Frequency Measurement System of Optical Clocks Without a Flywheel Oscillator

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***Abstract*— We developed a system for the remote frequency comparison of optical clocks. The system does not require a flywheel oscillator at the remote end, making it possible to evaluate optical frequencies even in laboratories, where no stable microwave reference, such as an Rb clock, a Cs clock, or a hydrogen maser exists. The system is established by the integration of several systems: a portable carrier-phase two-way satellite frequency transfer station and a microwave signal generation system by an optical frequency comb from an optical clock. The measurement was as quick as a conventional method that employs a local microwave reference. We confirmed the system uncertainty and instability to be at the low 10^{-15} level using an Sr lattice clock.**

***Index Terms*— Clocks, frequency measurement, optical frequency conversion.**

I. INTRODUCTION

NOT only national metrological institutes but also universities and research institutes are devoting much effort to the development of highly stable optical clocks [1]–[5]. Their superb uncertainties will pave the way to the redefinition of the second. When a university decides to evaluate the absolute frequency of an optical clock, it needs to establish a frequency link to a laboratory with a primary frequency standard, or to one with a time scale traceable to international atomic time (TAI). Also, in an optical clock comparison between two sites, a frequency link is necessary. An optical fiber link and a satellite link using GNSS or a geostationary satellite are widely used for frequency transfer between two sites [6]–[10]. The former is well known as a highly accurate and stable method, and it enables frequency transfer that gives access to the stability of optical clocks without degradation [11]. However, the availability of a fiber link is sometimes limited depending on the location of the laboratories or the rental fee requested for the access to the fibers. Although satellite-based links have inferior stability to optical fiber links [12], their availability is much better, especially for intercontinental frequency transfer. Satellite-based frequency transfer needs a long measurement time to reduce the measurement noise. On the other hand, the long operation of optical clocks remains a difficult task. To bridge the difference between the measurement time and operation time, a flywheel oscillator is normally employed [13]. When a frequency evaluation uncertainty at the low 10^{-15} level is required, a measurement time of $10^4 - 10^5$ s is necessary for satellite-based frequency transfer. Therefore, the frequency instability of the flywheel oscillator should be kept at the same level during the measurement. A hydrogen maser is typically adopted as a flywheel oscillator, though all laboratories do not have a hydrogen maser. Thus, we developed a system for the frequency measurement of remote optical clocks without a flywheel oscillator. In this system, frequency transfer by carrier-phase two-way satellite frequency transfer (TWCP) [14], [15] is performed with a portable antenna for wider availability. Since TWCP can reach an instability of the 10^{-15} level within a time on the order of 10^3 s, effort to extend the operation time is not required for the optical clocks. Furthermore, a microwave reference signal can be directly generated from an optical clock using an optical frequency comb. No flywheel oscillator is necessary in our system. Let us assume that a frequency signal $f_{\mathrm{UTC}(k)}$ of UTC(k) at laboratory k is used as a reference for frequency measurement and that a TWCP frequency link is established between laboratories a and k. In this case, two measurements, a local measurement of $f_{\mathrm{opt}} - f_{\mathrm{flywheel}}$ and a frequency transfer to measure $f_{\mathrm{flywheel}} - f_{\mathrm{UTC}(k)}$, have been performed independently. On the other hand, the frequency measurement demonstrated here simply measures $f_{\mathrm{opt}} - f_{\mathrm{UTC}(k)}$. In this paper, we report the details and performance of our frequency measurement system.

II. SYSTEM SETUP

Fig. 1 shows a schematic of the frequency measurement of an optical clock at laboratory a with respect to UTC(k) at laboratory k. At laboratory a, the frequency measurement system is installed to measure the frequency of an optical clock. The system consists of a portable TWCP station and a microwave signal generation system by an optical clock. The system configuration is presented in this section. The frequency is evaluated with respect to $f_{\mathrm{UTC}(k)}$, whose frequency difference from TAI will be given by circular T later. At laboratory k, a fixed TWCP station is assumed to be available. The frequency transfer between laboratories a and k is performed by the TWCP technique.

