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SI second: from microwave towards optical realization

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Abstract

Present definition of SI second is based on the hyperfine transition frequency (in the microwave region) in Cesium atoms since 1967. In the last two decades, frequency standards based on optical transition have shown remarkable progress by outperforming the best microwave frequency standard by at least an order of magnitude in terms of relative frequency uncertainty. This paper presents an insight on the present realization of a microwave SI second and the roadmap towards future realization based on optical transition frequencies.

1. Introduction

From tracking the movement of celestial bodies to mechanical clocks and now prevalent atomic clocks, timekeeping has been one of the greatest quests for finding stable and better oscillators. It is not possible to measure exact time but time interval and frequency are measured with the least uncertainty and best resolution. At present, SI second relies on the microwave transition in cesium atoms [1]. The best primary standards, based on laser-cooled cesium atoms, are able to realize the unit with a relative frequency uncertainty at low 10^{-16} level [2,3]. In other words, such clocks will not lose or gain more than one second in about 200 million years. Further improvement in the accuracy of cesium fountain clocks is possible but is highly impractical as the time needed to reduce the instabilities is longer for lower frequencies.

2. Limitation of Microwave Second

It is frequency that determines the statistical precision in the case of atomic clocks. Accurate atomic clocks rely on the measurement of a narrow spectroscopic linewidth ($\Delta\nu$) atomic resonance at a transition frequency of ν_0. The performance of the clock is measured in terms of the fractional frequency instability, which is minimized by repeatedly measuring the high-Q ($Q \approx \frac{\nu_0}{\Delta\nu}$) transition, and is given by the Allan deviation

$$\sigma(\tau) \approx 1/(Q\sqrt{N\tau}) \quad (1)$$

Where N is the total number of atoms or ions used in single measurement and τ is the total averaging time. Considering that the linewidth is limited by the quantum projection noise, a significant reduction in the clock instability can be achieved by using a transition with a higher frequency ν_0 (higher than that of microwaves) [4]. Frequency of an optical transition is five orders of magnitude higher than that of the Cesium microwave transition (9.192631770 GHz). This fact steered the research on more accurate optical clocks in the last two decades.

The concept of optical clocks was known for long but it was only around the turn of the 21st century that scientist overcame some of the technical hurdles in practical realization of an optical clock. Lasers with extremely stable frequencies and frequency comb are the key developments which triggered the first ever realization of an optical second.

3. Roadmap for the Redefinition of SI Second

Since 2001, several clocks based on optical transitions in ions and neutral atoms have been developed and have been consistently showing superior performance with around two orders of magnitude lower relative uncertainty with around two orders of magnitude lower relative uncertainty (at 10^{-18} level). A 10^{-18} level uncertainty means an error of less than a second in a billion years, the age of our universe. Based on better and consistent performance, optical clocks are pushing the case for a possible redefinition of SI second in terms of an optical transition. However, there is no consensus on the candidate/element and the confinement method for the eventual redefinition [4,5]. An optical clock can be realized either with single trapped ion or neutral atoms trapped in a lattice. Earlier realization has the advantage of long coherence time and thus lower uncertainty while the later one offers large S/N ratio thus providing better stability. At the same time, there are various species of ions (Yb+, Sr+, Al+, Ca+, Hg+ etc.) and atoms (Sr, Yb, Ca, Hg etc.) which are being investigated but no candidate has a clear and obvious advantage for redefining the time. Moreover, high accuracy time transfer/comparison links are required for inter-comparing the optical clocks being operated at different countries and continents around the world. It is clear that a significant amount of work still needs to be done before the redefinition of SI second. An envisioned possible timeframe for the redefinition is as early as 2030. However, in order to ensure a smooth transition to an optical second, the Consultative Committee on Time & Frequency (CCTF) under the international committee for weights and measures (CIPM), published a detailed framework with fixed milestones which have to be achieved in the domain of optical clocks before redefining the SI second [6-8]. The set of criteria include demonstration of better accuracy and stability, reproducibility of results, continuity with the current SI definition and even by inter-comparison of results from different laboratories with suitable time transfer methods. Until that happens, a number of optical transitions have been accepted as secondary representation of second (SRS) which have already started contributing to the maintenance of international atomic time (TAI) [9].

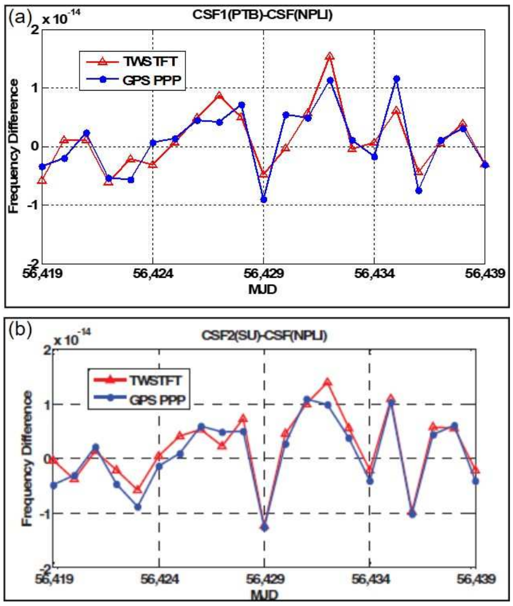

Fig. 1: Comparison of NPLI-CSF1 with fountain from (a) PTB (Germany) and (b) SU (Russia)

4. Present Primary Frequency Standards

Until redefinition of the SI second, Cesium fountain clocks remain the primary standards of time and frequency. Other than contributing to TAI, Cs fountains are also being used to steer the national timescales in many NMIs thus giving long-term stability and accuracy to timescales. Cs fountains have been operating almost continuously in most NMIs and are reliably being used for timescale steering. The countries which developed Cs fountain clocks which were approved as primary frequency standards (PFSs) and contribute/contributed data for the calibration of International Atomic Time (TAI) are France, Germany, USA, UK, Japan, Italy, India, Russia, China, Switzerland and Canada. Some of the fountains are running almost continuously and typically reports from about 6-8 fountains are being generated monthly data to calibrate TAI. Laboratories like PTB (Germany), LNE-SYRTE (France), USNO (USA) and INRIM (Italy) are steering their timescales with fountain data thus greatly improving stability and performance of their timescales. Even with a possible redefinition of SI second on the basis of an optical clock, Cs fountains will continue to play a significant role in T&F metrology just the way Cs beam clocks still continue to be the field workhorses for precision timekeeping. Even today, some of the laboratories like NPL (India), KRISS (Korea) and NMIJ (Japan) are developing new Cs fountain frequency standards.

At CSIR-NPL (NPLI), India's first ever Cesium fountain primary frequency standard was designed, developed and assembled indigenously. After successful international intercomparison in 2013 as shown in Fig. 1 and few contributions to TAI, NPLI-CsF1 was approved as a primary frequency standard (PFS) by CCTF. NPLI-CsF1 is currently being revived and upgraded for longer continuous operation for steering of UTC(NPLI) along with contribution to TAI. As a better and redundant option, a second-generation Cs fountain, is also under development at NPL. The present status of both the fountain clocks at CSIR-NPL will be discussed in this paper.

5. Summary

In summary, there has been a remarkable progress in the field of timekeeping with atomic clocks. From the present definition of SI second, best realized with laser cooled cesium fountain clocks, scientific endeavor in the field of optical clocks is pushing for a future redefinition of SI second on the basis of an optical transition. With a number of viable candidates and confinement techniques, a framework has been set-up by CIPM to ensure smooth transition to a new definition of SI second.

6. References

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