Construction and Characterization of a Prototype External Cavity Diode Laser

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1 Introduction

1.1 Laser Cooling

Cooling atoms with lasers is achieved through radiation pressure of light. An atom that absorbs a photon gains that photon's momentum. This absorption is most likely to occur when the light's frequency matches that of an atomic transition. By shining laser light that is tuned slightly to the red (lower frequency) of such an atomic transition, a force is imparted on the atoms which is greater for atoms moving towards the laser, or against the direction of propagation of light. This is due to Doppler shift; the atoms moving towards the laser will see slightly bluer light according to the Doppler shift formula for light:

$$\lambda_{obs} = \lambda_{emit}\gamma\left(1+\frac{v}{c}\right), \tag{1}$$

where:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}. \tag{2}$$

Here, v is negative for atoms moving towards the laser.

Since the laser is red detuned, the Doppler shift moves the light towards the atomic resonance. Atoms moving in other directions will feel a much smaller force since very few off-resonance photons will be absorbed. Atoms that do absorb the light will eventually re-emit a photon, however this emission is in a random direction. Thus, averaged over time, there will be a net force slowing the motion of atoms moving towards the laser. Using six counter-propagating lasers, two for each axis, atoms will feel a braking force in all directions. This has been named an "optical molasses."[1] This only slows the atoms, however, the actual trapping is achieved through magnetic coils. The magnetic field splits the energy levels the atom is resonating between slightly, by an amount dependent on the position since the field strength depends on position. This Zeeman splitting, through the light from the laser, causes a restoring force and completes the magneto-optical trap. A good introduction to laser trapping which puts the effect into easily understood language is an article by Sarah Gilbert, "Laser Cooling and Trapping for the Masses" in the July 1993 issue of Optics and Photonics News.[2]

The lasers used in such a setup need to have an output frequency spectrum that is very narrow - a narrow line-width on the order of the atomic line width of the atom to be cooled. Also, the output frequency must be stable yet also continuously tunable over some range. The continuous tuning range of lasers is typically limited by so-called mode-hopping where the laser abruptly switches from one resonant frequency of the laser cavity to another.

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[1] Chu 98

[2] Gilbert 93

1.2 Diode Lasers

Diode lasers are the most commonly used type of laser in magneto-optical trapping, due to being small and cheap. They have a much larger line-width than is acceptable for cooling, however. To effectively cool atoms, the line-width must be on the order of the width of the relevant atomic transition lines or, preferably, narrower.[3] Optical feedback is used to improve the line-width, by sending light which is locked very tightly to a specific frequency back into the laser diode, along with some sort of mechanism for narrowing the feedback light's line-width. Light that is not used for feedback is the output light, so there is a tradeoff between using enough feedback light so that it is effective while maintaining the highest possible power of output light.

1.3 External Cavities

External cavities are used to provide feedback to the laser diode. In general they reflect some of the light back into the laser diode at a narrower bandwidth, with the rest of the laser's light being the output. There are several means for providing this feedback. One of the more common methods is to use a diffraction grating that is aligned so that the 1st order diffracted light travels back to the laser diode while the light specularly reflected from the grating (the 0th order) is used for output.[4] The design I am working on uses an interference filter for line-width narrowing, and is described in detail below. The line-width is also narrowed by the interference between the wave leaving the laser diode and the wave being reflected back into the diode, which imposes stringent conditions on the frequencies of the optical wave resonant in the cavity. The amount of feedback should have an affect on the Finesse of the cavity and the narrowness of the output.

2 ECDL Prototype Design

The design for the diode laser's external cavity is based on work done by Lauren Levac, working under Dr. Thad Walker at the University of Wisconsin - Madison. Their design is described in Lauren Levac's senior thesis,[5] and is itself based on Philip Bouyer's use of an interference filter to narrow the line-width and choose the lasing frequency. The optical components are mounted to a cage mount system[6] for the prototype for ease of alignment, and to make it easy to adjust parameters such as cavity length and to switch between interference filters.

There is a tradeoff between the amount of light that is used for feedback, and the output intensity. Since having the highest possible output intensity is desirable, it is important to

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[3] Gilbert 93

[4] MacAdam 92

[5] Levac

[6] Thorlabs made 30 mm cage mount

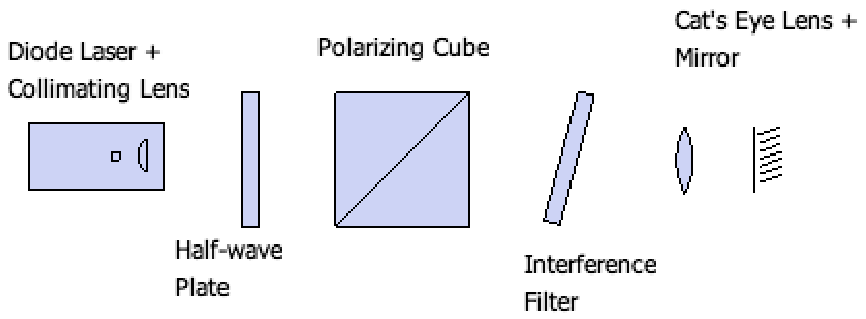

Figure 1: The design of the external cavity for the diode laser, with the parts labelled.

determine how little feedback light can be used while still providing enough to improve the laser's performance. A rotatable half-wave plate is used with a polarization cube to adjust the feedback intensity.

This design uses an interference filter to help narrow the line-width of the laser and to pick out the frequency of the laser. The interference filter is a bandpass filter whose peak output wavelength varies with angle. This means that the wavelength of the laser is easily adjustable. This can also be used to help tune the laser's output wavelength.

A lens with a mirror at its focal point is used to reflect the light back to the laser diode. This setup is called a "cat's eye" since it reflects light back to its source even if the angle of incidence is not perpendicular to the optic axis of the lens. Off-perpendicular and off-axis light is reflected back at the same angle, although there can be some translation orthogonal to the propagation axis. As long as the laser's light hits the lens, the mirror can be adjusted to minimize this translation, as shown in the figure. Once set up properly, the cat's eye provides feedback to the laser diode that is very stable with respect to small changes in beam angle due, for instance, to the flexure of the external cavity assembly arising from air currents and temperature gradients. The mirror is glued to a piezoelectric transducer (PZT), which is glued to a mirror mount. The PZT is used to move the mirror to shorten or lengthen the cavity by small amounts to tune the laser's output frequency. It will also be used to stabilize the cavity against small changes in length due to mechanical vibrations.

