4-3 Frequency Transfer Using Optical Fibers

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Frequency transfer using optical fibers is one of candedates which realizes preise frequency dissemination without degradation of stability of optical frequency standards. In this report, the RF transfer system and optical carrier transfer system developed in NICT are introduced.

Keywords
Optical frequency standard, Frequency transfer, Optical fiber

1 Introduction

In recent years, remarkable progress has been made in optical frequency standards[1]-[4]. In order to verify the accuracy of frequency standards, it is necessary to compare values with those of the standards provided by other institutes, and to prove the validity. However, since the preexisting frequency comparison methods via satellites have only the stability of the comparison in itself that is extremely inferior to those of the standards[5], there has been a demand for development of an alternative high-precision frequency transfer method. A high-precision frequency transfer via optical fiber has proved a leading candidate. Compared with preexisting methods that transmit through the atmosphere, transmission through optical fiber has less error causes, which allows for highly precise transfer. In addition, the transfer distance can be extended to greater degree than with coaxial cable on account of low signal loss. Moreover, this method which transmits the signal itself allows for signal dissemination to users who do not have expensive frequency standards. For these reasons, it is actively developed not only as a method for comparison of frequency standards, but also as a method for providing standard signals to linear accelerators, VLBI array antennas and other equipment[6][7].

Three methods can be considered for frequency transfer via optical fibers: 1. RF transfer, 2. Optical frequency transfer, and 3. Optical frequency comb transfer[8]-[18]. In method 1, the light modulated by an RF signal is transmitted. In method 2, the light itself is transmitted, by which the most precise results are currently achieved. An optical frequency comb is a frequency ruler in optical region, and is widely used for optical frequency measurement[19]. In method 3, these optical frequency combs are transmitted. With the gaps between the teeth of the comb, optical frequency comb allows for dissemination of both the light itself and RF signal to users. This is considered difficult because not only the physical length of the optical fiber but also the wavelength dispersion must be constantly stabilized.

NICT first started development on the RF transfer system from method 1, and has achieved some significant results[20]-[22]. Next, the optical frequency transfer system from method 2 is under development aimed at highly precise transfer and direct comparison of optical frequency standards. In this paper, we introduce the outlines and results of these various methods.

2 Frequency transfer

2.1 RF transfer system

In general, the RF signal transfer system sends through a dark fiber an optical signal modulated with an RF signal in a laser current, detects the optical signal by the photo detector at the destination, and extracts the RF signal[9][17][18][20]-[22]. The frequency stability of the RF signal extracted at the destination is degraded from that of the original RF signal due to the length variations of the optical fibers that is caused by temperature or pressure changes, and to phase noise that is experienced during transmission. Therefore, if one wants to transmit a highly stable signal, they need a mechanism to maintain the optical fiber at a fixed length and cancel out the accumulated phase noise. Cancellation of the phase noise is performed by using the light which is first sent to the destination, then sent back through the same optical fiber, and thus returned. One can consider as to how to accomplish this procedure: an electrical cancellation method where the error signal is returned to a VCXO (voltage controlled crystal oscillator) and an optical method where a controllable delay line is introduced. Since the latter has a limitation about the variable length range, it is necessary to beforehand estimate the length change in the optical fiber link. In contrast, the former method does not have such limitation. Regarding this electrical cancellation method, various measures have been tried out as to how to synchronize the transmitted RF signal with the reference signal. At the LNE-SYRTE in France, cancellation has been successfully achieved by using different RF frequencies for the modulation of the going and returning lights[9]. Figure 1 shows the RF transfer system developed at NICT. This system enables 1 GHz or 10 GHz signal transfer, where the transmitted and received RF signals are the same frequency. It applies a communication band of 1.5 μm for laser wavelength, uses a single mode optical fiber for optical fiber, and adopts the method of electrically canceling the phase noise. Details for the system are provided in the following paragraph.

