Stability Measurements of the Ca and Yb Optical Frequency Standards

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***Abstract*—We describe two types of optical atomic clocks. The first is based on freely expanding calcium atoms and is optimized for experimental simplicity and high stability. The second is based on Yb atoms confined to an optical lattice that is designed to yield minimal shifts for the clock transition at 578 nm. Measurements of the effective beatnote between the clocks via a femtosecond-laser frequency comb show a fractional frequency instability of <5 x 10^{-16} @ 100 s averaging time.**

I. Introduction

The field of optical atomic clocks is progressing rapidly. Due to their high oscillation frequencies ($\nu_0 \sim 10^{15}$ Hz), optical clocks can achieve high line Q factors, which can lead to extremely high frequency stability [1]. Additionally, these clocks can potentially have small systematic shifts, yielding extremely accurate clocks as well. Here we describe two different types of optical clocks based on neutral atoms. The first uses Ca atoms that are laser-cooled and then allowed to expand ballistically during the clock spectroscopy [2]. This system is quite simple and offers an attractive route for construction of a relatively compact optical atomic clock. However, Doppler effects resulting from the free expansion of the atomic clouds lead to shifts that require considerable attention in order to achieve small absolute uncertainties. The second clock described here overcomes Doppler limitations by confining Yb atoms in a specially designed laser trap *during* the clock spectroscopy [3,4]. This allows construction of a clock that can achieve both high stability and high accuracy, albeit with a more complicated apparatus. Here we briefly describe the two clock apparatus and then present some initial measurements comparing the two that demonstrate frequency stabilities competitive with those of the best existing standards [1].

A. Previous Work on the Ca Clock Transition

The Ca optical clock is based on the 657 nm intercombination line and has been described in detail in several publications (see Figure 1) [2,5,6]. Its attractiveness lies in its convenient wavelength, narrow linewidth (374 Hz), and insensitivity to to external perturbations such as magnetic fields or atomic collisions. In order to reduce the size of the

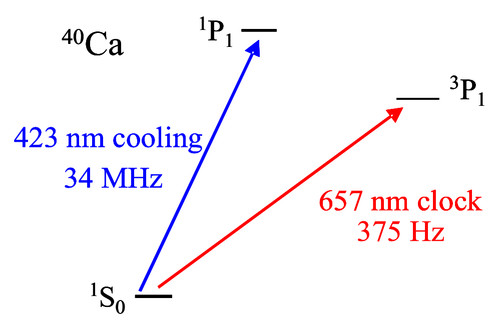

Figure 1. Relevant energy levels for the Ca optical clock

Doppler-related effects, laser cooling on the strong $^1S_0 \leftrightarrow {}^1P_1$ transition at 423 nm has been used to construct a magneto-optic trap that can collect 5-10 million atoms at a temperature of 2 mK. For more accurate measurements of the calcium transition frequency, a second-stage of laser cooling has been implemented by two groups to reduce the temperature of the calcium atoms to 10 μK [7,8]. Absolute frequency measurements with microkelvin atoms have been performed at NIST and PTB with femtosecond-laser frequency combs that connect the Ca standards to primary Cs fountain standards. The most recent NIST absolute frequency measurement yielded a result of 456 986 240 494 135.8 (3.4) Hz with a fractional frequency uncertainty of 7.5 x 10^{-15}, which was limited by technical issues that could be readily addressed in the future. The measured value agrees with the most accurate

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measurement at PTB to about a part in 10^{14}, making this optical transition one of the most accurately measured in multiple laboratories [2].

B. A Compact, High Stability Version of the Ca Clock

While more accurate measurements of the Ca transition frequency would certainly be valuable, we describe a different direction in this paper. The goal of this new work is to construct a greatly simplified version of the Ca clock apparatus that will achieve exceptionally high stability, albeit with reduced absolute accuracy. Such an apparatus would enable the exceptional stabilities already seen in laboratory optical clock demonstrations to become accessible to a wider range of applications, including space navigation and communication, and timing for high energy accelerator experiments and the next generation of high speed electronics. Other potential transportable clock systems based on thermal atoms or molecules have been previously demonstrated [9, 10]. The clock described here uses laser-cooled atoms to achieve a higher level of performance without over-extending the level of experimental complexity. This type of compact, stable clock capitalizes on the strengths of the calcium transition, namely, demonstrated high stability, reproducibility, and experimental convenience.

