TRANSMISSION OF REFERENCE RF SIGNALS THROUGH OPTICAL FIBER AT XFEL/SPRING-8

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Abstract

The pulse width of an X-ray laser at XFEL/SPring-8 is several tens of femto-seconds, which requires reference rf signals to have the same time-stability. The reference signals are sent to LLRF modules in 19" racks distributed along the accelerator though an optical transmission system. The temperature drift of the optical fiber is minimized by using a thermally insulated duct, where temperature-controlled water is fed. A test operation of a water cooling system at the XFEL was done. The fluctuation of the cooling-water temperature was about 0.2K (P-P), and that of the cable temperature was 0.18K (P-P), which corresponds to a 360 fs phase shift of a transmitted 5712 MHz rf signal in the case of a 400 m optical fiber with a thermal optical-length coefficient of 5 ps/km/K. The temperature stability of the water will be improved by the PID parameter tuning of the cooling utility system. The vibration of an optical fiber also degrades the quality of transmitted signals. A test to evaluate the effect of the vibration of the fiber to a transmitted signal phase was carried out. The result of the preliminary test shows that the coefficient of the time variation to the vibration amplitude of the fiber is 0.013 fs per 1 μm, and this contribution is negligible for our stability requirement.

INTRODUCTION

XFEL/SPring-8, Japan is under construction to provide bright and coherent light in the wavelength region of X-rays [1]. This accelerator-based X-ray source requires a very severe tolerance to the phase and amplitude (50 fs and 1E-4 in rms) of the rf field induced at accelerating cavities. To fulfill this request, a transmission system of the rf reference line with high precision is needed [2].

The electron beam from a thermionic gun is compressed by a velocity bunching process, and by using sub-harmonic bunchers with sub-harmonic frequencies of the C-band, and accelerated by C-band (5712MHz) traveling wave structures. Therefore, we have to deliver not only a 5.7 GHz signal, but also its sub-harmonic signals. Because of a large loss of the coaxial cable at the C-band for a long-distance transmission of 400 m for an XFEL machine, an optical transmission system is used to deliver the reference rf signals [3]. These reference signals are delivered by using the wavelength division multiplexing (WDM) method to reduce the number of optical fibers.

Figure 1 shows a schematic diagram of the optical transmission system for the reference signals. A master oscillator with a low phase noise is located at the end

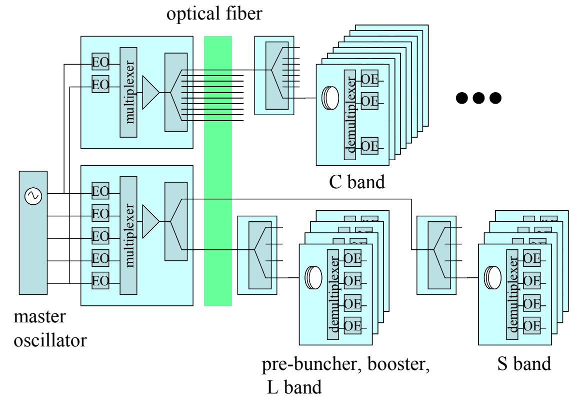

Figure 1: Schematic diagram of the transmission system for the reference signals.

place upstream of the accelerator. The reference signal of 5.7 GHz and its sub-harmonic frequency signals are converted to optical signals by using electrical-to-optical (EO) converter modules, which include laser diodes and LN modulators. The optical signals are combined, fed into one optical fiber, and amplified by using an optical amplifier (Erbium Doped Fiber Amplifier). Then, the optical signal is divided and sent to the receiver points, whose total number is nearly 100. At the receiver point, the optical signal is converted to an electrical one by using optical-to-electrical (OE) converter modules comprising a demultiplexer and a photodiode.

The lengths of the optical fiber cables from the transmitting point of the reference signals to the receiving points are varied from 30 m to 400 m along the XFEL machine. In this optical system, the path length of the optical fiber should be kept constant, and therefore the temperature of optical fibers should be stabilized. The vibration of the optical fiber also affects the phase of the transmitted optical reference signal. Tests to measure the effects of the ambient temperature change and vibration to the optical fiber were performed. The details are described in this paper.