The 100 MHz signal from the VCXO is converted to 1 GHz using a multiply-by-ten frequency multiplier. The VCXO with a low

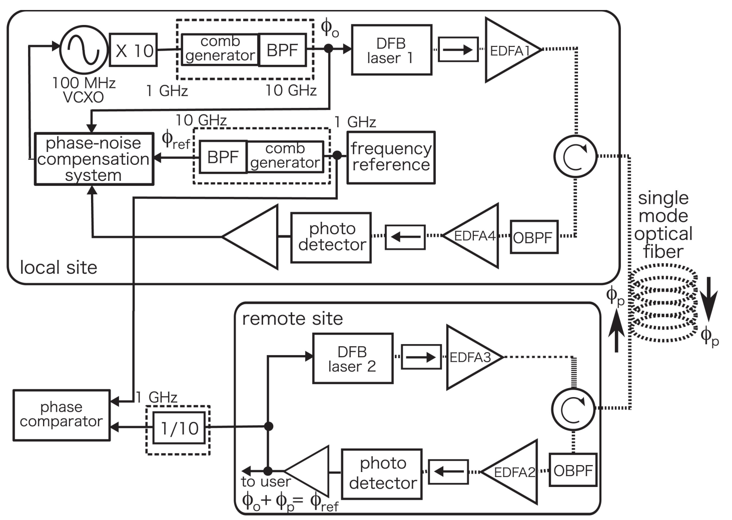

Fig.1 *Schematic for the 1 GHz, 10 GHz signal transfer system*

BPF: band-pass filter, OBPF: optical band-pass filter, DFB laser: distributed feedback laser, EDFA: erbium-doped fiber amplifier. “×10” and “1/10” indicate a multiply-by-ten frequency multiplier and a divided-by-ten prescaler. EDFA1 and EDFA3 are used as amps and EDFA2 and EDFA 4 are used as preamps. The equipment in the dashed lines is not used for 1 GHz signal transfer.

phase noise of approximately −150 dBc/Hz for a 1 kHz offset is adopted in order to maintain the purity of the RF signal after transmission. For transfer of a 10 GHz signal, the resultant 1 GHz signal is further input into a comb generator, and thus 10 GHz signal is clipped out through a bandpass filter to be used as the RF signal source. Modulate the current of DFB laser 1 (distributed feedback laser) with this RF signal; then, a CW (continuous wave) optical signal with AM and some FM is generated by the DFB laser. Having been first amplified by an EDFA (Erbium doped fiber amplifier), the light is transmitted through an optical circulator to differentiate both-way light. In this document, the site from which the light is emitted is referred to as the local site and the destination as the remote site. The light transmitted to the remote site first passes through an optical circulator, takes amplification on an EDFA, and then enters the fast photo detector. The detected RF signal passes through the amplifier to be provided for the user. A portion of the detected RF signal modulates the current of DFB laser 2. This optical signal is sent from the remote site back to the local site through the same optical fiber. The wavelength of DFB laser 2 is separated from that of DFB laser 1 by 50 GHz in order to prevent light interference. At the local site, the light that has passed through the optical circulator and taken amplification with the EDFA is detected by a fast photo detector, and then the RF signal is extracted. That signal is sent to the phase noise cancellation system, and makes comparison with the reference signal and returns an error signal to the VCXO. This leads to the cancellation of the phase noise that was accumulated during transmission, and secures the same stability as the reference signal of the local site for the RF signal that is transmitted to the remote site. The schematic of the phase noise cancellation system we have developed is shown in Fig. 2. Here, as well as with the DMTD (dual mixer time difference), a shared IF signal is used to cancel the phase noise. The original RF signal generated by the VCXO: $\omega t+\phi_0$, and the reference signal phase: $\omega t+\phi_{ref}$, having been down-converted by IF signal $\omega_{if}\,t+\phi$, are mixed respectively with the reference signal and the RF signal that has been transmitted back to the local site via optical fiber, and then converted to $\omega_{if}t+\phi-\phi_0+\phi_{ref}$ signal and $\omega_{if}t+\phi+\phi_0+2\phi_p-\phi_{ref}$ signal. In this process, the optical fiber is assumed to experience equal phase noise over the both-way transmission path, and is therefore indicated as ϕ_p. Furthermore, the mixture of these two signals results in the phase noise 2 $(\phi_{ref}-\phi_0-\phi_p)$. Feeding this signal back to the VCXO derives the following equation:

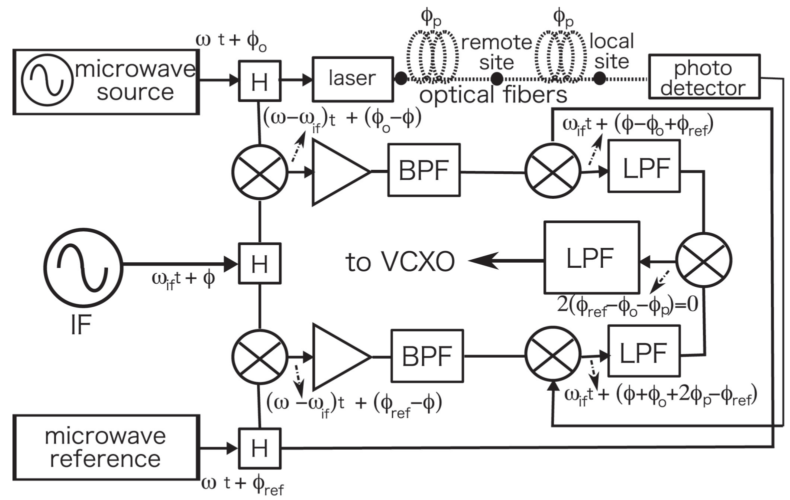

Fig.2 *Schematic of electrical cancellation system for phase noise*

H: power divider, LPF: low-pass filter

$$\phi_{remote} = \phi_0 + \phi_p = \phi_{ref} \qquad (1)$$

Specifically, the stability of the signal sent to the remote site becomes equivalent to that of the reference signal. Since evaluation of the transmission system necessitates comparison between signals before and after transmission, the remote and local sites are set up at the same location. Then, the phases of the reference signal and the transmitted RF signal are compared with each other, through which transmission stability is evaluated.

In the above paragraph, we introduced the RF transfer system developed by NICT. We adopt 1 GHz or 10 GHz signal as the frequency for modulation of the laser. Additionally it is possible to offer the 10 MHz signal by dividing the transmitted 1 GHz signal by a 1/100 prescaler[24]. This is because, in case of the modulation frequency being under 100 MHz, the phase resolution was not sufficient, and thus a transmission stability in the 10^{-14} level was not achieved. Still, we can flexibly select frequencies taking into account the frequency and stability of the signal required at the remote site. Furthermore, RF transfer does not require a narrow-linewidth laser because the RF transmission is performed by the detuned sideband of the optical signal.

2.2 System for optical frequency transfer

In optical frequency transfer, the CW laser light itself is transmitted[10]-[16]. Since this enables signal transfer at a high precision in a short amount of time, systems for it are under active development at research institutes in the US and Europe. Owing to the double-pass function of an Acousto-optic modulator (AOM), the phase noise of the light transmitted to the remote site occupies the half of that of round trip light, which can prepare a simpler structure than an RF transfer system. The majority of systems being under development employ AOM to conduce to few structural differences, with minute differences such as where to install the optical amplifier or how much frequency shift to set. Figure 3 shows the system for optical frequency transfer being under development at NICT. The light source must maintain coherence before and after transmission. For this reason, a transmission of over 100 km needs a narrow-linewidth light source of approximately 2 kHz. This system applies the 1.5 μm fiber laser with a narrow linewidth as the reference light source. The light from the laser passes through the optical circulator and is input into the first AOM. This AOM is driven by the VCO (Voltage controlled oscillator) of 100 MHz, and the light frequency is shifted by −100 MHz. Thereafter, the light is sent from the local site to the remote site through a single

