

## Compact, All-Diode-Laser, Optical Frequency Reference Based on Laser-Trapped Atomic Calcium

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An important application of diode lasers in the standards community is the development of the next generation of frequency/wavelength references, where semiconductor laser technology will enable higher performance in portable, inexpensive, and reliable systems. At NIST we are working on an all-diode-laser, optical frequency reference based on the  $^1S_0$ - $^3P_1$  intercombination line in Ca at 657 nm. This transition is one of those recommended for the realization of the meter, and its absolute frequency has been measured with an uncertainty of 450 Hz, the most precise of any visible reference.<sup>1</sup>

Our work has addressed several important challenges. First of all, we have stabilized the frequency of a 657 nm extended-cavity diode laser to <100 Hz to allow resolution of the 400 Hz natural linewidth of this transition. Second, we have implemented a master-oscillator power-amplifier (MOPA) at 657 nm in order to produce 20 mW of usable light needed for spectroscopy of this weak transition. Finally, we have generated 35 mW of light at 423 nm (through frequency doubling of an 846 nm high power diode laser) and used it in a magneto-optic trap (MOT) which can provide samples of up to  $2 \times 10^7$  Ca atoms. The use of trapped atoms for our spectroscopic sample offers the extended interaction time needed for sub-kilohertz resolution and greatly reduced systematic effects. With this system we have observed Ca resonances as narrow as 6 kHz and should be able to reduce this further in the very near future.

To generate the frequency-stabilized light at 657 nm (see Figure 1), we start with a grating-tuned extended-cavity diode laser (ECDL), which yields 3 mW output power and a laser linewidth of  $\sim 100$  kHz. After passing the beam through an optical isolator (50 dB isolation), we split the light into two paths, one for frequency stabilization and the other for spectroscopy. In the first path, 1 mW of light goes through a double-passed acousto-optic modulator (AOM) (for precise tuning of the laser frequency) to a high finesse Fabry-Perot cavity (50 kHz fringe linewidth). Our cavity consists of two mirrors optically contacted to a ultra-low expansion (ULE) spacer, which is placed inside a thermally and vibrationally isolated vacuum can. Using FM optical heterodyne techniques we derive an error signal which we filter and then feed back to the diode laser current (to correct fast laser frequency fluctuations) and to a PZT on the laser feedback mirror (to correct slow drifts). With the laser locked, the error signal indicates residual frequency fluctuations of

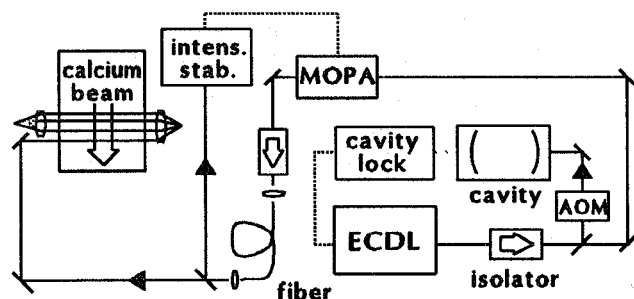


Figure 1 Diagram of 657 nm diode laser setup for optical Ramsey spectroscopy of a Ca atomic beam.

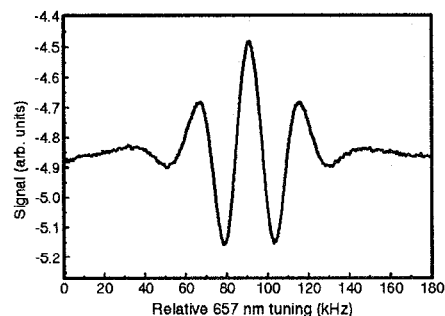


Figure 2 Optical Ramsey fringes at 657 nm taken with setup in Figure 1.

