Time and Frequency Transfer and Dissemination Methods Using Optical Fiber Network

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***Abstract*—In the time and frequency transfer and dissemination field, it is important to provide cost effective remote frequency calibration services with an uncertainty of around 10^{-12} for end users. It is also required to develop ultra precise transfer methods with an order of 10^{-15} or better uncertainty for the comparison between ultra stable frequency standards which are under developing. This study shows two methods using optical fiber networks to satisfy these demands. First, it is an economical remote calibration method using existing synchronous optical fiber communication networks. The measured frequency stability (the Allan deviation) of the transmission clock is 2×10^{-13} for an averaging time of one day. The result indicates the method is promising for the simple remote frequency calibration service. Second, it is an ultra precise two-way optical fiber time and frequency transfer method using a newly proposed bi-directional optical amplifier. In this method, wavelength division multiplexing (WDM) signals are transmitted along a single optical fiber. The preliminary measured frequency stability is less than 10^{-15} ($\tau=10^4$ s) for a 100-km-long fiber with the bi-directional amplifier. It suggests that the method has capability for improving TAI (International Atomic Time) and UTC (Coordinated Universal Time).**

1. INTRODUCTION

In the traditional calibration services, certified agencies or other clients have to bring their standard-oscillators to NMIJ. For overcoming this inconvenience, NMIJ started the remote calibration service using the GPS common-view method this year [1]. Frequency end users still need much more simple and economical frequency standard distribution. The required uncertainty is roughly 10^{-12}. To meet the demands, we began to study the method using synchronous optical fiber communication networks which are already existing.

Moreover, considering the rapid performance progress of the primary frequency standards, it is also important to study ultra precise time/frequency transfer methods using fibers [2]-[5] in addition to many active and reliable technologies using GPS or communication satellites. It will contribute to improve TAI in a mutually reinforcing way. This paper shows the two methods using optical fiber communication networks and their initial test results.

2. SIMPLE AND ECONOMICAL FREQUENCY SUPPLY METHOD

A. Configurations

To distribute frequency standard as simple and economical as possible, existing synchronous optical fiber communication networks are utilized in the method. The network node clocks (Rb oscillators) are hierarchically synchronized to the master clock (Cs oscillator) through fiber links as shown in the middle of Fig.1. End customers obtain frequency source directly from the transmission clock. The obtained frequency can be traced to UTC (NMIJ) if the master clock of the telecommunication network is synchronized to UTC (NMIJ). This direct dissemination is ideal, however, some negotiations with telecommunication companies will be needed. On the other hand, it is easy to trace the frequency to UTC (NMIJ) by the common-view method as shown in Fig.1.

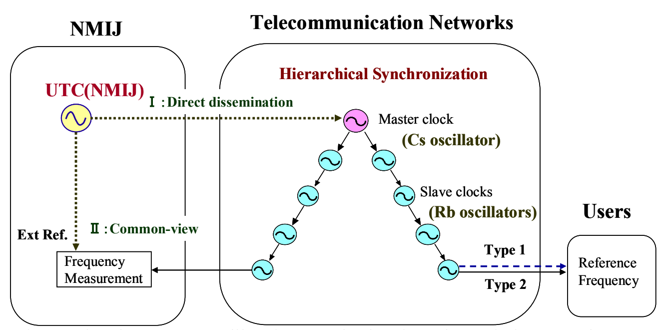

Fig.1. Simple remote calibration method using the existing synchronous optical fiber communication networks.

There can be two types for access system configurations to distribute the frequency standard from access center to user site. Type 1 is the direct distribution. The standard frequency, 5 M or 10 MHz is synthesized at the access center. Therefore users can use the standard frequency directly as shown in Fig.2. Frequency synthesizers are used at user sites in the type 2 configuration.

