Unbelievable: The Story of a Laser

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Abstract

At least 100 mW of low-linewidth tunable laser light at 671 nm is required for a Lithium Magneto-Optic Trap experiment. Use of diode lasers to achieve this is desirable, due to their reliability, low-cost, and potential tunability. However, the required powers are not available from single mode diodes. A system based on a single-mode Master and two levels of amplification (a single-mode Slave and a multi-mode BAL amplifier) was constructed and is described in detail.

Single-mode devices of a variety of free-running wavelengths were tried as both Master and Slave. Ultimately, 17 mW of usable light at 671 nm was obtained using a Lumex OED-LDH66003E as both Master and Slave. The diodes required heating to work at 671 nm, and this heat lead to premature failure of one of the diodes.

Three types of BAL diodes from RPMC were tried. Surprisingly, the most functional amplifier was a free sample, discarded by the manufacturer due to an anomalous front facet coating. With this device, 140 mW of output power was obtained from 14 mW of input power. This is thought to be due to the device’s accidental low front-facet reflectivity.
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Chapter 1

Introduction

1.1 Report Background and Purpose

This report details work undertaken to build a Broad Area Laser (BAL) amplifier system, producing laser light for a Lithium Magneto-Optic Trap. The work was carried out by Peter Eugster and Aviv Keshet in the summer of 2005, in the Quantum Degenerate Gas lab at the UBC Physics / Astronomy Department, led by Dr. Kirk Madison.

The purposes of this report are:

- To describe, in detail, the methods and results of our work.
- To serve as a guide in the continuation of the BAL project.
- To provide recommendations for the future directions of the BAL project.

1.2 Project Motivation

1.2.1 QDG Research Interests

Research at the QDG lab at UBC focuses on applying ultra-cold gases to the study of many-body quantum systems. The first achievement [2] of a Bose-Einstein Condensate (BEC), in 1995, has resulted in a flurry of interest in these ultra-cold quantum systems. An in-depth discussion of Bose-Einstein condensation and Fermi-degenerate gases is beyond the scope of this report. The reader is instead referred to introductory articles [11, 17].

As of July 2005, one of the immediate research goals of the QDG lab is the construction of a mixed-species Rubidium BEC / Lithium degenerate gas, using a combination of either $^{87}$Rb & $^6$Li, or $^{85}$Rb & $^6$Li. Using a mixed BEC / degenerate gas makes it possible to cool the degenerate gas of fermions to temperatures which cannot be reached when cooling fermions alone. A cold gas can then be put into an “optical lattice”, to study and simulate electrons in a periodic potential and search for phenomena such as superconductivity and superfluidity. A mixed-species trap can also be used to study the interaction potential between Lithium and Rubidium.
1.2.2 Ultra-cold Techniques

Ultra-cold gas research generally studies systems in the 10 nK to 100 µK range. At these temperatures, atoms must be almost perfectly isolated from the environment. Thus, most ultra-cold techniques revolve around trapping and cooling a cloud of atoms in a vacuum chamber.

Trapping and cooling neutral atoms poses a challenge. Unlike with ions, which can be moved around at will by electrostatic fields, neutral atoms are comparatively hard to control. There is a zoo of atom trapping and cooling schemes in use, most of which take advantage of magnetic or electric dipole effects. One of the most popular schemes, especially as the first stage in a cooling process, is the Magneto-Optic Trap (MOT).

The cooling in a MOT is primarily provided by 6 counter-propagating laser beams, tuned slightly below the resonant frequency of the atom to be trapped. This de-tuning causes atoms in the trap to preferentially scatter photons (and hence absorb momentum) from the beam opposing their motion. In addition, a magnetic field with a zero in the middle of the trap causes a Zeeman shift in the atoms’ resonant frequency which increases as they move farther from the trap center. In concert with the de-tuned laser, this Zeeman shift serves to hold atoms trapped. For further details, the reader is advised to turn to the original paper [14].

Construction of a Lithium MOT and a Rubidium MOT will be the first steps towards the lab’s mixed-species trap goal. A MOT consists of several fairly independent systems – laser system, vacuum system, magnetic coils, atom sources, control system, etc. This project was entirely focused on the laser system for the Lithium MOT.

1.3 Project Background

1.3.1 Laser Requirements and Options

Laser cooling is relatively demanding when it comes to the spectral properties of the cooling light. The linewidth of the cooling light must be on the order of the atomic transition linewidth, in our case around 1 MHz. The light must be tunable within a few MHz of the accurately locked absorption line (in our case, 670.977 nm). Two frequencies of light are needed for the Lithium MOT. One color is for the cooling light, and one color is to continuously pump atoms into the correct hyperfine state for cooling and trapping. An energy level diagram for $^6$Li is provided in Figure 1.1.

For each color, each of the 6 independent beams requires about 10 mW of power. Taking into account losses in the optical system, this means about 200 mW of power is required for each of two colors of laser light.

The required tunability, linewidth, and power can be obtained from a variety of laser systems. Historically, dye lasers were the workhorses of such experiments. However, dye lasers are expensive, extremely messy, and unpleasant to work with. In the words of Brian King, “Working with dye lasers isn’t so bad, in theory, and neither is giving yourself an appendectomy with a blunt spoon and no anesthetic.”
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pressure corresponds to a temperature difference of about 100 ◦C. Therefore, as long as $T_2 \geq 280$ ◦C, there will be no build up of sodium in the second chamber. For $T_2 < 280$ ◦C, sodium will start condensing in the second chamber, rather than going into the slower and the experiment. At this point, the flux of atoms is completely determined by the vapor pressure given by $T_2$, and heating the first chamber even further would not increase it. Therefore, when running in sodium-only mode we heat up the lithium reservoir to 280 ◦C as well. This means that some lithium atoms are wasted, but these numbers are negligible. This oven has now replaced the sodium oven on our BEC apparatus, and in sodium-only experiments it gives the same results as the old one.

2.4 Laser cooling of $^6\text{Li}$

2.4.1 Some laser cooling basics

In our experiments we use standard techniques of atom beam slowing and magneto-optical trapping [43]. Here I will briefly mention the relevant experimental methods and parameters only in as much detail as is needed to compare and contrast the laser cooling of $^{23}\text{Na}$ and $^6\text{Li}$.

The ground state of alkali atoms has one unpaired electron in the $S$ shell, $2^2S_1/2$ in lithium, $3^2S_1/2$ in sodium. The first excited state is of the $(2^2P_J)$ form, and is split by $\vec{L} \cdot \vec{S}$ coupling into $J = 1/2$ and $J = 3/2$ states. Laser cooling is done on the $D_2$ line, connecting the ground state and the $2^2P_{3/2}$ excited state. The wavelength of this transition is 671 nm in $^6\text{Li}$, and 589 nm in $^{23}\text{Na}$. The diagram of relevant energy levels is shown for $^6\text{Li}$ in Figure 2-3.

Figure 1.1: Energy level diagram for laser cooling of $^6\text{Li}$. From [9]

The Miracle of Diode Lasers

Riding on the coattails of ever-advancing semiconductor technology, experiments in this field are moving towards diode lasers. An excellent overview of the many uses of diode lasers in atomic physics is presented in [19]. The principle of operation of diode lasers, outlined later in this introduction, gives rise to a number of key features:

- Diode lasers do not require a pump laser.
- Due to their relatively broad gain spectrum, diode lasers have the potential to be tunable.
- Compared to dye lasers, diode lasers are easy to operate and are highly stable and reliable once set-up.
- Diode lasers are amenable to external cavity feedback schemes, which allow their linewidth to be significantly narrowed.

1.3.2 Power Limitations with Diode Lasers

While diode lasers possess many desirable traits, they face a major limitation when it comes to output power. The narrow linewidth requirements for laser cooling favor the use of “single mode” diodes, which have front facet dimensions on the order of 1 wavelength and thus only oscillate in a single transverse mode. However, this small front facet size places a limit on the power which these diodes can produce. Beyond about 80 mW, there is a significant risk of catastrophic output facet damage. The small volume of the gain medium of a single mode diode makes even these powers a challenge to reach. “Multi mode” diodes, with facet dimensions exceeding 1 wavelength, are capable of higher output powers, but at the cost of a broadened spectrum.
CHAPTER 1. INTRODUCTION

Fortunately, there are a number of power amplification techniques which can be used to mitigate the power limitations of narrow linewidth lasers. In a Master-Oscillator Power Amplifier (MOPA), a narrow-bandwidth “master” laser is stabilized and locked to the desired wavelength, and power from the master laser is run through amplification stages.

The simplest MOPA system is injection locking, in which light from the master laser shines directly into a higher power “slave” laser, pulling the slave laser’s spectrum to that of the master. This scheme is used as the first stage of amplification in this project, as detailed in Chapter 3.

Another common technique is the use of a “tapered amplifier,” essentially a gain-medium waveguide into which the master laser is coupled, to be amplified as it propagates. Due to market peculiarities, however, tapered amplifiers are not presently manufactured at the wavelength of interest for this project. Furthermore, anecdotal evidence indicates that they are not as straightforward to operate as their apparent simplicity suggests.

BAL Double-Pass Amplification

The amplification system implemented for this project is commonly referred to as either “BAL Double-Pass Amplification” or “BAL injection locking”. To differentiate the technique from the conceptually different injection locking of a single mode slave, we prefer the former term. Keep in mind, however, that in the literature both terms are used interchangeably.

A Broad Area Laser (BAL) is a laser diode with one of its front facet dimensions much larger than 1 wavelength. A typical BAL has front facet dimensions of 1 x 100 to 1 x 200 µm. They are available in power ranges up to several Watts. Their multiple transverse-mode structure results in a broad lasing spectrum. BALs are typically used in applications where power is more important than spectral quality, such as in pumping of other lasers or LASIK eye surgery.

In a simplistic picture of Double-Pass Amplification, a seed beam is injected into the front facet of a BAL, propagates twice through the gain medium (by reflecting off the rear facet) of the BAL and emerges from the front facet amplified (see Figure 1.2). Unlike in injection locking, the BAL still outputs free-running light when being used as an amplifier. However, this free-running behavior is partially suppressed, as the seed beam competes for gain with the BAL’s free-running modes. The seed beam is injected at an angle, in order to spatially separate the amplified beam from the free-running light.

The simple picture presented above ignores several key issues in the BAL amplification process. The biggest complication is the effect of front facet reflectivity. A non-negligible front facet reflectivity suggests that the double pass picture should be replaced by a multi-pass picture, as illustrated in Figure 1.3. More importantly, front-facet reflectivity can make it difficult for the injected seed to compete for gain with the BAL’s free-running modes.
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Figure 1.2: Double Pass Amplification concept. From [7]

Figure 1.3: Complications to the Double Pass concept. From [10]
1.4 Diode Laser Basics and BAL amplification

A laser is a feedback amplifier for light. A diode laser is no different. This section will briefly explain how a diode laser achieves amplification and feedback, and will contrast lasing behavior with the desired behavior we wish to achieve with a BAL.

All lasers used in this experimental setup were semiconductor diode lasers. In a diode laser, lasing occurs at a junction between N-type and P-type semiconductors. An N-type semiconductor is doped to have an excess of electrons, while a P-type semiconductor is doped to have extra holes (positive charge carriers).

A forward bias can be applied across the p-n junction, such that the positive terminal is connected to the p-type region, and the negative terminal is connected to the n-type region. The holes are repelled from the positive terminal while the electrons are repelled from the negative terminal, resulting in a movement of holes into the n-type region and electrons into the p-type region. If a hole and electron meet they can recombine, which results in the emission of a photon (spontaneous emission) with an energy equal to the bandgap of the semiconductor (the energy difference between the valence band and conduction band).

Spontaneous emission is not sufficient for lasing; stimulated emission must occur. Stimulated emission occurs when a photon, with an energy equal to the band gap, encounters an electron and hole pair that has not yet recombined. This photon will stimulate the electron to drop out of its excited state, releasing a second identical photon. If electron-hole pairs are pumped into a region fast enough that their concentration exceeds the concentration of valence electrons, then a “population inversion” is achieved and this stimulated emission effect dominates over the medium’s absorption. This is the mechanism behind amplification of light in a diode laser.

The conduction and valence bands in a semiconductor laser do not contain only one energy level. In fact, the conduction band can be considered to contain a continuum of allowed energy levels. This means that, in contrast to lasers which rely on atomic transitions between discrete states for stimulated emission (i.e. gas lasers), diode lasers have broader gain spectra. This “tunability through sloppiness”, in the words of Robin Coope, is the reason that diode lasers can be coaxed to lase several nanometers from their free-running peaks. In a Fabry-Perot laser diode (all diodes in this report were Fabry-Perot type), the front and back facets are cleaved, resulting in a pair of flat, parallel surfaces. The interface between semiconductor and air acts as a partially reflecting mirror (usually around 30% reflectivity for uncoated facets). These mirrors reflect some photons back into the semiconductor, providing the other key ingredient to a laser – feedback. Usually the rear facet is given a high-reflective coating to prevent losses out the back, and the front facet is given a coating (around 12% reflectivity, for instance) to optimize laser performance.

The combination of feedback and amplification result in a chain reaction. A spontaneously emitted photon can cause as “cascade” of stimulated photons. If the cascade is steady state, this is called lasing. If not, this is called Amplified Spontaneous Emission (ASE). Until the gain medium is saturated, the more photons in a given mode of the laser that are present in a cavity the more it is amplified. When a laser is turned on, it very rapidly settles to steady-state oscillation in the modes which are most favored by the gain medium and the feedback mechanism.
In BAL double-pass amplification, described in this report, it is desirable for the BAL to act like a gain medium rather than a laser. The photons which should cause stimulated emission are provided from an external source (the slave laser), therefore a low front facet reflectivity is desired to minimize the amount of feedback. The seed beam and the feedback of the BAL’s spontaneously emitted light must compete for gain in the BAL gain medium. The lower the BAL’s front facet reflectivity, the better the seed beam is able to compete.

1.5 Literature Review

Detailed discussions of theory and numerical studies into double-pass amplification are beyond the scope of this project. This review of literature focuses on experimental advances.

1.5.1 Experimental Work

Interest in the use of high-power laser diodes as amplifiers began in the mid 1980s. Early research focused mostly on injection of diode arrays and single-pass amplification through large diodes (the precursor to today’s tapered amplifiers). The first forays into double-pass amplification using a BAL [1] were for the purpose of better understanding diode-array injection. The uniform gain medium of a BAL provided a simplified model system compared to more heterogeneous diode arrays. Extensive further work was carried by Lew Goldberg (see [8], for example).

Use of a BAL as an amplifier for applications requiring narrow linewidth was first investigated in the mid 1990s [6]. Using a 810 nm 500 mW BAL with a 5% front-facet reflectivity, 60 mW of locked output was obtained from 9 mW of injected power. The linewidth of the output was below 1 MHz. The study also indicated that BALs were just as suitable for such applications as their more-expensive brethren, diode arrays.

BAL double-pass amplification has been demonstrated [13] at 671 nm, Lithium’s transition wavelength. 130 mW of output power was achieved with an injected power of 9.6 mW, allowing for the capture of $10^6$ Lithium atoms in a MOT. The BAL used (Coherent S-67-500C-100C) was rated to 500 mW, with an undisclosed front-facet reflectivity.

