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ALL-DIODE-LASER OPTICAL FREQUENCY STANDARD BASED ON LASER-TRAPPED Ca ATOMS

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ABSTRACT

We describe a high performance optical frequency standard at 657 nm based on laser-trapped Ca. Using two semiconductor laser systems (423 nm for trapping and 657 nm for spectroscopy), we have been able to obtain sub-kilohertz optical linewidths and a relative Allan variance of 1.3×10^{-14} at one second, with prospects for considerable improvement. This Ca standard will be used to make a phase-coherent frequency measurement of the 282 nm $^{199}Hg^{+}$ optical standard.

1. INTRODUCTION

We have developed a table-top apparatus which is beginning to realize the considerable potential of the $^1S_0$ (m=0) → $^3P_1$ (m=0) intercombination line at 657 nm in neutral ^{40}Ca for use as a frequency standard. This transition is an attractive optical frequency standard due to its narrow linewidth (400 Hz), insensitivity to external perturbations, and convenient wavelengths for trapping and spectroscopy (see Figure 1).

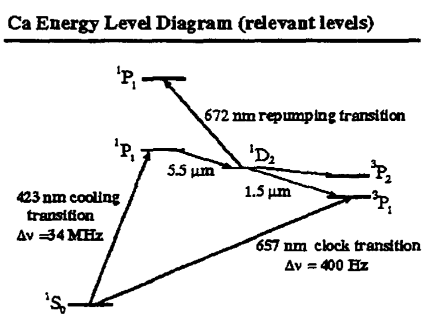

Figure 1. Cooling and clock transitions in Ca.

Since the pioneering efforts of Barger et al. in 1979, this line has been the subject of many experimental investigations[1]. The group of Helmcke and Riehle at Physikalisch Technische Bundesanstalt (PTB) has achieved numerous milestones with this transition, including a recent measurement of its absolute frequency with only 120 Hz uncertainty[2]. This makes it the most precisely know optical frequency of those recommended for the realization of the meter[3].

As an optical frequency standard, this transition offers remarkable potential for both stability and accuracy. For practical experimental parameters, we estimate an attainable fractional-frequency instability of $\leq 3\times10^{-16}\tau^{-1/2}$, nearly two orders of magnitude smaller than the projected instability of Cs fountain standards. Moreover, it has been estimated that a fractional frequency uncertainty of 10^{-15} or less is possible[4], although critical systematic effects such as collision shifts still need to be evaluated.

In order to approach this performance with a relatively straightforward apparatus, we had to address several critical issues. The first was a simplified design for a Ca magneto-optic trap (MOT), which included the development of a frequency-doubled semiconductor laser system to generate 50 mW of trap light at 423 nm. Next, we had to construct a 657 nm diode-laser system with the frequency stability required to resolve sub-kilohertz optical linewidths. Finally, to approach atom shot-noise-limited performance, we needed to implement a "shelving" detection technique, which enables us to achieve a high signal-to-noise ratio even at sub-kilohertz resolution.

2. APPARATUS

This apparatus has been described in detail elsewhere, so we will just outline the essential aspects here[5,6]. Our Ca MOT uses 50 mW of trapping light generated by frequency doubling 200 mW of 846 nm light from a master-oscillator power-amplifier (MOPA) semiconductor laser system. We load the trap directly with slow atoms from a thermal beam emerging from a 600°C oven. To increase the atom flux through the trap region, we locate the trap only 13 cm from the Ca oven. We also add a laser beam counter-propagating to the atomic beam to slow the atoms and increase the loading rate (by an order of magnitude), but we do not employ Zeeman slowing magnets as used in other schemes. This slowing/trapping combination can load as many as 10^7 atoms into our trap in 20 ms. The trapped sample has a temperature of 2 mK and a lifetime of ~20 ms, which is limited by optical pumping to the $^3P_2$ state through the $^1D_2$ state.

