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Fortson Lab
UW Physics REU report
8-22-06

For the 2006 UW physics REU program I worked in professor Norval Fortson's single ion trapping group, working most with Jeff Sherman and Eryn Cook. The task was to set up a laser frequency-doubling cavity for a 2.051 μm laser, to facilitate locking the laser to an ultra-stable cavity for frequency stabilization purposes. This laser is used to investigate atomic transitions in barium. Along the way, I learned a lot of interesting atomic physics and picked up some valuable optics experience.

A clock frequency is useful as a time measurement tool but also as an absolute frequency reference. The meta-stable $5D_{3/2}$ transition in Barium (t~83sec) has a very precise frequency as a result of time-energy uncertainty at 2.051 μm and so makes a very good clock. Also, $^{137}Ba^{+}$ has a clock transition free from a systematic stark shift, another reason it makes an excellent clock. Other ions make good clocks too, and this is valuable because comparing super stable clock frequencies based on different atomic systems allows for the investigation of changes in fundamental constants with respect to time. This is new physics!, suggested by some theories outside the standard model.

At the heart of the lab was the ion trap system, surrounded by lasers and optics to cool and investigate. Earnshaw's theorem prescribes that a static electric potential cannot trap a charged particle. This becomes apparent when examining Laplace's equation in free space, $\nabla^2\varphi = 0$. This means that no matter the geometry, we will always have a trap that leaks in at least one direction, and so we need to employ a more complicated solution. One method is a Penning trap, which uses a strong magnetic field to provide the additional confinement. Another option is to use some sort of pseudo-potential (a potential that is instantaneously unstable, but on average to the ion, stable) to confine it. A Paul trap uses a combination of static E fields and E fields alternating at radio frequencies to accomplish this. The ideal Paul trap has hyperboloid shaped electrodes. However, this set up is challenging to build and problematic optically, so as a result, the experiment uses a ring-shaped Paul-Straube trap. Although this geometry is not as clean, by adjusting the RF to compensate confinement is achieved with access for laser cooling and investigation. There is a small oven adjacent to the trap, which when heated provides the barium. A filament and anode accelerates electrons into the barium ionizing it; the ions are then confined in the trap. Once confined, the ion can be cooled and interrogated. See fig 1.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Fig. 1, Ring ion trap[1]

The 2.051 μm clock laser was the project I worked on this summer. In order to precisely investigate the clock transition in the ion, you have to have a very narrow frequency laser. Out

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[1] Jeff Sherman

of the box, any laser will have some amount of spread in its frequency as well as long-term drift. Probably the best way to stabilize this behavior is to lock the laser to a transmission line of a Fabry-Perot cavity. The cavity only transmits when the optical path length between the mirrors is an integer number of half wavelengths, and if that length doesn't change then the frequency of a transmission line that gets through won't change either. The plan for stabilizing the 2 μm laser used this set-up as well. A special, vertically mounted, ULE (ultra low expansion) cavity will be the reference cavity. Unfortunately the cavity is designed for 1 μm light (high reflective coatings can be made better at 1 μm). However, this is accessible, provided we frequency double the 2 μm laser. See fig. 2 for a cartoon of the set-up.

