Laser Frequency Stabilization with Optical Cavities

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Abstract

Effective laser cooling requires the laser's frequency to be precise, with a frequency drift of no more than a few megahertz. Optical cavities can be used as frequency monitors and provide feedback to tunable lasers for correcting frequency drift. In the University of Washington Quantum Computing with Trapped Ions lab, Fabry-Perot resonator cavities were designed and built to stabilize the frequency of two lasers used for laser cooling trapped barium ions.

INTRODUCTION

Many atomic physics experiments use high level laser techniques such as laser cooling, photoassociation, and optical trapping. These applications require that the laser frequency control be precise, however laser frequencies tend to drift, requiring a method of stabilization. In the University of Washington Quantum Computing with Trapped Ions lab, Fabry-Perot resonator cavities were designed and built to provide a feedback signal for stabilizing the frequency of two lasers used for laser cooling trapped barium ions.

Laser cooling is based on manipulating an atom's or ion's energy state with a laser whose frequency is properly tuned. Shining a laser, whose frequency is resonant with an energy transition, on to an ion allows the ion to absorb a photon and jump into an excited energy state. The ion also takes on the momentum carried by the photon, giving the atom a momentum boost in the direction of the photon's initial travel. The ion will then spontaneously decay back to the ground state, emitting a photon. To conserve momentum the ion will get another momentum kick but in the opposite direction of the photon's emission. Reducing the frequency of the laser to just below the transition frequency of the ion is known as red detuning. Red detuning prohibits a motionless ion from absorbing a photon. However, as a result of the Doppler effect, an ion moving towards the laser will see the laser light at a higher frequency, resonant with the energy transition, and the ion will then absorb a photon, acquiring its momentum. Since the photon's momentum was opposite the ion's momentum, the ion will slow down. When the ion decays back into the ground state a photon is emitted. This emission is in a random direction, therefore, after several absorptions and emissions the momentum kicks from the emissions cancel out and the net effect on the ion is the slowing from the photon absorption, effectively cooling the ion. A trapped ion's motion is already limited by the trap so a warm ion will move towards an incident laser beam at least part of the time, during which the ion will lose momentum but because of the frequency detuning the ion will not be affected by the laser when it is moving away from the laser.[1] Effective cooling requires the frequency detuning to be precise, with a frequency drift of no more than a few megahertz. An optical cavity can be used as a frequency monitor and provide feedback to a tunable laser for correcting the frequency drifts.

Currently, the University of Washington Quantum Computing group is using a single wavemeter to stabilize the frequency of a 495 nm laser and a 650 nm laser used for laser

cooling trapped barium ions. However, the wavemeter can only monitor and provide feedback to one laser at a time. While the wavemeter is monitoring one laser, the other laser has time to drift outside the frequency range ideal for laser cooling. To address this problem an optical cavity was built for each laser. The optical cavity will provide a feedback signal to correct the frequency drift when the wavemeter is not stabilizing the frequency.

THEORY

A Fabry-Perot optical cavity consists of two mirrors separated by some distance. When a laser beam incident with the cavity has a wavelength such that an integer number of half wavelengths is equal to the mirror spacing there is constructive interference within the cavity and light is transmitted out of the cavity. However, if an integer number of half wavelengths does not match the mirror spacing there is destructive interference within the cavity and no light is transmitted. Using mirrors having the same reflectivity reduces the equation for transmittance to the Airy function

$$T = \frac{1}{1 + F sin^2(\delta/2)} \tag{1}$$

where $\delta = \frac{2\pi l}{\lambda}$, l = length of the cavity, and λ = wavelength of the incident light. F is defined as the finesse constant which is dependent on the reflectivity of the mirrors,

$$F = \frac{4R}{(1-R)^2}. \tag{2}$$

So when $\delta = N\pi$, corresponding to an integer number of half wavelengths equaling the cavity length, $T = 1$ and the cavity transmits the incident light.[2]

Important characteristics of an optical cavity can be found by looking at the cavity's transmittance as the frequency of incident light is varied or, equivalently, by varying the length of the cavity. The cavity's response to such a scan would look like Figure 1. The distance between the peaks is the free spectral range (ΔFSR) and is dependent on the length of the optical cavity. Another characteristic is the width of the peak at half-maximum ($\Delta\nu_{1/2}$). Together these two characteristics make up the finesse of the cavity, which is defined as

