Progress to coherent frequency transfer over a telecom fiber link at NICT

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***Abstract*— We performed the 1-GHz and 10-GHz transfer over the 114-km and 90-km urban optical fiber links in Tokyo, respectively. The phase noise in the free-run link was huge because almost 50 % of the optical fibers were not buried under the ground. Nevertheless, we achieved the phase-noise cancellation ratio of 45 dB by an electrical phase-noise compensation system using a VCXO and the stability of 6×10^{-18} at 1 day in the 10-GHz 90-km transfer. Besides, the RF transfer over the 204-km link was performed by the cascade system. It proved that the transfer stability degrades only $\sqrt{N}$ times by the cascade of the N-th systems.**

I. Introduction

With the significant progress of optical frequency standards, necessity of ultra-stable frequency transfer system is emphasized [1], [2], [3]. To enable such transfer is difficult for the traditional frequency transfer via satellite considering the error sources between ground and satellite [4]. Alternatively, it is thought that frequency dissemination using optical fibers is the possible candidate. A stable RF distribution and optical carrier transfer are actively studied [5], [6], [7], [8], [9], [10]. The both transfer stabilities are beyond those of traditional transfers, especially that of optical carrier transfer reaches to 10^{-17} level at 1 second.

NICT has developed 1-GHz distribution system [11] and performed the proving test on a 114-km urban telecom fiber link in Tokyo area [12]. Because the half of the 114-km fiber link was exposed to air, not buried under the ground, the originated phase noise in the link was huge and the amplitude of the diurnal fiber-length variation reached to 10 meter over the link. Nevertheless, with an electrical phase-noise compensation system using a voltage controlled crystal oscillator (VCXO), we succeeded at continuous stable RF transfer for more than 1 week with the transfer stability of 10^{-18} level at 1-day averaging time. The next concern for frequency transfer over a fiber link is to extend the transmission length without substantial stability degradation. We performed the 204-km transfer by the cascade system which connected two phase-noise compensation systems in series. Furthermore, to improve the stability for one compensation system, we have tried the 10-GHz transfer and started the development of the optical carrier transfer system. The progress of the RF transfer system as well as the optical carrier transfer is described in this report.

II. RF transfer via optical fiber

A. RF transfer system

The schematic diagram of the 1-GHz distribution system using optical fibers is depicted in Figure 1. A 100-MHz signal from a VCXO is converted to 1 GHz using a multiply-by-ten frequency multiplier; the resultant 1-GHz signal is used as the microwave source. The microwave signal modulates the amplitude of a continuous wave (CW) optical signal from a distributed feedback (DFB) laser with a wavelength of 1.55 μm. An amplified optical signal by an Erbium doped fiber amplifier (EDFA) with a detuned sideband spectrum of 1 GHz is transmitted through a standard single-mode optical fiber from a local site to a remote site. At the remote site, an EDFA is inserted to compensate the optical signal loss, and a fast photo-detector (PD) demodulates the optical signal and converts to the 1-GHz signal. A portion of the 1-GHz signal is used as the microwave source of the modulation of the second laser, transmitted back from the remote site to the local site

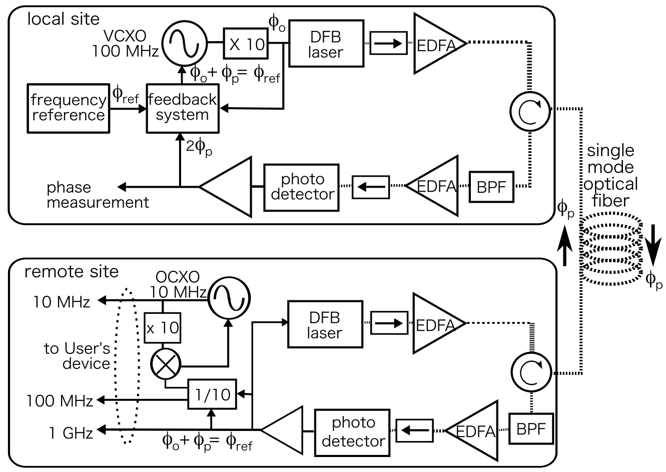

Fig. 1. Schematic of the 1-GHz distribution system.

