Passive Reference Cavities for Frequency Stabilization of Yb^+ Cooling Lasers

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Abstract

Sympathetic cooling will be used to cool Ba^+ ions by laser cooling Yb^+ ions. The relevant Yb^+ transition will require the use of a 370 nm cooling laser and a 935 repump laser. To ensure lasing at the correct frequency, each laser will be locked to a reference cavity. The design and construction of these two cavities is detailed. Thermal stability is tested and the resulting drift in frequency for the cavities is estimated. The transmission spectrum of the cavities is investigated and cavitation verified.

1 Introduction

Systems of cold trapped ions are one of the more promising candidates for quantum computing. These systems fill many of the DiVicenzo criteria, notably being scalability [2]. Trapped ions store quantum information in their internal states. Motional degrees of freedom that link the ions serve as logic gates, creating the need to keep the ions extremely cold; should the ions gain too much motional energy the ability to accurately perform computational operations on the ions will be lost [1].

Doppler cooling is a key technique in the preparation of atoms at the beginning of an experiment. Given a suitable electronic transition, laser light is redshifted from the peak of the transition's absorption spectrum. Atoms moving toward the laser light then see the light on resonance. As the atom absorbs a photon from this light, it randomly emits a photon and drops back to the ground state, allowing the process to be repeated. The end result of absorbing a photon with opposing momentum to the atom is a slight reduction in the atom's momentum and thus its temperature. There is a practical limit to this cooling based upon this random photon emission [4].

Two levels of an ion's hyperfine structure are used to store the qubit information. As discussed, doppler cooling is vital to helping keep these ions cool. The caveat is that both doppler cooling and quantum information use the internal states of the ions, meaning we cannot do both simultaneously. The solution is sympathetic cooling. A second species is introduced and doppler cooled. Couloumbic coupling, the force between objects that is proportional to the products of their electrical charges, ensures that the first species is also cooled [1]. Efficient use of this technique requires two species of similar mass.

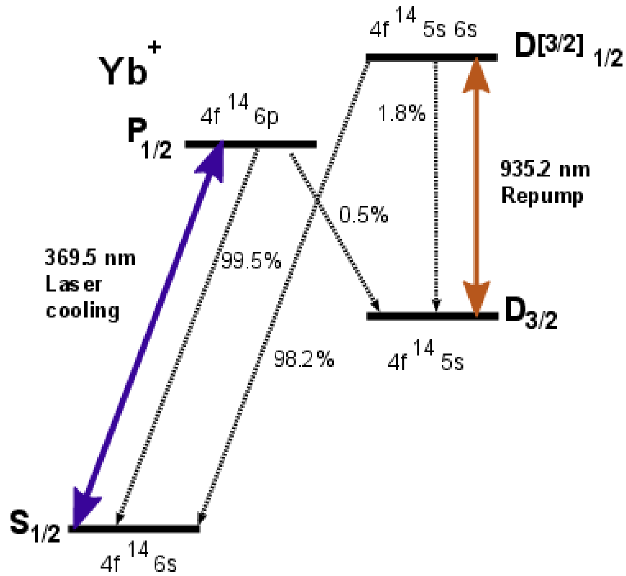

Figure 1: Yb^+ electronic transitions

In the Trapped Ion Quantum Computing group at the University of Washington, Ba^+ ions are trapped and used as qubits. The group's next goal is to use Yb^+ as the second species that can sympathetically cool Ba^+. The electronic transitions in Yb^+ will require two lasers [Figure 1]. A 370 nm cooling laser will drive the transition from the $S_{1/2}$ to the $P_{1/2}$ state. This state can decay to the $D_{3/2}$ state, requiring a repump laser to drive this state to the $D[3/2]_{1/2}$ state, which will then decay to the $S_{1/2}$ state.

Doppler cooling requires a laser with a stable frequency. Laser frequency naturally drifts with ambient conditions and thus requires active modulation. Reducing the frequency drift of the laser can be done by locking the laser to a transmitted frequency peak through a reference cavity. A feedback loop controls a piezo on the laser head, allowing automated tuning of the laser.

