A Compact High Stability Optical Clock Based on Laser-Cooled Ca

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We report new measurements and modifications for a simple, compact, Ca atomic clock at 657 nm. External measurements were made against an independent Yb lattice optical clock via a fs-laser frequency comb. These results lead to upper limits for the Ca clock instability that are competitive on short time scales with the best existing atomic standards.

I. INTRODUCTION

This is an exciting time in the field of optical atomic clocks. Not only have the optical clocks been demonstrating higher stability than their microwave counterparts [1], but they are beginning to show excellent reproducibility as well [2]. Very accurate clocks will find important applications in precision metrology as well as enabling a possible redefinition of the second. However, widespread applications (space navigation, communications, etc.) may benefit more from the precise timing that results from high stability rather than extreme accuracy. It is perhaps timely to consider how such applications might access the timing revolution that is promised by the optical sources.

The problem of transferring the high stability of the optical clocks to the more tractable microwave domain has already been addressed by the fs-laser frequency comb [3]. But the challenge of getting the stable light (or microwaves) to the end users still remains. This challenge is particularly daunting since most optical atomic clock apparatus are fairly complicated, sometimes covering multiple optical tables. One approach is to keep the clocks at a few sites and then to disseminate the stable time through optical fibers. This possibility is under investigation, but will require significantly more infrastructure than currently exists to disseminate high stability clocks with high fidelity [4]. An alternative approach, considered here, is to make a compact optical clock that can be transported to the location where it is needed.

The idea of transportable optical clocks based on atoms in beams or molecules in vapor cells has been investigated previously [5, 6]. Here we describe a system based on laser-cooled atoms that could achieve the goal of transportability while still achieving extremely low instability (approaching 10^{-15} at 1 s). This system uses the clock transition at 657 nm in neutral calcium, which has been studied by various groups for over 25 years now. Previous demonstrations in our lab and at PTB used two stages of laser cooling to reduce the atom temperature to 10 microkelvin in order to achieve an absolute frequency

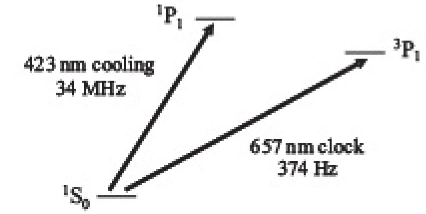

FIG. 1: Partial energy level scheme for neutral ^{40}Ca, showing transitions relevant to the Ca optical frequency standard.

uncertainty of 10^{-14} or below [7, 8]. In this paper we describe a simpler version of this clock that can still achieve high stability (albeit with higher systematic uncertainty) but with an apparatus whose size could be reduced to the transportable level. In contrast to state-of-the-art lattice-based [9] or trapped-ion clocks [2], which have measurement cycle times of 100's or 1000's of ms, our system has a cycle time of 3.5 ms, which reduces problems associated with cavity noise and simplifies the apparatus. Internal measurements on an earlier version of a compact Ca clock led to an estimated fraction frequency instability of 4 x 10^{-15} at one second [10]. Here we present independent measurements of the performance of a recent version of this clock, which show an upper limit for the fractional frequency instability of 3 x 10^{-15} at one second, averaging down to the mid 10^{-16} range at 200 s.

II. EXPERIMENTAL APPARATUS

The experimental setup has been described in detail in earlier publications [10, 11], but here we summarize the apparatus and describe recent modifications. The $^1S_0$ (m=0)→ $^3P_1$ (m=0) intercombination line at 657 nm (see Figure 1) is well-suited for a frequency standard due to its narrow linewidth (374 Hz), convenient wavelength, and inherent insensitivity to external perturbations. In order to reduce first-order Doppler uncertainties, we use laser cooling to reduce the temperature of the atomic sample to 2 mK before performing the clock spectroscopy. The atoms are then excited with a diode laser whose frequency is pre-stabilized by locking it tightly to a narrow fringe of an environmentally isolated Fabry-Perot cavity. The

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resulting spectroscopic signals from the clock transition are then used to fix the frequency of the clock laser on the center of the atomic transition.

Since it is necessary to extinguish the laser cooling light before performing the spectroscopy (to minimize light-induced shifts of the clock frequency), we employ a sequential measurement cycle. The cycle commences with a loading period (3 ms duration) during which we fill a magneto-optic trap based on the strong cooling transition at 423 nm with atoms from a thermal calcium beam. The resulting atomic sample contains roughly 5 x 10^6 atoms and has a (near Doppler-limited) temperature of 2 mK. The cooling light is generated by doubling the frequency of the light from a semiconductor laser system at 846 nm to produce 40 mW of light at 423 nm.

The atoms are then released to expand ballistically and excited by a four-pulse Bordé-Ramsey sequence [12]. With this method the atoms are first illuminated by a pair of pulses (separated in time by a duration, T) from one direction, and then are immediately illuminated by a second pair from the opposite direction. This pulse sequence leads to a sinusoidal excitation probability with a period of 1/(2T). This spectroscopic technique enables high resolution while maintaining a high signal-to-noise ratio. The degree of excitation induced by probe pulse sequence is read out by a single near-resonant pulse at 423 nm, which measures (with a high signal-to-noise ratio) fluorescence from the depleted ground state.

