INTERFERENCE FILTER STABILIZED EXTERNAL-CAVITY DIODE LASERS

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Abstract

This document comprises the work of Matthias Scholl in the winter of 2010 and William Cairncross in the summer of 2011 to design, construct and optimize interference filter (IF) stabilized external cavity diode lasers (ECDLs) at 767nm and 405nm. A pair of 767nm ECDLs were constructed by Matthias Scholl and are currently used in the University of Toronto Ultracold Atoms laboratory. A single 405nm ECDL was completed by William Cairncross, and is near a level of optimization where it might be useful in experiment. Included are characterization measurements for two lasers at 767nm and one at 405nm, and an expanded and revised edition of the step-by-step instruction manual for building an IF-stabilized ECDL.
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1 Acknowledgements

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2 Introduction

2.1 Project history

During the winter of 2010, Matthias Scholl designed and constructed a pair of interference-filter stabilized external-cavity diode lasers (IF-stabilized ECDLs) at 767nm, following the method of Clairon et al. [1]. Both are currently used in the Thywissen lattice lab, and have been found to be comparable in stability to commercial diode lasers.

In the summer of 2011, it was therefore decided that a pair of new IF-stabilized ECDLs should be constructed at 405nm for the manipulation of \(^{40}\)K through the \(4S^{1/2} \rightarrow 5P^{3/2}\) transition. These lasers would supplement and potentially replace the lab’s only 405nm laser, the Toptica DL100.

Summer student Will Cairncross was tasked with constructing these lasers, to be based on Matthias’ original design. With only minor modifications to the design (including a new heat sink and a longer external casing) a pair of lasers were constructed, and tested with a number of inexpensive 405nm diodes with powers ranging from 20mW–150mW. It became evident that single-mode operation was difficult to achieve without an anti-reflection (AR) coated laser diode, and so a single 405nm AR-coated laser diode was purchased from Sacher Lasertechnik. The new laser diode permitted single-
mode operation through currents sufficient to provide $\sim 15\text{mW}$ of output power; approximately the goal of the project.

Theoretical background of the IF-stabilized ECDL may be found in Matthias Scholl’s March 2010 report [1] – this document is limited to discussion of the construction of the lasers, and a brief description of their measured characteristics.

### 2.2 Design overview

The interference-filter-stabilized external-cavity diode laser is a compact design, intended to combine low cost, stability and tunability. The lasers use a monolithic aluminum cavity design for thermal and vibrational stability, an anti-reflection coated laser diode as a light source, and an interference filter as the wavelength-selective element (Fig. 1).

The highly divergent light emitted by a laser diode is collimated by an aspheric lens of high numerical aperture (NA), before passing through an interference filter with an approximately Gaussian transmission profile ($T_{\text{peak}} \approx 0.90$, FWHM $\approx 0.30\text{nm}$). The laser is out-coupled by a partially reflecting mirror in a cat’s-eye configuration, to decrease sensitivity to misalignments.

The IF-stabilized laser is in theory less susceptible to mechanical vibrations than the traditional Littrow configuration, as the transmission maximum of the interference filter is $\sim 60$ times less sensitive to filter angle [1].

### 3 Construction

#### 3.1 Parts list

**Drivers & controllers**

- LD current controller (ITC502 or LDC202C)
- LD temperature controller (ITC502 or TED200C)
- Base temperature controller (TED200C)
- Piezo voltage driver (MDT694A)
Mechanical parts

- Base plate
- Back plate
- Main cavity
- Collimation lens mount
- Cat’s-eye lens mounts
- Piezo & out-coupler mount
- Collimation lens mount mount
- Diode mount
- Cylinder for heat conduction

Optics & electronics

- Collimation lens (C230TME)
- Cat’s-eye lenses (352220 & 352280)
- Laser diode socket (S8060 or S7060R)
- Piezo ring actuator (Piezomechanik HPSt500/10-5/5)
- Base thermoelectric cooler (TEC) (Digi-Key 102-1682-ND)
- Diode TEC (TeTech CH-41-1.0-0.8)
- Out-coupler mirror (CVI Melles-Griot PR1-|λ|-11-0512)
- Heat sink (College Home-Hardware)
- Interference filter (Iridian Spectral Technologies |λ|-0.3)
- AR-coated laser diode
- 2 thermistors (Digi-Key 495-2142-ND)

Miscellaneous

- Heat sink grease (GC Electronics Type Z9 Heat Sink Compound)
- Epoxy (Epage 11)
- Razor blades
- Acetone
- Kimwipes & paper towel
Figure 2: Ultrasonic bath for cleaning mechanical parts. The outer basin of the bath is filled with water, and the inner beaker filled with acetone.

