DEVELOPMENT OF FREQUENCY TRANSFER VIA OPTICAL FIBER LINK AT NICT

Motohiro Kumagai, Miho Fujieda,
Tadahiro Gotoh, and Mizuhiko Hosokawa
National Institute of Information and Communications Technology,
4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan
E-mail: ***mkumagai@nict.go.jp***

Abstract

NICT in Japan has developed a radio frequency (RF) dissemination system using an optical fiber link. The phase noise induced during the transmission through the optical fiber is actively cancelled by a compensation system. A proving test has been conducted on the 114-km urban telecom optical fiber link in Tokyo. The transfer stability in the 10^{-18} level at an averaging time of 1 day was achieved.

INTRODUCTION

In the last few years, optical frequency standards have improved significantly and attained high frequency stability **[1,2]**. Such significant improvements make it difficult to compare the optical clocks between distant laboratories without performance degradation by using conventional time transfer methods via a satellite link **[3]**. A low-noise frequency distribution system is demanded in the field of astronomy and particle accelerators, as well as time and frequency metrology **[4,5]**. Frequency distribution using an optical fiber link has attracted worldwide attention as one of the candidates to connect the distant sites in higher stability. In general, however, during a transmission through optical fiber, the transmitted frequency is exposed to the Doppler effect, which is attributed to fiber length variation caused from mechanical stress or temperature variation. The longer the transmission distance is, the larger the effect becomes. For stable dissemination via optical fiber link, active compensation to cancel the Doppler shift is required.

Recently, various optical fiber dissemination systems have been demonstrated in several laboratories. Stable RF frequency distribution has been developed and has achieved a transfer stability level of 10^{-18} for an averaging time of 1 day in an 86-km optical fiber link **[6,7]**. Optical carrier transfer, which requires optical frequency combs to bridge to local references, has been developed and achieved ultra-stable transfer stability **[8-10]**. The National Institute of Information and Communications Technology (NICT) also has been developing a stable optical-fiber dissemination system. NICT has maintained highly stable and accurate frequency standards, such as the cesium atomic fountain NICT-CsF1 **[11]** and a Cryogenic Sapphire Oscillator (CSO) **[12]**. To distribute these frequency signals to users, who do not have optical frequency combs, as well as to compare the optical clocks at an ultra-high level, we have developed an RF (1-GHz) frequency dissemination system via optical fiber **[13]**. Our target is a transfer stability in 10^{-18} at a 1-day averaging time. Previously, we performed a first proving test on a 10-km urban telecom fiber link and confirmed the transfer stability of 1×10^{-17} at an averaging time of 1 day. As an application, an ultra-stable 1-GHz signal based on the CSO was transferred through a 25-km optical fiber. A fractional frequency stability of 10^{-15} level was obtained in the absolute frequency measurement of the clock laser using an optical frequency comb, whose repetition rate was locked to the transmitted 1-GHz signal **[14]**. Recently, we improved our compensation system for over 100-km fiber link, and performed proving tests in a 114-km urban fiber link. In this paper, our compensation system and the latest results are reported.