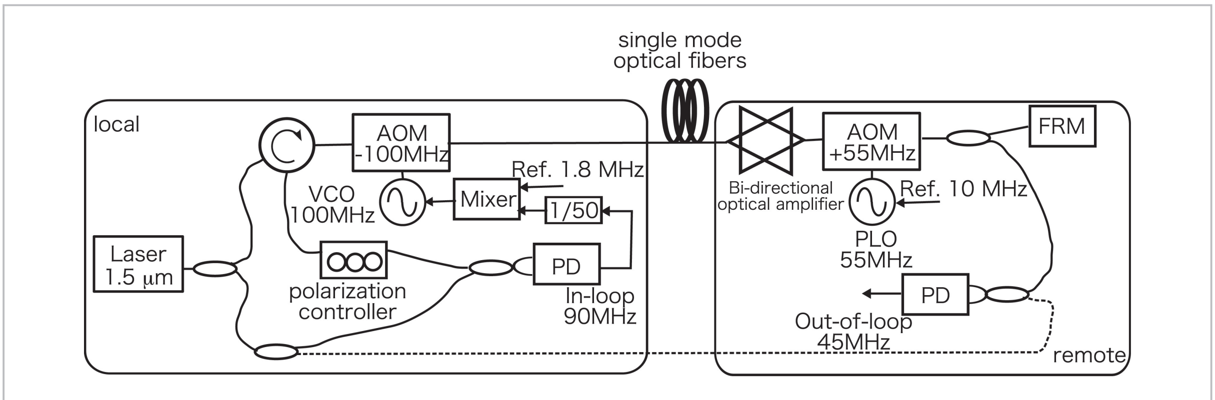

Fig.3 *Schematic for optical frequency transfer system*

AOM: Acousto optic modulator, FRM: Faraday rotator mirror, PD: Phase detector, PLO: Phase locked oscillator, VCO: Voltage controlled oscillator mode optical fiber. For the compensation of optical loss at the remote site, a bidirectional optical amplifier is installed. The light is then input into the second AOM. This AOM is driven by the PLO (Phase locked oscillator) of 55 MHz that is synchronized to a 10 MHz signal from an atomic clock available at the remote site. Thereafter, the light is divided in two by an optical divider; one is provided to users, and the other is reflected by an FRM (Faraday rotator mirror) to be returned to the local site through the same single mode fiber. The returned light is distinguished from the transmitted light by the optical circulator, thus extracted, then combined with the reference light, and its heterodyne signal is detected by the photo detector. This system composes an interferometer whose one arm consists of a long-distance single-mode fiber, and the detected signal is called the In-loop beat signal. In this system, the returned light undergoes a frequency shift of −100 + 55 + 55−100 =−90 MHz the beat signal becomes a signal of 90 MHz. This signal is divided-by-50 and mixed with a local signal of 1.8 MHz. By feeding the obtained error signal back into the VCO, the phase noise experienced in the transmission and return paths is cancelled to make the light transmitted to the remote site coherent to the reference light. The details of how to cancel the phase noise are explained below.

Let $\omega_0 t+\phi_0$ denote laser light, $\omega_1 t+\phi_1$ and $\omega_2 t+\phi_2$ frequency shift experienced by the first and second AOMs, and ϕ_p the phase noise accumulated in the transmission path. Here, assume that the phase noise experienced on the optical fiber is equal both for going and returning. Then, the light transmitted from the local sight becomes $(\omega_0+\omega_1)t+\phi_0+\phi_1$, and can be expressed as $(\omega_0+\omega_1+\omega_2)t+\phi_0+\phi_1+\phi_p+\phi_2$ before the remote site FRM. This light again returns to the local site through the second AOM, single mode optical fiber and the first AOM. Since the reference light $\omega_0 t+\phi_0$ and the returned light $(\omega_0+2\omega_1+2\omega_2)t+\phi_0+2(\phi_1+\phi_p+\phi_2)$ are mixed before the local site PD, the detected heterodyne signal is $2(\omega_1+\omega_2)t+2(\phi_1+\phi_p+\phi_2)$. This signal is mixed with the local signal $2(\omega_1+\omega_2)t+\phi_{lo}$. By feeding the error signal back to the VCO, the following equation is achieved:

$$\phi_1+\phi_p+\phi_2-1/2\,\phi_{lo}=0 \tag{2}$$

Since the ϕ_{lo} is here synchronized with a reference signal such as a hydrogen maser that can be used in the laboratory, its fluctuation can be considered nearly zero in comparison with ϕ_p. Specifically, the light sent to the remote site can be expressed as:

$$\begin{aligned}&(\omega_0+\omega_1+\omega_2)t+\phi_0+\phi_1+\phi_p+\phi_2\\&=(\omega_0+\omega_1+\omega_2)t+\phi_0+1/2\,\phi_{lo}\end{aligned} \tag{3}$$

$$\fallingdotseq(\omega_0+\omega_1+\omega_2)t+\phi_0 \tag{4}$$

Thus, the phase noise experienced during the transmission is cancelled to maintain the original stability. Optical frequency transfer system should be evaluated likewise with both the local and remote sites installed in the same location. Combining the transmitted light with the reference light, detecting its heterodyne signal by the photo detector, and measuring the frequency, we can evaluate the precision of the transmitted light.

The transmitted light itself is provided for users in the optical frequency transfer system. Therefore, for the convenience of users who need the RF signal, an optical comb at the remote site is necessary to convert the optical frequency to the RF. It can be said that the optical frequency transfer system is suitable for cases such as one requires the light whose wavelength is calibrated or one attempts to compare optical frequency standards. While it has a simpler structure compared with an RF transfer system, a narrow-linewidth laser is necessary to maintain coherence at the destination; thus it is more expensive than with RF transfer as far as the laser is concerned. In the optical frequency transfer, on the other hand, since the phase noise carried by the light can be traced as it is to the RF signal by heterodyne detection, it is admissible that the RF signal has even as poor stability as the frequency ratio of approximately 10^6 times between the light and RF. It can be said that such a large frequency ratio leads to the high precision of the optical frequency transfer. For example, if the AOM drive signal is stabilized at the approximately 10^{-12} level, a stability in the 10^{-18} level can be achieved in the optical region around the passage through the AOM. For this reason, the phase noise of the RF signal source that drives the AOM is sufficient at approximately −80 dBc/Hz at a 1 kHz offset and accordingly can be purchased at a low price. Furthermore, since there is no need to control the RF signal with high precision thanks to the frequency ratio, we can beneficially obtain the high transmission stability with relative ease without any special care taken in the cabling or handling of connectors.

2.3 JGN2plus optical fiber link

NICT operates the optical testbed JGN2plus (Japan Gigabit Network 2 plus) for the purpose of promoting the research of new generation networks[23]. As part of this, a test bed is provided using a low-loss optical fiber link, which connects together NICT Koganei, Otemachi and Hakusan. We carried out verification experiments with the use of the JGN2plus optical fiber link in order to demonstrate transmission on an optical network installed in an urban area. The connections of the optical fiber link put in use for the experiments are shown in Fig. 4. The lengths of optical fiber links used were 114 km with an optical loss of approximately 40 dB and 90 km at 30 dB. These optical fiber links are known to have an extremely large amount of phase noise. One of the reasons for this may be that approximately half of the link is installed in the open air, which presumably causes a large amount of phase noise. The remaining portions seem to be installed alongside subway lines, which makes us assume that train operations would also have some effect.

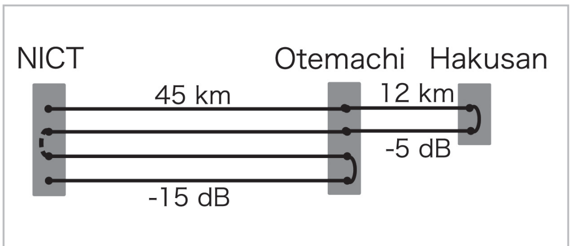

Fig.4 Schematic of optical fiber link connecting NICT Koganei, Otemachi and Hakusan

2.4 Results for verification experiments

Verification experiments for frequency transfer systems were carried out on the JGN2plus optical fiber link. So was RF transfer experiment on a 114 km link connecting NICT, Otemachi and Hakusan, and optical frequency transfer experiments on a 90 km link connecting NICT and Otemachi.

