

An All-Diode-Laser Optical Frequency Reference Using Laser-Trapped Calcium

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Abstract

The 657 nm calcium intercombination line is an attractive optical frequency/length reference due to its high line Q (10^{12}) and insensitivity to external perturbations. In this paper we describe progress towards an all-diode-laser-based reference using laser-trapped Ca. To generate 35 mW of 423 nm trap light, we double the frequency of a 150 mW, 846 nm diode laser with a nonlinear crystal (KNbO_3) inside a resonant build-up cavity. We use this light to trap 2×10^7 atoms in a compact, magneto-optic trap. Spectroscopy of the narrow 657 nm transition is performed with a frequency-stabilized diode laser system. With the trapped atoms we have measured optical Ramsey fringes with a linewidth of 6 kHz. We discuss future improvements as well as potential performance which could achieve a fractional frequency instability of $< 3 \times 10^{-15}$.

Introduction

Due to their narrow linewidth and insensitivity to external perturbations, the intercombination lines in alkaline earth atoms are attractive optical frequency/length references.[1,2] From preliminary work on the lowest lying $^1S_0 - ^3P_1$ lines in Ba, Ca, and Mg, potential uncertainties in the determination of the line centers were estimated to be < 1 Hz in the best cases.[3,4,5] This predicted performance is particularly attractive when compared with that of two well-known systems, the iodine-stabilized HeNe laser at 633 nm, and the two-photon system in Rb at 778 nm, which have uncertainties > 1 kHz.[6,7] Thus, there is a strong impetus for further investigations and development of these alkaline earth-based references.

In particular, the 657 nm intercombination line 1S_0 ($m=0$) \rightarrow 3P_1 ($m=0$) in atomic calcium is an excellent candidate due to its high line Q (10^{12}) and convenient wavelength. Ca also has a strong $^1S_0 \rightarrow ^1P_1$ transition at 423 nm which is well suited for laser cooling and trapping.

The use of laser-cooled samples offers two benefits for a Ca frequency reference: (i) the extended interaction time needed to resolve the 400 Hz (FWHM) natural linewidth of the 657 nm transition, and (ii) greatly reduced systematic errors. Another attractive feature of Ca is that the 657 nm and 423 nm transitions are accessible with semiconductor laser systems, enabling a compact, reliable, and low power frequency/length reference. These factors led the BIPM in 1994 to recommend that this be one of those transitions used for the realization of the meter.[6]

The first high resolution Ramsey spectroscopy on the narrow 657 nm transition was performed in 1979 where a frequency-stabilized dye laser was used to achieve linewidths as narrow as 6 kHz.[1] Since then there have been numerous measurements using thermal atoms, laser-cooled atoms, and even laser-trapped atoms, with resolutions just now approaching the natural linewidth.[3,8] Recently PTB has used an optical frequency synthesis system to measure the absolute frequency of this transition with an uncertainty of less than 450 Hz,[9] making it the most precisely known optical reference. There are presently several groups around the world developing optical frequency/length references based on this transition.

At NIST our work has focused on the development of a such a reference based on semiconductor laser systems (most previous work used dye lasers at 423 nm and 657 nm). This required construction of a diode laser system at 657 nm with high frequency stability and high power, and another at 423 nm which can generate sufficient blue light for use in a Ca magneto-optic trap (MOT)[10]. Additionally, we have designed a simple, compact MOT which stores samples of $\sim 2 \times 10^7$ atoms suitable for high-resolution spectroscopy at 657 nm.

This paper will first describe our present apparatus, beginning with the diode laser systems. We will then present some preliminary spectroscopic results which indicate that, when optimized, our frequency reference could attain a fractional frequency instability of $< 3 \times 10^{-14}$ in 1 sec. Finally, we will outline some modifications to this initial experimental setup which promise much improved performance in the near future.