- Electrostatic dissipation strap and cord
- Assorted screwdrivers and hex keys
- Needle-nose pliers
- Assorted optics (mirrors, $\lambda/2$ waveplates, PBSC etc.)
- BNC panel mount female connectors
- BNC cables
- SUB-D15, SUB-D9 connectors, male and female
- Wires
- Heat-shrink tubes
- Assorted screws & washers (steel and teflon)

**Note:** Part numbers are Thorlabs unless otherwise specified.

### 3.2 Cleaning of mechanical parts

After machining, the mechanical parts are often dirty and oily, with chips sticking in small corners and threads. All parts must be cleaned before assembling the laser. Every part should be cleaned well in the sink with soap and water, and in addition, for small parts:

1. Prepare an ultrasonic bath (borrowed from the Van Driel lab, Fig. 2) and fill it with water.
2. Put some of the small parts into a beaker and fill it with acetone until every part is covered. Place the beaker into the water-filled bowl of the bath. Turn it on and wait for 10-15 minutes.
3. Dry the parts after cleaning and store them on a clean surface, e.g. in aluminum foil.

Repeat until every part has been cleaned.
3.3 Fitting of mechanical parts

Test the fit of as many parts as possible before beginning assembly. Frequently there will be errors in fabrication of the mechanical parts, or in the laser components themselves. In particular:

- Check the fit of the laser diode in its mount. Frequently the mount will need some small modification for a close (but not tight) fit.
- Make sure that the TECs fit well into their corresponding pockets. It is important for good thermal contact that both sit very flat on a smooth surface.
- The piezo tube mount should fit smoothly into the large bore in the cavity main part.
- All threaded parts should fit smoothly and easily.
- When the main cavity part is bolted to the base plate, the corresponding pockets for the base TEC should be aligned.
- The holes in the base plate should be large enough that a 1/4˝-20 screw should not touch when the laser is bolted to an optical table.
- Both cat’s-eye lenses should fit into their mounts snugly (so that the cavity is well-aligned) but without forcing.
- Check the alignment of all parts defining the optical axis.

3.4 Wiring: electrical connections

The electrical connections for these ECDLs are provided by three connectors: A D-sub 15-pin male (DA-15m) panel mount connector provides thermal management wiring, and a pair of BNC panel mount connectors are used for laser diode current and piezo voltage control (Fig. 3).
Figure 4: Home-built cable for thermal management, with a pair of DE-9m connectors opposite a single DA-15f connector.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Designation</th>
<th>Pin # (DA-15f)</th>
<th>Pin # (DE-9m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Diode</td>
<td>thermistor</td>
<td>+ 2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 10</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>TEC</td>
<td>+ 1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 9</td>
<td>5</td>
</tr>
<tr>
<td>Base</td>
<td>thermistor</td>
<td>+ 5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 13</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>TEC</td>
<td>+ 4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 12</td>
<td>5</td>
</tr>
</tbody>
</table>

### 3.4.1 Thermal management wiring

The ECDL’s DA-15 connector is used for thermal management wiring, i.e., the TECs and thermistors for the base and laser diode. Since a separate temperature controller must be used for each of the base and laser diode, a split cable must be assembled with a female DA-15 connector opposed by a pair of male DE-9 connectors (Fig. 4). Pin assignments for this cable are listed in Table 1. The double-end of the cable will be connected to the Thorlabs temperature controllers’ CAB420-15 cables via their DE-9 connectors. Take care to solder the correct connections, and cover the D-Sub connectors with the appropriate shells.