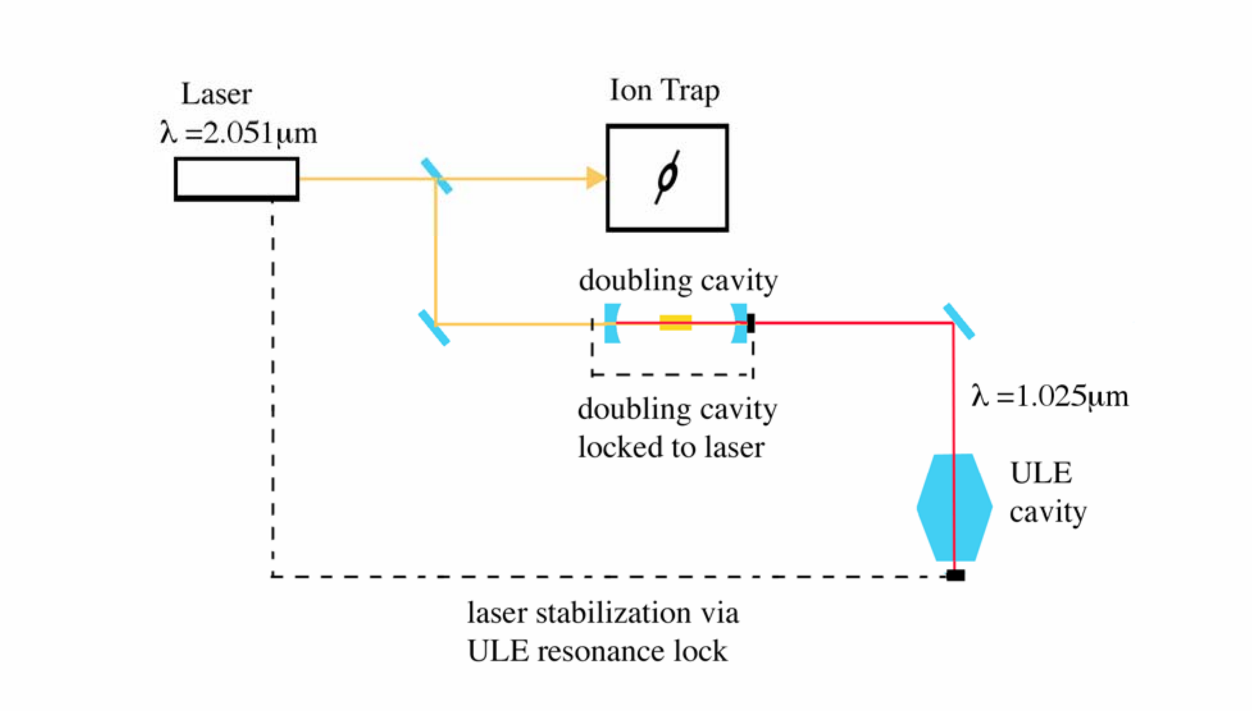

Fig. 2, 2 μm Laser System

Doubling the 2 μm laser via second harmonic generation (SHG) ended up being the majority of my project. Normally the polarization in a material depends linearly on E. However, in some nonlinear crystals, the electric susceptibility can be expanded in terms of higher powers of E, $P = \varepsilon_0(\chi E + \chi_2 E^2 + \chi_3 E^3 ...)$ and this can be shown to give higher harmonics of the incident frequency.

There are complications to overcome. The incident beam and the 2ω beam need to be phase matched, otherwise the 2ω beam generated at one point in the crystal will tend destructively interfere with the light generated at a later point in the crystal. This can be addressed by tilting the crystal, a process known as critical phase matching, so that the effective index of refraction that the 2ω light sees allows it to travel at the same speed as the incident beam. Another method is to switch the orientation of the nonlinear crystal at precise intervals, so that the 2ω light constructively interferes. This method is known as quasi-phase matching and is what is employed in our lithium niobate crystal (or PPLN for periocially polled lithium niobate). Temperature adjustment of the crystal is also very useful for adjusting the phase matching.

The efficiency of SHG depends on a variety of factors as can be seen in eqn 1 for a periodically poled crystal.

$$\eta_{2\omega} = \frac{8\pi(2/m\pi)^2 d_{eff}^2 (NL_C)^2 I_\omega}{\varepsilon_0 n_\omega^2 n_{2\omega} c \lambda_\omega^2} \exp[-(\alpha_\omega + \alpha_{2\omega}/2)L] h(\sigma,\beta,\kappa,\xi,\mu) \qquad \text{Eqn. } 1^2$$

Some parameters are fixed, such as the wavelength, indicies of refraction, length of the crystal (NL), and absorption. One parameter we do have control over is the geometry of the beam,

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[2] Sutherland, p.100

contained in h. There is an ideal laser beam waist size for a given crystal length that will maximize the output power. This problem takes into account the Gaussian profile of the beam, the wavelength and related divergence of the laser, and was solved (see Boyd, Kleinman in sources). Using their results gives the ideal waist size for our crystal of about 45 μm. This necessitates using a lens to collimate and a lens to focus the incident beam.

Another consideration we have control over is power. The efficiency is proportional to the input power, so the output power depends on the input squared. We were able to get second harmonic generation with a single pass through the crystal but the output was not enough power for coupling into the ULE cavity. This can be addressed, however, by building a resonant cavity around the crystal, either a linear cavity with two mirrors or a more complicated 4 mirror bowtie ring cavity. For our system, a linear cavity became the best option. At first we constructed a cavity using mirrors we had on hand. However, the mirrors could not produce a tight enough waist for the crystal, so new mirrors (focal length 25mm) had to be ordered.