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Trapping Ca with Diode Lasers

There were two important technical challenges in the construction of a compact, diode-laser-based Ca trap. The first was to generate blue light with sufficient power, tunability, and frequency stability to trap Ca. Since there are no suitable semiconductor laser sources at 423 nm, we instead double the frequency of a high-power diode at 846 nm. Figure 1 shows the apparatus used to generate the blue light.[11] A 150 mW beam from a solitary diode is sent through beam-shaping optics and an optical isolator to a resonant cavity containing a KNbO₃ nonlinear crystal cooled to -10°C. With 105 mW incident on the build-up cavity (x20) the crystal produces 30 mW of light at 423 nm. We control the frequency of the high-power diode by injection-locking it with a lower power (20 mW) extended-cavity diode laser (ECDL). Long-term drifts of the laser frequency are suppressed by locking the master ECDL to an absorption signal derived from our Ca beam apparatus.

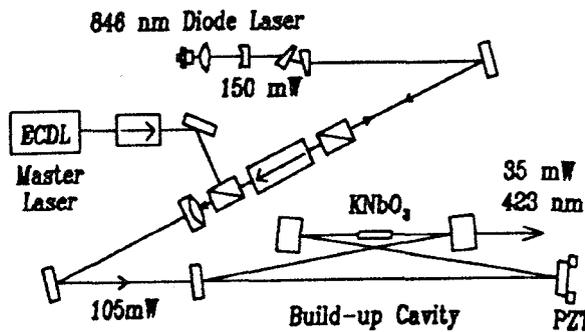


Figure 1. Schematic of the frequency-doubling apparatus which generates >30 mW of 423 nm light.

The second important challenge was to find a compact design for our Ca MOT. Simple vapor cell MOT designs which are commonly used for Cs and Rb are difficult for Ca, since Ca must be heated to over 400°C to generate adequate vapor pressure for trap loading. Previous Ca MOT designs[3,12] relied instead on loading from laser-slowed atomic beams. They achieved efficient loading via the technique of Zeeman slowing, which keeps the atoms resonant with the slowing laser beams as their velocities are reduced. The Zeeman slowing technique, however, requires large magnetic field coils. We chose instead to modify a design first demonstrated at Stanford[13] using Li atoms and more recently at PTB using Ca[7], which traps slow atoms directly from an atomic beam without using a Zeeman slower. Such a trap compensates the reduced range of trapped atomic velocities by placing the trap much closer to the atomic source, thus increasing the flux of atoms through the trap region.

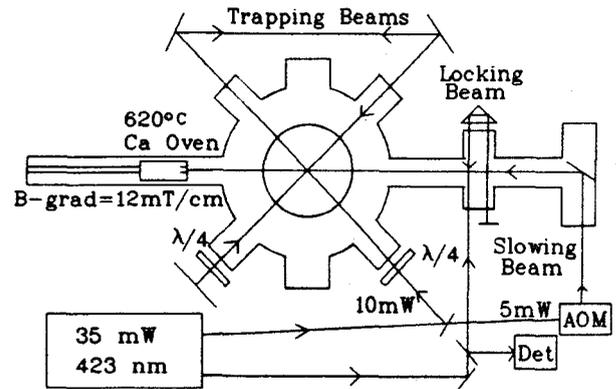


Figure 2. Design of a compact Ca MOT. A retroreflected vertical beam is omitted for clarity.

In our design (shown in Figure 2) the trap is located 13 cm from the oven nozzle, which operates at 620°C. We use 8 mW of 423 nm light in a single horizontal beam (1 cm diameter) which is recirculated and retroreflected to generate the two perpendicular horizontal trapping beams, set at 45° relative to the atomic beam axis. The retroreflected vertical trapping beam contains 2 mW of blue power. We generate the large magnetic field gradient (12mT/cm) required by our trap by sending 150 amperes of current through a water-cooled pair of anti-Helmholtz coils. Under these conditions our MOT fills with more than 10⁶ Ca atoms with a loading time constant of 20 ms, apparently limited by optical pumping to the ¹D₂ state which lies below the ¹P₁ state. We observe the highest level of blue fluorescence from the trapped atoms with the blue light detuned ~30 MHz below the 423 nm resonance.