A distinctive aspect of this clock approach is its 3 ms cycle time, which is roughly 100 times shorter than that of other high stability clock systems. The resulting high servo bandwidth greatly relaxes the requirements for cavity thermal and vibration isolation, which complicate many optical atomic clock systems. A more efficient measurement cycle also reduces the amount of frequency noise added to the clock signal via the optical Dick effect [11].

This research extends our previous work [12] on a high stability apparatus in two ways. First, the apparatus is currently being modified with experimental simplification as a goal – the optics, electronics, and lasers for this version can be potentially fit into a single rack or less. Second, measurements of the stability will eventually be extended from the 1 s time scale to minutes, hours, and days to evaluate the range of applications for which this clock is well suited. Here we describe the modified apparatus and present some preliminary measurements of the clock stability.

C. The Ca Clock Apparatus

The basic apparatus has been described in detail elsewhere [2,5]. Here we briefly outline the principal parts along with relevant modifications. The physics package consists of two semiconductor-based laser systems, a vacuum system containing a calcium oven, two optical cavities, and relevant optics. Atoms are loaded from a thermal Ca beam into a magneto-optic trap based on the 423 nm cooling transition. To increase the loading rate, a Zeeman slower (10 cm in length) has been added. Since the apparatus efficiently recycles atoms, a 3 ms loading period can maintain more than 10^7 atoms in a volume of 1 mm^3. Light for the trapping and slowing beams is generated through frequency doubling of light from a MOPA (master oscillator power amplifier). Roughly 40 mW of light at 423 mW is produced with a build-up cavity containing a $KNbO_3$ crystal for 350 mW of 846 nm input light. With the magnetic quadrupole field (60 G/cm) left on (but all cooling and slowing light extinguished), we excite the freely expanding atoms with a four pulse (Bordé-Ramsey) sequence of light tuned near the 657 nm clock transition [2]. With this technique the atoms are illuminated by a pair of pulses from one direction separated by a period T. After a dark period of 3 µs, the atoms are illuminated by a second pair of pulses from the opposite direction. The spectroscopic resolution is determined by the relation, $\Delta\nu = 1/4T$. This main advantage of this technique is that it enables efficient excitation of the atoms, even at high resolution. Before the excited atoms have a chance to decay, the depletion of the ground state is read out with a near-resonant pulse at 423 nm. This detection scheme achieves a signal-to-noise ratio near the projection-noise limit [13,14], and when combined with modulation of the probe frequency (f_{mod} = 150 Hz), does not require normalization to account for shot-to-shot fluctuations in atom number.

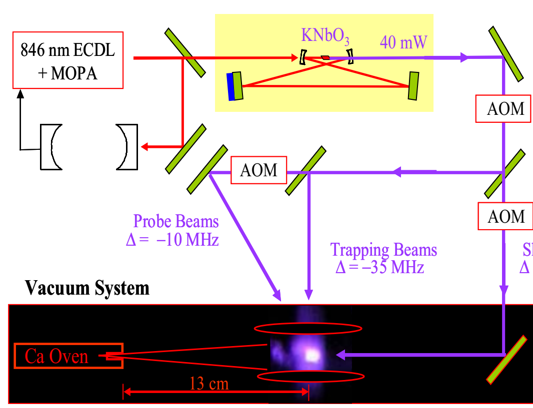

Figure 2. The trapping apparatus for the Ca clock. Omitted for clarity is a Zeeman magnet coil between the oven and the trap center.

In order to achieve the high spectroscopic signal-to-noise ratios required for good clock stability, the frequency noise of the probe laser needs to be reduced through stabilization on a narrow fringe of a Fabry-Perot reference cavity. We use an ULE cavity with a finesse of 200,000 that has been placed inside a vacuum can on an optical table that is isolated from vibrations. With modest thermal isolation, the cavity exhibits drifts less than 10 Hz/s. Due to the fast correction time afforded by the short measurement cycle, these drifts lead to offsets of less than 100 mHz. Through comparison with a second narrow laser, the linewidth of the probe laser (with a linear frequency ramp applied to a synthesizer controlling the light frequency via an acousto-optic modulator to compensate cavity drift) has been measured to be 1-2 Hz on a time scale of 4 s. To increase the available power, the stabilized diode laser is used to injection-lock two additional diode lasers. Output from the first is sent through a noise-compensated optical fiber to a femtosecond-laser comb for evaluation of the clock performance versus other standards. When the femtosecond-laser comb is locked to the Ca-stabilized light, the comb transfers the stability of the Ca standard directly to a countable microwave signal, thereby turning our frequency standard into a clock [1].