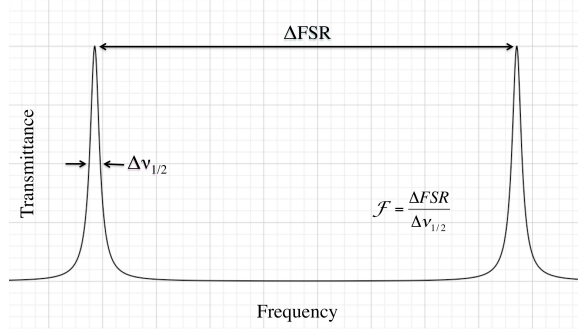$$\mathcal{F} = \frac{\Delta FSR}{\Delta\nu_{1/2}}. \tag{3}$$

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FIG. 1: Theoretical optical cavity response to changing frequency (Eq. 1), free spectral range (ΔFSR), and full width at half-maximum ($\Delta\nu_{1/2}$) [2].

Finesse is a description of the cavity's resolution. When using a photodetector to measure the transmitted light intensity it is important to have a high finesse. If the finesse is too low, the slope on the side of the peak is small, therefore a small change in frequency may result in a change in transmission too small for the photodetector to measure.

An optical cavity having a set mirror separation and a photodetector can be used to monitor a laser's frequency because of the transmissions' dependence on the frequency. A measured change in the cavity's transmitted intensity can be used in a feedback loop to correct the frequency of a tunable laser, locking the laser frequency to the cavity. A simple locking method is a side lock, where the cavity length is set so that the desired laser frequency corresponds to a transmitted intensity on the side of the peak. By locking the laser to the left side of the peak a measured increase in transmitted intensity indicates an increase in frequency while a decrease in transmitted intensity indicates a decrease in frequency. Optical cavities are very sensitive to small changes in frequency and in some applications a well tuned and stable cavity can be used to keep frequency drifts to a fraction of a millihertz from the desired frequency. However, for laser cooling it is only necessary to keep drifts within a few megahertz from the target frequency, higher precision provides no added benefit.

CAVITY DESIGN

Two optical cavities were designed and built to stabilize a 495 nm (605 THz, aqua) laser and a 650 nm (491 THz, red) laser used for laser cooling barium-137 ions. The goal was to build cavities capable of stabilizing the lasers to within 5 MHz of the desired frequency. The
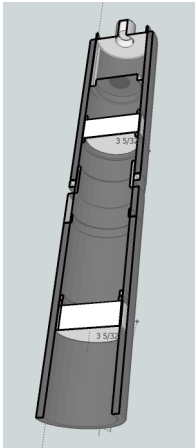
FIG. 2: Optical cavity diagram.

495 nm beam is produced using frequency doubling of an infrared laser, the cavity designed for stabilizing this beam was done in the infrared. A pair of spherical mirrors with curvature radius of 7.5 cm and diameter of one inch were used in each cavity. The reflectivity of the mirrors was chosen to be 0.98 for the frequency range of the laser to be stabilized. The main structure of the cavity is made from two aluminum SM1 optical tubes from Thor Labs. A length adjustor tube was placed in the center so that the cavity can be made confocal. A confocal cavity is maded by setting the mirror spacing equal to the radius of curvature of the mirrors and results in a stronger transmitted signal. One mirror is placed between a cylindrical piezo and a rubber o-ring and the other is held in place with two retaining rings. This allows for the mirror spacing to be finely tuned by varying the voltage applied to the piezo, moving the mirror against the o-ring. A photodiode designed to be used with the SM1 tubes sits behind the stationary mirror. The laser beam passes through the hollow center of the piezo, through the first mirror, resonates in the cavity before being transmitted out through the second mirror and onto the photodiode. A diagram of the cavity is shown in Figure 2.

It is necessary for the piezo to be able to move the mirror over a range equal to a halfwavelength of the incident light, or several hundred nanometers, to guarantee that a peak can be found for locking. The cylindrical piezo moves between one and two nanometers per applied volt. Thus, a high voltage supply is needed to drive the piezo. The piezo driver circuit shown in Figure 3 was built to amplify a program voltage from a computer. This circuit has a gain of 100, so a program voltage range of 0-5 V results in a applied voltage
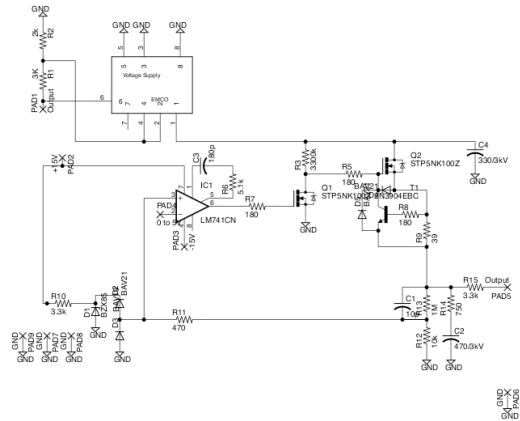
FIG. 3: Piezo driver circuit schematic based on a design from *The Art of Electronics, 2nd ed.* by Horowitz and Hill [3].

