Direct Comparison of Distant Optical Lattice Clocks at the $10^{-16}$ Uncertainty

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Direct Comparison of Distant Optical Lattice Clocks at the 10⁻¹⁶ Uncertainty

Atsushi Yamaguchi, Miho Fujieda, Motohiro Kumagai, Hidekazu Hachisu, Shigeo Nagano, Ying Li, Tetsuya Ido, Tetsushi Takano, Masao Takamoto, and Hidetoshi Katori

Communications Technology (NICT) is optically transferred state-of-the-art optical clocks has not been attempted yet. Using a 4-km-long optical fiber, a Sr lattice clock was referenced to a neutral Ca clock to evaluate systematic residual instability below 10⁻¹⁶. The transferred laser is frequency doubled and the Ti: sapphire-based optical frequency comb at UT is then phase-locked to it. The systematic frequency corrections in each clock are estimated as <3 mHz) in both telecom laser operating at the wavelength of 1538 nm, which is phase-locked to this optical frequency comb through its frequency-doubled light (769 nm), is transferred to UT through a phase-noise-cancelled 60-km-long optical fiber. Two optical lattice clocks employing spin-polarized fermionic Sr atoms are developed separately at UT and NICT. An ensemble of roughly 10⁴ atoms is laser cooled to 3 μK and loaded to the vertically oriented one-dimensional (1D) optical lattice potentials. After optically pumping to one of the stretched magnetic sublevels, the 5s⁴ ¹S₀ (F = 9/2, m_f = ±9/2) → 5s⁵ ³P₀ (F = 9/2, m_f = ±9/2) transition is probed using a clock laser propagating along the strong confinement axis of the lattice to suppress the Doppler and recoil shifts. By probing both sides of a lineshape at its full width at half maximum, the deviation of the clock laser frequency from the atomic resonance is detected and used for clock stabilization. At UT, the clock transition is observed with the Fourier-limited linewidth of 4 Hz for a 200 ms interrogation time. In a clock cycle time of 1.5 s, atoms are loaded into lattices and one side of one of the magnetic sublevels (m_f = ±9/2) is probed. At NICT, the clock transition is observed with the Fourier-limited linewidth of 20 Hz in a clock cycle time of 1.3 s.

The systematic frequency corrections in each clock are independently evaluated as summarized in Table I. The wavelength of the lattice laser is stabilized to the "magic" wavelength where the AC Stark shift for the ground and excited states becomes equal, leading to suppression of the differential scalar and tensor AC Stark shift to -0.19 (10) Hz at UT and -0.10 (10) Hz at NICT. The polarization direction of the linearly polarized lattice laser is parallel to the bias magnetic field. The higher-order AC Stark shift (hyperpolarizability) is negligibly small (<3 mHz) in both

Fiber-based remote comparison of Sr lattice clocks in 24 km distant laboratories is demonstrated. The instability of the comparison reaches 5 x 10⁻¹⁶ over an averaging time of 1000 s, which is two orders of magnitude shorter than that of conventional satellite links and is limited by the instabilities of the optical clocks. By correcting the systematic shifts that are predominated by the differential gravitational redshift, the residual fractional difference is found to be (1.0 ± 7.3) x 10⁻¹⁶, confirming the coincidence between the two clocks. The accurate and speedy comparison of distant optical clocks paves the way for a future optical redefinition of the second. © 2011 The Japan Society of Applied Physics
systems. The first-order Zeeman shift and the vector AC Stark shift are suppressed by taking the center of transitions from stretched magnetic sublevels of spin-polarized atoms. Due to the Pauli exclusion principle, the ensemble of ultracold spin-polarized fermions is also beneficial for suppressing the collisional shift to 0.00 (10) Hz at UT and 0.04 (12) Hz at NICT. The second-order Zeeman shift caused by bias magnetic fields of 230 and 99 μT is estimated to be 1.24 (10) Hz and 0.23 (10) Hz at UT and NICT, respectively. The elevation of the lattice clock at UT from Earth’s geoid surface and correction of the corresponding gravitational shift are 20.37 ± 2 m and −0.95 (9) Hz, respectively, and 76.33 ± 1 m and −3.57 (5) Hz at NICT. The overall systematic frequency shift of the frequency difference, ν_{NICT} − ν_{UT}, amounts to 3.66 (31) Hz.