< 100 Hz. In the second path we send 1.3 mW to injection-seed a MOPA, so we can increase the power for the spectroscopy. This MOPA system produces 240 mW at 657 nm and adds negligible frequency noise to the light. As a first test of this system we sent the MOPA output through an optical fiber to an optical Ramsey fringe spectrometer, which used four interaction zones with a Ca atomic beam to probe the  $^1S_0$ - $^3P_1$  ( $m=0$ - $m=0$ ) transition. With 8 mW of probe power we were able to obtain Ramsey lineshapes with good contrast and a high signal-to-noise ratio. Figure 2 shows a scan taken at 11.5 kHz resolution with a data acquisition time of 1 minute to average 40 scans. Our resolution was limited by the fast atom transit time and the geometry of our setup. Using this lineshape as a reference we were able to characterize the long term stability of our frequency-stabilized diode laser system.

To achieve higher resolution we have constructed a Ca MOT. Previously, three Ca MOTs have been demonstrated, all of which used dye lasers at 423 nm to trap atoms from a slowed atomic beam.<sup>2,3</sup> In order to have a simpler, more compact system, we have designed a Ca trap apparatus which uses frequency-doubled diode laser light for cooling and trapping. As shown in Figure 3, a grating-tuned ECDL provides stable tunable light, which we use to injection lock a high-power slave diode laser. 5 mW of injection power produces 150 mW of slave output at 846 nm. We correct the slave laser's astigmatic and asymmetric spatial mode with an anamorphic prism pair and a cylindrical lens. After passing this beam through an optical isolator, we have 105 mW incident on a ring build-up cavity containing a 1 cm KNbO<sub>3</sub> non-linear crystal. With a build-up factor of ~20 we generate 35 mW of stable 423 nm light.

For our atom trap, we modified a simple MOT design demonstrated for lithium<sup>4</sup> (and recently for calcium by workers at PTB<sup>2</sup>) which relies on trapping atoms directly from a short (12 cm) atomic beam. We find that adding a single-frequency slowing beam along the atomic beam axis leads to an 8-fold increase in the number of trapped atoms. We collect about  $2 \times 10^7$  atoms with the trap light detuned 35 MHz red of the  $^1S_0$ - $^1P_1$  cooling transition and a magnetic field gradient of 12 mT/cm. Figure 4 shows a trapped sample of  $>10^6$  Ca atoms, one of the first demonstrations of laser trapping with frequency-doubled diode lasers. We have performed optical Ramsey spectroscopy upon the trapped atoms and have obtained features as narrow as 6 kHz, suitable for use as a high precision frequency reference.

#### References:

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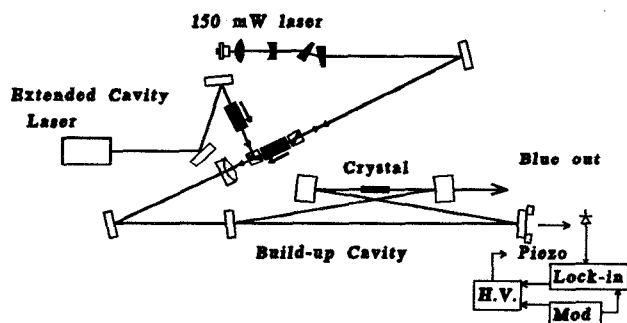


Figure 3 Frequency-doubling of 846 nm diode laser light to generate 35 mW of 423 nm cooling light.

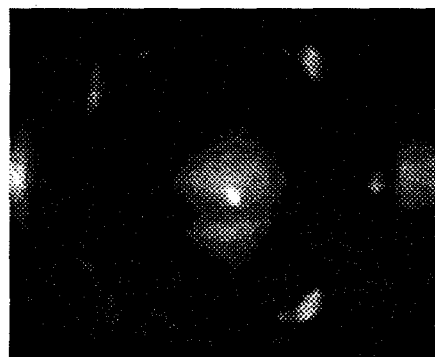


Figure 4 Ca MOT using frequency-doubled diode lasers. The central bright spot is fluorescence from  $>10^6$  atoms.