An unsuccessful attempt to achieve BAL amplification is documented in great detail in [10]. The paper is a good introduction to the theory of diode lasers and multi-pass amplification. The document concludes that the attempt at amplification was scuttled by a high BAL front facet reflectivity.

Finally, a goldmine of BAL double-pass amplification information is presented in [16]. Shvarchuck worked at 780 nm, and achieved a total of 410 mW of power out of a BAL with 35 mW injected. After fiber-coupling the remaining amplified power was 160 mW. The BAL used had a front facet reflectivity of less than 3%.
1.5.2 Open Questions

While BAL double-pass amplification is a reasonably common technique, there are a number of open questions relating to it. In particular, there is no published systematic experimental study of the effect of front facet reflectivity on double-pass amplification. The interplay between front-facet reflectivity and ideal injection angle is also experimentally unstudied, though theoretical treatments of double-pass amplification predict a relationship between these variables. Such studies would be valuable to people trying to construct BAL amplification systems, assisting them in selecting BAL diodes and coatings.

1.6 Report Outline

An overview of the BAL experimental setup and measurement devices will be presented after this introduction. Following this will be a chapter detailing the assembly, set-up, alignment, and tuning of a Master and Slave laser system. The design of the BAL will then be discussed, including the diodes, housing, electronics, and optics. A step-by-step procedure for installing the BAL, as well as aligning for double-pass amplification, is included. Next, the measurements and results of the entire BAL system are presented, including free-running characterization, seeded characterization, and an investigation into front facet reflectivity. Finally, the report will close with a discussion of results, recommendations for future work, suggested improvements to the BAL setup, and a top-notch conclusion summarizing the project.
Chapter 2

Experimental Setup

2.1 Table Layout

The layout of the optics table is shown in Figure 2.1. It should be noted that this is a schematic diagram, and the relative distances between optics components are not to scale. It is also important to note the coordinate system defined in Figure 2.1. This coordinate system will be referred to frequently throughout this document, and unless indicated otherwise, any reference to x-, y-, or z-axes should be considered in this coordinate system.

Broadly, the set-up consists of a narrow linewidth Master, an injection locked Slave, a BAL for amplification, an instrumentation set-up, and associated optics. A half-wave plate and beamsplitter (see Section 3.4 for an introduction to beamsplitters) allowed for the Master’s light to be divided between the measurement setup and Slave injection. The measurement setup is shown highlighted in yellow in Figure 2.1. Included in this was a custom-built Fabry-Perot interferometer, and a fiber leading to an Optical Spectrum Analyzer (both these instruments are detailed in Section 2.2. Using the information from these instruments, the Master could be tuned to emit single-mode light at a desired wavelength.

Another half-wave plate and beamsplitter combination controlled how much Slave light went to the BAL, and how much went to the measurement setup. The light that was sent to the measurement setup was reflected off a removable mirror. This mirror was on a kinematic base (Newport BK-2A), which allowed quick and easy removal and replacement of this mirror. If the mirror was removed, the measurement setup was observing the Master, while if the mirror was in place then the Slave would be observed. This quick mirror changing ability saved countless hours of realignment that would otherwise be necessary, and made checking the lock of the Master extremely easy. The kinematic base is pictured in Figure 2.2.

The majority of the Slave light was sent to the BAL. Before it reached the BAL, it passed through an Anamorphic Prism Pair (Thorlabs PS871-B), which expanded the beam 4x in the x-axis. The light was also reflected off two mirrors in ultrastable mirror mounts (Klinger). These mounts were used because of the high precision and stability
Figure 2.1: Layout of Optics Table
2.2. MEASUREMENT DEVICES

needed for injecting the Slave beam into the very small BAL front facet. A 150mm cylindrical lens (Edmunds NT46-024) was used to adjust the injection angle into the BAL. The cylindrical lens also served to horizontally collimate the BAL. The cylindrical lens was held in a lens holder (Newport CYH-2) and rotational stage (Newport RSP-2T), and the rotational stage was connected to the table with a crossed pair of linear stages (Newport UMR5.16). These three stages allowed rotation about the z-axis, and translation in the x- and y-axes. After the cylindrical lens, the light passed through a 4.5mm collimating lens (described in Section 4.2) before entering one side of the BAL diode.

The amplified output beam left the opposite side of the BAL. A small portion of this power was reflected to a BAL instrumentation set-up, using a glass slide as a beamsplitter. This light was filtered, and imaged with a CCD camera (Panasonic WV-BP334), in order to observe the BAL’s near-field radiation pattern. The light transmitted by the glass slide passed through the cylindrical lens a second time, to be “picked off” by a small mirror and sent to a photodetector (Newport 818-SL). The light that went to the photodetector could also be redirected to the measurement setup (FP and OSA) using a second kinematic mirror mount, however, for clarity this is not illustrated in Figure 2.1.

2.2 Measurement Devices

A number of instruments were used in the set-up and characterization of the Master, Slave and BAL.
CHAPTER 2. EXPERIMENTAL SETUP

Tektronix TDS-3054 Digital Oscilloscope

This scope was used to view Fabry-Perot traces, and power vs. current traces, along with the standard electronic test equipment uses. Data was captured using a GPIB to USB adapter, or with a floppy disk.

Ando AQ-6315A Optical Spectrum Analyzer

Some of the light being analyzed in the measurement set-up was directed into an optical fiber, which was connected to this OSA. This spectrum analyzer makes use of a moving diffraction grating to repeatedly scan light intensity as a function of wavelength. Although capable of scanning between 350nm and 1750nm, the span was usually confined to 5nm or 10nm on either side of 670nm. Alignment instructions for the OSA are provided in Appendix A.

Custom-built Fabry-Perot Interferometer

A Fabry-Perot interferometer is composed of two partially reflecting concave surfaces that are as close to co-axial as possible. If a collimated beam of light is shone into this interferometer, and the output is focused, an interference pattern (composed of circular fringes) should be visible. This pattern is caused by differing path lengths giving rise to constructive and destructive interference. If the distance between the partially reflecting surfaces is varied, then the interference fringes will move, and can be counted by a photodiode.

In this particular interferometer, coarse adjustment of the distance between the partially reflecting surfaces is provided by a micrometer screw. A piezoelectric actuator provides fine distance adjustment. This actuator is driven by a custom-built piezo driver, which is in turn driven by a function generator outputting a triangle wave. A PCX50 lens collimates the incoming beam to be examined, while a PCX40 lens focuses it onto a photodetector (New Focus 1801). By examining the photodetector output on an oscilloscope, the mode structure of the laser of interest can be determined. This interferometer had a free-spectral range of 2GHz. Figure 3.10 shows the difference between a single-mode and multi-mode signal.

A photograph of the FP cavity is provided in Figure 2.3. Appendix A gives alignment instructions for the Fabry-Perot Interferometer.

Newport 1825-C Power/Energy Meter

This power meter was used with a Newport 818-SL photodetector, and Newport 883-SL attenuation plate. With a sensitivity ranging from nW to W, this instrument was used to measure beam power. In cases where the beam was larger than the photodetector active region (for example, the BAL free-running beam), a PCX50 lens was used to focus the beam onto the active region. Calibration of the power meter is necessary, as the sensitivity of the photodetector varies with wavelength. The power meter used for the experiments described in this report had already been calibrated previously.
2.2. MEASUREMENT DEVICES

Panasonic WV-BP334 CCD Camera

This camera was used with a 100mm imaging lens to look at the near field radiation pattern of the BAL. The light for this measurement was reflected off a glass slide which served as a beamsplitter. The slide was placed between the BAL and the cylindrical lens. Due to the high output power of the BAL, the light had to be further filtered and reflected off another glass slide before it had a low enough intensity to be visible on the CCD without saturation. The CCD was isolated from stray room light using an aluminum tube with a filter on the end. The filter reduced ambient light from the room, and the tube ensured that only light that was directed straight at the CCD (the laser light) was imaged.
Chapter 3

Master and Slave

This chapter will give step-by-step instructions in setting up, aligning, and tuning the Master and Slave lasers. The Master and Slave system provides the light to be seeded into the BAL. In this set-up, a few tens of milliwatts are needed for BAL seeding, and no diodes are currently available that can produce this much power on their own. Therefore, two lasers are used in a Master / Slave configuration to produce the required amount of light.

The Master is used to produce stable, locked\(^1\), narrow linewidth light at relatively low powers (a few milliwatts)\(^2\). This is accomplished using external-cavity grating feedback to select and narrow the Master’s wavelength. This light is then injected into a Slave laser, which is a higher power (but still single-mode) diode with a free-running wavelength near the Master’s locked wavelength. By injecting a few milliwatts of Master light, it is possible to force the Slave to lase with the same frequency and phase as the Master. Amplification can occur due to the higher power of the Slave, and the result is stable, locked, narrow linewidth light with power on the order of tens of milliwatts.

One advantage of this set-up is that any beam steering caused by Master tuning or frequency-shifting is not propagated beyond the Slave, as the Slave always emits a beam in the same direction regardless of the direction that light is injected into it. This effectively isolates the (very sensitive) BAL alignment from any adjustments made to the Master.

3.1 Master Housing Assembly

The housings used to hold the master and slave diodes were designed by Bruce Klappauf (based on the design presented in [3]), and machined by the UBC Physics machine

\(^1\)Ultimately the Master laser will be locked to the Lithium absorption line, however, in this prototype stage the Lithium absorption cell was not yet ready. Instead, the Master was simply set to an arbitrary wavelength that was very near 671nm.

\(^2\)The Master used for the work in this report was capable of putting out several tens of milliwatts, however, only a few milliwatts were needed to inject the slave.
shop. The slave housing that was used was an already-assembled prototype housing, however, the master housing required assembly. This section describes the master assembly process, and some minor modifications that were necessary. A partial diagram showing how the master fits together (the base and walls are omitted) is shown in Figure 3.1.

The main components of the master system are the modified mirror mount, diode, grating, TEC and piezos. The modified mirror mount was originally a regular Newport mount, but had been altered by the Physics machine shop so that both the diode and grating could be attached to it. The diode was held in the base of the modified mirror mount, while the grating was attached to the movable part of the modified mirror mount. This allowed the angle of the grating to be moved relative to the diode, allowing for tuning of grating feedback (for a brief explanation of grating feedback, see Section 3.4.1). Piezos allowed for fine control of grating movement. The TEC temperature-controlled the entire assembly.

The first step in assembly was to install sorbothane dampers in the springs of the modified mirror mount to prevent vibrations. The springs were simply extended and a small piece of sorbothane rubber was “flossed” in between the coils, such that when the spring was retracted the sorbothane was in contact with both the spring and spring hole. In addition, the 3 point contact had to be advanced slightly to allow for room to adjust the collimating lens.

Next, the copper bar (to which the modified mirror mount attaches) had to be altered. The centre hole was too small, so it had to be clear drilled for 6-32. In addition, it was later found that the modified mirror mount was not well-secured to the copper bar - it kept twisting about the single mounting screw. The solution to this was to use a lock washer on the single 6-32 mounting screw. However, this necessitated the milling of a larger diameter counterbore (for the centre hole on the copper bar).

After the machining steps on the copper bar, a 10 KOhm thermistor and LM35 temperature sensor were installed into it. Thermally conductive material (Bergquist GapPad Soft 0.125) was used to ensure good thermal contact between the sensors and the copper bar. This material could be pushed into the sensor holes like a putty due to its softness. The sensor leads were then soldered and heat-shrunk, and 4-40 screws and washers were installed to hold the sensors in place. It is important to note that the leads for the thermistor are very delicate, and it was important to clamp (with the 4-40 washer) the heat-shrunk wires instead of the fragile leads.

More thermally conductive sheet (Bergquist SilPad1500-0.010) was used between the copper bar and the modified mirror mount. A 15mm x 45mm piece was used under the mount, and a 15mm x 12.7mm piece was used in the relief cut into the copper bar. Each piece had to have a hole cut into it to allow a screw to pass through; the most effective way was to simply fold it in half and give it a small snip in the centre with a pair of scissors, and then fold it in the other direction and snip again.

The copper barrel was placed in the modified mirror mount, and held in place by a 6-32 screw (with lock washer) that passed through the modified mirror mount, 2 thermal sheets, and copper bar. A second 6-32 screw secured the copper barrel to the side of the modified mirror mount. The master laser diode was installed into a collimating tube, along with a collimating lens (Thorlabs C230TM-B, \( f = 4.5\text{mm} \)). This tube was installed into the copper barrel, which was squeezed with another 6-32
Figure 3.1: Partial Assembly Diagram for Master
screw to clamp the tube.

Next, a pair of 3/4" 8-32 Nylon screws were modified. The counterbore had been made too small on the copper bar for these two holes, so the easiest remedy was to take a small amount off the nylon screws’ heads using a lathe. The copper bar was then attached to the master housing baseplate using the nylon screws. In between the copper bar and the baseplate were a pair of 15mm x 20mm thermal pads (Bergquist SilPad1500-0.010) and a TEC (Melcor CP1.0-63-08).

A mirror (Newport 05D20ER.2) was epoxied to the modified mirror mount. Caution should be taken to ensure that no glue or scratches get onto the mirror surface. Next a piezo chip, with two leads soldered to it, was glued to the grating mount with cyanoacrylate (Krazy Glue), and a diffraction grating was glued on top of the piezo. Problems were encountered with the master housing shocking users, due to electrical contact between the grating mount and the solder on the piezo leads. Although for this particular master it was possible to repair the piezo’s solder, it is recommended for future masters that a thin glass slide cover be glued between the piezo chip and the grating mount.

On the end of the horizontal adjustment screw for the modified mirror mount, a sapphire window was installed, and in front of that a small piezo actuator was placed. The window and piezo were held in place by the spring force of the modified mirror mount. The sapphire window prevented the screw tip from damaging the piezo.

Finally, all electrical connections (TEC, 2 piezos, LM35, thermistor, diode leads) were soldered, and the walls and top of the master housing were installed. A diode protection circuit was also installed in the back panel of the master, along with a switch that allowed the diode to be shorted.

### 3.2 Master and Slave Diodes

Three different diodes were tried in various master and slave configurations for the BAL setup. The details of each diode are given in Table 3.1.

Initially, the Hitachi was tried as a master, however, its free-running wavelength was centered near 675nm. Despite efforts to pull this wavelength using both external-cavity grating feedback and cooling, the diode could not be forced to lase at 671nm. When the laser was cooled to 15.5°C, the wavelength could be grating-tuned from about 676nm to 673nm, but no lower.