The red probe laser power (12 mW) is about one third that used in ref. [10] due to the demise of a high power optical amplifier at 657 nm. We partially offset this loss by using a beam with a $(1/e)^2$ diameter of only 3.3 mm. We also have added a Zeeman slower to our apparatus, which increases the loading rate of atoms into our trap by a factor of five. Since we no longer chop a linear (or quadrupole) magnetic field in this present version, we have been able to reduce power supply line noise that was written on to our atom number via the magnetic field. Another modification to the setup described in [10] is the addition of 657 nm velocity probes in all three dimensions. These probes enable us to minimize atomic cloud drift velocities thereby rendering the setup less sensitive to drifts in laser beam alignment. Reduction of the cloud drift velocity should enable the clock to be more stable on long time scales.

III. POTENTIAL ADVANTAGES OF A SHORT CLOCK CYCLE

The Bordé-Ramsey sequence described in the previous section takes about 0.5 ms, yielding a total measurement time of 3.5 ms. While our short measurement time means that the achieved line Q is lower than that of some other cold atom clocks, there are several potential advantages to the short cycle. First,

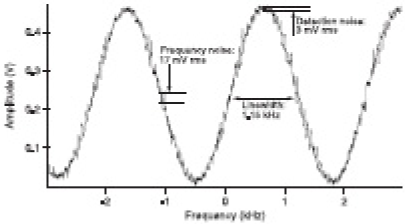

FIG. 2: The central fringes of the Bordé-Ramsey signal taken with a resolution of 1.15 kHz. The signal is the result of a single 2 s scan (no averaging) with a measurement time of 3.5 ms per point.

because the vast majority of the atoms do not have time to leave the trap volume during the spectroscopy, they can be recaptured by the next trap cycle. This recycling of the atoms leads to a large number of atoms with a short loading time. The large number of atoms yields a high signal-to-noise ratio for the spectroscopic signals.

A second advantage of the short measurement cycle is that we can potentially have reduced frequency noise. The fairly large servo bandwidth (> 150 Hz) for correcting reference cavity fluctuations greatly relaxes the performance requirements for the optical cavities - we can operate the clock in the presence of residual seismic noise below 5 Hz (and large thermally driven cavity drifts) without significant concern. Minimizing the duration of the loading cycle also reduces the optical Dick effect [13], which aliases noise from higher Fourier frequencies into the spectroscopic signal. Finally, thermal noise levels for optical reference cavities [14], which may limit the achievable noise floor for lasers locked to such cavities, are predicted to be lower at higher Fourier frequencies (for the calcium clock, the relevant frequencies are around 1 kHz). Perhaps it will be possible to reduce deleterious effects of fundamental thermal noise in optical cavities by locking rapidly to atoms.

A third advantage of the short cycle is that the atom trap fluctuations are much smaller on the millisecond scale than they are on the second scale. For a modulation frequency of 160 Hz, we find that we can run the clock without needing to normalize against shot-to-shot trap number fluctuations. This simplifies the apparatus and reduces the amplitude noise.

IV. MEASUREMENTS OF THE CLOCK STABILITY

Shown in Figure 2 is the spectroscopic signal taken at our usual working resolution of 1.15 kHz. From this signal we estimate an amplitude noise level limit to the frequency instability of 1 x 10^{-15} at 1 s for the Allan Deviation, with a frequency noise level 5-

6 times higher. Since the majority of the frequency noise is measured to be around 50-60 Hz, we should expect some suppression of this noise due to our high bandwidth. For an external evaluation of the Ca clock performance, we sent light from the Ca-stabilized laser to a fs-laser comb that was locked to a Yb lattice-based clock [15], which also has high stability. The noise introduced by the fibers transporting the light from the standards to the combs was measured and actively cancelled. In Figure 3 we show the measured fractional frequency instability for the beat between the Ca light and the nearest comb tooth for averaging times from 1 to 400 s.

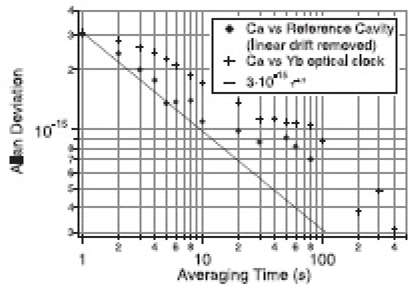

FIG. 3: Allan Deviation of the beatnote between the Ca and Yb optical clocks (crosses). Also shown (diamonds) is the Allan Deviation for the beatnote between the Ca clock and Yb clock laser locked to its reference cavity (with the linear drift removed). For reference we have included a solid line showing an Allan Deviation of 3 x $10^{-15}\tau^{-1/2}$.

Since the Yb clock servo system has an attack time of several seconds, the instability at 1 s is probably that of the Ca system. On longer times the measured fluctuations are probably that of the Yb clock, as is implied by the difference between the measurements for the Yb laser when it is locked to the atoms or just to its reference cavity. The reference cavity for the Yb clock is the same as that used for the Hg^+ optical clock and has demonstrated a 1 s instability below the levels measured here [16]. Based on this data, we estimate that the Ca clock has an instability at or below 3 x $10^{-15}\tau^{-1/2}$ (the solid line in the figure) out to 100 s. Clearly, more measurements (with longer averaging times) are needed to verify these results as well as to determine the time scale on which the long-term drifts of the Ca clock begin to be significant.

V. FUTURE PLANS

In the near term we plan to continue simplifying and reducing the size of the apparatus. Since the clock is based on just two semiconductor laser systems, it could be contained in a fairly small volume. Additionally, a more compact arrangement of the optical system could substantially reduce its present 3-4 square meter footprint. With the implementation of more powerful probe lasers, we can improve the contrast of the fringes and perhaps reach a one second instability of 1 x 10^{-15}, a value we think we can hold for times of several 1000 seconds or longer. It will also be interesting to make some absolute frequency measurements to see how reproducible the frequency of this standard could be - a level of 10^{-14} seems feasible.

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