### 3.4.2 Wiring for laser diode current and piezo voltage

BNC cables are chosen for both laser diode current and piezo tube voltage due to their good electrical shielding, as the frequency of the ECDL is highly sensitive to changes in both cavity
Table 2: Pin allocations for laser diode current & piezo voltage.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Polarity</th>
<th>Pin (BNC)</th>
<th>Pin # (DE-9f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD</td>
<td>+</td>
<td>inner</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>−</td>
<td>shield</td>
<td>3</td>
</tr>
<tr>
<td>Piezo</td>
<td>+</td>
<td>inner</td>
<td></td>
</tr>
<tr>
<td></td>
<td>−</td>
<td>shield</td>
<td></td>
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</table>

length and diode current.

The output of the laser diode current supply (Thorlabs ITC502 or LDC202C) is a DE-9 male connector, so a BNC to DE-9 adapter must be assembled from a female BNC panel-mount connector, a DE-9 female connector, and a DE-9 shell. Pin assignments for this adapter are listed in Table 2. Also solder a small wire from pin #1 to pin #5 to short circuit the interlock of the Thorlabs current driver. Glue the BNC connector to one side of the D-Sub shell to avoid stress on the wires.

Install a female BNC panel-mount connector on the back plate for the piezo voltage control.

3.5 Assembling: out-coupler to piezo

Choose a clean, flat and level surface to work on. Get some slow glue ready (e.g. Epage 11 regular epoxy). Avoid 5-minute epoxy, since it degases more than slow epoxy, which may damage the coating on the mirror.

1. Place the out-coupler mirror (OC) on a few layers of optical paper and make sure the partial reflecting coated side points up, as indicated by the arrow on the side of the mirror (Fig. ??). Make sure the up pointing side is very clean and blow all dust particles away with the "hand
dust blower” since after the gluing it’s very hard to clean this side of the mirror!

2. Place the piezo on top of the mirror in the right orientation (the cables of the piezo should be near the OC mirror) and center it.

3. Place a weight (New Focus pedestals work well) very gently on top of the piezo and check by eye if it is still centered on the out-coupler (Fig. 7). Choose the weight with regard to not damage the out-coupler or the piezo, but heavy enough to keep a nice, parallel contact between the two. Make sure your weight puts pressure uniformly on the piezo.

4. Glue the piezo with 3 glue points to the mirror. Make the glue points very small, since the glue expands on the mirror surface while curing and one doesn’t want the glue to expand to the center of your mirror!! In Figure 8 on the left the expanded glue can be seen (dark spots). One can see that one glue point has expanded to the inner circle of the piezo, so in this case the limit is reached! The image on the right shows an better example.

**Hint 1:** Use a thin wire and dip the tip into the glue, then dip it to the point you want to set your glue point, until both orthogonal faces are connected by the glue. This should be a reasonable measure of how much glue you need for one point.

**Hint 2:** Mix the two components of the glue, but wait for approx. 1 hour before setting the 3 glue points. During that hour the glue gets more viscous. Therefore the glue expands less while curing and it is easier to make very small glue points. If a different glue is used, do some test runs on a glass sample to see the expansion properties of the glue in dependence of preparation time before setting glue points.

5. Check again if everything is centered and let it cure over night.

### 3.6 Assembling: piezo & out-coupler to cat’s-eye mount

After finishing the gluing in the previous section, check by eye that everything is nice and parallel and still in good condition. If anything went wrong remove the glue by putting a few drops of a solvent on the glue and scratching it away with a spiky tool. Soapy water or methanol are milder

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Figure 6: Arrow on Melles-Griot PR1 out-coupler mirror, indicating the side that should face into the laser cavity.
Figure 7: Assembly for gluing together the piezo tube and out-coupler mirror.

Figure 8: Gluing detail for piezo tube and out-coupler mirror. The left image shows an excess of glue that has spread to the inside of the piezo tube. On the right, the correct amount of glue has been used.
options; acetone should be used as a last resort as it is damaging to the piezo tube [7]. Check to
be sure that the glue has not expanded to the inside of the piezo ring.