2 Design

A passive reference cavity can be constructed by attaching two mirrors onto a bored cylinder of Invar. Invar is a nickel-iron alloy that is unique in its low thermal expansion properties, relative inexpensiveness, and machinability, making it ideal for a cavity that is to be used as a reference.

There are additional parameters that a design should consider. The free spectral range (FSR) of the cavity is the spacing between longitudinal modes and is given by [3]

$$FSR = \frac{c}{2l}$$

where c is the speed of light and l is the cavity length. The first step to designing a reference cavity is to select a length giving a desirable FSR. For both cavities a length of 75-80 mm was chosen, giving a FSR of about 2 GHz.

Cavity stability is also essential. A cavity is stable if it has a periodic ray path [3]. Alternatively, stability can be defined by the cavity geometry in terms the dimensionless parameter g [3]

$$g \equiv 1 - \frac{l}{R}$$

where l gives the separation of the mirrors, and each R corresponds to the radius of curvature of the mirror. A cavity is stable if it fits the criteria [3]

$$0 \leq | g | \leq 1.$$

For the purposes of this cavity, the design should be nearly confocal (cavity length equal to radius of curvature of the mirrors), but not completely. A confocal cavity would give a transmission spectrum with two peaks for every FSR, making laser locking difficult. Commercially available and affordable mirrors limit options, so the process is to select the best of what is offered. Mirrors with R=100 mm were used, complimenting the final length of the cavity, $l = 79$ mm.

A final consideration was the reflectivity of the mirror. A reflectivity of 98% was chosen based upon available options as well as the application of the cavities. Too high of a reflectivity and the transmitted peaks would be too narrow to lock to; too low of reflectivity and the peaks would begin to interact and their structure would be difficult to resolve and thus lock to with a simple and inexpensive feedback mechanism.

Two identical cavities were constructed out of a 1.25 in diameter rod of Invar. For detailed schematics see. Each cavity was cut to 3.5 in. The inside of each cavity was drilled out to a diameter of 3/4 in. On each end of the cavities a roughly 1 in diameter, 3/16 in deep recession was made to hold the mirrors. A small recession was drilled into the side of each cavity to accommodate a thermistor, an electronic device whose resistance varies with temperature. Each cavity was then wrapped with 7-10 Ω's of wire for use as a heating element.

It is important to emphasize the care taken to ensure that the recessions on the ends of each Invar piece were parallel. The ease of seeing caviation is linked directly to how precisely the mirrors are aligned. Construction of these cavities was primarily done using a lathe. Using a gauge, concentricity was checked each time the rod of Invar was inserted into the vice of the lathe. Concentricity for both cavities was kept to ± 0.0015 in.

A 3 in diameter rod of acrylic was cut to two pieces of 4.2 in length. Each was drilled out to snugly accommodate a cavity wrapped in foam. The purpose of this setup was to protect the mirrors while also helping to insulate the cavities, allowing better temperature stabilization. End caps were machined for the cavity holders and holes drilled and bored to accommodate posts, allowing the cavities to be used on laser tables.

The mirrors were installed one at a time on each cavity. Four drops of five minute epoxy provided the needed adhesion. The pieces discussed before the mirror installation can be see in [Figure 2].

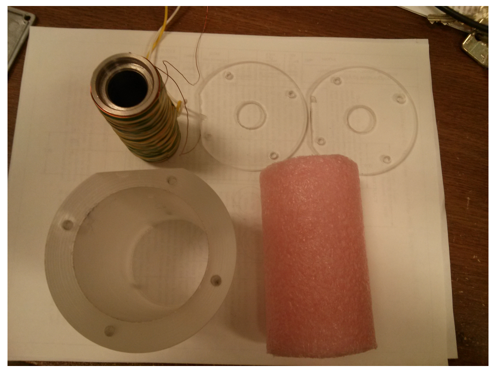

Figure 2: Pieces of cavity before assembly. Mirrors were not installed at this time. You can see the finished piece of Invar, wrapped with wire and taped. Also shown is the foam wrapping and the acrylic casing pieces.