range of 0-500 V.[3]

PRELIMINARY TESTING

The initial tests were designed to determine the finesse and long-term stability of the cavities. Both tests require that the incident laser beam have a stable frequency. The infrared counterpart of the 495 nm laser was stabilized using a wavemeter to test the cavity designed for infrared laser and a HeNe laser, having a stable frequency in the red, was used to test the cavity designed for the 650 nm, red laser. When the frequency of the incident light is held constant the transmittance through the cavity can be controlled by changing the mirror spacing. Since the mirror spacing is controlled by the voltage applied to the piezo, the tests can be conducted in terms of the program voltage to the piezo driver and the output voltage of the cavity's photodiode.

The finesse of the cavities were measured by pushing the movable mirror through its full range of motion and recording the photodiode output.. The mirror is moved by applying a scanning voltage of 0-500 V to the piezo controlled by scanning the program voltage to the piezo driver from 0-5 V. The voltage output of the red cavity is shown in Figure 4. Each peak in the photodiode's voltage is where the mirror spacing equaled an integer number of half wavelengths of the incident laser light. This response looks similar to Figure 1 except the length of the cavity is being varied instead of the frequency of the incident light. The
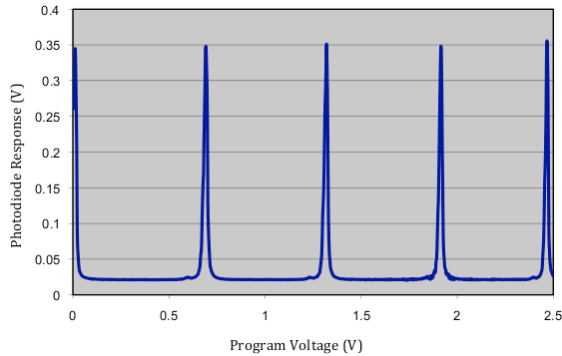
FIG. 4: Photodiode response as the program voltage is increased from 0-2.5 V, changing the mirror spacing in the optical cavity designed for the red laser.

free spectral range of this response is about 0.54 V (program voltage) and the full width at half maximum is approximately 0.02 V giving a finesse of approximately 27. This low finesse is possibly a result of using the HeNe laser which has a slightly lower frequency than what the mirrors were chosen for resulting in a lower reflectivity. However, this finesse still allows for locking the cavity.

The cavity's long term stability was tested by using a side lock to set the length of the cavity for a target transmittance. A target value for the photodiode response was chosen for the cavity's locking point. A PID (proportional-intergral-derivative) locking computer program was used to generate a feedback signal that was sent to the piezo driver. The inputs to the PID program are the measured voltage from the photodiode and the target value. The generated feedback signal was based on a weighted sum of the current difference between the target and measured value, a sum of all the measured differences, and the rate that the difference is changing. After a few iterations the photodiode's response signal would be set to the target value. The first graph in Figure 5 shows the photodiode's response when the red cavity was locked to the HeNe laser. Ideally, the feedback signal would settle to a single value, indicating that the voltage applied to the piezo corresponding with the correct cavity length had been found. Unfortunately the feedback signal had a long term drift as seen in the second graph of Figure 5. Since the cavity tubes were made from aluminum, the cavities are extremely vulnerable to thermal expansion, resulting in a change in the mirror spacing. This is likely cause of the drifts seen in the feedback signal, though further tests need to be done to verify and characterize the cavities response to thermal changes. Despite
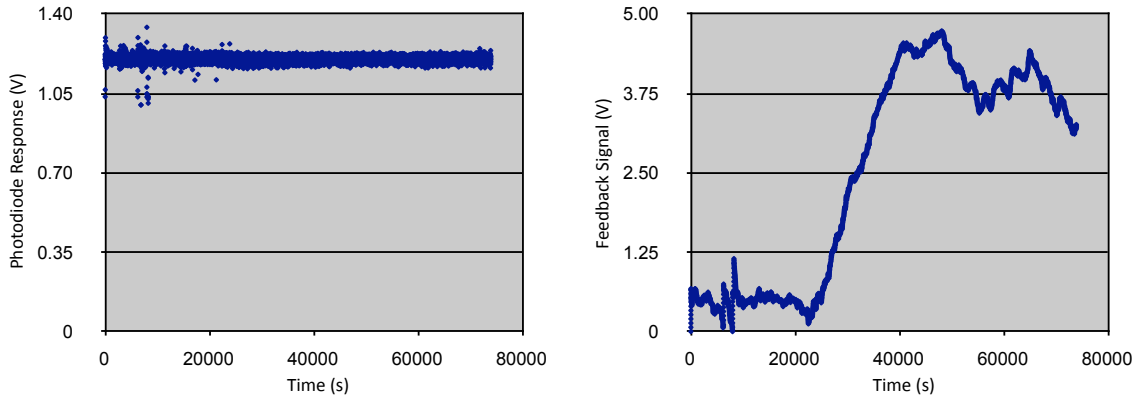
FIG. 5: Photodiode response and feedback signal over a 20 hour time frame. The photodiode response was locked to a target value of 1.20 V.

