

LETTER OF TRANSMITTAL

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April 2nd, 2007

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Dear Dr. Young and Dr. Nakane:

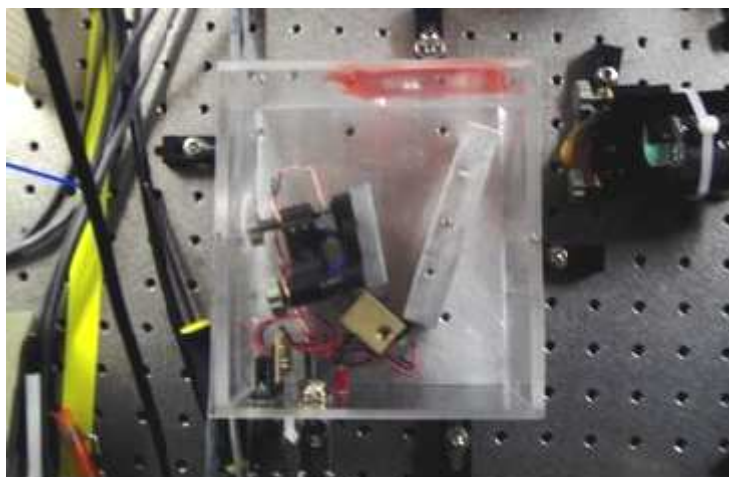
We are writing to you with the project report titled Frequency Locking System for Grating-Stabilized Diode Lasers enclosed. The purpose of writing this report is to analyze the project in detail in terms of designing, construction, and testing as part of the APSC 459 Project Report. This project officially started on January 7th and was completed on April 1st, 2007 in the UBC Quantum Degenerate Gas Laboratory. The sponsors for this project are Dr. David Jones, and Dr. Kirk Madison. A few other personnel including research associate Dr. Bruce Klappauf and graduate student Jannelle Van Dongen assisted in the completion of this project. The report focuses on the design and construction of the grating-stabilized diode laser and includes details on testing the complete frequency locking system. The visual results under the results discussion section display a very intuitive explanation of the how each debugging and testing method was formed. This is submitted as a final copy of the report. Please let us know if you have any concerns.

Sincerely,

Eric Bakke, Peter Chen, and Pavle Djuricanin

APSC 459 Students, Project 0717

Encl. Project Report



FREQUENCY LOCKING SYSTEM FOR GRATING-STABILIZED DIODE LASERS REPORT

Eric Bakke
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Project Sponsors:
Dr. David Jones
Dr. Kirk Madison

Applied Science 459
Engineering Physics
The University of British Columbia
April 2nd, 2007

Project Number 0717

Executive Summary

The aim of this project is to design a system to lock the frequency of a Grating-Stabilized Diode Laser (GSDL) to a master laser at a constant frequency difference. The significance of such a device is applied in laser cooling and manipulating of ultra-cold atoms at the quantum level. Laser cooling requires multiple lasers at specific frequency differences apart from an atomic transition of the gas being cooled. Locking laser frequency directly from absorption peaks of Rubidium is complicated and costly. The purpose of this project is to design an alternative method of locking the frequency of a GSDL by means of comparing its output frequency to that of an existing locked laser. Thus using the results of this experiment one could lock any number of GSDLs to frequencies ranging from the exact frequency of the reference laser to 2 GHz offset on either side for fractions of the cost of using current methods. Larger offsets are presumed possible with faster responding photo-diodes as this is the limiting component in our project.

Our group has built an enclosed, portable, slave GSDL for frequency locking with a known external cavity diode laser setup; the Littman configuration. This configuration sends the 1st order beam from a diffraction grating back into the laser as a source of feedback and frequency tuning. Light from a Master Laser, which is locked to an atomic transition of Rubidium, will interfere with light from the Slave GSDL to create a beatnote with a frequency proportional to the frequency difference between the two lasers. This beat-note frequency is compared with a stable reference signal to generate an error signal. The error signal output is fed to a PI Servo that changes the piezoelectric driver input. This piezoelectric driver input changes the angle of mirror in the external cavity of the slave GSDL, changing the output frequency of the slave GSDL, so that the frequency difference between the two lasers stays constant. The production and design of the sensor, digital comparator and PI Servo are not part of this project and are designed by other personnel in the optics laboratory.

The key testing methods are to monitor the absorption spectrum of Rubidium and the beat-note signal using a spectral analyzer and analog oscilloscope. Monitoring the Rubidium absorption spectrum provides an intuitive visual output of mode-hop free regions. The laser we have built is able to lock on to the master laser frequency for several minutes at a time however the slave laser did not maintain the lock for the a prolonged amount of time as initially desired.

This project is sponsored by professors Dr. Jones and Dr. Madison of the optics laboratory at the University of British Columbia. And all experiments were performed in the Quantum Degenerate Gases Laboratory.

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Table 1: Electronic Equipment Listing

Table 2: Tabletop Optical Components

Table 3: Developed Components

LIST OF ABBREVIATIONS

AOM

Acousto-Optic Modulator

ECDL	External Cavity Diode Laser
FLS	Frequency Locking System
FVC	Frequency to Voltage Converter
GSDL	Grating Stabilized Diode Laser
PTZ	Piezoelectric Transducers
QDG	Quantum Degenerate Gasses

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1.0 INTRODUCTION

Laser cooling is a recently developed technique used to slow down atoms and subsequently cool down their temperature. This technique can be exploited to study and analyze the atom at a quantum level by manipulating ultra-cold atoms.

Laser cooling of atoms, however, has proven to be a difficult task as it requires multiple frequency-variable lasers locked at very specific frequencies relative to one another. It is not sufficient to simply tune two lasers to the appropriate wavelengths as the lasers will not maintain that output frequency. Lasers have a tendency to drift, or in more precise terms, slowly shift their outputted wavelength. The current frequency locking system employed in the Quantum Degenerate Gas (QDG) Laboratory requires expensive components and a complicated assembly procedure. Converting such a system to enable locking through electronic means rather than optical would be both cost efficient, and more flexible than the current system. The main component of such a system requires the use of an External Cavity Diode Laser (ECDL). Single mode laser diodes commercially introduced in the last decade are acceptable in performing high-resolution spectroscopy on atoms and molecules. However the tunability of these diodes is not sufficient for applications in laser cooling where the diode laser needs to lase at 780 nm. [3] The performance of the frequency tuning on these diode lasers can, however, be improved by introducing an external cavity that provides optical feedback to generate sensitive tuning.

The Frequency Locking System (FLS) uses the superposition of optical signals from the ECDL and a master laser to generate a beat-note with a frequency equal to the difference of the respective frequencies of the lasers. With this beat-note divided down to a suitable frequency, it is compared with a synthesized signal to produce an error that is used to lock the slave laser at a constant frequency difference from the master laser.

The project is aimed to design and construct an ECDL that tunes its own frequency according to a frequency from another laser using a diffraction grating; a Frequency Locking System for Grating Stabilized Diode Lasers. The approach in designing this frequency-tunable laser is by constructing an external cavity consisting of a diffraction grating and an angularly adjustable mirror to send the diffracted 1st order beam back into the laser for feedback.

1.1 Background

Although the focus of this report and project is centered on the design and construction of a GSDL and FLS, background on laser cooling is important to recognize the significance of the FLS and its purpose. This section briefly explains what laser cooling is and how it works as well as the existing technique employed to lock a frequency of a laser in the QDG Laboratory at the University of British Columbia.

1.1.1 Laser Cooling

D. J. Wineland first demonstrated laser cooling in 1978. It is essentially a method that utilizes lasers to freeze atoms in a contained space. The basic concept of laser cooling is to transfer energy and momentum from the photon to the atom in order to slow it down. The temperature of a collection of gas molecules is related to their kinetic energy (i.e. their average velocity). By slowing down the atoms in a localized region, it is possible to rapidly cool down the temperature of the gas to a fraction of a millikelvin. The following diagram will aid in the discussion.



Figure 1: One-dimensional simplified schematic of photon-matter interaction.

To simplify the discussion of laser cooling, only the one-dimensional case will be focused upon. When a photon, propagating at a resonant frequency, strikes an atom, it is absorbed and an electron within the atom makes a transition to a higher state given by the equation:

$$E_1 - E_0 = h\nu_0$$

The atom then spontaneously emits this energy in a random direction.

However, if the atom is moving in the opposite direction of incoming light, it will see a higher frequency due to the Doppler shift effect. Therefore, by adjusting the frequency (ν_0) of the incoming photon slightly below resonance, the moving atom will see a resonant

frequency photon. The atom will absorb this photon, again causing a transition jump of the electron and then later a spontaneous emission. Looking closely at the energy components, the energy of the absorbed photon is:

$$E_p = h\nu_p$$

The energy released by the atom upon spontaneous emission is given by (1). Since the resonant frequency ω_0 is larger than the photon frequency ω_p , the atom will lose more energy than it receives, causing it to slow down.

When the atom travels in the opposite direction, it sees the photon frequency below ω_p and is therefore unaffected by its presence. In order to stop an atom traveling to the right, a light source is set up to the right of the atom with the incoming light pointed to the left. Thus the use of the two lasers aimed in opposite directions will slow down the atom almost to a complete stop.

Expanding the design to a three dimensional environment requires three coupled lasers in the three respective coordinates of space. The atoms cannot be completely stopped since there is recoil when they spontaneously emit a photon in a random direction.

1.1.2 Current Rubidium Gas Transition Locking System

Current FLSs are very similar to the one shown in Figure 2. The light output from the laser is split into two parts, one part is used as the output light and the other is used to perform the locking. The laser output that is used to perform the locking of the frequency to a particular atomic transition is back reflected from the Rubidium cell. This light is then sent into the photodiode in order to convert the optical signal into an electronic one that can be used by the Lock Box. The lock-in mechanism is usually a PID controller which adjusts certain actuators on the laser (usually current and piezo) to lock the lasers frequency. With the laser locked to a specific Rubidium transition, the output light frequency is shifted by an Acousto-Optic Modulator (AOM) to the Doppler shift frequency. This is the light used to accomplish laser cooling. The drawback of this system is that AOMs only have a limited range in which they can shift the output frequency. This poses an overall limit on the frequency range that a laser's output light can be locked.

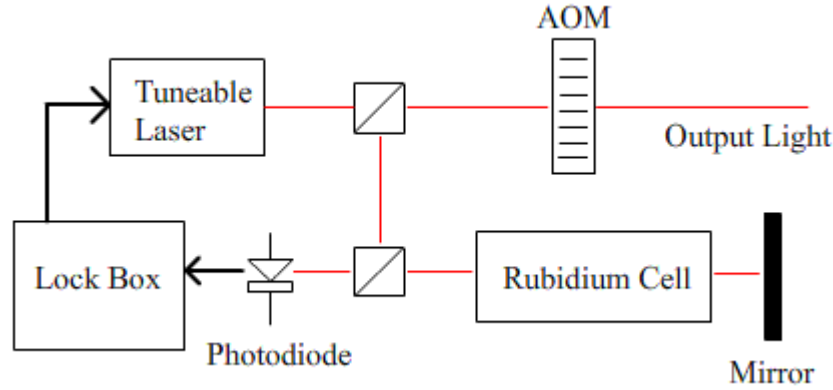


Figure 2: A similar setup to the current use of Rubidium vapor atomic transition frequency to stabilize diode laser frequency [2]

With the development of high-speed photodiode detectors that have a capability of detecting signals up to 10 GHz, a more flexible FLS than the one currently used could be constructed. This new FLS would also have the capability of locking to frequencies much further apart from atomic transitions. The description of this FLS works, along with topography is provided in the next section.

