First experiment of ultra-stable frequency transfer system via optical fiber in NICT

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***Abstract*— We have developed an RF dissemination system via optical fiber. The phase variation during transmission is actively canceled out by electronic compensation system. In a laboratory test, this system demonstrates a stability of 2×10^{-17} at 30000 s after 1-km dissemination with respect to the reference signal.**

I. Introduction

In the past decade, significant improvements have been done with the development of atomic frequency standards. Typically, cesium atomic fountain clocks in the microwave domain have already performed an accuracy of 10^{-15} or better [1], [2], and, optical frequency standards based on single ion trap and optical lattice have already demonstrated accuracies in the 10^{-16} or better [3], [4], [5]. The frequency standard in the optical region is said to have the potential to reach the accuracy of 10^{-18} [6]. On the other hand, the clock comparisons between distant laboratories have been performed using a satellite link, such as GPS [7], [8] or two-way satellite time transfer systems [9], [10], giving a resolution of a few parts in 10^{15} at one-day averaging time. These methods are thus insufficient for frequency comparison of drastically improved atomic frequency standards. The comparison between highly precise standards requires ultra-stable signal transmission method without degradation of the precision of the standards.Furthermore, establishment of ultra-stable frequency distribution system is awaited anxiously by radio astronomy and particle accelerator. Array antennas like ALMA project [11] and triggering system for next generation linear collider [12] also demand low-noise frequency distribution system.

Nowadays, an optical fiber is used to distribute the RF signal to a remote site because the transmission loss of the optical fiber is much smaller than that of a metal cable. Simple optical fiber distribution is, however, not sufficient for our requirements because the phase fluctuation due to mechanical stress and temperature variation of the fiber occurs. To distribute the RF signal via optical fiber with high stability, the active phase compensation system is required. The novel compensation technique has been studied in some laboratories [13], [14]. The optical fiber dissemination system with phase compensation is one of the state of the art techniques for the short or middle distance link ($\sim$ several hundreds km).

NICT has started a research on the microwave dissemination via an optical fiber. Our objective is to establish the optical link, which enables distribution of RF signal to the remote site in the 10^{-18} level per day. In this paper, we describe our system, the preliminary results as well as the future plan.

II. RF dissemination system

A. Principle

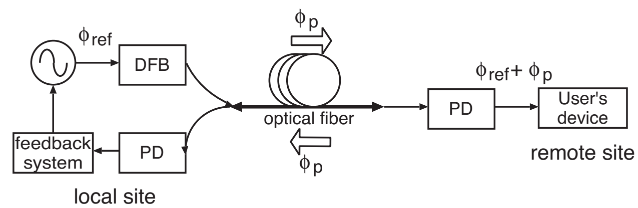

Fig. 1. Schematic of RF dissemination system via optical fiber.

Basic schematic of the dissemination system via optical fiber is depicted in Fig. 1. Here DFB and PD represent distributed feedback laser and photo-detector, respectively. The frequency we disseminate is 1 GHz and the initial phase is represented by ϕ_{ref}. The microwave reference modulates an amplitude of cw optical signal. The optical signal with 1 GHz detuned sideband spectrums is transmitted via optical fiber. At a remote site, a fast PD demodulates the optical signal and convert it to a microwave signal, since the optical fiber induces excess phase noise, ϕ_p, during the transmission and degrades the frequency stability of the transmission signal. Therefore the phase of the transmitted signal to the remote site becomes $\phi_{ref} + \phi_p$. One of the induced phase noises is caused by temperature variation in the optical fiber and limits the stability above the 10^{-15} level in the case of a few km-long fiber at long averaging time. Then a portion of the transmitted signal is sent back to local site through the same optical fiber and used for active phase compensation to cancel out the induced phase noise during the transmission, that is, to satisfy the relation of $\phi_p = 0$.