RF DISTRIBUTION SYSTEM WITH ELECTRICAL COMPENSATION

The schematic diagram of the RF dissemination system using optical fiber is shown in Fig. 1. In order to cancel out the phase noise induced during the transmission, a voltage-controlled crystal oscillator (VCXO) is used for an electrical compensation. The VCXO has a large dynamic range, which is suitable for compensation of large phase fluctuation. The 100-MHz output from the VCXO is up-converted to 1 GHz using a multiply-by-ten frequency multiplier. The resultant 1-GHz signal $\omega + \phi_o$ modulates the amplitude of a continuous-wave optical signal from a distributed feedback (DFB) laser with a wavelength of 1.55 um. By an Erbium-doped fiber amplifier (EDFA), the modulated optical carrier is boosted up to +15 dBm, which is below the threshold for stimulated Brillouin scattering (SBS). A polarization scrambler is inserted after the EDFA to avoid the stability degradation due to the polarization mode dispersion (PMD). The polarization of the laser light is depolarized at a frequency faster than 60 kHz. The amplified and depolarized optical signal with the 1GHz sidebands is transmitted through a standard single-mode optical fiber from a local site to a remote site. To compensate for an optical loss during the fiber transmission, another EDFA is inserted in the front of a fast photo-detector. Here, the EDFA works as a preamplifier. The amplified optical signal is demodulated and converted to the 1-GHz signal. Without any compensation, the transmitted signal is exposed to a phase noise, ϕ_p, induced during the transmission, with the result that the frequency stability of the 1-GHz signal derived at the remote site is degraded. To quantify how much fiber noise is imposed, a portion of the derived microwave signal modulates another DFB laser at the remote site, and the modulated optical signal is transmitted back to the local site through the same optical fiber. To avoid the interference of colliding laser beams, which degrades the frequency stability, the laser at the separated ITU-grid from the first laser is used for transmission back. The forward and backward beams are distinguished by optical circulators and optical bandpass filters. On the return path, similarly, two EDFAs compensate for the optical signal loss and another polarization scrambler depolarizes the second laser. The return optical signal is inserted into the fast photo-detector to convert it into the 1-GHz signal at the local site. Supposing the phase noise induced in the return path is equal to that induced in the forward path, the round-trip signal exhibits double of one-way fiber noise, $2\phi_p$. This round-trip signal $\omega + \phi_o + 2\phi_p$ derived at the local site is used for fiber noise cancellation.

Figure 2 shows the electrical compensation system. A dual-mixing time difference (DMTD) technique, where simultaneous down-conversion of two signals with a common reference makes it possible to enlarge the phase noise and improve the resolution of the measurement, is often used for precise phase measurement of RF signals. In fact, we evaluate the 1-GHz transmitted signals with our DMTD measurement system, which has a noise floor of 4×10^{-15} and 3×10^{-18} for averaging times of 1 and 10,000 s at 1 GHz, respectively **[13]**. We employ this DMTD technique on the electrical compensation system, too. Both the 1-GHz signal based on the VCXO $\omega + \phi_o$ and the 1-GHz reference $\omega + \phi_{ref}$ are down-converted to 900 MHz by a common 100-MHz IF signal $\omega_{IF} + \phi_{IF}$. The down-converted signals are expressed as $\omega - \omega_{IF} + \phi_o - \phi_{IF}$ and $\omega - \omega_{IF} + \phi_{ref} - \phi_{IF}$. These 900-MHz signals are mixed with the 1GHz reference $\omega + \phi_{ref}$ and the 1GHz round-trip signal $\omega + \phi_o + 2\phi_p$, respectively, and down-converted to the 100-MHz signals, which are represented as $\omega_{IF} + \phi_{ref} - \phi_o + \phi_{IF}$ and $\omega_{IF} + \phi_o + 2\phi_p - \phi_{ref} + \phi_{IF}$. By feeding back the error signal obtained by mixing these 100-MHz signals to the VCXO, the following equation is satisfied:

$$\phi_o + \phi_p = \phi_{ref} \tag{1}$$

Thus, the phase of the transmitted signal derived at the remote site becomes equal to that of the reference at the local site. In this way, the phase coherence of the reference is transmitted to the remote site. The bandwidth of the feedback loop is limited by the propagation time τ of the transmission thorough optical fiber link. For example, in the 100-km fiber link, the maximum cut-off frequency is about 160 Hz. To achieve high stability in the short term under this limitation, a low-phase-noise VCXO is used in our system; the phase noise is -130 dBc/Hz at a 100-Hz frequency offset.

PROVING TEST WITH A 150-KM SPOOLED FIBER

For a laboratory test, the frequency dissemination through a 150-km spooled optical fiber was performed. The total optical loss of the 150-km spooled fiber is -40 dB. Since both local and remote sites were placed in the same room, the phase difference between the signals before and after transmission through the 150-km fiber and that before and after the round trip were simultaneously evaluated. When the phase compensation works properly, equation (1) is satisfied, and the phase of the 1-GHz signal transmitted to the remote site becomes $\phi_{remote} = \phi_o + \phi_p = \phi_{ref}$, whereas the phase of the round-trip signal is expressed as $\phi_{round\text{-}trip} = \phi_o + 2\phi_p = \phi_{ref} + \phi_p$. Thus, the one-way fiber noise ϕ_p is left in the round-trip signal, which is equivalent to the imposed fiber noise in a free-running condition (no phase compensation). Optical fiber is susceptible to the environment: vibration, temperature variation, etc. Especially, the behavior of a laid-down optical fiber link depends on the weather on the measurement day. It is important to measure both the transmitted and the round-trip signals simultaneously for validity check of the compensation system.