Next a Lumex was tried as master. Despite having a quoted wavelength range of anywhere between 655nm and 660nm, this particular diode in fact had a free-running wavelength around 663nm at room temperature. By heating to 42°C and using grating feedback, this diode could be made to lase at 671nm stably. If the temperature was reduced below 42°C, the laser would not remain at 671nm stably. Running at its operating current (125mA), approximately 15mW of 671nm light was obtained. After passing through optics and isolators, this was reduced to about 12mW for injection into the slave.
3.3. MASTER AND SLAVE ELECTRONICS

<table>
<thead>
<tr>
<th>Diode</th>
<th>Hitachi HL6714G</th>
<th>Lumex OED-LDH66003E (both diodes)</th>
<th>Mitsubishi ML101J21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quoted Output Power (mW)</td>
<td>10</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Quoted Minimum Wavelength (nm)</td>
<td>660</td>
<td>655</td>
<td>654</td>
</tr>
<tr>
<td>Quoted Typical Wavelength (nm)</td>
<td>670</td>
<td>658</td>
<td>658</td>
</tr>
<tr>
<td>Quoted Maximum Wavelength (nm)</td>
<td>680</td>
<td>660</td>
<td>662</td>
</tr>
<tr>
<td>Actual Free-Running Wavelength at 22 Degrees (nm)</td>
<td>675</td>
<td>663.5</td>
<td>658.0</td>
</tr>
<tr>
<td>Actual Free-Running Wavelength at 47 Degrees (nm)</td>
<td>Not measured</td>
<td>668.1</td>
<td>662.7 (extrapolated)</td>
</tr>
</tbody>
</table>

Table 3.1: Master and Slave diode properties

A second Lumex was also tried as a slave diode with good results. Unfortunately, it had to be run even hotter than the master, at 47°C, and was also run at a higher current (140mA). It output approximately 22mW of light, which was reduced to 17mW after the final isolator. Thus 17mW of 671nm light could be injected into the BAL. Ultimately, the diode met an early demise, possibly due to the harsh operating temperature.

It was hoped that an 80mW Mitsubishi could be used as a slave diode, potentially with higher output power than the Lumex diode. Unfortunately, the Mitsubishi’s centre wavelength was about 5nm lower than the Lumex, and did not work at all as a slave. The Mitsubishi was not tried as a master.

3.3 Master and Slave Electronics

The Master and Slave diodes were both driven by in-house built current controllers, capable of providing up to about 140mA. Each diode had a protection circuit nearly identical to the BAL’s (see Section 4.3.1).

The Master and Slave’s TECs were controlled by a pair of in-house built temperature controllers. These had been further customized by the addition of a “hot/cold” switch, which connected an extra resistor in parallel across the “R-High” connection on the controller board when switched. This modification was made to adjust the temperature range of the controller, so that higher temperatures could be reached. At the “COLD” setting, a temperature range of about 5°C - 35°C was possible, and at the “HOT” setting a temperature range of 30°C - 67°C was possible. Given in Table 3.2 are some selected set-points and their corresponding temperatures.
### Table 3.2: Temperature at various Master/Slave controller settings

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Switch</th>
<th>Knob Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.7</td>
<td>COLD</td>
<td>550</td>
</tr>
<tr>
<td>25.0</td>
<td>COLD</td>
<td>600</td>
</tr>
<tr>
<td>25.6</td>
<td>COLD</td>
<td>630</td>
</tr>
<tr>
<td>30.3</td>
<td>HOT</td>
<td>0</td>
</tr>
<tr>
<td>41.8</td>
<td>HOT</td>
<td>570</td>
</tr>
<tr>
<td>47.4</td>
<td>HOT</td>
<td>700</td>
</tr>
<tr>
<td>60</td>
<td>HOT</td>
<td>1000</td>
</tr>
</tbody>
</table>

3.4 Master and Slave Set-up and Alignment

A schematic of the on-table Master and Slave set-up is shown in Figure 3.2. The beam height for the optical isolator (2.59") differs slightly from the lab standard beam height (2.5"). This is an important detail to keep in mind when aligning the set-up. The height of the beam at various points in the set-up is indicated in Figure 3.3. Another key detail to keep in mind is beam polarization – optical isolators are polarization sensitive and polarization altering (see Figure 3.4).

For an annotated photo of the set-up used, see Figure 3.6. Two mirrors are used to align the Master Laser with its isolator (Isowave I-67-T5-M). After the isolator, the Master beam passes through a half-wave plate (HWP) / beam-splitting cube combination, which allows power to be divided between slave injection and instrumentation.

A beamsplitting cube (illustrated in Figure 3.5) transmits horizontally polarized light and reflects vertically polarized light\(^3\). By placing a half-wave plate in front of the beamsplitting cube, the incoming polarization can be varied, thus affecting how much light is transmitted and how much is reflected.

Light which is reflected from the cube is steered, via two mirrors, into the side-port of the Slave’s isolator (Isowave I-67-T5-H), depicted in Figure 3.11. Due to the polarization of the master light, it is reflected by the isolator’s polarizing prism backward through the isolator. An HWP matches this beam’s polarization to the Slave polarization, and master light is coupled via two mirrors into the Slave.

Light from the Slave retraces the path of the injected beam into the Slave isolator, and passes through it. A lens after the isolator is convenient for improving the Slave beam collimation. The Slave beam is then bounced off two mirrors to return it to the lab standard beam height. The Slave passes through another HWP / beam-splitting cube combination, once again to divide its power between instrumentation and BAL amplification.

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\(^3\)Vertical polarization is often referred to as S-polarization while horizontal is called P-polarization, from the German words *senkrecht* and *parallel*. For non-German speakers, the words *sperpendicular* and *parallel* serve as an equally intuitive mnemonic, provided they are not confused with the terms *perpendicular* and *sparallel*. 
3.4. MASTER AND SLAVE SET-UP AND ALIGNMENT

Figure 3.2: Schematic of Master and Slave set-up.

Figure 3.3: Beam height diagram.
Figure 3.4: Polarization diagram.

Figure 3.5: Diagram of a beamsplitting cube
3.4. Master and Slave Set-up and Alignment

3.4.1 Grating Stabilization of Master

A grating stabilized diode laser falls into the broader class of extended-cavity diode lasers (or ECDLs). In essence, ECDLs steer and stabilize a diode laser by giving feedback that is strongly wavelength-dependant. In the case of grating stabilization, wavelength selective feedback is achieved by using a diffraction grating to reflect light back into the diode. The wavelength of light that is reflected into the diode is set by the grating’s angle. Steering the grating angle results in steering of the feedback wavelength, and thus the lasing wavelength of the diode.

Beyond simply steering the laser wavelength, grating stabilization can also significantly narrow a laser’s linewidth. Free-running diode lasers typically oscillate in multiple longitudinal modes, each of slightly different wavelength. If the grating feedback wavelength lies sufficiently close to the wavelength of one of the laser’s longitudinal modes, then this mode will dominate, and suppress oscillation in other longitudinal modes. Thus grating stabilization can select out a single longitudinal mode of the laser, causing a substantial decrease in linewidth.

Further details about the specific grating stabilization design used in this project are available in [3]. Discussion of other types of grating stabilization and ECDLs is available in [19] or the excellent [4].

The first step of setting up the Master and Slave laser system is the achievement of grating stabilization of the Master laser. This step-by-step section details how this is done in practice. This section assumes that:

- The Master laser and its support electronics are fully assembled.
The Master is being operated at a temperature and current for which grating stabilization of the particular diode at 671 nm is possible.

Thinking Inside the Box

1. **Rotate the Master diode for vertical polarization.** The beam from a single-mode diode is slightly astigmatic. It is desirable, for better grating feedback, to align the beam’s wide axis horizontally, to illuminate a larger number of grating lines. This corresponds to aligning the beam polarization vertically.
   
   A convenient way to perform this step is to aim the beam at a polarizing beam-splitting cube, and use a power meter to measure light that is transmitted through the cube. Then, rotate the diode to minimize this power. This adjustment is not particularly sensitive – good grating locking was achieved with a polarization a few degrees removed from parallel.

2. **Adjust Master collimation.** As a rule-of-thumb for grating stabilization, the Master laser should be collimated to minimize its long-distance spot size. Place a card several meters down the Master beam, and adjust the collimating lens to minimize the spot size. The correct tool to use is the small “hooked collimation wrench,” as the Thorlabs spanner wrench will not fit the confined space (see Figure 3.7).

3. **Vertically align grating feedback.** The grating must be aligned so that the re-
3.4. MASTER AND SLAVE SET-UP AND ALIGNMENT

Vertically misaligned

(a) Vertically misaligned

(b) Vertically aligned

Figure 3.8: Scope traces for vertical alignment and misalignment. The purple triangle wave trace is current (inverted), while the green trace is optical power.

There are two alignment methods, both of which were used successfully. The first is to modulate the Master current around the diode’s threshold current, while monitoring the power on a power meter. Ensure that the back-reflection from the power meter is not directed toward the diode. While monitoring the power vs. current behavior near threshold on an oscilloscope, adjust the screw to minimize the threshold current. Figure 3.8 illustrates the difference between the aligned and misaligned scope traces.

The second alignment method relies on examination of the Master’s beam shape. Turn off the lab light, and run the Master above threshold. Place a card in the beam about 10 cm from the box’s aperture. While fiddling with the vertical (and horizontal) adjustment screws, a side lobe should appear which is steered around by these adjustments. Moving the side lobe close to the main lobe of the beam causes the lobe to be “absorbed” into the main lobe, disappearing just before reaching the main lobe. This is an indication of grating feedback. Furthermore, there is sometimes a sharp increase or decrease in the main lobe intensity alignment is reached. The master is vertically aligned when the screws are adjusted so the the side-lobe would be at the same height on the card as the main lobe if it hadn’t been absorbed into the main lobe. This alignment method is alluded to in [3], though we were not aware of this when we uncovered it.

In practice, the second alignment method is often more convenient, is quite sensitive, and has given results which are just as good as the first method. However, it may make sense to experiment with both methods, both to assess the a diode’s ability to be locked, and to see which gives better results.

4. Horizontally align grating feedback. The coarse adjustment of the grating angle must be set to lock the master at 671 nm. The adjustment screw is indicated in Figure 3.9. While monitoring the Master spectrum on the OSA, adjust this
screw to steer the locked peak toward 671 nm. In order to see a locked peak, it may be necessary to play with the Master current and temperature settings and vertical feedback alignment. If this still does not work, it may be necessary to run the Master through an optical isolator before this step. Alignment instructions for the isolator are in the following subsection.

**Thinking Outside the Box**

1. **Align Master’s optical isolator.** The optical isolator is quite sensitive to alignment. If the input beam is misaligned, most of the power will be lost. Using a height gauge marked with the isolator beam height (2.59 in), adjust the first mirror after the Master so that the beam height at the second mirror after the master is at the isolator beam height. Place a power meter at the output of the isolator, and optimize the horizontal adjustments of the 2 Master mirrors to maximize the power transmitted through the isolator.

   Loosen the sleeve holding the isolator, and rotate the isolator about the beam axis to maximize the transmitted power. The isolator input port should now be set up to accept vertically polarized light, as indicated by the white scribe mark on the end of the isolator.

2. **Align Master with instrumentation.** The following steps require examination of the Master spectrum in detail. The Master beam should be aligned with an
3.4. MASTER AND SLAVE SET-UP AND ALIGNMENT

Figure 3.10: Fabry-Perot scope traces indicating locked and unlocked Master. The purple triangle wave trace is the Fabry-Perot piezo position, while the blue trace is the Fabry-Perot photodiode output.

OSA and a Fabry-Perot interferometer. Alignment instructions for the instrumentation are provided in Appendix A

3. **Tune for grating stabilization.** While monitoring the Fabry-Perot scope trace, adjust the grating angle and cavity length using the piezo driver to produce a trace indicating good grating locking, with the Master oscillating in a single longitudinal mode (see Figure 3.10). Ensure, when a locked scope trace appears, that the OSA still indicates a spectrum centered around 671 nm.

It may be necessary to make fine adjustments to the Master current or temperature to achieve a stable lock. Furthermore, note that it can take on the order of an hour for the Master temperature to stabilize. Before the temperature is stable, the piezos will require periodic attention to keep the master locked.

### 3.4.2 Injection Locking the Slave

The second stage of the Master and Slave laser system is alignment of the Master and Slave diodes and tuning of the Slave to achieve injection locking. This section assumes that:
The Slave laser and its support electronics are fully assembled.

The Slave is being operated in a temperature and current range in which injection is possible at 671 nm.

**Slave Set-up**

1. **Collimate Slave.** With the Slave running just above threshold, adjust the collimating lens using the Thorlabs spanner wrench to minimize the Slave’s long-distance spot size.

2. **Rotate Slave** For the purposes of beamshaping, it is desirable to have the Slave diode’s wide axis aligned horizontally, to better match the beamshape of the BAL. Loosen the Slave in its clamp and rotate until the wide axis of the beam is aligned horizontally, then re-tighten. Alignment by eye is sufficient.

3. **Align Slave with isolator.** The procedure for doing so is the same as for aligning the Master through its isolator.

4. **Rotate isolator to proper orientation.** To make use of the Isolator side-port, through which the Master light will be coupled, it is necessary that the sideport be aligned to accept light which is in the horizontal plane. When the slave is on and shining through the isolator, a certain amount of light from the slave will be reflected out of the sideport. Using the isolator beam height gauge (or a card with the appropriate isolator beam height, 2.59 in, marked on it) placed about a meter down this side-port reflection, rotate the Slave isolator so that the beam is at the Isolator beam height. This makes the beam parallel to the table.

5. **Match Slave and Isolator polarizations.** Place a power meter after the output port of the Slave isolator. Rotate the Slave’s HWP to maximize this transmitted power.

**Injection Alignment and Tuning**

1. **Direct Master power to Slave.** About 1 mW of power should be directed from the master towards the Instrumentation set-up, in case periodic checking of the Master lock is necessary. The rest of the power should be diverted by a beamsplitting cube towards the Isolator sideport coupling mirrors.

2. **Align Master with Slave Isolator** Turn off the lab lights. Using a card a few cm away from the Isolator sideport, examine the Slave beam being reflected out of the sideport. Locate 2 back-reflected beams, about 10 degrees apart. A beamsplitting cube can be used to confirm that one beam, the stronger one, is horizontally polarized. The weaker beam is vertically polarized.

   The isolator and its side-port, along with the correct laser polarizations, are depicted in Figure 3.11. To couple the Master light into the Isolator sideport, the Master must be aligned with the vertically polarized beam. Using the two mirrors coupling the Master and the Slave isolator, align the Master with this beam.
3.4. MASTER AND SLAVE SET-UP AND ALIGNMENT

![Polarization of Light in the Slave’s Optical Isolator.](image)

Figure 3.11: Polarization of Light in the Slave’s Optical Isolator.

to roughly align the Master with the Isolator sideport. For an introduction into aligning two beams, see Appendix B.

Turn off the Slave laser. Use the power meter to measure the Master power shining into the Slave. Adjust the sideport coupling mirrors to maximize this power. Losses should be on the order of 10% to 20%.

3. **Align Master and Slave.** Using the two mirrors nearest the Slave, align the injected Master and outgoing Slave beams. This accomplishes the rough injection alignment.

Next, modulate the slave current near threshold while monitoring the power coming out of the Slave Isolator output port. Examine the power vs. current behavior on the oscilloscope. Adjust the two mirrors nearest the slave to minimize the threshold current. When this alignment is complete, the power vs. current behavior should change dramatically when the Master beam is blocked from entering the sideport.

4. **Adjust Slave Current.** Monitor the Slave’s Fabry-Perot trace on the oscilloscope. When the Slave current is moved, a group of peaks with one large central peak should appear to move in the trace. These lines correspond to the Slave’s free-running behavior or to “partially locked” Slave modes with wavelengths close to the injected wavelength. In addition, a small fixed peak may be visible which corresponds to the Master’s grating stabilized behavior. To lock the Slave, tune the Slave current while watching the trace, until you see a locked trace, as indicated in Figure 3.12. When locked, the large peak lines up with the Master’s
Figure 3.12: Fabry-Perot scope traces indicating locked and unlocked Slave. The purple triangle wave trace is the Fabry-Perot piezo position, while the blue trace is the Fabry-Perot photodiode output.