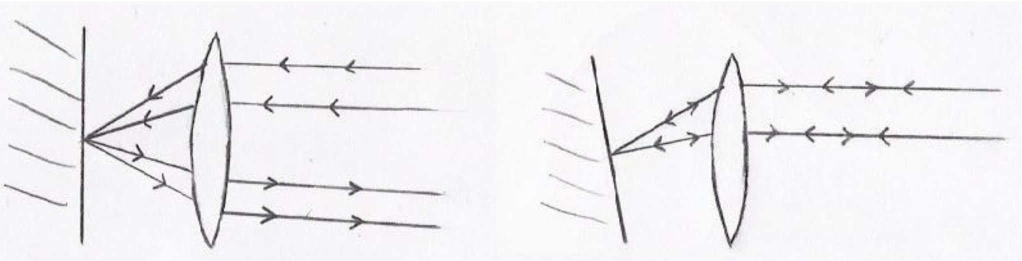

Figure 2: Two examples of cat's eyes. On the left the lens and mirror are set perpendicular to the optical axis, but the incoming light is not centered. On the right the mirror is adjust to compensate for this translation. The incoming light is reflected back along exactly the same path with little or no translation, and at the same angle.

3 Methods for Alignment

The diode laser's output must be collimated to be useful. I used a commercial diode laser mount from Thorlabs that includes a collimating lens[7]. This lens's position can be easily adjusted to collimate the laser's output. This is simply a matter of looking at the laser at a large distance, approximately 1.5 meters in my case, and adjusting the collimating lens until the beam size is the same as at short distances.

Most of the alignment of the external cavity is straightforward, due to using a cage mount system. However, the diode laser's mount was machined by myself and has considerable amount of play, thus the laser isn't precisely on axis. However, as mentioned above, it is sufficient to make sure the light strikes the cat's eye lens, and then adjusting the mirror.

A simple way to make sure the light is being reflected back into the laser diode is that if the light is providing feedback, the laser will require less current to lase. Input current is set close to the threshold, and is modulated by a triangle wave. A photodiode is placed at the laser's output and is read with an oscilloscope that also measures the current modulation. The laser power will suddenly increase at the threshold current. The mirror angle is then adjusted until the threshold current is at a minimum. This method is also used to place the lens optimally, since the cat's eye is most efficient when the mirror is precisely at the focal point of the lens.

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[7] Thorlabs made, part no. LT110P-B

4 Methods and Results for Laser Characterization

4.1 Interference Filter Angle vs. peak Wavelength

The interference filter's bandpass is a function of angle of incidence, that is, if the filter's angle is changed, the wavelength the filter passes changes, and so, the wavelength of the feedback light. Using an optical spectrum analyzer (OSA)[8] I determined the wavelength the laser was lasing at. Unfortunately the mount for the interference filter does not have any angle markers on it. To estimate the angle, I measured where the reflection off of the filter went, and took the arctangent of the distance off of the optical axis divided by the distance along the optical axis from the filter. I took several datapoints to fit how the wavelength changes with angle. There were some obstructions to deal with. For the wider interference filter I was able to move some optical components out of the way, but for the narrower filter I had to measure the angle through the polarization cube to characterize its angle-wavelength relationship around 780 nm. Neither fit is very accurate, but for the prototype it should be sufficient to determine approximately how much the angle needs to be adjusted by in the final laser housing.

The relationship can be approximated as linear for small changes in angle. Thus, using a linear fit, I was able to approximate the change in wavelength under a change in angle around 780 nm. For the wider interference filter[9], I found 0.48 ± 0.03 nm per degree, and for the narrower[10], 0.27 ± 0.04 per degree. These fits are shown in figures 3 and 4.

4.2 Mode-hops

A diode laser will lase at the frequency of the mode which receives the most optical gain (modified by the optical feedback). It is also possible for it to lase on multiple modes if the feedback and therefore optical gain is comparable (in this case the laser is said to be multi-mode and is an undesirable form of operation). The laser will hop to another mode if the feedback becomes greater for that mode if the interference filter's angle is changed, for instance. Changes in current can also change the internal mode structure of the laser, and also cause it to mode-hop. The output frequency of the laser was monitored by the transmission through a passive Fabry-Perot resonator (with a cavity length of 12 mm and a Finesse of about 100). The laser mode-hops were observed under current changes and under cavity length changes, using the PZT behind the cavitys mirror.

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[8] Ando made, part no.

[9] Melles-Griot made, part no. XLL-785.0-12.5M, with a central wavelength of 785 nm at normal incidence and a 3nm bandwidth

[10] Many thanks to Philip Bouyer for the donation of these filters, with a central wavelength of approximately 782 nm at normal incidence, and an approximately 0.3 nm bandwidth

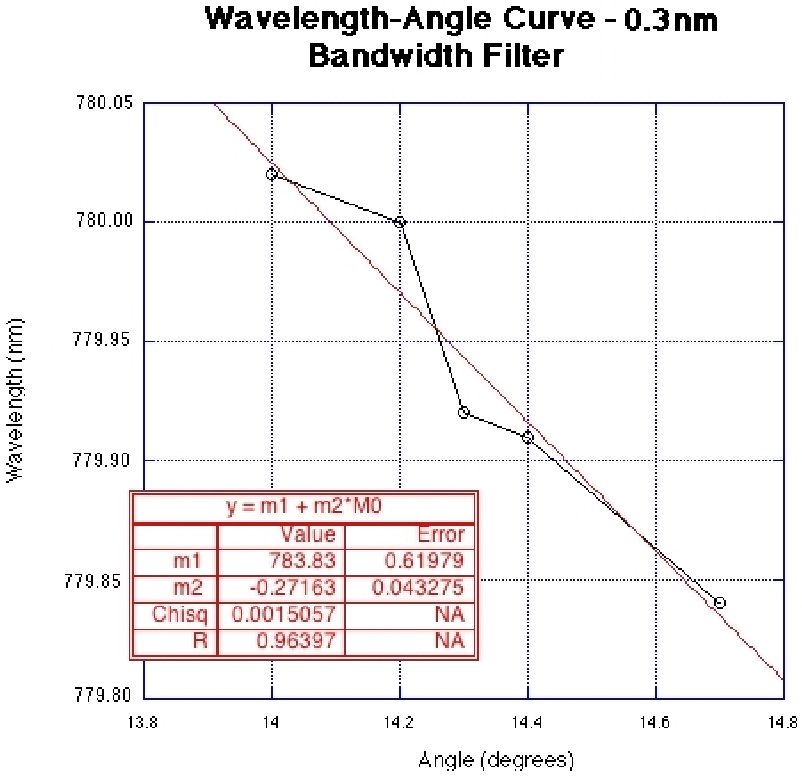

Figure 3: Linear fit on the central wavelength's dependence on angle for the narrower (0.3 nm bandwidth) filter.