Light from the second injection-locked laser is sent through acousto-optic modulators to make the probe pulses. Optical fibers between the modulators and the vacuum system provide spatial filtering for the probe light. Figure 3 shows a spectroscopic signal taken at the usual working resolution of 1.1 kHz. These raw data contain no averaging and were collected with a measurement time of 3.5 ms per point. The signal-to-noise ratio on top of the fringe would support fractional frequency instability of 10^{-15} for 1 s averaging time, a factor of two larger than the predicted shot-noise-limited instability based on our experimental parameters. The noise on the side of the fringe is about three times larger and results from residual frequency noise around Fourier frequencies of 50-60 Hz.

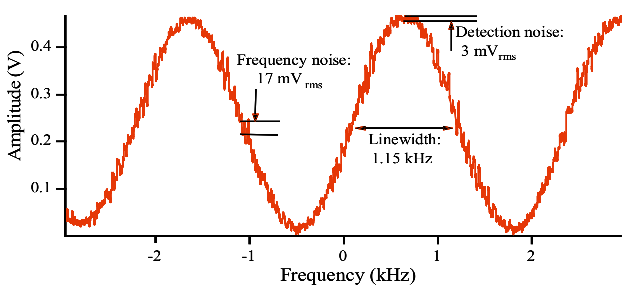

Figure 3. (Un-modulated) Bordé-Ramsey signal from the Ca spectrometer.

II. THE YTTERBIUM OPTICAL FREQUENCY STANDARD

A. Introduction to the Yb Lattice Clock

The Yb standard follows an approach that was first proposed for Sr [15] in an effort to reduce the systematic shifts associated with Doppler motion while maintaining the high signal-to-noise ratio achievable with a large number of neutral atoms. In this approach one confines atoms tightly in potential wells of a far-detuned optical lattice [3]. Spectroscopy of the trapped atoms along the direction of tight confinement can be insensitive to Doppler effects (i.e., broadening and recoil), thereby enabling high resolution spectroscopy with a single traveling wave probe pulse. Moreover, the long confinement times provided by such a lattice can enable a spectroscopic resolution approaching 1 Hz.

A critical aspect of this technique is the design of a lattice that minimizes its effect upon the clock transition. This can be achieved to first order by tuning the wavelength of the lattice laser to a point where it yields equal Stark shifts for the ground and excited states of the clock transition. In order to minimize the sensitivity of this cancellation to lattice polarization, clock states with spherical symmetry are used [3]. Specifically, for Sr and Yb, a transition between the $^1S_0$ ground state and the lowest lying $^3P_0$ state is nearly ideal for this application [3,16]. In the odd isotopes this forbidden transition is sufficiently allowed through mixing of the $^3P_0$ state with other more allowed states via the magnetic moment of the non-zero nuclear spin. Our work is distinct from other lattice-based clocks in that we use an even isotope (I=0), whose clock transition we access through use of a small static magnetic bias field [17]. The even isotopes have the advantages of reduced magnetic field sensitivity and single-peaked spectra that are immune from optical pumping effects. In this paper, we present our latest spectroscopic results along with our first measurements of the stability of the probe laser at 578 nm when locked to the clock transition.

B. The Yb Lattice Clock Apparatus

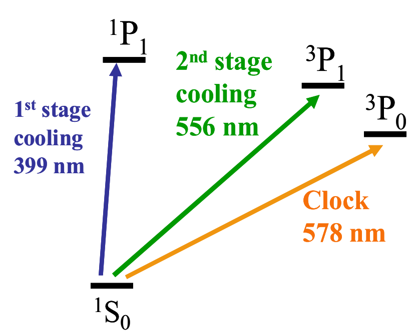

Figure 4. Relevant energy levels for the Yb lattice clock.

Shown in Figure 4 are the relevant energy levels in Yb for the lattice clock apparatus [4]. Before probing the clock transition at 578 nm, we need to load the atoms into the 1-D optical lattice. Since the trapping potential of the lattice is fairly shallow (~50 μK), it is necessary to cool the atoms to roughly this level for sufficient transfer of atoms to the lattice.