B. Dissemination performance evaluation system

A phase measurement equipment plays an important role for the evaluation of the disseminated frequency performance. At present, some commercial equipment, including TSC 5110A [15] and one made by Nittsuki, are available for phase measurement. Their performances and specifications are not enough to our target level, 10^{-18}, however. We developed a high-stability frequency down converter and combined it with the TSC 5110A and achieved our target system noise. The measurement frequency for TSC 5110A is up to 20 MHz. The frequency down converter consists of commercial

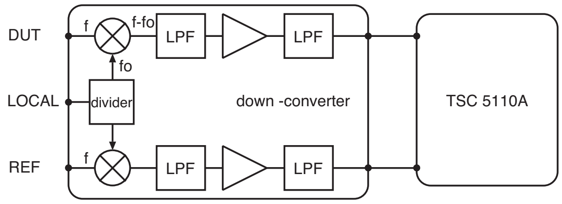

Fig. 2. Schematic of phase difference measurement system. LPF represents low-pass filter.

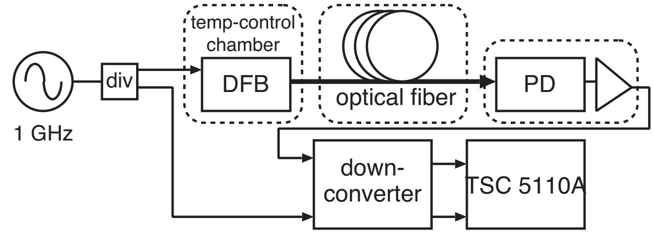

Fig. 4. Schematic of temperature characteristic measurements. DFB laser, PD and optical fiber are put in temperature-control chamber in turn and the phase fluctuation is measured by our evaluation system.

RF modules, filters, mixers and amplifiers to convert the frequency into the available frequency range of TSC 5110A. The schematic of our phase measurement system is depicted in Fig. 2. The frequencies of DUT signal and reference are almost same, denoted by f. These frequencies are converted by a common signal at a frequency fo to $(f - fo)$ in the down converter and their phase difference between the DUT signal and the reference is enlarged by the rate of $f/(f - fo)$. Then they are launched to the TSC 5110A and the phase difference is measured precisely there. It is possible to evaluate the phase difference at a frequency up to 1.5 GHz in our system. Fig. 3 shows the system noises measured by the TSC 5110A at 10 MHz, our system and commercial phase difference measurement equipment made by Nittsuki at 1 GHz, respectively. The result shows that our evaluation system has enough system noise to measure phase difference at our target level, below 10^{-14} and 10^{-18} at 1 s and 10^5 s, respectively.

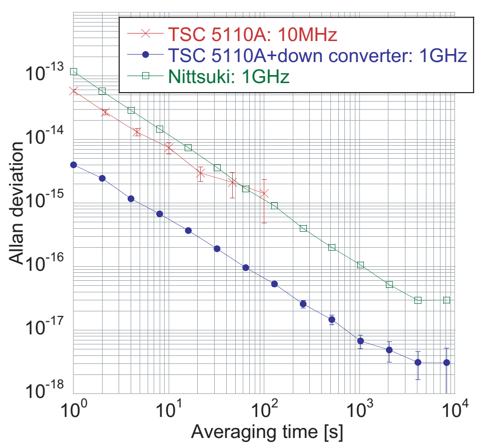

Fig. 3. Frequency stability of 1 GHz phase measurement system.

C. Temperature characteristics

To estimate the temperature characteristics of DFB laser and PD as well as optical fiber, we measured their phase variations due to the temperature variation using a temperature-control chamber. Fig. 4 shows the schematic, where we measured the temperature dependences of the DFB laser, the PD with the RF amplifier and the optical fiber in turn by putting them into the chamber. Then other equipment were placed in an temperature-stabilized experimental room. There the PD is always used with the RF amplifier because the output power level of the PD is very small for the evaluation system. We used ORTEL 10371A, 10382S DFB lasers at 1.55 μm, ORTEL 10450A PD and 1-km long SMF-28 fiber for the measurements. The temperature using the chamber varied periodically from 10 to 30 °C and the room temperature was kept within 19±1 °C. The transmitted microwave signal was at 1 GHz frequency. The phase difference between before and after transmissions through the optical fiber was measured by our evaluation system. Figure 5 shows the phase variations due to the temperature variation. The black line represents the temperature dependence of the DFB laser, and the blue line does that of the PD with the RF amplifier. The red line depicts the temperature variation in the chamber. The temperature coefficients obtained from the measurements are summarized in Table I. It is found that phase fluctuation induced by temperature variation in the optical fiber is dominant, but those due to the temperature variations in the DFB laser and the PD with the RF amplifier are not negligible.