4.3 Passive Fabry-Perot Spectrum Analyzer

The free spectral range of a cavity is defined by:

$$\nu_{\mathrm{fsr}} = \frac{c}{2L} \tag{3}$$

where c is the speed of light and L is the optical path length of the cavity, that is, the length times the index of refraction, keeping in mind that the index of refraction depends on the material the light is passing through. Therefore, if the laser frequency is fixed, the transmission varies periodically, with period $\Delta L = \lambda/2$. One observes multiple transmission peaks, corresponding to the transmission of higher order transverse modes occurring at different cavity lengths. In the case of our Fabry-Perot (FP) spectrum analyzer, this

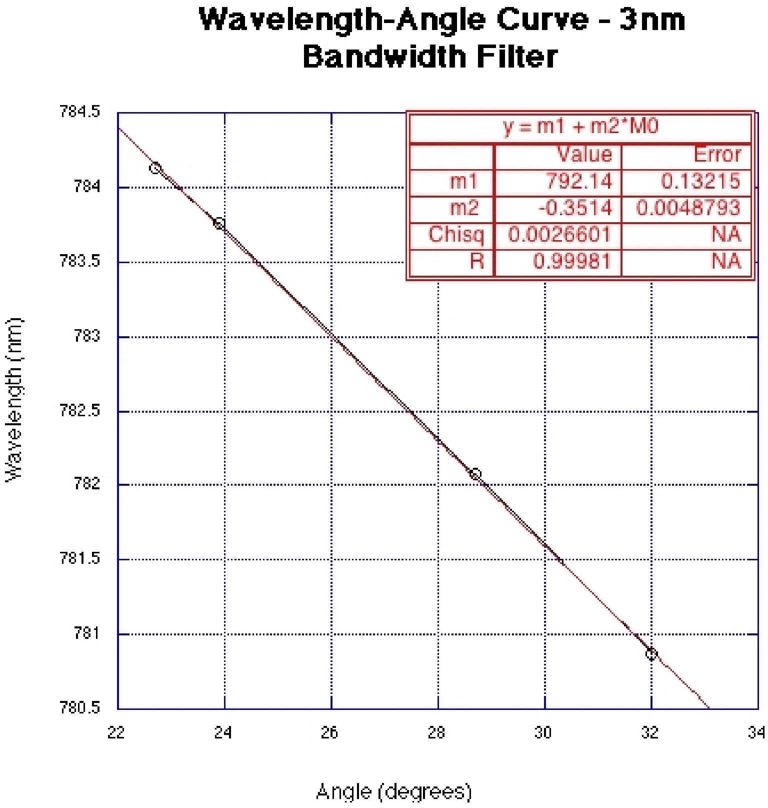

Figure 4: Linear fit on the central wavelength's dependence on angle for the wider (3 nm bandwidth) filter.

transmission pattern is repeated as the length of the FP analyzer is scanned, by ramping the voltage supplied to a PZT on one of the mirrors. For so-called "confocal cavities," like our FP analyzer, where the cavity length is equal to the radius of curvature of the two mirrors that make up the cavity, the transmission is maximum at two distinct sets of positions, where either all of the odd or all of the even modes are simultaneously passed. In this case, the transmission appears to be periodic with period $\Delta L = \lambda/4$, half that of a cavity with flat mirrors. The output frequency of the laser, modulo the free spectral range of the FP analyzer, by the position of the transmission peaks for a given transverse mode through the cavity. If the output frequency of the laser changes, the position of the transmission peaks will move to a different location in the FP analyzer length L. The change in laser frequency can therefore be determined by monitoring the shift of the resonance positions as the FP length is scanned linearly and comparing this shift to the periodicity of the FP

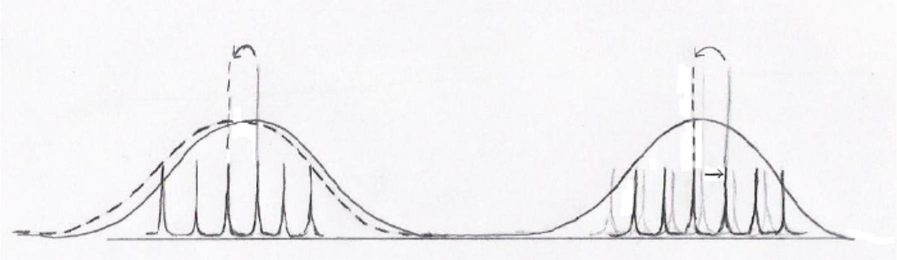

Figure 5: Shifts in the modes of the external cavity and the diode laser's own internal cavity will cause mode-hops. The broad peaks are the diode laser's own internal structure, while the narrow peaks are the external cavity's. On the left, the current is adjusted so that the internal mode structure is shifted until the laser's mode hops to a different external mode. On the right, the external cavity length is adjusted until the laser hops to different mode.

analyzer. A shift of the laser frequency by exactly the free spectral range $\nu_{mathrmfsr}$ will shift the periodic pattern by exactly one period and no change will be observed. Since for a confocal cavity, the periodicity appears to be half that of a standard cavity, the effective free spectral range is half that defined above, so $\nu_{\mathrm{fsr}} = \frac{c}{4L}$. For smaller shifts in laser frequency, the transmission pattern will shift by an amount less than the periodicity, and the change of the laser frequency can be estimated as

$$\delta\nu = \nu_{\mathrm{fsr}} \times \frac{\delta L}{\Delta L} \tag{4}$$

where δL is the shift of the periodicity of the pattern in L and ΔL is the periodicity of the pattern in L. Unfortunately there is no way to distinguish between changes in frequency that are larger or smaller than the free spectral range of the FP analyzer. However, when observing a mode-hop, the size of the hop measured by the FP analyzer can be converted to a corresponding cavity length. In the QDG lab, the length of the FP is scanned such that the free spectral range is scanned in 10.3 ms (meaning transmission features have a period of 10.3 ms as well). One can measure the size of the mode-hop in ms, and since the FP analyzer is approximately 12.4 mm long, and is a confocal cavity, the cavity length causing the mode-hop would be $12.4 \cdot \frac{4}{2} \cdot \frac{10.3}{T}$, where T is the size of the mode-hop in ms.

