Lattice-based optical clock using an even isotope of Yb

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ABSTRACT

We describe progress toward an optical lattice clock based on an even isotope of Yb. The $^1S_0 \rightarrow {}^3P_0$ clock resonance in ^{174}Yb is accessed through a magnetically induced spectroscopic technique. Using $\approx 1\,\text{mT}$ static magnetic fields and $\approx 10\,\mu\text{W}$ of probe light power we generate Rabi frequencies of several hertz. The narrow spectroscopic features that result ($< 10\,\text{Hz}$ FWHM) require a highly stabilized laser at the clock transition wavelength of 578 nm. We describe a new all solid-state laser system that shows hertz level stability. In order to cancel the slow drift of the cavity, spectroscopy is performed on the clock transition to provide feedback to the laser. Using a Ca neutral atom frequency standard as a reference oscillator,we show high stability and an effective method for investigating clock frequency shift systematics.

Keywords: Atomic Clocks, Metrology, Optical Lattices, Precision Spectroscopy

1. INTRODUCTION

Optical frequency atomic clocks based on neutral atoms trapped in optical lattices are a fairly new paradigm. While optical clocks based on single trapped ions promise to achieve 10^{-18} fractional frequency uncertainty,[1,2] clocks based on free-falling neutral atoms were deemed limited to the few parts in 10^{-16} level due to Doppler related systematic shifts.[3] The use of optical lattices to confine large numbers of neutral atoms to the Lamb-Dicke regime for Doppler and recoil-free spectroscopy promises a path to achieving uncertainty below the 10^{-17} level. The key to achieving such low uncertainty in the presence of the highly perturbing field of the lattice is the ability to render the differential polarizability of the clock states insensitive to lattice intensity and polarization. This is accomplished by tuning the lattice frequency to the "magic" frequency where the first order AC Stark shifts on the clock states are equal and by choosing polarization-insensitive J=0 to J=0 clock states. Katori et al.[4] suggested that such a clock based on the hyperfine induced $^1S_0 \rightarrow {}^3P_0$ transition in ^{87}Sr could achieve below 10^{-17} uncertainty and stability. Soon after, ^{171,173}Yb were also suggested as prime candidates for optical lattice clocks.[5]

Since then progress has been rapid. Three groups have measured frequencies of the clock transition[6–8] in ^{87}Sr that agree to within 1×10^{-14}. In addition, a number of groups have started optical clock projects based on Yb. The clock transition in the odd isotopes of Yb has been observed in cold atomic clouds[9,10] and in an optical lattice. The clock transition in the even ^{174}Yb isotope has also been observed in an optical lattice by means of a magnetically induced spectroscopic (MIS) technique.[11,12] In this paper we describe the current state of our Yb standard, its general operation, and our progress toward a high-accuracy frequency measurement.

Until recently, the measurements of the clock transitions in Yb made in our lab at NIST were performed with light from a highly stabilized dye laser system that was fiber coupled from the Hg^+ clock experiment to our lab. For a long-running project such an arrangement was impractical and limited the ability to directly compare the Yb and Hg^+ frequencies. Therefore, we built a solid state laser system to probe the clock transition in Yb, and we include a description of the construction and specification of this system in this paper.

Before Yb can be used as an accurate optical frequency standard systematic frequency shifts have to be investigated, measured, calibrated, and controlled. The main shifts include the first order (polarizability) and

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second order (hyperpolarizability) AC Stark shifts due to the optical lattice, and in the even isotopes the second order Zeeman shift and the light shifts due to the probe at 578 nm. Evaluating these shifts to a high degree of accuracy requires a stable oscillator for use as a reference. Often these measurements have been made with the ultra stable cavity of the probe laser as the only reference. While this technique can be effective, optical frequency comparisons with the Ca optical frequency standard located in the same lab as our Yb clock allows us higher precision. We include examples and discuss the merits of these comparisons between Ca vs. Yb clocks as a tool for systematic evaluation.