Figure 2(a) shows the time record of the frequency difference, ν_{NICT} − ν_{UT}. Thanks to the highly stable optical link, a Hz-level frequency difference between distant 87Sr optical lattice clocks is clearly visible over the time scale of minutes. The observed frequency difference is attributed to different systematic shifts between two clocks as listed in Table I. It is noticeable that the largest contributor to the frequency difference is the gravitational shift of 2.62 Hz.

The instability between the two clocks is measured to be $1.6 \times 10^{-14}/\sqrt{\tau}$ as shown in Fig. 2(b). It is noteworthy that the averaging time of 1000 s is sufficient to reach a fractional
instability of $5 \times 10^{-16}$, which indicates more than two orders of magnitude improvement over the remote comparison via the best current satellite-based microwave link.\(^{3}\) The intrinsic noise of the clock laser and the dead time in the clock cycle cause aliasing noise that is referred to as the Dick effect.\(^{19}\) The Dick-effect-limited instability is expected to be $6 \times 10^{-15}/\sqrt{\tau}$ for the clock at UT and $1.5 \times 10^{-14}/\sqrt{\tau}$ for the clock at NICT. These instabilities are consistent with the result shown in Fig. 2(b). This remote comparison system, therefore, allows us to investigate the relative instabilities of distant Sr lattice clocks that were previously masked by the instabilities of Cs clocks and relevant microwave links.\(^{3-5,20}\)

Frequency differences have been evaluated as summarized in Fig. 3, by taking eleven separate measurements over five weeks. In each measurement, we correct the corresponding systematic frequency shifts, which vary from day to day by less than 10 mHz due to small fluctuations in experimental conditions. The thin blue error bar indicates the systematic uncertainty of 0.31 Hz, except for the data on January 26th where the uncertainty is 0.49 Hz. The bold red error bar shows the standard error for each run that has measurement records in the range of 900 to 12000 s, from which the weighted mean is calculated to be 0.04 Hz, as shown by the solid black line in Fig. 3. This result demonstrates that the two distant Sr lattice clocks generate the same frequency within the systematic uncertainty of 0.31 Hz ($7.3 \times 10^{-16}$ fractionally) for the 429 THz carrier frequency. This uncertainty is shown in Fig. 3 by dashed lines.

In summary, we have demonstrated for the first time the stringent and expeditious evaluation of distant optical clocks using optical fiber links, which significantly surpass previous frequency comparisons employing Cs clocks or satellite links. The uncertainty of the reproducibility identified here would be further reduced by rigorously managing the systematic shifts\(^{17,21}\) and using less noisy fiber networks accordingly. Such endeavors will certainly push forward the optical redefinition of the second. The technique discussed here has a wide range of applications.\(^{22}\) Recently invented compact frequency combs based on microresonators\(^{23}\) can be stabilized to the remote elaborate reference by the transfer technique demonstrated here. Fully referenced transportable optical atomic clocks will enable highly sensitive measurements in fieldwork. Synchronous frequency comparison between distant optical clocks,\(^{13}\) in which lasser noise is canceled out as common noise, may uncover tiny temporal variations in the gravitational potential in real time, which might give new insights into geodesy.