1.1.3 The Frequency Locking System

From Figure 3, the master laser is locked to a certain Rubidium atomic transition and outputs light, at a constant frequency, onto a beam splitter. The slave laser also directs a beam towards the beam splitter by the use of a mirror. The two signals interfere at the photo-detector resulting in a beat-note with a frequency proportional to the frequency difference between the two lasers. The detector used in the system can detect frequencies up to 2 GHz.

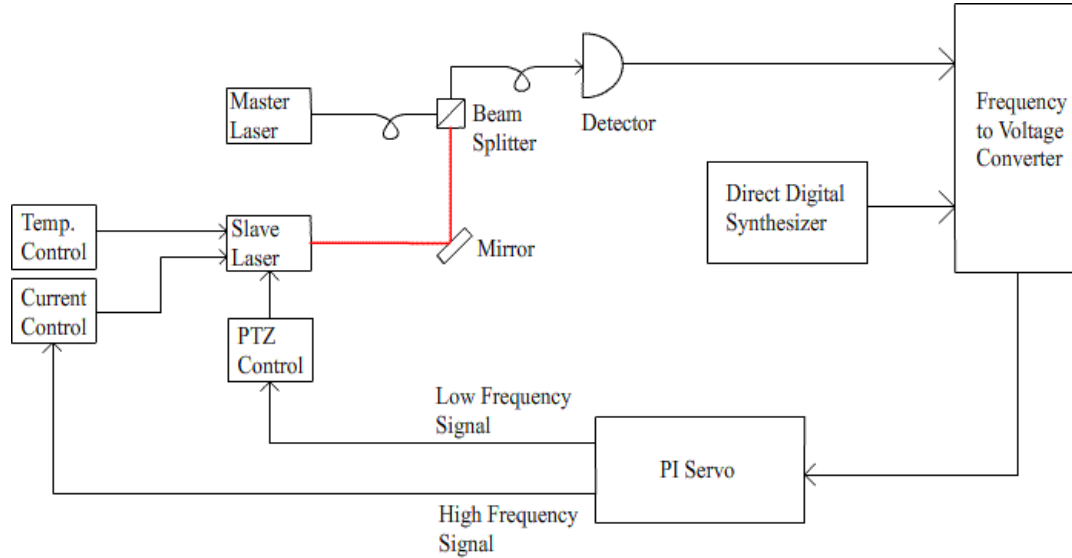


Figure 3: Schematic Diagram of the Overall Project

The signal from the photo-detector is compared to a reference signal generated by a Direct Digital Synthesizer (DDS) in the Frequency to Voltage Converter (FVC). The FVC has a frequency limit of 150 MHz and it generates an error signal that is proportional to the phase of the frequency difference of the two input signals. The output of the FVC is sent to the PI Servo. The PI servo has 3 adjustable gains, one corresponding the high frequency control signal which is fed to the current controller. The other two gains are the proportional and integral, and they control the piezo driver. This thereby provides the feedback portion of the control system. Now that the actuation signals for the current and piezo are carried into their respective controllers, the current and piezo will shift accordingly in order to keep the beat-note frequency constant, and thereby lock the slave laser.

The main advantage of this FLS is that once a master has been locked to a Rubidium transition, the slave laser can be locked to any frequency within the limits of producing a beat-note which can be detected by the photodiode. Thus using an avalanche photo-detector with an upper limit of 10 GHz and appropriate frequency division to meet the standards to the FVC frequency limit, the slave laser can lock to anywhere within the 10 GHz supported by the detector.

1.2 Project Objective

1. Design modification of GSLD

The current design utilized by Dr. Jones and Dr. Madison are intended for more rugged, all around purposes and as such contain extra components that complicate and interfere with the purposes of this project. A simpler more dependable design is required that satisfies the purposes of only this project.

To address this we intended to submit a final design for approval by Dr. Madison and Dr. Jones by January 20, 2007.

2. Construction of GSLD

a. *Laser Temperature Stabilization*

To extend the life and optical strength of the diode laser, the diode must be maintained at a stable, low temperature of approximately 5°C. Using a TEC cooler system, this portion of the design consisted of a thermistor, thermal paste, a TEC cooler and an off the shelf electronic control unit (TEC 2000 2A / 12 W).

b. *Controlled Angle of Diffraction Grating*

In order to change the frequency of the laser, the angle of the back reflecting mirror must be finely tunable. To accomplish this the angle of the mirror is controlled electronically via a piezo electronic transducer. The piezo unit is placed behind one end of the mirror and a steel pivot is placed behind the other end. This allows the mirror angle to be adequately controlled on the magnitude of 1/1000 of a degree.

The controlling of the PTZ is done by the circuitry provided by the electronics shop. The voltage levels applied by the PTZ driver vary between 0V and +150V.

c. *Operational Laser Diode*

The laser diode did not require to be redesigned but was rather incorporated into the GSLD design. Dr. Jones and Dr. Madison delivered the required diode for the GSLD.

We had intended to have a completed GSLD ready for testing by February 16, 2007.

3. Creation of Beatnote and Combination of System Components

The outputs of the master and slave lasers are superimposed to produce a beat-note. This beat-note is then delivered to a high-speed photo-diode. The output of this photo-diode is then passed on to the error producing Frequency-to-Voltage converter. The Frequency-to-Voltage converter reads in the frequency of the beatnote, compares it to a reference frequency and then outputs an error that is connected to a PI locking electronics system. The output of the PI locking system is then amplified and used to control the piezo and laser current.

4. Operational Frequency Locking System

Once the beat-note is produced and an error signal obtained, the final and main objective of this project is to obtain a stable null error by utilizing the fast and slow outputs of the PI lock box to control the frequency of the GSLD. Proper values for the overall gain, proportional gain, integral gain and fast and slow attenuation are experimentally determined to maximize the stability of the GSDLs frequency.

1.3 Scope and Limitations

The scope of this report is encompassed in the analysis of the design specifications of the Frequency Locking System as well as the results of testing procedures used during the design and construction of the ECDL. Also, details from the testing of the FLS are identified in this document. Specifications regarding the design and schematics of external electronics including photo-detector, frequency dividers, digital comparators, and the PI servo control, however, will be briefed but not closely examined as the core focus of the project lies in the design and construction of the grating stabilized diode laser. The omission of such details should not produce a large impact on this report, as the electronics provided had no major changes and issues with the progress of the project.

1.4 Organization

This report is composed of sections describing the theory of frequency locking to illustrate the different approaches in designing a frequency tunable laser; Littman and Littrow configurations. The discussion section will also include an analysis of the initial design, final design, temporary tabletop setup, and changes made to the designs. A general overview of the complete negative feedback system of the FLS is addressed in the discussion section. Finally, visual results and graphical data are analyzed in the results section as well as an evaluation of the frequency locking results.

2.0 DISCUSSION

This section of the report is separated into theory, method, design, data, results, and laser locking. Before the design of the grating stabilized diode laser, different setups of external cavity feedback systems were analyzed; particularly the Littman and the Littrow ECDL setups. These are the focused components of the complete laser frequency locking system that is developed within this project. Different analysis and testing procedures were used during the design of the ECDL and these are closely examined to present the rationale on the formation of the initial design as well as modifications before and after the construction of the ECDL. These procedures included a set of data to understand the relationship between injection signal strength with respect to mirror placement and beam position. Visual and graphical data results are illustrated under the results section and studied including the Rubidium absorption spectrum, Rubidium absorption spectrum by beat-note resonance, and the beat-notes signal. Finally the results from the finalized GSDL is presented and evaluated along with the stability in the laser locking capability of the complete system.

2.1 Theory

Prior to the commencement of the project, two setups of the GSDL were considered and discussed in meetings with the project sponsors. These two different setups of GSDL are the Littrow and Littman configurations. Both of these setups involve an external cavity diffraction grating that splits the diode laser output into several orders. The 0th order beam is used as the output, while the 1st order beam is reflected back into the diode as a source of feedback. The differences between the two configurations are presented in section 2.2.2.

An ECDL with a mode-hop free region of 100 GHz is possible in the industrial development environment [3]. However, engineering an ECDL with mode-hop free tuning over 2+ GHz is a challenge in mechanical precision and accuracy within an undergraduate environment. The secondary goal in this project was to obtain a large enough mode-hop free bandwidth to cover a span of 8 GHz from the master laser. This, ideally, is approximately the width of the Rubidium Absorption Spectrum of the Rubidium-85 and Rubidium-87 isotope gases.

2.1.1 Rubidium Electron Transition

Since much of the laser cooling applied at the QDG laboratory consists of cooling Rubidium, the spectral features of Rubidium need to be discussed. Below is a figure showing the 4 Doppler-broadened absorption dips of Rubidium. As can be seen from the figure, these 4 dips cover a frequency bandwidth of approximately 8 GHz, centered at 780.24 nm (384.6 THz). In order to analyze the mode-hop free region (section 2.2.4) of the GSDL, this spectrum is compared to that of the GSDL in order to determine the largest possible mode-hop free scan of the laser.

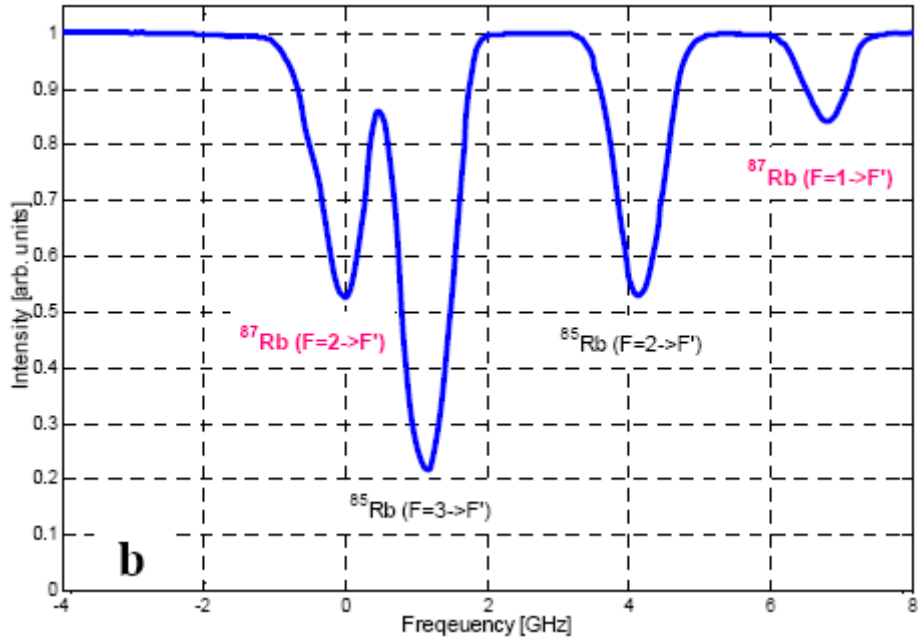


Figure 4: Rubidium absorption spectrum displaying the four absorption peaks (or minimums) over a range of frequency. [9]

2.1.2 Grating Stabilized Diode Laser

The main requirement of this project consists of the design of an ECDL capable of tuning its frequency without mode-hops. This fine-tuning is established by designing a laser with an external cavity, diffraction grating and a mirror. The diffraction grating is used to reflect light onto a mirror, and back into the laser diode. By adjusting the length of the cavity or the angle of either the mirror or grating (depending on the configuration used), the laser can select the frequency that it will amplify. There are several existing designs for GSLDs. The two most common designs are referred to as the Littrow and the Littman configurations.

