Laser Stabilization for Quantum Computing with Trapped Barium ions

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ABSTRACT

The goal of this project was to stabilize a laser cooling system used to trap and cool Ba^+ ions used for quantum computation research. The lasers, at 650 and 985 nanometers, needed to be stable at the 5 megahertz level in order to be effective. The proposed system involved constructing Fabry-Perot optical cavities to provide short term stabilization with a wavemeter providing long term corrections. The cavities were very sensitive to temperature fluctuations and have not yet been tested in stabilizing a laser. The project was left as yet unfinished due to time constraints.

INTRODUCTION

Trapped Ion Quantum Computing requires a number of pieces to work in tandem to successfully perform experiments, including trapping ions themselves. A trap works using both a laser cooling system and an oscillating magnetic field to constrain ions. As explained below, the stability of the lasers used in the cooling system is important to its success. A proposed method to stabilize lasers is to use an external Fabry-Perot optical cavity to monitor the wavelength of the laser, which then provides feedback to correct the laser if it has moved away from its target frequency.

The system outlined in this paper involves constructing two Fabry-Perot cavities to work with a wavemeter to stabilize a laser at 650nm and another at 985nm. The wavemeter can accurately correct either laser when needed, but only one at a time. In the time it takes to fix one laser, the other may drift away from its target frequency. If the system is expanded past two lasers, the time between corrections can grow large enough to introduce significant error in any individual laser's frequency.

A proposed solution to this problem that does not involve any extra wavemeters is to use optical cavities to hold each laser at a steady frequency while a single wavemeter cycles between the other lasers to correct them. While an optical cavity may have flaws preventing its use for long term stability, it may serve to maintain a laser within an acceptable frequency range in the timeframe necessary for a wavemeter to correct other lasers. Thus it is a viable option to pursue in developing a stabilization system.

LASER COOLING

A stable laser is necessary for successful laser cooling. The exact range of frequencies a laser must be within are largely determined by the width of the absorption lines in the spectrum for a given atom, and so varies from experiment to experimnet. To have successful laser cooling, a laser frequency is detuned to have energy just below the energy of a transition in the atoms to be cooled. This detuning allows the photon to be absorbed more readily if the atom is moving toward the laser beam due to the doppler effect:

$$f' = f\left(\frac{v}{c+v}\right) \tag{1}$$

The doppler effect also prevents the atom from absorbing efficiently if the atom travels in a parallel direction with the laser beam propagation.

When an atom absorbs a photon, it gains that photon's momentum. Conversely, when atoms emit photons they recoil with equal and opposite momentum of the emitted photon. For a stationary atom, the absorption causes motion in the direction of the photon. However, the atom will spontaneously decay in a random direction within a short time if the lifespan of the state is short. If a laser is incident on an atom with the proper frequency, the atom will absorb photons from the laser and emit photons randomly. The average momentum gain from absorption is in the direction of the laser beam, while the average momentum lost in emission is zero because the direction is random and after many emissions the net change is zero. A laser will thus cause an atom to travel parallel to its propagation.

When six lasers are aligned to intersect at a point, with each of three axes having beams propagating in both directions, so called "optical molasses" is created. The effect of optical molasses is that if an atom is at the intersection of the beams, if it moves in any direction the lasers propagating in the other direction oppose it, and the lasers propagating in the direction of motion have a limited effect due to the doppler effect. This arrangement keeps the atom held to a local area, effectively cooling it.

An effective method to cool ions is to trap them in an oscillating field, so that they are sitting at the bottom of an effective potential well in 3D space. The ion can then move about in the trap as long as its energy is not sufficient to escape, but further cooling may be necessary to perform experiments on the ion. By passing a laser

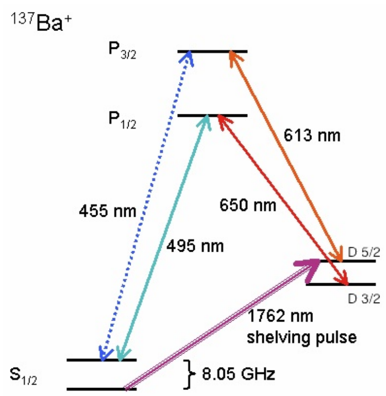

FIG. 1: Relevant Energy Levels in Ba^+ Ions [2]

through the bottom of the trap, the ion will at times move against the direction of propagation causing a cooling effect. When the ion moves in the same direction or a perpendicular direction to the laser, the cooling effect is minimal due, again, to the doppler effect. Thus a single laser cools an ion in a trap.