We perform the high resolution spectroscopy with a frequency-stabilized 657 nm laser diode in an extendedcavity configuration. The frequency of the laser is locked to a high finesse cavity (finesse = 60 000) by feeding back primarily to the diode laser injection current. With a servo bandwidth of more than 3 MHz, we can achieve a fast laser linewidth of <20 Hz. Our reference cavity is environmentally isolated but still contributes measurable noise to the laser frequency. Recent improvements in acoustic and vibration isolation have reduced the cavity noise to <100 Hz in 1 s. We are able to tune the laser frequency relative to this stable reference cavity with a microwave synthesizer which feeds a double-passed acousto-optic modulator (AOM).

Since we require high power for time-domain optical Ramsey spectroscopy, we send the output from the frequency-stabilized master oscillator to a power amplifier. After spatially filtering the power amplifier output with an optical fiber, we have ~40 mW of useful probe power. We then chop this output beam with AOM's to generate the desired probe pulses.

3. OPTICAL RAMSEY SPECTROSCOPY WITH SHELVING DETECTION

After turning off the trapping fields, we excite the narrow 657 nm transition with a sequence of red pulses in accordance with the technique of time-domain optical Ramsey spectroscopy[4,7,8]. This four-pulse sequence enables us to maintain a high signal-to-noise ratio when going to high resolution. To improve the signal-to-noise ratio further, we have implemented a shelving detection technique first developed for probing trapped ions[9,10]. In our version we first probe the atoms with a nearly resonant 423 nm probe pulse. The induced fluorescence level gives us a measure of the number of ground-state atoms present at the beginning of the measurement cycle. We then excite a fraction of the atoms with the four-pulse Ramsey sequence. Before the excited atoms can spontaneously decay back to the ground state, we read out the modified ground state population with a second blue probe pulse. The ratio of fluorescence induced by the second blue pulse to that induced by the first then gives the depletion of the ground state due to red excitation. Since we can cycle many blue photons per atom per measurement, we get a much cleaner measure of the excitation and can approach 100 % detection probability per atom. Moreover, since we measure the *fraction* of atoms excited, we are effectively normalizing the signal against trap number fluctuations, which can be as large as 10 %.

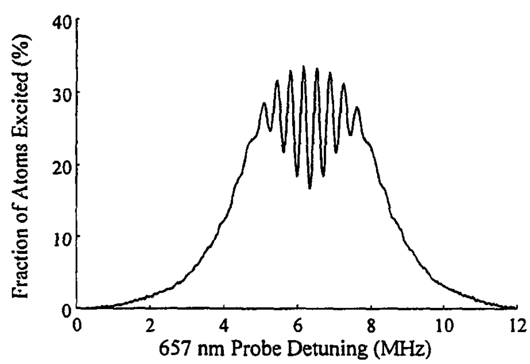

Figure 2. Low resolution optical Ramsey fringes. Total measurement time was 15 s.

An example of low resolution optical Ramsey spectroscopy taken with this system can be seen in Figure 2. The Ramsey fringes are superimposed on a Doppler background that corresponds to a temperature of 2.4 mK. By increasing the time between red pulses we can generate fringes with a much shorter period. Figure 3 shows the central fringes taken at a full-width half-maximum (FWHM) resolution of 960 Hz (resulting from a Ramsey time of 260 μs for each pulse pair).

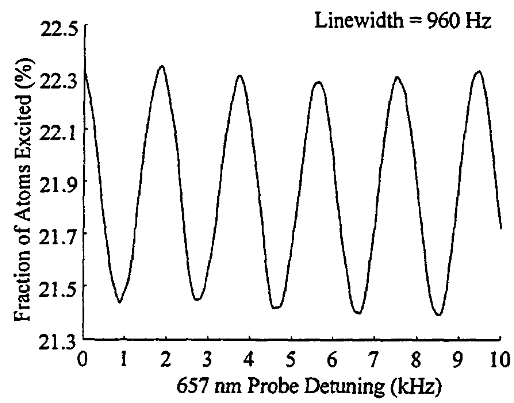

Figure 3. Sub-kilohertz optical Ramsey fringes with shelving detection. Total measurement time was 30 s.