A. Microwave Signal Generation From an Optical Clock

Fig. 2 shows a schematic of the microwave signal generation system, where an optical frequency comb converts the frequency from optical to microwave. The comb is locked to

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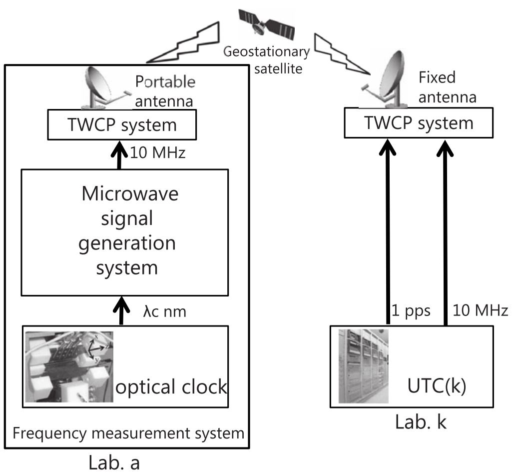

Fig. 1. Frequency measurement of an optical clock at laboratory *a* with respect to UTC(k) at laboratory *k*.

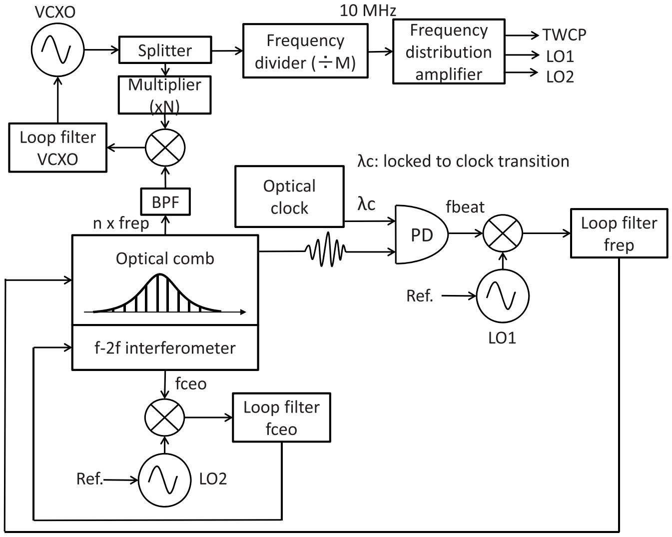

Fig. 2. Microwave signal generation system from an optical clock. PD: photodetector. VCXO: voltage-controlled crystal oscillator. LO1 and LO2: signal generators.

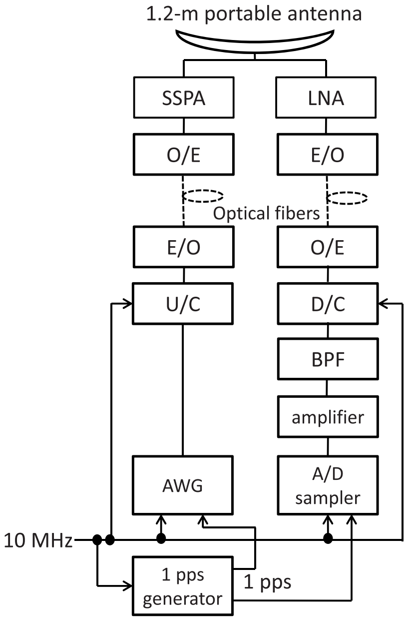

Fig. 3. Schematic of the portable TWCP station. U/C: frequency upconverter. D/C: frequency downconverter. E/O: electrical-to-optical converter. O/E: optical-to-electrical converter. SSPA: solid-state power amplifier. LNA: low-noise amplifier. AWG: arbitrary waveform generator. A/D: analog to digital. BPF: bandpass filter.

