Frequency Stabilization for a 486nm Dye-ring Laser

by

Charles A. Sievers

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Physics

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Abstract

For my thesis, I worked towards using two reference cavities to provide frequency stabilization to a 486nm dye-ring laser. After a doubling cavity doubles the frequency to 243nm, the laser beam is used to excite ground state hydrogen to the 2S state: the first step of an experiment to accurately measure the 2S-NS transitions of hydrogen and measure the Lamb shift and Rydberg's constant. Two stabilization cavities were used to prevent the frequency from drifting and to narrow the laser's line-width. I aligned the majority of the optics and coupling light into fiber-optic cables and Fabrey-Perot cavities. Coupling light into a high finesse Fabrey-Perot cavity requires matching the radius of curvature of constant phase of the laser with the geometry of the cavity. To do this, I first measured the physical properties of the laser beam and then numerical arrived at a solution using two lenses to match the conditions imposed by the cavity's geometry. I aligned the cavity and then observed a Pound-Drever-Hall error signal. This error signal will be fed back into the laser to stabilize the frequency. It is anticipated that when the electronics to utilize the error signals are completed, the laser frequency will be stabilized to a hundred hertz, an four order of magnitude improvement over the stability provided by the commericial laser.

Thesis Supervisor: Thomas Greytak
Title: Professor of Physics; Associate Department Head for Education

Acknowledgments

I would like to take this opportunity to show my gratitude towards Cort Johnson for the many hours he spent teaching me the theory behind lasers and showing me techniques for working with optics. I would also like to thank everyone in the Ultracold Hydrogen Group for all the help they gave me.

I would also like to thank my advisor, Professor Thomas Greytak, for giving me the opportunity to to join his group and perform the work contained within this thesis.

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Chapter 1

Introduction

Hydrogen has long held a special place in science. With the main isotope containing only one proton and one electron, it is the simplest atom and the only one that has an analytic quantum mechanical solution. Hydrogen fusion powers the sun. The 21-cm line of hydrogen, the hyper-fine splitting caused by interactions between the electron's and proton's magnetic field, allows for astronomers to track gas clouds and corroborate the rotation rate of the Milky Way. Even more import than these, hydrogen proves to be the first test of any new physical theory. Quantum mechanics was originally derived to explain the spectral lines of atomic hydrogen.

The Ultracold Hydrogen group is trying to measure the 2S-NS transitions of hydrogen. The group is capable of cooling hydrogen to 30 micro-Kelvin. At these temperatures, the doppler shift of the atomic levels becomes negligible. Improved measurements of the 2S-N2 transition will give better values for such fundamental constants as Rydberg's constant and the Lamb shift. Current efforts within the group focus on measuring the 2S-8S and 2S-10S transitions. However, before these transitions can be measured, the hydrogen 1S-2S transition must be excited. This transition requires two 243 nm photons of light. Furthermore, the natural line width of this transition is only 1.3 Hz wide. A strong monochromatic laser is need to excite this transition. While the group currently has one laser that fulfills this requirement, efforts are being made to create a second one that has a narrower linewidth for more precise measurements.

Chapter 2

Pound-Drever-Hall Stabilization

The Pound-Drever-Hall method is a powerful technique to stabilize frequency. A Fabry-Perot cavity is used as a frequency reference. Sidebands, which are low-amplitude light that has a slightly higher or lower frequency than the main beam, are added. When the light is reflected off the Fabry-Perot cavity, it can be mixed with a local oscillator whose frequency is the frequency of the beat notes between the sidebands and the main beam. The net effect of the system is to create a DC error signal. This error signal can control a servo system to stabilize the frequency and to narrow the line width.

2.1 Fabry-Perot Cavity

A Fabry-Perot cavity consists of two reflective pieces of glass that are parallel. The light is passed through one of the pieces of glass and forms a standing wave in the cavity. The finesse of the cavity, defined below, is a measure of how many times the light is reflected in the cavity before it is transmitted. Here r is the Fresnel reflection coefficient.

$$F \equiv \left(\frac{2r}{1-r^2}\right)^2 \tag{2.1}$$

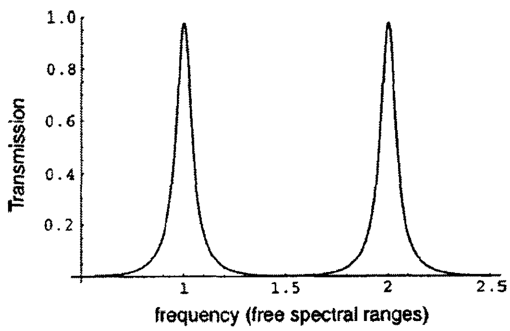

Figure 2-1: The transmission rates for a Fabry-Perot cavity with a finesse of around 12. As the finesse increases, the bumps at the free spectral ranges get thinner. This plot was taken from Black [5]

Standing waves can only form in a Fabry-Perot cavity if the wavelength of light is an integer divisor of twice the cavity length. The free spectral range of the cavity is the frequency difference between supported modes, $\frac{c}{2L}$. If this boundary condition is not met, the phase shifts through every cycle. This difference in phase causes the light to destructively interfere and be annihilated. For cavities that have low finesse, the frequency can be slightly off resonance and still partially transmit. For higher finesse cavities, the thickness of these peaks rapidly narrow. In particular, the ratio of the free spectral range to the full width at half height of one of the peaks is equal to F.

The transmission peaks allow for a laser's frequency to have something to lock onto. While one measurement of the transmission peak gives little information, a second measurement at a slightly shifted frequency gives the slope of the transmission line. Since the slope of the line is zero at a free spectral range, one could modulate the laser frequency at some frequency Ω, then adjust the average laser frequency until the intensity of the transmitted light contained no component at Ω_0. Assuming that the Fabry-Perot cavity in insulated from thermal changes, the laser light is now locked to the cavity resonance frequency. A servo system can be used to prevent the laser frequency from drifting.

While a Fabry-Perot cavity frequency lock system described above works, it has some weaknesses. The response time of the frequency stabilization is limited by the response time of the Fabry-Perot cavity. Furthermore, the laser frequency must be constantly varying to measure the slope.