2.1.2.1 Littrow Configuration

The Littrow design, as shown in Figure 5, uses the 1th order diffraction beam to select the frequency of amplification, whereas the 0th order beam is used as the output of the laser. This design however changes the angle of the output beam and therefore the coupling optics must also physically move in sync with the GSDL components in order to properly couple the outgoing light into a fiber.

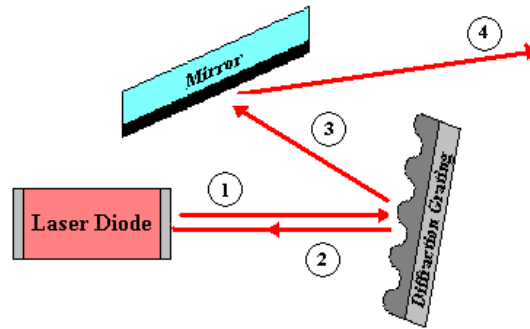


Figure 5: The Littrow Configuration: 1) Laser Diode Output 2) Amplification Beam 3) Diffraction Beam 4) GSDL Output

2.1.2.2 Littman Configuration

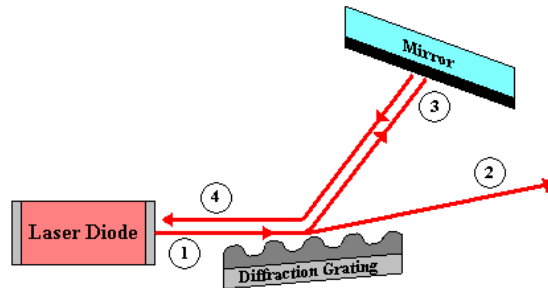


Figure 6: The Littman Configuration: 1) Laser Diode Output 2) 0th Order Diffraction Beam 3) 1st Order Diffraction Beam 4) Diffracted Amplification Beam

The Littman configuration, as shown above in Figure 6, is able to select a particular frequency by adjusting the angle of the mirror. This is done by the use of a Piezoelectric Transducer (PTZ). The 1st order diffraction beam bounces off the mirror and back into the diode laser. This is how the lasing frequency is selected. The 0th order diffraction beam is used as the output. The Littman configuration is a more desirable design as the GSDL output is always at a constant angle and is therefore easier to couple into a fiber.

2.1.3 The Negative Feedback Control System

The complete Frequency Locking setup can be simplified into a compartmentalized negative feedback control system as illustrated by a block diagram in figure below.

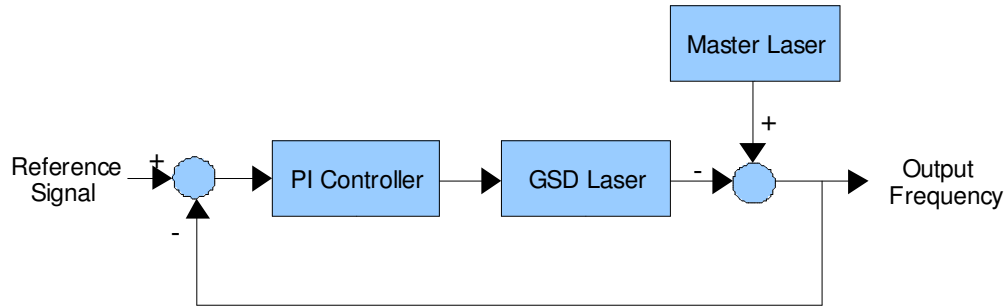


Figure 7: The block diagram of the negative feedback control system representing the complete frequency locking system.

This figure illustrates much of what was previously discussed in section 1.1.3. The error signal generated by the beatnote is compared to a stable reference and fed through to a PI Controller which controls the slave GSDL. When the slave laser frequency is tuned fairly close to the master frequency (from MHz down to the kHz range), the error signal is switched from frequency locking to phase locking between the master and slave laser. This is done in order to lock the phases of the two lasers as well as their frequencies.

Figure 7 also presents a future possibility in improving the performance of the control system. Mathematically modeling the slave GSDL by a transfer function relating the output wavelength to the current and piezo voltage inputs would be beneficial to simulating this system. With the proper GSDL model, the gain values of the PI Controller could be determined, or even a new PI controller could be designed which would carry out the laser locking in a more efficient manner.

2.2 Methods and Testing Protocols

Several optical components were used during the design, construction, and testing of the laser. Most of the electrical equipments and optical components were provided without the need for purchase by the QDG group. The electronics and optical devices used as well as their models and specifications are listed below. Most of these optical components are not part of the final design of the laser but are used in testing procedures to help debug and determine issues with slave laser stability.

2.2.1 Experiment Equipments and Parts

The following tables list the set of electronic equipment used during the duration of this project. Only the PTZ needed to be replaced, due to the fact that the original would no longer perform its full elongation requirements.

Electronic Equipments

Table 1: Electronic Equipment Listing

Equipment	Model
Current Controller	Thorlabs LDC 500 500 mA
Temperature Controller	Thorlabs TEC 2000 2A/12W
Power Meter	Newport: Power/Energy meter — Model 1825C
Infrared Viewer	N/A
Frequency Lock Box	UBC-Physics & Astronomy E04-010
Oscilloscope	Tektronix TDS 2004
Spectral Analyzer	Tektronix RSA 3303 A Real-time Spec Analyzer DC-3 GHz
Power Supply	BK Precision DC Regulated Power Supply 1627A
Power Supply	Lambda Dual Regulated Power Supply LPD 422 FM
Piezoelectric Transducer	Dual Low Voltage PTZ Driver YJ048-Q7

Tabletop Components

Table 2: Tabletop Optical Components

Component	Price	Units
Mirror Mount	NPR	10+
Isolator	NPR	1

Laser Diode	NPR	1
Diode Clamp	NPR	1
Piezoelectric Transducer #1	NPR	1
Piezoelectric Transducer #2		2

NPR = No Purchase Required (Part of equipments available in QDG Lab)

Developed Equipments

Table 3: Developed Components

Component	Price	Units
Grating Holder	NPR	1
Grating Mount	NPR	1
Mirror Mount Stand	NPR	1
Base and Plates	NPR	1

NP = No Purchase Required (Part of equipments available in QDG Lab)

2.2.2 Experimental Internal Setup of the Laser

The initial laser diode housing used for testing the Littman configuration was based on a slave laser design commonly used by the QDG group. In this design only the laser diode is enclosed in a box, along with its protection circuitry. This enclosure isolates the diode laser from external temperature changes. The design is as shown below.

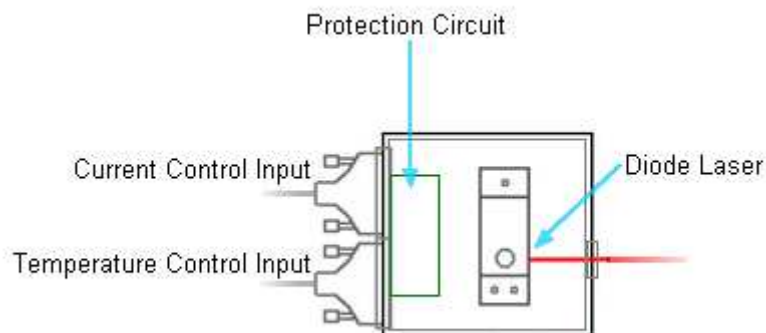


Figure 8: Simple internal schematics of the enclosed diode laser used initially to do testing with bandwidth optimization.

This laser diode source was later replaced by an open clamped base without the front sides and a loose back input port. Even though the diode was susceptible to environmental temperature changes the plates had to be removed in order to move the mirror mount as close as possible to the diode laser. This was necessary since minimizing the external cavity spacing improves the laser's stability.

2.2.3 Experimental Setup of the External Cavity

In order to design a portable enclosed laser box, angles needed to be determined to achieve the largest mode-hop free range. Initially a few angles, α , between 0 and 45 degrees (between grating and the 0th order beam in figure below) were selected. It was found that increasing the angle of the diffraction grating increased the amount of feedback to the laser diode. This resulted in a drop in the threshold current of the laser diode. Approximately 40 degrees was the maximum attainable angle at which the laser could still be tuned. In fact, an attempt to make the diffraction grating angle higher than the Littrow angle was carried out, however this only un-stabilized the laser frequency providing no tuning of the output frequency. The experimental ECDL is shown below.

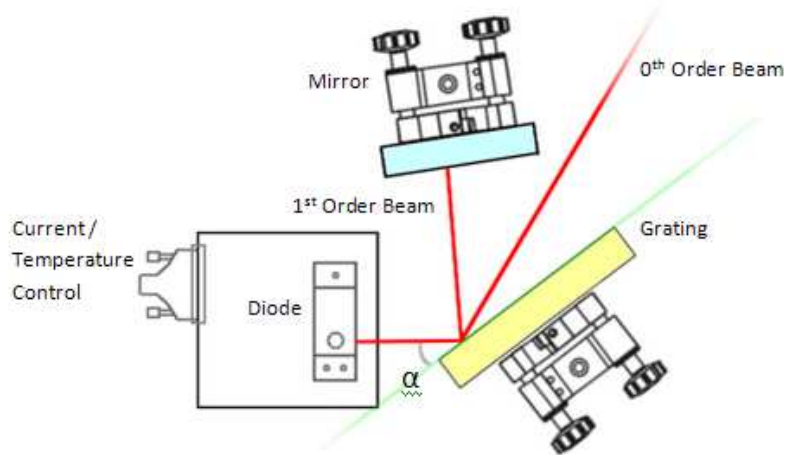


Figure 9: The laser setup with the experimental setup of the external cavity. The external cavity is the path between the laser diode to the diffraction grating to the mirror providing the feedback.

Both the diffraction grating and mirror were placed on mirror mounts to allow for precise control of the light beams. Once feedback was achieved, the output frequency of the optical signal could be shifted by an adjustment of the horizontal angle of the mirror. In order to analyze the spectral features of the ECDL, the output light was coupled into a fiber used by the spectroscope. The experimental setup of this stage of testing is shown below.