1. Prepare the piezo mount, making sure it is clean – especially the surface the piezo sits on.
   Also make sure the out-coupler mirror is still clean and undamaged. Get a mechanical help
   construction for gluing ready (Fig. 9).

2. First get the wires of the piezo through the hole inside the mount while keeping the piezo
   with the OC on it in your hands. This helps the piezo to keep its position later on since the
   wires are very springy. Don’t touch the mirror on the faces! Now get the piezo down to its
   position. Try to play around with the wires to make the piezo sit in position by itself.

3. Prepare a few layers of optical paper (2 or 3 layers, not too thick). Cut it, so that it fits into
   the mount hole and lay it down on the OC mirror. Place the mechanical help construction
   softly upside down on the OC mirror and center it. Never touch the mirror directly with the
   metal; make sure optical paper is always between the two.

4. Turn the whole assembly (help construction, piezo, out-coupler and mount) upside-down,
   keeping a small amount of pressure on the help construction to keep everything in position.

5. With the mount upside-down, the back of the piezo tube is visible from the other side of the
   mount. Centre the mount’s hole with the piezo hole, making sure that the help construction
   stays centered. When everything is in position, glue the piezo from the back with three points
   of glue. These points may be larger than the ones used for the out-coupler mirror, since there
   is now little danger of the glue reaching or blocking the optical axis (Fig. 10).

6. Place a weight gently on top of the mount in order to hold everything together nicely. Place
   the weight very gently so as not to change the relative positions of any of the parts. Wait
   one night for the epoxy to cure.
3.7 Soldering & testing: TECs, thermistors and laser diode socket

Before assembling the whole laser, the TEC and thermistor should be tested to make sure that they are functional, to find the correct orientation and to make sure that the home-made cables work well.

3.7.1 Soldering

1. Screw a male DA-15 connector with soldering cups to the back plate of the laser.

2. Cut some heat-shrink tubes to a reasonable length and put them over the wires of the TEC for the base. Solder the TEC to the correct pins of the DA-15 connector (Table 1). Check each TEC’s data sheet for the polarity (usually red→ +, black→ −).

3. Repeat (2) with the TEC for the laser diode. For this part the orientation is less critical, as the wires can be more easily twisted than for the base TEC.

4. Since the leads of the thermistors are too short, add a thin (32AWG) wire to each of the leads for the base thermistor. Solder the base TEC connections by twisting a pair of wires around each other and then soldering the connection.

5. To the diode thermistor, attach a Molex KK 2-pin male connector to the thermistor and a female connector to a pair of 32AWG wires. Plug in this connector for now.

6. Solder the wires for the base and LD thermistors to the corresponding pins on the DA-15 connector. Make sure to put heat-shrink tubes on all connections to avoid short-circuits.

7. Solder two 28AWG wires to a female BNC panel-mount connector. The length of the wires should be such that when the BNC connector is attached to the back plate of the ECDL, the
3.7.2 Testing

Test all elements of the ECDL thermal management before applying any thermal grease or glue.

1. Screw the back part of the laser to the base plate and place the base TEC in its cavity.
2. Place the cavity main part on top (no need to screw it in) and place the thermistor for the base in its hole.
3. Connect your self-made cable to the DA-15 connector, and the DE-9 connector corresponding to the base to a Thorlabs temperature controller.

Figure 11: TECs and thermistors soldered.

Figure 12: Pin assignments for (a) Sacher Lasertechnik 405nm laser diode [8] and (b) Eagleyard 767nm laser diode [1].

wires reach approximately one inch into the laser cavity. Solder these wires to the correct leads on the laser diode socket (Fig. 12). Twist the wires to avoid electrical noise pickup.
4. To test if the thermistor works, simply touch it with your hands. You should observe the \( T_{act} \) value drop. To test the orientation of the TEC, set \( T_{set} \) to a high value (e.g. 14k\( \Omega \)). When the TEC is on, the cavity should become cold. If instead the cavity becomes hot, flip the TEC and try again.

5. Repeat the same procedure with the TEC and thermistor for the laser diode. Do this testing without the diode in the copper mount.