3 Testing

Testing was needed in order to verify that the cavities are capable of performing in the required capacity. This requires verifying cavitation as well as temperature stabilization.

3.1 Temperature Stabilization

Testing cavity temperature stabilization was straightforward. A Wavelength Electronics PID-1500 was wired to stabilize the cavities' temperatures. The temperature fluctuations were measured using thermistors which record temperature as a function of voltage. Using Lab View, these voltage fluctuations were then recorded

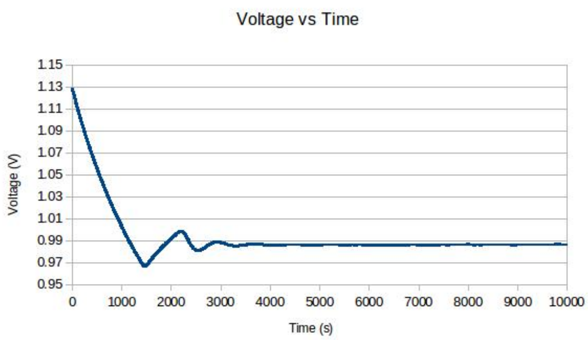

Figure 3: Voltage while stabilizing 370 nm cavity with PID

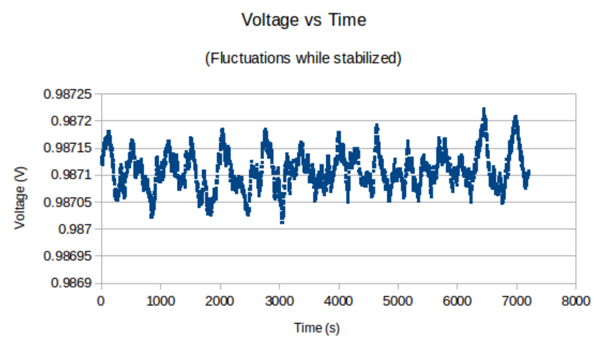

Figure 4: Detailed voltage of cavity after multi-day stabilization

over time [Figure 3]. From the data, the cavity completes its major stabilization in ≈1 hr. This time estimate includes two regimes: the time for the PID to bring the temperature close enough to the setpoint to start undergoing damped oscillations and then the time for the damped oscillations to nearly disappear as the PID stabilized the temperature.

In order to better understand the stability of the cavities, a more thorough understanding of the voltage variations was needed. After having the cavity connected to the PID for several days, a 4 hour run was performed [Figure 4]. With this data, the fluctuations in voltage can be correlated to frequency space, giving an idea of the stability of the cavity in regards to stabilizing the laser frequency.

The relationship between temperature and voltage for a thermistor (for a constant current) is

$$T(v) = \frac{B}{\ln\left(\frac{V}{V_0}e^{\frac{B}{T_0}}\right)}.$$

Ultimately what we want to see is the uncertainty in the frequency of the cavity. Using propagation of uncertainty, it can be shown that

$$\triangle f = \frac{c\alpha_L T_0^2 \Delta V}{2\lambda B V_0}.$$

Here c denotes the speed of light, α_L the thermal expansion constant for Invar, T_0 the initial temperature, ΔV the variation in voltage, λ, B the thermistor constant given by the manufacturer, and V_0 the initial voltage.

To get an idea of the frequency drift of the cavities, we analyze the data from the 4 hour run 4. From this, $\Delta V \approx 150\mu V$ can be seen. Using the previous relationship, we find that for the 370 nm cavity there is an expected frequency drift when using this PID of $\implies \Delta f \approx 1.4MHz$. This is an upper limit that will be suitable for locking to transitions with full width at half maximum's of about 25 MHz.

3.2 Testing for Cavitation

The final step in testing was to investigate if the cavities would operate correctly at their respective wavelengths. Testing this was complicated by the lack of a 370 nm and 935 nm laser, which at the time of this writing are still in development. Available wavelengths in the lab were 399 nm and 986 nm.