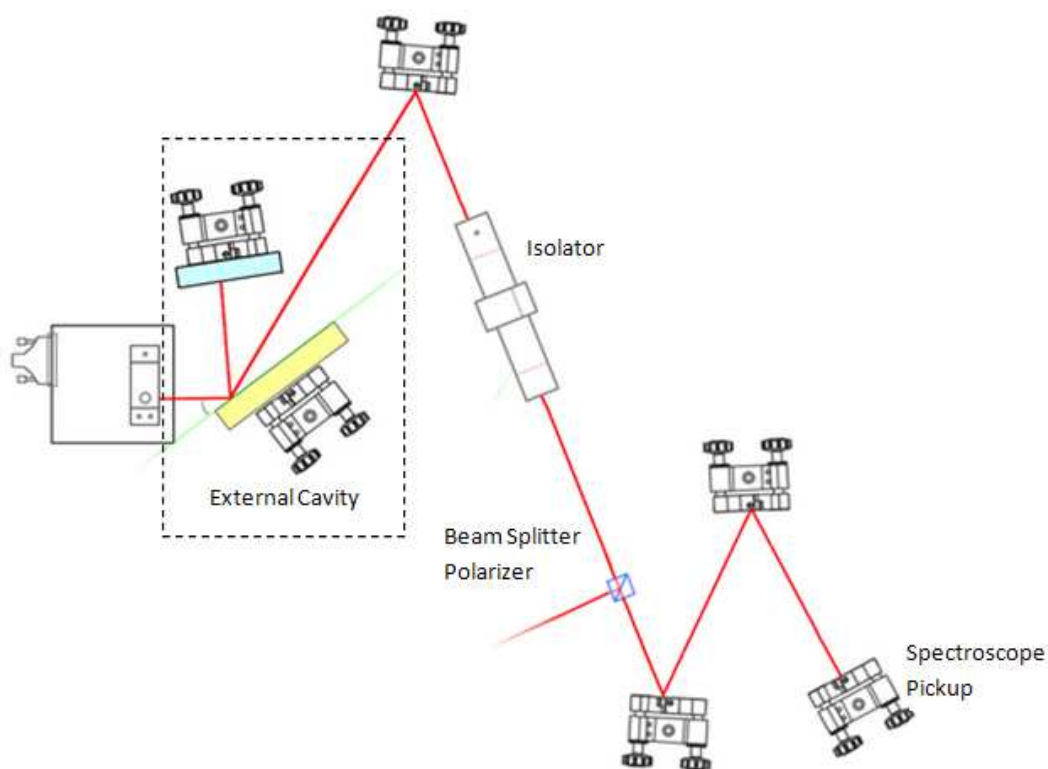


Figure 10: The complete setup of experimental setup with extended path to spectroscopy pickup. The beam splitter between the isolator and the mirrors splits the beam towards Rubidium absorption segment as shown in Figure 11.

An isolator was placed at the output of the laser in order to prevent feedback from back reflection of external optical components. The light was then passed through a beam-splitter. This gave the flexibility of analyzing the spectral features of the light and using the other beam to perform extra operations such as analyzing the mode-hop free tuning range. The light coupled into the Spectroscopy Pickup was carried out by the adjustment of two mirrors.

Initially coarse wavelength tuning was carried out to establish the tuning range of the laser diode. This was accomplished by turning the horizontal knob on the mirror mount that held the mirror. The following graph presents the relationship between wavelength and position of the angle-controlling knob. Each Knob Turn Number corresponds to turning the horizontal angle knob by 18 degrees.

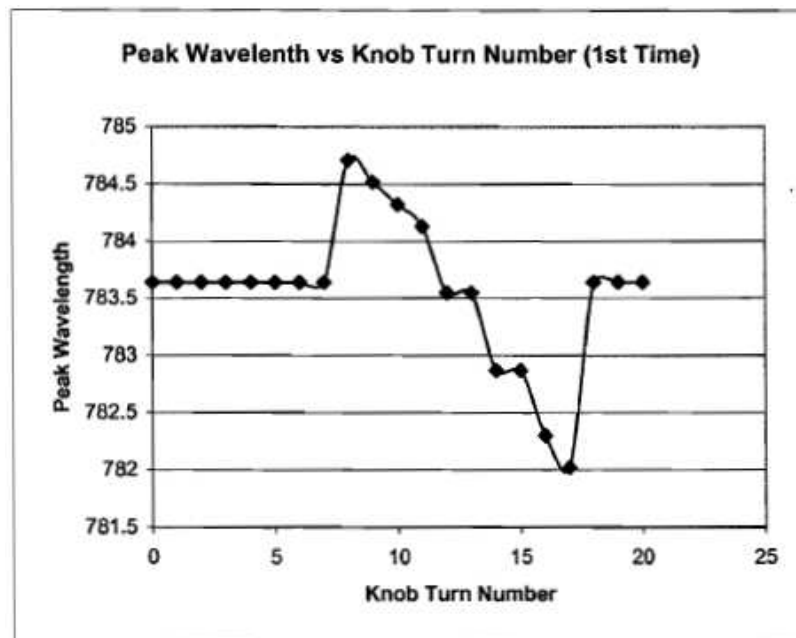


Figure 10 (b): Peak Wavelength vs Knob Turn Number

Although this test was carried out with the diode cooled at room temperature, the output wavelength was controlled over the whole gain spectrum of the laser diode (~ 3.5 nm) with a free lasing wavelength of 783.640 nm. The angle of the diffraction grating (\angle) in this experiment was 30 degrees. Lowering this angle corresponded to decreasing the coarse tuning range of the diode. When placing the grating at 15 degrees, a tenability range of only 0.5 nm was observed. This is primarily due to the decreasing intensity of the feedback as the diffraction grating is moved to smaller angles.

2.2.4 Bandwidth Optimization

The experimental setup in determining the bandwidth using the spectrometer was not sufficient to verify whether the laser frequency was anywhere close to the desired master laser frequency of 780.24 nm. Since the resolution of the spectrometer was relatively low, it is not suitable to detect mode-hops. In order to see if the laser was operating without mode hopping, a ramping voltage was placed on the PTZ in order to change the wavelength of the laser. Part of the laser output was double passed through a Rubidium gas cell and then received by a photo-detector as shown in the figure below.

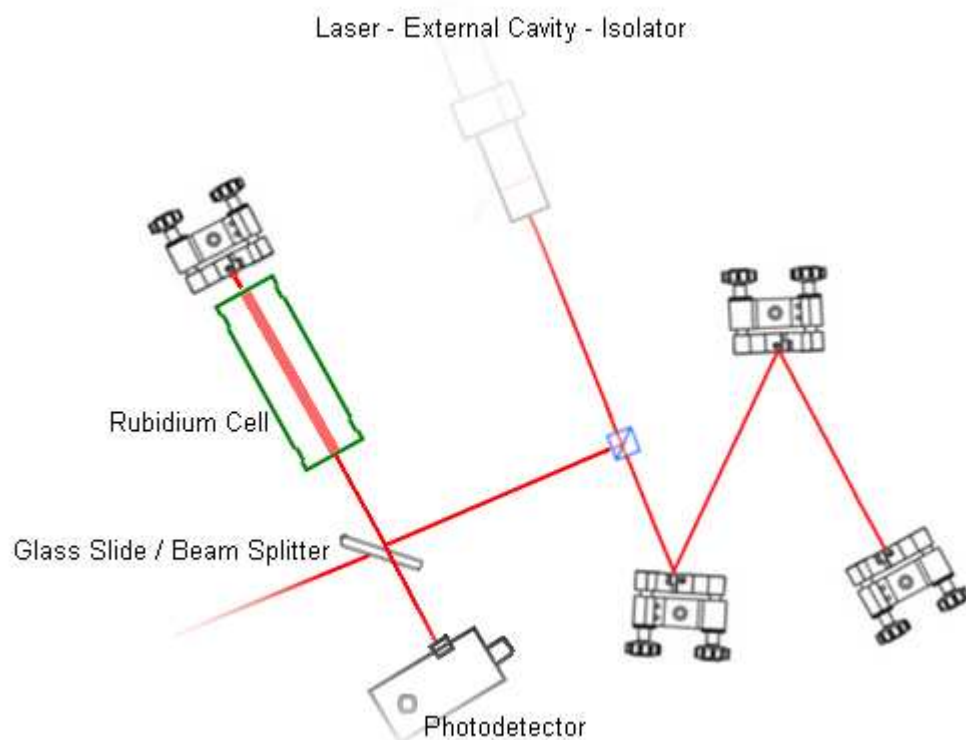


Figure 11: The setup after the beam splitter that is sent through a glass slide to separate the beam to Rubidium cell and feedback to a photo-detector (or power meter).

A quick method to determine whether the laser was near the desired 780.24 nm wavelength consisted of monitoring the Rubidium cell with an infrared viewer. When the resonance frequency is reached, the Rubidium cell should produce florescence and glow under the infrared viewer as shown in the figure below.

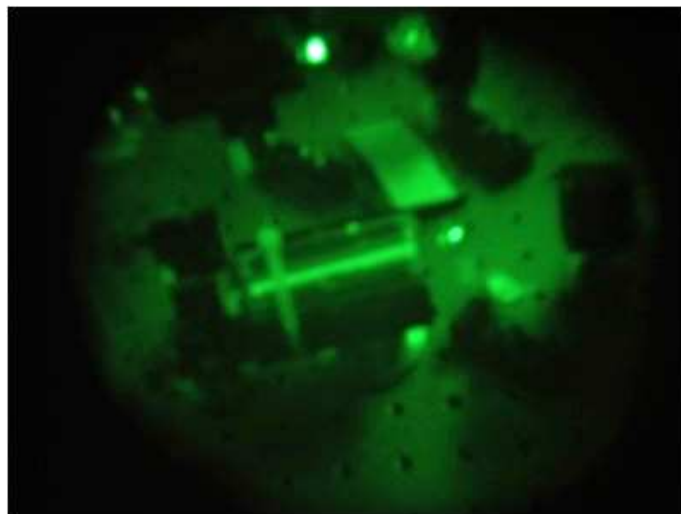


Figure 12: A photo displaying the florescence of Rubidium as seen through the infrared viewer to determine whether the resonance frequency is obtained.

The beam input into the photo-detector varies as the frequency is oscillated since at certain frequencies, the Rubidium cell electrons undergo photon energy absorption, and emission simultaneously. The output of the photo-diode then provides a graph of Intensity vs. Frequency (Figure 13 below), which can be compared to the accepted graph of Figure 4. Mode-hops are generally easy to spot, as the curve becomes discontinuous, or repeats the same pattern. The graphical data in Figure 13 does not seem to display any apparent mode hopping. However, given Figure 4, it is possible to identify the drop at approximately 4000 ns as a mode-hop since no absorption peaks should occur adjacent to the Rubidium-87 peak in Figure 13. The saturation peak at 6000 ns displays the electron excitations of different quantum states.

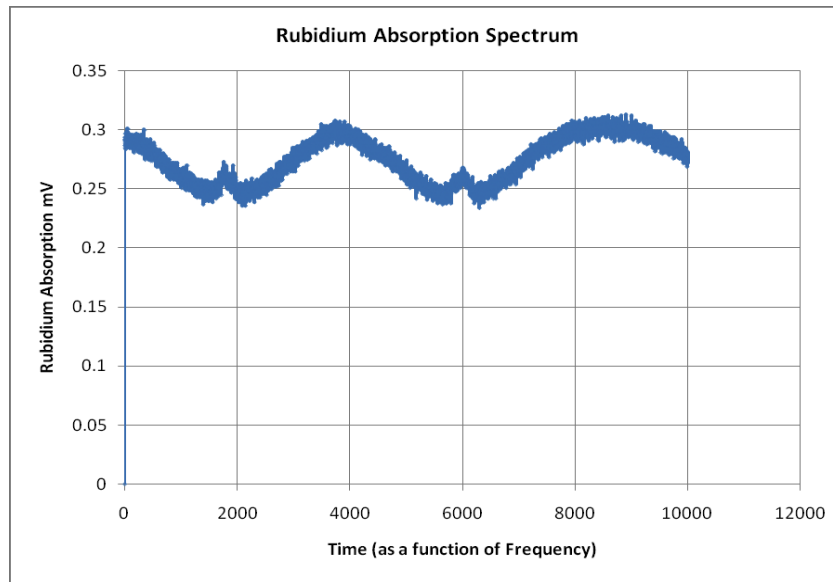


Figure 13: The above is an example of several absorption scan data obtained from the Tektronix oscilloscope. The plot displays the Rubidium-87 re-pump peak needed for frequency lock testing.

