver

The WDM transmitter transforms an input electrical signal into an optical signal with an electrical-to-optical (E/O) converter. The light source of the E/O converter is a distributed feedback laser diode (DFB-LD) in a wavelength region of 1550 nm. A $LiNbO_3$ Mach-Zehnder modulator provides sinusoidal amplitude modulation to the laser light. In total, five rf signals (238 MHz, 476 MHz, 1428 MHz, 2856 MHz and 5712 MHz) and a trigger signal are converted to optical signals and multiplexed into one optical line with a WDM combiner. The wavelength interval of each optical signal is 1.6 nm. The combined signal is amplified with an erbium-doped fiber amplifier) EDFA, and distributed to various accelerator components.

The distributed signal is detected by a WDM receiver. The WDM divider separates the input signal into individual optical signals. Each signal is fed into a PIN photodiode in an O/E module, and the electrical rf signal is reproduced. The rf signal is then passed through a narrow-band band-pass filter and an rf amplifier.

In general, an optical system is unsuitable for the transmission of a low duty-cycle pulse signal, such as a trigger signal. Therefore, the trigger signal is modulated with a 5712 MHz phase shift keying (PSK) signal before the E/O conversion, and demodulated after the O/E conversion. Although the rise time of the signal becomes much longer than the carrier rf period after PSK modulation and demodulation, the trigger edge is sharpened again with a special trigger circuit [2]. The rise time of the trigger signal is approximately 100 ps and the trigger jitter is less than 1 ps in rms.

Optical Comb Generator

The optical comb generation technique [3] is one of the optical modulation methods used to generate a short-pulse signal appearing every rf period. We use a $LiNbO_3$ modulator in a Fabry-Pérot cavity for comb generation. Since the comb signal is a sharp pulse, it can be a more precise trigger than a sinusoidal signal. We developed a 5712 MHz comb generator. The pulse width is approximately 1 ps at FWHM.

Optical Transmission Line

The path-length fluctuation of the optical transmission line should be as small as possible. Therefore, we employ phase-stabilized optical fibers (PSOF) [4] to reduce the thermal coefficient of the path length. The coefficient of PSOF is 2 ppm/K, at most. Furthermore, to suppress the temperature drift, the fiber cables are placed into a thermal insulation duct with cooling water channels in which water regulated within ± 0.2 K is circulated. Since the water channel may cause vibrations, the water flow rate is set sufficiently small. A heat simulation shows that the temperature of the fiber is regulated to within ± 0.2 K. Therefore, the fiber length variation of a 1 km-long fiber is suppressed to within ± 0.4 mm, corresponding to a propagation time drift of ± 2 ps.

Fiber Length Stabilization

To eliminate any fiber length fluctuation down to the femtosecond level, an active fiber length stabilization device is necessary. Therefore, we prepared a length-stabilized fiber link in addition to a WDM signal line, as shown in Fig. 1. The stabilized link provides a precise 5712 MHz rf signal to control the propagation delay of the WDM line. By using the two fiber links, we can compensate the length fluctuation of not only the transmission fiber, but also the optical components, such as EDFAs through which the returned light is hard to pass.

A block diagram of the length-stabilized fiber link is shown in Fig. 2. The frequency-stabilized laser light is sent to the receiver and reflected back to the transmitter. The reference light of the interferometer is picked up just after the laser source. The returned light is mixed with the reference light to measure the fiber length variation.

The frequency-stabilized laser is a length standard of the stabilized link. To measure the length variation of a 1 km fiber with 1 μm accuracy, the frequency error must be

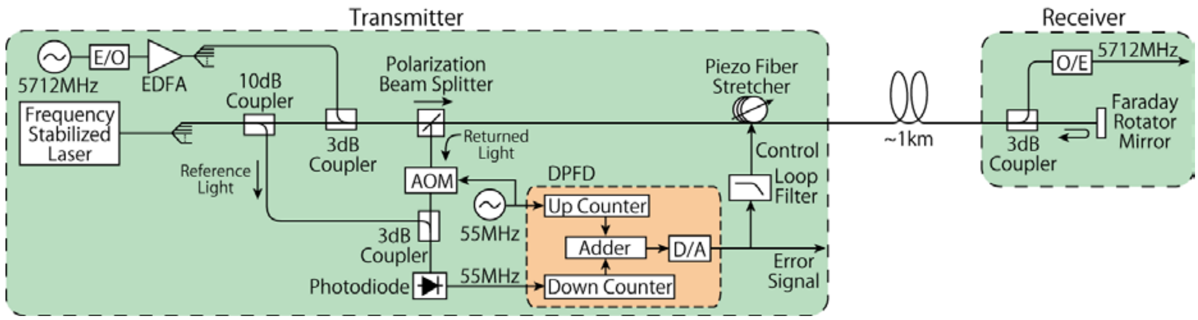

Figure 2: Block diagram of the length-stabilized fiber link.

less than 10^{-9}. However, a usual DFB-LD does not satisfy this demand. Therefore, the laser frequency is locked into one of the molecular absorption lines of acetylene. The root Allan variance of this frequency-stabilized laser was measured to be less than 10^{-9} for over 10 hours.