an optical clock by optical phase-locked loop. The beat signal between the frequency comb and the clock laser is detected by a photodetector and locked to a signal generator named LO1 through a loop filter. The carrier envelope offset frequency f_{ceo} is detected by an $f - 2f$ self-interferometer and locked to a signal generator named LO2 through a loop filter. The signal generators LO1 and LO2 are locked to the external reference generated from the microwave signal from the comb. Therefore, both the repetition and the carrier envelope offset frequencies f_{rep} and f_{ceo}, respectively, become synchronized with the optical clock, enabling an operation free from a local microwave reference. The microwave signal to be transferred is generated from f_{rep}. The nth harmonic of f_{rep} is extracted by a photodetector and a bandpass filter. The signal from a voltage-controlled crystal oscillator is locked to the harmonic through a frequency multiplier ($\times N$). Its frequency is divided by a frequency divider ($\div M$). To finally achieve a 10-MHz signal, appropriate values of n, N, and M are selected. When a signal is transmitted to the air in a TWCP station, the deviation of the center frequency should be kept within a licensed frequency range. To comply with the regulation, the following are performed: a VCXO with a rather narrow tuning range is inserted for phase-locking of the harmonic of f_{rep} to avoid a frequency jump exceeding the licensed frequency deviation when an optical clock unlocks to the clock transition. The LO1 frequency is finely adjusted to keep the deviation of f_{rep} below 10^{-5} Hz. A microwave signal coherent to the optical clock is generated in this way, and its frequency is divided by a frequency divider to produce a 10-MHz reference signal. In actual measurement, we confirmed using a frequency counter with the 10-MHz reference signal that the frequency deviation was less than 3×10^{-6} Hz.

B. Portable TWCP Station

In this section, the details of the portable TWCP station are described. Its schematic is shown in Fig. 3. The station is equipped with a 1.2-m portable antenna and optical fibers for signal transfer between indoors and outdoors. It is easy to install in various places. An arbitrary waveform generator (AWG) is used as a signal generator [16]. The AWG generates a direct-sequence spectrum spreading signal with a bandwidth of 200 kHz at a center frequency of 70 MHz. The signal frequency is upconverted to 14 GHz by a frequency upconverter (U/C). The amplitude of a 1.3-μm CW light is modulated by the 14-GHz signal in an electrical-to-optical converter (E/O). The light is transmitted through an optical fiber to outdoors. Since the signal loss in an optical fiber is as low as 0.2 dB/km, the length is not an issue. The light is converted to the 14-GHz signal by an optical-to-electrical converter (O/E).

It is amplified by a solid-state power amplifier and transmitted to a geostationary satellite. The signal is frequency-converted by an oscillator in the satellite and transmitted back to earth. The reception signal is amplified by a low-noise amplifier, converted to light by another E/O, and sent indoors. Another O/E extracts the microwave signal of about 10 GHz. The signal is converted to 70 MHz by a frequency downconverter (D/C). The 70-MHz signal is bandpass-filtered and amplified. Finally, the carrier-phase information is determined by software from the sampling data obtained by an analog-to-digital (A/D) sampler [17]. The configuration of the portable TWCP station is identical to that of conventional two-way satellite time and frequency transfer (TWSTFT) stations except to the AWG and A/D sampler. The AWG, A/D sampler, U/C, and D/C are connected to the 10-MHz reference signal. The 1-pulse-per-second (pps) signals are generated by a 1-pps generator from the 10-MHz signal and supplied to the AWG and A/D sampler. The time difference between the two TWCP stations is calculated from the carrier-phase information and can be converted to a frequency difference. The computation method is described in [15].