1.1 Magnetically Induced Spectroscopy (MIS)

The $^1S_0 \to {}^3P_0$ atomic transition in the odd isotopes of the alkaline earth-like elements is well suited to optical lattice clocks. It is doubly forbidden (spin and angular momentum), generating extremely narrow natural linewidths (few millihertz), and is only weakly sensitive to polarization of the lattice potential. The latter characteristic is vitally important to the control of the lattice induced light shifts and the ultimate accuracy of the clock. This same transition in the even isotopes is even less sensitive to lattice polarization, and could simplify the control requirements of the lattice polarization and allow for even more accurate clocks.[13] In addition, the lack of Zeeman substructure simplifies the spectroscopy and eliminates optical pumping issues. Unfortunately, the mechanism that induces the polarization sensitivity in the odd isotopes, the hyperfine interaction, also generates the non-zero excitation probability between the two states. In the even isotopes, which have no nuclear spin, the hyperfine interaction is absent, leaving the single photon excitation probability between the two states essentially zero.

In order to generate some excitation probability, one needs a mechanism for mixing small amounts of the electric dipole allowed states like the $^1P_1$ and $^3P_1$ states into the upper $^3P_0$ clock state. Others have proposed two- or multi-photon techniques to generate excitations to the excited state, but these require multiple lasers and difficult nonlinear optics to recreate the clock excitation frequency.[14,15] The magnetically induced spectroscopic (MIS) method we have developed requires only the addition of a static magnetic field to induce accessible excitation probabilities between the clock states.[11]

In first order, time independent perturbation theory, the admixture of the $^3P_1$ state into the $^3P_0$ state is given by the ratio of the magnetic dipole matrix element $\Omega_B = \left\langle {}^3P_1, m_j = 0 \right| \vec{\mu} \cdot \vec{B} \left| {}^3P_0 \right\rangle / \hbar$ and the detuning Δ. The new perturbed state is then $\left| {}^3P_0' \right\rangle = \left| {}^3P_0 \right\rangle + \Omega_B/\Delta \left| {}^3P_0, m_j = 0 \right\rangle$. The excitation probability is then allowed through the second term and, the Rabi frequency is given by

$$\Omega = \frac{\Omega_B \Omega_l}{\Delta}, \tag{1}$$

where Ω_l is the on-resonance Rabi frequency from the ground state to $^3P_1$ state. Rewriting this in terms of the fields one gets $\Omega = \alpha |B| \sqrt{I} \cos\theta$, where θ is the angle between the polarization and the magnetic field and $\alpha = 186\,\mathrm{Hz}/\left(\mathrm{T}\sqrt{\mathrm{mW/cm^2}}\right)$ for Yb. This means that only relatively small magnetic fields of 1 mT (10 G) are required to generate experimentally feasible Rabi frequencies (e.g., 1 mT and 100 mW/cm^2 generates about 2 Hz Rabi frequencies or a π pulse in 250 ms). In addition to the induced Rabi frequency, one must calculate the shifts due to the extra fields. The second order Zeeman coefficient is dominated by the mixing of the excited state with the $^3P_1$ state and is given by $\Delta_B = \Omega_B^2/\Delta$, or approximately $-6.2\,\mathrm{MHz/T^2}$. Because the induced linewidth is small, we also have to be more concerned with the probe induced light shift, which has been estimated to be $15\,\mathrm{mHz/(mW/cm^2)}$. These shifts are reasonable, and it has been estimated that with good field control the shifts could be held to well below 10^{-17}. The clock transitions in ^{174}Yb and ^{88}Sr have been observed in an optical lattice with the MIS technique,[12,16] and it has proved to be very simple to implement experimentally.

2. EXPERIMENT

Before one can perform spectroscopy on the atoms with the MIS technique, it is necessary to load the atoms into a "magic" wavelength lattice to create the long coherence times required for the small Rabi frequencies generated. The light for the 1D optical lattice at the "magic" wavelength of 759.35 nm is generated by an injection-locked, 2 W output Ti:sapphire laser system. The light is then fiber coupled to the vacuum chamber that is used for