2.2 The Pound-Drever-Hall Method

The Pound-Drever-Hall system improves on a Fabry-Perot system. A derivation of the Pound-Drever-Hall stabilization presented by Eric Black [5] will be followed. The reflection coefficient of a monochromatic beam, $F(\omega)$ is described by:

$$F(\omega) = \frac{E_ref}{E_inc} = \frac{r\left(exp\left(i\frac{\omega}{\Delta_\nu f sr}\right) - 1\right)}{1 - r^2 exp\left(i\frac{\omega}{\Delta\nu_{fsr}}\right)}. \tag{2.2}$$

Adding a phase modulation to monochromatic light and expanding it in Bessel functions gives:

$$\begin{aligned} E_{inc} =& E_0 e^{i(\omega t + \beta in\Omega t)} \\ &\approx \left[J_0(\beta) + 2iJ_1(\beta) \, sin\Omega t\right] e^{i\omega t} \\ &= E_0 \left[J_0(\beta) e^{i\omega t} + J_1(\beta)^{i(\omega+\Omega)t} - J_1(\beta) e^{i(\omega-\Omega)t}\right]. \end{aligned} \tag{2.3}$$

These three different frequencies represent the main frequency and the two sidebands. When this light is reflected, each frequency reflects according to equation 2.2 independently.

$$E_{ref} = E_0 \left[F(\omega) J_0(\beta) e^{i\omega t} + F(\omega+\Omega) J_1(\beta) e^{i(\omega+\Omega)t} - F(\omega-\Omega) J_1(\beta) e^{i(\omega-\Omega)t}\right] \tag{2.4}$$

The power of an electric field is proportional to the square of the electric field. The power of the reflected light is:

$$
\begin{aligned}
P_{ref} =& P_c|F(\omega)|^2 + P_s\left[|F(\omega+\Omega)|^2 + |F(\omega-\Omega)|^2\right] \\
&+ 2\sqrt{P_cP_s}Re\left[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)\right]cos\Omega t \\
&+ 2\sqrt{P_cP_s}Im\left[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)\right]sin\Omega t + (2\Omega)\,. \qquad (2.5)
\end{aligned}
$$

Where P_s is the power in one of the sidebands and P_c is the power in the center band. The other terms are caused by interference. Modulating the phase makes it possible to measure the error with one measurement. When this system is implemented, the driving frequency Ω is large compared to the natural line width of the cavity, allowing the center frequency to be on resonance while neither side band is. In this case,

$$
F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega) = -2iIm\left[F(\omega)\right]. \qquad (2.6)
$$

In this regime, the cosine term in equation 2.5 vanishes leaving the sine as the only piece that varies with Ω. If this power is measured and then mixed with a sine signal frequency Ω and then put through a low band-pass filter, a DC current remains. This DC output is the error signal ϵ and it takes the form plotted in figure 2-2.

$$
\epsilon = -2\sqrt{P_cP_s}Im\left[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)\right] \qquad (2.7)
$$

When the laser is very close to resonance, the reflected power essentially vanishes. $|F(\omega)|^2 \approx 0$. However, the first order solution is:

$$
P_{ref} \approx 2P_s - 4\sqrt{P_cP_s}Im\left[F(\omega)\right] + Order\left(2\Omega\right) \qquad (2.8)
$$

The following equation is also true.

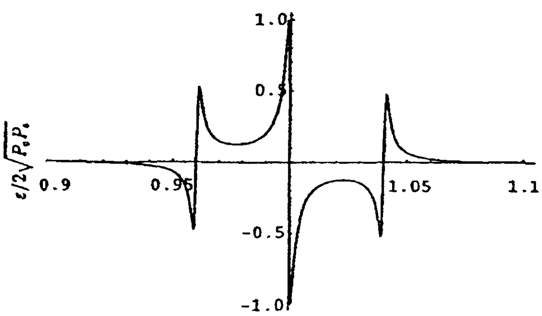

Figure 2-2: The Pound-Drever-Hall error signal for a large driving frequency in a cavity. The cavity has a finesse of 500. The driving frequency is four percent of the free spectral range. This plot was taken from Black. [5]

$$\frac{\omega}{\Delta\nu_{fsr}} = 2\pi N + \frac{\delta\omega}{\Delta\nu_{fsr}}. \tag{2.9}$$

If the cavity has a high finesse, the reflection coefficient can be approximated as $\frac{i}{\pi}\frac{\delta\omega}{\delta\nu}$, where $\delta\nu$ is the free spectral range divided by the finesse. As long as this frequency is much larger than the frequency error off resonance, the error signal is linear. Plugging equation 2.8 and substituting it into equation 2.7 and linearizing the solution using equation 2.9 produces the error signal:

$$\epsilon \approx \frac{4}{\pi}\sqrt{P_c P_s}\frac{\delta\omega}{\delta\nu}. \tag{2.10}$$

For small deviations in the resonance frequency, the error signal is linear. Furthermore, the error signal is zero when the laser is on resonance. This can be used to provide negative feedback to to the laser transducer to prevent frequency drift. While a Fabry-Perot cavity can be used with a varying frequency to obtain an error signal, the Pound-Drever-Hall technique better uses a Fabry-Perot because it requires only one measurement, thus allowing faster response time and better stabilization.

Chapter 3

The Laser System

My thesis work has been to work towards stabilizing a 243nm ring-dye laser. This laser was designed to be used to excite the 1S-2S transitions in hydrogen. Once in the 2S state, other lasers can further excite transitions to higher energy levels. A 413nm krypton pump laser was used, model Coherent Innova Sabre. This laser acted more as a power-supply by providing approximately 5 watts of power but has a wide linewidth. This light passes directly into the Coherent 899-21 Ring Laser. This laser uses a dye jet containing Coumarin 480 to convert the 413nm light to 486nm. A series of mirrors creates a light cavity the narrows the laser beams linewidth. This laser beam enters a doubling cavity that changes the frequency to the requisite 243nm needed to excite the 1S-2S transition. Two stabilization cavities and the needed optics for them provide a feedback system to improve the linewidth and stability of the laser. A diagram of the laser can be seen in figure 3-1.

3.1 The Laser

The Coherent Innova Sabre Ion Laser is the pump laser used. It is a cavity filled with krypton gas and with mirrors at both ends. A high voltage is placed across the cavity exciting the gas. The relaxing krypton then releases a photon at 413nm. If the photon is moving transversely through the cavity multiple times, aggregate stimulated emissions cause the intensity to increase and preserve relative phase. The