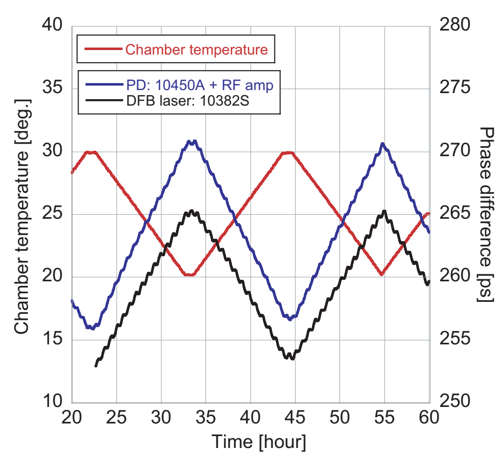

Fig. 5. Phase fluctuations induced by a periodical temperature variation in the temperature-control chamber. Blue and black lines represent the temperature dependence of PD with RF amplifier and DFB laser, respectively.

III. Active Phase Cancellation System

We have developed an electronic active phase compensation system using a phase locked loop (PLL) with a voltage controlled crystal oscillator (VCXO). Fig. 6 shows the schematic.

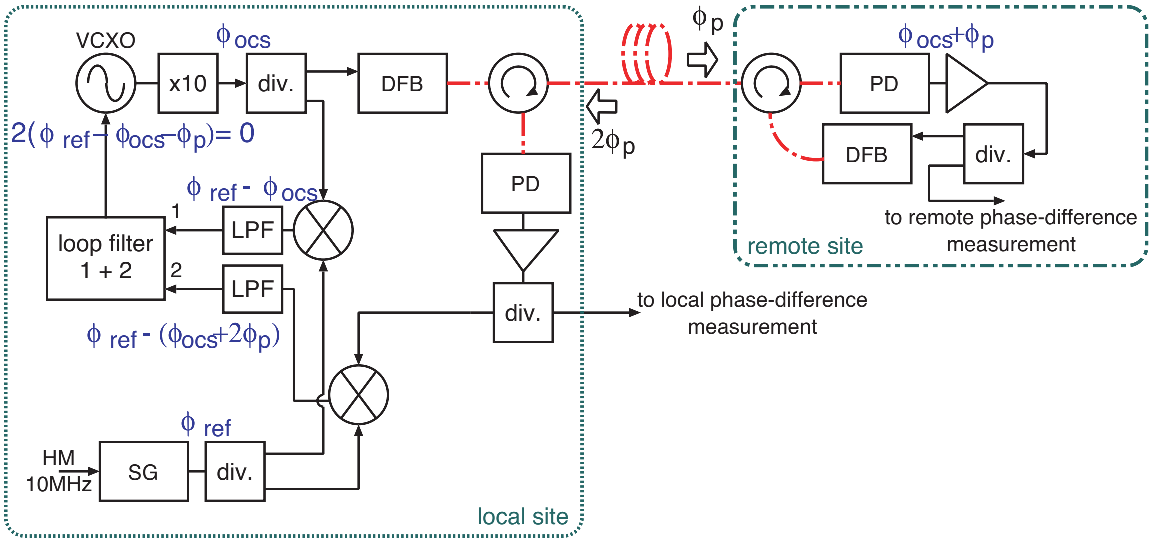

Fig. 6. Schematic of electronic phase compensation. LPF and div. mean low-pass filter and divider.

TABLE I
TEMPERATURE COEFFICIENTS.

	Model	temp. coeff. [ps/K]
DFB laser	ORTEL 10382S	-1.2
DFB laser	ORTEL 10371A	-0.6
PD + RF amp	ORTEL 10450A	-1.4
SMF-28 fiber 1km		-33

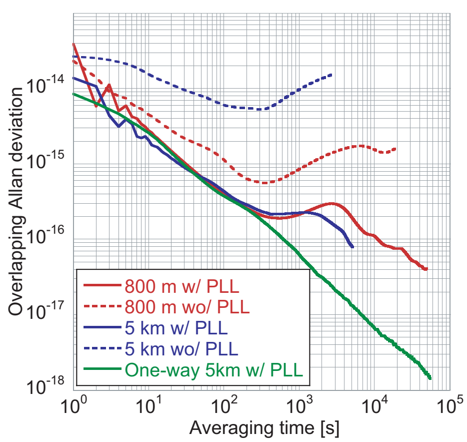

Fig. 7. Frequency stability with and without electronic compensation at remote site.