5. **Reduce injected power.** If it is necessary to injection lock multiple slaves from the same Master laser, then it is possible to injection lock the Slave with quite a bit less than the Master’s full power. While assessing the Slave’s lock on a Fabry-Perot, experiment with lower injection powers (by directing more of the Master power towards Instrumentation). After each Master power adjustment, it may be necessary to adjust the Slave current (since the reduced injected power causes the diode to become slightly colder, and thus have a slightly different optical path length). In our experience, it was possible to get as much as 16 mW of injection locked Slave light with only 2 mW of Master light being injected at 671 nm.
Chapter 4

BAL Design

This chapter will give a description of the BAL diodes, electrical support components, and housing design.

4.1 BAL Diodes

Three pairs of laser diodes were obtained from RPMC Lasers, for a total of six diodes. Only one of each pair was used extensively in the experiments for this report, since both members of any given pair were essentially the same. Both diodes in the third pair were tested due to one’s unexpected behavior, and both diodes performed comparably.

The diodes were manufactured by LDX Optronics, and were mounted to a C-Mount by RPMC. The C-Mount package is pictured in Appendix H. The device properties are listed below, while their free-running characteristics are shown in Section 6.1. All devices were Broad-Area type diodes. The diodes had overall dimensions of approximately 400 $\mu$m (wide) x 100 $\mu$m (tall) x 1 mm (deep), while the active region had the dimensions 150 $\mu$m (wide), 1 $\mu$m (tall), 1 mm (deep).

The tolerances for attachment of the diode to the C-Mount were given as follows: +/- 2 $\mu$m in the y-dimension, +/- 0.5 mm in the x-direction, and negligible error in angle between diode and C-Mount in all axes.

**Laser Diode A** - 680 nm, 800 mW, 6% AR coating on front facet
**Laser Diode B** - 665 nm, 800 mW, 8% - 12% standard coating
**Laser Diode C** - 665 nm, 200 mW, ‘mistakenly got a low facet coating reflectivity’

Each diode had test datasheets included, which are shown in Appendix F. Referring to the first two data sheets, both device A and B appear to behave like lasers; they have a definite threshold current, and output power increases linearly above this point. At a given current, both these devices have comparable output powers.

Referring to the third datasheet in Appendix F, it can be seen that device C has no definite threshold; instead, it has a soft “knee” in its PI curve, such that it turned on more gradually than would be expected from a laser. At a given current, this device ex-
hibits significantly lower output power than diode A and B. The following explanation was obtained from an RPMC engineer:

*They were created by a misaligned bar coating fixture that lead to "shadowing" of the facet coating, and the layer thickness deposited on the facet was not what we intended.*

Further investigation into what happened to BAL Diode C is presented in Section 6.3.2.

### 4.2 BAL Housing

The BAL housing was designed to:

- Allow for fine positioning of the diode.
- Allow for temperature stabilization of the diode.
- Protect the diode from dust and air currents.
- Allow for seeding of the incoming laser beam into the diode.

The housing was composed of three separate pieces, each of which was bolted directly to the optics table: a diode mount, a collimating lens mount, and a Plexiglas shield.

#### Diode Mount Assembly

As discussed in Section 4.1, the diodes were attached to a C-Mount by RPMC. The C-Mount was attached to a machined copper plate (Part F in Figure 4.1), which served as a temperature-stabilized heatsink, as well as one of the electrical contacts for the diode. The other electrical contact was a copper clamp (Part G in Figure 4.1) that was mechanically attached but electrically isolated from the copper heatsink. Also attached to this copper heatsink was a pair of power resistors (Part H in Figure 4.1). One power resistor (5.6 Ohm, 35W, Digikey TCH35P5R60J-ND) was intended to heat the copper heatsink while the BAL was off, in order to prevent large temperature fluctuations and reduce realignment time. The other power resistor (1 Ohm, 35W, Digikey TCH35P1R00J-ND) was part of a diode protection circuit (see Section 4.3.1), and was mounted to the heatsink simply so its heat could be efficiently removed. Finally, a thermistor (Thorlabs TH10K) was embedded in the copper heatsink to allow for temperature measurement.

Four copper heatsinks were created. The motivation for this was to keep diodes on their own heatsink as much as possible, thereby reducing the number of times each diode had to be handled, thus reducing the risk of damage.

A thermoelectric cooler (Melcor UT4-12-40-F1, Part E in Figure 4.1) was sandwiched between the copper heatsink and a larger aluminum heatsink (Part D in Figure 4.1) to provide temperature stabilization. Thin sheets of thermally conducting pad (Bergquist Sil-Pad A1500) were placed between the thermoelectric cooler (TEC) and
both heatsinks to improve heat conduction. The TEC was held in place between the two heatsinks simply with compression forces caused by four lengths of nylon threaded rod.

This nylon threaded rod had been converted into custom screws by cutting four equal lengths, and epoxying a nut to each end. The rods threaded into the copper heatsink, and were tightened against the back of the aluminum heatsink. The need for custom nylon screws was caused by the fact that there were no readily available nylon screws in the correct length. The threaded rod (10-32 threads) for these screws was obtained from Pacific Fasteners in Burnaby. M5 threaded nylon rod was also obtained for the custom nylon screws described in the next paragraph.

The aluminum heatsink was fastened to a linear stage (Klinger, Part B in Figure 4.1) using custom nylon screws. The stage permitted translation in the x-axis. Nylon screws were used to restrict heat conduction to the stage, and a Plexiglas spacer (Part C in Figure 4.1) with an air cavity in the middle was also sandwiched between the stage and the aluminum heatsink in a further attempt to limit heat conduction. The intention was to prevent heat fluctuations in the aluminum heatsink from being transferred to the stage, would could result in changes to the position of the stage, or creep. Finally, an adapter plate (Part A in Figure 4.1) was used to connect the stage to the optics table.

The aluminum heatsink was designed to be fairly large, such that it had a large thermal mass. This provided the TEC with a large, stable reservoir in which to dump heat, which would not undergo fast temperature fluctuations. Initially it was hoped that heat exchange through convection with still air would be sufficient to keep the aluminum heatsink in thermal equilibrium at a reasonable temperature, however, it was
found that heat was not removed quickly enough while the BAL was running, and the aluminum heatsink became excessively hot. Cooling fins (not pictured in Figure 4.1) were attached to the top and rear of the aluminum heatsink, but these also proved to be insufficient. The addition of a fan that forced air over the fins proved to remove enough heat to keep the aluminum heatsink in thermal equilibrium, at a reasonable temperature. The fan was attached to the table with the help of sorbothane bumpers which eliminated vibration transfer to the table.

Collimating Lens Mount

The light emitted from the BAL is highly divergent, thus a collimating lens is needed very close to the diode in order to collimate the beam. In conversations with Shvarchuck, it was indicated that the z-position of the collimating lens relative to the diode is an essential adjustment. Thus, a high-precision linear stage (Edmunds NT56-422, Part E in Figure 4.2) was obtained. Attached to this stage was a two-axis lens positioner (Thorlabs CT102, Part A in Figure 4.2), which held the collimating lens (Thorlabs C230TM-B, f = 4.5mm) in a collimating tube (Thorlabs LT230P-B), and allowed for translation of the collimating lens in the x- and y-axes. In Figure 4.2, Parts B, C, and D were posts and a clamp used to connect the linear stage to the lens positions. Part F was an adapter used to connect the linear stage to the optics table.
Plexiglas Shield

A small shield was used to cover both the diode mount assembly and the collimating lens mount. This shield, made of Plexiglas and bolted directly to the optics table, had an AR-coated window (Thorlabs WL11050-C11) installed in the front, and was open at the back to allow the large aluminum heatsinks cooling fins to poke out and be cooled by the fan. There was a small gap between the shield and the components it was protecting. Also in the front of the shield was a small hole which allowed adjustment of the z-stage while the shield was in place. Plexiglas was chosen as the material so that the BAL could be observed while being adjusted and while in operation.

This shield was designed to prevent air currents from affecting the temperature-stabilized copper heatsink. It also restricted the movement of dust towards the BAL diode. Although not implemented for this prototype stage of operation, the shield was designed so that a thin piece of rubber sheet could be installed to completely seal off the small gap between the shield and components. This would further reduce dust contamination, and also reduce the effect of water vapor on the diode, if desiccant material was placed inside the shielded region. Dust is a large concern in this application. As the C-Mount is an open laser package, the laser diode is completely exposed and unprotected. RPMC warned that unless precautions are taken, dust will accumulate on the front facet, and laser performance will degrade prematurely, albeit slowly. It should be noted that after approximately one month of operation with the shield in place, but no rubber seal, BAL Diode C showed no obvious dust accumulation when viewed with the SEM.

4.3 BAL Support Electronics

The BAL, being a high power device, runs at a higher current than the other laser diodes used in the lab. Thus, the current controller used to drive the BAL differs from the one used for the other in-house diodes, and the diode protection circuit is slightly modified.

4.3.1 BAL Diode Protection Circuit

Diode lasers are notoriously easy to destroy with high-voltage spikes. Precautions are taken in multiple stages of the BAL electronics system to shield the diodes from such spikes. The diode protection circuit is the last line of defense.

The protection circuit includes a reverse-voltage protection diode, which protects the diode from destruction in case the current controller is connected to it backwards. A ferrite and pair of capacitors act as a low-pass filter, shielding the diode from voltage spikes.

The electrical design of the circuit is based on the lab-standard protection circuit, but with a few modifications. Due to the higher current that this diode runs at, the conventional 10Ω lead resistor is replaced by a 1Ω power resistor for power considerations.

Depicted schematically in Figure 4.4, the protection circuit is built right onto the BAL’s copper heatsink to minimize its distance from the diode. The lead resistor’s
Figure 4.3: BAL Mount Assembly.
heatsink (along with a heater resistor) is connected directly to the copper plate, for heat dissipation. The copper plate also provides the anode (+) lead connection. An image of the copper plate and diode protection circuit is provided in Figure 5.2.

Lab standard protection circuits have a built-in diode shorting switch. In this case, the connector for the BAL protection circuit can be plugged into a “shorting plug” when the diode is being stored, to protect it from static (see Figure 5.1). When the protection circuit is plugged into the current controller, a switch spliced into the lines from the current controller acts as the shorting switch (see Figure 4.5).

### 4.3.2 BAL current controller

The BAL diode operating current of 1.5 to 2 A is too high for the lab built current controllers. Instead, we purchased an MPL2500 laser diode current driver from Wavelength Electronics (Figure 4.6). This driver is rated to 2.5 A, which exceeds the BAL current by a comfortable margin. The controller was purchased along with a cable assembly, part number WCB102. The MPL2500 is depicted photographically in Figure 4.6, and the cable (along with its color scheme) is given in Figure 4.7. Refer to the MPL2500 product manual for more information.

The MPL itself has no user readout output, and only two built-in user adjustments – potentiometers for set current and limit current. When operating the BAL, it is desirable to have a set / limit current readout, an enable switch, a current monitor BNC connector, a current modulation BNC connector, and a modulation switch. All of these features are provided by a custom MPL control box. The control box presently in use is showing the signs of feature creep – it is recommended that for future BALs, a small number of these simple control boxes are constructed in a more permanent manner. The control box circuit diagram is depicted in Figure 4.8. Photos of the control box are presented in Figure 4.9.
CHAPTER 4. BAL DESIGN

Figure 4.5: BAL Shorting Switch.

Figure 4.6: MPL 2500.
### Figure 4.7: MPL 2500 Cable (WCB102) and color scheme. From [18]

<table>
<thead>
<tr>
<th>PIN</th>
<th>WIRE COLOR</th>
<th>CABLE #</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RED</td>
<td>1</td>
<td>V+</td>
</tr>
<tr>
<td>2</td>
<td>ORANGE</td>
<td>1</td>
<td>Modulation Input</td>
</tr>
<tr>
<td>3</td>
<td>GREEN</td>
<td>1</td>
<td>Monitor GND</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>N/A</td>
<td>Constant Power Feedback</td>
</tr>
<tr>
<td>5</td>
<td>JMPR</td>
<td>N/A</td>
<td>Constant Current</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>RED</td>
<td>2</td>
<td>Laser Diode Anode</td>
</tr>
<tr>
<td>8</td>
<td>BLACK</td>
<td>2</td>
<td>Laser Diode Cathode</td>
</tr>
<tr>
<td>9</td>
<td>BLACK</td>
<td>1</td>
<td>GND</td>
</tr>
<tr>
<td>10</td>
<td>BLUE</td>
<td>1</td>
<td>LD Enable</td>
</tr>
<tr>
<td>11</td>
<td>WHITE</td>
<td>1</td>
<td>Power Monitor</td>
</tr>
<tr>
<td>12</td>
<td>BROWN</td>
<td>1</td>
<td>Current Monitor</td>
</tr>
<tr>
<td>13</td>
<td>YELLOW</td>
<td>1</td>
<td>Limit Current Monitor</td>
</tr>
<tr>
<td>14</td>
<td>GREEN</td>
<td>2</td>
<td>PD Anode</td>
</tr>
<tr>
<td>15</td>
<td>WHITE</td>
<td>2</td>
<td>PD Cathode</td>
</tr>
</tbody>
</table>
CHAPTER 4. BAL DESIGN

Figure 4.8: Electrical schematic of control box for MPL2500.

(a) Left view  (b) Right view

Figure 4.9: Photographs of MPL2500 control box.
In the design phase for the BAL electronics, there was a plan to wire a heater resistor which would turn on whenever the BAL was off, to help keep the temperature of the BAL assembly more stable. The control box was wired to support this feature. In the existing control box, the BAL’s enable switch is actually a double pole switch (not drawn): one pole is used to enable the BAL, and the other to enable the heater when the BAL is disabled. The intent, initially, was for the heater current to run directly through this switch. However, it was realized that the wiring used for this purpose would be marginal for carrying such current loads, and thus the heater feature was never used.

During early testing of the MPL2500, it was discovered that even though the manual states that a mechanical relay in the MPL shorts the leads of the laser when the laser is disabled, there was still a 2.9 mV drop across the leads. At first, a faulty relay was suspected, but conversations with an engineer and Wavelength confirmed that this behavior was common to MPL2500. The voltage across the “shorted” diode leads was also verified in our second MPL2500. Wavelength claims that the voltage can build up due to contact resistance in the relay. Thus, part of the purpose of the custom-added diode shorting switch was to properly short the diode when it was not in operation.
4.4 Additional Optics Components

Several additional components were essential to the functioning of the BAL. These have already been described briefly in Section 2.1, however, since each BAL setup will need a set of these components, they are listed again here for easy reference.

Anamorphic Prism Pair

The Anamorphic Prism Pair (APP) (Thorlabs PS871-B) was used for beamshaping the slave beam before it was seeded into the BAL. For our particular slave diode, an expansion of the beam 3x in the horizontal axis was appropriate, while the beam size in the vertical axis was left untouched, as it was quite close to the BAL’s beam height. An image of an APP is shown in Figure 4.10, however, it should be noted that this is a 4x expander, while the one used for the experiments in this report was 3x.

