Developments of Optical Frequency Standards at NICT and All-Optical Comparison Against a Remote Clock in University of Tokyo Using 60km Fiber Link

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Abstract

At National Institute of Information and Communications Technology (NICT), we have lately developed a lattice clock using ^{87}Sr atoms as well as a single ion clock based on $^{40}Ca^{+}$. Besides the comparison of the two atomic standards inside the institute, all-optical fiber-link to transfer frequency standards to the University of Tokyo (UT) has been developed to evaluate the uncertainty and stability of our standards by referring the state-of-the-art lattice clock locating in UT. The initial evaluations have resulted in the relative stability of 10^{-16} level, clearly showing the differential frequency of 4-5Hz mainly caused by the 45m difference of the elevation.

1. Introduction

To establish stable and accurate frequency standards in the optical region, NICT has developed two types of optical frequency standards. One is an ^{87}Sr optical lattice clock (Figure 1 (a)) and the other is a $^{40}Ca^{+}$ single ion clock (Figure 1 (b)) [1]. At University of Tokyo, the lattice clock was invented in 2005 [2] and has been operational for several years. To compare the frequency of these optical frequency standards, we have physically linked two campuses by a 60km optical fiber, and the phase noise coupled to the fiber was compensated by the fiber-noise cancelling technique [3]. In this paper, the overview of our optical frequency standards and the fiber-transfer system will be first introduced, and then the initial results of the direct comparison over the fiber link will be presented.

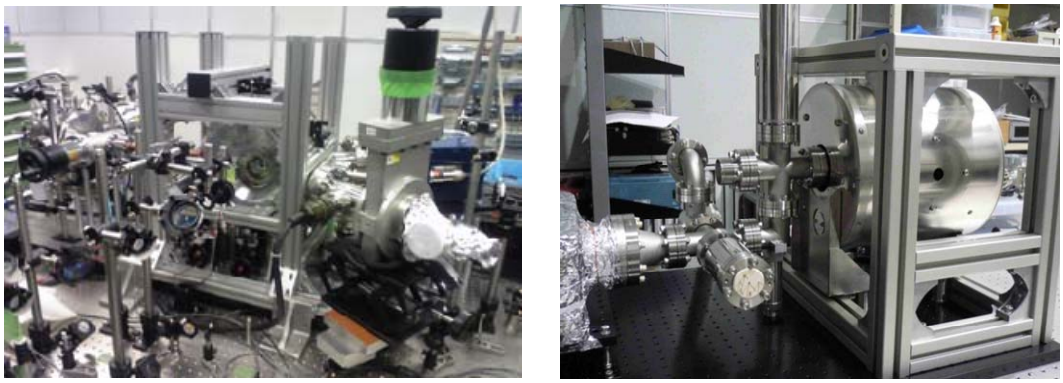

Figure 1 (a) Optical lattice clock based on ^{87}Sr atoms. **(b)** Optical frequency standard based on a single Ca^{+} ion.

2. Optical frequency standards at NICT

Our ^{87}Sr optical lattice clock employs one dimensional lattice. More than 10^5 ^{87}Sr atoms are laser-cooled by two stage magneto-optical trapping process and ~10^4 atoms are loaded into the lattice. The atoms are alternatively spin-polarized to m_F=-9/2 and 9/2 states of the ground state, and the frequency of 698 nm clock laser is locked to the midpoint of the two recoil-free resonances of the stretched states, obtaining the resonant frequency free from 1st order Zeeman shift. In the $^{40}Ca^{+}$ single ion clock, a 729-nm clock laser was stabilized to the $^2S_{1/2}$-$^2D_{5/2}$ clock transition. While the instability of 5×10^{-15} at 100 - 1000 seconds in 2008 was determined by the ambient magnetic

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field [1], we have switched to a magnetically-shielded new chamber, resulting in the ten-fold reduction of the observed spectral width down to 30Hz (FWHM). The instabilities of both optical clocks were investigated by the direct comparison bridged by a Ti:Sa based optical frequency comb [3]. As shown in Figure 2, the instability has reached in 10^{-16} regime in 1000s and further averaging has resulted in 2×10^{-16} instability.