Figure 5 shows the free spectral range of the the external cavity (the sharp, closely spaced lines) and the diode laser's own internal cavity (the broad lines). As the amount of current supplied to the diode laser changes, the internal mode structure shifts. After enough of a shift, a different external cavity mode will line up with the laser's own mode, and the laser's output will mode-hop. In this case the output frequency will remain relatively constant until the laser hops (shown on the left side of the figure). Similarly, the external cavity's mode structure can be shifted by applying a voltage across the PZT, changing the cavity length. Here, the laser's output frequency will scan until a different mode lines up under the diode laser's mode, when the laser will again mode-hop (shown on the right side

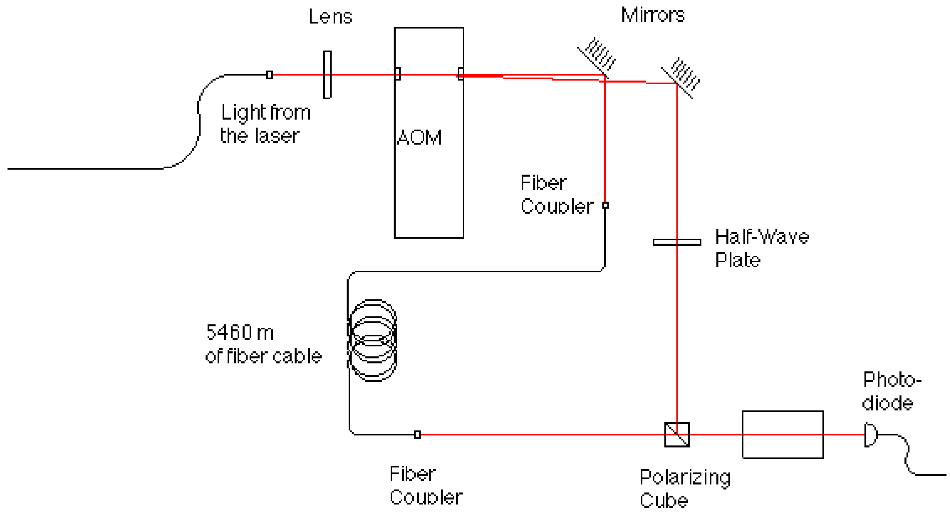

Figure 6: This is a schematic of the optics used to create a self-heterodyne beat signal.

of the figure). By changing the current and the cavity length simultaneously, it should be possible to tune over a much larger frequency range before a mode-hop occurs. This range has not been investigated yet, however.

Using the equation above, and the measured jump of 1.6 ms while changing the laser's current, we determined that the laser's mode hops corresponded to an optical cavity length of 160 mm. The physical length of the cavity was about 145 mm when this test was done, but more than 25 mm of that is glass, from the polarizing cube and the other optical components, with an index of refraction of about 1.5. In previous mode-hop measurements we had accidentally omitted the factor of two from the fact that the FP analyzer is confocal. Thus we thought that the mode-hops were the result of a cavity about half the size of the external cavity for the laser, and this led us to believe that some of the optical components were reflective enough to create their own cavity and the polarization cube was tilted to compensate for this. Doing this should have no adverse effects on the laser's performance, and the resulting translation of the laser beam is corrected for by adjusting the cat's eye mirror.

4.4 Self-Heterodyne Beat Signal

The line-width of our external cavity laser is too narrow for our optical spectrum analyzer[11] (with a 0.1 nm resolution) to resolve, so a self-heterodyne technique is used to mix the

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[11] made by Ando, part no.

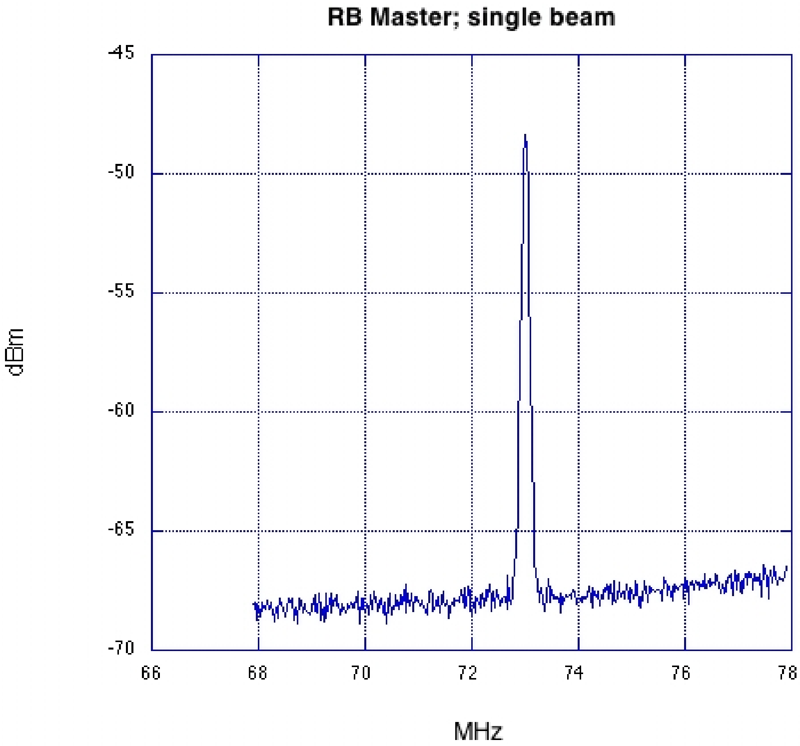

Figure 7: The spectrum of the AOM shifted light from an existing Rb Master laser.

optical wave down to the radio-frequency range and the line-width is measured by an RF Spectrum analyzer, which has the necessary resolution.

Figure 6 shows a schematic of the optics used. The light from a laser is split into two beams, one of which is shifted by some tens of MHz. The other beam is sent through approximately 5460 meters of optical fiber to create a ’copy’ of the original optical wave that is delayed by an amount sufficient that its frequency fluctuations are independent of the non-delayed beam. The two beams are then recombined using a polarization cube and are aligned to interfere with each other on a photodiode. It is critical that the two beams area absolutely co-linear. By reading the resulting beat note between the two optical waves, which is centered around the frequency shift, with photodiode with a radio frequency spectrum analyzer one is able to measure the lasers optical line-width. The long fiber is used to create an independent copy of the laser optical wave which has the same central frequency and the same range of frequency fluctuations but the frequency fluctuations are independent of the non-delayed beam. Without this delay, the instantaneous frequency fluctuations, which limit the laser line-width and are the very thing we are trying to measure, would be the same in the shifted and non-shifted beams and would therefore cancel out.

It was found that a relatively strong signal was measured on the photodiode at the AOM's frequency with just the 1st order beam, the beam that is shifted in frequency, and is not run through any fiber cable. This signal was strong in our measurements of the existing Rb Master laser, but was negligible for the prototype laser. It is not clear if this difference in power is a function of the laser itself or not. The spectrum of the AOM shifted light from the Rb Master is shown in figure 7. The strength of the actual beat note itself is strongly dependent on very precise alignment of the two beams, so if the alignment was better when the line-width measurement of the prototype was taken, it would explain this discrepancy. The signal from the AOM shifted light from the Rb master laser was removed from its beat note before the line-width was calculated. It was found, however, that in the case of the prototype laser, removing the AOM shifted light's spectrum had a negligible effect.

The light through the 5460 meter long fiber is strongly attenuated. The attenuation depends on wavelength - shorter wavelengths are affected the most. At 780 nm approximately 0.1% of the incoming power came through the cable. The AOM amplitude is adjusted such that the two beams have approximately the same power when they interfere on the photodiode.