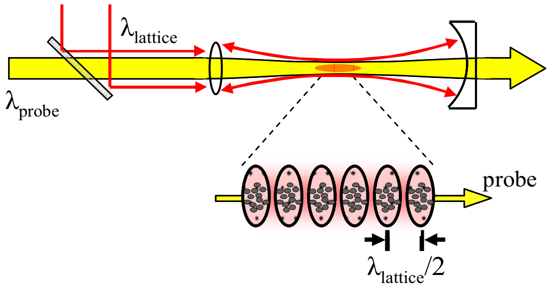

Figure 5. Lattice apparatus showing the 1-D horizontal standing wave and the co-propagating single-pass probe. Roughly 10-20 atoms are contained in each pancake-like potential well.

We do so with two stages of laser cooling. The first stage uses the strong cooling transition at 399 nm to load atoms from a thermal beam into a traditional magneto-optic trap. A focused laser beam propagating opposite to the atomic beam increases the loading rate, although a Zeeman slower is not employed. We use diode lasers to generate the necessary cooling light, and within 300 ms we can load 10^6 atoms with a resultant temperature of ~ 5 mK. The second stage magneto-optic trap uses the narrower 556 nm intercombination line and can reduce the atom temperature to around 50 µK for the even isotopes of Yb, and to a somewhat cooler temperature for the odd isotopes [18].

The lattice light is left on during the entire measurement cycle. After 50 ms of second stage cooling, about 10^4 atoms are loaded into the 1-D standing wave (see Figure 5). To avoid broadening and shifts of the clock transition, it is necessary to tune the lattice wavelength close to its Stark shift-canceling value, which is near 759 nm for Yb. Light near this wavelength is generated with a Ti:Sapphire laser, which is injection-locked by a tunable diode laser [19]. The output of the Ti:Sapphire laser passes through an acousto-optic modulator for intensity control and an optical fiber for spatial filtering. After the fiber, 1 W of 759 nm light is available for the lattice, which is formed by focusing the light to a 30 µm waist and retroreflecting it off a curved mirror. The 1-D lattice is oriented in a direction perpendicular to that of gravity.

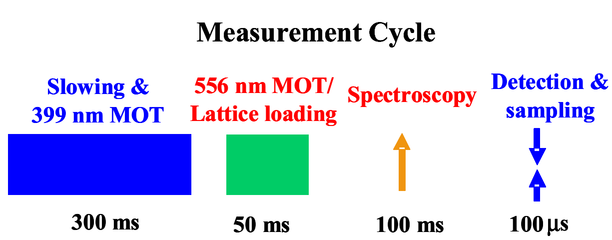

Figure 6. The measurement cycle for the Yb lattice clock. The lattice light remains on throughout the entire cycle. The spectroscopy period ranges from 1 ms at low resolution to 200 ms for high resolution.

Before the clock transition is probed, the cooling lasers are extinguished (see Figure 6). The 578 nm probe light is overlapped with the lattice beams, although it has a beam waist twice that of the lattice light. Additionally, it is passes through the atoms just once, since the curved mirror is weakly reflecting at 578 nm. The probe light is derived from a dye laser whose frequency is pre-stabilized on a high finesse cavity. The reference cavity is one that has been developed for the Hg^+ ion optical clock laser, which has demonstrated a sub-hertz linewidth for a measurement time of 20 s [20]. We step the probe laser frequency with an acousto-optic modulator that is driven by a direct digital synthesizer, and the measurement cycle is repeated for each probe frequency. A cycling detection pulse at 399 nm measures the number of atoms remaining in the ground state. For probe times of 200 ms we have seen spectra as narrow as 4 Hz (see Figure 7), which corresponds to a line Q of greater than 10^{14}.

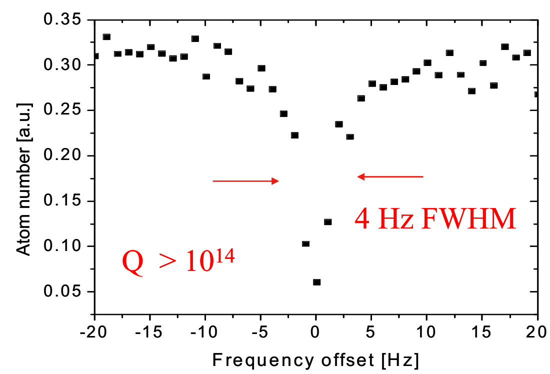

Figure 7. High resolution spectroscopy of the Yb clock transition. Excitation leads to a depletion of the ground state population as measured by a near-resonant 399 nm detection pulse.