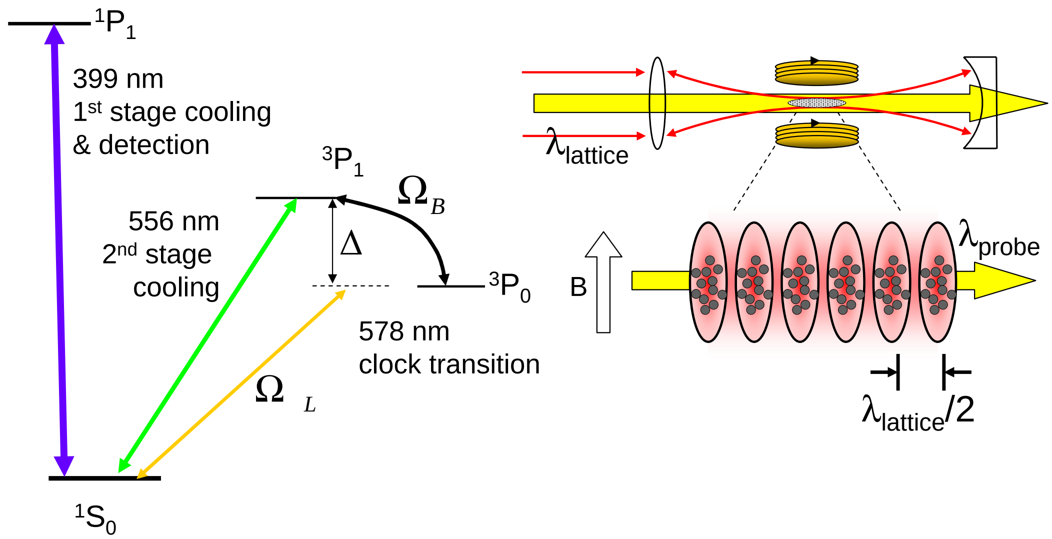

Figure 1. A description of the magnetically induced spectroscopy (MIS) technique. After the Yb atoms have been cooled and trapped on the 399 nm and 556 nm transition and loaded into a lattice near the "magic" wavelength at 759.35 nm the bias magnetic field is turned on. The bias magnetic field mixes the ^3P states inducing a non-zero excitation probability on the clock transition. The atoms are then excited with a highly stabilized laser at 578 nm.

atom trapping. Here 1 W of laser power is focused to a 30 μm waist and then retroreflected with a curved mirror placed one focal distance away. The resulting standing wave structure generates a lattice with a depth of about 1 MHz (or 50 μK).

We generate a large number of atoms with temperatures less than the trap depth through the use of two stages of magneto-optical traps (MOTs). The first MOT is based on the broad (29 MHz) $^1S_0 \rightarrow {}^1P_1$ cooling transition at 399 nm. The laser source for this cooling light is generated with InGaN diodes. The MOT is loaded from an atomic beam produced by a 450 °C oven. Using the strong transition, we can collect and cool, to millikelvin temperatures, approximately 10^6 atoms in 300 ms. To cool the atoms further, we transfer most of the atoms into a MOT based on the $^1S_0 \rightarrow {}^3P_1$ intercombination line at 556 nm. The laser source for this transition is a frequency doubled Yb doped fiber laser. With a linewidth of 180 kHz, this transition allows us to cool the atoms to a couple of tens of microkelvins in less than 50 ms. The lattice is left on during the whole cooling process, and roughly ten thousand atoms are loaded into the lattice.

Once the atoms are loaded into the lattice, we generate the static magnetic field for the MIS technique by switching the current direction in one of the MOT coils. The coils, which are then in a Helmholtz configuration, allow us to generate fields up to 100 Gauss. Once the magnetic field has settled, the resonant probe light at 578 nm is shined on the atoms along the lattice direction, along which the atoms are well confined in the Lamb-Dicke regime. After the excitation pulse (up to 200 ms, limited by the trap lifetime) the number of atoms remaining in the ground state are measured by applying a resonant pulse on the strong 399 nm transition and observing the fluorescence. After the detection pulse, the cycle begins again with a total period of approximately 500 ms. Spectra can be taken by stepping the frequency of the acousto-optic modulator (AOM) that controls the probe light. Locking of the probe laser to the line is accomplished by alternating on the half power points of the line, demodulating with a microcontroller, then feeding back to the frequency of the AOM.