6. Test the laser diode socket and its wiring with a simple LED using the current controller.

3.8 Assembling: cavity to base plate

3.8.1 Cavity, TEC and base plate

1. Clean the surfaces of the TEC, as well as the pockets in the main cavity and base plate where the TEC will make contact.

2. Cover the bottom surface of the TEC with a thin layer of heat sink grease, using a razor blade to spread the grease evenly. Press the TEC softly and symmetrically from the top into place on the base plate. It should stick to the base plate tightly, so that lifting it up again is difficult. If it does not stick well, use slightly more heat sink grease. **Note:** Use caution when handling heat sink grease; it is difficult to remove, bad for optics and tends to get everywhere. Keep lots of Kimwipes or paper towel handy to remove any excess.

3. Cover the top surface of the TEC with a thin layer of heat sink compound and press the cavity main part on top. Use M4 nylon screws to tighten the main cavity down on the TEC. Turn each nylon screw a small amount at a time, in order to apply even pressure to the TEC. Do not over-tighten, as thermoelectric coolers can be cracked easily. Place the laser on a flat surface and use a level to make sure the main cavity is screwed down symmetrically. To get a feeling for a reasonable amount of force to apply, use a small screwdriver and screw without putting pressure on top. When the driver jumps out of the notch, the pressure on the TEC should be sufficient.

Take care not to squeeze the wires of the base TEC.

3.8.2 Thermistor for base

1. Clean the hole for the thermistor and use a zip-tie or a small piece of wire to fill it with heat-conductive glue.

2. Cover the thermistor with activator and stick it into the hole.

3. Give the glue a few hours to cure.
3.9 Assembling: laser diode to copper housing

3.9.1 Mounting the diode

When mounting a laser diode, keep in mind:

- Never touch the laser diode’s face
- Laser diodes are very sensitive to electrostatics. When working with a laser diode, always wear the electrostatic dissipation strap to ground yourself.
- Never wear rubber gloves while touching the laser diode, as rubber gloves can carry electrostatics even when wearing the strap.

Due to the sensitivity of the laser diode, all assembly from this point forward should be performed on a grounded optics table. Tape down a layer of aluminum foil to work on, so as not to lose parts down the holes.

To mount the laser diode, carefully insert it into the hole in the copper mount and attach the bracket. If the bracket does not hold the laser diode securely, apply a thin ring of nail polish to the surface where the bracket and the diode make contact. The diode should be oriented with the odd pin directed away from the TEC and thermistor wires (Fig. 13).

3.9.2 Comments

In previous design iterations, the laser diode was glued to the copper mount using thermal conductive epoxy. While this method was effective for inexpensive parts, it did not allow for removal or adjustment of the part once it had been glued in place. For AR-coated diodes (ranging in price up to ~$12000), a non-destructive mounting technique was implemented.
A small pocket was milled in a copper diode mount and a small aluminum bracket machined to fit inside the pocket, flush to the rear surface of the mount (Fig. 14). The hole in the center of the aluminum bracket was drilled just slightly smaller than the diameter of the laser diode, so that it is held in place with uniform pressure around the edge. Counter-sinks were drilled in the bracket so that 2-56 screws would lie flush with the surface, allowing good thermal contact between the mount and the laser diode TEC.

3.10 Assembling: cat’s-eye & piezo mount to cavity

Using tweezers, pull the wires for the piezo tube back out of the hole in the side so that they are not pinched when the mount is inserted into the hole in the main cavity. Take care not to touch the surface of the mirror, or to apply too much force to the glued parts.

Push the part into place and use three M2 screws to fix it in position. After that, use the tweezers to get the piezo leads through the hole again. Solder two wires to the BNC mount in the back panel of the laser and to the leads. Choose the length of the wires so that they are not tight, but do not get in the way. Cover all connections with shrink tubes.

3.11 Heat sinking

3.11.1 Modification and assembly

The heat sink purchased from College Home Hardware must be modified using the milling machine in the student machine shop, in order to fit the rear of the cavity (or not, if the cavity has been redesigned).