For further information on laser cooling and trapping, see [1]

The specific ions used in this experiment are Barium Ions, and the energy levels used for laser cooling are shown in FIG. 1. The lasers used for cooling must match the transitions between the $S_{1/2}$ to $P_{1/2}$ and $D_{3/2}$ to $P_{1/2}$ energy levels. The 495 nm transition is the one that is actively used for cooling. Should the $P_{1/2}$ state decay to the $D_{3/2}$ state instead, a 650 nm laser is used to excite the atom back into the cooling cycle.

In order to maintain effective laser cooling, the lasers must be kept accurate within about 5 megahertz. Also, though a 495 nm laser is needed for cooling, a 980 nm is doubled to create a beam of the correct wavelength. Thus the two lasers used in this project were at 650 nm and 980 nm.

OPTICAL CAVITIES

The ability of an optical cavity to create constructive and destructive interference allows it to be used in wavelength discrimination. Of course, the intensity and wavelength of the incident light and the length of the cavity affect the light transmitted. In particular, the Lorentzian characteristic of the output intensity, given by

$$I_{\mathrm{Tr}} = \frac{I_{\mathrm{In}}}{1 + \mathcal{F}\,\sin^2(\delta/2)} \tag{2}$$

allows one to use a cavity of fixed length to stabilize a laser wavelength, where $\delta = \frac{2\pi}{\lambda}$ [3].

The technique used to lock a laser frequency using an optical cavity is called a side lock. In principal, the cavity is adjusted to the correct length while the laser is

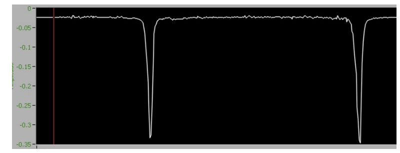

FIG. 2: A free spectral range of the optical cavity used

maintained at the correct frequency by a wavemeter. The length is chosen such that the intensity of the transmitted light is about half of its peak value. When the cavity has been adjusted correctly, it is set to maintain that length and the laser ceases to be maintained by the wavemeter. Instead, the transmission of the optical cavity is monitored to control the laser. Should the transmission of the cavity increase, it implies an increase in frequency of the laser. Likewise, a decrease in transmission implies a decrease in frequency. So, assuming the cavity's length remains constant, the laser's frequency can be held reasonably steady with an optical cavity alone.

A cavity is limited in its effectiveness for this task by a quantity called the finesse. The finesse can be expressed as

$$\mathcal{F} = \frac{\Delta FSR}{\Delta 1/2} \tag{3}$$

[3] In this case, Δ FSR represents the free spectral range of the cavity, which is the distance in Hz between adjacent modes of resonance in the cavity. Δ 1/2 represents the full width (Hz) at half maximum of a single peak. The finesse is a good representation of the accuracy of the cavity. A higher finesse corresponds to a thinner and steeper peak to lock to. But, if the side of the Lorentzian curve is too steep, it can become very difficult to lock a laser to it. On the other hand, too shallow a curve may not provide enough accuracy. Thus it is important to choose a finesse that is appropriate for the purpose at hand. In practice, the way to control finesse is to choose the reflectivity of the walls of the optical cavity, giving a finesse as

$$\mathcal{F} = \frac{\pi\sqrt{R}}{1 - R} \tag{4}$$

Results of Testing

Our cavity was built with mirrors having 98% reflectivity, leading to a theoretical finesse of about 155. When measured experimentally, our finesse was lowered but not by a significant enough value to prevent the cavity from being effective. Using a piezo electric transducer (PZT), we were able to scan multiple free spectral ranges of our cavity, one of which is shown in FIG. 2

To test the stability of the cavity, a stable laser was shone through and the cavity was locked to the laser by

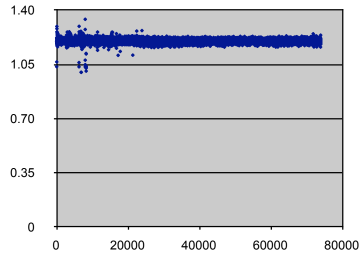

FIG. 3: Graph of intensity of light emitted from the cavity over time (s).