In order to have good control over the lattice laser frequency, we lock the lattice laser to an optical frequency comb (see Fig. 4). The beat note between the stabilized comb and a portion of the lattice laser is amplified and filtered, then passed through an RF interferometer that consists of a splitter, a delay line, and a mixer. With a delay line of ~ 1.5 m the interferometer produces fringes with a free-spectral range of about 100 MHz. The beat note is then stabilized to the side of the fringe by applying feedback to a piezo element in the lattice laser. The lock is generally stable to 100 kHz for short time scales but wanders on the order of a couple megahertz due to long term thermal drifts. This lock is a compromise between robustness (large capture range), simplicity (no

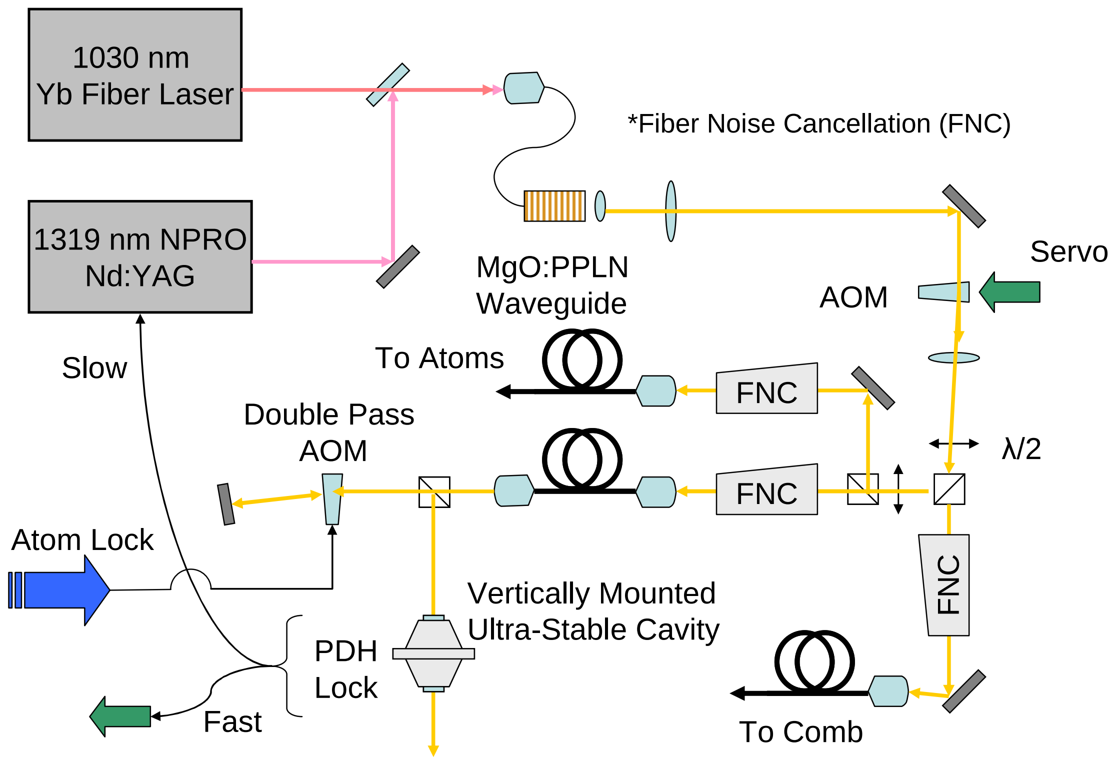

Figure 2. Schematic of the 578 nm clock laser system. The 578 nm light is generated with sum frequency generation of two IR solid state lasers. The 578 nm light is stabilized to a high finesse ultra stable cavity by an external AOM for fast feedback and the piezo of the 1319 nm laser. All fiber paths use fiber noise cancellation (FNC) to ensure transfer of the coherence. The laser system is further stabilized to the ^{174}Yb clock transition by use of the MIS technique for the spectroscopy and the double pass AOM for the feedback.

additional references), and tunability, which is limited to zero crossings of the interferometer. Tunability can be extended by adding a tuning element in the delay line used for the interferometer.

2.1 578 nm Clock Laser

A prime requirement for any optical clock is an ultra stable laser with which to perform the spectroscopy. Instabilities below 1×10^{-15} in one second can be provided by locking to vibrationally and enviromentally isolated high finesse (200 000 to 500 000)[17] cavities made of ultra low expansion (ULE) glass. In addition to mirror, vibration isolation, and material technology, recent work into cavity spacer designs that are insensitive to vibrations have improved the simplicity of such systems.[18,19] The cavity that we are using for our clock laser system is a vertically mounted cavity of the Notcutt-Ye[20] design and has a finesse of $> 200\,000$. The cavity is mounted on rods of PCTFE and housed in a temperature stabilized aluminum vacuum chamber with an aluminum radiation shield to maximize thermal stability. The chamber is placed on a 50 cm × 60 cm active vibration isolation platform, which is placed inside a commercial acoustic isolation chamber.