Fig. 3 (a) and (b) show the phase differences and frequency stabilities of the transmitted and the round-trip signals relative to the reference signal, respectively. As mentioned above, the round-trip signal with proper compensation represents the behavior of a free-running link. The phase of the transmitted signal was shifted 500 ps during 17 hours of measurement time without any compensation. It was because the 150-km fiber length varied due to the temperature change. However, with the active phase compensation, it can be seen that the phase drift was well suppressed. A transfer stability of 2×10^{-17} at an averaging time of 10,000 s was achieved with a measurement bandwidth of 5 Hz. The short-term stability might be limited by the narrow bandwidth of the feedback loop.

RF TRANSFER IN 114-KM OPTICAL FIBER LINK

NICT provides an open testbed network named the Japan Gigabit Network 2 plus (JGN2 plus), which is aimed at conducting R&D on information and communications technology **[15]**. An optical testbed link consists of urban telecom optical fiber links between NICT's Koganei headquarters and Hakusan station in the Tokyo area. It is established by interconnecting several different sections of single-mode fibers and neither amplifier nor switch is included there. The fiber length between NICT's Koganei headquarters and Hakusan station is 57 km. Connecting two parallel 57-km optical dark fibers at Hakusan station, we performed the RF transfer with the 114-km fiber link. The total optical loss of the 114-km link is -42 dB. To measure the transfer stability, both local and remote sites were placed at NICT's Koganei headquarters.

Figure 4 shows the results of the 114-km transfer. Fig. 4 (a) shows the phase-noise spectrum density. With phase compensation, the phase noise was reduced 30 dB. A bump at around 200 Hz was due to the cut-off frequency of the feedback loop. The phase variations, frequency deviations, and frequency stabilities are shown in Fig. 4 (b), (c), and (d), respectively. It is clearly seen that the phase of the transmitted signal in a free-running link had a diurnal variation and the amount of phase variation was 60 ns per a half day. It corresponded to the fiber length variation of more than 1 m per hour. And the frequency deviations indicate that the fiber link receives much noise in the daytime. Applying our compensation system to this noisy link, the phase drift and the frequency deviation of the 1-GHz transmitted signal were well suppressed. The transfer stability with phase compensation was much higher than that without compensation. The suppression ratio reached up to 40 dB in the long term. Thanks to the noisy link, we have confirmed that our electrical compensation system has a high cancellation ratio of 40 dB, which is higher than the result previously reported in **[6]**. However, strictly speaking, the diurnal phase variation of a few ps was still remained, although the compensation worked, which is seen in Fig.4 (b). It was because the fiber noise originated from the free-running link was significantly large and the 40-dB compensation was not sufficient for this link. Compared with LNE-SYRTE's result in the 86-km fiber link **[7]**, which is plotted in Fig. 4(d), our JGN2 plus link in a free-running condition was much noisier. Typically, the transfer stability of our link is several orders of magnitude larger than other reports **[8-10]**. The large phase variation is attributed to the fact that more than 50% of the parts among our link are exposed to the air and much influenced by the air temperature change in Tokyo. It is considered that if we use a deeply buried fiber link, the fiber noise will be completely cancelled out by our 40-dB electrical cancellation system.