For delay fibers corresponding to a delay time much longer than the coherence time of the laser, the spectrum on the photodiode can be assumed to be a Lorentzian, with a FWHM twice that of the line-width of the laser. [12]

4.5 Line-width

To make sure the self-heterodyne setup was working properly, lasers with known line-widths were measured with it. One is the "Lithium laser", a laser devoted to laser cooling of Li, and the other one is a "Rubidium laser", a laser devoted to laser cooling of Rb (a home-built, grating stabilized master oscillator).

The "Lithium laser"[13], runs at 671nm. At this operating wavelength, we found that there was even greater attenuation through the 5460 m fiber; 23 mW were sent to the self-heterodyne table and most of that coupled into the long fiber, but only 2 μW were measured by the photodiode[14].

The data taken is on a log scale (dBm), to convert to relative power the following relationship is used:

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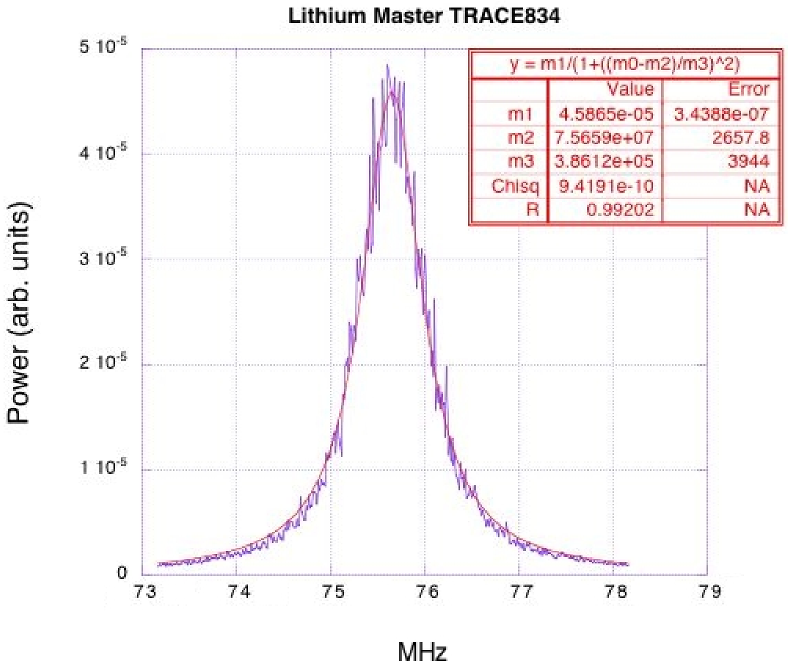
[12] Ludvigsen 98

[13] The "Lithium laser" is a Toptica DL Pro laser

[14] The photodiode used is a 125 MHz photodiode from New Focus, Inc



y = m1/(1+((m0-m2)/m3)^2)		
	Value	Error
m1	4.5865e-05	3.4388e-07
m2	7.5659e+07	2657.8
m3	3.8612e+05	3944
Chisq	9.4191e-10	NA
R	0.99202	NA

Figure 8: Line-width measurement of a laser used to cool Lithium. The fitted curve is a Lorentzian, and has a line-width of about 770 kHz.

$$P_{rel} = 10^{\frac{dBm}{10}} \tag{5}$$

This data is then fit to a Lorentzian:

$$P = \frac{P_o}{1 + \left(\frac{x - x_o}{\gamma}\right)^2}, \tag{6}$$

shown in figure 8. Here, P_o is the peak power, x_o is the center frequency, and γ is the half-width half-maximum. The full-width half-maximum, however, is used to calculate the line-width.

The Li master was measured to have a beat note line-width of 770 kHz, corresponding to a laser line-width of 385 kHz, which is considerably larger than the manufacturer rated 100 kHz.

The beat note line-width of one of the Rb master lasers was also measured, and found to be approximately 2 MHz, corresponding to a laser line-width of 1 MHz. Figure 9 shows the spectrum and Lorentzian fit of the beat note, with the AOM shifted beam (shown in figure 7), removed. In this case, previous measurements of the line-width, obtained by beating two different Rb masters together, found a 2.5 MHz line-width.

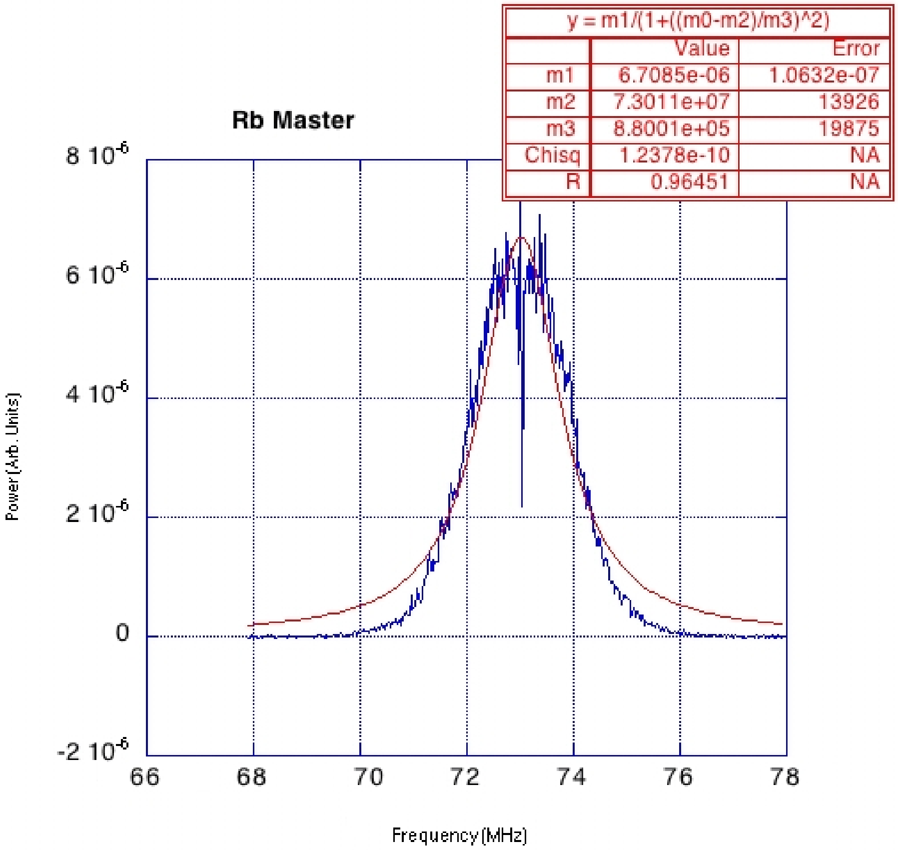
Due to the laser's narrower line-width, there are noticeable lobes in its spectrum, as you can see in figure 10. These lobes should be one over the delay time in the fiber in size. In this case, the lobes are approximately 40 kHz wide, and it is assumed that the fibers have an index of refraction of 1.48. Thus one can calculate how long the delay fiber is based on the lobe size:

$$L = \frac{c}{n \cdot f_{lobes}} = \frac{3 \times 10^8}{1.48 \times 40000} = 5067 \tag{7}$$

This isn't quite accurate (the fiber is approximately 5460 m in length), but it is close.