In previous versions of this type of MOT[7,12] one or more frequency sidebands were added to the trapping light in order to extend the capture velocity, thus increasing the loading rate. We instead implemented a slowing beam counter-propagating to the atomic beam, which slows atoms (without benefit of Zeeman slowing coils) before they reach the trapping region. We could not however, simply send this light through a window downstream from the oven. A window in this position quickly becomes coated with Ca from the atomic beam and no longer transmits the blue slowing beam. To avoid this problem we send the slowing light through a window on the side (see Figure 2) and reflect it off a mirror located inside the vacuum system downstream from the oven. It turns out that layers of deposited Ca make a fairly decent mirror (~70% reflectivity) at 423 nm, so the mirror continues to reflect the slowing beam even after becoming coated with Ca. Tuning the frequency of this beam 110 MHz to the red of the cooling transition gives a

tenfold increase in the loading rate, producing laser-cooled samples of $\sim 2 \times 10^7$ atoms in ~ 20 ms.

We used the narrow 657 nm transition to measure the temperature of the cold atom cloud via the first-order Doppler effect. Typical temperatures of the trapped atoms range from 2-3 mK, depending on trap laser intensity and detuning. These temperatures are higher than those routinely achieved in alkali traps due to the absence of Zeeman structure (and hence polarization gradient cooling) in the Ca ground-state. Without such structure, the minimum achievable temperature is set by the Doppler cooling limit.[14] For Ca this limit is 0.8 mK, which corresponds to a root-mean-square velocity of 40 cm/s (see ref. [3] for further discussion).

High-Power, Frequency-Stabilized 657 nm Diode Laser System

The requirements for the red diode system are (i) its frequency be sufficiently stable to resolve the 400 Hz natural linewidth of the intercombination line and (ii) its power be greater than 10 mW to excite this weak transition by the Ramsey method.

To achieve sufficient frequency stability we started with an extended-cavity diode laser at 657 nm, which yielded 3 mW output power (see Figure 3). To reduce the

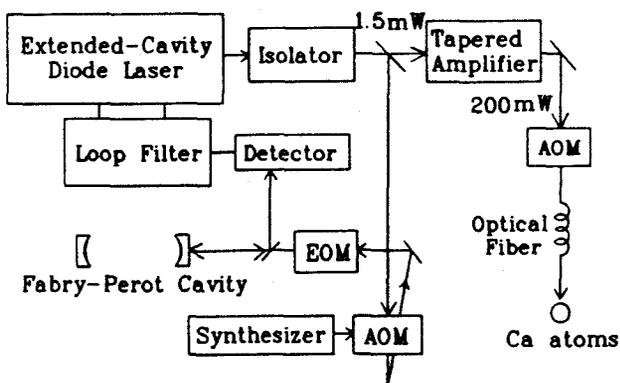


Figure 3. Block diagram of the frequency-stabilized laser system at 657 nm used for high resolution spectroscopy.

100 kHz linewidth of this laser, we lock its frequency to a resonance of a high-finesse, Fabry-Perot cavity (3 GHz FSR and 50 kHz fringe FWHM). We send 100 μ W of the laser output to this cavity and use the Pound-Drever-Hall technique[14] to derive a high signal-to-noise error signal using a modulation frequency of 13.3 MHz. We then filter this signal to correct laser frequency fluctuations via the laser current (fast corrections) and a PZT-driven mirror on

the laser cavity (slow corrections). A servo bandwidth of over 3 MHz yields fast laser linewidths of < 100 Hz, as inferred from the error signal relative to the cavity. To reduce long-term frequency fluctuations due to drifts of the reference cavity, we constructed the cavity spacer out of ultra-low expansion (ULE) material and placed it inside a vacuum chamber. This chamber was then placed inside a thermally-stabilized, vibrationally-isolated environment. To enable precise tuning of the laser frequency relative to the cavity resonance, we use a double-passed, acousto-optic modulator (AOM) before the cavity.

