

Towards microwave modulation in a wavelength-tuned magneto-optical trap

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In this project, I present a new method for trapping Rubidium-87 atoms. The method proposed is microwave modulation of an external cavity diode laser. The modulation is designed so as to produce frequency sidebands for hyperfine pumping in addition to the main cooling frequency. It is designed for use in magneto-optical trapping.

GENERAL MOTIVATION

Doppler cooling of atoms is a central process in the field of atomic, molecular, and optical (AMO) physics. Doppler cooling is central to laser trapping, the formation of Bose-Einstein condensates, quantum computing, and proposed schemes in molecular trapping. Doppler cooling allows atoms to be slowed down many orders of magnitude below their room temperature velocity, which allows these atoms to be more easily controlled and studied. Doppler cooling can best be understood by its relationship to the thermodynamics of atoms.

A collection of atoms at room temperature has an average velocity, \bar{v} , that follows from its kinetic energy and the Maxwell-Boltzmann distribution [1];

$$(1) \bar{v} \equiv \sqrt{\frac{3k_B T}{M}}$$

where k_B is Boltzmann's constant, T is temperature, and M is mass. Lasers used for cooling are designed so as to be slightly detuned from a resonant frequency, ν_0 , of an atomic transition. As the individual atoms interact with incident laser light, the atoms observe a Doppler shifted laser frequency, ν_L , given by;

$$(2) v_L = v_0 \left(1 + \frac{v_z}{C}\right)$$

where v_z is the velocity of the atom and C is the speed of light. Atoms moving towards the laser light observe blueshifts and atoms moving away observe redshifts. The lasers are detuned so that incoming atoms are more likely to absorb the photons. Once absorbed, the atoms re-emit the photons in a random direction in three-dimensional space. These photons carry both momentum and energy and give the atoms a recoil velocity given by [1];

$$(3) v_r = \frac{\hbar k}{M}$$

where $\hbar k$ is the momentum of the photon. Overall, the atoms observe a net decrease in energy, velocity, and hence temperature because of scattering of the photons. The atoms scatter more photons as they move closer towards the beam; the net effect is the atoms slow down. The slowing force is proportional to the atomic velocities. The atoms for this project are alkali atoms: Rubidium -87.

Alkali atoms are a suitable choice for laser cooling because of the atomic energy levels

radiation. Typical Alkali atoms have electrons that occupy all but one closed shell. The remaining electron is in an s orbital in a higher shell [2]. This extra electron allows these atoms to be treated quantum mechanically as a hydrogen atom. The nuclear spins are coupled to the electronic spin only from the magnetic field produced by the electronic spin. There is no magnetic field at the nucleus due to the electronic orbital motion, because the electron has no orbital angular momentum. In the case of Rubidium-87, this facet of the electron helps contribute to it having an atomic transition nearby commercially available diode lasers: 780 nm. The ground electronic configuration of

Rubidium is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 5s^1$. The electron outside of the closed shells causes the structure to resemble hydrogen. The nuclear quantum number of ^{87}Rb is $I=3/2$.

SPECIFIC MOTIVATION

There are additional quantum mechanical interactions in Rubidium-87. The energy splittings in Rubidium -87 are due to the kinetic and potential energy, the fine structure, and the hyperfine structure. These interactions can be expressed as [3];

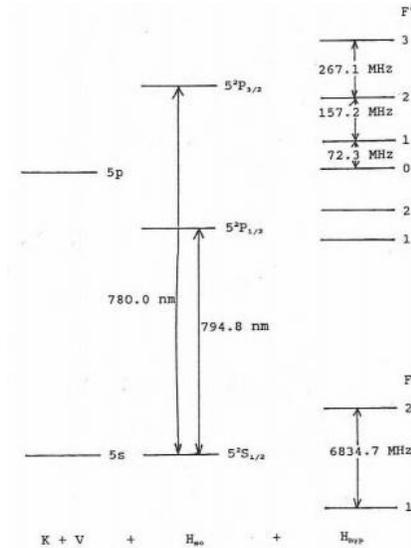
$$(4) \quad \mathcal{H} = K + V + H_{SO} + H_{1,hyf} + H_{2,hyf}$$

or in the expanded form[3];