To compensate the residual phase fluctuation, we have added a temperature control system to the electrical noise cancellation system. The modified RF transfer system is shown in Figure 5. We prepared an additional laser at the local site and a temperature-controllable 60-m fiber at the remote site. The additional laser is used for a transmission of the 1-GHz reference. Comparing this transmitted signal and the electrical phase-compensated signal (the 40-dB suppressed signal), it is possible to quantify one-way fiber noise at the remote site. By monitoring the large phase variation and controlling the temperature of the 60-m fiber, the remained phase variation is suppressed. This temperature feedback loop was closed within the remote site, which is available in the case that the remote site is far from the local site. Fig. 5 (a) and (b) show the results of the modified RF transfer in the 114-km link. Combining the electrical compensation and the temperature compensation, a transfer stability of 3×10^{-18} at a 200,000-s averaging time was observed. So far, we have achieved a phase cancellation ratio of 45 dB. The parameter search for the temperature control has been continued; thus, there is a possibility to improving the long-term stability more. And we have confirmed that our compensation system worked continuously for more than 1 week without any phase jump due to cycle slips or any unlocking due to abrupt changes, although the JGN2 plus 114-km link was clearly noisy. This alignment-free system will become a powerful tool for long-term comparison of clocks.

CONCLUSION

We have developed an RF distribution system through optical fiber for the purpose of the transfer of an ultra-stable reference, as well as the remote comparison of optical clocks. The RF transfer in the JGN2 plus 114-km optical fiber link was performed, in which with the electrical phase compensation system with the VCXO, 40-dB phase suppression at the averaging time of 10,000 s was obtained and the transfer stability in the 10^{-18} level at an averaging time of 1 day was achieved with a combination of the electrical and the temperature compensations.

The transmittable distance of stable fiber dissemination is limited by many factors; optical loss, fiber length fluctuation, a cut-off frequency of the servo loop, dispersion noise of fiber link, and so on. The EDFA can compensate the optical loss; however, the usage near the amplified spontaneous emission (ASE) noise level of the amplifier degrades the frequency stability. And,high-power insertion into the fiber generates the SBS, which also degrades the stability. The longer the fiber length is, the lower the cut-off frequency of the compensation loop is. The narrow bandwidth becomes one of the reasons to limit the short-term stability. The chromatic dispersion and the PMD also will be real and substantial problems in a long-haul fiber link. One of the solutions to overcome these difficulties is a cascade configuration. By cascading the compensation systems, it is possible to extend the distribution distance. Naturally, the transfer stability degrades by a factor of the square root of the number of cascaded systems; nevertheless, it is highly likely that it has a still higher transfer stability than the conventional satellite link.

ACKNOWLEDGMENT

The authors would like to thank S. Nagano at NICT for technical support of the compensation system and K. Nakamura at NICT for arrangement of the JGN2 plus optical fiber link.

REFERENCES

[1] T. Rosenband, *et al.*, 2008, "*Frequency ratio of Al^+ and Hg^+ single-ion optical clocks; Metrology at the 17th decimal place,*" **Science**, **319**, 1808-1812.

[2] A. D. Ludlow, *et al.*, 2008, "*Sr lattice clock at1×10^{-16} fractional uncertainty by remote optical evaluation with a Ca clock,*" **Science**, **319**, 1805-1808.

[3] A. Bauch *et al.*, 2006 "*Comparison between frequency standards in Europe and the USA at the 10-15 uncertainty level,*" **Metrologia**, **43**, 109-120.

[4] H. Kiuchi, T. Kawanishi, M. Yamada, T. Sakamoto, M. Tsuchiya, J. Amagai, and M. Izutsu, 2007 "*High Extinction Ratio Mach-Zehnder Modulator Applied to a Highly Stable Optical Signal Generator,*" **IEEE Transactions on Microwave Theory and Techniques**, **55**, 1964-1972.

[5] J. Frisch, D. Bernstein, D. Brown, and E. Cisneros, 2001, "*A High Stability, Low noise RF Distribution System,*" in Proceedings of the 2001 Particle Accelerator Conference (PAC), 19-22 June 2001, Chicago, Illinois, USA (IEEE Publication), **Vol. 2,** pp. 816-818.

[6] F. Narbonneau, M. Lours, S. Bize, A. Clairon, G. Santarelli, O. Lopez, C. Daussy, A. Amy-Klein, and C. Chardonnet, 2006, "*High resolution frequency standard dissemination via optical fiber metropolitan network,*" **Review of Scientific Instruments**, **77**, 064701.