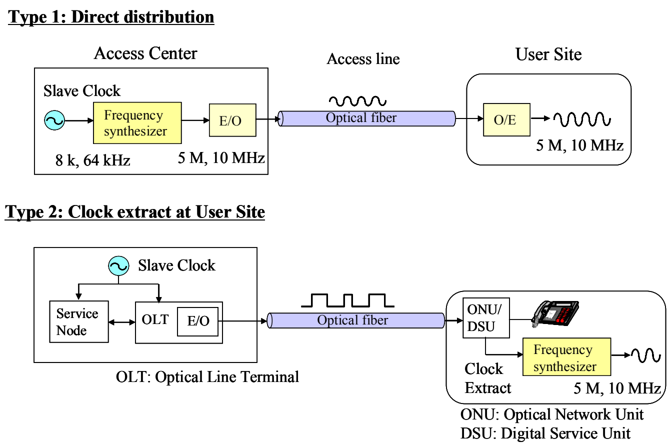

Fig.2. Access System Configurations for Frequency Standard Distribution.

B. Stability test results

To confirm the stability performance of the method described above, the transmission clock was measured at NMIJ as shown in Fig.3. The clock was extracted from the digital service unit (DSU) which is necessary for

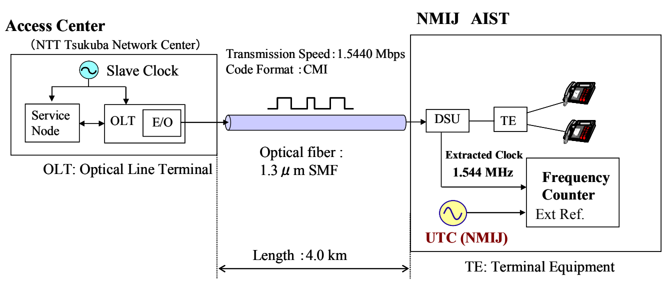

Fig.3. Frequency measurement setup.

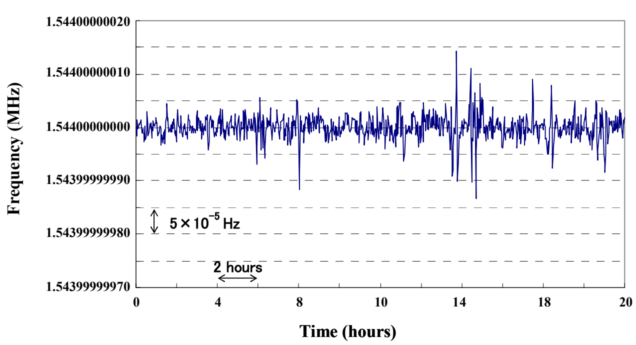

Fig.4. Measured frequency of extracted clock.

synchronous telecommunication services. The telecommunication service used in the experiment was INS 1500 provided by NTT. The frequency measured by a counter with a 100-s gate time is shown in Fig.4. The transmission nominal frequency is 1.544 MHz. The relative frequency deviation (1 day averaging) was -8.6×10^{-14}. The relative expanded uncertainty (k = 2) was 5.3×10^{-13}.

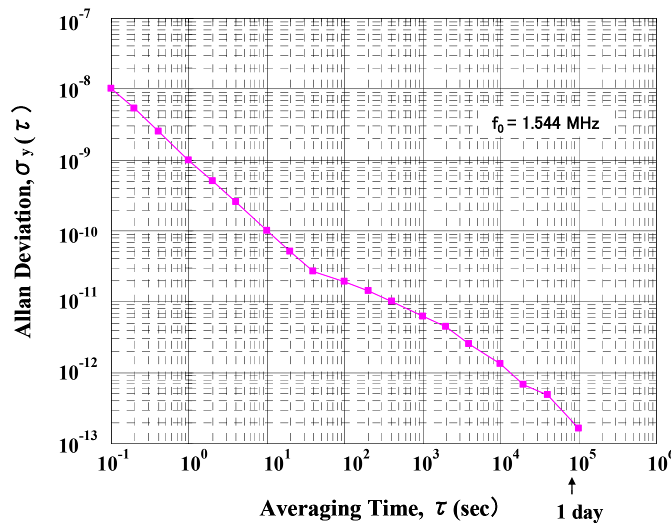

Fig. 5. Measured frequency stability of extracted clock.

Preliminary measured stability (the Allan deviation) of the transmission clock was 2×10^{-13} for an averaging time of one day as shown in Fig.5. The results indicate the method is promising for economical and stable frequency standards distribution.

