Optical lattice clocks: Hz-level spectral width with sub-Hz reproducibility

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Abstract. State-of-the-art optical clocks have surpassed microwave clocks in this century, causing discussions to redefine the SI second based on an optical transition. The superiority of optical standards was clearly revealed by two of optical-optical comparisons, one of which is a remote comparison of two strontium lattice clocks, and the other is a characterization of a single Ca⁺ ion clock using a Sr lattice clock as a frequency reference. The former for the first time demonstrated the frequency reproducibility of physically separated clocks at the 10⁻¹⁶ level. The latter has confirmed the capability of single Ca⁺ clocks to reach the ~10⁻¹⁶ instability.

1. Introduction
Atomic clocks based on optical transitions have been proposed since the invention of the laser, where a laser as an optical oscillator is kept to be resonant to atomic transitions, providing stable ticks of clocks. To realize the frequency reproducibility of the optical clocks, it is critical to pursue “spectral line shapes” of Lorentzian with its width determined solely by the lifetime of the excited states. Electrically trapped single ions have been the most promising playground to obtain such simple line shapes. The progress of the laser cooling technique has enabled single ions trapped in the vibrational ground state, which has a spatial distribution much smaller than the wavelength of the clock laser, realizing Doppler- as well as recoil- free spectrum. It is also possible to laser-cool neutral atoms. The invention of the magneto-optical trap has allowed us to trap large number of ultracold atoms, leading to quantum degenerate gas such as Bose-Einstein condensate. However, it has long been impossible to extract a “pure line shape” from ultracold neutral atoms. While the tiny spatial distribution of the atomic wave packet is realized by optical lattice potential made of the interference pattern of intensive far-detuned radiation, this trapping laser causes different amount of ac shark shift to ground and excited state, which causes considerable shift of the transition frequency. This drawback of using neutral atoms has been overcome by the invention of lattice clocks [1]. Choosing species and the wavelength of the far-detuned laser, identical shape of the trapping potential similar to ion traps is generated for ground and excited state. The recoil-free spectroscopy based on this idea is first performed using ¹⁰⁸Sr ⁴P₁ transition of the ⁸⁸Sr, where the recoil-free nature is confirmed by the comparison of the line shapes with and without lattice potential [2]. The success of the recoil-free spectroscopy strongly pushed the quest for the lattice clock using the ultranarrow ¹⁰⁸Sr ⁴P₀ transition of ⁸⁷Sr [3, 4].
$^{87}$Sr lattice clocks are currently operated in five laboratories. The inaccuracy of the state-of-the-art clocks is evaluated to be $1 \times 10^{-16}$, predominantly limited by black body radiation [5, 6]. This inaccuracy is smaller than that of state-of-the-art Cs fountain clocks. Therefore, as long as we employ frequencies based on the SI second, this situation causes trouble to investigate the agreement of the frequencies developed in physically separated laboratories. As shown in Fig. 1, the agreement of the absolute frequencies is currently in $10^{-15}$ level, limited not by lattice clocks but by the uncertainty of the realization of the SI second as well as of the frequency link between the Cs clocks and lattice clocks.

Fig. 1 also indicates that Tokyo metropolitan area has two $^{87}$Sr lattice clocks at University of Tokyo and National Institute of Information and Communications Technology (NICT). The distance of two laboratories is 24km in a crown line, which is short enough to implement an optical fibre link using a dark fibre without intermediate amplifiers. Dark fibre cables of 48km are fortunately available from NICT to the downtown Tokyo for research in telecommunication network, and we additionally rented commercially available 12km part from the downtown to U. Tokyo campus, giving the feasibility to compare two physically separated lattice clocks. This all-optical direct comparison no longer relies on the SI second. Therefore it is expected that the reproducibility of physically separated clocks is confirmed beyond the International Atomic Time (TAI).

The limitation of microwave standard also lies in the requirement of long signal integration time compared to optical standard. Optical frequency standards have a significant advantage in the speed of the comparison, requiring less than 1000 seconds instead of more than six hours to evaluate a fractional frequency difference with $\sim 10^{-16}$ uncertainty. Comparison also enables the rapid evaluation of systematic shifts by investigating the dependence of the frequency on various experimental parameters. We demonstrated an optical comparison of locally available Ca$^+$ clock against the lattice clock as a tool to characterize optical clocks.

2. **Lattice clock at NICT**

The detail of the $^{87}$Sr lattice clock at NICT is found in [9]. The inaccuracy attributed to the Sr system was evaluated to be $5 \times 10^{-16}$, mainly determined by collision shift, 2nd Zeeman shift, and AC stark shift due to the black body radiation and lattice beam. When the fibre link experiment was demonstrated in 2011, the clock laser at 698nm was not as stable as other clock lasers. We effectively phase locked the clock laser to a Ca$^+$ clock laser via an optical frequency comb. The short term instability of the clock
laser was $3 \times 10^{-15}$. Since then, the instability of the clock laser has been improved by implementing optical compensation against vibration-induced phase noise, details of which are described elsewhere. By this technique the short term instability is currently $< 2 \times 10^{-15}$ at 1s and no longer requires the stability transfer technique employed previously.