$$(5) \quad H = \frac{p^2}{2m} - \frac{Z_{eff} e^2}{4\pi\epsilon_0 r} + \zeta(r) \mathbf{L} \cdot \mathbf{S} + \alpha \mathbf{J} \cdot \mathbf{I} + \frac{\beta}{2I(2I-1)J(2J-1)} \left[3(\mathbf{I} \cdot \mathbf{J})^2 + \frac{3}{2}(\mathbf{I} \cdot \mathbf{J}) - I(I+1)J(J+1) \right] (J)$$

where p is the atomic momentum, m is the mass, Z_{eff} is the effective atomic number for Rubidium, \mathbf{L} and \mathbf{S} are the orbital and spin angular momenta of the electron, \mathbf{J} and \mathbf{I} are the total electron and nuclear angular momenta, $\zeta(r)$ is the magnetic hyperfine structure constant, and β is the electric quadrupole interaction constant [3]. K is the kinetic energy of the single electron and V is the Coulomb interaction of the electron with the nucleus and core electrons. The $K + V$ interactions separate the 5s ground configuration and the 5p excited configuration. H_{SO} is the fine structure and is due to relativistic effects and spin-orbit coupling. We ignore the relativistic effects. Spin-orbit coupling is the torque exerted on the magnetic dipole moment of the spinning electron and is from the magnetic field of the closed shell. $H_{1,hyf} + H_{2,hyf}$ is collectively called the hyperfine interaction. The hyperfine interaction is due to the magnetic hyperfine and electric quadrupole hyperfine interactions. The spherically symmetric electric monopole of the Rubidium

nucleus gives rise to the Coulomb interaction with the electron. The electrostatic interaction is between the electron and the nuclear electric quadrupole moment and results from the total angular momentum, F . F couples the electron angular momentum (J) and nuclear angular momentum (I) via $F = J+I$. The energy splitting are given as follows [3]:



The selection rules for the total angular momentum quantum numbers are part of the selection rules for electric dipole transitions.:

- 1.
- 2.
- 3.

This is a cycling transition, and once the electron relaxes, it has a high probability of falling back to the $F=2$ state. There is a finite probability of the electron relaxing to the $F=1$ hyperfine state. These two hyperfine states are 6.8347 GHz away. Usually, two lasers are needed when trapping atoms, the cooling laser for the cycling transition, and

the repump laser for the hyperfine transition. The repump laser is designed to depopulate state that the atom can continue to be cooled by the cooling laser as discussed before.

WHY MICROWAVE MODULATION

The purpose of microwave modulation is to generate the additional re-pump frequencies needed. The setup must modify the laser diode injection current [11] and produce sidebands (also known as frequency chirps [1]) onto the main laser light. The two important points that need to be discussed are the operation of diode lasers and the phenomenon of modulation.

Diode lasers are just semiconductor lasers, and operate on the same principles as semiconductors. A typical diode laser is a p-doped semiconductor stacked on an n-doped semiconductor with a cavity in between. P-doped means positively doped, and has an abundance of positive charge carriers, like holes. N-doped means negatively doped, and has an abundance of negative charge carriers, the predominant choice being electrons. An injection current supplies electrons and holes to the entire structure. When an injection current is applied, the structure resembles a light-emitting diode (LED) as the population density of the electrons in the valence band outnumber the population density of the electrons in the conduction band. The injection current modifies the charge carrier [10] density, which in turn enhances the induced electric field between negative and positive carriers. This electric field changes the index of refraction. In addition, the movement of charge carriers causes a temperature change in the structure. This

temperature change causes shifts in the cavity length, and hence the allowed modes of the internal cavity structure. In addition, the electromagnetic radiation can be thought of as being in thermodynamic equilibrium with the system [7], so as the output wavelength is temperature-dependent, an increase in current leads to an increase in wavelength. Once a threshold current is reached, the population density of electrons in the conduction band surpasses the number in the valence band, which is called population inversion. Once population inversion is achieved, stimulated emission can occur from the electrons and holes recombining. Stimulated emission combined with a suitable cavity is the proper condition for lasing.