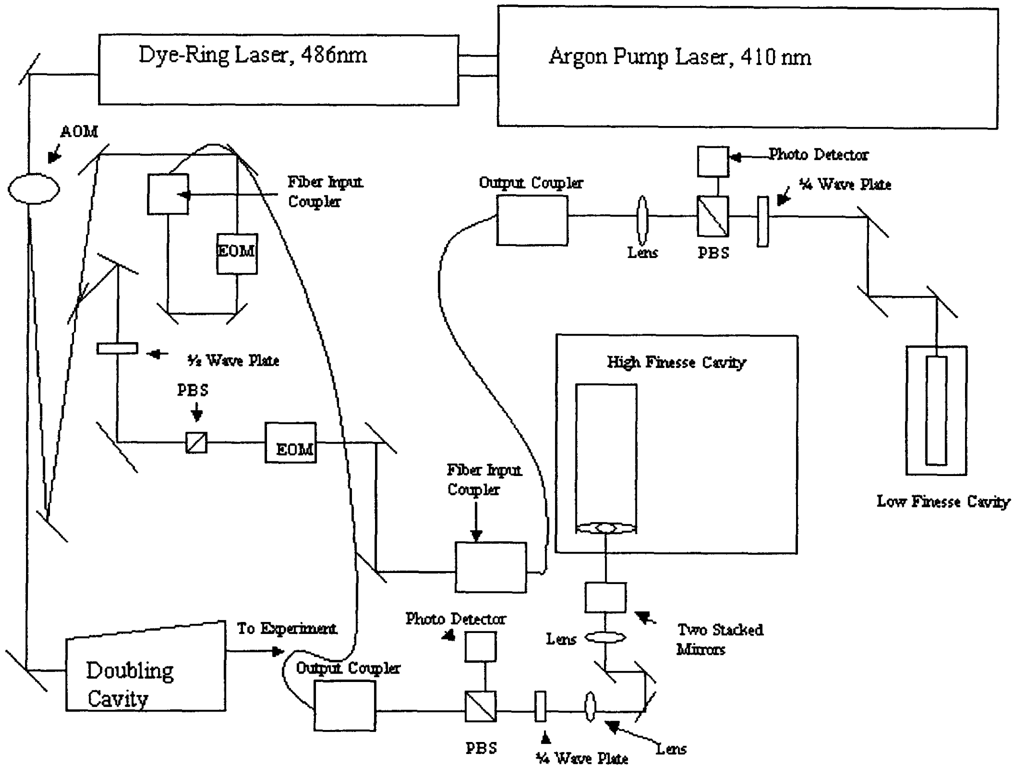

Figure 3-1: A diagram of the laser table.

laser lases. Two Brewster windows allow the laser to lase in only one polarization. One of the side mirrors is partially transparent allowing the laser beam to leak out. Under normal operating procedures, the laser beam has a $(\frac{1}{e^2})$ diameter of 1.6 mm and 100:1 vertical polarization [1]. The maximum intensity of the laser beam is approximately 5 watts.

After exiting the pump laser, the beam enters a second laser, a dye laser model Coherent 899-21 Ring Laser. A jet sprays a flat stream of Coumarin 480 across the 413 nm laser beam from the Innova. Most of the light is scattered but much of it is readmitted at 486nm. This readmitted light is directing into a cavity formed by a ring of mirrors. This ring of mirrors imposes a periodic boundary condition on the light, restoring the frequencies that the cavity can support. This acts to narrow the linewidth of the laser. Furthermore, Brewster windows in the optical cavity again allow only one polarization to be supported. Once light is able to lase within this cavity, some of the light is able to escape through a semi-transparent output coupler.

The Coherent 899-21 Ring Laser has a active frequency stabilization builtin utilizing two etalons within the cavity. An etalon consists of two pieces of glass within the cavity that serves to impose another boundary condition further constraining the supported frequencies. The laser has a built in low-finesse reference cavity that controls the separation in each of the etalons. With this system, the laser has a linewidth of 500 kHz. [2] The power output is 300 milliwatts.

3.2 Stabilization Optics

While 500 MHz is over a million times smaller than the frequency of the laser, it is still too broad for exploring hydrogen. This 500 MHz linewidth becomes 1 GHz when the light enters the frequency doubler. This linewidth is huge compared to the 1.3 Hz natural line width of the 1S-2S transition of hydrogen. Since the hydrogen is at tens of micro-Kelvin, doppler effects do not substantially broaden the linewidth either. A weaker laser with a very small linewidth is more useful than a powerful laser that has a large one. Furthermore, the measurement resolution is inversely proportional to the linewidth; the less monochromatic the laser light, the more error in the measurement. For this reason, much care has been taken to produce the narrowest feasible linewidth.

An acousto-optic modulator (AOM) is used to split a small amount of the laser beam off the main beam into a stabilization equipment. An AOM is a cavity that holds a standing acoustic wave. Part of the incoming laser beam Bragg diffracts off the sounds waves at small angles. The first order diffraction is frequency shifted by the frequency of the standing acoustic wave. The zeroth order light remains unperturbed by the AOM. By adjusting the AOM, anywhere between zero and eighty percent of the incident light can be put in first order diffraction. This AOM serves to diffract a small percentage of the light away from the main beam and into the reference cavity optical system. A normal beam splitter would not have been ideal it can not shift the frequency of the light as is necessary to make a comparison with the reference cavity frequencies.

As seen in figure 3-1, two reference cavities are used: a high finesse cavity and a low finesse cavity. The high finesse cavity has a finesse of 50,000 while the low finesse has a finesse of 1000. A beam splitter is used to divide the light equally between these two cavities. The physical equipment used for the two cavities are very similar except for the finesse of the respective cavities. The laser beam bound for the stabilization cavities is monochromatic, but shifted in frequency, when it leaves the main beam. For the Drever-Pound-Hall stabilization system to work, sidebands need to be added. An electro-optic modulator (EOM) added these sidebands. An EOM is a crystal whose index of refraction depends on the voltage placed across it. If a sinusoidal voltage is applied across the EOM crystal, it acts to sinusoidal shift the phase of the light. This phase modulation creates the needed sidebands. (See equation 2.3)

Care must be taken that only the phase and not the amplitude of the light is changed by the EOM. The laser beam is initially linearly polarized. The EOM has a preferred direction caused by the voltage being applied from one side of the crystal to the other. If these orientations are not perpendicular, the light will suffer an amplitude modulation which in turn produces a spurious DC offset in the error signal. The error signal arises from mixing a local oscillator with the beat note between the main beam and the sidebands. If the amplitude varies at the beat note frequency, it will mix with the local oscillator to produce a false DC offset regardless of the reflected main beam power. A half-wave plate and polarizer were used to properly align the polarization angle and insure no amplitude modulation takes place.

Once the sidebands are added, the laser beam is coupled into a fiber optic cable. The fiber optical cable functions to separate the alignment of the first part of the optics from that of the second. Every time the laser is turned on, the power output needs to be tuned up. Much of the power can be lost in periods as short as a day. Tuning up the laser redirects the laser beam, misaligning all the subsequent optics. Fabry-Perot cavities are incredibly sensitive to the beam's direction and correctly aligning the beam is a slow, painstaking process. A fiber optic cable allows for the coupling in the Fabry-Perot cavities to remain aligned and unperturbed during the process of tuning up the laser.

Once the light comes out of the the fiber optic cable, it passes through a polarizing beam splitter (PBS). The PBS transmits one polarization and reflects at a right angle the other. The transmitted laser beam then passes through a quarter-wave plate that shifts the polarization from linear to circular. The light is focused by one or two lenses and then coupled into a Fabry-Perot cavity. For improved stability, both cavities are thermally and vibrationally stabilized. The light reflected by the Fabry-Perot cavity returns through the quarter-wave plate, shifting the polarization back from being circular to being linear with a net rotation of 90 degrees. The BCS then reflects all the light at 90 degrees into a photodetector.