STABILIZATION OF THE OPTICAL PATH LENGTH

To reduce the effect of temperature variation on the optical path-length change of the long-distance optical fiber cable, a phase-stabilized optical fiber (5 ps/K/km) is used. Even though this optical fiber is employed, the change of the group delay of the transmitted optical signal reaches 4 ps by a temperature change of 2 K in the case of an optical fiber length of 400 m. This value of 4 ps is 80-times larger than the target vale of a 50 fs time change. Therefore, the fibers are installed into a thermally

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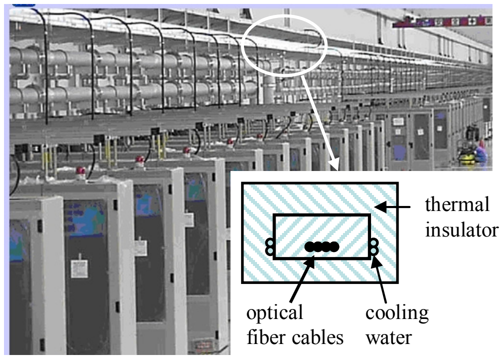

Figure 2: Schematic view of the duct and a photo of the klystron gallery.

insulated duct. Figure 2 shows a cross-sectional view of the duct, together with a photo of the klystron gallery of the XFEL. The duct consists of an outer metallic duct, a 60 mm thick glass-wool thermal insulator and an inner metallic duct. Cupper pipes are attached to the inner duct, and temperature-controlled water within +/- 0.2 K is fed to the pipe to stabilize the optical fiber temperature. The metallic duct forms an isothermal surface and equalizes the temperature distribution inside the inner duct.

A test at a manufacture factory was performed to evaluate the performance of the duct using a 2 m prototype duct. Figure 3 shows the measured results. The ambient temperature had a variation of 29.08 ± 1.71 K (P-P) with the time interval between the peak-to-peak change of the temperature being near 15 minutes, while the fiber temperature in the duct was kept within 26.21 ± 0.08 K (P-P) by flowing cooling water with 26.06 ± 0.12 K (P-P). The calculated delay time of the heat transfer from outside to inside of the duct was 45 minutes. The suppression ratio of the variation of the inner temperature to that of the ambient temperature is about 1/20 in this case.

A test operation using the duct installed at the klystron gallery was performed. A trend of the measured temperature of the fiber cable is shown in Fig. 4. The temperature variation of the optical fiber cable was within 0.18 K (P-P), while that of the ambient was about 0.7 K (P-P). The suppression ratio was about 1/4, which is about 1/5 lower than that of the factory test. This is because the

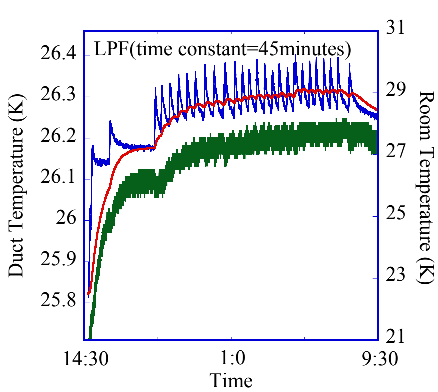

Figure 3: Trend of the temperature of the ambient and inside the duct at a factory test.

time of an ambient temperature change at the actual XFEL machine was much longer than that of the factory test. The temperature variation of the optical fiber was 0.18 K, which corresponds to 360 fs in the time variation of the signal transmitted along the 400 m long optical fiber cable. A precise parameter tuning of the water-cooling system of the facility will be done after the completion of all components installation of the accelerator, and, then, the stability of the cooling water will be improved.

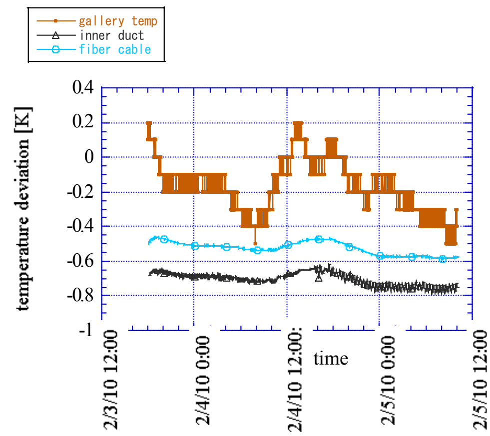

Figure 4: Temperature variation of the optical fiber and the ambient for 48 hours operation at the klystron gallery.

VIBRATION EFFECT ON THE TRANSMITTED SIGNAL PHASE

If the water flow at the fiber duct induces the vibration of the optical fiber, the effective optical path could be modulated by this vibration. To evaluate this effect, the relation between the transmitted signal phase and the vibration amplitude along an optical fiber cable was measured by using the experimental apparatuses shown in Fig. 5. A part of an optical fiber string with a total length of 2 m was fixed at the two end points apart for 160 mm in distance. A vibrator was located near the centre of the two fixing points. A 5.7 GHz rf signal from an rf oscillator was split into two. One was sent to an EO module for electrical-to-optical conversion, and the converted optical signal was transmitted though the optical fiber. Then, an electrical signal converted from the optical signal with an OE module was compared with the

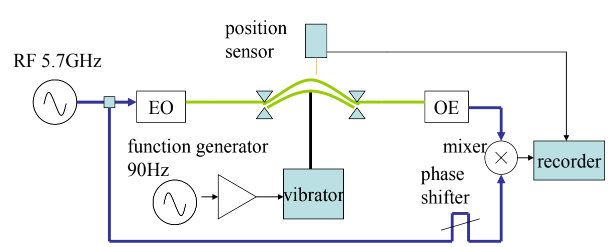

Figure 5: Measurement setup of the phase change of the transmitted signal with a condition of applying vibration to the optical fiber.

original signal generated with the oscillator. For this comparison, a mixer was used as an rf phase detector. The vibration amplitude of the fiber was measured by using a laser position sensor.