The laser source that we lock to the cavity is an all solid state design. The system is based on the sum frequency generation of two CW IR lasers in a MgO doped periodically poled lithium niobate (PPLN) waveguide*. The two lasers used to generate the light at 578 nm are a Nd:YAG monolithic ring oscillator at 1319 nm and a 1030 nm single mode Yb doped fiber laser. The 1319 nm laser is a compact, rugged, and stable laser with a specified linewidth below 2 kHz. This laser also has excellent modulation characteristics with a piezo element giving ∼ 30 MHz of tuning at 100 kHz bandwidth. The output power of the laser is 350 mW. The 1030 nm Yb fiber laser also has very desirable characteristics, including 1 W output power and less than 5 kHz linewidth.

*Laser sources at twice the clock wavelength and of sufficient power were not available, making sum frequency generation the next preferrered option.

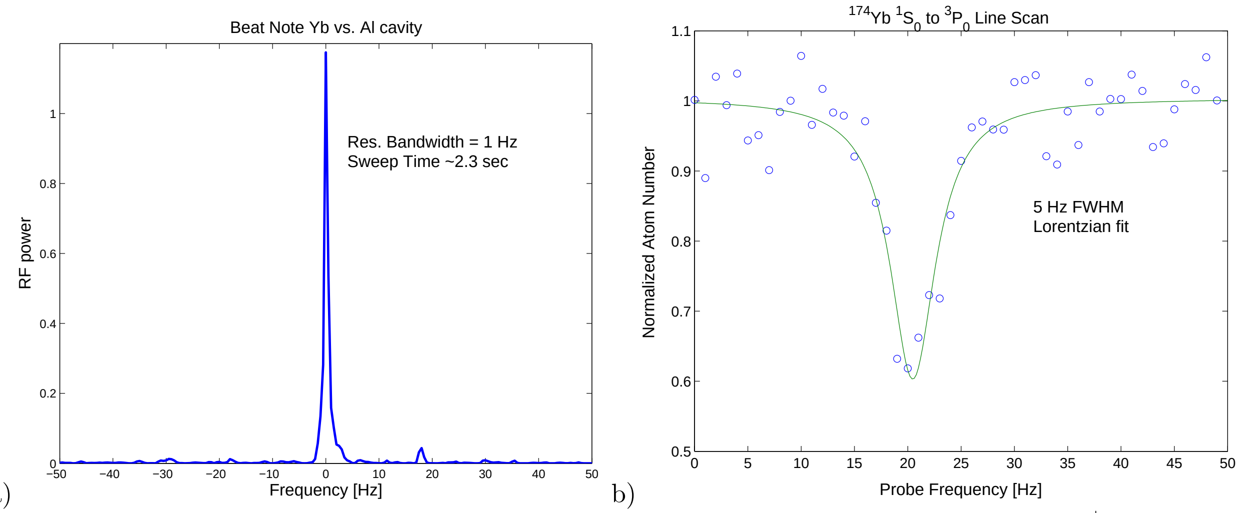

Figure 3. Tests of laser linewidth. a) Beat note between the cavity stabilized Yb laser at 578 nm and Al^+ laser at 1080 nm using a optical frequency comb. The linewidth is less than 2 Hz in a 2.3 s scan, limited by the resolution of the measuring device. b) Lineshape of the ^{174}Yb clock transition using magnetically induced spectroscopy. Each point is a single measurement with a total scan time of 44 s. The line has a width of 5 Hz which was limited by the spectroscopic probe time.

The two lasers are overlapped spatially with a dichroic mirror and then coupled into a 1064 single mode fiber that was butt coupled to the waveguide by the manufacturer. The large intensity and long interaction length provided by the waveguide leads to very efficient, single-pass sum frequency generation. With 50 mW coupled from each laser into the waveguide, we can generate more than 10 mW of 578 nm light.