Finally, maximum bandwidth needed to be achieved and hence the 1st order beam would have to be tested along different positions of the back-reflecting mirror. When the mirror changes angles to inject different frequencies of light into the diode, the external cavity length also changes thereby altering the frequencies of the modes in the external cavity.

Mode-hops occur when the frequency corresponding to the original number (m) of wavelengths in the external cavity no longer corresponds to the mode frequency with the most amount of injected light. So the $m+1$ (or $m-1$) mode now corresponds to a frequency that has more back reflected light being injected into the diode and the laser mode-hops and begins to lase at the new frequency. This causes a discontinuation in the frequency sweep. To correct for this phenomenon it was believed that there should be a point on the mirror where the change in length of the piezo caused the external modes of the laser to change frequency by the same amount as the center of the injected light.

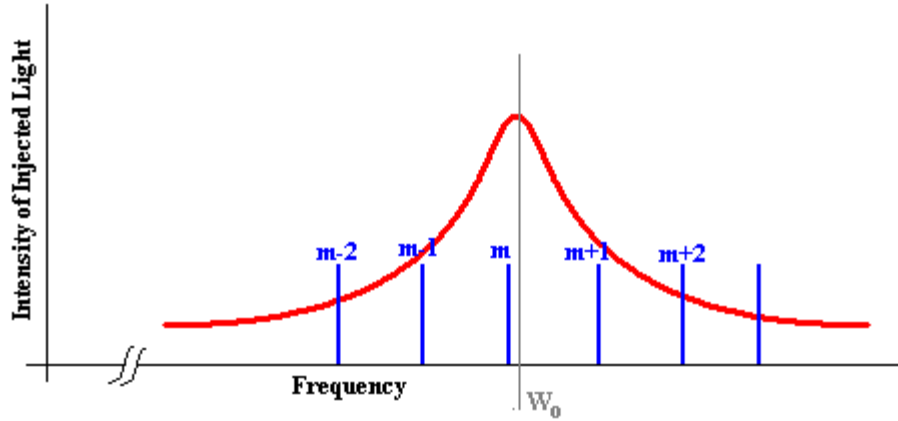


Figure 14: The red line illustrates the bandwidth of the light be injected into the diode by the back reflection mirror. The blue delta functions indicate frequencies that satisfy the boundary conditions imposed by the external cavity of the GSLD.

Finding this position on the mirror was accomplished by sliding the mirror mount and stand in a parallel fashion along the direction of the mirror. To accomplish this task, a linear stage was used to hold the mirror mount such that the linear stage allows smooth sliding of mirror to adjust 1st order beam position.

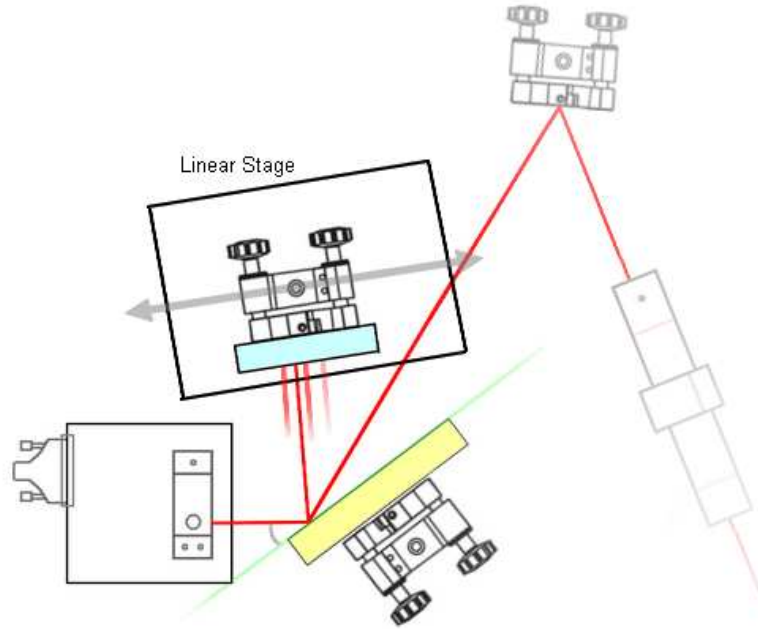


Figure 15: The setup of the mirror mount placed on a linear stage to slide the mirror along the parallel direction of the mirror surface to allow the beam to hit different positions on the mirror.

Different points on the mirror were tested ranging from 8 mm to 22 mm (from the pivot). With each position, data was recorded directly from the oscilloscope to measure the amount of continuous (mod-hop free) bandwidth achieved without feed forward. The

maximized position proved to be ~12 mm from the pivot where a minimum of approximately 3 GHz was observed without any proportional current correction.

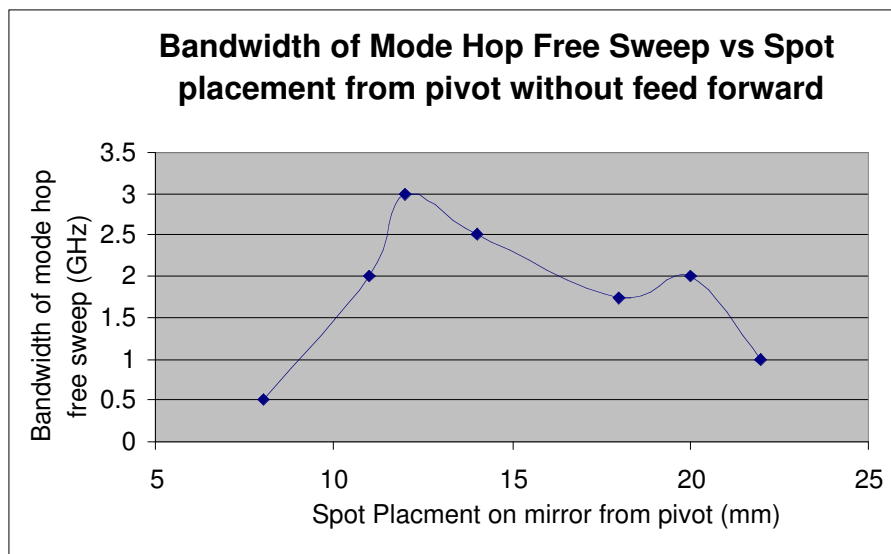


Figure 16: Bandwidth of mod-hop free sweep vs spot placement graphical data.

2.3 Design Proposal

With the experimental setup completed and tested to optimize laser frequency, an initial design of a moveable enclosed laser is proposed with proper schematics. The exact schematics of each component are listed in the Appendix of this document.

2.3.1 Design Criteria and Requirements

Criteria s were given in order to meet a more narrow design and specific proposal. The criteria s are as follows:

1. The laser needs to operate at Rubidium transition energy or laser frequency. This is the 780 nm range.
2. The laser should achieve a mode-hop free region of all 8 GHz. This is a secondary requirement to attempt a sweep large enough to cover Rubidium absorption scans with the Littman configuration. At the very least, the laser should be able to tune its frequency without mode hopping within a range of frequency to cover one of the re-pumps of Rubidium.
3. The enclosed GSDL should be as compact as possible to minimize space on optics lab bench.
4. No component should have to be changed once all components (mirror, grating, and diode clamp) have been bolted down.
5. The GSDL needs to be completely enclosed to prevent temperature change from airflow.

2.3.2 Initial Design Proposal

The initial design consisted of measuring angles and distances of the prototype on the optical table. These distances enabled the drawing of components and their placement on a base plate. The initial proposal of the laser is shown on the left in Figure 17.

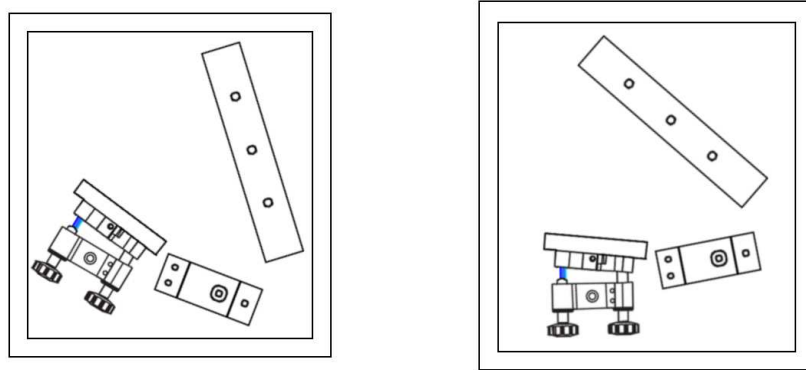


Figure 17: Initial design setup of the grating stabilize diode laser. The left is the original proposal. The right displays changes made to the base orientation in order for the beam to output normal to the left-side plate.

2.3.3 Pre-Construction Changes to Design

The original schematics were given to Bruce Klappauf to review before the GSDL construction. As instructed by Bruce, a few changes had to be made. These changes included:

1. Laser beam preferred to come out normal to the side plates such that it is easier to position and clamp down on the optics table when in use. Therefore the box orientation had to be rotated 40... counterclockwise.
2. Increase grating mount thickness from 0.5 in to 0.75 in. This is to use larger sized screws; an 8-32 threaded screw because the QDG laboratory had more supply of this screw.
3. The bottom of the mirror and grating mount had an indented relief (see Appendix). These reliefs were changed from a rectangular stand to only two sided reliefs to minimize area of contact. This is to prevent uneven surface defects on the base plate from changing the angle of the mirror or grating.

4. The mirror mount screws were changed from 6-32 threaded to 8-32 threaded and the depth of the holes were changed from $\frac{1}{8}$ in to $\frac{1}{4}$ in to improve stability.

The final schematics are attached in Appendix. The resulting design is shown on the right in Figure 17 above.

2.4 Final Design

With the bandwidth optimized, mirror and diode positions determined, a final design was developed. The bandwidth maximization process took place during the construction of the base-plate, side-plates, and mounting components. Once the positions were determined, the final holes to tighten the mirror mount, grating mount and diode clamp was drilled in the end to complete the GSDL.