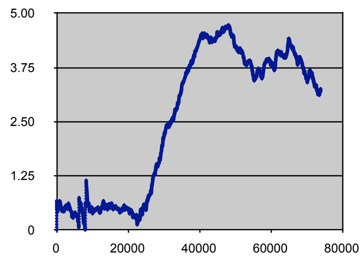

FIG. 4: Graph of error signal corresponding to the data in FIG. 3 over time (s).

adjusting the length of the cavity using the PZT. FIGs. 3 and 4 show a typical run of locking the cavity and monitoring the error signal of the cavity. Despite the fact that the cavity remains locked for the majority of the collection time, the error signal never stabilizes. As the laser was held at a stable frequency, this means the cavity length needed to be constantly adjusted due to fluctuations of the cavity, not the laser. There are two major proposed sources of this error.

Intensity Noise

As shown in Eq. 2, the intensity transmitted is directly proportional to the intensity incident on the cavity. However, the locking system relies on the transmittance being stable in intensity. This is due to the fact that the current lock system measures the intensity transmitted as though it were the transmittance. If the intensity were to drop, it would appear that the transmittance has dropped indicating a drop in frequency. This causes a frequency correction that is unnecessary, and might be a significant source of noise on some of the lasers used.

The solution to this problem is straightforward in principle: split the beam before it enters the cavity, and compute the ratio of intensity of light before entering and transmitted through the cavity. This is a scaled version of transmittance, which can be used to eliminate intensity noise entirely. This system was implemented but not tested efficiently because splitting the laser beam caused the intensity of the transmitted to drop too low. The second photodiode was removed to continue other testing, but may be useful in the future.

Temperature effects

The effects of temperature on the cavity seem to be significant. While no data has been taken to quantify temperature effects, watching the feedback signal and taking actions of change the temperature of the cavity showed a clear correlation. When a person stands near the cavity, the heat of their body produces enough change in the temperature of the cavity to cause thermal expansion, resulting in a large dip in the feedback signal. Placing a hand near the cavity has even more dramatic effects. When the hand and person are removed, the feedback signal increases as the cavity cools and contracts.

A preposed solution to this problem is to place the cavity in an acrylic box to minimize convection currents near the cavity. Since the cavity needs to be stable only long enough to allow the wavemeter to stabilize the other lasers, the box may provide enough stability in temperature without further refinements.

LOCKING AND IMPROVING PERFORMANCE

Control System

The proposed control system involves controlling the laser solely with the cavity, and altering its frequency by adjusting the cavity length. Assuming that the cavity has been calibrated and set to the proper length, the voltage to the piezoelectric control is set to a constant, in order to lock the cavity length to the proper distance. Then, the intensity on the photodiode is used to determine how the laser has drifted, and the feedback from the intensity controls the correction of the laser. In order to ensure that the cavity is locking the laser to the proper frequency, a wavemeter is employed to check the wavelength of the light. If the wavelength is off, the wavemeter will send a feedback signal to the cavity to adjust its length. This change in length causes the cavity to send a feedback signal to the laser, fixing its frequency. A diagram of this system is shown in FIG. 5.

The feedback loop used to control this lock is a standard PID control loop. For cavity testing purposes, the program locks the cavity length to the laser frequency, opposite of the final lock. It is currently implemented on a computer, with plans to switch to a microcontroller for the final product. The speed of the computer may be affecting the efficiency of the current lock, as the cavity may drift in the time it takes for the computer to process the next iteration. Also, the current DAC being

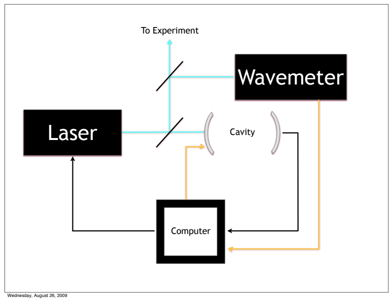

FIG. 5: Proposed control system to stabilize the lasers

used is a USB port, allowing only one input or output to be active at once. With a microcontroller, the processing time should increase and the limitations of a USB DAC will be eliminated, creating a better locking system and improving performance.

CONCLUSION

The project to stabilize the lasers was not completed and further testing is needed to see if the proposed system is still feasible. As it stands, the temperature error source may be contained by encasing the cavity to prevent convection from causing temperature drifts. A possible solution, if that is not sufficient, is a temperature controller to ensure the cavity does not have major thermal expansion or contraction. Should the intensity fluctuations need removed, another photodiode may provide the necessary correction as explained above. The next step in the project is to temperature stabilize the cavities so that they may be tested in stabilizing the lasers.

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[1] Metcalf and ver der Straten, *Laser Cooling and Trapping* (Springer-Verlag New York, Inc., 1999).
[2] URL `http://depts.washington.edu/qcomp/research`.
[3] D. Meschede, *Optics, Light and Lasers* (Wiler-VCH Verlach GmbH and Co., 2004).