After the 578 nm light is generated, it is passed through an AOM (see Fig. 2) that is used as a fast feedback mechanism for the cavity lock. After this AOM, the light is split into three paths: the first goes to the ultra-stable cavity for locking, the second goes to the atoms for interrogation, and the third goes to a Ti:sapphire frequency comb[21] for comparison with other optical and microwave frequency standards. All three paths are fiber coupled to their various tasks, and each fiber path is actively stabilized to ensure the frequency is stable at each location. We remove the fiber noise by using an AOM to phase lock the beat frequency generated by a Michelson interferometer that consists of a short path before the AOM and a long arm containing the fiber and two passes through the AOM.[22]

The light coupled to the cavity platform is first passed through a double-pass AOM that is used to frequency tune the laser while it is locked to the cavity. The light is then sent through an isolator and EOM that places 22 MHz phase modulated sidebands on the laser for Pound-Drever-Hall locking. About 10 % of the laser power is generated in each first order sideband, and care is taken to minimize residual amplitude modulation that can cause laser offsets. The light is then mode-matched into the cavity with a 40 cm lens. Care is taken in the alignment of all the optics to minimize stray reflections and etalons that can cause spurious low frequency noise. The reflected light is extracted with a polarizing beamsplitter and a quarter waveplate and detected by a fast silicon photodetector. About 40 % of the light is mode matched into the cavity, and the total throughput of the cavity is 5 %. The RF signal from the detector is amplified, mixed down to DC, then filtered and amplified further with a home-built loop servo with two paths for frequency feedback. The first path is for small fast deviations and is fed back to the frequency modulation port of the signal generator used to drive the feedback AOM. This loop has a servo bandwidth of about 500 kHz. The second path is the integrated signal of the first path and is fed back to the piezo on the 1319 nm laser. This loop has a bandwidth of aproximately 20 kHz and keeps the AOM in the center of its range. When the second path is placed in full integrating mode, the laser can remain locked for hours at a time, and is limited only by the drift of the two lasers and the range of the 1319 nm piezo.

To characterize the lock and maximize its performance we compared the system with a number of other stable lasers located at NIST via a Ti:sapphire optical frequency comb. Figures 1-2 show the performance of

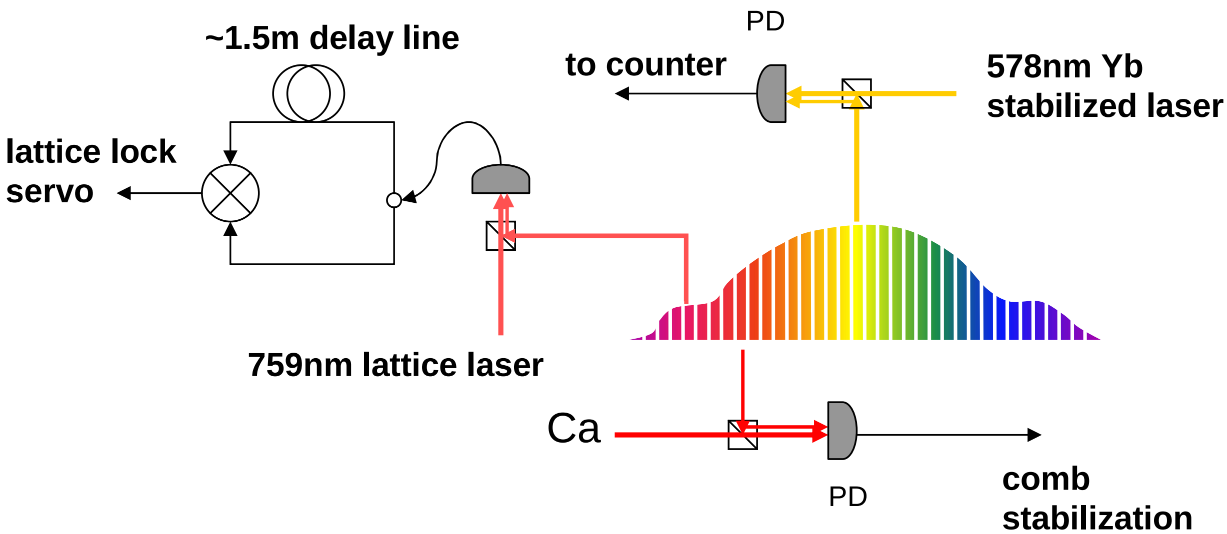

Figure 4. A Ti:sapphire optical frequency comb is used to compare the Yb clock to other standards. The usual operation for the measurements is to lock the repetition rate of the comb to the Ca optical standard; the beat note between the comb and Yb optical standard is then counted with a 1 s gate time and recorded. The comb is also used as a reference to stabilize the lattice laser. The use of an RF interferometer provides a compromise between robustness, simplicity, and tunability.

this laser compared to the laser used for the Al^+ optical frequency standard. As can be seen, the linewidth is less than 2 Hz in a 2.3 s scan and is limited by the resolution bandwidth of the spectrum analyzer. In addition, the fractional instability can start off as low as 2.2×10^{-15} in one second†. The temperature induced drift rate of the cavity can be held below 0.5 Hz/sec.