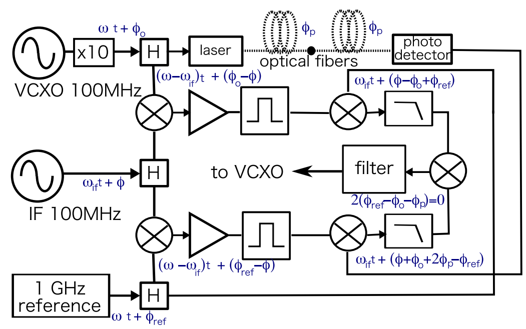

Fig. 2. Schematic of the phase-noise compensation system.

and used to cancel the phase noise accumulated on the way to the remote site. Our system enables to provide the coherent 10-MHz and 100-MHz signals to a frequency reference as well as the 1-GHz signal at the remote site.

Figure 2 shows the phase-noise compensation system. Thanks to the DMTD technique, the 1-GHz reference signal and the round-trip signal through the fiber link are down-converted to the IF, 100MHz, and then they are mixed into the error signal which is fed back to the VCXO. The following equation is satisfied by the compensation system;

$$\begin{aligned} 2(\phi_{ref} - \phi_o - \phi_p) &= 0 \\ \phi_{ref} &= \phi_o + \phi_p = \phi_{remote}. \end{aligned} \quad (1)$$

Here, ϕ_{ref} and ϕ_o are the phases of the reference signal and 1-GHz signal generated from the VCXO, respectively. ϕ_p and ϕ_{remote} are those induced in the path to the remote site and at the remote site, respectively. At last, the phase of the signal transmitted to the remote site becomes equal to that of the 1-GHz reference signal.

B. JGN2+ optical fiber link

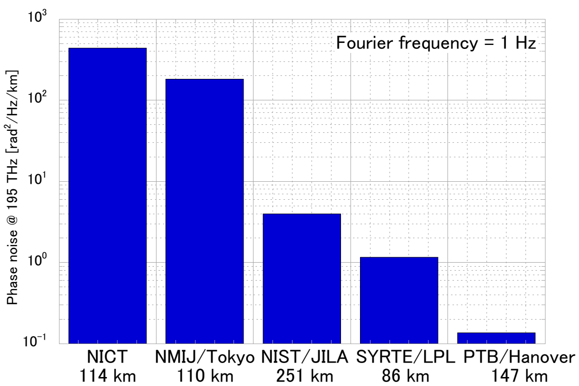

Fig. 3. Phase noise per 1 km of the free-run optical fiber link.

We have performed the proving tests on an urban telecom fiber links named JGN2+ in Tokyo area, which is an optical test bed provided by NICT and aims at conducting R&D on information and communications technology [13]. The links are established by interconnecting several different sections of laid single mode fibers and any amplifiers are not included there. We used four parallel 45-km links between NICT and Otemachi close to Tokyo station, and other two parallel 12-km links between Otemachi and Hakusan close to Univ. of Tokyo. Connecting their 45-km and 12-km links at Otemachi and jointing them at Otemachi and Hakusan, we established two round-trip optical links with a length of 90-km and 114-km where optical losses were 30 dB and 40 dB, respectively.

Figure 3 depicts the phase noises at 195 THz of the free-run links of SYRTE/LPL 86 km [5], PTB/Hanover 147 km [8], JILA/NIST 251 km [10] and NMIJ/Tokyo 110 km [7]. Only the JILA/NIST 251-km link includes the spooled fiber of 175 km and the others are the laid fiber links. Because we have not measured the phase noise at 195 THz yet, the estimated value from the result at 1 GHz is depicted in our case, NICT 114 km. Those of NMIJ/Tokyo and NICT are clearly larger than the others. This is because almost half parts of their two links are exposed to air, that is, the all fibers are not buried underground. Our JGN2+ link is further noisier than NMIJ/Tokyo link because it goes across the center of Tokyo. Unfortunately, our free-run link is noisiest among reported fiber links so far.

C. 1-GHz transfer over 114-km link

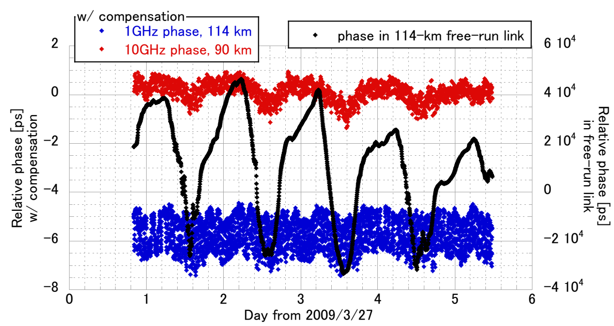

Fig. 4. Relative phases in the free-run and phase-noise compensated links.