The prototype laser was also run at several cavity lengths, which is described in detail in the next section. Analysis on the narrowest looking spectrum, which was taken with the cavity length at approximately 235 mm, was done by Bruce Klappauf. The analysis done was based on a 1998 paper written by Hanne Ludvigsen et al., which describes how to account for a too short decohering fiber cable, and the equations that should be fit to the data as well as how to interpret the results. According to Ludvigsen, the fourier transform of the following equation will fit the spectrum resulting from using a self-heterodyne technique to mix the laser frequency down to the radio frequency range:

$$G_E^{(2)}(\tau) = E_0^4 \left[\left(1 + \alpha^2\right)^2 + 2\alpha^2 cos \omega_m \tau e^{-2s(\tau, \tau_0)} \right], \tag{8}$$



y = m1/(1+((m0-m2)/m3)^2)

	Value	Error
m1	6.7085e-06	1.0632e-07
m2	7.3011e+07	13926
m3	8.8001e+05	19875
Chisq	1.2378e-10	NA
R	0.96451	NA

Figure 9: The beat note measurement of one of the existing Rb master lasers, with the spectrum of the AOM shifted beam removed.

where

$$s\left(\tau,\tau_0\right)=\frac{2}{\pi}\int\limits_{-\infty}^{\infty} sin^2\left(\frac{\omega\tau}{2}\right) sin^2\left(\frac{\omega\tau_0}{2}\right) S\left(\omega\right)\omega^{-2}d\omega \tag{9}$$

and

$$S\left(\omega\right)=S_0+\frac{k}{|\omega|}. \tag{10}$$

Here, S_0 is the power dependent noise, and $k/|\omega|$ is the $1/f$ noise, k being a constant. τ_0 is the delay time, that is, the time the light spends traveling through the 5460 km of fiber;

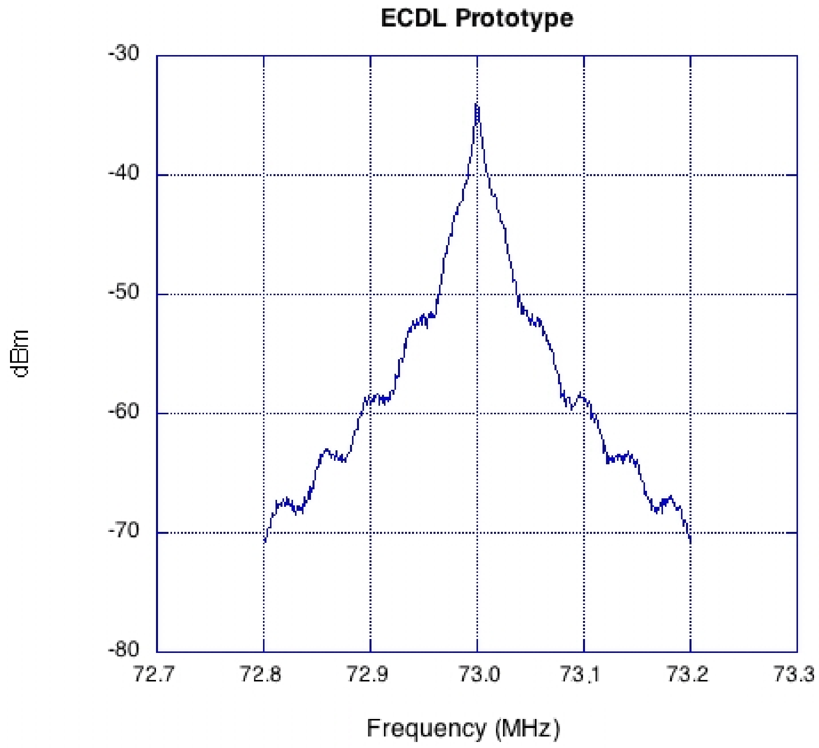


Figure 10: This is the self-heterodyne beat spectrum of the prototype laser. Here the cavity length of the laser is 140 mm. At such narrow line-widths, there are visible oscillations which are a result of the delay fiber not being long enough compared to the laser's coherence time. These oscillations become obscured by the laser's own spectrum at larger line-widths, like for the other two lasers that were tested.

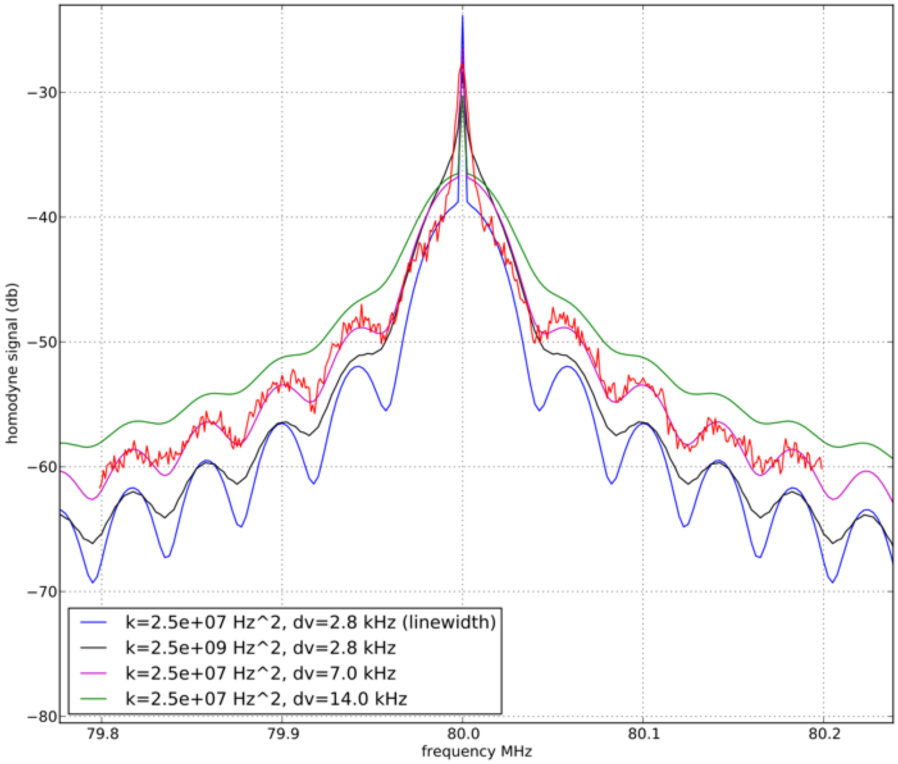


Figure 11: Shown here is the ECDL prototype's spectrum around 80 MHz (in red), as well as several simulated lines. The purple line, corresponding to a 7 kHz line-width fits closest, although it is not a perfect fit, especially towards the center of the spectrum.

