Precision Timing and Rf Signal Dissemination for XFEL by Delivering Optical Frequency Comb through Length-stabilized Fiber

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Abstract

We have developed the precision timing and rf signal dissemination system for the X-ray free electron laser (XFEL), under construction in Japan. The optical frequency comb was transmitted through a 1-km length-stabilized optical fiber for disseminating both rf and timing signals. The phase fluctuations of the rf signals at 5.712 GHz was suppressed down to 0.0042 radian that is used for synchronizing linear accelerators, and the timing jitter between optical pulses are suppressed down to 50 fs that is used for providing X-ray trigger timing to the users, both of which satisfy the requirement of the XFEL.

1. Introduction

Precision distribution of the frequency reference signal using photonic method plays important role in communications, astronomy, fundamental physics and metrologies, in which the laser light at the optical communication band (λ=1.55μm) carries the reference signal through optical fibers. Compared with the conventional method of distributing electric signal through metallic wires, photonic method has the following advantage that the higher frequency signals up to a few hundred THz can be delivered for longer distance of more than a few 100 km. The mechanical vibrations and thermal expansions of the fiber result in the fluctuation of the fiber length, which causes additional phase noise applied to the delivered signals. Therefore the fiber length fluctuations should be actively suppressed for the precision fiber link. We have developed the precision signal disseminations system in which the length of the long fiber is precisely measured by using optical interference, and the length fluctuations is suppressed to smaller than the wavelength of the light (sub-μm). Our precision fiber link system has been applied to the local oscillator distribution for a large sub-mm radio telescope array (ALMA-project) in which the rf signal up to 900 GHz was delivered over 25km[1], or frequency comparison between remote atomic clocks in which the frequency standard was delivered as the optical carrier over 120km[2].

In the present paper, we report the photonic timing and rf signal distribution system for the XFEL project. XFEL is an X-ray free electron laser facility which is now under construction located at the RIKEN SPring-8 campus, Hyogo, Japan[3]. The XFEL consists of a 700-m linear accelerators and undulators that is designed to generate coherent X-ray at the wavelength of 0.1 nm by SASE (self-amplified spontaneous emission) process. In order to accelerate electron bunches effectively, all the accelerator components (two bunchers and three accelerators) require the distribution of the rf signals up to 5712 MHz to synchronize them whose phase fluctuations should be less than 0.24 degree. The XFEL also requires the timing signal distribution to the users at the remote end of the XFEL facility for providing X-ray pulse timing, whose timing jitter should be lower than 100 fs. We have developed the signal distribution system in which the optical frequency comb was delivered through the precision fiber link to distribute both rf and timing signals at a time. In the frequency domain, the optical frequency comb consists of a series of longitudinal modes with the same frequency difference, and therefore the rf signals can be delivered as a beat note between each comb modes. In the temporal domain, on the other hand, the optical frequency comb is a short pulse train with the same intervals, and can deliver timing signal.

The photonic signal transmission system is especially suitable for such acceleration facilities whose circumstances are filled with the strong electro-magnetic noises.

2. Experiment

The schematic diagram of the precision signal transmission system is shown in Fig.1, which consists of an optical frequency comb, a frequency-stabilized laser, and a length-corrected fiber link. The optical frequency comb was generated by using an electro-optic modulator (EOM)-based optical frequency comb generator (OFCG) developed by Optical Comb Inc [4]. A continuous wave (cw) laser light from an external-cavity laser diode (ECLD) at the wavelength

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of 1.55μm was phase modulated by an EOM crystal at 5.712 GHz to generate frequency sidebands, and an optical cavity enhanced the comb bandwidth up to 5 THz.