3. PRECISE TIME AND FREQUENCY TRANSFER METHOD

A. Configurations

Time/frequency transfer system using bidirectional optical amplifiers is shown in Fig.6. To cancel the phase fluctuation induced by temperature change, bi-directional signals with different wavelength are used along a single fiber. A key component in this method is a bi-directional optical amplifier to compensate the fiber loss.

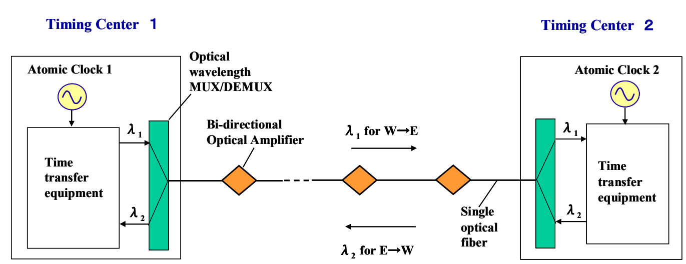

Fig. 6. Time and frequency transfer system using bi-directional optical amplification.

Single-directional optical amplifiers are used in the present Dense-WDM systems. Optical isolators in them are important for stable amplification. Otherwise it begins to oscillate because of the reflection light between 2 optical connectors of the amplifier. A proposed new type bidirectional amplifier is shown in Fig.7. Two wavelengths for time transfer signals (West→East and E→W) are divided by optical wavelength couplers. Optical isolators are equipped for each divided optical signal as shown in Fig.7. This configuration makes it possible for bidirectional amplification and cutting off the reflected light for each wavelength λ_1 and λ_2.

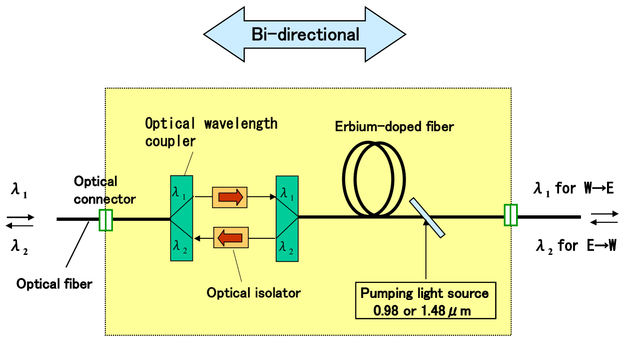

Fig. 7. A proposed new type bi-directional optical amplifier

B. SNR calculation and estimated stability

The amplified spontaneous emission (ASE) noises from each optical amplifier are accumulated along the cascaded optical amplifier line. The ASE generates beat noises with signal light in addition to shot noises [6][7]. Then the received signal to noise ratio (SNR) for optical pulses is expressed as in (1) where symbol definitions are shown in Table 1.

Table 1 Symbol definitions and values used in the calculations

Symbol definitions	values used in the calculations
Related optical amplifier	
G: Gain	G=20 dB
γ : Optical fiber loss of one span	γ =20 dB
m_t: Aggregate number of guided transverse modes	m_t=2 (EDFA)
n_{sp}: Population inversion parameter	n_{sp}=2 (NF=6 dB)
K : Total number of optical amplifier	K=1～200
Δf: Optical filter bandwidth (FWHM)	Δf=25 GHz
$\langle n_{in} \rangle$: the mean number of photons per unit time at the first optical amplifier input	Optical power at the first optical amplifier input : -20 dBm
Receiver noise	R_L=50 Ω～1 M Ω (Neglected when K is large)

The calculated SNR is shown in Fig.8 using the values in Table 1. The SNR of 74.8 dB at K=125 is obtained. The total length of the system reaches 10,000 km if the repeater spacing is 80 km. This length enables us to transpacific transmission. Carrier levels (radio frequency sinusoidal components) are depending on the modulation format, however, there is a possibility to obtain CNR of around 70 dB. The Allan variance is inversely proportioned to the CNR as is well known. The estimated stability for the CNR of 70 dB and 80 dB is shown in Fig. 9. If we can get the CNR of 70 dB at 10 MHz with 10 kHz bandwidth, The Allan deviation will be less than 10^{-15} at τ =1day.