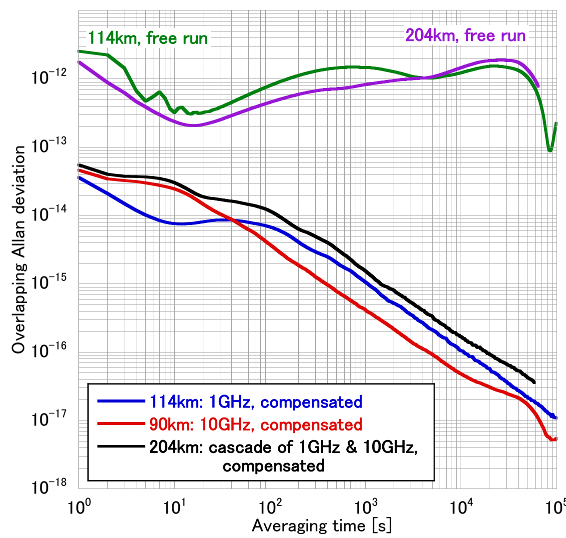

Fig. 5. Transfer stabilities in the free-run and phase-noise compensated links.

We have performed the 1-GHz transfer in the 114-km optical fiber link. To evaluate the compensation system, both local and remote sites were installed in NICT. In our system, the relative phases of the forward and round-trip signals to the reference signal are measured at the remote and local sites by phase comparators every second. When the phase-noise compensation system works, the phase noise induced in the path to the remote site is cancelled. Therefore, the phase of the round-trip signal represents that in the free-run link as $\phi_{local} = (\phi_o + \phi_p) + \phi_p = \phi_{remote} + \phi_p = \phi_{ref} + \phi_p$. Figure 4 shows the 1-GHz relative phases of the free-run and the phase-noise compensated 114-km links. In the case of the free-run link, the length variation of the optical fiber link reached 60 ns, that is, 12 m in one day. Regarding [5], the stability of the 86-km free-run link is about 5×10^{-15} at a half day. It seems that the fiber length changes about 0.04 m in one day there. It is clear that the free-run link noise in the JGN2+ optical fiber link is awfully large. Nevertheless, the huge phase-noise was cancelled successfully by our compensation system, where diurnal amplitude of the fiber-length variation was less than 2 ps. We achieved the cancellation ratio more than 45 dB.

Figure 5 shows the transfer stabilities. We achieved the transfer stability of 1×10^{-17} at 10^5 s in the 1-GHz 114-km transfer. The bump from 10 s to 100 s are shown in the case with the phase-noise compensation, which is attributed to the remained phase oscillation shown in Figure 7. When the phase variation rate, that is, Doppler rate in the free-run link was 1 ps/s, the remote phase rotated one revolution in about 1000 s. Besides, the period of the oscillation varied according to the variation of the Doppler rate in the free-run link.

D. 10-GHz transfer over 90-km link

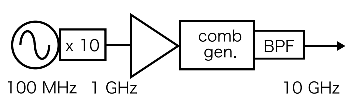

Fig. 6. Schematic of the 10-GHz generation system.

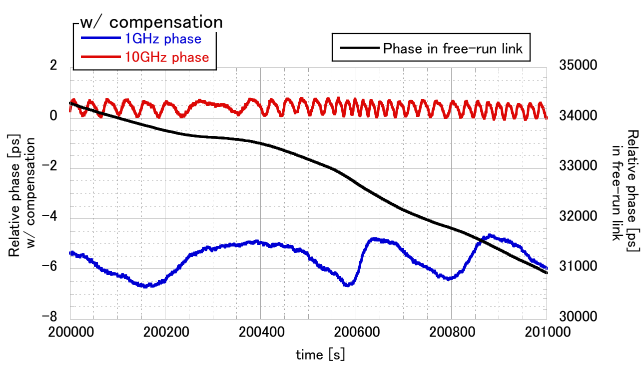

Fig. 7. Zoomed relative phases in the free-run and phase-noise compensated links.