To measure the vibration amplitude along the fiber, the lowest resonance mode of the fiber string was excited by the vibrator. This is because the lowest resonance mode is a simple mode, and it is easy to analyze the displacement of the fiber. This displacement gives a stress to the fiber, deforms its shape, and causes a mode change and a guided wavelength change of optical transmission on the fiber. Finally, the phase of the transmitted signal is changed. The vibration frequency f of the string with two fixed points can be expressed as,

$$f = \sqrt{\frac{T}{\lambda}} * \frac{m}{2L}, \tag{1}$$

where T is the tension, λ the line mass density of the string, m the mode number and L the length of the string. The calculated frequency is 90 Hz, where the parameters of $T = 600\ g * 9.8\ \mathrm{m/s^2}$, $\lambda = 7$ g/m, L =0.16 m and m = 1 are substituted into Eq. 1.

By applying a 90 Hz vibration to the fiber string, the rf phase change was measured. Figure 6 shows the result of the measurement. A phase change of less than 0.0013 degree (rms) in the 5.7 GHz signal was observed at a vibration amplitude of 50 μm (rms), as shown by the symbols with a filled triangle. This value corresponds to a 0.013 fs (rms) time variation at a 1 μm (rms) vibration amplitude, and this perturbation is negligibly small compared with the rf phase tolerance of the XFEL. To simulate the situation that the fiber was bent by an external force, a measurement was made by changing the height of the fixing point of the vibrator in 0.5 mm steps. At a large bend angle, the vibration shape of the fiber string was not a natural bow shape, and became a triangle. One of the corners of the triangle was the point of action of force generated by the vibrator. In this case, the phase change was dramatically increased by the motion of the triangle shape with large distortion at the action point. This phase change reached 0.024 degree (rms), as shown in the symbols with an open square, when the action point was lifted up to 1.5 mm from the horizon. This result indicates that the fiber should be installed with taking care not to apply an excessive tension to the fiber.

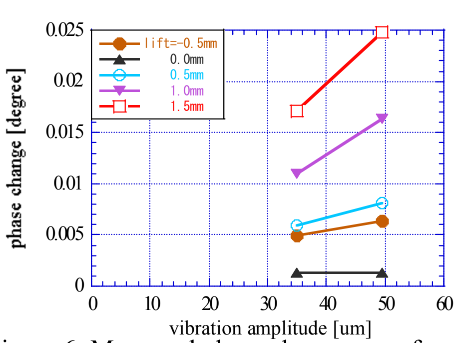

Figure 6: Measured phase changes as a function of the applied vibration amplitude. The phase changes were measured with various vibration amplitudes at the center of the optical fiber.

The actual vibration amplitude of the fiber installed at the XFEL klystron gallery was measured by using an acceleration sensor, ADXL311 (analog devices). No significant peak was seen in the vibration spectrum, as shown in Fig. 7. The vibration spectrum of the cable was almost identical to that of the floor of the klystron gallery. The integrated vibration amplitude from 200 Hz to 20 Hz shown in figure was less than 1 μm.

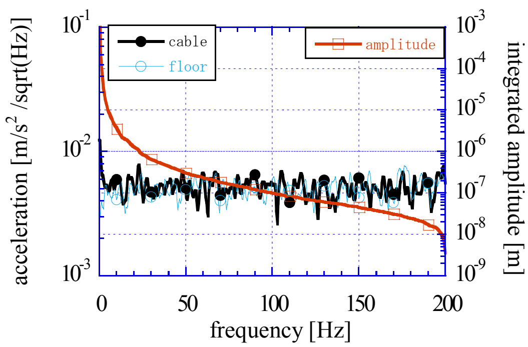

Figure 7: Measured vibration amplitude of the optical cable in the duct and that of the floor of the klystron gallery.

SUMMARY

To distribute the reference signals to the LLRF units located along the 400 m accelerator of the XFEL/SPring-8, an optical-fiber transmission system was developed. The optical fiber is installed in the temperature-controlled duct. A test operation to evaluate the duct indicated that the temperature stability was less than 0.18 K (P-P). The vibration displacement of the installed fiber was less than a few μm. This displacement corresponds to an rf phase variation of less than 0.1 fs in a 5712 MHz transmitted optical signal and this effect is negligible. Installation of the optical transmission system for the reference rf and timing signals is under progress in accordance with our scheduled plan.

ACKNOWLEDGEMENTS

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