III. Stability Measurements for the Clocks

In order to measure the stability for each of the clocks, it is necessary to compare them to a more stable reference. However, since these clocks are pushing the state-of-the-art, suitable references are not readily available. As a first test we compared the Ca and Yb clocks to each other, which puts an upper limit on the instabilities of each of the clocks. Since the two clock frequencies are separated by 62 THz, they could not be beat directly together. Instead we spanned this gap with a femtosecond-laser frequency comb whose direct spectral output covers the range from 550-1100 nm [21]. This broad output enables self-referencing of the comb without the need of additional spectral broadening. We locked the probe lasers to square-wave modulated versions of the respective spectroscopic signals similar to those shown in Figures 3 and 7.

For the Ca standard we used a resolution of 1.15 kHz, while the Yb standard used a resolution of 20 Hz. When a tooth of the self-referenced comb was locked to light from the Yb standard, the stability of the standard was transferred to the rest of the comb teeth [1, 22]. Then a beatnote between a tooth near 657 nm and the Ca-locked light displayed the combined frequency fluctuations of the two standards. Figure 8 shows a preliminary Allan deviation taken between the two standards. The Ca servo had a 10 ms time constant, while the servo for the Yb light took about 3 s. Some evidence for the Yb servo time is visible in Figure 8 as the Allan deviation begins averaging down as approximately $\sigma_y(\tau) = 5 \times 10^{-15}\tau^{-1/2}$ after a few seconds. If the two standards contributed equally, this would yield an Allan deviation of $3.5 \times 10^{-15}\tau^{-1/2}$ for each of the standards, which is reasonably consistent with independent estimates based on the spectroscopic signals. After 200 s averaging time, the imprecision is less than 5×10^{-16} or 0.2 Hz, so clearly, very high precision is accessible for these systems with a conveniently short averaging time. However, more data are required to extract more detailed information about the individual clock performance levels.

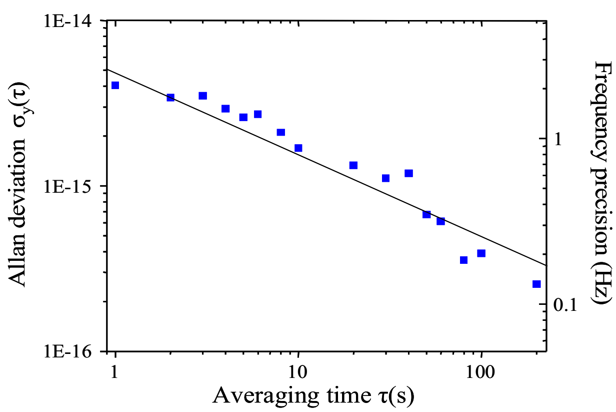

Figure 8. Allan deviation (squares) of the effective beatnote between the Yb and Ca standards. Shown for reference is a line corresponding to an Allan deviation of $5 \times 10^{-15}\tau^{-1/2}$.

IV. Future Work

As both clock apparatus near maturity, the most important near term goals for the two standards are measurement-based. For the Ca clock we need to measure its stability on longer time scales to see how far down it averages and how long it takes to reach its noise floor. Because residual Doppler effects need to be canceled to such a high degree, drifts in trap alignment (leading to a change in the drift velocity of the atomic cloud) or probe beam alignment would lead to drifts of the clock frequency. We estimate that with reasonable environmental control the clock frequency could be stable to one part in 10^{15} for a day or more, but this needs to be confirmed by experiment.

For the Yb standard a detailed evaluation of potential shifts of the absolute clock frequency will be performed. For this investigation, perhaps the most critical issue is a more precise determination of the zero-shift wavelength along with an evaluation of the effects of higher-order polarizability due to a nearby two-photon transition [16]. Other important shifts include ac Stark effects due to the probe and Zeeman effects due to the magnetic bias field. The evaluation of these effects will be greatly accelerated due to the high stability of the optical clocks. In particular, we will use the Ca standard as a reference and change the relevant Yb parameters to quantify the critical sensitivities. From Figure 8 we see how hertz-level shifts can be measured with only seconds of averaging.

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