[7] O. Lopez, A. Amy-Klein, C. Daussy, C. Chardonnet, F. Narbonneau, M. Lours, and G. Santarelli, 2008, "*86-km optical link with a resolution of 2×10^{-18} for RF frequency transfer,*" **European Physical Journal D**, **48**, 35-41.

[8] S. M. Foreman, A. D. Ludlow, M. H. G. de Miranca, J. E. Stalnaker, and S. A. Diddams, 2007, "*Coherent optical phase transfer over a 32-km fiber with 1s instability at 10^{-17},*" **Physical Review Letters**, **99**, 153601.

[9] P. A. Williams, W. C. Swan, and N. R. Newbury, 2008, "*High-stability transfer of an optical frequency over long fiber-optic links,*" **Journal of the Optical Society of America B**, **28**, 1284-1293.

[10] G. Grosche, B. Lipphardt, H. Schnatz, G. Santarelli, P. Lemonde, S. Bize, M. Lours, F. Narbonneau,

A. Clairon, O. Lopez, A. Amy-Klein, and C. Chardonnet, 2007, "*Transmission of an optical carrier frequency over a telecommunication fiber link,*" in Proceedings of the Conference on Lasers and Electro-Optics (CLEO), 6-11 May 2007, Baltimore, Maryland, USA, 1-2, 10.1109/ CLEO.2007.4452577.

[11] M. Kumagai, H. Ito, M. Kajita, and M. Hosokawa, 2008, "*Evaluation of caesium atomic fountain NICT-CsF1,*" **Metrologia**, **45**, 139-148.

[12] M. Kumagai, H. Ito, G. Santarelli, C. Locke, J. Hartnett, and M. Hosokawa, 2008, "*Development of Synthesis Chains Based on Cryogenic Sapphire Oscillator,*" in Proceedings of the 2008 IEEE International Frequency Control Symposium (FCS) Jointly with the 22nd European Frequency and Time Forum (EFTF), 19-21 May 2008, Honolulu, Hawaii, USA (IEEE Publication CFP08FRE-CDR), pp. 576-580.

[13] M. Fujieda, M. Kumagai, T. Gotoh, and M. Hosokawa, 2007, "*First experiment of ultra stable frequency transfer system via optical fiber in NICT,*" in Proceedings of TimeNav'07, IEEE Frequency Control Symposium (FCS) Joint with the 21st European Frequency and Time Forum (EFTF), 30 May-June 1 2007, Geneva, Switzerland (IEEE Publication 07CH37839), pp. 840-846.

[14] M. Fujieda, M. Kumagai, T. Gotoh, and M. Hosokawa, 2008, "*Ultra-stable Frequency Dissemination via Optical Fiber at NICT,*" **IEEE Transactions on Instrumentation and Measurement, 58,** in press.

[15] Japan Gigabit Network 2 plus, *http://www.jgn.nict.go.jp/jgn2plus/english/index.html*