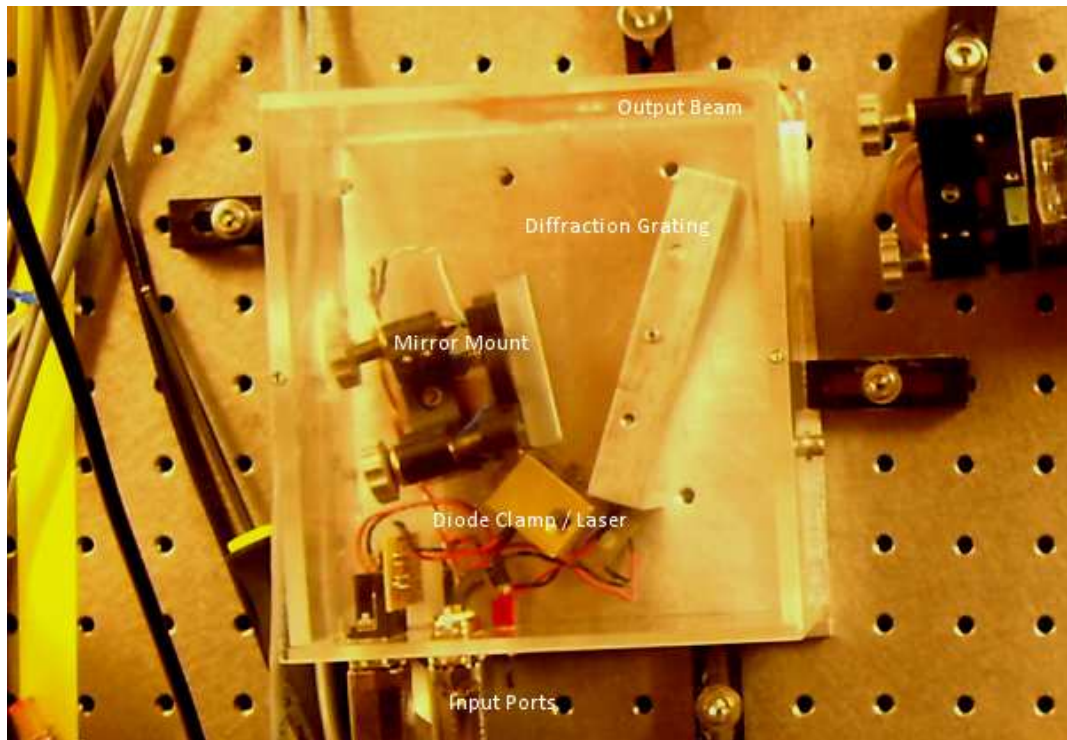


Figure 18: The top view of the final constructed grating stabilized diode laser with labeled components.

2.4.1 Finalized Laser

The complete Littman laser is enclosed into a rectangular box of dimensions 7 x 6.75 x 0.75 (inches). It is composed of an aluminum base with Plexiglas side and top plates. Three components are mounted onto the base of the slave laser: grating mount, mirror mount, and a laser diode clamp as shown in the figure below.

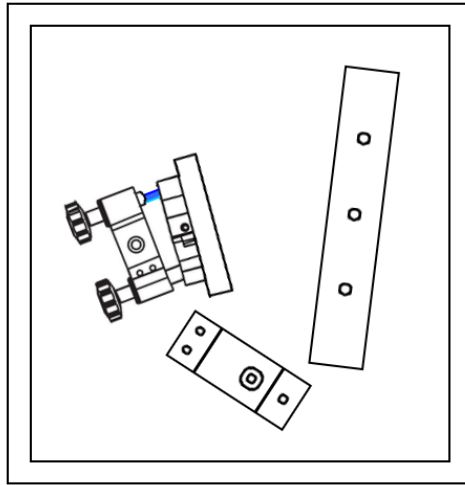


Figure 19: A schematic view of the final design of the grating stabilized diode laser.

The input ports are: laser diode current control, laser temperature control, and a piezoelectric driver source. Again, the finalized component details are listed in the Appendix.

2.4.2 Post-Construction Changes to Design

A few changes were made in order to optimize the laser frequency bandwidth after all components were bolted down onto the base plates. These changes are listed as follows:

1. The base-plate has been rotated such that the short sides of the side-plates are the input (temperature control, current control, piezoelectric driver) and outputs (laser beam).
2. Mirror mount used only one threaded hole instead of both holes (as can be seen from the schematics in the appendix).

3. Mirror mount stand was rotated backwards such that the complete mirror mount on top was pushed back and away from the diffraction grating to increase the cavity length.
4. The side plate behind the mirror mount had to mill an indent to allow spacing for the knobs on the mirror adjustment mount. A mistake was made during machining so a hole was made to clear out the indent and a glass slide was glued on to seal off the box.

2.5 Data

The following is a set of recorded data on optimized frequency settings of the laser for different occasions.

Date mm-dd-yy	Event	Current	T _{set}	T _{act}	Bandwidth
01-22-07	Optimizing with amplifier on the PTZ driver	73.8 mA	19.175 k‰	19.170 k‰	Not Taken
01-23-07	Optimizing with amplifier enclosed for PTZ driver	80.8 mA	18.149 k‰	18.149 k‰	Not Taken
01-23-07	Aligning height of mirror and grating	69.9 mA	11.776 k‰	11.776 k‰	Not Taken
01-26-07	Minimize mode-hopping for lower temperature and current	47 mA	18.387 k‰	18.387 k‰	Not Taken
02-01-07	Initial attempt to optimize Rubidium cell curve	62 mA	18.163 k‰	18.163 k‰	Approx. 3 GHz
02-01-07	Resetting	78 mA	18.168 k‰	18.168 k‰	Not Taken
02-20-07	Adjusted optical component settings	77.2 mA	18.243 k‰	18.239 k‰	Approx. 2 GHz
02-27-07	Optimization based on 1 st order beam position	80.6 mA	18.531 k‰	18.536 k‰	Approx. 2 GHz
02-27-07	Optimization based on 1 st order beam position	76.4 mA	18.237 k‰	18.237 k‰	Approx. 2 GHz
02-28-07	Low Grating Angle	92.7 mA	18.357 k‰	18.355 k‰	Approx 4 GHz
02-28-07	Feed Forward on Laser Current	92.7 mA	18.357 k‰	18.357 k‰	Approx 10 GHz
03-02-07	Optimization with Feed Forward	75 mA	17.688 k‰	17.684 k‰	Approx 6 GHz
03-02-07	38... Diffraction angle	90.9 mA	18.083 k‰	18.082 k‰	Approx 7 GHz
03-26-07	Lost Optimization, tried again	79.6 mA	18.06 k‰	18.06 k‰	Approx 4 GHz
03-26-07	Attempt 2	81.2 mA	18.07 k‰	18.07 k‰	Approx 4.5 GHz

2.6 Results

The finalized GSDL was in the end capable of producing an adequately stable bandwidth of frequencies encompassing the master lasers frequency. The GSDL was stable enough to maintain its mode and allow for smooth alterations of the output frequency by the frequency locking system. The system successfully produced a beat note and was succeeded in temporarily locking the frequency for various amounts of time, the greatest of which was approximately 5 minutes. It was however primarily due to confusion with the locking electronics as to why a longer period of stable locked frequency was not obtained. It is believed by the members of this group as well as Dr. Jones that a semi-permanent frequency lock could be obtained with this system by further exploring and understanding the capabilities of the error producing, frequency to voltage converter.

2.6.1 Discussion of Project Data

The GSDL, when combined with the master laser light, successfully produced a beat-note that was detected by the high-speed photo diode. The frequency of this beat note behaved as expected.

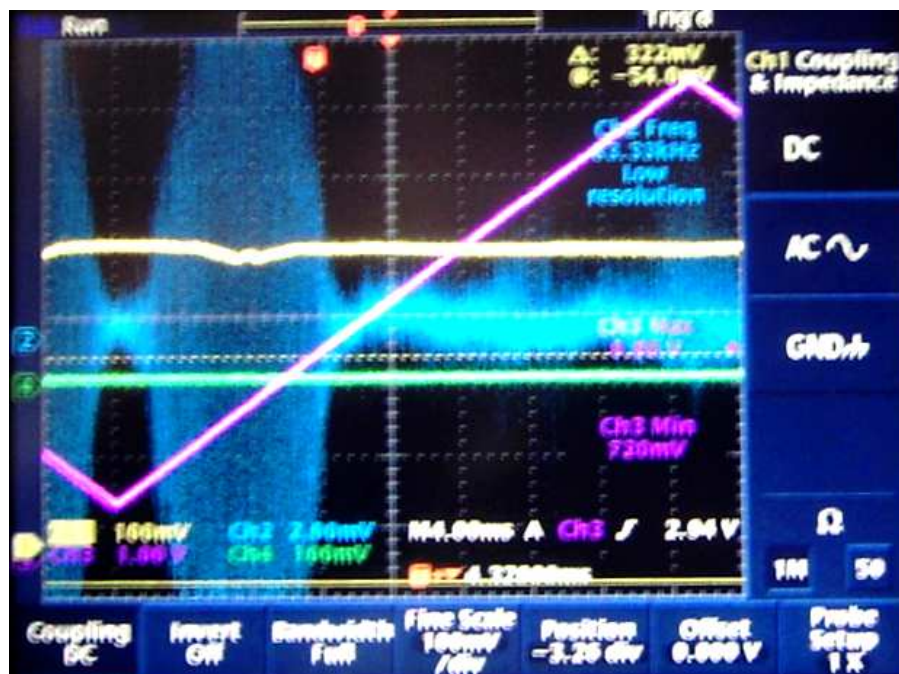


Figure 20: An oscilloscope trace and photo displaying the ramped current of the PTZ (pink) and the resonance beat-note signal (blue) and the Rubidium absorption spectrum of an Rubidium-87 re-pump peak.

In the above graph, the frequency of the GSDL was ramped over a range of several GHz while the master frequency was kept constant. The blue plot is the beat note as detected from the photodiode. The yellow plot is the signal from the power meter that is arranged such to capture the absorption peaks of the Rubidium cell. The pink plot is the ramp voltage being delivered to the piezo, and the green plot is not connected. The master laser is locked to a frequency corresponding to the middle of the absorption peak on the yellow plot.

In the next scope trace below, the beat note is split in two. The blue plot still represents the unaltered beat note. Now however the beat note also goes through a bandpass filter set at 135 MHz with a bandwidth of approximately 10 MHz. The output of the filter is illustrated by the green plot below. It can be observed that the amplitude of the filtered beat note rises dramatically in two distinct spots within the range of the absorption dip (the yellow plot). At both of these points the beat note has a frequency of 135 MHz \pm 5 MHz. Therefore the frequency of the master laser can be observed to be right in between the two green pulses. Thus producing a 135 MHz beat note when the GSDL is 135 MHz higher than the master laser and when the GSDL is 135 MHz less than the master laser. Also this provides a frequency scale on the plot, since the frequency between the the green pulses must be 2×135 MHz.

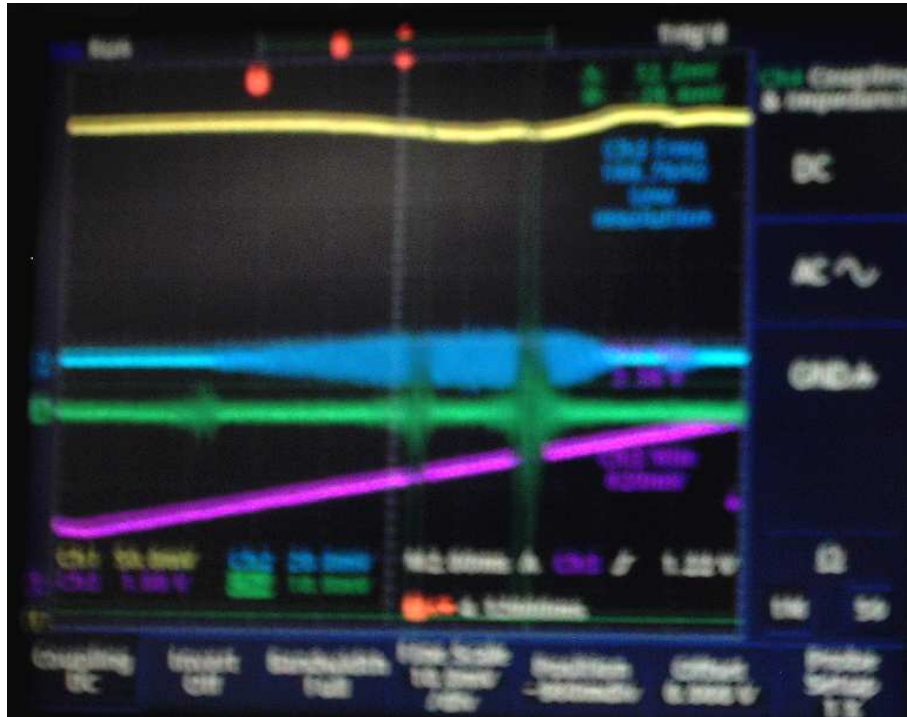


Figure 20: A similar oscilloscope trace and photo displaying the ramped current of the PTZ (pink) and the resonance beat-note signal (blue) and the Rubidium absorption spectrum of an Rubidium-87 re-pump peak and an amplified resonance beat-note signal (green) indicating saturation points of the absorption spectrum.