One of the advantages that comparison with another stable optical source affords is the ability to look for issues relating to the stability of our laser. One major issue we observed is the shift of the cavity frequency with power. We found that this shift is a fairly large (65 Hz/μW) for our cavity. For the 16 μW typically used for the locking, this means that we have to control the cavity power to better than one part per thousand to keep the power induced shifts below 1 Hz. Overall, the system performance is more than adequate, although we have not reached the thermal noise limit of about 1×10^{-15} for this cavity. The strength of the Ca system includes its ease of use and general operational stability.

2.2 Optical Comparisons for quick evaluation of systematics

We have begun measuring the systematic shifts that can affect the unperturbed frequency of the clock transition. The measurement of these shifts involves changing parameters and looking for shifts versus a stable reference. In the interests of time, it is desirable to use a reference with high short term stability. Often the ultra stable cavity used for the clock laser can serve this role, and modulated measurement schemes can push this technique further. At some point, using a cavity as a reference reaches its limit and a local reference with a higher long term stability is needed. This is when the presence of the other optical frequency standards at NIST and JILA becomes a tremendous benefit. Currently, in addition to the Yb optical lattice clock, there are four other high performance optical frequency standards with which we can compare the Yb standard via optical frequency combs: the neutral Ca clock, two ion standards Hg^+ and Al^+,[2,23] and the Sr lattice clock located in JILA.[8] The JILA group has recently implemented a coherent optical frequency fiber transfer system that could allow them to compare with clocks at NIST ultimately to the 10^{-19} level. The standard we have used most often as a stable reference for systematic shift studies is the neutral Ca clock, due to its robustness and availability.

The neutral Ca frequency standard at NIST is based on Ramsey-Bordé spectroscopy of laser cooled clouds of ^{40}Ca. The Ca standard is currently run with a single stage of laser cooling to millikelvin temperatures, which

†The fractional frequency instability of the Al^+ laser has been shown to be $< 1 \times 10^{-15}$ in one second, so it does not limit the measurement.

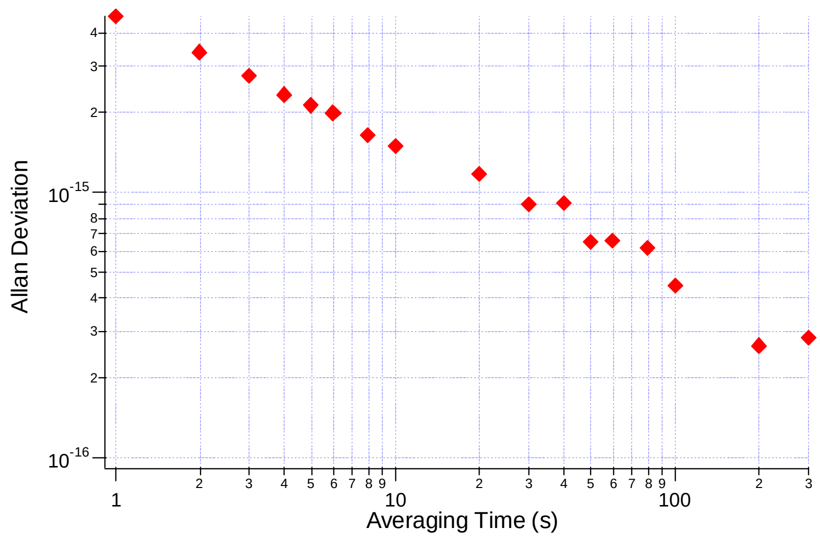

Figure 5. Allan deviation between the Yb and Ca frequency standards for 1000 seconds of data as measured by the frequency comb. The two standards reach relative instability of a few parts in 10^{-16} in 200 seconds. Long term instabilities in the Ca standard limit the stablity to about 2×10^{-16}.

limits its overall ultimate accuracy due to increased Doppler-related systematics. In this configuration however, the short term stability can be extremely good, with instabilities beginning at 4×10^{-15} in 1 s and quickly averaging down to a minimum of $\sim 2.5 \times 10^{-16}$ in one hundred seconds. We believe this noise floor is determined by uncontrolled drifts in the MOT-spectroscopy beam alignments. The long term drift of this standard is also fairly good, with a deviation of the center frequency of a few hertz over a day of measuring.