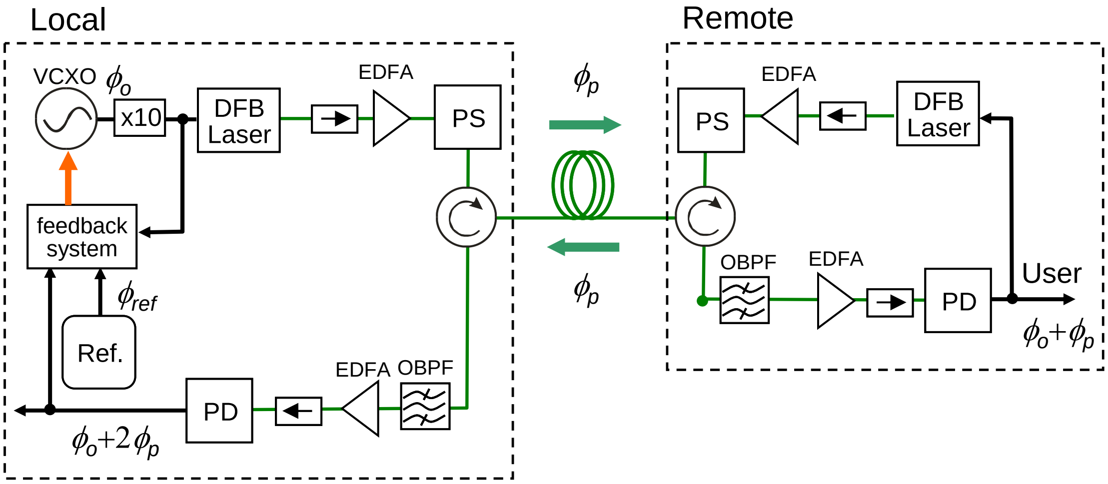

Figure 1. Schematic of RF distribution system using optical fiber link. PS: polarization scrambler, OBPF: Optical bandpass filter, PD: photo detector.

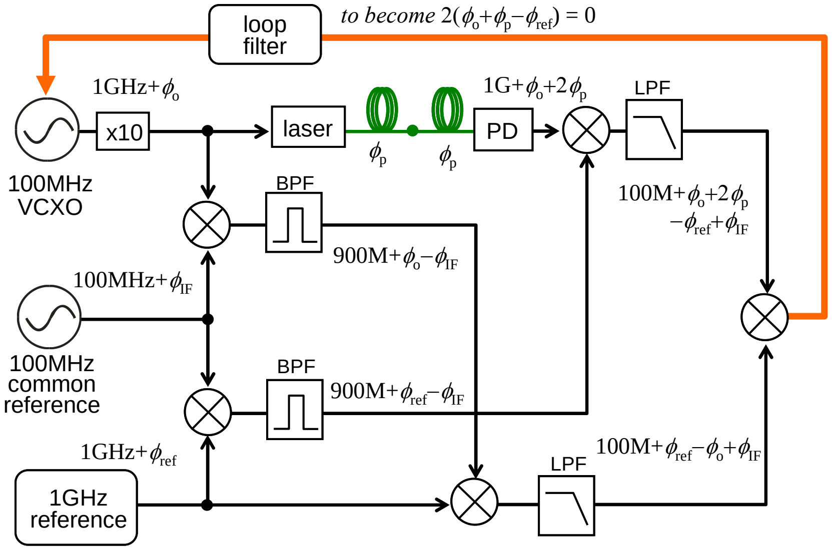

Figure 2. Schematic diagram of electrical phase compensation system for 1-GHz distribution. BPF: band-pass filter, LPF: low-pass filter.

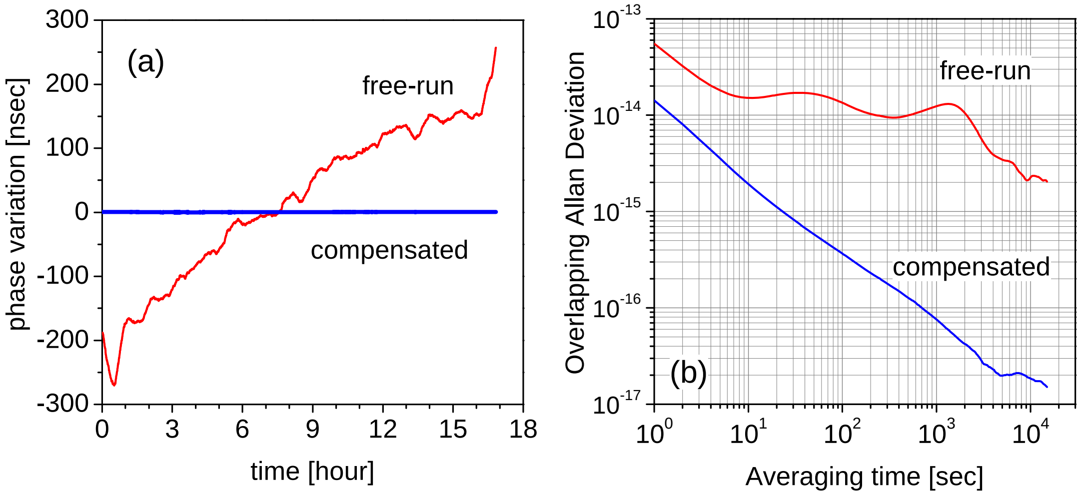

Figure 3. Proving test using 150-km spooled fiber. (a) phase variance of transmitted signal in free-running and compensated conditions; (b) transfer stabilities.