The photodetector signal is mixed with a local oscillator whose frequency is the beat note frequency between the sidebands and main beam. The output of the mixer is put through a low-pass filter to obtain an error signal. The electronics needed to convert the error signal into a negative feedback system has yet to be fabricated. The error signal from the low-finesse cavity will be feed back into an EOM in the dye-ring laser. Applying a DC voltage across the crystal in the EOM changes the optical path length of the cavity and hence the frequency of light the laser produces. The error-signal of the high-finesse cavity will be passed into an AOM placed right outside the right laser.. The frequency of the laser can be adjusted by changing the frequency of the acoustic waves driving the AOM and putting the majority of the power into the first order diffraction.

A more stable laser will have a smaller linewidth. Most of the noise in the laser originates from the mirrors vibrating in the dye-ring laser. This changes the cavity length and hence the frequency of light the laser produces. Higher frequency vibrations from the dye jet also lead to frequency error. The former is acoustic noise that varies at a few hundred hertz. The latter change on the microsecond time-scale. The low-finesse cavity servo is designed to compensate for both noises while the high finesse cavity servo system will reduce only the acoustic noise. Because the electronics has yet to be build, the actual linewidth improvement of the laser has yet to be measured. However, it is believed that this system is capable of reducing the linewidth to under 100 Hz.

With the two stabilization cavities, the laser frequency has become very stable. However, for the laser to successfully excite the 1S-2S transition, the frequency must be set correctly. While the stabilization cavities can hold a frequency, a tellurium oven is need as a standard to set the frequency. Tellurium produces a very detectable absorption line at the same frequency at a known distance from the 1S-2S hydrogen transition. The commercial laser is frequency tunable. This tellurium absorption line is the standard used to set the laser frequency.

Chapter 4

Gaussian Optics

Coupling light into a Fabry-Perot cavity requires mode matching. Matching the laser beam's physical properties to the geometry of the reference cavity requires an understanding of Gaussian Optics.

4.1 Gaussian Optical Theory

Classical optics says a beam of light will travel in a straight line. The light may be reflected by mirrors, bent by materials with a non-constant index of refraction, or scattered, but it will always travel between point A and B in a path that minimizes time. But light is a wave, and waves do not follow classical optics. Rather, waves have properties like phase, and will disperse. A treatment of light beam profile that takes into account these wave-like physical properties is called Gaussian Optics. It starts with a monochromatic beam of light traveling in the z-direction whose x,y dependence is a gaussian function of $r = \sqrt{x^2 + y^2}$. The propagation of this field can be derived using Maxwell's Equations, here the wavelength is assumed to be small compared to the width of the beam.

$$
\begin{aligned}
\nabla \times \mathbf{H} &= \epsilon \frac{\partial \mathbf{E}}{\partial t} \\
\nabla \times \mathbf{E} &= -\mu \frac{\partial \mathbf{H}}{\partial t} \\
\nabla \cdot \epsilon \mathbf{E} &= 0
\end{aligned} \tag{4.1}
$$

Quoting the results in Yariv [4], the electric field is:

$$
\mathbf{E} = \psi\left(x, y, z\right) e^{ikz} = e^{ikz} e^{-i\left[P(z) + \frac{kr^2}{2q(z)}\right]} \tag{4.2}
$$

where P is given in terms of q, and q is the solution to the equation:

$$
P' = -\frac{i}{q} \tag{4.3}
$$

$$
\left(\frac{1}{q}\right)^2 + \left(\frac{1}{w}\right)' + \frac{k_2}{k} \tag{4.4}
$$

k_2 is some characteristic of the medium. If the medium is homogeneous, $k_2 = 0$; a simple expression of q results:

$$
q = z + q_0 \tag{4.5}
$$

In describing the electric field, the following definitions prove useful and physically meaningful.

$$q_0 = iz_0 = \frac{i\omega_0^2 n}{\lambda} \tag{4.6}$$

$$\lambda = \frac{2\pi n}{k} \tag{4.7}$$

$$w(z)^2 = w_o^2\left[1 + \left(\frac{\lambda z}{\pi w_0^2 n}\right)\right] = w_0^2\left(1 + \frac{z^2}{z_0^2}\right) \tag{4.8}$$

$$R = z\left(1 + \frac{z_0^2}{z^2}\right) \tag{4.9}$$

$$\eta = tan^{-1}\left(\frac{z}{z_0}\right) \tag{4.10}$$

Here q_0 is the value of q at the beam waist, the spot where the beam width is smallest. w_0 is the 1/e electric field beam radius at the waist. $w(z)$ is that same 1/e radius but this time as a function of z. z_0 is the distance the beam travels until the beam radius spreads out to from ω_0 to $\sqrt{2}\omega_0$. R is the radius of curvature of constant phase. η is a phase correction factor. With these definitions, the electric field can be written as follows.

$$\mathbf{E}(x, y, z) = \frac{\mathbf{E_0}}{\sqrt{1 + \frac{z^2}{z_0^2}}} exp\left[-i\left[kz - \eta(z)\right] - r^2\left(\frac{1}{w^2(z)} + \frac{ik}{2R(z)}\right)\right] \tag{4.11}$$

The intensity of light is proportional to the square of the electric field In the exponent of equation 4.11, the only non-imaginary part is $-\frac{r^2}{\omega(z)}$. The intensity in the x and y axes remains a gaussian function whose 1/e width is $\omega(z)$. $\omega(z)$ is a hyperbola. Furthermore the gaussian exponent is normalized by the $1/\left(1 + (z/z_0)^2\right)$ factor modifying the electric field strength. The $\frac{-ikr^2}{R(z)}$ term shows that the phase fronts have a well defined radius of curvature.

Equation 4.11 is a convenient function because it contains only two parameters, the frequency of the light and the beam waist. The smaller the beam waist, the faster the beam will spread out. A plot of the electric field at the waist can be seen in figure 4-1

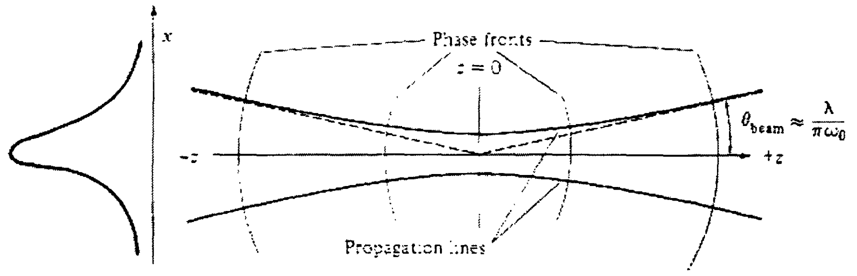

Figure 2-5 Propagating Gaussian beam.