III. System Performance

To evaluate the performance of the frequency measurement system, we measured a microwave signal derived from an Sr lattice clock relative to UTC(NICT). The lattice clock with an uncertainty of 8.6×10^{-17} was developed by the National Institutes of Information and Communications Technology (NICT) [18]. The Sr clock was operated for a few hours. An Yb optical fiber comb was used in the frequency measurement system and generated a 1-GHz signal from the fourth harmonic of f_{rep} (=250 MHz). A 100-MHz VCXO was locked to the 1-GHz signal through a ten-times frequency multiplier. The 100-MHz signal was divided by a 1/10 frequency divider. The resultant 10-MHz signal was used as a reference signal of the system. On the other hand, a fixed TWCP station with a 1.8-m antenna was connected to the signal of UTC(NICT). The frequency difference between the downconverted 10-MHz signal and UTC(NICT) was measured by the TWCP technique via a geostationary satellite. Both fixed and portable TWCP antennas were installed on the same rooftop. A phase comparator also measured the frequency difference for the comparison of the results. The resultant time difference is shown in Fig. 4. The line labeled TWCP shows the result obtained by the frequency measurement system. The result measured by the phase comparator is shown in the gray dashed line. The vertical offsets were adjusted for better visibility. The measurement rates were 1 point per second for both. The gray solid line shows the double difference of them. Its slope was 9×10^{-17}, which indicates good agreement between the two frequency differences. The Allan deviation of the frequency difference is shown in Fig. 5. The stability at 1 s measured by TWCP is better than that measured by the phase comparator because the 1-s data of TWCP are calculated by averaging 50 points detected every 20 ms. The stability was 1.4×10^{-15} at 1000 s, which was comparable to that of a frequency measurement using a local hydrogen maser.

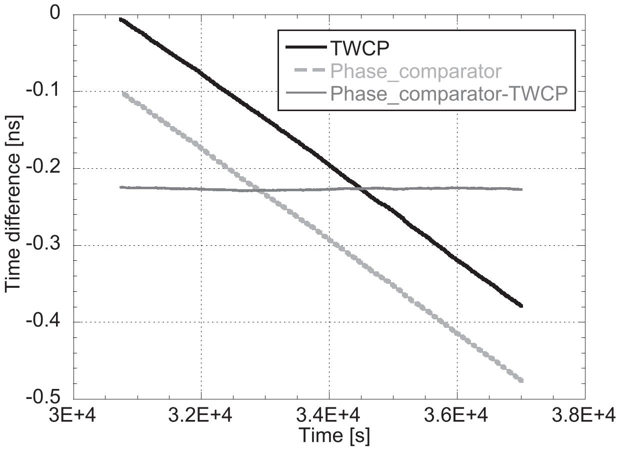

Fig. 4. Time difference between Sr-based microwave and UTC(NICT).

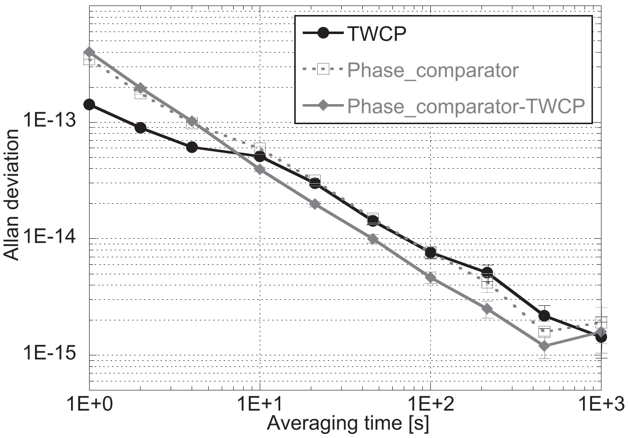

Fig. 5. Allan deviation of frequency difference between Sr-based microwave and UTC(NICT).