Using the Ca frequency standard as a reference, we can quickly evaluate systematic frequency shifts at a level of a few times 10^{-16}. In operation, the optical frequency comb's offset frequency is stabilized to a maser referenced frequency synthesizer, and a single tooth of the comb is locked to the Ca frequency standard, thus stabilizing the whole comb. The heterodyne beat frequency between the Yb stabilized laser and a single tooth of the comb is then measured in 1 s intervals with a 12-digit counter and recorded with a computer. The power of this method is easily seen in Fig. 6, which shows a trace of the beat between the Yb and Ca optical standards. The discrete jump in Fig. 6 resulted from a change in the AC Stark shift associated with probe light. With 100 s averaging time, the relative frequencies of the two standards can be measured to about 0.2 Hz. In Fig. 6 the probe power was increased to about 4.5 times the normal pulse power, inducing an extra 5.4 Hz shift. This indicates that the shift at the lower intensity would be roughly 1.2 Hz. The ability to measure these small shifts accurately allows us to rapidly evaluate relevant systematic shifts. As another example of measurements made using this method, we varied the atomic density in the lattice by changing the 399 nm MOT time and thus the total number of atoms in the trap. By switching between the maximum density and half maximum density, we were able to rapidly limit the density shift to less than 1 Hz or 2×10^{-15} in a few minutes of data collection. With the ability to compare against the Ca clock we will rapidly be able to measure all systematic shifts to the 10^{-16} level.

3. CONCLUSION

In this paper we have described the progress made toward an optical lattice clock based on the even ^{174}Yb isotope. We have constructed a new ultra stable, all solid state clock laser at 578 nm and have demonstrated its performance against other stable laser sources ($\approx$ 1 Hz linewidth) and with magnetically induced spectroscopy of the Yb atoms (5 Hz spectroscopic lineshapes). We have also demonstrated that optical comparisons against the Ca optical standard provides a rapid method for measuring systematic frequency shifts at the 10^{-16} level. We should now be able to rapidly evaluate clock frequency shifts such as: polarizability ("magic" wavelength), hyperpolarizability, second order Zeeman shifts, probe light shifts, and density shifts. This will lead to a frequency

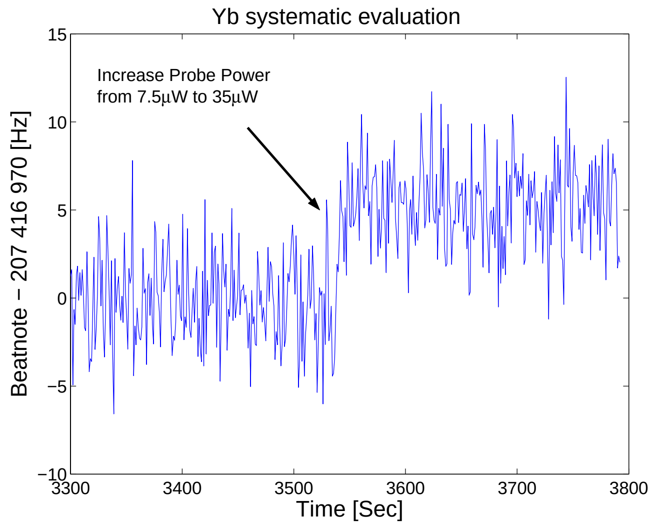

Figure 6. Measurement of the probe light shift. The power of the 578 nm light used to probe the clock transition was increased from 7.5 μW, to 35 μW causing a shift of 5.4 Hz. This shift was clearly observed in the beat note between Yb and Ca. The shift could be determined to about 0.2 Hz in 100 s averaging time.

measurement of the ${}^1S_0 \rightarrow {}^3P_0$ clock transition in ^{174}Yb at the 10^{-15} level in the near term and possibly at the 10^{-17} level in the future.

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