Using a cavity also introduces other issues, one is mode matching, analogous to impedance matching in an electrical system. A cavity also requires a servo-locking mechanism to keep it fixed on resonance. One way to lock a linear cavity is to use a Pound-Drever-Hall locking scheme; this is the method we are planning to use on our cavity. In short, the method looks at the difference between the promptly reflected and stored leakage to generate an error signal for locking the cavity on resonance.

There have been a variety of challenges that have arisen during this project. One main one is simply that an infrared laser is hard to work with. You can't see the beam except with a photodiode or mood ring card. Another challenge has been parts delays, our cavity mirrors didn't arrive until about a week before I was to leave. Also, we discovered this summer that the laser seems to not be scanning as much frequency as it should for an applied voltage which could be a problem later when it comes to locking the laser.

What I have gotten done: I've set up cavities with other mirrors to practice aligning the 2 micron laser and to practice with various mode matching lens configurations. I've also practiced single-passing the PPLN to get a feel for aligning the nonlinear crystal. I've written programs in MatLab to investigate the behavior of Gaussian beams for different cavity and mode matching lens configurations. The cavity program used formulas derived from the ABCD matrix formalism. I built a beam profile measurement device. It utilizes a lead sulfite detector with a chopper. Differentiating the output signal gives us a relative beam size measurement, useful for finding beam waists.