We increased the 657 nm laser power available for Ca spectroscopy by using 2 mW of light from the stabilized ECDL to injection-lock a semiconductor tapered amplifier (TA). The stabilized ECDL serves as the master laser and the tapered amplifier as the power amplifier in a master-oscillator power-amplifier (MOPA) configuration. With 1.9 amperes of current in the TA, the MOPA produces a remarkable 240 mW of light without adding significant phase noise to the frequency-stabilized light. After spatially filtering the output with an optical fiber, however, we have typically only 10-20 mW of usable light, a level adequate though somewhat low for the Ramsey spectroscopy. The MOPA system also allows us to stabilize the intensity level of the light after the fiber by feeding back to the TA current.

As a first test of this system we performed spectroscopy on a thermal beam of calcium. To achieve high resolution while maintaining good signal-to-noise ratio, we used the optical Ramsey fringe technique.[16] This technique is analogous to the microwave Ramsey technique but uses four (rather than two) spatially-separated interaction regions in order to cancel the first-order Doppler effect. The distance between the four traveling waves (along with the most probable velocity of the atomic beam) then sets the spectral resolution for a given measurement. We generated Ramsey lineshapes by measuring the induced atomic beam fluorescence downstream from the interaction region.

Figure 4 shows an example of a Ramsey fringe taken at a probe power level of 8 mW (40 scans averaged - total data accumulation time of 1 minute). Here the spacing between each pair of beams was 15 mm, which yields a Ramsey resolution of 11.5 kHz for our most probable velocity of 700 m/s. Actually seen here are the two recoil components for this transition, which are separated by 23.1 kHz. Our Ramsey resolution of 11.5 kHz was chosen so the fringe patterns of the two components would interfere constructively in order to give the best contrast, which was about 25%.

Note that such a signal can be used as an optical frequency reference simply by locking a laser to one of the two recoil components, one of which can be suppressed, if so desired.[17] If limited only by the signal-to-noise ratio demonstrated in Figure 4, one should attain a fractional frequency uncertainty of 5×10^{-13} in 1 sec. Workers at PTB

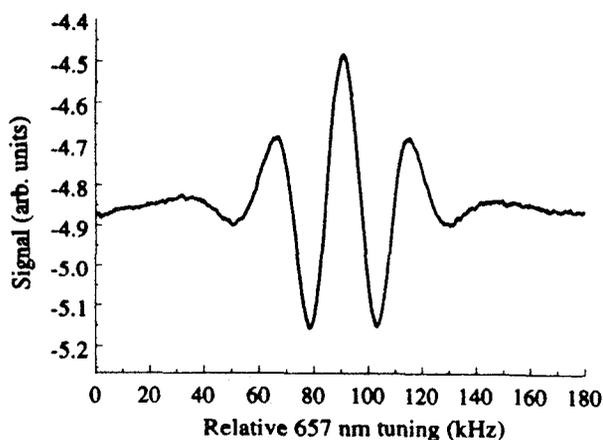


Figure 4. Optical Ramsey fringes in a Ca atomic beam.

are presently constructing a compact version of this type of device to use as a transportable frequency reference.[8] They have determined, however, that a laser locked to a Ramsey fringe derived from an atomic beam is susceptible to drifts as large as 1 kHz, which seriously compromises its long-term performance.[8]

High-Resolution Spectroscopy with Laser-Cooled Ca Atoms

Presently we perform spectroscopy on the narrow red transition using laser-cooled and trapped atoms. Optical Ramsey spectroscopy with trapped samples differs from that in a beam in that one must separate the four interaction zones temporally rather than spatially.[3,4] Thus this second spectroscopic investigation uses four pulsed traveling waves (two in one direction followed by two in the opposite) to excite the narrow transition. In this case, the time, T , between the pulses of each pulse pair determines the Ramsey fringe resolution, $\Delta\nu=1/(4T)$. An added complication is that we must turn off the blue trap light during this excitation time so that the relevant atomic levels are unperturbed.

A typical measurement cycle commences with 5-10 ms for trapping, after which we shut off the trap light and magnetic field gradient. Next we illuminate the atoms with four pulses (controlled by two AOM's) from our frequency-stabilized 657 nm laser system. The cycle ends with a 300 μ s detection period, during which we collect red fluorescence with a photomultiplier tube. We typically repeat this cycle 200 times for each frequency data point.