To distinguish the reflected light at the receiver from backgrounds due to scattered light at other parts, we use a polarization beam splitter (PBS) in the transmitter and a Faraday rotator mirror in the receiver. When the polarization of the transmitted light is adjusted to pass through the PBS, the returned light is reflected to the other port of the PBS.

The optical phase is detected by the optical heterodyne method. The returned light makes a frequency-shift at 55 MHz with an acousto-optic modulator (AOM) driven by a 55 MHz local clock. This light is then mixed with the reference light. The mixed light is detected by a photodiode, and a 55 MHz beat signal is obtained. The phase difference between the local clock and the beat signal is detected by a digital phase-frequency discriminator (DPFD) [5]. This phase is identical to the optical phase of the returned light, since this interferometer is based on the heterodyne technique.

The DPFD [5] is a phase detector that has a much larger dynamic range than 2π. The DPFD has two 12-bit counters. One is an up counter for the local clock, and the other is a down counter for the beat signal from the photodiode. These counts are added and converted to an analog signal. The output analog signal represents the phase difference, which is proportional to the path-length variation. The full range of the length measurement is 4096 λ, corresponding to 6 mm.

A Piezo-electric fiber stretcher is used as a phase shifter of this system. An optical fiber is coiled around a Piezo-electric actuator. The actuator controls the path length by expanding the fiber. The frequency response of our fiber stretcher is flat up to 5 kHz. The dynamic range is about 6 mm.

Temperature Regulation of 19-inch Racks

The temperature of an optical component should be sufficiently small to reduce any thermal drifts. Therefore, all of the components are installed in temperature-regulated 19-inch racks. These racks are equipped with heat exchangers to regulate the air temperature. The coolant is water regulated within ± 0.2 K. Therefore, the stability of the air temperature is also ± 0.2 K when the heat load is constant.

PERFORMANCE OF DEVELOPED INSTRUMENTS

Optical Transmitter and Receiver

A set composed of a WDM optical transmitter and receiver was manufactured. We measured single-sideband (SSB) phase noise of the transmitted rf signal with Agilent E5500. The transmitter and the receiver were connected with a 500m-long PSOF. The results of the measurements are shown in Fig. 3. The phase noise after signal transmission through the optical system is almost identical to that of the signal source. No noise growth can be seen below 1 MHz. Although a small deterioration is found above 1 MHz, this effect is equivalent to a timing jitter of a few femtoseconds. This is sufficiently small for our application.

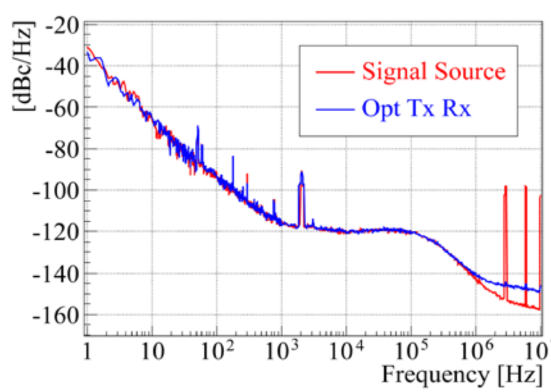

Figure 3: SSB phase noise before and after the WDM optical distributer. The blue line shows the phase noise of the 5712 MHz signal after transmission. The red line shows the phase noise of the signal source.

Optical Comb Generator

The optical comb generator driven by a 5712 MHz rf signal was developed. The output pulses and spectrum of the optical comb signal are shown in Fig. 4. For the oscilloscope measurement, a photodiode with a 22 GHz bandwidth was used as an E/O converter. The short pulse is appropriately generated every 175 ps, which has a period of 5712 MHz. The spectrum is very wide, and it contains many peaks whose interval is 5712 MHz. The pulse width of the comb signal is estimated to be approximately 1 ps from the spectrum.