Each cavity's mirrors are 98% reflective at their respective wavelengths. To test these cavities using the available lasers, the mirrors were individually tested to ensure that their reflectivity at the alternative wavelengths was close to their reflectivity at their intended wavelengths. For the 370 nm mirrors, 399 nm light was used. Reflectivity was found to be $\approx 99\%$. For the 935 nm mirrors, 986 nm light was used. Reflectivity was found to $\approx 98\%$. These values indicate that the available lasers can be used to test for cavitation.

Knowing that the lasers available would work, the cavities were then set up on the laser tables. The general process was as follows. A pick off was used to provide a laser beam to work with. Using two adjustable mirrors, the laser light was directed to the cavity. On the other side of the cavity a photodiode was placed, allowing measurement of the transmission spectrum of the light while sweeping the laser frequency.

To see cavitation, the laser beam needs to be aligned correctly with the cavity. Rough adjustments were performed by adjusting the position of the cavity, which was then locked down. Fine adjusting followed from a system of walking the mirrors. By separately adjusting the horizontal or the vertical adjustments on the two mirrors, the beam alignment could be fine tuned.

The first cavity tested was the 370 nm cavity using the 399 nm light. Once the laser was coupled to the cavity decently well, moving the laser head by adjusting the piezo brought the transmission on and off resonance, showing we had cavitation. Unfortunately due to limitations in the laser infrastructure, sweeping of the laser was not able to be performed, meaning no finer resolution of the transmission spectrum was possible.

Testing of the 935 nm cavity using 986 nm light followed. Once more cavitation was seen by using the same techniques. In this situation, a more controlled sweeping of the laser frequency was performed. A lens was put in place to couple the laser light into the cavity better. With this coupling and increased sweeping, the transmission peaks were able to be optimized further.

This process allowed for a clean image of the FSR [5]. We can see the FSR as the distance between the two dominant peaks. The other peaks are higher order modes. Spacing is of the order of 100-200 MHz, which is perfect for the in lab techniques that will be used to laser lock. It is also interesting to note that by adjusting the coupling of the laser to the cavity, these peaks can be altered so as to give the smaller peaks the more dominant transmission. This image is exactly what we want to see in a reference cavity.

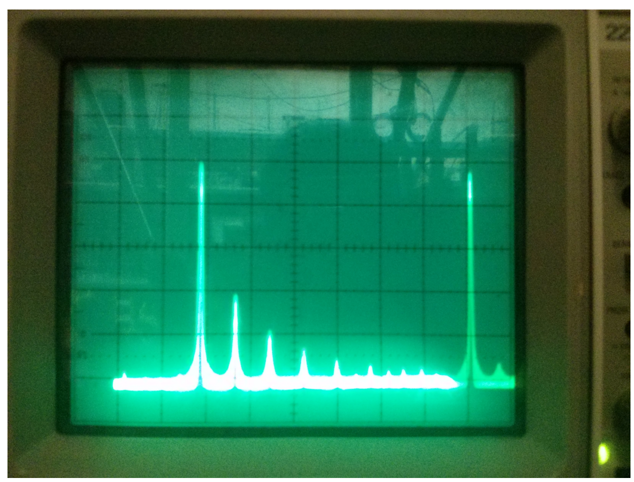

Figure 5: Transmission spectrum of cavity shown as light intensity versus frequency. The distance between the two dominant peaks is the free spectral range. The smaller peaks are higher order modes.

4 Summary

The goal of the REU project was to create two reference cavities that could be used to stabilize Yb^+ cooling lasers. The cavities were designed, built, and tested. The design and construction offered excellent hands on experience and an appreciation for experimental work.

Most importantly, testing of the cavities shows that they work. Cavitation was verified. Temperature stability was explored and found to be good. The cavities are thus ready to be used when the 370 nm and 935 nm lasers are done.

5 Acknowledgements

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