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1. A. Bauch, J. Achkar, S. Bize, D. Calonico, R. Dach, R. Hlavac, L. Lorini, T. Parker, G. Petit, D. Piester, K. Szymaniec, and P. Urich: Metrologia 43 (2006) 109.
2. A. Wallard: Metrologia 44 (2007) 97.
3. G. K. Campbell, A. D. Ludlow, S. Blatt, J. W. Thomsen, M. J. Martin, M. H. G. de Miranda, T. Zelevinsky, M. M. Boyd, J. Y., S. A. Diddams, T. P. Heavner, T. E. Parker, and S. R. Jefferts: Metrologia 45 (2008) 539.
4. X. Baillard, M. Fouche, R. L. Targat, P. G. Westergaard, A. Lecallier, F. Chapelier, M. Abgrall, G. D. Rovera, P. Laurent, P. Rosenbusch, S. Bize, G. Santarelli, A. Clairon, P. Lemonde, G. Grosche, B. Lipphardt, and H. Schnatz: Eur. Phys. J. D 48 (2008) 11.
5. F. L. Hong, M. Misha, M. Takamoto, H. Inaba, S. Yanagimachi, A. Takamizawa, K. Watanabe, T. Iegami, M. Imae, Y. Fujii, M. Amemiya, K. Nakagawa, K. Ueda, and H. Katori: Opt. Lett. 34 (2009) 692.
6. N. R. Newbury, P. A. Williams, and W. C. Swann: Opt. Lett. 32 (2007) 3056.
7. A. D. Ludlow, T. Zelevinsky, G. K. Campbell, S. Blatt, M. M. Boyd, M. H. G. de Miranda, M. J. Martin, J. W. Thomsen, S. M. Foreman, J. Ye, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, Y. Le Coq, Z. W. Barber, N. Politi, N. D. Lemke, K. M. Beck, and C. W. Oates: Science 319 (2008) 1805.
8. M. Misha, F. L. Hong, K. Nakagawa, and K. Ueda: Opt. Express 16 (2008) 16459.
9. H. Jiang, F. Keferritian, S. Crane, O. Lopez, M. Lours, J. Millo, D. Holleville, P. Lemonde, Ch. Chardonnnet, A. Amy-Klein, and G. Santarelli: J. Opt. Soc. Am. B 25 (2008) 2029.
10. G. Grosche, O. Terra, K. Prudnik, R. Holzwarth, B. Lipphardt, F. Vogt, U. Sterr, and H. Schnatz: Opt. Lett. 34 (2009) 2270.
11. S. Nagano, H. Ito, Y. Li, K. Matsubara, and M. Hosokawa: Jpn. J. Appl. Phys. 48 (2009) 042301.
12. L. S. Ma, P. Jungnner, J. Ye, and J. L. Hall: Opt. Lett. 19 (1994) 1777.
13. M. Takamoto, T. Takano, and H. Katori: Nat. Photonics 5 (2011) 288.
14. Y. Takamoto, F. L. Hong, R. Higashii, and H. Katori: Nature 435 (2005) 321.
15. T. Akatsuka, M. Takamoto, and H. Katori: Nat. Phys. 4 (2008) 954.
16. T. Mukaiyama, H. Katori, T. Ido, Y. Li, and M. Kurwata: Physics 2011 (2012) 113002.
17. P. G. Westergaard, J. Lodevyck, L. Lorini, A. Lecallier, E. A. Butt, M. Zawada, J. Millo, and P. Lemonde: Phys. Rev. Lett. 106 (2011) 210801.
18. M. Takamoto, F.-L. Hong, R. Higashii, Y. Fujii, M. Imae, and H. Katori: J. Phys. Soc. Jpn. 76 (2007) 104302.
19. G. Santarelli, C. Audoin, A. Makdisii, P. Laurent, G. J. Dick, and A. Clairon: IEEE Trans. Ultrason. Ferroelect. Freq. Control 45 (1998) 887.
20. S. Falke, H. Schnatz, J. S. R. Vellore, T. Middelmann, S. Vogt, S. Weyers, B. Lipphardt, R. Holzwarth, B. Lipphardt, F. Riehle, U. Sterr, and H. Schnatz: Eur. Phys. J. D 48 (2008) 11.