2.7 Laser Locking Results

After obtaining and filtering the beat-note signal (see section 2.5.1), the rest of the control system was connected (as in Figure 3 in section 2.1.3). The FVC only works within 5 MHz of the reference frequency (135 MHz), so the DC bias of the piezo has to be adjusted until the beat-note frequency is within this range. While the error signal was generated, the proportional, integral and then AC Fast gains were adjusted (in that order) in an attempt to lock the frequency of the laser. Initially the error signal looks like a square wave while the proportional gain is adjusted. Upon adjusting the AC Fast gain, the square error signal collapses into a straight line. In this portion of the locking, the frequencies of the two lasers are the same, and the controller attempts to lock the respective phases of the two signals.



(a)



(b)



(c)

Figure 24: (a) A signal of the beat-note (divided down) with low resolution (b) The same beat-note with a higher resolution displaying an almost perfect sine wave. (c) The same beat-note with high resolution (though not very clear).

The outcome of this procedure resulted in locking the frequency for a brief period of time. This was tested by creating an acoustic vibration by clapping and monitoring the error signal. Upon the creation of the acoustic vibration, the slave laser becomes un-stabilized causing the error to go back into a square wave. After a brief period of time (1 second approximately) the square wave collapses again into a straight line, meaning the relocking has taken place. Unfortunately the error signal carries with it a DC bias, which is either below or above zero. This causes the voltage of the integrator to increase. Once the limit of this voltage is reached, the laser un-stabilizes and locking is lost.

A number of factors seemed to improve amount of time the laser was locked. By increasing the integration gain, and lowering the time constant of integration after locking was achieved allowed the laser to remain locked for approximately 5 minutes. Also by adjusting the DC offset slowly in the opposite direction of the DC bias of the error signal forced the DC bias in the opposite direction and caused the integrator voltage to decrease. This solution however would not be viable as there is a limit on the amount of voltage which can be placed on the piezo (between 0-150 volts).

3.0 CONCLUSION

Many frequency scan widths were achieved with the constructed GSDL. The produced GSDL has a periodic instability that produces an issue of different scan widths at different times. Generally, without having to re-tune the laser from the knobs of the mirror mount, a minimum of 3 GHz can be achieved without a feed forward though approximately 4.5 GHz was obtained in a couple of instances. With a feed forward placed on the current controller, a minimum of approximately 5 GHz can easily be obtained. Though the secondary goal of creating a laser with 8 GHz of mode-hop free bandwidth was not met, a scanning range of 3 GHz is appropriate for laser locking. Frequency locking with the GSDL worked periodically. It was able to lock its frequency and reject any input disturbance (such as a clap near the laser) for approximately 3 minutes. However, the instability of the laser at times loses the PI tuning control of the frequency lock and the locking doesn't work permanently without having to retune the gain values.

4.0 RECOMMENDATIONS

Since the main parts of the project were to develop a tunable laser and a FLS, a set of recommendations will be made for each of the components. The performance of the laser is vital to improving the locking of the FLS, thus the recommendations for the laser should be taken into closer consideration.

4.1 The Present Laser System

Considering the Littman configuration laser created during the course of the project and the components at the disposal of the QDG laboratory, the following recommendations should be taken into account to improve upon the performance of the laser already built.

4.1.1 Anti-Reflection Coated Laser Diode

The main concern with the Littman configuration is that the feedback provided by the diffraction and mirror system is not sufficient to force the laser to output light at a single mode. Although the laser system implemented did accomplish to achieve such an effect, the presence of modes although much less intense is present. To improve the performance of the laser an Anti-Reflection coated laser diode should be purchased. This would increase the amount of feedback to the diode and thereby force the laser to lase at a single mode.

4.1.2 Acoustic Vibration Isolation

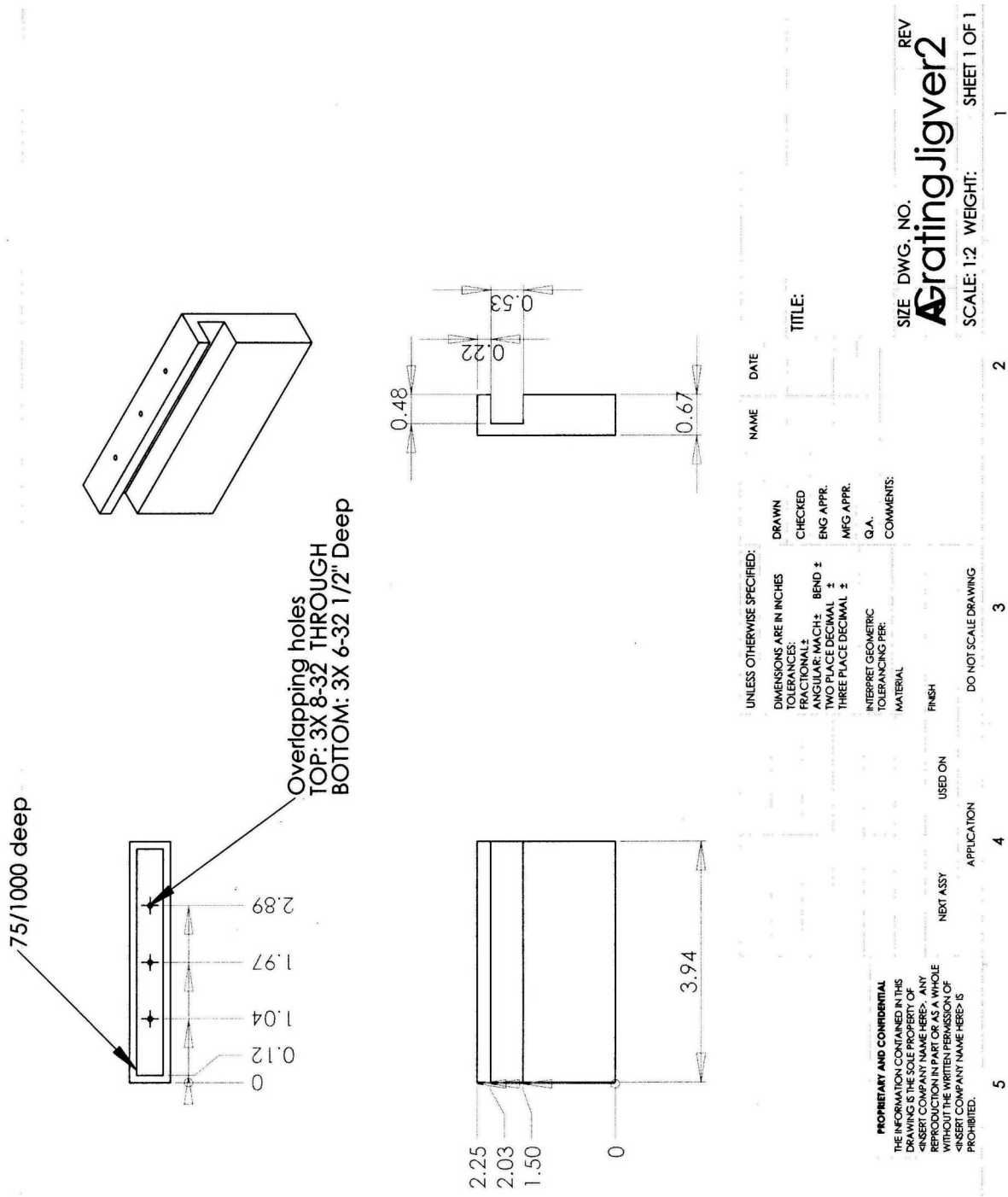
The second recommendation is that the laser be isolated from acoustic vibrations. Although all the components (mirror, grating and diode) are securely locked in place, there is still the presence of small vibrations which move the components fractions of nanometers, and cause instability in the laser. Thus moving the laser to the Acousto-isolating table will increase the lasing stability of the laser.