The next stage after lasing is modulation of the laser light. The physical process is to apply an alternating current to the injection current of the laser. This continuously changes the charge carrier density, index of refraction, temperature, and therefore the output frequency. As before, the index of refraction is modified by an electric field. I liken the process of a rapidly changing index of refraction to an oscillating charge, producing some radiation of some frequency. The continuously changing temperature continuously shifts the internal cavity around some value, allowing it to support more modes. The temperature effects dominate. We modulate around the original frequency, so it remains, but the process creates newer frequencies on the side (Sidebands) with a power dependent on how much modulation power there is. The expression for a DC current with an AC component is given by[8]:

$$(6) I = I_0 + i_m \sin(\omega_m t)$$

Mathematically this gives the frequency of the modulated light to be[8]:

$$(7) E = E_0 \exp[j(\omega_0 t + \beta \sin(\omega_m t))].$$

where [8]

$$(8) \beta = 2\pi\Delta F/\omega_m$$

Expanding (7) into a Fourier Series yields the spectrum of the frequency-modulated wave and gives first-order Bessel function terms[8]:

$$(9) E = J_0(\beta)E_0 \sin(\omega_0 t) + J_1(\beta)E_0 \sin((\omega_0 - \omega_m)t)$$

$$- J_1(\beta)E_0 \sin((\omega_0 + \omega_m)t) + \dots + J_l(\beta)E_0 \sin((\omega_0 + l\omega_m)t) + (-1)^l J_l(\beta)E_0 \sin((\omega_0 - l\omega_m)t)$$

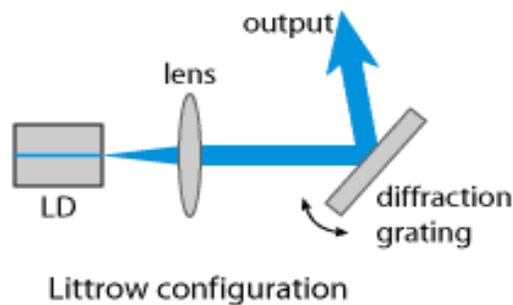
Squaring the coefficients of the sine terms yields the sideband intensities in the radiation spectrum.

PROPOSE IDEA

The main idea of this project is to find the atomic transition signal of my atoms, lock my laser to that spectrum to prevent drift away from resonance, and then to actually modulate the diode laser injection current. In order to lock the laser there are a few things needed: a spectrum to lock to and electronics to lock onto the signal. The method used to obtain the correct spectrum is Doppler-Free-Saturated Absorption Spectroscopy. The electronics used for locking are a diode laser side-lock servo. In order to modulate the current, a microwave source is needed along with proper connections between electronics. The microwave source is a Yttrium-Iron Garnet (YIG) oscillator. The YIG oscillator has a coil around the YIG ball. Once current passes through the coils, a magnetic field is generated. The YIG ball responds by resonating at microwave frequencies. The exact values for the YIG ball are 20MHz/mA frequency output, so we found that 331.1 mA is needed to give 6.8 GHz of microwave frequency.

EXPERIMENT

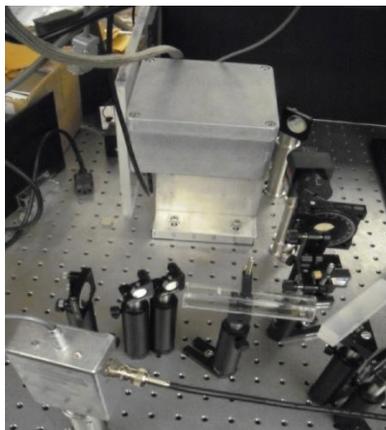
The first step to progress in my project was to first setup my external cavity. The external cavity of my setup is a Littrow configuration. The principle behind this configuration is that the laser light that comes out from the diode laser diffracts off of the diffraction grating. The goal is to attain cavity feedback. This is characterized by the first order diffraction being retro reflected onto itself. This results in a standing wave being formed between the lens collimating the diode laser light and the diffraction grating. The evidence of this is the threshold current being lowered as the standing wave causes an amplitude increase in the light wave. Therefore, there is less current needed to obtain lasing. An example diagram is as follows[6]:



Once feedback is attained, the next step is wavelength tuning. By moving the grating horizontal, the standing wave is stretched, yielding continuous tuning of the wavelength mode amplified [1]. Moving the grating angular relative to the beam allows one to choose the frequency feedback. Therefore, external cavity diode lasers allow precise laser tuning.

The final part of stabilization is current and temperature stabilization. A current/temperature controller is used to stabilize the current input as well as the temperature of the system. To prevent laser drifts the Littrow cavity is further enclosed in a metal casing.