Remove $\sim 0.080''$ from each side of the heat sink, and chamfer the corners using a file. Holes must also be drilled for the M4 screws holding the heat sink to the cavity, and for the leads of the laser diode. To ensure good thermal contact between the heat sink and the copper cylinder, remove a thin layer of material ($\sim 0.010''$) from the front-facing contact surface of the heat sink.
Once the necessary modifications have been made, place the heat sink in its location behind the cavity and screw it in very loosely with a pair of M4 screws and washers. It is necessary to remove the back plate of the laser to access these M4 screws, however when doing so take care not to stretch the wires already soldered in place. It is very helpful at this point to have chosen the length of the wires appropriately.

3.11.2 Mounting the ECDL to the optical table

At this point in the assembly, the ECDL should be semi-permanently mounted to the optical table, using copper braid for heat sinking and 1/4” rubber for vibration damping.

1. Using a large pair of clippers, cut eight $\sim 2”$ sections of copper braid. Fray the ends slightly so that the braid becomes slightly thicker and will not move about underneath the ECDL.

2. Cut four $\sim 2” \times 1”$ pieces of rubber mat (purchased from McMaster-Carr) and using a sharp tool or screw, make holes for the 1/4”-20 bolts that are used to mount the laser to the optical table (Fig. 15).

3. Use four 1/4”-20 screws and large washers to mount the ECDL to the table, ”sandwiching” the base plate between two layers of rubber. Stack the copper braid so that it makes the best contact possible with both the base plate of the ECDL and the surface of the optical table.

4. Tighten the 1/4”-20 screws just enough so that the rubber is slightly compressed. The copper braid should be lightly held between the base plate of the ECDL and the optical table.

3.11.3 Comments

Immediately following the construction of the 405nm ECDLs, it became apparent that the LD temperature controller was struggling; a minimum temperature of $\sim 17k\Omega$ could be achieved, even
at modest diode currents. At first it appeared that the temperature controllers were simply unable to supply sufficient current, however it was Joseph’s insight that proved to be correct: The flimsy heat sink used in the initial construction was in fact bowing under the force of the M4 screws fixing it to the cavity, causing it to lose nearly all surface contact with the copper cylinder.

New heat sinks were purchased from College Home Hardware and modified in the machine shop to fit the gap in the back of the main cavity part. The copper cylinder was no longer glued to the heat sink but instead attached only using thermal grease. These heat sinks were much sturdier and more massive than the original choice, allowing for better contact and more effective heat sinking.

### 3.12 Assembling: laser diode & copper housing to cavity

To get an overview of how the laser will look after the following steps, see Fig. 16. Assembling this portion of the laser is one of the most difficult parts of the ECDL construction.

1. The heat sink should be already in place, attached very loosely to the cavity main part using M4 screws with washers.

2. Using kimwipes and acetone, clean the surfaces of the TEC, heat sink, copper cylinder and diode mount. If the surfaces have become rough or damaged, make them as smooth as possible using fine sandpaper.

3. With a razor blade, apply heat sink grease to one side of the copper cylinder and press it firmly onto the front surface of the heat sink. Rotate the cylinder back and forth to ensure good contact between the surfaces. Accurately placing the copper cylinder is not especially important here.

4. Apply heat sink grease to the cold side of the LD TEC and press it firmly into the diode mount, following the same process as in (3).

5. Thread the diode socket through the holes in the heat sink and copper cylinder. Plug the diode into the socket. The strength of the connection and the stiffness of the diode wires is usually sufficient to support the mount in this position.

6. Very carefully apply a thin layer of heat sink grease to the front surface of the copper cylinder, rotating it in order to reach the entire circumference.

7. Press the entire assembly together, again rotating it back and forth slightly to ensure good contact on all surfaces. The stickiness of the heat sink grease should be sufficient to hold all of the parts together. In order from front to back, the assembly should consist of: copper diode mount with diode plugged into socket, TEC, copper cylinder, heat sink.

8. Insert M4 screws with shoulder washers and spacers. Tighten just to the point of resistance.

9. Using a very thin allen key, screwdriver or piece of wire, move the copper cylinder into place so that it does not touch the walls of the hole in the main cavity. Tighten the M4 screws evenly and in small increments, taking care not to crack the TEC.