From this figure we estimate a fractional frequency instability of close to $10^{-14}\tau^{-1/2}$. With our system we have actually been able to resolve linewidths as narrow as 400 Hz, equal to the natural linewidth of this transition.

The choice of optimal Ramsey resolution for the frequency standard is a compromise between narrow linewidth and high signal-to-noise ratio, which for our present system yields an optimal operating linewidth of ~1.6 kHz. As we improve the system and reduce excess low-frequency noise, we expect to operate nearer to the theoretical optimal resolution of 630 Hz (FWHM). To lock the red laser to a Ramsey fringe, we modulate the probe laser frequency with a 100 Hz square wave, then demodulate the resulting excitation, and feed back to the laser frequency. To evaluate the fractional frequency instability properly, we should either build a second system for comparison or compare our system to a more stable one. Lacking either of these at present, we can still make an estimate of the Allan variance by measuring the fluctuations of the Ca signal relative to the reference cavity (after subtraction of the cavity drift). This "relative" Allan variance actually includes the cavity noise, so we think that our Ca system may actually be better than this measurement, although any relative linear drift of the Ca system is suppressed. Nonetheless, we see in Figure 4 promising performance with a relative instability of 1.3×10^{-14} at one second.

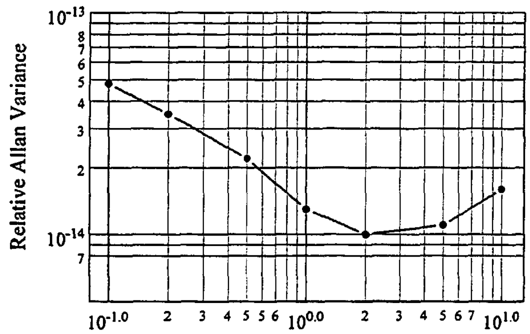

Figure 4. Relative Allan variance between the Ca transition and the optical reference cavity. A Ramsey fringe linewidth of 1.9 kHz was used for this measurement.

We have not yet reached the shot-noise capability of our system, because there is still some residual amplitude noise due to imperfect normalization.

4. FUTURE WORK

As a first application of our frequency standard, we are currently constructing a frequency chain to transfer knowledge of the Ca frequency (based on the PTB value) to the 282 nm transition in the Hg^+ ion frequency standard under development at NIST[11]. This phase-coherent chain is discussed in another paper at this conference[12]. The ultimate goal of this optical frequency measurement work will be to connect both the Ca and Hg^+ optical transitions to the Cs microwave standard with a (nearly) all-optical, phase-coherent frequency chain.

An essential part of this work involves sending Ca-stabilized light through a 100 m fiber to another room for frequency comparison. An initial measurement of the frequency noise written on to the light by the low frequency fluctuations caused by the fiber is shown in Figure 5. Here we have sent light through the fiber and then shifted its frequency with a double-passed AOM before sending it back. Beating this return light against the incident light yields twice the single-pass fiber noise contribution. It was important to perform this measurement with the laser locked to the optical cavity to prevent laser frequency noise from contributing to the noise spectrum. The ~1.5 kHz single-pass broadening seen in Figure 5 can be removed with a fiber-noise-cancellation technique first demonstrated by Ma et al.[13].

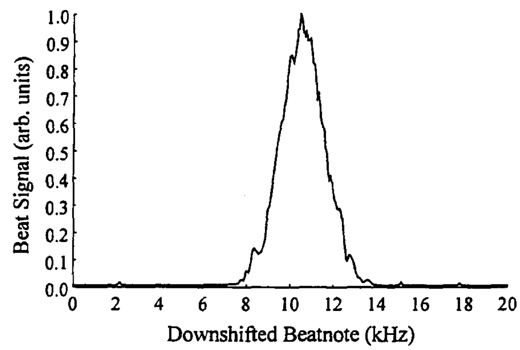

Figure 5. Beatnote between light before and after fiber with an averaging time of 5 s. Note that this shows the noise accumulated due to *two* passes through the fiber.

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5. REFERENCES

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