α is the ratio of the power in each of the two interfering beams, and ω_m is the frequency of the AOM.

To determine the line-width of the prototype laser, a Lorentzian was modeled and set as S_ω, with a guess for the line-width. Then $s(\tau, \tau_0)$ and $G_E^{(2)}(\tau)$ were calculated, and the fourier transform was taken. This was repeated for several line-widths and values of k, which is shown in figure 11. A 7 kHz line-width fits the data the closest.

This same technique was used to fit a set of data from one of the other master lasers, probably the Toptica "Lithium laser" based on the line-width found. The data was not labeled, and was used as an exercise to see if the fits were working properly. This fit is shown in figure 12. The black line, with a 330 kHz line-width, fits the best.

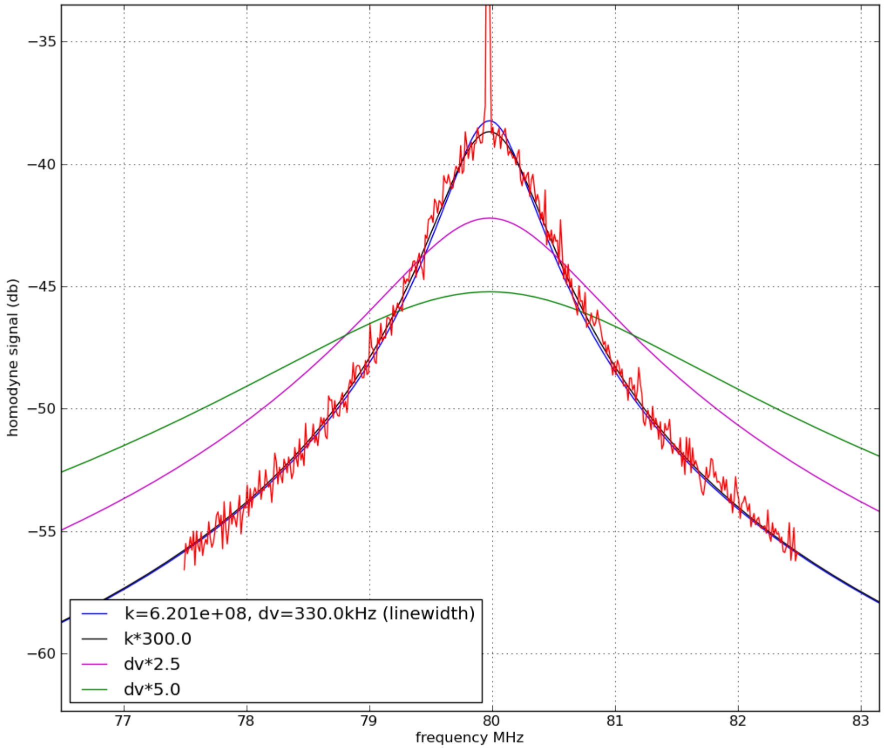


Figure 12: A fit of the line-width for an unknown laser (probably the Toptica "Lithium laser." The black line, a 330 kHz line-width, fits very well.

4.6 Cavity Length

One parameter of the laser that was tested was how the line-width behaves under varying cavity length. One can define a quality factor Q of an oscillator such that:

$$Q = 2\pi f_o \frac{\text{Energy} \quad \text{Stored}}{\text{Power} \quad \text{Loss}} = \frac{f_o}{\Delta f} \tag{11}$$

where f_o is the peak frequency and Δf is the line-width. As the cavity length is increased, the amount of energy stored in the cavity increases, but the power lost per cycle remains effectively constant since the major form of power loss is in scattering off of optical surfaces. Thus Q increases and Δf decreases. However, increasing the cavity length also can have adverse effects on the line-width; mechanical stability is reduced with a longer cavity, for instance.

The cavity length of the prototype was increased to approximately 290 mm. It was noticeably more difficult to align the cat's eye mirror properly, which came as somewhat of a surprise. Without any mathematical analysis, it is clear that the linewidth of the laser has increased somewhat from the shorter (140 mm) cavity, the lobes that are clearly visible in the line-width measurement of the shorter cavity are now smaller than the laser's beat note spectrum. It is possible that mechanical vibrations and temperature fluctuations and gradients become great enough to outweigh the theoretical improvements that come from a longer cavity. If that is the cause of the larger line-width, it may not be useful to apply these results to the final laser design, which will be much stabler.

The line-width was also measured at an intermediate cavity length, approximately 235 mm. Here, the line-width appears to be similar to that of the 140 mm cavity, and perhaps even somewhat narrower. No measurements were done at cavity lengths smaller than 140 mm since the optical components with their mounts would not fit inside such a small cavity.

5 Discussion

The use of a "cat's eye" and interference filter to provide feedback to a laser diode has been found to dramatically improve the line-width of the laser output compared to a more traditional grating feedback system. The design also allows for greater and more independent control over various parameters such as feedback intensity and output wavelength. This ease of control was invaluable in characterizing the laser's performance.

The use of a cage mount was also useful for a prototype, and aided greatly in alignment and in being able to adjust the cavity's length. It is not clear, however if such a mount is stable enough to provide accurate results for longer cavity lengths, or if there are other mechanisms at work that dominate the theoretical improvement in line-width as the cavity length increases. Since the production model of this prototype will not have an adjustable cavity length, it seems best to build it at about 140mm.

It is clear that the amount of feedback should be just enough to make sure that the feedback dominates over the diode's own natural frequency, although somewhat more feedback seems to have no detrimental effects. Past approximately 50% feedback, however, the line-width begins to broaden, and furthermore, the output power drops, of course. It appears that around 70-80% feedback is sufficient to prevent multi-mode behavior under most operating conditions, although as the power of the laser is reduced, it may be necessary to increase the amount of feedback. It is possible to run the laser with less feedback, and thus increase the output power, but care must be taken to ensure that the laser is single-mode. Carefully adjusting the current, the PZT voltage, and temperature slightly can help; this is probably due to the laser being most stable when the frequency of the laser corresponds to a resonant mode of both the diode's internal modes and the external