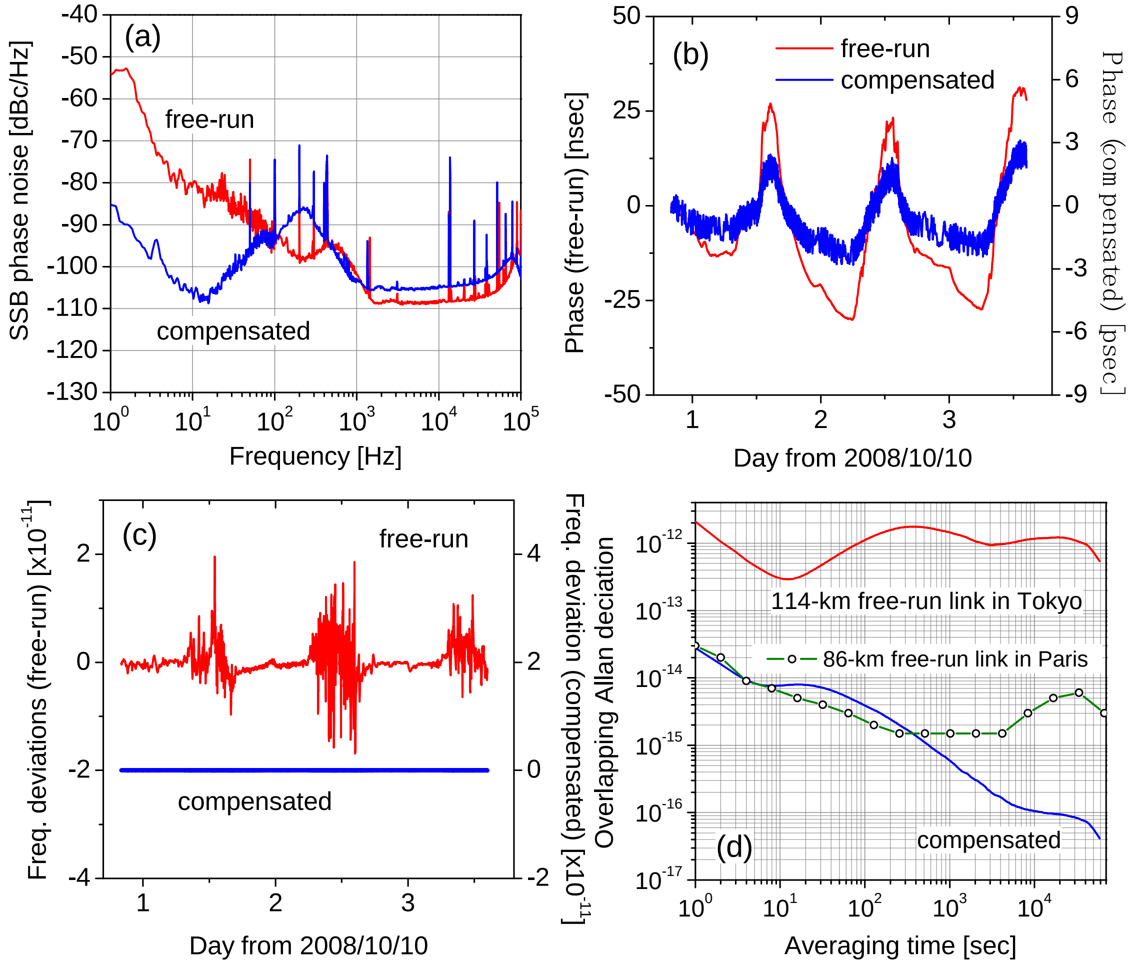

Figure 4. Results of RF dissemination through JGN-2 plus 114-km fiber link in Tokyo. (a) Phase noise spectral density of free-running and compensated link, (b) phase variance, (c) frequency deviations, and (d) transfer stabilities including LNE-SYRTE 86-km free-run link **[7]**.