TABLE I
Mean Frequency Difference Between the Sr-Based Microwave and UTC(NICT)

Mean frequency difference	Sr-Microwave - UTC(NICT) (1e-15)
Calculation	-58.8±2.0
TWCP	-60.0±1.6
Phase comparator	-59.9±1.6

The uncertainty of the system is discussed next. The frequency of our Sr clock was already known [18] and the agreement with other Sr lattice clocks developed by the University of Tokyo and Physikalisch-Technische Bundesanstalt had been confirmed [11], [19]. Thus, we can calculate the frequency difference between TAI and the optically generated microwave signal based on the Sr clock. The frequency difference between TAI and UTC(NICT) is published with a delay in Circular T. Table I shows the frequency differences obtained by calculation and measurements using the system and phase comparator. The calculation includes the combined uncertainty of 2×10^{-15}, which is predominantly determined by the TAI-UTC(NICT) link uncertainty. The bias frequency of the calculation was caused by the roughly tuned frequencies of LO1 and LO2 shown in Fig. 2. The uncertainties of TWCP and

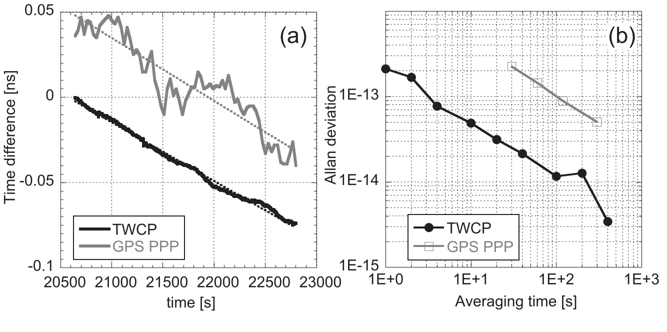

Fig. 6. Result of one of 40-min measurements "run 1". (a) Time difference and (b) Allan deviation between microwave generated from $^{40}\text{Ca}^+$ system and UTC(NICT).

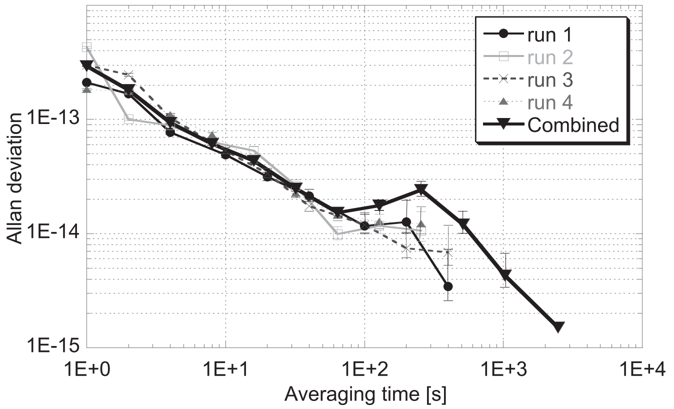

Fig. 7. Frequency stabilities of four 40-min measurements and their combination with three 5-min intervals. They are measured by TWCP.

the phase comparator are mainly determined by the double-difference instabilities of the two techniques at 1000 s shown in Fig. 5. Besides that, the residual disagreement of 9×10^{-17} between them is also included. As shown in Table I, the uncertainty of our frequency measurement system was at the 10^{-15} level.

IV. APPLICATION OF THE SYSTEM

A linear trap system of a single $^{40}\text{Ca}^+$ ion has been developed at Osaka University for experiments related to quantum information processing [20]. Our portable system for optical frequency measurement was installed to establish a frequency link along a baseline of 500 km from NICT to Osaka University, where there was no atomic clock available to generate a reference signal. A microwave signal was generated from the $^{40}\text{Ca}^+$ system that was locked to the clock transition ($^2S_{1/2} -^2 D_{5/2}$, 729 nm). The portable TWCP antenna was installed on a rooftop of a building with a portable GPS antenna nearby. A dual-frequency GPS receiver was also installed with the reference signal generated from the $^{40}\text{Ca}^+$ system and used for frequency measurement. The frequency of the clock transition was evaluated with respect to UTC(NICT).

