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PROGRESS IN THE EVALUATION AND OPERATION OF THE NRC STRONTIUM SINGLE ION FREQUENCY STANDARD AS AN OPTICAL ATOMIC CLOCK

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Abstract

Improved functionality and accuracy of the NRC Sr^+ single trapped ion 445-THz standard is described. Absolute frequency stabilization of all laser sources has been achieved together with loading of the ion trap using photo-ionization methods. An Erbium fiber laser based frequency comb is used to directly measure the 445-THz clock frequency. A 9 hr preliminary measurement was performed with statistical uncertainty of 1.4 Hz (3×10^{-15}) in excellent agreement with a previously reported value in 2005. A new endcap trap with probing and micromotion correction in three dimensions has been assembled and will have uncertainties approaching 10^{-17} in the near future.

Introduction

In the last few years, the fusion of a number of new technologies has allowed frequency and time from optical sources to be realized at the highest stability and accuracy. Among these new approaches, optical frequency standards based on the use of a single laser cooled and trapped atomic ion have shown to be one of the most promising. These systems are currently being explored as successors to the Cs definition of the SI second, sensitive probes to the time variation of fundamental constants, and in sensitive tests of relativity. One of the systems currently recommended as a secondary realization of the second and having great potential for extremely high accuracy is the electric quadrupole allowed 0.4 Hz natural linewidth, $5s \text{ } ^2\text{S}_{1/2} - 4d \text{ } ^2\text{D}_{3/2}$ transition in $^{88}\text{Sr}^+$ whose reference frequency is at 445 THz (674 nm) [1,2]. The relative simplicity of the system and its potential to be widely replicated and implemented make it an attractive choice for highly accurate frequency and time realization.

Improvements on the NRC Strontium Single Ion Frequency Standard

As with many of the single ion based optical frequency standards, the Sr^+ single ion system requires a multiplicity of laser sources for the operation of the device. In past work, frequency stabilization of the probe laser system at 445-THz, using a cascaded arrangement of two successively higher finesse Fabry-Pérot cavities, has resulted in resolved ion transition linewidths of 5-Hz [3] with probe laser drift rates now obtainable at better than 12 mHz/s . A saturation dip stabilized 422-nm diode laser source stabilized to the $5s \text{ } ^2\text{S}_{1/2} - 6p \text{ } ^2\text{P}_{1/2}$ ^{85}Rb transition in an absorption cell [4] provides long-term stable and optimized laser cooling of the ion. By using a transfer cavity method, the remaining repumping laser source on the 1092-nm D-P transition and the 1033-nm $^2\text{D}_{5/2}$ state clear out transition laser have also been servo stabilized such that drift in these sources are eliminated. Tests on these laser sources have shown unattended stable operation over indefinite periods of time (days to weeks). Recent tests have shown that the combined system can provide unattended, stable operation of the ion trap system for extended periods.

In collaboration with recent work at our labs for the trapping and laser cooling of neutral Sr, a resonant photo-ionization source at 461 nm was developed which delivered $200 \text{ }\mu\text{W}$ to the ion together with a 1-mW source at 405 nm . The two sources provide efficient two-step resonant photo-ionization of the neutral Sr entering the ion trap volume thus reducing the necessary Sr beam flux by a factor of 50 with mean loading times reduced to the $1\text{-}3 \text{ s}$ regime. The new loading system will therefore prevent material

deposition and the build up of space charge. This will result in a reduction of micromotion and ensure stable, long-term correction of systematic offsets.

Fiber Laser Frequency Comb Connection to the 455-THz Reference Transition

A key element in the single ion standard is the creation of a continuous, long-term link with the RF (from our recently developed Cs fountain clock) or with other optical frequencies. We have developed and tested a frequency comb system using an erbium doped fiber ring laser system which circulates 120-fs pulses at 100 MHz. The output is split between two fiber paths where it is amplified and its spectrum is spread in highly non-linear fiber. One of the two branches generates an octave of bandwidth (1-2 μm) and is used for the self-referenced stabilization of the carrier offset frequency of the comb. The second branch is optimized for comb generation at 1348 nm.

Figure 1. Measured $^{88}\text{Sr}^+$ ion S-D clock transition frequency. The plot is the combined data from the probe laser offset to the ion centre frequency and the comb measured probe laser frequency. The ion-probe offset has the quadrupole and tensor portions of the Stark shifts removed by the method described in [1]

A portion of this comb is frequency doubled in periodically poled $\text{MgO}:\text{LiNbO}_3$ to generate 230 μW at 674 nm in a 0.8-nm FWHM band near the reference ion frequency. Heterodyne signal-to-noise ratios of over 30 dB (100 kHz bandwidth) between the comb and the NRC probe laser system are obtained. Extended periods of the locked comb have been achieved over 8 days and continuous measurements of the probe for over 3 days were obtained showing instabilities commensurate with the reference hydrogen maser used down to 1×10^{-15} at 1000 s. In another series of measurements, the frequency of the S-D transition of the $^{88}\text{Sr}^+$ standard was measured in a continuous run of over 9 hours. An average frequency of $f_{2005} = 444\,779\,044\,095\,477.6\text{ Hz} \pm 1.4\text{ Hz}$ was obtained in agreement with

the 2005 Ti:Sapphire based measurements of $f_{2005} = 444\,779\,044\,095\,478.0 \pm 4.3\text{ Hz}$. Both measurements exclude systematic shift corrections due to micromotion effects and illustrate the high level of reproducibility of the current ion standard.

Next Generation Ion Trap System for the NRC Ion Frequency Standard

Figure 2. Photo of the NRC next-generation ion trap in a UHV chamber as viewed from the fluorescence collection port of a photon counting camera system. Also seen in the foreground are the radial trim electrode and Sr oven source.

We have designed, constructed, and assembled a new endcap trap system which will enable us to reduce and fully evaluate micromotion and other systematic shifts in the ion standard. The trap is fabricated with non-magnetic materials for minimal perturbation of the ion with chamber pressures below 10 nPa ensuring low collision rates and ion heating. Probing and cooling is provided over three orthogonal directions. Work is currently underway to test the new trap system and results will be reported at the meeting.

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