Visible in the figure is the printout of the sheet used to align the APP. On the Thorlabs website, a table of prism angles is given, and their corresponding magnification. Using a CAD software program, it was possible to make scale sketches of the prisms, and position their relative angles very precisely. This sketch was then printed and taped to the prism pair mount. The prisms could then be placed (by eye) on the sketch, and clamped. This was a very reliable method of setting up prism pairs if the magnification needed was known. However, it was very cumbersome if a variety of magnifications were to be tried. A recommendation for a better APP mount is given in Section 7.2.2.
4.4. ADDITIONAL OPTICS COMPONENTS

Ultrastable Mirror Mounts

Nearly all mirrors used on the Optics table were standard high reflectivity dielectric mirrors, in standard Newport Ultima U100-A mirror mounts. However, the two mirrors which directed the slave beam into the BAL diode were ultrastable mounts, which featured high precision adjustment screws and very small amounts of creep in the mirror setting. High precision was required because the slave had to be directed into a very small spot (the BAL was only 1 µm tall). Ultrastability was important because there was a fairly large distance between the mirror and the BAL chip, so if the mirror position crept over time, a very small angular change could result in a large change in the position of the beam at the BAL facet. The mirror mounts were obtained from a pile of used equipment, and although no model number is printed on them, it is suspected they were manufactured by Klinger, an optics company which no longer exists. A photograph of one of the ultrastable mirror mounts is given in Figure 4.11.

Cylindrical Lens and Mount

A $f = 150$mm cylindrical lens (Edmunds NT46-024) was used to set the slave injection angle, and to collimate the BAL’s slow axis (the horizontal direction). The cylindrical lens was held in a Newport CYH-2 Lens Holder. Unfortunately the only available rotational stage was a rather bulky Newport RSP-2T. This allowed the lens to be rotated about the z-axis. The rotational stage was mounted on a pair of linear stages, which allowed translation on the z- and x-axes. An image of the lens, lens holder, and rotational stage is given in Figure 4.12.
Pick-off Mirror

This mirror (Figure 4.13) was used to pick off the amplified BAL beam from the free-running BAL beam. A small plane mirror was found in a pile of used equipment, and was clamped into a beamsplitting cube mount (Thorlabs KM100P). It was attached to a linear stage using optics posts, and the stage allowed translation in the x-axis. This allowed the mirror to be moved further into or out of the BAL beam, since the amplified beam was not always in the same location (it depended on a number of alignment parameters). This stage allowed the position of the pick off mirror to be optimized so that all of the amplified beam was caught, but a minimum amount of the BAL free-running beam was caught. It was also important to make sure that none of the injected slave beam was blocked by the pick off mirror.
Chapter 5

BAL Installation and Alignment Procedure

These step-by-step instructions should allow the reader to replicate our BAL double-pass amplifier. The section assumes:

- All of the BAL housing parts are machined, and all of the support electronics are assembled and wired.
- The Master laser is grating stabilized, and the Slave laser is injection locked.

5.1 BAL Installation

Before anything, the BAL must be installed on the copper heatsink, and mounted in its housing. During these handling steps, extreme caution must be observed. The BAL is very fragile, and can be destroyed by a static discharge.

1. **Connect the “shorting plug” Molex connector to the copper heatsink.** This simply shorts the two leads of the diode so that no static voltage can build up while you are handling the diode and heatsink. See Figure 5.1.

2. **Install BAL C-Mount on copper heatsink.** The C-Mount attaches with a single 2-56 screw; ensure that the sides of the C-Mount are parallel with the sides of the copper heatsink using a square. Hold the square tight against the side of the C-Mount until the single 2-56 screw has been fully tightened. Then tighten the clamp screw, so that the small copper clamp closes on the C-Mount’s wire lead. See Figure 5.2.

3. **Attach copper heatsink to aluminum block.** Hold the copper heatsink in front of the aluminum heatsink, insert the 4 nylon screws, and begin to tighten. Before fully tightened, lower the TEC between the two heatsinks, with the “COLD SIDE” label facing towards the copper heatsink, and centre it (just by eye).
4. **Attach BAL’s Electrical connections.** The wires running to the BAL current driver have a shorting switch spliced in (Figure 4.5). Set this switch of “OFF” to short the leads. Disconnect the “electrical short” Molex connector from the BAL (see Figure 5.1), and plug the BAL into the 6-pin Molex connector. Connect the TEC to the current controller’s output connector.

5. **Install the BAL collimating lens assembly.** If the collimating lens assembly is already assembled, simply screw its aluminum baseplate to the table while ensuring that the baseplate is aligned with the table using a square. If the collimating lens assembly is not assembled, or if misalignment of the assembly is suspected, disassemble it and then assemble as indicated by Figure 4.2, while aligning it thusly:
5.1. BAL INSTALLATION

The collimating lens 2-axis positioner should be installed so that its optical axis is parallel with the direction of travel of the z-axis linear stage. The easiest way to ensure this is now described. Install the z-stage onto its aluminum baseplate. Next, hold the long edge of the aluminum baseplate against the optics table (to make sure it’s parallel with the ground). Finally, hold a level against the 2-axis positioner and rotate it until the level is flat, and then tighten the mini post clamp to secure the entire collimating lens assembly.

![Figure 5.3: The installed collimating lens assembly](image)

6. **Temperature stabilize the BAL.** Ensure that the cooling fan is on, plugging it into its DC adapter if necessary. Turn on the temperature controller, set it to the appropriate temperature, and enable its output.

7. **Turn BAL On.** With the BAL shorting switch still set to OFF (i.e. shorted), turn on the “Enable” switch on the BAL control box. Note that the copper heatsink should not be touched while the BAL is on. Adjust the current on the BAL current controller to well below the diode’s threshold current. Turn the current Enable switch OFF, turn the diode shorting switch ON, and turn the Enable switch ON. Turn the BAL current up until the diode is lasing (as the next alignment stage works better when you align for laser light, not ASE).

8. **Perform preliminary BAL alignment.** If the cylindrical lens is installed, remove it by unscrewing the cylindrical lens mount from the rotating lens mount.
If the BAL is uncomfortably bright during this stage, simply insert a ND filter into the beam. Using a card about 1 m from the BAL, adjust the collimating lens’ z-position until the beam is vertically collimated (so that it forms a broad, short stripe).

Adjust the collimating lens’ y-position so that the beam is at a 2.5 in height about 1 m from the BAL. Adjust the x-positions of the BAL and the collimating lens such that the collimating lens is nearly centered in its adjustment, and so that the beam runs along the bolt line which the collimating lens is centered on.

9. **Install Plexiglas shield.** Turn the BAL off using the “Enable” switch for this step (as mentioned before, touching the copper heatsink while BAL is on is inadvisable). While placing the shield over the BAL housing, ensure that the wires leading to the copper heatsink are pushed out of the way, so that the shield has enough room to fit over the copper heatsink. In addition, ensure that the collimating mount’s z-stage adjust knob is not rubbing on the side of its clearance hole. Tighten two 1/4”-20 screws with washers down to keep the shield in place. The BAL can now be turned back on with the “Enable” switch.

![The Plexiglas Shield](image)

**Figure 5.4: The Plexiglas Shield**

### 5.2 Alignment for Double-Pass Amplification

The following steps assume that:

- The BAL is being operated at a temperature and current for which the given diode will serve as an amplifier at 671 nm.

- The BAL has been fully assembled and preliminarily aligned, as described in the previous subsection.

- The Master / Slave set-up is operating and locked at 671 nm.
1. **Adjust Slave Beamshape** The shape of the Slave beam must be adjusted, so that the BAL and Slave have the correct beamshapes relative to each other. Insert a mirror into the Slave beam path before it hits the ultrastable mirror mounts, and direct it far away to a white card. Insert mirrors to redirect the BAL towards this white card as well. Ensure that both beams have propagated approximately the same distance when they reach the card. Reinstall the cylindrical lens for this step, and adjust its z-position to collimate the BAL’s slow (wide) axis.

Both the BAL and Slave far-field patterns should be visible on the card, similar to Figure 6.8. The goal of this step is to obtain a slave beam with a far-field shape that is approximately the same height as the BAL, and somewhere between a third and half the width of the BAL. If the slave was installed with the wide axis of its beam horizontal, as directed in Section 3.4.2, then it should already be somewhat wider than it is tall.

A number of tools are available for beamshaping, including cylindrical lenses, plano-convex (PCX) lenses, and Anamorphic Prism Pairs (APP). For the work described in this report, an APP was used to expand the beam’s horizontal shape; a 3x expander proved to give a beam that was approximately the correct size. In addition, a PCX ($f = 400\text{mm}$) lens was used to conveniently improve the Slave’s collimation without adjusting the Slave’s collimating lens. This is effectively a beamshape modification as well. A method of beamshaping that allows for greater control is recommended in Section 7.2.2.

Regardless of the beamshaping method used, the slave beam should be approximately the same height, and between half and a third the width of the BAL before proceeding. Once this is achieved, remove the mirrors that send the Slave and BAL light to the card, and uninstall the cylindrical lens before moving on.

2. **Align BAL with CCD.** For these experiments, a Linux computer with a framegrabber card was used to monitor the CCD output. To start the framegrabbing software, open a terminal window and type `xawtv`, then right click on the image window to bring up the options menu. Select `NTSC`, and play with the contrast and brightness settings until an image is visible. Adding or removing filters from in front of the CCD camera may be necessary. Adjust the locations and angles of the CCD mirrors, filters, and lenses, so that the image of the BAL near-field is centered in the CCD. Care must be taken that the BAL beam does not clip on these components.

3. **Alignment of Slave with BAL axis.** Turn the BAL either below threshold or OFF (using the Enable switch on the control box). If high slave powers are being used, it may be prudent to inject only a fraction of the Slave power for this step to avoid front facet damage to the BAL. This precaution comes from a phone call with Shvarchuck. However, for Slave powers on the order of 20 mW, as we have been using, we feel it is safe to inject all of the Slave’s power.

While monitoring the BAL near-field using the CCD, use the two ultrastable mirror mounts to “walk” the slave beam until it is both at its brightest and centered on the BAL chip. The brightness of the spot indicates that the beam is not only
hitting the BAL chip’s center, but is coming in on the z axis. Another indication that the beam is on axis is that, if the BAL collimating lens is moved back and forth along the z axis, the slave beam will appear to blur in the near field CCD image. If the Slave beam is not on the z-axis, then the the beam will not only blur but will also translate. Both adjustment axes of both mirrors must be adjusted to achieve this on-axis injection.

When the beam is being injected on axis, then the Slave will appear to illuminate the front facet of the BAL, even when the BAL is off. This is yet another positive alignment indication.

Further alignment adjustment can be attained by attempting to minimize the BAL threshold current. Modulate the BAL current, and examine its output power off a glass slide using a power-meter. Monitor the power vs. current behavior on the oscilloscope. By adjusting the ultrastable mirrors and collimation, it should be possible to increase the height of the peaks, change their shape, and see some “structure” in the photodetector trace. Figure 5.5 illustrates how the photodetector trace should change when the BAL is being successfully seeded.

4. **Position cylindrical lens.** Screw the cylindrical lens back into its mount. Align the cylindrical lens and adjust its x-position to be on axis, by aligning the cylindrical lens’ back-reflections of the slave light. This can be accomplished by

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**Figure 5.5**: Illustration of the difference in power vs. current behavior (near threshold) of the BAL when the Slave is aligned. The current vs. time, not shown, is triangle-wave ramping up and down near the BAL threshold.
5.2. ALIGNMENT FOR DOUBLE-PASS AMPLIFICATION

Seed beam injected

Seed beam blocked

Figure 5.6: BAL near-field image, with and without seeding beam.

placing a card with a hole in it near the cylindrical lens, and allowing the slave light to pass through the hole.

Note down the cylindrical lens’ x-stage micrometer position. This is the zero position; every 80 µm of translation results in a 1° shift in injection angle. For the injection direction used in this report, the micrometer reading is decreased from its zero position by the appropriate amount. This ratio is obtained from Equation 5.1, where \( d \) is the cylindrical lens’ offset and \( f \) is the focal length of the collimating lens. This equation comes from [16].

\[
\theta \approx \frac{d}{f} \tag{5.1}
\]

5. Re-Align for angled injection. There are a number of ways this step can be performed. The first may be to once again optimize the BAL’s threshold current, as in Step 3 above. It may also be helpful to examine the BAL near field on the CCD. When the seed beam is well aligned, there should be low intensities emanating from the entrance side of the BAL front facet (due to depletion of the gain medium there) and high intensities from the exit side of the BAL front facet (due to the amplified beam). This is illustrated in Figure 5.6.

Increase the BAL current to the intended running current, and allow the temperature to stabilize. Install the pick-off mirror. The best way to do this is to examine the edge of the BAL far field radiation pattern for a side lobe – the emerging amplified beam. Move the pick off mirror in to cut off only this side lobe, and direct it to a power meter.

Block the slave beam, and there should be a drop in the power in this side-lobe. While blocking and unblocking the slave, adjust the fine position of the pick-off mirror to maximize the difference in power in this sidelobe. Now, every adjustment should be used in turn to maximize the power in this side-lobe. Start
with the ultrastable mirror mounts – keep in mind that you must “walk” both of them to find a global maximum in sidelobe power. Moving just one mirror to maximize power will not generally result in optimal performance. Optimize the z-position of the collimation lens, the rotational adjustment of the cylindrical lens, and the z-position of the cylindrical lens. Re-optimize the pick-off mirror location as described earlier, and repeat this whole process once or twice more.

If all has gone well, then congratulations, you have achieved BAL double-pass amplification. Take a vat of epoxy and pour it over the optics table to make sure that everything stays aligned. If not, don’t despair. There are many variables to play with, such as BAL temperature and current and BAL diode.
Chapter 6

BAL Measurements and Results

6.1 Free Running Characterization

Each of the three BAL diodes (A, B, and C) was installed in turn onto the diode mount. Two different measurements were made while the BALs were free-running (not seeded):

**PI Curves** (Output Power vs. BAL Current, also known as LI curves) were obtained by triangle-wave sweeping the BAL current at a rate of 8.5 Hz. The current was swept in a range spanning from below the threshold point, up to the operating current. The free-running output light of the BAL was recorded with a photodetector and power meter, while the BAL current was monitored using the ‘Current Monitor’ port on the BAL current controller. Data was recorded using a digital oscilloscope. Curves were taken at three different temperatures (10°C, 15°C, and 20°C).

**Spectra** were not taken while the BAL current was sweeping, but rather at a variety of steady diode currents. At each current, the free-running light from the BAL was directed into an optical fiber, which was connected to the Optical Spectrum Analyzer (OSA). Data was digitally recorded onto a floppy disk. Spectra were only taken at 15°C.

It should be noted that the spectrum for BAL Diode A was recorded using a linear scale, while the spectra for Diode B and C were recorded using a logarithmic scale. Also note that the power in PI curves is presented in arbitrary units. Absolute power was not recorded.
CHAPTER 6. BAL MEASUREMENTS AND RESULTS

Figure 6.1: Free-Running Power vs. Current for BAL Diode A.