Figure 4-1: A plot of equation 4.11 showing the spreading out of gaussian beam. Taken from Yariv, p 49. [4]

4.2 ABCD Law

The ABCD law is a simple way to explore what will happen to a gaussian beam when it passes through various media such as free space, going through a lens, etc. The results here quoted came from Yariv. [4] Looking back at equations 4.2 and 4.4, it is shown that the electric field profile can be written only as a function of the complex number q. If a beam propagated through a medium according to equation 4.11 for some fixed distance, and reflects from a mirror or is focused by a lens, the ABCD law provides a simple way to compute how q is changed. The ABCD law says that for some value of A, B, C, and D, the transformation of q is:

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D}. \tag{4.12}$$

Furthermore, if the light travels through multiple different objects, the resulting effect on q can be computed by placing A,B,C, and in a matrix and then multiplying the ABCD matrices together as shown below.

$$\begin{pmatrix} A_t & B_t \\ C_t & d_t \end{pmatrix} = \begin{pmatrix} A_2 & B_2 \\ C_2 & D_2 \end{pmatrix} \begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} \tag{4.13}$$

A few examples of common objects are found in the table below.

(1) Straight section length d	$\begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$
(2) Thin lens: focal length f	$\begin{pmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{pmatrix}$
(3) A spherical mirror, radius R	$\begin{pmatrix} 1 & 0 \\ \frac{-2}{R} & 1 \end{pmatrix}$

Since the beam width and the radius of curvature of constant phase can be written as a function of q alone, the way that the ABCD law shows q's evolution means the problems in gaussian optics can be solved easily.

Chapter 5

Coupling

Coupling laser light into cavities and cables is a tedious process involving moving mirror knobs by fractions of a turn. Furthermore, coupling usually requires changing two or more mirrors as well as lenses simultaneously. Maximizing the power coupled requires maximizing along six or more degrees of freedom, each of which could remove all the power if even slightly off.

5.1 Walking Mirrors

Two mirrors are needed to redirect light from one direction and position to an arbitrarily different direction and position. For example, if the laser light starts parallel to the table at a height of 5 cm but it needs to be parallel at a height of 10 cm, one mirror is needed to point the light upward and another mirror is need to redirect the light parallel again. This is a simple example that shows that one mirror is not sufficient. Two mirrors are always sufficient to redirect the light arbitrarily. Each mirror has two degrees of freedom, vertical and horizontal tilt, for a total of four degrees of freedom. Likewise, a beam of light has four degrees of freedom: three positions and two orientations with the constraint that the positions can lie anywhere along a line and still describe the same beam.

Since two mirrors are requisite to completely redirect the laser beam, two mirrors are placed before any object that has a narrow aperture. This allows for the light be properly aligned to enter the aperture. The first object that has a narrow aperture in the stabilization optics is the EOM. To point the light through the EOM, the mirrors were placed and aligned at the same height as the EOM aperture and parallel to the table. This was achieved by first measuring the height of the aperture with a ruler. The ruler was then placed close to the second mirror, the one closest to the EOM, the first mirror was adjusted so that the laser beam hit the ruler at aperture height. The ruler was then placed a few feet away from the second mirror and that mirror was adjusted until the laser beam again hit the ruler at the aperture hight. The EOM was then placed in the beam path and adjusted until some light went through.

Once some light came through the EOM, an intensity meter was placed in the laser beam after the EOM. One of the axes was selected, either vertical or horizontal. The second mirror was varied along that axis to find the maximum intensity. A mental note of that intensity was made. The first mirror was moved on the same axis a slight amount and the second mirror again was varied to find the maximum intensity. These two intensities provide a slope for moving the first mirror. This process was continued along the same axis until no more substantial gain in the intensity is achieved. The same process is then done on the second axis. The process is repeated alternating between axes until no more intensity gain can be achieved. This process of maximizing the intensity is called walking mirrors.

The reason walking mirrors works is that to a certain degree the two axes are independent. The laser beam has a gaussian distribution and the aperture are usually round. This means that if there is error in the y axis, this offsets the maximum intensity possible while exploring the x-axis, but not the position where the maximum intensity is found. In theory, each axis should only need to be adjusted once, but experience shows that adjusting each axis alternatively multiple times produces much better results.

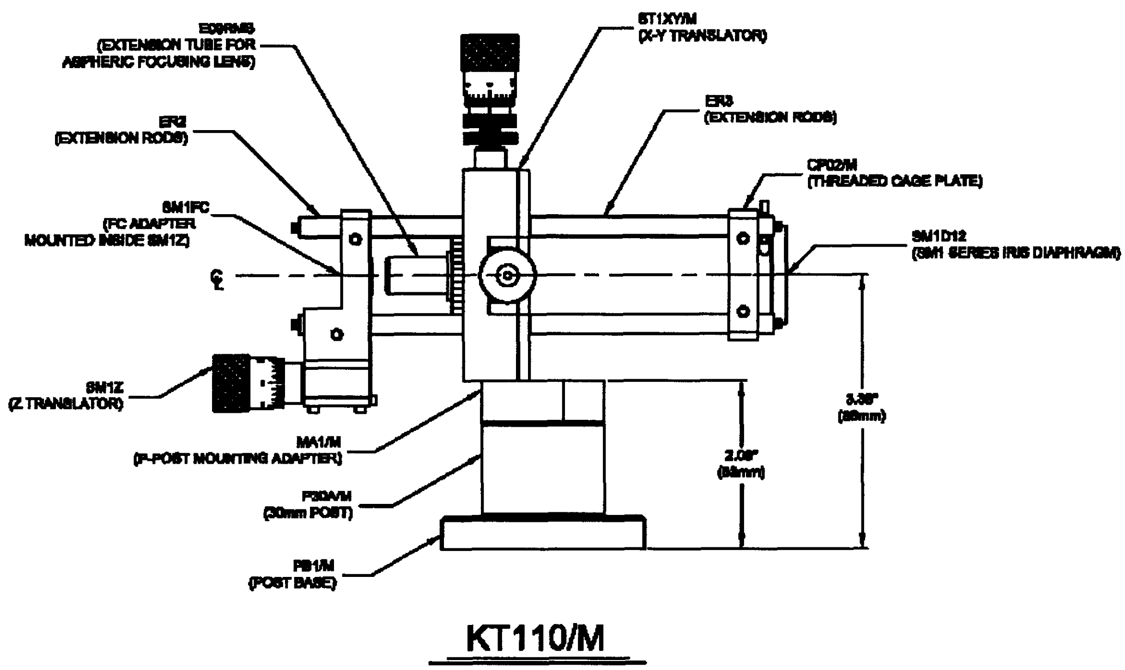

Figure 5-1: A schematic of the fiber optics input coupler. The laser beam enters on axis from right to left. Picture courtesy of Thorlabs [3]

5.2 Coupling into a Fiber Optic Cable

Once the laser beam was put through the EOM, the next step was coupling the light into a fiber-optic cable. A schematic of the input coupler is shown in figure 5-1

Coupling into a fiber optics cable is significantly harder than walking two mirrors to point the light through the EOM. First of all, there is a lens that is used to focus the light onto the fiber tip, producing three extra degrees of freedom (moving the lens in the x-y plane and the tip along the z axis) along with the normal four degrees of freedom from the two mirrors.