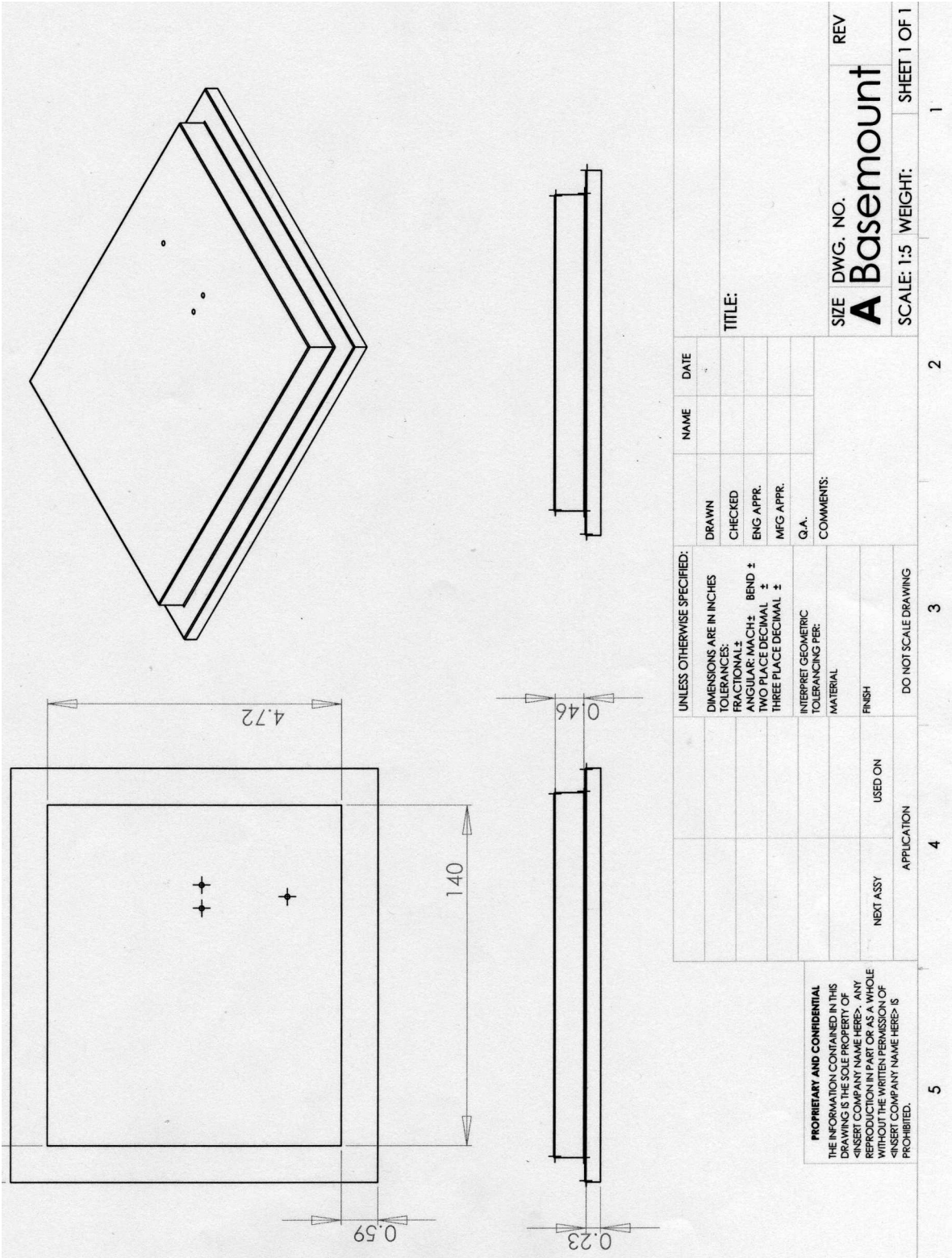
4.2 The Frequency Locking System

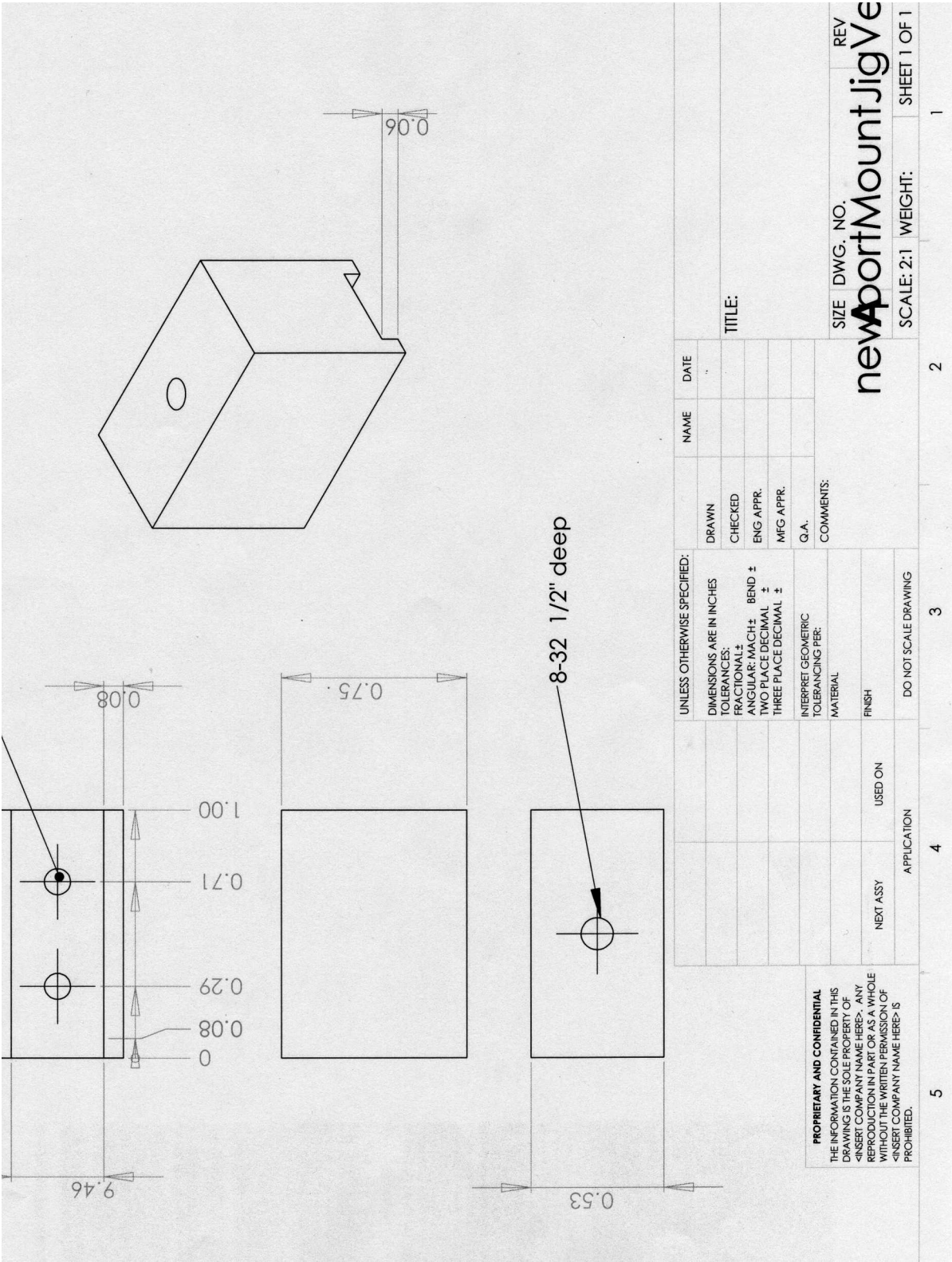
4.2.1 Beatnote Frequency Division

As discussed in section 2.7, the VTC only generates a proper error signal when the beat-note frequency is within 5 MHz of the reference signal. Since the beat-note frequency drifts are much larger (20 MHz), forcing the slave laser to lock is difficult since the generated error signal drifts out of range quickly. Dividing the beat-note frequency by a minimum of 4 would allow an error signal to be generated even when the beat-note signal before division is 20 MHz away from the reference. This would allow the user ample time to adjust the Lock Box gains to lock the slave laser.

5.0 APPENDICES





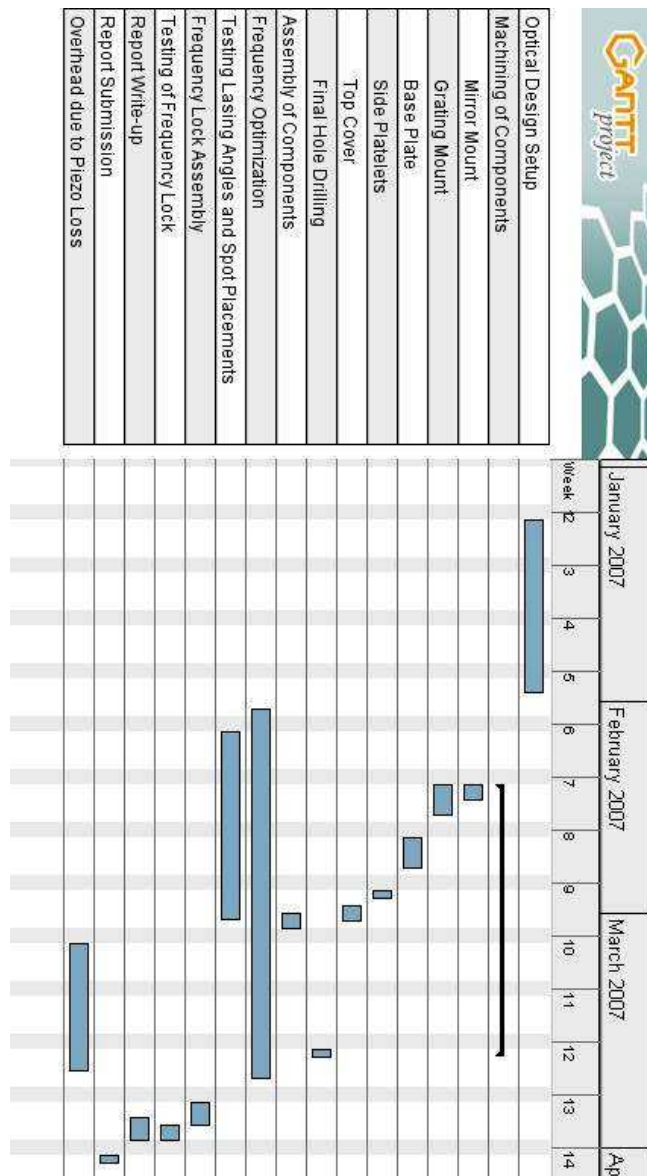


6.0 REFERENCES

- [1] Park, S.E, T. Kwon, E. Shin, H. Lee. 2003. A compact extended-cavity diode laser with a littman configuration. IEEE 0018-9456/03.
- [2] Gawlik, W. J. Zachorowski. Stabilization of diode laser frequency to atomic transitions. *Optical Applicata Vol XXXIV, No. 4, 2004*.
- [3] Kraft S., A. Deninger, C. Tr ck, J. Fort gh, F. Lison, C. Zimmermann. Rubidium spectroscopy at 778—780 nm with a distributed feedback laser diode. Wiley InterScience. Laser Phys. Lett. 1—6 (2004) / DOI 10.1002/lapl.200410155.
- [4] Pedrotti, F., L. Pedrotti, and L.M. Pedrotti. Introduction to Optics 3rd Edition. Prentice Hall. 2007: 229-230, 614-616.
- [5] Truscott, A.G., N. Heckenberg, H. Rubinsztein-Dunlop. 1999. Frequency stabilised grating feedback laser diode for atom cooling applications. *Optical and Quantum Electronics*. 31: 417-430, 1999.
- [6] Wieman, C., L. Holberg. 1991. Using diode lasers for atomic physics. *Rev. Sci. Instrum.*. 62 (1)
- [7] Wikipedia: Laser Cooling. Retrieved 1st November 2006 from the World Wide Web: http://en.wikipedia.org/wiki/Laser_cooling
- [8] FU Berlin: Chapter 7 - Pump probe spectroscopy of Ultra-cold Rb₂ Molecules. Retrieved March 29th, 2007 from the World Wide Web: <http://www.diss.fu-berlin.de/2007/104/chapter7.pdf>
- [9] Ido B., A. Eisenstein, G. Eisenstein. Characterizing Absorption Spectrum of Natural Rubidium by Using a Directly Modulated VCSEL. Retrieved Feb 20th, 2007 from the World Wide Web: <http://tycho.usno.navy.mil/ptti/ptti2005/paper62.pdf>

PROJECT EVALUATION

The following is the renewed Gantt project diagram. Since actual work did not really follow the assignments, all group members worked on the same tasks at any given point in time, so the renewed Gantt does not give assigned names to each task.



As can be seen, the project status was in good condition until early March when a mishap occurred and the PTZ was no longer functional. An amplifier with a very large gain was connected to the PTZ and power was improperly disabled. This paved a 3 weeks overhead in March and pushed the project back severely during the wait for new orders of the PTZ.

Most of the project did not progress the way the proposal was intended to. However, this project could not have been anticipated in detail of organization and scheduling. For example, where the holes are drilled and where the mounts are placed on the base-plate could not be approximated beforehand. Even with a proper value of settings found on the experimental setup, the slightest cavity length change can change the results of the frequency bandwidth.

In the end, a deliverable was completed and frequency locking was partially accomplished. The objective was to design a frequency locking system using the Littman configuration of GSDL. The only goal that wasn't met is the 8 GHz bandwidth that was asked for. This however, was not crucial in creating an operational FLS.