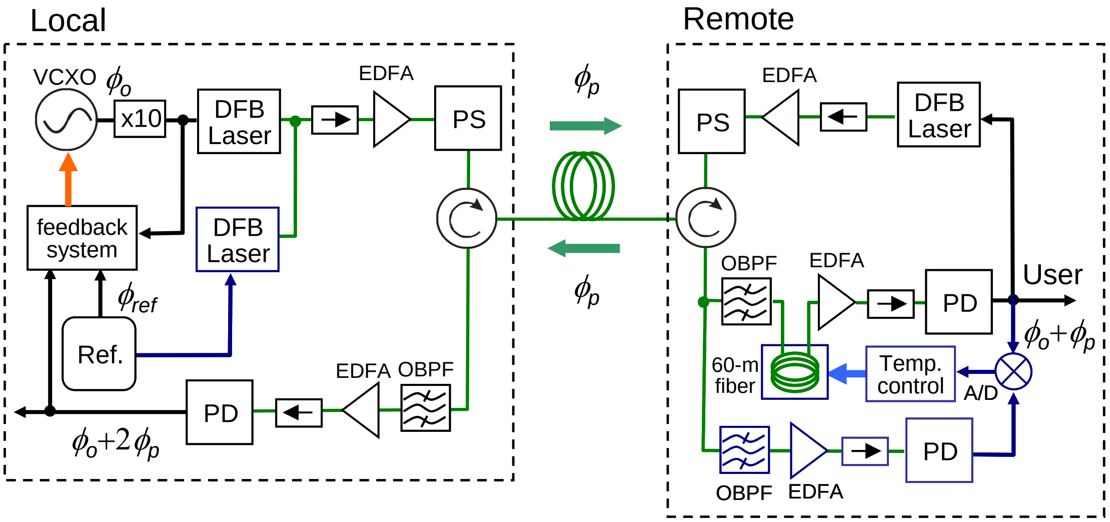

Figure 5. Schematic of modified RF distribution system including temperature-control compensation.

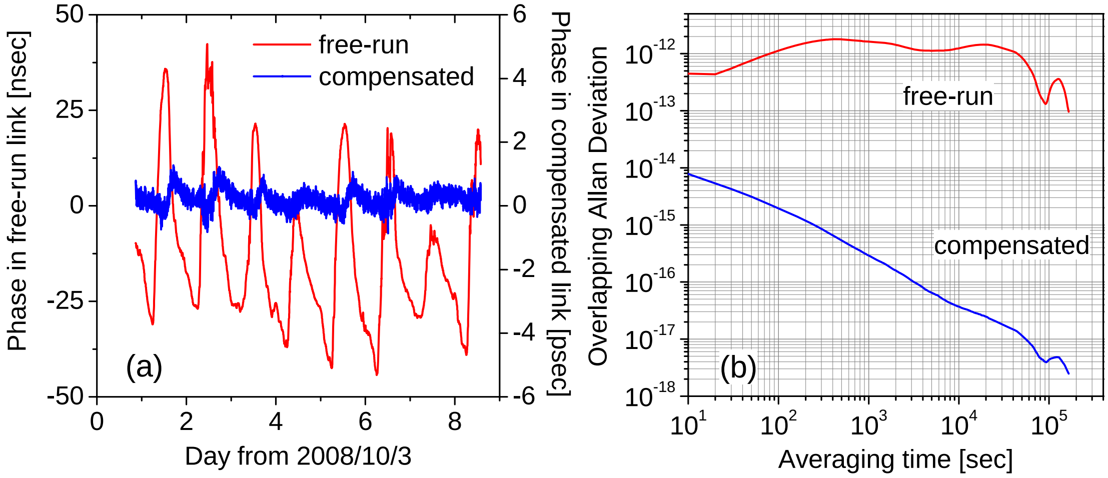

Figure 6. 114-km transfer results with electrical and temperature compensations. (a) phase variations and (b) transfer stabilities.