The process of coupling starts by removing the lens and the whole back part where the fiber optic cable is situated. This gives seven inches to level the beam. A diaphragm is located at the entrance of the coupler. The diaphragm can close to a small hole showing the location of the center axis of the input coupler. The mirrors are aligned to direct the light onto the hole in the diaphragm. A small calibration piece is designed to rest on the extension rods. It has a small hole that lies directly on the central axes. It is place around an inch behind the diaphragm. The mirrors are walked until the light is centered on this small hole. The beam width is much larger than the diameter of the hole. The calibration piece is then pushed further back along the extension rods and the beam is re-centered again. This process continues until the calibration piece can be placed anywhere along the extension rods and have the laser beam centered on the hole. The laser beam is on axis.

Once the beam is on axis, the lens in put back onto the the coupler. The calibration piece is placed on the back of the extension rods at the point where the laser beam width is smallest. The lens redirects the light and the laser beam no longer is centered on the calibration piece. The x and y translators on the lens are used to point the laser beam directly on the hole in the calibration piece. The calibration piece is taken on the input coupler and the back part containing the fiber optic cable tip is put back on the input coupler trying to put the tip where the beam width is a minimum.

At this point, approximately 10^{-5} to 10^{-6} of the light intensity should be coupled into the fiber-optic cable. The is enough light that with room light turned off, light can be seen coming out of the other end of the fiber-optic cable. The back end can be adjusted slightly to increase how much light is coupled. At this point, enough light is coupled through the cable so that a photometer can measure the intensity. An output coupler is attached to the other end of the cable and is pointed directly onto the photometer. The laborious process of multi-dimensional optimization begins. The two mirrors are walked to maximize the intensity. The z-axis is then moved slightly and the two mirrors are walked again. This process is continued till the mirrors and z-axis positions maximize the intensity. This part of coupling takes the longest time. The x-y translation on the lens can be partially corrected by the mirrors with little loss in intensity which makes the x-y translation much less sensitive. However, the z-axis is incredibly sensitive. The lens focuses the beam to sharp focus; slight deviations from this focus causes the beam to be much more spread out. Once the z-axis is in the correct position, the x-translation and the y-translation can be separately optimized. The z-axis needs to be reoptimised, but it is very close to being in the correct location. The process of optimizing the x, y, and z axes in turn, each accompanied with the mirrors can be continued for slight but useful improvements in the intensity.

A properly coupled fiber optic cable can transmit as much as 50% to 60% of the beam intensity. We achieved around 35% for both input couplers. Each coupler took an average of eight hours to properly couple. Every time the laser is turned on, the beam needs to be peaked-up. A process similar to walking mirrors is used to increase the power output of the laser. The downside of peaking-up the laser is that the beam is no longer pointing in the same direction and all subsequent optics are misaligned. The input couplers need to be recoupled. Thankfully, the process of recoupling the input coupler take only a few minutes instead of multiple hours. The most sensitive aspect of coupling is the z-axis. The correct z-axis is set by the beam width and the radius of curvature of constant phase. Fortunately, these two parameters are not effected noticeably when tuned-up the laser. Walking just the mirrors is sufficient to recoupling the laser beam into the fiber optical cable.

5.3 Conditions for Coupling into the High Finesse Cavity

Figure 5-2 shows a schematic of the high finesse cavity. The first lens is flat while the second lens has a radius of curvature of 50cm. It was shown that a gaussian beam will disperse in a hyperbolic form. Furthermore, the radius of curvature of constant phase was shown to follow equation 4.10.

The finesse of the high finesse cavity is approximately 50,000, which is the mean number of a times a photon is reflected within the cavity. If the light does not hit the mirrors at right angles and have the modes match, the intensity of light is quickly dispersed and lost. Since coherent light travels perpendicular to lines of constance phase, the radius of curvature of the mirrors must match the radius of curvature of constant phase. For the left part of the cavity, the radius of curvature is ∞, for the right its 50cm. If the radius of curvature matches the beam, light can couple into the cavity.

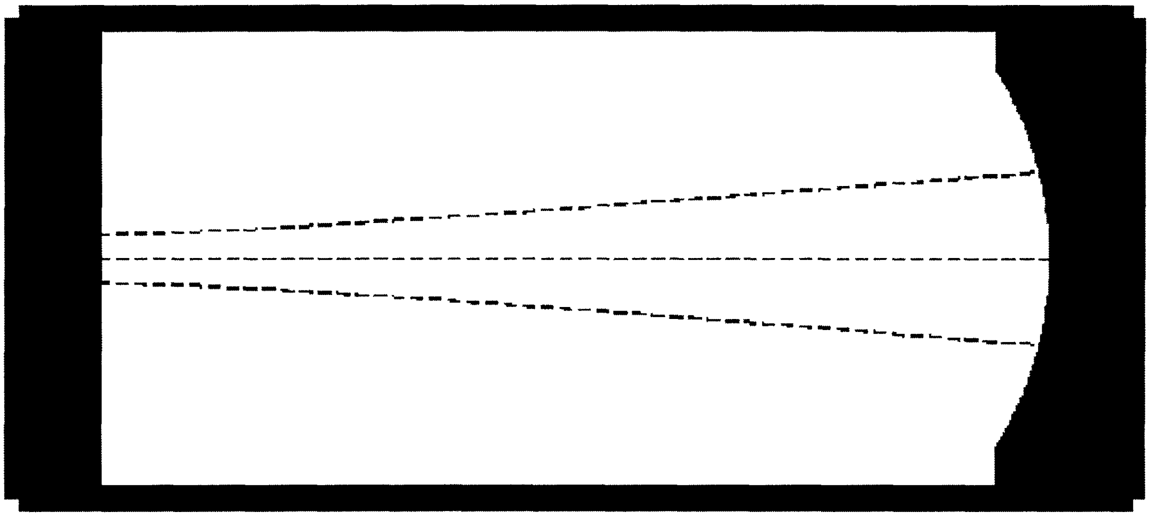

Figure 5-2: A schematic of the high finesse cavity. The reflective lens on the left is flat. The radius of curvature for the reflective lens on the right is 50cm. The cavity length is 20 cm. The dashed lines represent the path well coupled light would transverse.