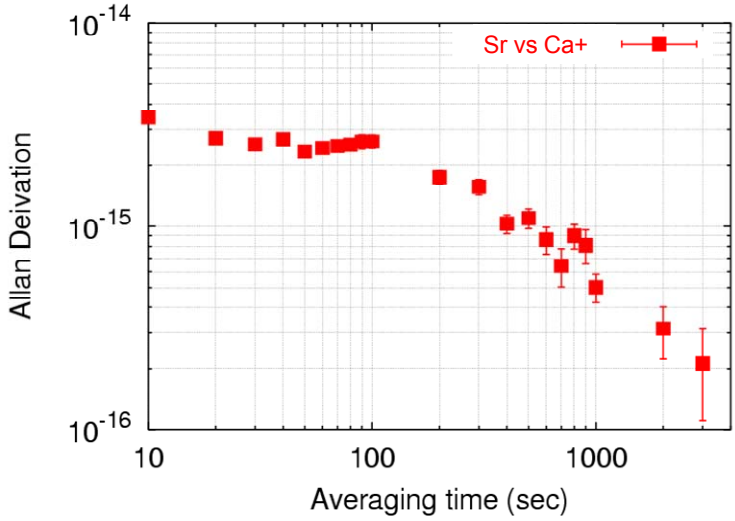

Figure 2 Frequency instability between the $^{40}Ca^{+}$ single ion trap system and the ^{87}Sr lattice clock system. It has been confirmed that both optical frequency standards have stabilities well better than 10^{-15}.

3. 60km optical fiber link and the system to compensate the fiber noise

The 60km fiber connecting NICT and UT is divided to two parts as shown in Figure 3. Main part of 45km connecting from the NICT headquarter to Otemachi (business district of Tokyo) is served by NICT as a testbed for R&D purpose. The residual 15km to University of Tokyo is loaned by a private company.

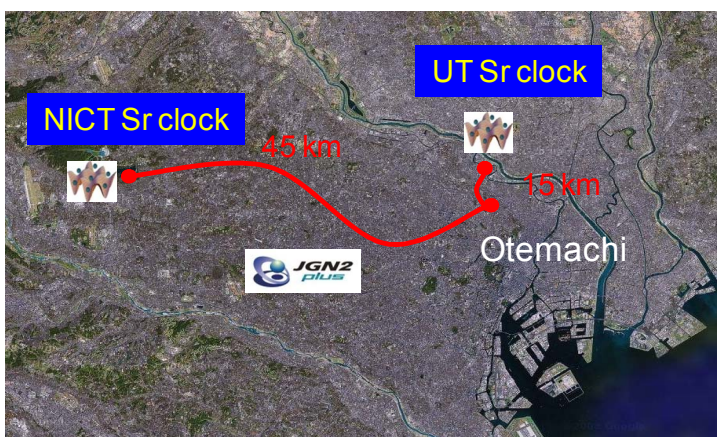

Figure 3 60km fiber link partly served by NICT as a part of JGN2+ testbed and the rest loaned from a private company

Figure 4 shows the schematic diagram of the all-optical frequency link from NICT to UT. The system consists of lattice clocks and optical frequency combs in each site and the 60km optical fiber link with the fiber-noise cancelling capability [4]. The frequency of the 1.5μm telecommunication band was converted to the near infrared by the second harmonic generation using waveguide PPLN crystal. The fiber link is first characterized by the comparison of two clock lasers, namely the 729nm laser for Ca^{+} clock locating at NICT and the 698nm laser served for the lattice clock at UT. The instability has resulted in 3×10^{-15} @ 1s, which is in same level as the

numbers independently evaluated in each sites. Since the instability of the frequency link has 1/τ dependence (τ: averaging time), the result indicates that the fiber link does not limit the overall instability of the NICT-UT lattice-clock comparison.