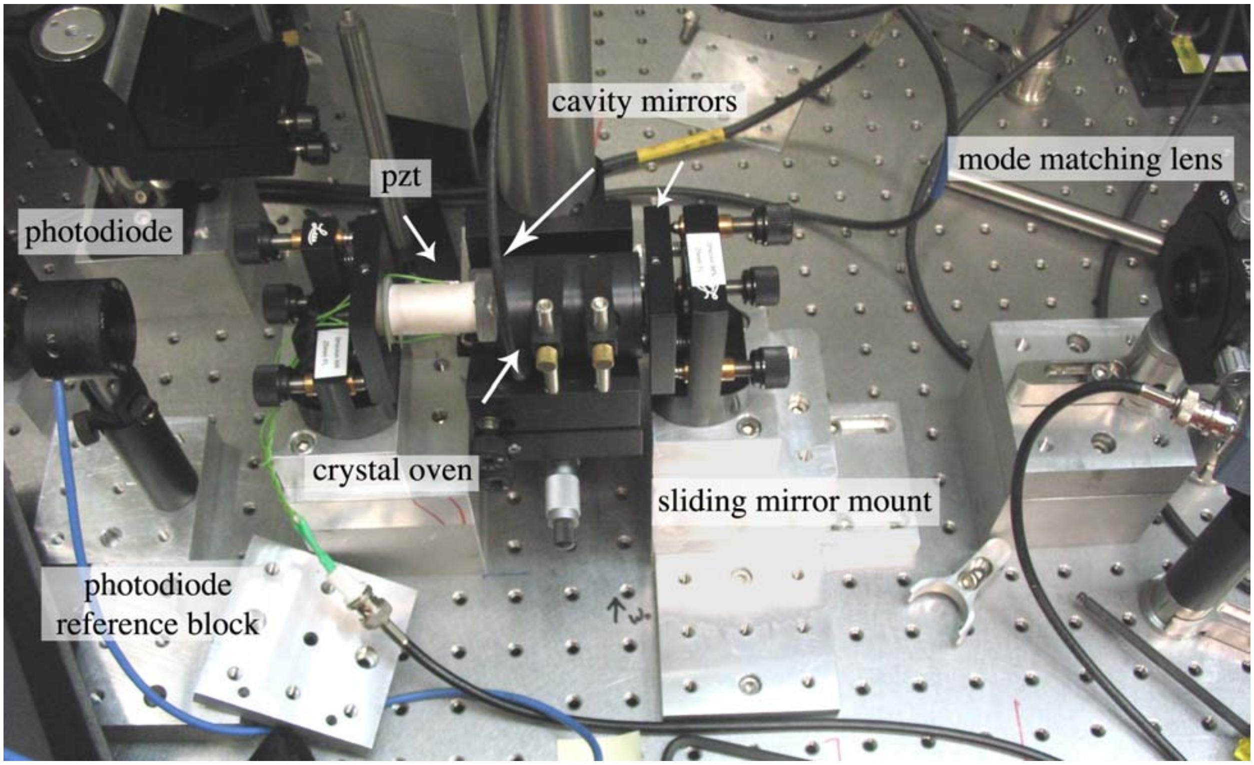

Fig. 3, 2 μm – 1 μm Doubling Cavity set-up

About a week before I was to leave, our cavity mirrors arrived and during my last week I was able to get 1 μm light out of our standing wave cavity; there should be more than enough power to lock to the ULE cavity, accomplishing the goal of the project. See above for a picture of the set-up. With some improvements in the locking and mounts, there should be reliable 1μm light. The procedure for setting up the cavity is attached as an appendix to this document

Thanks to Jeff Sherman and Eryn Cook, Will Trimble, Norval Fortson, Warren Nagourney , Amar Andalkar, and the rest of the group, as well as Jerry Seidler, Maya Kimura, UW, and the NSF for putting on the UW REU program.

Useful Sources:

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Appendix: 2 μm – 1 μm Doubling Cavity Alignment Notes

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1. A first step is the beam collimation. Collimation was done with the lens on the laser plate. We checked for collimation with the lead sulfide beam profile-measuring device. Putting the detector at the end of the beam path and sliding the chopper along the path shows the relative focus of the beam. By moving the lens around we could get relatively constant peak height, i.e. collimation.

2. Next was to make sure the beam was pointed along the table. We have two mirrors in the beam path so we can get proper pointing. By putting a photodiode on a block centered and at the proper height, and putting blocks on the table at the ends of the beam path to sit the photodiode block against, we were able to get the beam aligned along the table at 6''. It was useful to attenuate the beam, as the full power saturates the detector and the attenuated beam gives more control. This seemed to work pretty well as the photodiode for 2 μm is quite small.

3. The next step was putting the mode-matching lens in. This was necessary for single passing the PPLN and for the subsequent cavity as well. By putting the lens at the expected position for our desired waist position and then looking for the waist with the beam profile measuring set-up, we were able to move the lens around to get the waist to sit where the crystal would be, ~20cm from the cavity, farther than expected for the FL of the lens.

4. Next was to set up an initial Fabry-Perot cavity. The focal length for our mirrors was 25mm(gives the best waist); this means that for a cavity with no crystal in place, it's unstable for separation less than 5cm. This is a small cavity, small enough that the crystal won't fit. Thankfully, the PPLN crystal has an index of refraction of about 2.2 which gives us a shorter apparent path length in the crystal. Also, since the crystal is so long, about 4 cm, we can take significant advantage of this and it allows us to make a longer stable cavity when the crystal is in, about 7cm, although we do have to move the mirrors.

    a. We set up a cavity at about 4cm. Looking for back-reflections on the mood-card and aligning them over the hole in it was useful. We could do this with the second mirror in place and by reversing the input coupler. This gave us some hope that the beam was perpendicular to the mirrors.
    b. Next switch the input mirror around and look for 2μm peaks while scanning the mirror pzt. This is sort of a blind hunt initially but worked out for tuning up the cavity.
    c. Something that ended up being important at this point I think was to keep the beam in the cavity along our original beam path. This was difficult as the small radius mirrors can really steer it around. By keeping the detector looking at the transmission where we had it to measure the original beam path and tuning up the cavity to maximize the peaks at that detector position seemed to help. An addition test I think of if the beam in the cavity was along the original beam path was that moving the input coupler back and forth along the sliding mount didn't destroy the cavity alignment. It would shrink the peaks but they would still be there, indicating to me that the mirrors were more or less perpendicular to the beam and centered.

5. Next was to single pass the PPLN, with the second mirror in place and the input coupler removed. I set the PPLN in its mount where the cavity would be. By only moving the PPLN, we found a track that we had been using the ~155C one and tuned it up to a couple of μw of output 1 μm.
6. Next I put the 2 μm detector back up and put in the input coupler about as close to the oven as I could. From there I tuned up the 2μm transmission peaks once again.
7. Swapped out the detector for the 1 μm detector. Tune up 1 μm peaks- now everything is fair game: cavity mirrors, mode matching lens, steering mirrors, oven temperature.