The first step to coupling is to determine the needed q value for the two conditions on the radius of curvature to be met. Again, the function for of the radius of curvature as a function of z is:

$$R = z\left(1 + \frac{z_0^2}{z^2}\right). \tag{5.1}$$

At z=0, the formula dictates that the radius of curvature is infinity. (In point of fact, eqn 5.1 should have z replace by $(z - z_{waist})$. However, the first boundary condition determines that $z_{waist} = 0$.) The second boundary conditions gives:

$$50cm = 20cm\left(1 + \frac{z_0^2}{400cm^2}\right) \tag{5.2}$$

$$Z_0 = 20\sqrt{1.5}cm \tag{5.3}$$

Since $q_0 = iz_0$ and $q = z + q_0$, the boundary conditions are met if and only if $q = i20\sqrt{1.5}cm.$ at the beginning of the high finesse cavity.

5.4 Matching the Conditions for Coupling into the High Finesse Cavity

When the laser beam leaves the fiber optic output coupler, it has a particular value of q. The value of q must be measured. However, q does not have much physical significance. ω_0 does have significance, it is the 1/e radius of the electric field of the beam. Furthermore, starting from the functional form of $\omega(z)$, ω_0 can readily be determined.

$$\omega^2(z) = \omega_0^2 \left[1 + \left(\frac{z - z_{waist}}{z_0}\right)^2\right] \tag{5.4}$$

$$= \omega_0^2 + \frac{\lambda^2 (z - z_{waist})^2}{\pi^2 n^2 w_0^4} \tag{5.5}$$

After measuring ω at several different lengths, I fit my measurements to equation 5.5 obtaining results for ω_0 and z_{waist}. Knowing that $q(0) = i\frac{\pi\omega^2 n}{\lambda} - z_{waist}$, the value for q was quickly found to be: 70.3i - 46.3 cm. Note that the zero is now defined to be at the output coupler.

Once the q value coming out of the fiber optic cable and the needed q value to couple into the high finesse cavity were known, the next step was to match the two values using two lenses. While theoretically one lens would be sufficient, two lenses provide more a more stable coupling scenario.

A matlab routine was used to find the optimal parameters. The code for this routine can be seen in Appendix A. The laser beam was going to propagate a distance d1,d2, and d3 while being focused by two lenses l1 and l2 between the distances. Figure 5-4 demonstrates how the three distance and two lens are used to match the modes. A matlab routine used to solve this problem iterated l1 and l2 through a list of 8 focal lengths between 10cm and 100cm, and the distances d1 and d2 between 1cm and 100cm. The ABCD law allowed for easy calculation of the q value. If the imaginary part of q was acceptably close to the needed value, d3 was computed and

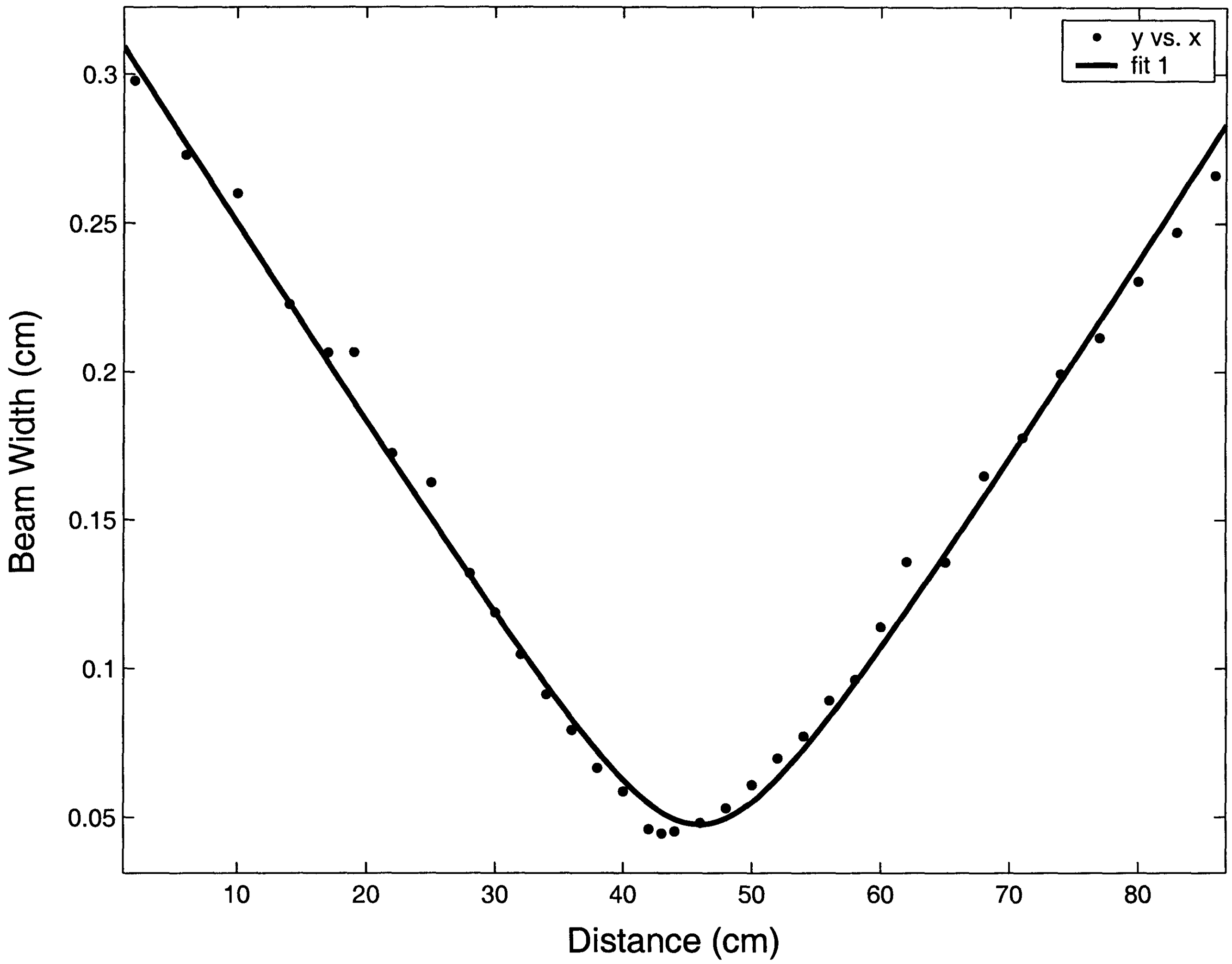

Figure 5-3: The plot of $w(z)$ fitted to find the value for ω_0 and z_{waist} , from which q could be determined.

the five number solution was stored in a list.