For a laboratory test, the RF dissemination system is put in an experimental room and a fiber spool is used instead of really laid fiber in network. A 1 GHz signal is generated from 100 MHz VCXO signal. The DFB laser output with amplitude modulation by the 1 GHz is transmitted via the optical fiber. At the remote site, it is demodulated by a fast PD and the 1 GHz signal remodulates another DFB laser. The optical signal returns through the same fiber as outward. Since the wavelengths of outward and return optical carriers differ slightly, interference between them in the fiber is avoided. At the local site, the signal is demodulated again and adopted for the feedback. The phase of the signal generated from the VCXO are represented as ϕ_{ocs}. A phase noise, denoted by ϕ_p, is induced during one-way transmission. The phase of the signal arrived at the remote site becomes $\phi_{ocs}+\phi_p$, and the phase of the signal returned to the local site is $\phi_{ocs}+2\phi_p$. What we want to transmit to the remote site is coherent signal with the phase of ϕ_{ref}. Therefore, the transmitted signal phase should satisfy following equations, $\phi_{ref} = \phi_{ocs}+\phi_p$. To realize the condition, we developed a loop filter which has summation and multiplying functions. Two phase differences, $\phi_{ref}-\phi_{ocs}$ and $\phi_{ref}-(\phi_{ocs}+2\phi_p)$, are combined at the loop filter. Then the VCXO is controlled electrically to satisfy the condition,

$$2(\phi_{ref}-\phi_{ocs}-\phi_p) \quad = \quad 0. \qquad (1)$$

Thus, the coherent signal with the phase of ϕ_{ref} is realized at the remote site. Because of the laboratory test, the error signal of $\phi_{ref}-(\phi_{ocs}+\phi_p)$ was also fed back to the VCXO and the relation, $\phi_{ref} = \phi_{ocs}+\phi_p$, were realized at the remote site after one-way path.

Figure 7 shows the frequency stabilities at the remote site, where the stabilities with and without the electronic compensation are depicted with that in the case of one-way dissemination. It is seen that the one-way case shows good characteristics in all range of the averaging time. This result proves that phase fluctuation during one-way dissemination is canceled well if an applicable error signal is fed back to the VCXO. In the cases of the round-trip control, however, the stabilities with the compensation showed bumps after 1000 s. A possible explanation is that the DFB lasers and the PDs at both sites induced excess phase fluctuation due to the temperature variation. If any unnecessary phase noise causes in a part of the dissemination system, the only half fluctuation is compensated at the remote site. For example, let us consider the case ϕ_D is induced only at the local site DFB laser. Then the control condition generated by the loop filter becomes

$$2(\phi_{ref} - \phi_{ocs} - \phi_p) - \phi_D \quad = \quad 0. \tag{2}$$

When the condition is realized, the phase obtained at the remote site is $\phi_{ref} + 0.5\phi_D$. Similarly, independent phase noise induced by DFB laser at the remote site or PD at each site will degrade the active cancellation of the remote site phase noise. The temperature coefficient of the DFB laser, 10382S, was -1.2 ps/K and the variation range of the room temperature was 1 K with a period less than 1 hour. These temperature coefficients and temperature variation are estimated to cause an instability of 3×10^{-16} at about a few thousands seconds, which is consistent with the bumps after 1000 s shown in Fig. 7.

To reduce the phase fluctuation due to the system components except for the optical fiber as possible as small, we moved the dissemination system to a room (named Room 1) whose temperature variation is within ± 0.3 °C. A 1-km fiber spool was put in another room (named Room 2) and 110-m long fibers connect between the rooms. Schematic of the measurement setup is depicted in Fig. 8. Fig. 9 and 10 show the phases and their stabilities of the transmitted signals at the local and remote sites relative to the reference signal. Here it should be noted that the local phase is not the phase of the signal transmitted to the local site, but that returned to the local site. Fig. 9 shows active phase compensation worked well for the remote phase, while it was not effective for the local phase, as is expected from equation (1). The stability at the remote site improved more in comparison with that in the case of 800 m. Therefore, the temperature stabilization of DFB laser and PD was effective.