For evaluation of the signal after transmission, the local site and the remote site were both placed in the same laboratory, and comparisons were performed between the signal serving as the RF reference and the transmitted signal, and between reference light and the transferred light. Figure 5 shows the results of phase noise measurements, and Fig. 6 shows the frequency stabilities. (a) is the results with the RF transfer of 1 GHz signal, and (b) the results for the optical frequency transfer of 1.5 μm light . “Free run” indicates the results without feedback of phase noise, and “Stabilized” the results with feedback. RF transfer has achieved a phase noise cancellation of approximately 32 dB, and optical frequency transfer approximately 56 dB. The latter, in particular, has reached the theoretical limit determined by the delay of the light going and returning[10]. Frequency stability was measured by a phase comparator for RF transfer and a Π type frequency counter for optical frequency transfer. As for the stability of “Free run”, RF transfer has shown an improvement of approximately 15 dB, and optical frequency transfer approximately 18dB. RF transfer stability has reached the 10^{-18} level at an averaging time of one day, and optical frequency transfer the 10^{-18} level at an averaging time of 400 seconds. The optical frequency transfer can better cancel phase noise. In RF transfer, it was found that the higher the frequency, the lower the system noise obtained as a result of transfer of 1 GHz and 10 GHz signals[22]. It is supposedly be-

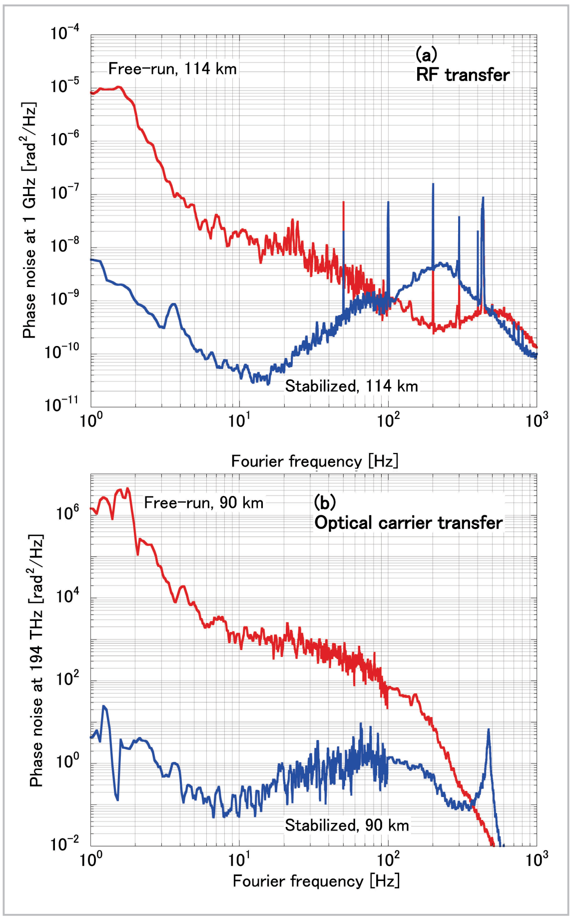

Fig.5 *Results of phase noise measurements on (a) RF transfer and (b) Optical frequency transfer*

(a) shows the phase noise after transmitting a 1 GHz signal over 114 km, and (b) shows optical phase noise after transmitting 1.5 μm light over 90 km.