The operation of the whole system, including the $^{40}\text{Ca}^+$ system continued from a few minutes to 1 h. The reference signal was stable, while the $^{40}\text{Ca}^+$ system was locked to the clock transition. When it was unlocked, on the other hand, the reference signal was generated from the free-running VCXO. Such a condition of the interrupted reference signal led to a difficulty in obtaining a stable clock solution in frequency transfer by GPS PPP. This is because the carrier-phase ambiguity and the receiver clock offset cannot be fixed in a short measurement in GPS PPP. When the operation time was longer than 40 min, we could obtain an appropriate result by GPS PPP. The length of the operation time was not an issue for TWCP, in which only an instantaneous phase difference between two stations was computed. Fig. 6 shows the time difference between UTC(NICT) and the microwave signal generated from $^{40}\text{Ca}^+$ system, from which the Allan deviation was calculated. The black and gray lines, respectively, depict the results measured by TWCP and GPS PPP. The GPS PPP computation was performed every 30 s using a static IGS orbit and 30-s clock products [21] with the software provided by Natural Resources Canada. The mean frequency differences obtained by TWCP and GPS PPP were $-3.4 \pm 0.6 \times 10^{-14}$ and $-3.7 \pm 5.0 \times 10^{-14}$, respectively. The uncertainties were determined from the Allan deviation at an averaging time of 300 s. There were a total of seven measurements, where the measurement time was longer than 40 min. We confirmed from them that the results obtained by the TWCP and the GPS PPP were in agreement within the statistical uncertainty. Additionally, the TWCP result reached 3×10^{-15} at 400 s. The frequency measurement system worked well even in a remote location. We performed 40-min measurements four times with an interval of five minutes between them to evaluate the frequency stability at longer averaging times. During the 5-min intervals, the optical frequency comb was adjusted to keep a phase locking to the clock laser of the $^{40}\text{Ca}^+$ system. The obtained Allan deviation is shown in Fig. 7. It was found that there was a bump due to the instability at the low 10^{-14} level around an averaging time of about 300 s. The reason for this bump is unknown at present. It proved, however, that the $^{40}\text{Ca}^+$ system has stability at the 10^{-15} level at an averaging time of 1000 s. Such measurement used to be impossible, because there is no stable frequency reference at Osaka University. The measurement based on UTC(NICT) has also revealed a fluctuation of the clock laser, which has triggered effort to reduce it by half. Our frequency measurement system could effectively provide a stable reference for Osaka University. The instability was similar to that of a local hydrogen maser linked to UTC(NICT).

V. CONCLUSION

We developed a frequency comparison system for optical clocks without a flywheel oscillator. It enables us to evaluate the frequency of optical clocks even in a laboratory, where there is no stable microwave reference, such as an Rb clock, a Cs clock, or a hydrogen maser. The system consists of a microwave signal generation system from the optical clock and a portable TWCP station. We confirmed the system uncertainty to be at the low 10^{-15} level by a frequency measurement using an Sr lattice clock. The system was actually installed at a remote university. We were able to prove that the system worked appropriately from the agreement with the GPS PPP and the resultant stability. Our system has a superior portability. The operation of the TWCP system is designed such that nonspecialists for satellite frequency transfer can handle it. If a portable optical clock [22] is available, the system and the optical clock as an optical frequency reference can be carried to various places and provide a reference signal linking to the second. This would be the case for the laboratories in universities as well as facilities of high energy physics, where a GPS-desciplined stable microwave oscillator is normally used.

After the redefinition of the second by optical clocks, a bridge from the optical region to the microwave region will be required because many instruments require a reference signal in the microwave region. The microwave signal generation system shown in this paper is expected to be helpful in various occasions.

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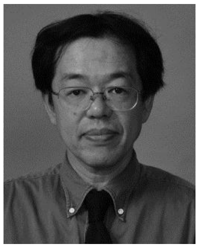

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