The local phase variation synchronized with the temperature in the Room 2, whose temperature coefficient was -30 ps/K. The remote phase also varied slightly, which was -2 ps/K. The electronic compensation system showed a 12 dB attenuation. When we intend to extend the transmission length, it seems that the phase variation is not suppressed enough because of the insufficiency of attenuation range.

IV. Summary and Future Plans

We have developed an RF dissemination system via optical fiber and its evaluation system. To compensate phase fluctuation during dissemination, an original feedback system was developed using a VCXO. In a laboratory test, stabilities of a few 10^{-14} at 1 s and 2×10^{-17} at 30000 s have been achieved using a 1 km fiber spool. In addition, it proves that the temperature coefficients of the DFB laser and PD also are not negligible at the 10^{-16} level. It seems that the present attenuation gain for phase variation is not enough to extend the dissemination length, however. The gain and balance in the loop filter should be optimized to obtain more attenuation level. We have also prepared an optical phase compensation system with a 1-km fiber spool heated for that purpose. A signal generator synchronized to 10 MHz signal from a hydrogen maser is used for 1 GHz reference at present. In future, use of a 1 GHz signal synchronized to the more stable frequency standard is expected.

We intend to perform a proving test in an optical fiber network in near future. As a first step, an experiment using the internal fiber network in our institute would be planned. Conventional frequency transfers like GPS carrier phase and two-way satellite time and frequency transfer would be performed together to compare the results.

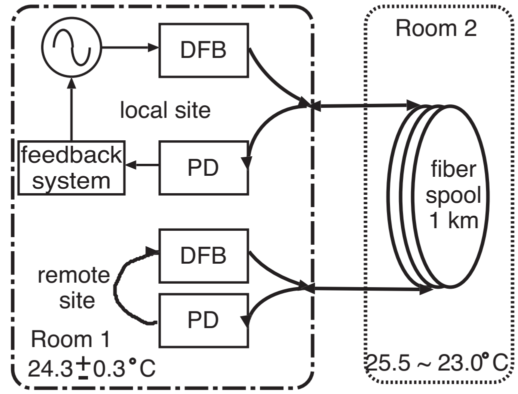

Fig. 8. Schematic of temperature characteristic measurement. DFB laser is mounted in temperature-control chamber and phase fluctuation is measured by the down-converter and TSC 5110A.

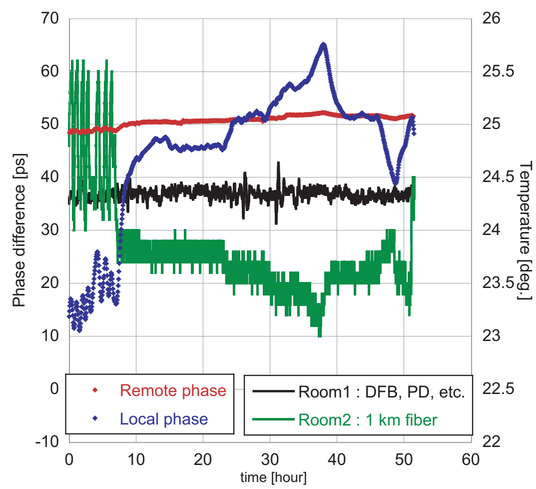

Fig. 9. Phase and temperature variation. Black and green lines represent temperature variation in Room 1 and 2, respectively. In Room 2, a 1 km fiber spool is put. Other equipment are put in Room 1.

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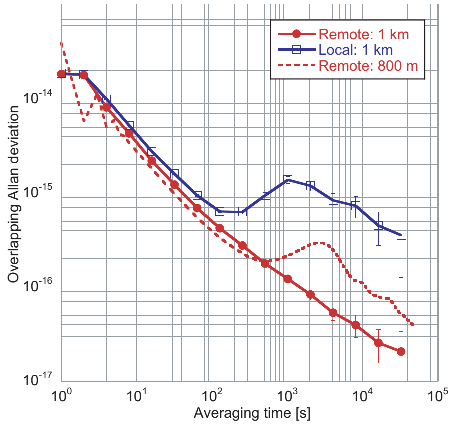

Fig. 10. Frequency stabilities at local and remote sites. Fiber length is 1 km.

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