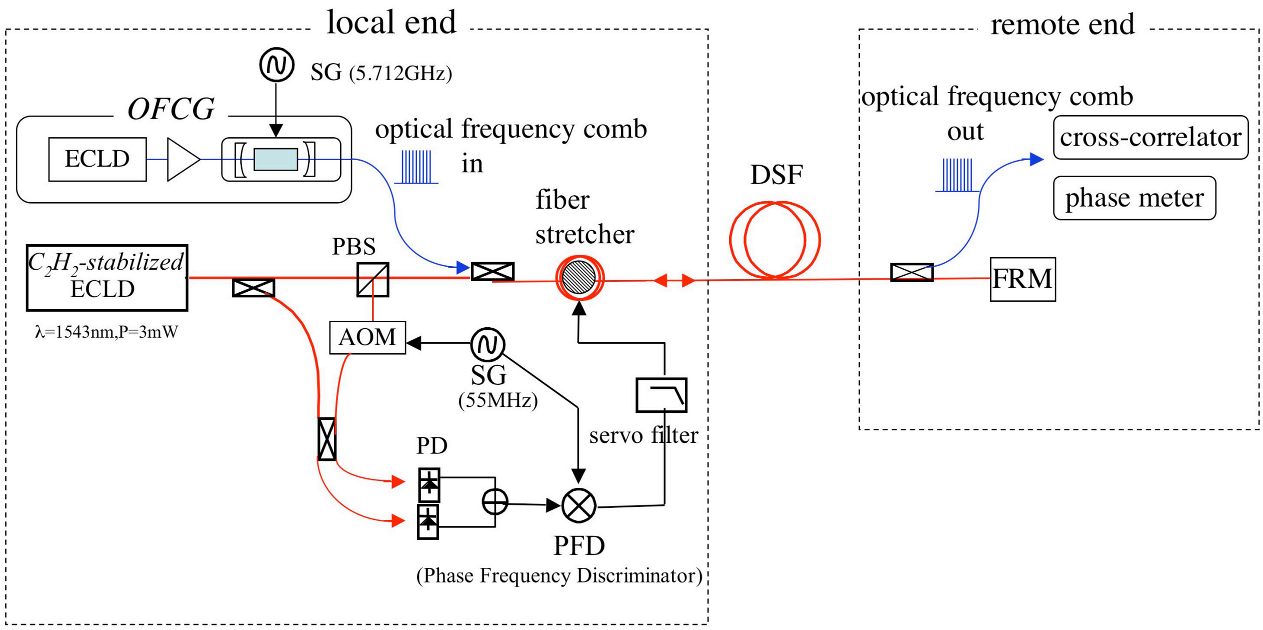

Fig.1 Schematic diagram of the precision rf and timing distribution system.
OFCG: optical frequency comb generator, ECLD:external-cavity laser diode,
FRM: Faraday rotator mirror, DSF: dispersion-shift fiber

The pulse duration of the optical frequency comb is around 1 ps. In the precision fiber link system, the length of the optical fiber was measured by using an anti-symmetric Michelson interferometer. The light source was an ECLD with the wavelength of 1543nm. The frequency of the ECLD was locked to the saturated absorption of the acetylene molecules, whose frequency stability is $\delta f/f = 4\times10^{-12}/\tau^{1/2}$ [5]. The light from the acetylene-stabilized laser was divided by a 3 dB fiber coupler; a part of the light was transmitted through the delivering fiber, and another light was used as a reference. At the remote end of the optical fiber, the transmitted light through a delivering fiber was back-reflected by a Faraday-rotator mirror (FRM) to go back through the optical fiber. As the polarization state of returned light was orthogonal to that of the input light, the round-trip light through the delivering fiber was picked off by a polarization beam splitter (PBS), and after frequency-shifted at 55 MHz by an acousto-optic modulator (AOM), the round-trip light was combined with the reference light at the local end of the fiber to detect beat signals. The phase fluctuations of the round-trip light were detected from the 55 MHz beat note between reference and round-trip light by mixed with the local oscillator at 55 MHz. Instead of using a conventional double-balanced mixer (DBM), we used a hand-made multi-bit phase-frequency discriminator (PFD) as a frequency mixer. The demodulated signal obtained from the PFD has 1000 times wider linear phase discrimination range over 2×10^3 radian than that obtained by DBM, which makes it possible to detect length fluctuation signal in the case that the length of the fiber is longer than the coherent length of the light source, details of which is described in ref.6. The phase signal from the PFD was filtered and was applied to a PZT-driven fiber stretcher to suppress length fluctuations of the delivering fiber. The fiber length fluctuation was suppressed down to 0.5 μm at the averaging time over 10 s which is evaluated from the error signal. In this experiment, as the fiber length is stabilized in reference to the wavelength of the acetylene-stabilized laser, the stability of the fiber length is limited by that of the acetylene stabilized laser. However, the phase noise limit determined by the acetylene-stabilized laser is 3 orders of magnitude lower than that of the requirement level, and is negligible.

3. Results and Discussions

The optical frequency comb with the mode space of 5.712 GHz was transmitted through a 1-km dispersion-shifted fiber. A low phase-noise rf signal generator (Agilent E4438C) drove the OFCG, and the single-sideband (SSB) phase noise of the beat note between comb modes was almost identical to that of the signal generator. The transmitted optical comb through the delivering fiber was detected by a fast photo detector to detect beat note between comb modes, and no noise growth can be seen in the SSB spectrum of the beat note below 1 MHz. The beat note of the transmitted comb was mixed with the local oscillator that drove the OFCG to evaluate the phase fluctuations of the transmitted rf signal. Fig.2 shows the root Allan variance of the phase fluctuations of the transmitted rf signal at 5.712 GHz. The phase fluctuations in free running state (green triangles) was suppressed down to 0.0042 radian (0.24degree) after fiber length correction servo was activated (stabilized: red circles). The phase fluctuations of the transmitted rf signal through length corrected fiber satisfied the requirement of the XFEL shown in Fig.2 as dotted trace.