To examine the remote-phase oscillation and improve the stability, we performed the 10-GHz frequency transfer over the 90-km urban optical fiber link. Figure 6 depicts the 10-GHz generation system. The signal from the 100-MHz VCXO was converted to 1-GHz signal by the frequency multiplier and its 1-GHz signal was inserted into a comb generator. The frequency comb spacing 1-GHz was generated and the 10-GHz signal was selected by a bandpass filter, which 10-GHz signal was used as a microwave source for the modulation of the DFB laser. The 10-GHz acceptable DFB lasers, fast photo-detectors and RF amplifiers were used in the 10-GHz transfer system. In the 10-GHz phase-noise compensation system, the 10-GHz signal was similarly generated from the 1-GHz reference signal by the comb generator and a 11-GHz signal was used as IF. Because the 10-GHz transfer system could not accept the optical loss of 40-dB in the 114-km fiber link, we tried the 10-GHz 90-km transfer at the same time with the 1-GHz 114-km transfer. The resultant relative phases and transfer stability are depicted in Figure 4, 7 and 5, respectively. It is clearly seen that the period of the 10-GHz phase oscillation was about 1/10 in comparison to that of the 1-GHz phase oscillation. Additionally its amplitude decreased less than 1 ps and the 10-GHz transfer stability was better than that of 1-GHz. It seems that the short-term stability is limited by the VCXO locked to the reference signal with the bandwidth determined by the round-trip delay. It proved that to use higher frequency is effective to improve the transfer stability.

As described above, phase oscillation was observed in both cases of 1-GHz and 10-GHz transfers. The reason has not been solved yet, but we consider possible reason here. To check the validity of our compensation system, we changed the compensation scheme to cancel out the phase noise of round-trip signal back to the local site as follows;

$$\begin{aligned} \phi_{ref} - \phi_o + 2\phi_p &= 0 \\ \phi_{ref} &= \phi_o + 2\phi_p = \phi_{local}. \end{aligned}$$

In this case, such phase oscillation in compensated signal was not observed. It proved that the phase oscillation was not attributed to our compensation system.

In phase-noise compensation by round-trip signal, it is generally supposed that the accumulated phase noises during the forward and return paths are equal. The equation (1) is expected to be satisfied by the compensation system. Suppose the phase drift in free-run link is huge, that is, a Doppler rate v is fast, it is considered that the phase noises during the forward and return paths are slightly different. Resulting, the equation (1) is broken and the term proportional to vt is remained due to its path asymmetry.

$$\phi_{remote} = \phi_o + \phi_p - vt.$$

When the free-run phase changes over one oscillation cycle of transferred signal, such phase oscillation is possible. With a Doppler rate v [ps/s], the 1-GHz signal oscillates with a period of T_{1ghz}/v [s] and the 10-GHz signal does with a period of T_{10ghz}/v [s], where T_{1ghz} and T_{10ghz} are 1000 and 100 ps, respectively. The output phase oscillations of the analog double balanced mixer (DBM) at the Doppler rate of 1 [ps/s] are simulated in Figure 8, where the oscillation periods of 1 GHz and 10 GHz signals are 100 s and 1000 s, respectively. This result agreed with those actually seen. We claim that the phase oscillation might be attributed to the fast Doppler rate in our link, however, the reason has been unsolved yet. Further investigation is still required.

E. RF transfer by cascade system over 204-km link

We performed the 204-km transfer by the cascade system combining of the 10-GHz 90-km and the 1-GHz 114-km

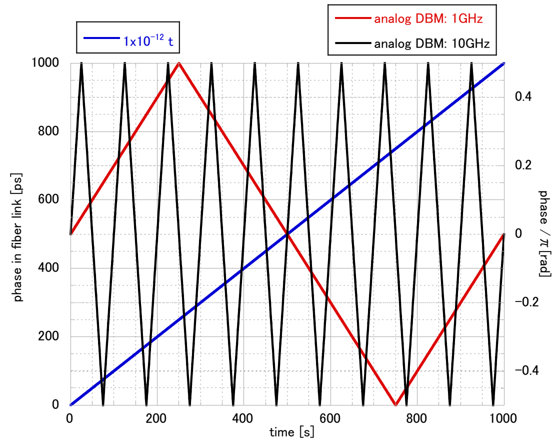

Fig. 8. Estimated phase variation from analog DBM with a Doppler rate of 1 [ps/s].

transfer systems in series. The schematic is shown in Figure 9. The transferred 10-GHz signal over the 90-km link was down-converted to the 1-GHz by a divided-by-10 prescaler. Then the 1-GHz signal was transferred over the 114-km link and it was compared with the 1-GHz reference signal. Figure 4 shows the achieved transfer stability. It was almost equal to the root sum square of those of the 1-GHz transfer and the 10-GHz transfer. The result confirms that the stability of the cascade of the N-th systems with a stability of σ degrades by a factor of $\sqrt{N}$ only. Suppose an RF signal transfer over 1000 km is performed by 5-th cascade system of our 204-km transfer systems, the stability is expected as 1×10^{-13} at 1 s and 4×10^{-16} at 10000 s, which are still better than the conventional transfer's stability.