3. **All optical link to another lattice clock in U. Tokyo**

Figure 1 illustrates a schematic diagram of the frequency comparison via telecommunication fiber link. The clock signal at the National Institute of Information and Communications Technology (NICT) is optically transferred to The University of Tokyo (UT) using a telecommunication fibre link in Tokyo. At NICT, a Ti:sapphire-based optical frequency comb is phase-locked to the clock laser at 698 nm. The telecom laser with wavelength of 1538 nm is phase-locked to this optical frequency comb through its frequency doubled light at 769 nm and transferred to UT through the phase-noise-cancelled 60-km-long optical fibre. The Ti:sapphire-based optical frequency comb at UT is phase-locked to the frequency doubled light of the transferred light. Thus, the frequency difference between two Sr lattice clocks is calculated from the frequency of the beat signal between the clock laser and the nearest tooth of the optical frequency comb at UT.

![Fig.2 Schematic diagram of the remote frequency comparison](image)

The frequency difference of the two clock frequencies $f_{\text{Sr}}(\text{NICT}) - f_{\text{Sr}}(\text{UT})$ is shown in Fig. 3. Each points obtained by a frequency counter have a gate time of 1 second. Ten seconds of signal integration reveals that the clock frequency in NICT is slightly higher than that of U. Tokyo. The average of the all data is 3.66 Hz. This difference is consistent with the difference of systematic corrections. The dominant differential correction is due to gravity shift. NICT has 56 m higher elevation than U. Tokyo, which corresponds to a 2.62 Hz larger blue shift. Subtracting the differential shift, the residual fractional difference has resulted in $1.0 \times 10^{-16}$ with uncertainty of $7 \times 10^{-16}$. This uncertainty consists of the systematic uncertainties of two clocks, $5 \times 10^{-16}$ for each. In terms of the uncertainty due to the fiber link, we confirmed that the instability of the frequency link reaches $\sim 10^{-18}$ and that there is no frequency shift beyond the instability [10]. Frequency comparison implemented here is simply a frequency ratio measurement of the two clocks, which is sufficient to evaluate the frequency reproducibility of lattice clocks.
3. **Lattice clock as a reference to characterize a Ca$^+$ clock**

Our institute has lately improved a single-ion clock based on the $^{40}$Ca$^+\, ^2S_{1/2} - ^2D_{5/2}$ transition. By installing a magnetic shield onto the vacuum chamber, we have reduced stray ac electromagnetic field that previously limited the spectral width to 300Hz [11]. Furthermore, the optimization of the clock laser has reduced its spectral width less than 5Hz and noise cancelling technique have contributed to obtain narrower spectrum. The resultant spectral width and inaccuracy is 30Hz and $2 \times 10^{-15}$, respectively. The uncertainty is reduced for 14 times than our previous report [11]. To confirm this level of frequency reproducibility, we first measured absolute frequency by referring a hydrogen maser which is linked to the international Atomic Time (TAI) via locally available Universal Coordinated Time UTC(NICT). However, the resultant absolute frequency has a fluctuation larger than the systematic uncertainty. In this measurement, the frequency of the hydrogen maser that a frequency comb refers is calibrated by referring Circular T, where the time differences of every five days between UTC(NICT) and TAI are reported. On the other hand, it takes only several hours for our frequency measurement. Therefore, the fluctuation of hydrogen maser during five days, which affects the HM-based frequency measurement, is averaged out in the TAI calibration. Optical-optical comparison, in other words the measurement of frequency ratio instead of absolute frequency, does not suffer this problem. A number of this ratio measurement for certain duration is sufficient to confirm the reproducibility of both clocks. Fig. 4 shows the result of the ratio measurement between the Ca$^+$ clock and the Sr lattice clock. Systematic shifts are corrected, whereas the error bars include only statistical uncertainty. Here, the standard deviation of the six data is calculated to be $6 \times 10^{-16}$. It is impossible to observe this level of the reproducibility by using the TAI link. The drift of the data at the last four points may indicate that some systematic shifts are slowly moving within the total systematic uncertainty of $2.3 \times 10^{-15}$.

![Fig.3 Frequency difference of the clock frequencies at NICT and U. Tokyo. The clock in NICT is slightly higher than that of U. Tokyo.](image-url)
Fig. 4 The result of all optical comparison between Ca\(^+\) clock and Sr lattice clock. The data includes the correction due to systematic shifts. The error bars only include statistical error.

4. Summary and Outlook

\(^{87}\)Sr lattice clock in NICT was compared to another lattice clock at U. Tokyo as well as a locally available single Ca\(^+\) ion clock. All optical comparison did not only accelerate the comparison process but also evade the limitation of accuracy in locally available microwave reference. The comparison against the lattice clock at U. Tokyo confirmed the reproducibility of lattice clock for the first time at 10\(^{-16}\) level. The comparison against the Ca\(^+\) clock demonstrated that the Ca\(^+\) clocks have an ability to reach 10\(^{-16}\) level of instability. These results imply that latest progress of optical clocks strongly requires frequency standards in optical region, making it realistic to redefine and share the SI second using optical transition instead of the microwave transition of Cs.

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