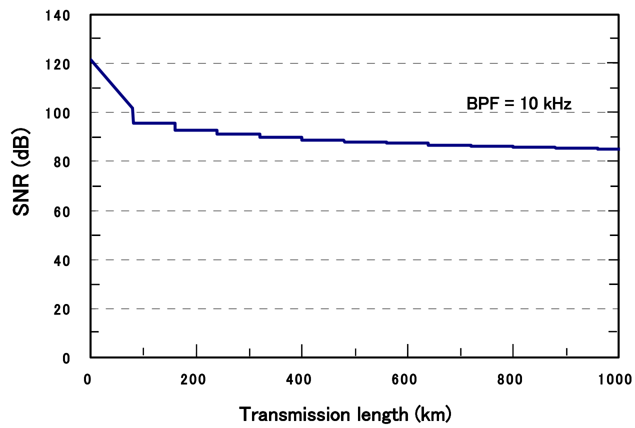

Fig.8. Calculated signal to noise ratio vs. transmission length.

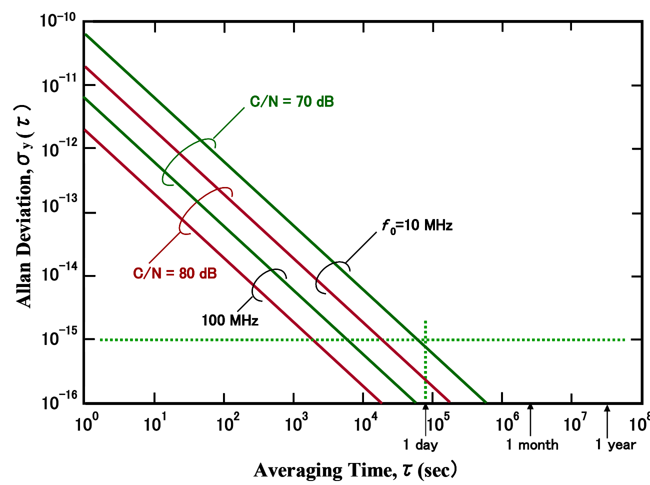

Fig.9. Estimated stability of optical fiber system.

C. Single way fiber transmission

The thermal expansion and refractive index change of a fiber causes the phase fluctuation. This effect is measured in a single way fiber transmission setup shown in Fig. 10. Fig. 11 shows the experimental results for 10 MHz radio

$$\frac{S}{N}=\frac{\langle n_{in}\rangle^2}{2B\left[\langle n_{in}\rangle+m_tKn_{sp}\gamma(G-1)\Delta f+2\langle n_{in}\rangle Kn_{sp}\gamma(G-1)+m_tK^2n_{sp}^{\;2}\gamma^2(G-1)^2\Delta f\right]+\dfrac{4kTB}{e^2R_L}} \qquad (1)$$

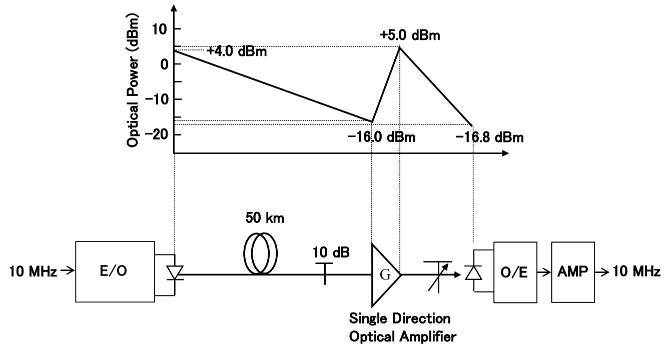

Fig. 10. Experimental setup for single way transmission.