Once a list of possible solutions, the process of selecting the best one continued. Solutions that contained negative distances were unphysical and thus rejected. Solutions that had the sum of the distances being too large were infeasible because they did not fit on the table. Also, physical limitation in placing the lenses forced the third distance from being too short. After these constraints were taken into account, only a few possible solutions were left. For each of these solutions, a instability function was calculated, $\sqrt{\left(\frac{dq}{dd1}\right)^2 + \left(\frac{dq}{dd2}\right)^2}$. The solution that had the smallest instability function was used, because it would make coupling into the high finesse cavity the easiest. The solution was d1=66cm, d2=58cm, d3=52 ,l1=75c, ,and l2=20cm.

5.5 Coupling into the High Finesse Cavity

Once the optimal lens configuration was known, the optics were placed on the table. The lenses were placed on movable bases so they could easily be moved to vary the distances. The mirrors were walked to direct the light onto the middle of the high finesse input window. The mirrors were farther adjusted to walk till the reflected beam off the window returned exactly to the output fiber coupler. This means that the beam impinged upon the window at a perfect ninety degree angle. The room lights were turned off and a piece of white paper was placed on the other side of the cavity to see if any light transmitted through the cavity. The light was a diffuse haze.

The next step involved turning that diffuse haze into point. The laser beam was not properly coupled into to cavity and the beam was bouncing from one side of the curved mirror to the other. This spread the beam throughout the cavity resulting in the beam's diffusion. The mirrors were walked some more to try to increase the brightness of the haze. At some point, the diffuse haze collapsed to a line, indicating that on one axis the light was properly coupled. Once the line appeared, the second axis was quickly adjusted to turn the line into a point.

Once a spot was obtained, a photodetector was placed to measure the transmitted intensity and was outputed to the y axis of an oscilloscope. The laser was set on frequency scan mode and the frequency set the x axis on the oscilloscope. For most of the scan, the photodetector saw little light. However, at certain frequencies, strong peaks in the intensity were seen. These frequencies corresponded to the resonance frequencies of the cavity. The mirrors were continued to be walked to maximize the transmission peaks. The lenses' placements were adjusted as well, however the transmission peaks did not dramatically change. The high finesse cavity was successfully coupled.

After the laser was coupled into the high finesse cavity, the next step was to observe the error signal from the high finesse cavity. The EOM was driven at 7 kHz.

A local oscillator of this frequency was mixed with the output of the photodetector. After this signal went through a low-pass filter it was displayed as the y axis of the oscilloscope. The laser was set to frequency scan. After slowing down the frequency scan rate and range and finding a spectral mode of the cavity, an error signal was seen similar to the one plotted in figure 2-2. A Pound-Drever-Hall error signal was successfully produced. This error signal will be used in future to stabilize the laser.

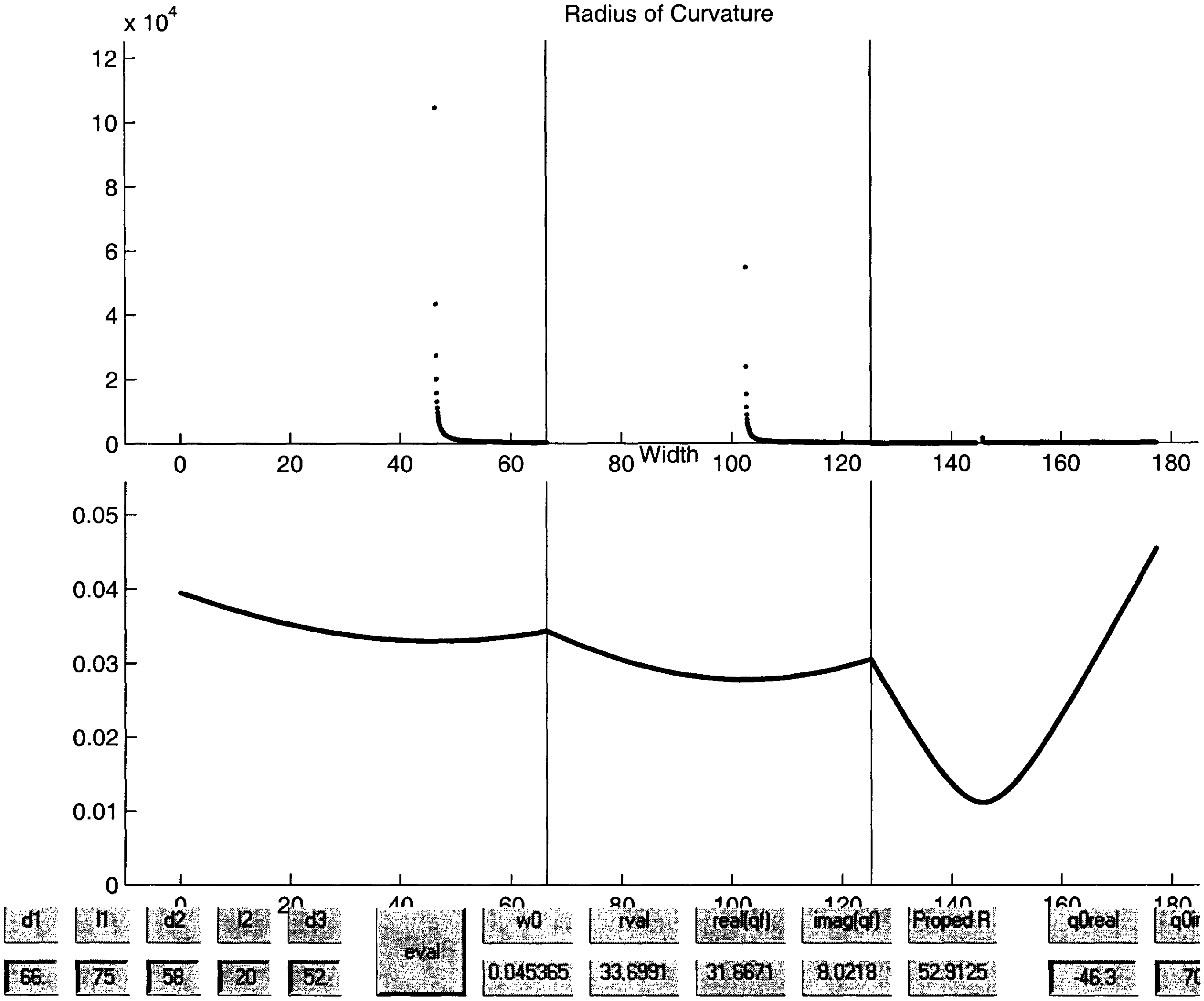

Figure 5-4: A plot of the radius of curvature and beam width for a set of d1, d2, d3, l1, and l2. This is a Matlab gui I created to visually inspect possible solutions.

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