Figure 6.2: Spectra of BAL Diode A at Varying Currents.
6.1. **FREE RUNNING CHARACTERIZATION**

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**Figure 6.3**: Free-Running Power vs. Current for BAL Diode B.

**Figure 6.4**: Spectra of BAL Diode B at Varying Currents.
CHAPTER 6. BAL MEASUREMENTS AND RESULTS

Figure 6.5: Free-Running Power vs. Current for BAL Diode C.

Figure 6.6: Spectra of BAL Diode C at Varying Currents.
6.2 Seeded Characterization

6.2.1 BAL Diode A

BAL Diode A had a free-running wavelength of approximately 682 nm. Despite attempts to cool the diode and inject with slave light at 671 nm, no significant amount of amplification could be observed. This was likely due to the large gap between the BAL’s free-running wavelength and the injected slave wavelength. Attempts to seed this diode were abandoned in favor of the other diodes.

6.2.2 BAL Diode B

BAL Diode B had a free-running wavelength close to 665 nm. Using injected slave light at 665 nm, the BAL output power was measured as a function of seeded slave power, at a variety of BAL currents. The data collected at an injection angle of 10° is presented in Figure 6.7. Similar data sets were taken at injection angles of 12.5° and 7.5° with very similar results. As can be seen from Figure 6.7, the BAL never put out more power than it was seeded with, in other words it was not acting like an amplifier. It is suspected that most or all of the output light observed is simply slave light reflecting off the back facet of the BAL. It is hypothesized that the front facet reflectivity of BAL Diode “B” is too high to allow it to act as a gain medium as intended; it is a much too effective laser, and its free-running modes dominate.

![Figure 6.7: Locked BAL Output Power vs. Injected Slave Power for BAL Diode B.](image)
The procedure for collecting saturation curves (like those in Figure 6.7) should be mentioned. The injected power from the slave was varied using a beamsplitter and half wave plate combination. The output power was picked off with a mirror and measured with a power meter. However, often some of the BAL’s free-running light would be caught by the mirror as well. In order to determine this “baseline” of free-running light, a measurement of output power was taken while the slave was blocked. This baseline was later subtracted from the total output power readings.

### 6.2.3 BAL Diode C

All measurements made in this section were with BAL Diode C. Initially slave light at 665 nm was used, since this matched the BAL’s free-running wavelength closely. Later, once favorable results had been obtained, we switched to 671 nm.

#### Far-field Beamshape

A comparison between the far-field radiation patterns of the slave and free-running BAL is shown in Figure 6.8. The slave beam is approximately one third the width of the BAL beam, and approximately the same height. Exact tuning of the beamshape was not possible due to a limited supply of cylindrical lenses, and the imprecision of the anamorphic prism pair adjustment. This beamshape was used for all the experiments presented below in this section.

![Figure 6.8: Relative Far-field Beamshapes of Slave and BAL.](image)
6.2. SEEMED CHARACTERIZATION

Amplification at 665nm

Amplification with this BAL setup was first demonstrated at 665 nm. This wavelength is closer to the master, slave and BAL Diode C’s free-running wavelengths, so more power was available and it was easier to lock at this wavelength. An injection angle of $10^\circ$ was chosen since this was close to Shvarchuck optimum value of around $13^\circ$. A more extensive investigation of injection angle was completed later.

The BAL was run at four different currents, and always at a (somewhat arbitrary) temperature of 16.65°C. The saturation curves (collected using the same procedure as described in the BAL Diode B section) are presented in Figure 6.9. It can be seen that a gain of nearly 10x was observed at maximum slave power. However, 665nm is not the desired wavelength, so the successive experiments focused on both optimizing BAL output power, and shifting wavelength towards 671nm.

![Locked BAL Output Power (mW) vs. Injected Slave Power (mW) at 665nm](image)

Figure 6.9: Saturation Curve for BAL Diode C at 665nm.

Injection Angle Investigation

With the BAL current at 1.8A, and the BAL temperature at 16.65 °C, saturation curves were obtained. This data is shown in Figure 6.10. The injected light for this experiment was still at 665nm. Interestingly, $5^\circ$ was found to be the optimal injection angle for this particular chip, beamshape, wavelength, current, and temperature. This data is re-plotted in Figure 6.11 to more clearly show the relationship between injection angle and gain. It should be noted that the optimum injection angle is expected to be highly
dependent on beamshape, and for this experiment only one beamshape (Figure 6.8) was attempted.

**Amplification at 670.5nm**

After determining that the optimum injection angle was 5°, the Master and Slave were pulled to 670.5nm assisted by heating both diodes to around 45°C and using grating feedback. This 670.5nm light was seeded into the BAL, and saturation curves were again produced. Data was taken at BAL temperatures of 20 °C and 30 °C, and at BAL currents of 1.8A and 2.0A. The results are presented in Figure 6.12. A gain of approximately 10 x was observed at high injection powers.
6.2. **SEEDED CHARACTERIZATION**

Figure 6.11: Gain versus Injection Angle for BAL Diode C at 665nm.

Figure 6.12: Saturation Curve for BAL Diode C at 670.5nm.
6.3 Front Facet Investigation

As can be seen from Section 6.2.3, BAL Diode C proved to be the best amplifier. This was an interesting surprise, since Diode C had been included in the diode shipment from RPMC as a free device - it was essentially junk to RPMC. The diode that was paid for (Diode A) did not work at all in this application, although it’s not entirely clear whether this was due to too-high front facet reflectivity, or a free-running wavelength that was too far from 671nm. Regardless, an investigation into why Diode C worked best was launched.

6.3.1 Optical Microscope

All three diodes were first examined with an optical microscope. No particularly interesting features were visible on the front facets of Diodes A or B, however, an interesting ‘flaking’ pattern was visible on Diode C. This optical microscope image, captured with a CCD camera, is shown in Figure 6.13. Unfortunately no further details could be resolved using the optical microscope.

6.3.2 SEM Images of Diode C

Next, a Scanning Electron Microscope (SEM) was used to image the diodes. The SEM at UBC Earth and Ocean Sciences (EOSC) was used; contact information is provided in Appendix E. Small aluminum mounting platforms are available for mounting sam-
6.3. FRONT FACET INVESTIGATION

Figure 6.14: Modified SEM Platform for C-Mount.

Samples to be imaged by the SEM, however, for these experiments a mounting platform (Figure 6.14) was modified in the machine shop to allow the C-Mount to be securely fastened and grounded. A 2-56 hole was drilled and tapped in the centre, which allowed the C-Mount to be screwed down. In addition, a small piece of solid-core wire was wrapped around the mounting platform, soldered in place, and bent upwards so that it contacted the C-Mount’s wire lead. The purpose of this was to electrically short the laser diode’s anode and cathode, preventing any static charge from building up while the diode was being imaged. Full directions for using the SEM are available in the EOSC laboratory.

Three different detection modes were used in the SEM experiments. Both Secondary Electron (SE) and Backscattered Electron (BSE) modes were used to image the diodes. SE provided more topological detail while BSE gave more details on material composition. In addition, X-Ray backscattering could be used to determine material composition of regions being imaged.

Note that the scale markings indicated in the SEM figures in this report are approximate.

The first SEM image (Figure 6.15) is provided to give a sense of scale, and an idea of where on the C-Mount the BAL is located. The large white block on the top-right of the C-Mount is an insulating material (Aluminum Oxide), and is where the C-Mount wire lead connects to the tiny wires leading to the BAL chip (cathode connection). The C-Mount body serves as the anode.

Figure 6.16 is taken at 385x magnification, in SE mode, and the image is of the front facet of the BAL diode. The flaking is clearly visible in this image, and it seems as if the two layers have slightly different topological heights. An identical image, but taken in BSE mode, is shown in Figure 6.17. This image seems to confirm that the two
different regions on the front facet are composed of different materials. Two closeup images (both SE) of the interface between the two regions are shown in Figures 6.18 and 6.19.

In order to determine the difference in material composition, two X-Ray backscatter spectra (using the SEM’s energy-dispersion X-ray spectrometer) were taken. This technique relies on the fact that elements emit X-rays with characteristic energies when bombarded with high-energy electrons.

One (Figure 6.20) spectrum was captured from the top half of the diode, while the other (Figure 6.21) was captured from the bottom half of the diode. As can be seen from the spectra, only Gallium and Arsenic are present in the top half, while Gallium, Arsenic, Silicon, Indium, and Titanium are present in the bottom half. Given that Titanium is a common material in diode coatings, this seems to indicate that the bottom half of this diode has received some kind of anti-reflection coating, while the top half has either not received this coating, or it has flaked off.

One final image (Figure 6.22) confirms that the active layer for this diode is on the bottom of the chip, near the heatsink. RPMC stated that the active layer is about $1\mu m$ from the bottom, and $1\mu m$ thick, and this is confirmed by this picture.

### 6.3.3 SEM Images of Diode B

After the intriguing SEM images and X-ray spectra from Diode C, similar measurements were taken of Diode B for the purposes of comparison.

The front facet images (Figures 6.23 and 6.24) of Diode B are qualitatively similar to those captured of Diode C. The major difference, of course, is the absence in Diode B of the coating flaking observed in Diode B. A piece of dust on the front facet is also prominent in these images. Figure 6.25 gives a close-up of the BAL active layers, which is very much like the corresponding image of Diode C.

The front facet of the chip is substantially wider than the width of the chip’s active region. However, the active layer appears to extend the chip’s entire width. During imaging of Diode C, it was unclear how the actual active region was different from the rest of the active layer. A potential explanation was stumbled upon while examining a dust particle on the diode’s active layer under high magnification (see Figure 6.26). As a side note, an X-Ray spectrum (not saved) indicated that this dust particle was in fact a piece of Gold.

Figures 6.26 and 6.27 show an interface material just below the active layer. The spacing between these two images is consistent with the interpretation that the white material is an electrical conductor, while the black is an insulator. This could give rise to a current density that is concentrated near the white conductor region, leading to an active region of the proper size.

A variety of X-Ray spectra were captured of Diode B. Figure 6.28 was taken of the front facet, far from the active region. The presence of Ga, As, and Si are indicated. Surprisingly, this is quite different from both the coated and uncoated spectra of Diode C (Figures 6.21 and 6.20 respectively). Evidently, either the coating for this diode has quite a different composition, or the diode is not coated at all while its active region contains some Si.
6.3. FRONT FACET INVESTIGATION

Figure 6.15: Low Magnification view of BAL and C-Mount.

Figure 6.16: Secondary Electron Image of BAL Diode C Front Facet.
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Figure 6.17: Backscattered Electron Image of BAL Diode C Front Facet.

Figure 6.18: Secondary Electron Image Detail of Flaking in Middle of BAL Diode C.
Figure 6.19: Secondary Electron Image Detail of Flaking on Side of BAL Diode C.

Figure 6.20: X-Ray Spectrum of Top Half of BAL Diode C Front Facet. Indicates presence of Ga and As.
Figure 6.21: X-Ray Spectrum of Lower Half of BAL Diode C Front Facet. Indicates presence of Ga, As, Si, Ti and perhaps traces of Al.

Figure 6.22: Secondary Electron Image of BAL Diode C Active Layers.
6.3. FRONT FACET INVESTIGATION

Figure 6.23: Secondary Electron Image of BAL Diode B Front Facet.

Figure 6.29 shows an X-Ray spectrum captured from the diode’s active layer. The detected elements are Ga, Al, Si, P, and In. Captures were also obtained of the hypothesized conducting and insulating materials at the bottom of the active layer, referred to above. The insulator’s spectrum is presented in Figure 6.30, detecting the presence of Ga, As, Si, Pt, In, and Ti. The conductor’s spectrum, in Figure 6.31, indicates the elements Ga, Al, Si, Pt, and In.

The characteristic X-ray lines of P and Pt are very close together. Thus, there is some uncertainty as to the identity of these elements in these spectra. The active layer was decided to contain P, while the insulating and conducting layers were thought to contain Pt. It is possible that all of the detected Pt is actually P, or vice versa.

6.3.4 Dummy Diode

An image (Figure 6.32) of a ‘dummy diode’ is included to show the importance of keeping diodes clean and free of dust. This is a particularly bad case since the diode was in a dirty case and not kept protected, however, it does give some idea of how detrimental dust on the front facet could be.
Figure 6.24: Backscattered Electron Image of BAL Diode B Front Facet.

Figure 6.25: Backscattered Electron Image of BAL Diode B Active Layer.
6.3. FRONT FACET INVESTIGATION

Figure 6.26: Backscattered Electron Image of BAL Diode B. Right insulator / conductor boundary.

Figure 6.27: Backscattered Electron Image of BAL Diode B. Left insulator / conductor boundary.
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Figure 6.28: X-Ray Spectrum of Diode B Front Facet. Indicates presence of Ga, As, and Si.

Figure 6.29: X-Ray Spectrum of Diode B Active Layer. Indicates presence of Ga, Al, P, Si, and In.
6.3. FRONT FACET INVESTIGATION

Figure 6.30: X-Ray Spectrum of Diode B Insulation Layer. Indicates presence of Ga, As, Si, Pt, In, and Ti.

Figure 6.31: X-Ray Spectrum of Diode B Conduction Layer. Indicates presence of Ga, Al, Si, Pt, and In.
Figure 6.32: Secondary Electron Image of dust on front facet of dummy diode.
Chapter 7

Conclusion and Recommendations

This chapter will summarize the completed work, and also address remaining questions and future directions of the BAL project and Lithium laser system.

7.1 Conclusion

At the beginning of this project, a need was identified for a laser amplifier system at 671nm, which would produce high-power, single-mode light to be used in a MOT for trapping Lithium atoms. Although dye lasers or tapered amplifiers were possible candidates, a broad area laser amplifier system was selected for reasons of cost, ease of use, and availability. The system was to be based on diode lasers, and would have several steps of amplification (Master, Slave, and BAL). A final output power of at least 100mW, and ideally 200mW (after passing through an optical fiber), locked to the absorption line of Lithium, was desired for this system.

In the initial stages of the project, all necessary optics components (that weren’t readily available) were ordered or otherwise acquired. A design for the BAL housing components was created, reviewed, and drafted in CAD. Power supplies were also assembled and wired for the current and temperatures controllers.

Challenges presented themselves early in the project. Construction of the Lithium heat pipe was delayed, and it would not be available during the summer, therefore locking to Lithium’s absorption line was not feasible. Instead, the Master was set to an arbitrary wavelength (approximately at 671nm), to be locked later. The long queue for machining tasks at UBC Physics Machine Shop also presented a challenge, as it resulted in much more machining work done in the Student Machine Shop than anticipated, and a delay in the delivery of the Master housing components. Despite this, the project stayed more or less on schedule.

The BAL Housing components were successfully machined and assembled, and the BAL diodes were installed. Once the Master housing arrived, the Master laser was
assembled, and the Master diode installed. The Slave diode was installed in an already-assembled prototype housing. First light (free-running) was quickly obtained from all three lasers, and characterization was done on all three.

The next steps involved grating stabilization of the Master and injection locking of the Slave. This was done at both 665nm and 671nm. Once a stable Slave beam had been obtained, investigation into seeding the BAL began. Despite extensive experimentation with injection parameters (beamshape, injection angle, temperature, mirror alignment, collimation, for example), amplification could not be achieved with either BAL Diode A or BAL Diode B. A free-running BAL wavelength too far from the seeded wavelength, and too-high front facet reflectivity, were two possible reasons why neither of these diodes worked.