the fluctuations in the feedback signal the cavities remain locked for many hours, and even have stayed locked for several days.

CONCLUSION AND FUTURE WORK

So far the mirror spacing has been adjusted to lock the photodiode's output. The next step is to set the mirror spacing for a target frequency and monitor the changes in the photodiode's output that are a result of frequency drifts of the laser. Using a PID locking program, similar to the one used for testing, a computer will generate a feedback signal for the tunable laser and correct the laser frequency. This will lock the laser frequency to the appropriate value for laser cooling.

The optical cavity and the wavemeter will be used together to stabilize the laser frequency as a two mode system illustrated by Figure 6 The majority of the time the laser frequency will be stabilized with just the cavity. Ocassionally the wavemeter will be used to check the laser frequency and it will detect if there is a discrepancy between the cavity and the wavemeter due to a drift in the cavity's mirror spacing. A signal from the wavemeter will be used to create a feedback signal that will go to the piezo driver and reset the mirror spacing. How often the wavemeter will need to check on the cavity length will be determined by the stability of the cavities.

The results of the cavity testing indicate that the cavities are stable enough for locking the laser frequency over a period of time that allows the wavemeter to be used with multiple
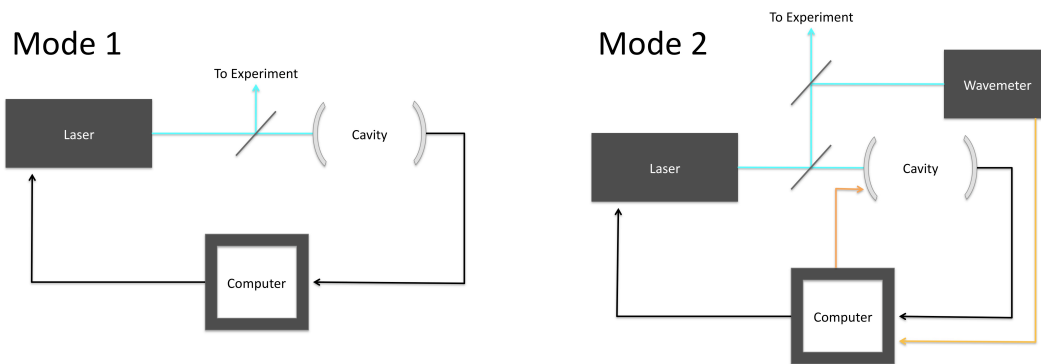
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FIG. 6: The two mode frequency locking system.

cavities. Thus locking the frequency of multiple lasers. The implementation of the cavities will hopefully keep the lasers' frequencies continuously stable allowing for more effective cooling of the barium ions.

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[1] Metcalf and ver der Straten, *Laser Cooling and Trapping* (Springer-Verlag New York, Inc., 1999).

[2] D. Meschede, *Optics, Light and Lasers* (Wiler-VCH Verlach GmbH & Co., 2004).

[3] Horowitz and Hill, *The Art of Electronics* (Cambridge University Press, 1989), 2nd ed.