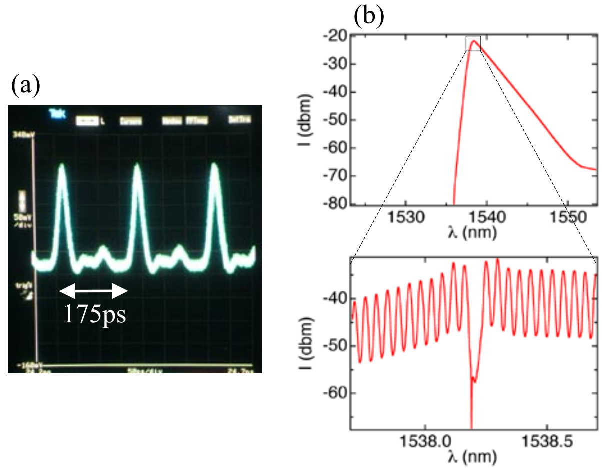

Figure 4: Oscilloscope image (a) and spectrum (b) of the optical comb signal.

Fiber Length Stabilization

The feasibility of the fiber length stabilization system was tested at the SPring-8 storage ring. We used an existing 2km-long PSOF. The experimental setup is illustrated in Fig. 5. An external cavity laser diode (ECLD) was employed as a light source. The ECLD light was transmitted through a 2 km fiber and fed into the interferometer. The optical heterodyne method and the DPFD were used for path-length measurements.

We recorded the DPFD output to evaluate the performance. Fig. 6 shows the amplitude of the DPFD signal in the frequency domain. The fiber length is appropriately regulated in the frequency range below 30 Hz. A value calculated by integration of the length fluctuation up to 100 Hz is approximately 1 µm. It corresponds to 5 fs, and satisfies our requirement. Although a large amplitude is seen in the range over 100 Hz, we think that this is not a length fluctuation, but rather noise of the electric circuit and the light source.

SUMMARY AND PROSPECTS

An XFEL accelerator requires precise timing and rf signals with femtosecond stability. To fulfill this demand, we designed an optical timing and rf distribution system. Five rf signals and a trigger signal are transmitted together in one optical fiber by using the WDM technique. The phase noise of the first product of the WDM transmission system was measured, and it was sufficiently small. An optical comb generator was also manufactured to provide short pulses of 1 ps width. A fiber length stabilization system with a Michelson interferometer was developed. This system was tested with a 2 km-long fiber and the length was properly controlled to within 1 µm in the frequency region below 30 Hz. Thus, the performance of each technology element has been confirmed. We will soon perform the integrated tests and begin production of the optical system for the XFEL.

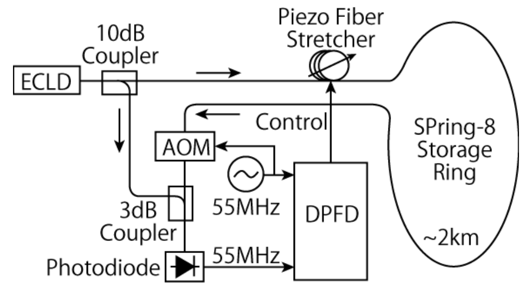

Figure 5: Schematic diagram of the experimental setup of fiber length stabilization at the SPring-8 storage ring.

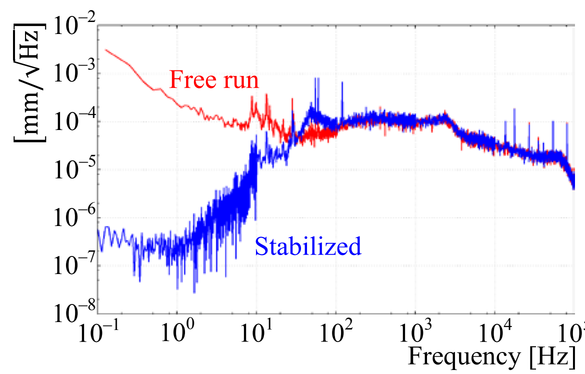

Figure 6: The output amplitude of the DPFD in the frequency domain. The blue line shows data when the fiber length was stabilized, while the red line shows data when the length control was switched off. The unit of the vertical axis is $\mathrm{mm}/\sqrt{\mathrm{Hz}}$.

REFERENCES

[1] Y. Otake *et al.*, “Timing and LLRF System of Japanese XFEL to Realize Femtosecond Stability”, proc. of ICALEPCS07 (2007).

[2] N. Hosoda *et al.*, “SCSS Prototype Accelerator Timing System”, proc. of APAC07 (2007).

[3] Optical Comb. Inc., “Principle of Optical Comb”, http://www.optocomb.com/eng/principle.html

[4] Kakuta, Tanaka, “LCD Coated Optical Fiber with Zero Thermal Coefficient of Transmission Delay Time”, Sumitomo Electric Industries Ltd., Yokohama, p. 244, Japan; S. Tanaka, “Phase Stabilized Optical Fiber”, Tec. Rep. of Sumitomo Electric Industries Ltd. (1989).

[5] M. Musha *et al.*, “Robust and precise length stabilization of a 25-km long optical fiber using an optical interferometric method with a digital phase-frequency discriminator”, Appl. Phys. B 82, 555–559 (2006).