Despite being a ‘reject,’ and free sample, BAL Diode C was tried as an amplifier. This diode had gotten an incorrect AR coating due to misalignment during the coating process, and displayed free-running behavior very unlike a ‘good’ laser (no obvious threshold current, slow turn on, wide emission linewidth). It was hypothesized that this behavior could be attributed to a low front facet reflectivity, and that perhaps this diode was exactly what was needed.

BAL Diode C was imaged using an SEM to try to determine what had happened to it. A flaking pattern was visible, and it appeared that only part of the diode’s front facet had received a coating. However, the flaking was on a part of the front facet that was far from the active region.

After optimizing all injection parameters, BAL Diode C proved to be an excellent amplifier. With an injected Slave power of 20mW, 180mW of single-mode light was obtained at 665nm, for a gain of approximately 9. At 671nm, 14.5mW of injected Slave light resulted in 145mW of single-mode output light, yielding a gain of 10. In both of these cases, the BAL had not yet fully saturated – in other words, more amplified light could be obtained if more Slave light was seeded.

However, the Slave powers given above were the maximum that could be obtained with the Master and Slave diodes used. In order to obtain 14.5mW at 671nm, both the Master and Slave had to be strongly heated, and driven at high currents. This lead to the premature failure of the Slave laser diode, after only approximately 2 months of use. Neither the Master nor Slave were particularly suited to operating at 671nm, as their free-running wavelengths were both around 663nm at room temperature.

Obtaining higher power, and longer lifetimes from the Master and Slave setup, is of the highest priority in the Lithium BAL project. One way to accomplish this is to find Master and Slave diodes with free running wavelengths as close to 671nm as possible. Although large amount of power are not required from the Master (a 10mW diode should easily suffice), a high power Slave is extremely important, as this is currently the most limiting factor on the output of the BAL system.
7.2 Recommendations

7.2.1 Alternative Laser Diodes

Single Mode

The Master and Slave system used in our project made unsustainable use of single-mode diodes. The Lumex diode used in both the Master and the Slave had to be heated substantially in order to work at 671 nm. Heating of diodes can cause drastic reduction in diode lifetime. Indeed, in the beginning of August, the diode being used as a Slave died.

Alternative single-mode diodes are always being sought. At the time of this writing, we are investigating the purchase of a number of promising candidates from QSI. A 5 mW laser may be available with a wavelength centered close to 671, which would make this diode a possible Master candidate. Other higher power diodes are, according to QSI, under development.

New diodes are constantly being posted by Toptica. It is recommended that their stock list is checked by the lab weekly for promising diodes. See http://www.toptica.com/Fabry_Perot_laser_diodes.php. At the time of this writing, their stock list includes promising 30 mW devices at around 675. These devices would make excellent slave candidates.

As evidenced by the early demise of the slave diode used in this project, it is preferable to steer diodes down in wavelength by cooling them, rather than steer them up by heating them. This may require apparatus to cool diodes to below the dew-point without damaging the diode.

BAL

The primary candidate for a further supply of BALs is RPMC, who may have additional stock of diodes accidentally given the same coating as our functional amplifier diode. We are awaiting word from RPMC about whether they can give more details of the errant coating these diodes received, and whether they have additional rejected devices of this ilk lying about. If so, this would be an excellent and hopefully low-cost source of a stock of BALs.

There are a few alternate possibilities under consideration. The prospect of the lab building and coating our own BALs, with the assistance perhaps of Dr. Tom Tiedje and Dr. Bob Parsons, is often raised. A single successful production run would be able to satisfy the lab’s needs for diodes for the foreseeable future, perhaps providing us with a surplus that could be sold to other labs to defray the production cost. However, this approach may be quite tricky. The prospect of buying uncoated diodes, from RPMC or another company, and coating them ourselves with help from Dr. Parsons may be easier to realize.

BAL diodes from other companies are also on the radar. For example, a device similar to the one used by Praeger [13], is manufactured by Coherent (http://www.cohr.com/Lasers/index.cfm?fuseaction=show.page&id=851&loc=834).
CHAPTER 7. CONCLUSION AND RECOMMENDATIONS

7.2.2 Future Work Recommendations

The following recommendations outline further work that should be done to improve or better understand the BAL / Lithium laser system.

Some tests that should be performed on the BAL setup include:

- **Long term stability test of BAL.** In order to be of use, the BAL and Lithium laser system will need to run continuously for hours to days at a time. Our experimentation suggests that, once set-up, the Master and Slave system is stable for at least a day. No long-term stability tests of BAL double-pass amplification have yet been performed. Such a test should be performed to assess the usefulness of the BAL set-up. It is suspected that, once the BAL temperature has stabilized, double-pass amplification will be stable over a similar timescale to the Master and Slave system.

- **Investigation of BAL amplitude noise.** Experience during data-collection suggests that there may be significant amplitude noise in the double-pass amplified light from the BAL. Power meter readings were noisy during collection of the many input power vs. output power graphs presented in this report. However, no amplitude noise data was collected. Amplitude noise may be an important consideration in the MOT laser system, thus such investigations are recommended.

- **Heterodyne beat measurement of BAL.** In order to show that the linewidth of the BAL amplified light matches that of the input light, previous investigators (such as [13] and [16]) have made use of heterodyne measurements, where light from the BAL and frequency-shifted light from its Master are mixed on a photodiode, and the resulting beat frequency spectrum in the light intensity is measured. Previous published investigations of this kind have all revealed the BAL to follow the Master laser precisely, to below the resolution of the measurement device. There is no reason to believe our BAL set-up does not also follow the master’s linewidth, but for completeness it may be a good idea to perform such a measurement.

- **BAL Diode A re-investigation.** BAL Diode A was the first diode to be tried as an amplifier. Although no amplification was observed at that time, it may be possible to make this diode work now (since much more experience has been gained in the alignment, beamshaping, and seeding of BALs since that diode was tried). It may turn out that, with proper alignment, BAL Diode A is a comparable amplifier to BAL Diode C.

- **Test Fibre Coupler.** A six-degree Fibre coupler (from Optics for Research) was purchased, and an adapter has been machined for it. However, no time was available to test how efficiently light could be coupled into a fibre. This is important for the BAL project, since ultimately light from the BAL will be sent via fibre to the MOT table. An investigation into the efficiency of the coupler is suggested.
Some features that need to be added to the BAL setup / Lithium laser system:

- **Cooling of Slave diode below dew-point.** Single mode diodes only seem to be available at least 5 nm above or below our 671 nm target wavelength. For this project’s Master / Slave laser system, diodes with too low a wavelength were heated until they could be stabilized or locked at 671. This led to premature diode death. Diodes available around 675 nm could be made to work at 671 nm if they could be cooled to around 0 °C. This would require a housing which protected the diode from accumulation of dew.

Due to the simplicity of the Slave laser system, it should be straightforward to implement such protection into the Slave diode. Unlike the Master, which must be opened and adjusted on a regular basis, the Slave laser is never touched once it is set-up. Thus, it would be possible to operate the Slave in an atmosphere without any humidity. Options include flowing dry Nitrogen gas through the Slave housing (as mentioned in passing in [5]) or by pumping out the Slave chamber (which would also allow for easier achievement of lower Slave temperatures.

- **Locking to Lithium absorption line.** For the purposes of this project, the Master laser was steered to roughly to 671 nm. For use in a MOT, the laser wavelength will need to be much more precisely locked. This will require a Lithium saturated absorption cell, and associated feedback system optics and electronics. Based on our experience viewing the Master and Slave Fabry-Perot traces and steering the Master wavelength via its grating angle piezo, the mode-hop free tuning range is not very wide. It may be necessary to experiment with more sophisticated feedback systems, incorporating for example current feed-forward to stop the Master and Slave from mode-hopping as they are being tuned.

- **Alternative Optics Layout Schemes.** If no suitable Master / Slave diodes can be found at or near 671 nm, with sufficient power, then it may be necessary to consider alternate optics layout schemes. For example, the possibility of using the output of the BAL to inject a second BAL has been raised. Even if only 10mW of slave power could be obtained, this would result in approximately 100mW of power to inject into a second BAL. This would certainly saturate the second BAL, and would likely provide the desired final output power. However, the difficulty and expense of having a second BAL must be considered. Another idea suggested was to amplify both colours of light - the cooling and repump beams - in a single BAL. Other schemes involving different combinations of Master, Slaves, and BALs could be considered as well.

The BAL project is still in the prototype stage. Lessons were learned in the design of the prototype. In this light, some modifications to the present design merit consideration:

- **BAL x-stage.** In the design phase, we elected to add x-adjustment to the BAL to compensate for the fact that, as one changes injection angle, one must also offset the beam slightly to compensate for translation of the beam [16]. However, for a number of reasons, this additional degree of freedom proved to be superfluous.
CHAPTER 7. CONCLUSION AND RECOMMENDATIONS

Adjustment of injection angle is not done all that often, and the requisite adjustment of beam position is easily accomplished with the BAL’s coupling mirrors. Thus, the design can potentially be simplified by removing this degree of freedom. With the x-stage eliminated, it may be feasible to use a TEC to actively cool the BAL’s aluminum block, dumping heat to the large thermal mass of the optics table, thus eliminating the need for cooling fins and a cooling fan.

• **BAL placement repeatability.** Each of the 4 copper heatsinks had slightly different dimensions. The consequence was that the location of the BAL was rather different for every heatsink, and swapping diodes necessitated re-alignment of the BAL setup. In future versions of the BAL set-up, a more repeatable way of mounting the diodes is recommended. This may be as simple as making each of the copper heatsinks quantum-mechanically indistinguishable (or at the very least, tightening the machining tolerances).

• **Cylindrical lens mount.** The cylindrical lens mount used in this setup is jarrringly large and inelegant compared to other components on the optics table. No alternative commercial lens mount that offered rotational adjustment of the cylindrical lens was found. While functional, the large size of the mount (and the large lens that is required for it) makes it difficult to place the cylindrical lens close to the BAL, forcing the use of a fairly long focal length lens. For future set-ups, it may be a good idea to make a customized cylindrical lens mount to interface with a smaller commercial lens-rotating mount, and to use smaller cylindrical lenses.

• **APP adjustment.** The Anamorphic Prism Pair used to adjust the seeding beam shape was quite awkward to adjust. This made it impractical to experiment with a wide range of input beam shapes. However, beam shape has a large effect on the efficiency of the seed beam’s coupling into the BAL. A system for continuously varying the APP magnification would be ideal, though this may be unrealistically complicated. Alternatively, replacing the APP with a cylindrical lens telescope system, combined with an ample selection of cylindrical lenses to draw from, would allow for easier experimentation with beam shape.

• **Minor BAL modifications.**
  
  – The control electronics for the BAL should be modified to allow for the use of a heater when the BAL is off.
  
  – Electrical tape is presently used to block light escaping from the top of the BAL shield, as the BAL can be uncomfortably bright when being operated. It may be more elegant to make the top piece of the shield (or perhaps the entire shield) from metal or opaque plastic.

• **Modifications to Master housing.** Our modifications to the Master housing are described in Section 3.1. This includes the use of a lock-washer in securing the modified mirror mount to the copper bar, and the solution to the electrocution problem caused by the grating piezo (a glass slide cover between the piezo and the grating mount).
7.2. RECOMMENDATIONS

Future projects that may be of interest to the BAL project:

- **BAL Coating project.** If additional low front-facet-reflectivity BALs like the anomalously coated ones from RPMC cannot be secured, it may be desirable to purchase uncoated BALs and coat them ourselves. Dr. Parsons has offered his expertise and equipment to create AR coatings for BALs.

  Boshier [4] has used a fairly simple coating method on single-mode diodes to achieve excellent tunable Master lasers in the 671 nm range. His coating method may be adaptable to a BAL diode, and could be of use on potential Master and Slave diodes as well.

- **BAL Reflectivity measurement project.** While it is known that front-facet reflectivity has a large influence on BAL double-pass amplification, we do not have solid knowledge of the front-facet reflectivity of any of our diodes. All we know is what we are told by RPMC. It may be interesting and beneficial to the project to develop a method to measure front-facet reflectivity. A method for doing this by examining the effect of external optical feedback on a diode’s threshold current is described in [15]. This work is applied specifically to BALs in [12].
Acknowledgments

Peter and Aviv would like to thank:

- Dr. Kirk Madison, for giving us the chance to take on this challenging project
- Bruce Klappauf, for his help and advice
- Dr. Igor Shvarchuck, for sharing his experiences with BAL setups with us
- The graduate and undergraduate students in QDG Lab
- Dr. Mati Raudsepp and Sasha Wilson at the UBC Earth and Ocean Science SEM Laboratory
- NSERC USRA program and the UBC Department of Physics for funding this project
Bibliography


Appendix A

Alignment Instructions for OSA and FP

Optical Spectrum Analyzer Alignment

Alignment of light into the fibre for this instrument is relatively simple. First, set the OSA's wavelength span wide enough to ensure that the light to be analyzed will be visible. In addition, set the “level” to AutoRef Level, to ensure that the instrument always sets the vertical range to the highest reading on each scan.

It is a good idea to have a pair of mirrors for coupling light into the fibre. Also, if coupling into raw fibre (i.e. no built-in collimating lens on the fibre), placing a microscope objective in front of the fibre proved to improve coupling into the fibre. A photograph of the fibre is provided in Figure A.1.

For initial alignment, it is easier if as much power as possible is sent towards the fibre. By eye, adjust the two mirrors until the light is roughly hitting the center of the fibre. Looking at the OSA, some kind of peak should be visible. If not, adjust the mirrors until something is visible. Once a peak can be seen, switch the OSA’s AutoRef Level setting to off, and manually set the reference level to about twice the peak height. Then continue optimizing with the mirrors. The reason for turning off AutoRef Level is it is much more intuitive to optimize the signal strength if its possible to see the peak height changing, which is not possible in AutoRef mode.

Fabry-Perot Alignment

Typically the Fabry-Perot is swept with a triangle wave on the order of a few volts. This is amplified by the custom-built piezo driver, however, it was determined that the function generator used had a large amount of noise at high voltage, therefore, it was preferable to run the function generator at low voltage, while using higher a higher gain setting on the piezo driver. Set the function generator to something on the order of 10Hz.

Alignment of a beam into the Fabry-Perot is a slightly tricky procedure, but not extremely difficult. Start by bolting the Fabry-Perot interferometer to the optics table,
and set up two mirrors to couple the light into the FP cavity. Adjust the two mirrors until the beam is roughly entering the centre of the cavity, and travelling straight through. At this point, turn out the rooms lights. Place a card behind the FP, and it should be possible to see two flickering points. Adjust both mirrors until the points move on top of each other. Figure A.2 shows how misaligned and aligned points look on the card. Once the points are aligned, some fascinating interference patterns should be visible on the card.