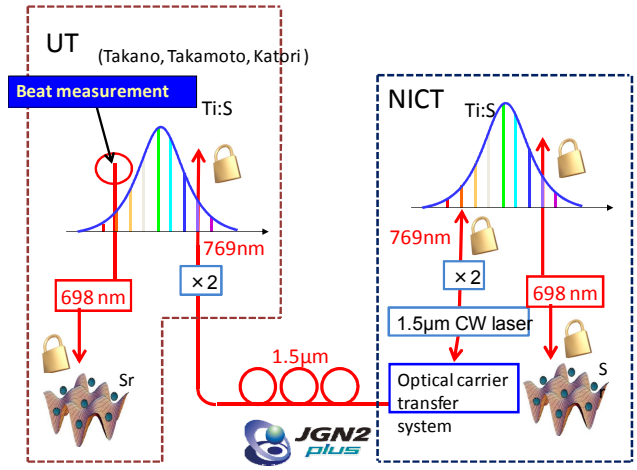

Figure 4 The optical fiber standard frequency dissemination system.

4. Direct comparison of two optical lattice clocks

The frequency comparison of two optical lattice clocks, one at NICT and the other in UT, was implemented by measuring the beat frequency between the 698nm clock laser at UT and its nearest component of the frequency comb which is phase coherently linked to the lattice clock at NICT. By tracing the frequency link and determining the mode number of related comb components, the frequency difference of the two lattice clocks is obtained as a simple algebraic function of the measured beat frequency. Figure 5 shows the resultant differential frequency showing the capability to measure in 0.5 Hz uncertainty. The differential frequency of 3.9Hz agrees with the total of the differential systematic shifts which are predominated by gravitational shift due to the 45m of the differential elevation between two sites. Lower panel shows the instability of the comparison which reaches 3×10^{-15} in 300 seconds of averaging.

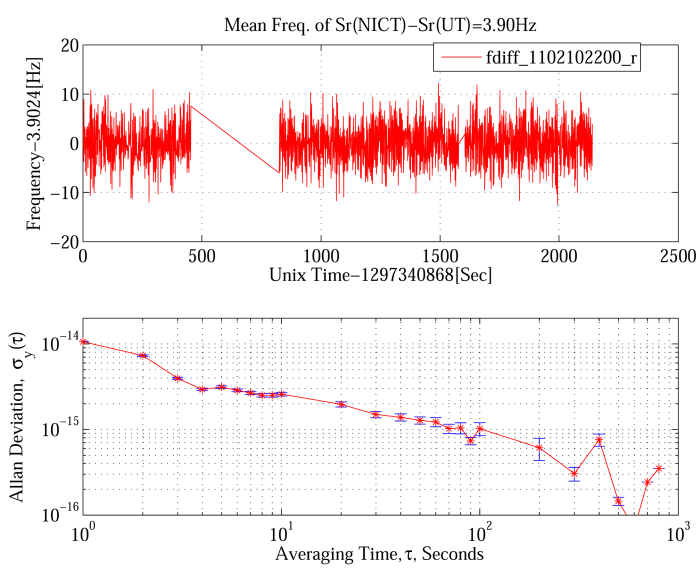

Figure 5 Differential frequency and its instability between two Sr lattice clocks at NICT and

University of Tokyo. The comparison was performed using a 60km fiber link.

5. Conclusions

All optical precise frequency comparison of two ^{87}Sr lattice clocks at NICT and UT has been demonstrated. The zero measurement of the differential frequency expected in this experiment is critical to confirm the potential of the lattice clocks to allow sharing optical standards in 10^{-16} level or less in separate places. The confirmation of the zero measurement would also rule out the existence of unmanageable systematic shifts.

6. Acknowledgments

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7. References

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