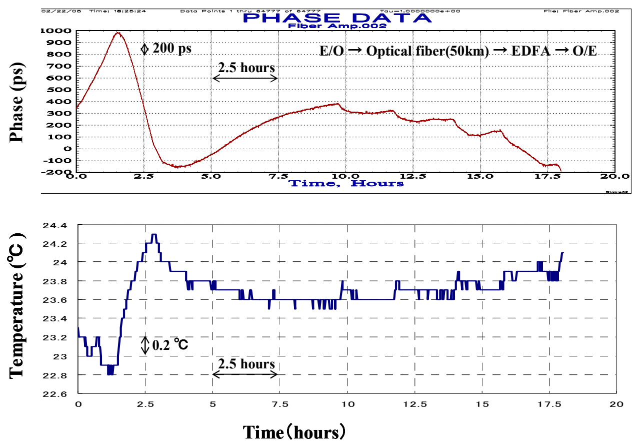

Fig.11. Phase fluctuation of a 50-km-long fiber due to temperature change.

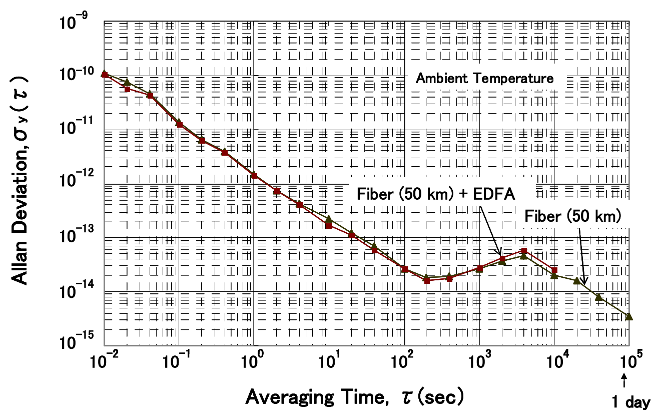

Fig. 12. Frequency stability for single way 50-km transmission.

frequency signal through 50-km of single-mode fiber (SMF) and a single direction optical amplifier (EDFA). In this experiment a tunable 1.55 μm laser diode was directly modulated by 10 MHz rf standard. The transmitted optical signal is directly converted to electrical signal with InGaAs-PD. Apparently the phase fluctuated in accordance with the change of ambient temperature as shown in Fig. 11. This is reflected in the Allan Deviation plots shown in Fig.12. The stability degraded at around τ = 4,000 s in both cases fiber with EDFA and fiber only. Therefore, we need the two-way transmission method for canceling the phase fluctuation.

D. Two-way 100 km fiber transmission

The system noise-floor level for the two-way fiber transmission was examined as the first step for development. The experimental setup is shown in Fig. 13. There is the proposed bi-directional optical amplifier between two 50-km bobbins of SMF for compensating the fiber loss. Two tunable lasers are directly modulated by the same hydrogen maser output signal at 10 MHz. As already studied in [2], the wavelength difference between 2 lasers (channel spacing) should be small for precise time comparison. In our experiment, two adjacent wavelengths (frequencies), arbitrary but equal to the ITU 100-GHz grid frequencies [8], are selected as shown in Fig. 14. This is advantageous to apply this method into existing WDM networks.

The phases of two signals after transmission in the counter direction are compared. The measured results are shown in Fig. 15. The Allan deviation of less than 10^{-15} (τ =10^4 s) for a 100-km-long fiber with the bi-directional amplifier was obtained while the frequency stability for single way transmission (W→E) was degraded due to fiber-induced phase fluctuation. As a reference, frequency stabilities for direct transmission E/O→O/E (without fiber, input optical power was -8.5 dBm) or an electrical circuits used in the experiment (without optical devises) are also shown in Fig. 15. Ambient temperature in this experiment was about 23 ± 1℃. The temperature of tunable lasers, optical wavelength couplers, and optical pump lasers for the bi-directional amplifier were controlled within 0.01 ℃.

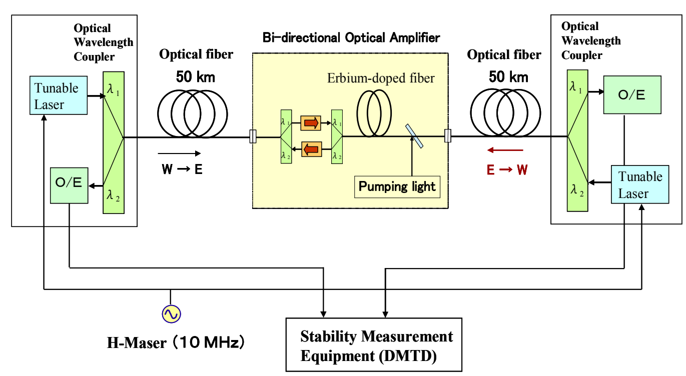

Fig.13. Experimental setup for system noise measurement of bi-directional transmission.