In order to peak lock the laser to the hyperfine spectrum we first need the hyperfine signal. To obtain it, Doppler free saturated absorption spectroscopy (Doppler-Free) was performed. Doppler-free is a form of nonlinear spectroscopy [3]. It is considered nonlinear because the radiation reaching the photodetector is dependent upon more than one beam (two in this case). This form of spectroscopy eliminates Doppler broadening. Doppler broadening is a type of inhomogeneous broadening. Inhomogeneous broadening is an effect that widens atomic linewidths by affecting the individual atoms differently. As previously stated, all atoms moving at room temperature have an average velocity. A stationary atom has a narrow linewidth that can be found from the uncertainty principle. As an atom moves toward a beam of light it sees a blue-shift. An atom moving away from a beam of light sees a red-shift in the light frequency. The collective result is a widening of the atomic response to light frequencies. There are two probe beams that pass through the Rubidium cell, as well as a pump beam. The pump beam crosses one of the probe beams. Both probe beams are directed into an autobalancing photodetector.



The uncrossed probe beam is directed to the reference photodiode. The crossed probe beam is directed to the signal photodiode. Both signals give a Doppler-broadened signal.

The signal beam also gives the hyperfine signal. The photodetector is designed to subtract both signals from each other. The result is that only the hyperfine signal remains. The locking mechanism is accomplished by achieving a derivative of the hyperfine signal. The electronics lock to the center of the slope of the derivative. As the laser attempts to shift up the slope the electronics shift the signal back down, and as it attempts to shift down, the electronics shift the signal up.



MEASUREMENT

The measurement technique utilized to visualize the spectral modes of the laser system was with a Fabry-Perot interferometer. The basic theory is that the cavity has adjustable mirror distances. Adjusting these mirrors adjusts the allowed modes of the cavity. A piezoelectric transducer is attached and scanned so that fine appearances of other wavelengths can be visualized. At the right cavity spacing, the lasing modes can be visualized. The free spectral range of the Fabry-Perot is 1GHz. The expectation is to see sideband frequencies at .8 GHz away from the main peak. This peak was not seen.



CONCLUSION

The measurement did not reveal the desired result. Problems with this could be that the diode laser cannot support 6.8GHz modulation, the microwave frequency is not

going into the current controller (which could be due to impedance mis-matching), or the microwave frequency is not coupling into the laser out of the current controller.

Adjustments to consider would be to test for microwave signals coming out from the current controller, to use a different microwave source that has the correct impedance matching, or to modify the input method from the microwave source using capacitors.

Improvements and future considerations would be to measure the amount of atoms trapped using this setup, attempt Bose-Einstein Condensation, and to implement some quantum computing schemes that require both trapping and pulsing.

REFERENCES

- [1] Ye, Cunyaun. *Tunable External Cavity Diode Lasers*. 5 Toh Tuck Link: World Scientific Co. Pte. Ltd., 2004. Print.
- [2] Griffiths, David J. *Introduction to quantum mechanics*. 2nd ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2005. Print.
- [3] "Advanced Lab Spring 2008." *University of Colorado at Boulder*. Web. 07 Aug. 2009. <http://www.colorado.edu/physics/phys3340/phys3340_sp09/>.
- [4] C. Wieman, G. Flowers, and
63 (4), 317-330 (1995)
- [5] Metcalf, Harold J., and Peter Van der Straten. *Laser Cooling and Trapping*. New York: Springer-Verlag New York, 1999. Print.
- [6] "Encyclopedia of Laser Physics and Technology - external-cavity diode lasers, ECDL." *RP Photonics Consulting - laser and amplifier design, nonlinear optics, fiber optics, fiber lasers and amplifiers, ultrashort pulses, optoelectronics, consultant*,

training. Web. 07 Aug. 2009. <http://www.rp-photonics.com/external_cavity_diode_lasers.html>.

[7] Pedrotti, Frank L., Leno S. Pedrotti, and Leno M. Pedrotti. *Introduction to Optics*. 3rd ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2007. Print.

[8] P. N. Melentiev, M. V. Subbotin, and V. I. Balykin, "Simple and effective modulation of diode lasers," *Laser Phys.* 11, 891-896 (2001)

[9] Pethick, Christopher. *Bose-Einstein condensation in dilute gases*. Cambridge, UK: Cambridge UP, 2002. Print.

[10]

Instrum. **62**(1), 1-20 (1991).

[11]

18, 649 (1993)