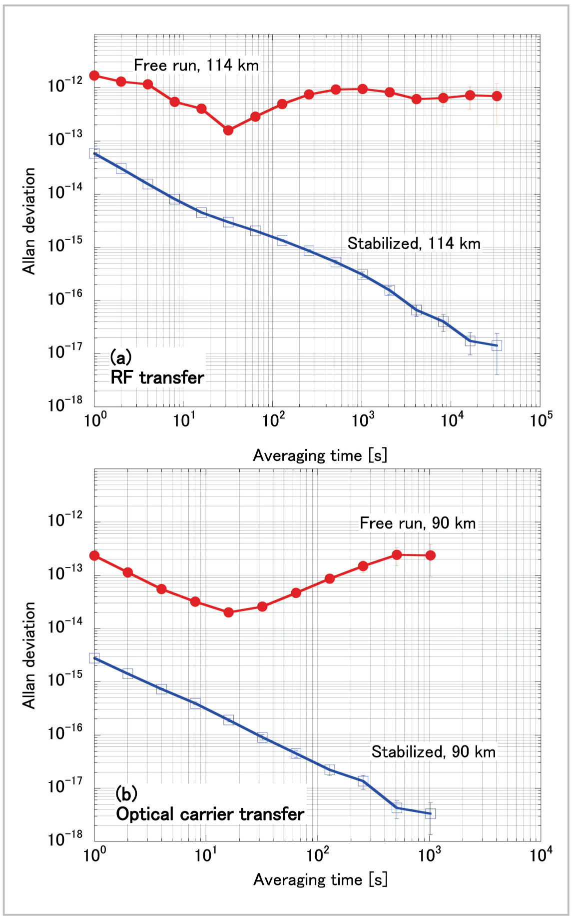

Fig.6 *Frequency stabilities of (a) RF transfer and (b) Optical frequency transfer*

(a) shows the transfer stability after transmitting a 1 GHz signal over 114 km, and (b) shows transfer stability after transmitting 1.5 μm light over 90 km.

cause the phase resolution improves as the frequency increases, allowing for more precise control of the phase. Frequency stability in Fig. 6 (a) is procured by adding an optical delay controller as well as the electrical phase noise cancellation system introduced in **2.1**. See reference [21] for details.

3 Conclusions

This paper introduced the systems of RF transfer and optical frequency transfer by means of optical fibers that facilitates the highly stable transfer of frequency signals. We have been already progressing with development of both systems; RF transfer has so far attained the frequency stability in the 10^{-18} level at an averaging time of one day, and optical frequency transfer in the 10^{-18} level at an averaging time of 400 seconds in verification experiments with optical fiber links installed in Tokyo. With optical frequency transfer, a simpler system could be constructed than with RF transfer owing to AOM, i.e., a frequency shifter that can be used in double pass. This also enables direct comparison between optical frequency standards with higher stability in shorter times. NICT and the University of Tokyo have been linked together by an optical fiber, and embarked on direct comparison of optical frequency standards.

Inasmuch as optical frequency transfer requires an optical frequency comb in order to provide the RF signal from transmitted light, RF transfer is more effective for RF users. In fact, a UTC (NICT) signal is supplied via a 1 km optical fiber to laboratories without a standard signal that are located in the premises of NICT[24]. As seen above, frequency transfer using optical fibers is a validated method for providing users who gain no possession of high-precision frequency standards with signals traceable to the national standard. This system chiefly involves the problem as to how long to potentially extend the transfer distance. Signal loss with optical fiber being taken into account, the maximum distance for one transfer system is considered approximately 150 km. However, connecting multiple systems in series warrants extension of the distance, and even in doing so, transfer stability degradation still remains at root of number of systems. An alternative method is to insert a bidirectional optical amplifier at intermediate points to ensure light permeability. In Germany, such a plan is actually underway as carrying out optical frequency transfer by connecting multiple laboratories and universities and installing bi-directional optical amplifiers in four intermediate points on an optical fiber link of approximately 900 km[25]. This plan estimates the stability for a transfer distance of 1,000 km from the phase noises that are measured in various optical fiber links around the world; the stabilities for 1,000 km transfer are 1×10^{-13} at 1 second and 1×10^{-17} at 10,000 seconds. They still exceed the comparative stability acquired by conventional frequency transfer methods using satellites.

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