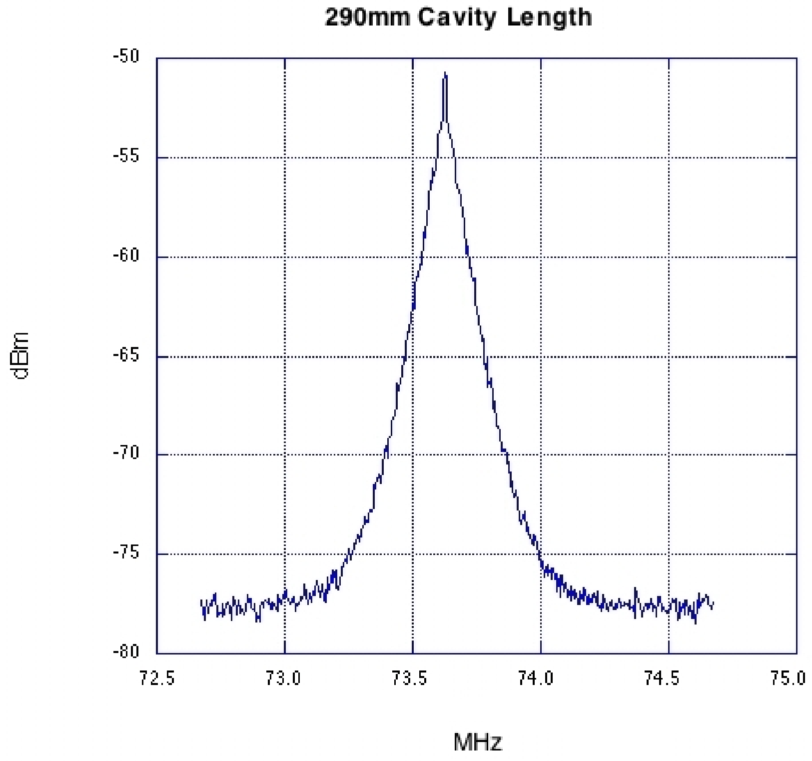


Figure 13: Line-width measurement of the laser with a cavity size of 290 mm. Notice that the oscillations are no longer visible. At this cavity length, the instabilities must be outweighing the benefits of a longer cavity. The line-width here is considerably larger than for a 140 mm or 235 mm cavity.

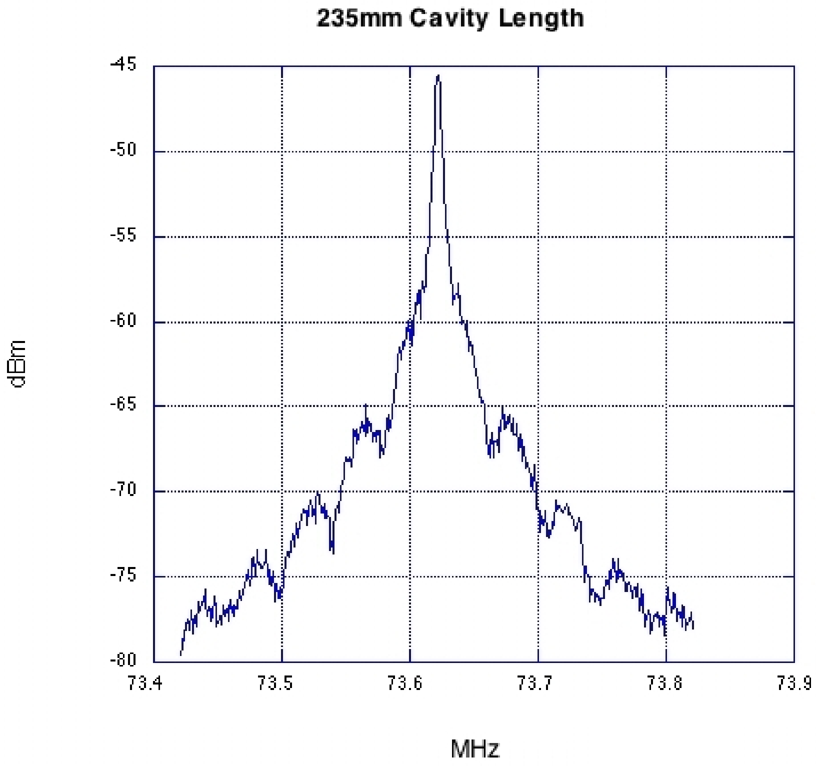


Figure 14: Line-width measurement of the laser with a cavity size of 235 mm. At this cavity length there does seem to be some slight narrowing compared to the 140 mm cavity.

cavity's mode. Adjusting the current and temperature shifts the resonant modes of the diode and adjusting the PZT voltage shifts the modes of the external cavity, by slightly changing its length. This is interesting if output power is a concern. In general, the risk of multi-mode behavior is greatly reduced by increasing the feedback power somewhat above the minimum required, and in this case the the laser should reliably run in single mode.

The transmission wavelength of each of the interference filters depends rather sensitively on the angle of the filter. How much they will need to be adjustable by depends on the desired tuning range. In any case, due to how precise the output wavelength needs to be, there will need to be a mechanism for fine-tuning the angle of the filter in the housing.

6 Conclusion

I have built and characterized an external cavity diode laser using an interference filter and "cat's eye" to narrow the laser's line-width and to choose the lasing frequency, and have then compared it to existing lasers in the Quantum Degenerate Gases lab at UBC. The laser outputs light with a much narrower line-width than the lasers currently used to cool Lithium and Rubidium.

How the laser's performance changes under parameters such as changing current and feedback power has also been investigated. I have determined that the laser is stable and single mode with sufficient feedback power, approximately 75%, and that the line-width begins to broaden feedback higher than 50%. The laser is somewhat tunable if the current to the laser and voltage to the PZT are adjusted simultaneously.

I have also roughly characterized the dependence of the transmitted wavelength of each of the interference filters on the angle of incident light.

I have investigated the effects of different cavity lengths; the laser's line-width appeared to narrow slightly with a somewhat longer cavity (from 140 mm to 235 mm), but then became considerably broader at much longer cavity lengths (290 mm). This broadening contradicts theory, but there are possible explanations for this behavior: the possibility of a lack of mechanical stability, for instance. This lack of stability should be addressed by the final housing design, so these results may not be applicable to such a housing.

7 Appendix

7.1 Equipment Used

671 nm laser	Toptica DL Pro
RF Spectrum Analyzer	Agilent E4407B
Acousto-Optic Modulator	IntraAction ATM-801A2
Photodiode	New Focus Inc. 1801-FS 125 MHz Bandwidth
Optical Isolators	Isowave I-80-T4-H
Interference Filters	Melles-Griot XLL-785.0-12.5M 3 nm Bandwidth Research Electro-Optics Inc. 0.3 nm Bandwidth
ECDL Mirror	Newport 05D20FR2
Current Controller	Thorlabs LDC500
Temperature Controller	Thorlabs TEC 2000

7.2 Lasers and Their Measured Line-Widths

Toptica DL Pro	385 kHz
Home-Made Rb Master	1 MHz
Prototype laser	
235 mm Cavity Length	7 kHz

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