Figure 5 shows a preliminary scan taken (without chopping the magnetic field gradient) with a total pulse separation of 80 μ s, which yields a Ramsey resolution of 6

kHz. One immediately notices that many more fringes are present than we saw in the case of atomic beam Ramsey spectroscopy. In a thermal beam the effective pulse separation time as seen by an atom depends on its velocity. Due to the wide range of velocities in an atomic beam, the resultant lineshape was in fact the superposition of fringe patterns with different resolutions, which washed out all but the central fringe. For samples of trapped atoms, however, all atoms see the same time separation between pulses, so the individual contributions add coherently, leading to a lineshape such as that seen in Figure 5.

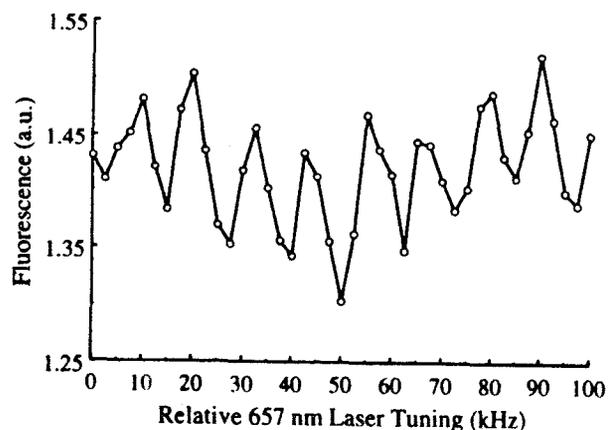


Figure 5. Optical Ramsey fringes at 657 nm using laser-trapped Ca atoms.

The actual situation is even more complicated due to the fact that we again have the two recoil components, thus producing two full fringe patterns (separated by 23.1 kHz). To have good fringe contrast, the Ramsey fringe period needs to be chosen to be an integral fraction of the recoil splitting (or one of the recoil components must be suppressed). In either case, one can then determine the central fringe (i.e. the line center) for each component by taking spectra at several different resolutions.

The signal-to-noise ratio in this preliminary scan was far from shot-noise limited and should be greatly improved in the near future. For our current apparatus, a shot-noise limited lineshape should yield a fractional uncertainty of 3×10^{-14} in 1 sec, a level comparable to one demonstrated in a similar setup at PTB using dye lasers.[8] A laser locked to such a fringe could then provide an excellent length reference. For use as a frequency reference, however, the frequency stability of the locked laser would first have to be transferred to the microwave domain using presently unavailable optical frequency-synthesis techniques.

Future Work and Prospects

While our present apparatus provides good performance, there are several aspects which can be readily improved. We presently collect less than 2% of the total fluorescence, so improved collection optics could increase our signal by at least an order of magnitude. To increase the signal further we are presently implementing a different excitation strategy which first uses a resonant blue pulse to measure the number of atoms in the sample before the four red pulses.[4] Immediately following the last red pulse, a second blue pulse can read out the fraction of atoms still in the ground state after the Ramsey interaction. Since we can scatter hundreds of blue photons per atom per blue pulse, we can have a much larger signal. Moreover, this signal is normalized to the number of atoms in the sample, reducing noise induced by shot-to-shot, trap-number fluctuations.

These improvements can, in principle, reduce the uncertainty of our optical frequency reference by one or more orders of magnitude. What will be the ultimate performance of such a system? This remains an open question as there have yet to be detailed studies of systematic effects associated with an optical reference based on trapped atoms. Independent estimates[4,8] predict that known systematic effects should contribute < 1 Hz (or a fractional frequency uncertainty of 2.5×10^{-15}), but several effects such as those due to cold-atom collisions[18] have not yet been investigated. Such studies will require comparisons between independent systems. The first Ca intercomparison, between a portable thermal beam apparatus constructed by PTB and our apparatus here, is scheduled for later this year.

Acknowledgements

We thank our colleagues in the group of J. Helmcke and F. Riehle at PTB, R.W. Fox and J.C. Bergquist at NIST, and J.L. Hall at JILA for useful discussions and suggestions. We also gratefully acknowledge the financial support of AFOSR.

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