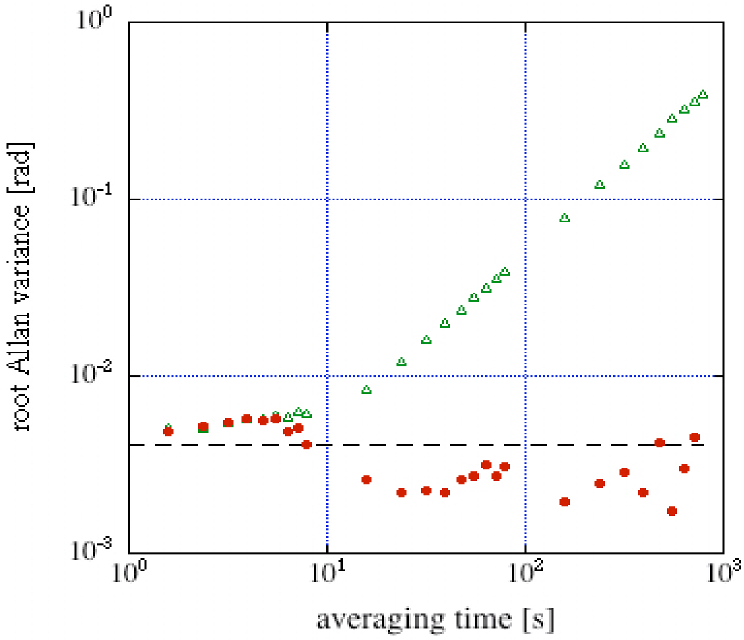

Fig.2 root Allan variance of the phase fluctuations of 5.712 GHz signal through delivering fiber.
triangles: free-running, circles: stabilized, dotted trace: requirement level

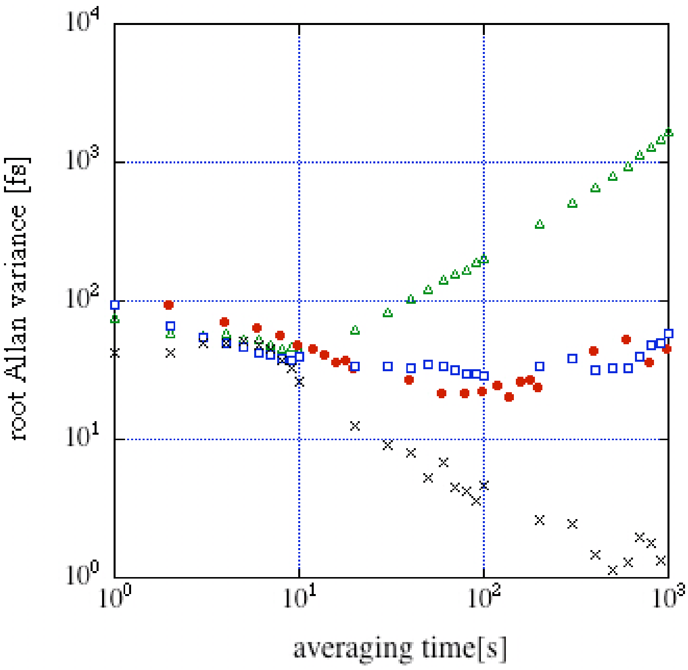

Fig.3 timing jitter of the pulse train. Triangles: free running, circles: stabilized
squares: system noise floor, crosses: calculated from fiber length fluctuations

The optical frequency comb kept its temporal pulse shape after transmitted through the 1-km dispersion-shift fiber, and the timing jitter of the transmitted pulse train in the optical frequency comb was evaluated by using a balanced cross-correlator. The root Allan variances of the transmitted pulse train are shown in Fig.3. The timing jitter of the pulse trains in free-running state (green triangles) was suppressed down to 50 fs (red circles) at the averaging time of longer than 10 s, which also satisfies the requirement of the XFEL. The measured timing jitter of the comb that was transmitted through the length-stabilized fiber was limited by the system noise floor of the timing jitter measurement which is shown in Fig.3 as blue squares. Crosses in Fig.3 indicate the expected timing jitter of the pulse train through the length-stabilized fiber link evaluated from the length fluctuations of the length-stabilized delivering fiber, which is much lower than that of the measured value. A timing jitter measurement system based on the crystal birefringence [7] can improve system noise floor, and the better timing jitter will be obtained by our system.

4.Conclusions

We have developed the precision rf and timing dissemination system based on an optical frequency comb and precision fiber link. The phase fluctuations and timing jitter of a transmitted optical frequency comb through a 1-km length-stabilized fiber link were suppressed down to 0.0042 radian and lower than 50 fs, respectively, which satisfies the requirement of the XFEL, and our timing and rf dissemination system will be installed in the XFEL near future.

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