Now place (but do not secure) a short focal length plano-convex (PCX) lens (about 50mm) in front of the FP cavity. It should be mounted in a way that its horizontal tilt can be adjusted. On the last coupling mirror before the FP, there should be two beam spots visible. One is the incoming beam, and the other is a back reflection from the PCX lens. Tilt the lens slightly so that the back reflection and incoming spot are vertically separated. Now adjust the distance between the lens and the FP (just by moving the lens mount around the table by hand) until the back reflection spot and the incoming spot are roughly the same size and shape, and adjust the horizontal position of the lens (again, just by moving it by hand) until the two spots are horizontally aligned. Secure the lens mount in place with a dog. Now readjust the horizontal tilt to move the two spots vertically, so that they are vertically aligned.

Now, increase the function generator frequency to something like 100Hz. Place another short focal length lens behind the FP cavity (where the card used to be). Position and alignment of this lens is highly non-critical. Now place a photodetector at the focus of the rear lens, and observe its output on the scope. A trace similar to Figure 3.10 should be visible now.
One further adjustment is the coarse micrometer screw on the FP. If the peaks on the oscilloscope look asymmetric, or if there are “shadow peaks,” then adjust this screw until these effects are eliminated.
Appendix B

Aligning Two Beams

The alignment of two lasers beams is a simple iterative process, and one that must be done fairly frequently when setting up optics components. For example, two beams must be aligned when sending a master beam into an optical isolator, or injecting a master beam into a slave diode.

The alignment process is illustrated in Figure B.1. This diagram assumes that two counter-propagating beams are to be aligned with each other. Each beam comes from its own source and both bounce off the same set of mirrors (A and B).

First, place a card at point ‘a’, and adjust only mirror ‘A’ until the two beams overlap on the card. It may be necessary to block one beam in order to see the other, since if one is particularly bright it may shine through the card and obscure the weaker beam. Once the beams are satisfactorily overlapping, move the card from point ‘a’ to point ‘b.’ Now, using only mirror ‘B,’ adjust the beams until they again overlap. Move the card to point ‘a’ again, and the two beams will likely no longer be aligned again. Readjust mirror ‘A’ to align the beams. Continue this iterative process until the beams overlap at both point ‘a’ and ‘b.’ By using only mirror ‘A’ when the card is at ‘a,’ and only mirror ‘B’ when the card is at ‘b,’ the alignment of the two beams will converge after these iterations. Adjusting in the opposite way will result in divergence of the alignment.

Figure B.1: Alignment Diagram for Two Laser Beams
Appendix C

Diode Serial Numbers

For the benefit of readers in Madison Lab, the serial numbers corresponding to Diodes A, B, and C are given below. The number after the dash was etched into each C-Mount by RPMC (1, 18 and 34).

- **Diode A** - LDX P2152-1
- **Diode B** - LDX P2531-18
- **Diode C** - LDX N1052-34
Appendix D

Work Schedule

In general, the pace of our work very closely matched our planned work schedule.

Week 1/2
Planned: Design BAL Housing, Obtain Components
Completed: The housing was completely designed, and two design reviews took place with Kirk and Bruce to fine tune the design. All mechanical drawings were created using CAD. All necessary optics components were either tracked down in the lab, or ordered from various suppliers.

Week 3/4
Planned: Machine BAL Housing, Assemble Master and Slave
Completed: Machining of the BAL housing took much longer than expected. This was largely due to delays and backlogs in the department machine shop, which necessitated machining many parts in the Student Machine Shop. In addition the BAL housing was more complex than originally envisioned. The Master and Slave system was delayed as important parts had not been received from the department machine shop by the end of week four.

Week 5
Planned: Assemble Master and Slave
Completed: Assembly of master and slave began. Work also continued on the last machining steps for the BAL housing.

Week 6
Planned: Free running assessment of BAL
Completed: Assembly of master and slave finished. First light was obtained from the master, slave and BAL. Work started on a better BAL cooling system.
APPENDIX D. WORK SCHEDULE

Week 7
Planned: Free running assessment of BAL
Completed: Master was characterized and stabilized, and more extensive characterization was done on the BAL diodes. Slave characterized free-running. Set up slave’s optical isolator to prepare for injection.

Week 8
Planned: Assemble BAL Optics
Completed: Reoptimized master alignment, began working towards injected slave with master. Investigation begun into new master/slave diodes, and possible AR coating sources. Set up Fabry Perot interferometer to further characterize master and slave.

Week 9
Planned: Assemble BAL Optics, Achieve Injection Locking
Completed: Successfully injected slave with master at 671nm, and got master/slave stable. Got master/slave temperature as low as possible, while still locking at 671nm. Attempted to seed BAL Diode B with slave light. Set up CCD camera to image BAL near field.

Week 10
Planned: Achieve Injection Locking
Completed: Decided to try seeding BAL Diode B at 665nm instead of 671nm to start with. Saw some sort of effect with Diode B, but unfortunately after extensive characterization it was determined that no amplification was taking place.

Week 11
Planned: Achieve Injection Locking
Completed: Seeded BAL Diode C at 665nm and found that it performed the best of any diode. Spent majority of time at Triumf Summer Institute.

Week 12
Planned: Data collection and interpretation
Completed: Further characterization of BAL Diode C at 665nm. Again, spent majority of time at Triumf Summer Institute.

Week 13
Planned: Data collection and interpretation
Completed: Characterized BAL Diode C performance as function of injection angle. Successfully injected Diode C at 671nm, and characterized. Called RPMC to investigate a mystery coating on Diode C. Tested Mitsubishi 80mW diode and found that its wavelength was too low to work as a slave. Investigated BAL Diode C on the SEM.
**Week 14**

Planned: Data collection and interpretation  
Completed: Spent majority of time writing report. Confirmed that BAL Diode C still worked after being imaged in the SEM. Found that only a fraction of previously used master power was required to inject the slave. Designed and machined an adapter for the fiber coupler.

**Week 15**

Planned: Documentation  
Completed: Continued writing the bulk of the report. Imaged BAL Diode B.

**Week 16**

Planned: Documentation  
Completed: Finished writing report. Trained successors in the use of the BAL setup, and installed new slave diode to replace the dead slave.
Appendix E

Contact Information

E.1 Report Authors

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Peter Eugster
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Earth and Ocean Science SEM Lab
The two contacts are Dr. Mati Raudsepp (mraudsepp@eos.ubc.ca) and Sasha Wilson (swilson@eos.ubc.ca). Use of the SEM is available at a rate of $20 per hour. http://www.eos.ubc.ca/research/infrastructure/sem.htm

RPMC Lasers
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Dean Micke, dean@rpmclasers.com, Ext 225
Janson Ayer, janson@rpmclasers.com
Appendix F

BAL Data Sheets
Device Number: P2152-1
Device Type: 680nm 150μm 800mW
Customer Name:
Comments: Laser Temperature=20°C

### Parameters:

- **Slope**: 1.083 W/A
- **Threshold Current**: 687.9 mA
- **Operating Temp**: 20 °C
- **Operating Power**: 800.0 mW
- **Operating Current**: 1429.3 mA
- **Operating Voltage**: 1.988 Volts
- **Calibration Factor**: 73.0 μA/W

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**Graph:**
- **Power (mW):** 100.0, 200.0
- **Current (mA):** 1527.2, 1928.5
Appendix G

Diode Survey
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<td>670</td>
<td>250</td>
<td>Roithner</td>
<td>RLT6730T</td>
<td>M</td>
<td>$315</td>
<td>TO3 Mount</td>
</tr>
<tr>
<td>670</td>
<td>500</td>
<td>Sony</td>
<td>SLD1332V</td>
<td>BAL</td>
<td>$474</td>
<td>Photonic Products</td>
</tr>
<tr>
<td>670</td>
<td>500</td>
<td>HPD</td>
<td>HPD-1305</td>
<td>BAL</td>
<td>$635</td>
<td>100um BAL</td>
</tr>
<tr>
<td>670</td>
<td>500</td>
<td>Coherent</td>
<td>1082884</td>
<td>BAL</td>
<td>$2,150</td>
<td>Will not do AR for small runs</td>
</tr>
<tr>
<td>670</td>
<td>500</td>
<td>Other</td>
<td>MLD670-500M9N</td>
<td>M</td>
<td>$895</td>
<td>From Intelite</td>
</tr>
<tr>
<td>670</td>
<td>1000</td>
<td>HPD</td>
<td>HPD-1310</td>
<td>BAL</td>
<td>$1,065</td>
<td>200um BAL</td>
</tr>
<tr>
<td>675</td>
<td>25</td>
<td>Sacher</td>
<td>N/A</td>
<td>S</td>
<td>$1,450</td>
<td>With monitor PD</td>
</tr>
<tr>
<td>675</td>
<td>30</td>
<td>Topica</td>
<td>LD-0675-0030-1</td>
<td>S</td>
<td>$905</td>
<td>AR costs 3-4k</td>
</tr>
<tr>
<td>660 - 680</td>
<td>1000</td>
<td>Sony</td>
<td>SLD1333YT</td>
<td>BAL</td>
<td>$5,820</td>
<td>Photonic Products</td>
</tr>
<tr>
<td>680</td>
<td>800</td>
<td>LDX</td>
<td>LDX-2815-680</td>
<td>BAL</td>
<td>$900</td>
<td>RPMC</td>
</tr>
<tr>
<td>780</td>
<td>40</td>
<td>Sacher</td>
<td>SAL-0780-040</td>
<td>S</td>
<td>$1,450</td>
<td>With monitor PD</td>
</tr>
<tr>
<td>780</td>
<td>100</td>
<td>Sacher</td>
<td>SAL-0780-100</td>
<td>S</td>
<td>$1,540</td>
<td>With monitor PD</td>
</tr>
<tr>
<td>780</td>
<td>500</td>
<td>Roithner</td>
<td>RLT78500G</td>
<td>M</td>
<td>$448</td>
<td>9mm Mount</td>
</tr>
</tbody>
</table>
Appendix H

C-Mount CAD Drawing

Source: RPMC
Appendix I

BAL Housing CAD Drawings
<table>
<thead>
<tr>
<th>Drawing Title</th>
<th>Material</th>
<th>Assembly Figure and Part ID</th>
<th>Units</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optics Table / X-Stage Adapter</td>
<td>Aluminum</td>
<td>4.1, A</td>
<td>M</td>
<td>Adapts bolt pattern of Klinger linear x-stage to bolt pattern of optics table</td>
</tr>
<tr>
<td>Heatsink Insulator</td>
<td>Plexiglas</td>
<td>4.1, C</td>
<td>M</td>
<td>Provides air gap to insulate Klinger linear x-stage from large Aluminum heatsink</td>
</tr>
<tr>
<td>Large Aluminum Heatsink</td>
<td>Aluminum</td>
<td>4.1, D</td>
<td>M</td>
<td>Absorbs heat from TEC, and connects the TEC/copper heatsink to the Klinger linear stage. Also attached to the Aluminum heatsink are cooling fins, not depicted in this drawing.</td>
</tr>
<tr>
<td>Copper Heatsink</td>
<td>Copper</td>
<td>4.1, F</td>
<td>M</td>
<td>Holds BAL diode and power resistors, and temperature stabilizes them. The TEC is sandwiched against the back face of the copper heatsink.</td>
</tr>
<tr>
<td>C-Mount Clamp (Top)</td>
<td>Copper</td>
<td>4.1, G</td>
<td>M</td>
<td>When the 2-56 screw is tightened, this piece clamps down on the cathode wire lead of the BAL diode.</td>
</tr>
<tr>
<td>C-Mount Clamp (Bottom)</td>
<td>Copper</td>
<td>4.1, G</td>
<td>M</td>
<td>This piece is attached to the copper heatsink using nylon screws, and a piece of insulating material is placed between the copper heatsink and this clamp. This piece is electrically insulated from the copper heatsink, and attaches to the diode anode.</td>
</tr>
<tr>
<td>Drawing Title</td>
<td>Material</td>
<td>Assembly Figure and Part ID</td>
<td>Units</td>
<td>Function</td>
</tr>
<tr>
<td>-----------------------</td>
<td>----------</td>
<td>----------------------------</td>
<td>-------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Z-Stage to Table Adapter</td>
<td>Aluminum</td>
<td>4.2, F</td>
<td>I</td>
<td>Adapts the bolt pattern of the z-stage to the bolt pattern of the optics table</td>
</tr>
<tr>
<td>MiniPost Bottom</td>
<td>Brass</td>
<td>4.2, D</td>
<td>I</td>
<td>Using a 5/16-24 set screw, this post attaches to the z-stage</td>
</tr>
<tr>
<td>Post Clamp</td>
<td>Brass</td>
<td>4.2, C</td>
<td>I</td>
<td>This clamp secures the MiniPost bottom and MiniPost top pieces together</td>
</tr>
<tr>
<td>MinPost Top</td>
<td>Brass</td>
<td>4.2, B</td>
<td>I</td>
<td>Using an 8-32 set screw, this post attaches to the collimating lens positioner</td>
</tr>
<tr>
<td>Shield Clamp</td>
<td>Aluminum</td>
<td>n/a</td>
<td>I</td>
<td>This clamp secures the shield assembly to the optics table</td>
</tr>
<tr>
<td>Shield Front</td>
<td>Plexiglas</td>
<td>n/a</td>
<td>I</td>
<td>The front of the shield assembly. An AR-coated window, in an optics holder, is glued to the large hole in the centre. The smaller hole at the bottom allows the z-stage to be adjusted while the shield is in place.</td>
</tr>
<tr>
<td>Shield Side</td>
<td>Plexiglas</td>
<td>n/a</td>
<td>I</td>
<td>Side of the shield assembly. The shield clamp attaches here</td>
</tr>
<tr>
<td>Shield Top</td>
<td>Plexiglas</td>
<td>n/a</td>
<td>I</td>
<td>Cover the top of the shield assembly</td>
</tr>
<tr>
<td>Fibre Coupler Adapter</td>
<td>Brass</td>
<td>n/a</td>
<td>M</td>
<td>Allows a standard optics post to be attached to the fiber coupler using an 8-32 set screw. Allows for mounting of the fiber coupler on the optics table.</td>
</tr>
</tbody>
</table>
ALL DIMENSIONS IN METRIC
UNLESS OTHERWISE NOTED

ALL DIMENSIONS IN METRIC
UNLESS OTHERWISE NOTED
ALL DIMENSIONS IN METRIC UNLESS OTHERWISE NOTED

17.00
(2.9")

4.50
(depth not critical)

6.35
(1/4")

74.00
(2.9")
ALL DIMENSIONS IN METRIC
UNLESS OTHERWISE NOTED
Copper Heatsink

ALL DIMENSIONS IN METRIC UNLESS OTHERWISE NOTED
ALL DIMENSIONS IN METRIC
UNLESS OTHERWISE NOTED
C-Mount Clamp Bottom (Copper)

- 2-56 tap
- 2-56 clear

Dimensions:
- 0.00 to 5.00
- 4.00 to 10.00
- 1.50
- 7.00
Z-Stage to Table Adapter (Aluminum)

All dimensions in inches.
ALL DIMENSIONS IN INCHES

5/16-24 UNF - 1B

Ø0.50

0.40

0.30
Shield Clamp (Aluminum)

ALL DIMENSIONS IN INCHES

ALL DIMENSIONS IN INCHES

Housing Clamp
ALL DIMENSIONS IN INCHES
ALL DIMENSIONS IN INCHES
ALL DIMENSIONS IN METRIC
UNLESS OTHERWISE INDICATED

Fiber Coupler Adapter (Brass)