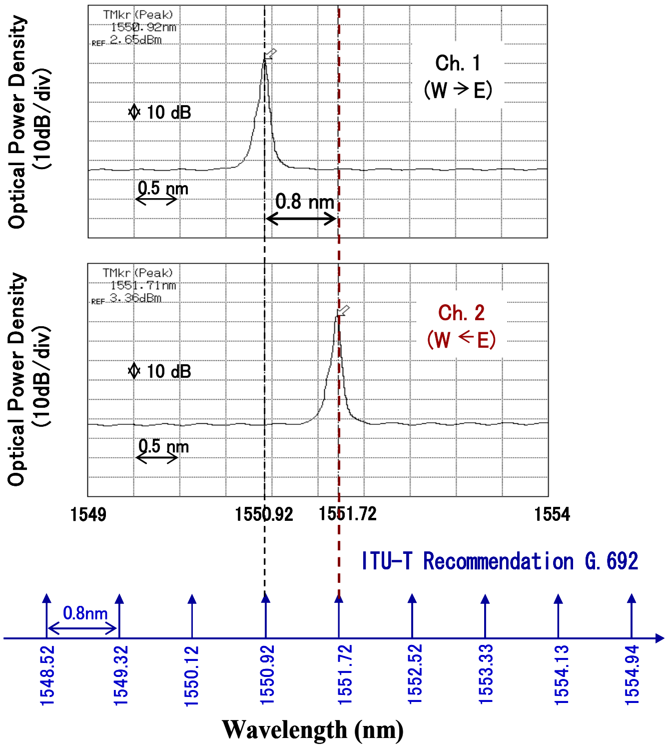

Fig. 14. Optical power spectrum of transmitter light.

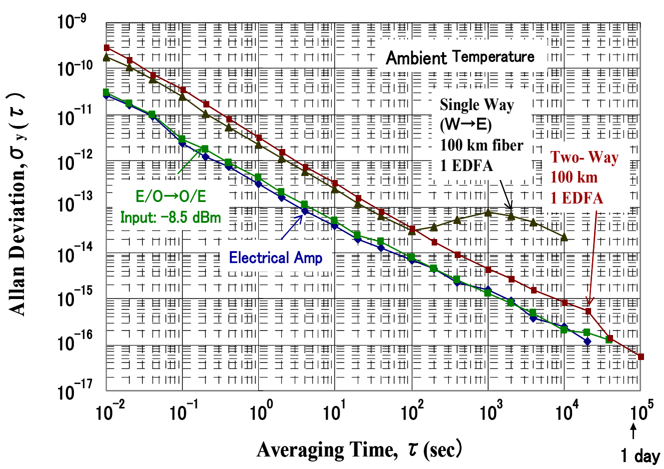

Fig. 15. System noise of two-way 100-km transmission with bi-directional amplifier.

4. CONCLUSIONS

A simple and economical frequency distribution method was considered for satisfying the remote frequency-users' demands. Existing synchronous optical fiber communication networks are used in this method. The frequency stability of the transmission clock which is hierarchically synchronized to the master clock (Cs oscillator) was measured. The Allan deviation was 2×10^{-13} at 1-day averaging time. The result indicates the method is promising for simple remote frequency calibration service. It was also shown that an ultra precise two-way optical fiber time and frequency transfer method using a newly proposed bi-directional optical amplifier. In this method, wavelength division multiplexing (WDM) signals are transmitted along a single optical fiber and amplifiers. The preliminary measured frequency stability was less than 10^{-15} ($\tau=10^4$ s) for a 100-km-long fiber with the bi-directional amplifier. It suggests that the method has capability for improving TAI and UTC.

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