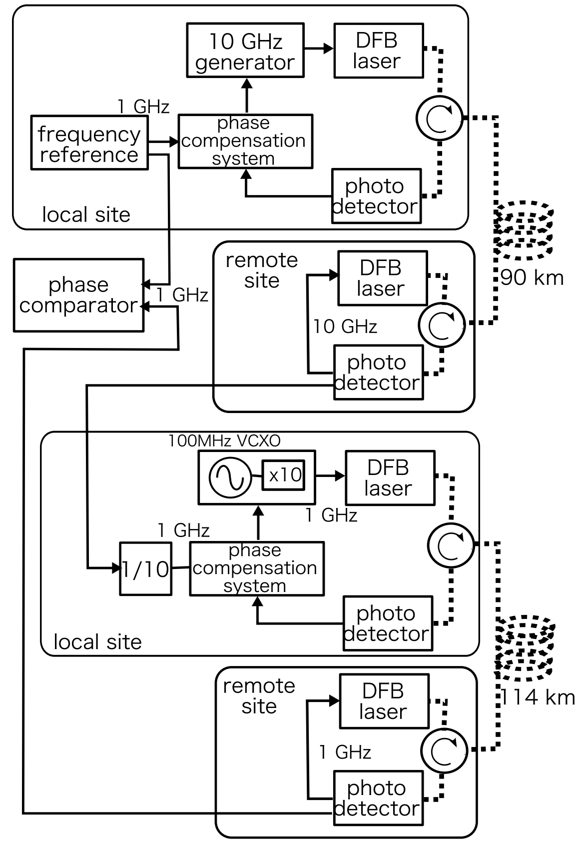

Fig. 9. Schematic of the cascade system for 204-km transfer.

III. Optical carrier transfer

To improve the short-term stability, we have started the optical carrier transfer. We evaluated the phase noise of the 114-km free-run link and a free-running fiber laser as shown in Figure 10. The phase noise of the fiber laser was measured by inserting a 100-km fiber spool into an arm of the interferometer to make the reference and measured lights incoherent. The measurements were done by a phase comparator with the bandwidth of 500 Hz. The phase noise of the free-running fiber laser was inferior in comparison to a stabilized laser to a cavity, but it was enough lower than that of our free-run link. We will evaluate the effect due to the phase noise attributed to the fiber laser and develop a stabilized laser if required. According to [6], we estimated the theoretical limit of the transfer stability from the result. In our 114-km link, the phase noise in the free run is about $5 \times 10^4 / f^2$ $[rad^2/Hz]$ and the transfer stability is calculated to be $1 \times 10^{-15} t^{-3/2}$.

IV. Conclusion

We performed the 1-GHz and 10-GHz transfers over the 114-km and 90-km urban optical fiber links in Tokyo, respectively. The phase noise in the free-run link was huge because half of the optical fibers was not buried under the ground. Nevertheless, we achieved the phase-noise cancellation ratio of 45 dB by an electrical phase-noise compensation system using a VCXO and the stability of 6×10^{-18} at 1 day in the 10-GHz 90-km transfer. Besides, the RF transfer over the 204-km link was performed by the cascade system. It proved that the transfer stability becomes only $\sqrt{N}$ times worse by the cascade of the N-th systems. With the phase-noise compensation, the residual phase oscillation was observed. It seems that the asymmetry between the phase noises in the forward and return paths was attributed to as well as high Doppler rate in the free-run link.
We have started to study optical carrier transfer. For optical clock comparison, an optical fiber link between NICT and Univ. of Tokyo is planned.

Acknowledgment

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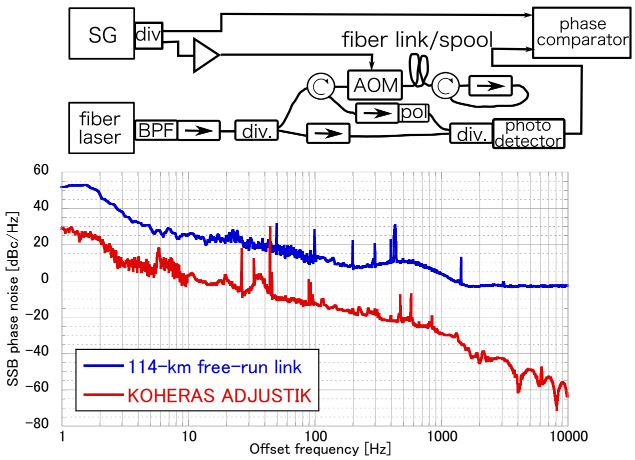

Fig. 10. Schematic of the phase-noise measurement system and result.

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