10. Tighten the M4 screws for the heat sink. Just as when mounting the cavity to the base plate, only tighten a small amount past the point of resistance. Gauge the horizontal and vertical
alignment of the copper diode mount using
   a. the visibility of the heat sink screws on the front side of the cavity, and
   b. the collimation lens mount mount, looking from the side and top.
11. Screw the back plate in place again and connect the current and temperature controllers.
12. Switch on the TECs for the base and laser diode and set them near room temperature; from this point they should stay on indefinitely. Turn on the laser diode and check that light is emitted.

3.13 Optical setup for testing and optimization

3.13.1 767nm ECDL

In the next chapters the lenses will be aligned and optimized to make the laser as efficient, powerful and stable as possible. Then some saturation spectroscopy on Potassium vapour will be done to test if every part of the laser is working fine as well as to find the best angle for the interference filter and to optimize the emission frequency to the Potassium line.

All these steps can be done with the optical setup shown in Figure 17a without changing, moving or realigning components. There may be hundreds of other setups to perform the optimization but this uses a minimum of optical components and it’s very easy to set it up, but feel free to create an own setup ;)

Figure 16: Schematic diagram of the ECDL cavity assembly. In order from left to right: heat sink, copper cylinder, main cavity part, nylon washer, TEC, diode socket, diode, copper diode mount, nylon shoulder washer, M4 screw.
It might be convenient to align the setup as recently as going through the following sections, just because a collimated beam is needed to align it.

3.13.2 405nm ECDL

Figure 17b shows schematically the optical components required to fully optimize the 405nm ECDL, including the generation of an error signal (mirrors for alignment are excluded). In these steps it is not necessary or possible to align a cat’s-eye for modulation of the laser frequency; instead just send a single beam through approximately the center of the potassium vapour cell until fluorescence is established.

3.14 Assembling: lenses

3.14.1 Collimation lens

The light coming out of the laser diode is divergent and needs to be collimated. Always turn the laser off when changing or adding parts to the cavity. Assemble the collimation lens as follows:

1. Screw the lens into the round brass mount using the appropriately sized socket wrench.
2. Wrap a few layers of teflon tape around the thread for the brass mount and screw it into the hole in the aluminum mount.
3. Place the aluminum mount over the diode copper housing and use four M4 screws (25mm) and steel washers to attach it to the cavity. The edge of the bottom washers will have to be trimmed using a large pair of cutters in order to make them fit.
4. Turn on the laser and turn the current up to where the beam is easily visible on an IR-card or sheet of paper. Adjust the position of the collimation lens so that the beam is centered on the out-coupler and tighten the M4 screws just enough so that the lens stays in place.
5. By eye, roughly collimate the beam inside the laser cavity. To aid with this, a mirror can be inserted into the cavity at 45° and the beam collimated a few feet away.

3.14.2 Cat’s-eye lenses

1. Place the two cat’s-eye lenses in their corresponding mounts.
2. Make sure by eye that the lens is lying flat in its hole. Glue each lens in using three very small points of epoxy on the sides. As in the case of the out-coupler, give the glue some time to become more viscous before placing the glue points, so that the glue does not spread into the optical axis.
3. Screw each brass mount into place on its corresponding side of the out-coupler.
Figure 17: Reduced schematic of optical setup for optimization and testing of (a) 767nm ECDL and (b) 405nm ECDL.
3.15 Observing the threshold

The threshold current of an ECDL is a measure for the quality of your external cavity feedback; the better your feedback is the lower the threshold. Therefore you can optimize the lens positions by minimizing the threshold current.

3.15.1 767nm ECDL

Observing the threshold from a 767nm laser diode is more difficult due to the human eye’s low sensitivity to near-infrared light. It is therefore it is useful to use electronics to ramp the laser diode current and observe the threshold on an oscilloscope.

Turn the current on to 50-100mA and align the distances between the lenses and the out-coupler coarsely, use the second lens to collimate the outgoing beam.

Set the laser diode current to a value around 40mA and modulate the laser diode current with a triangle signal of 1V peak to peak and 10-100Hz using a function generator. Simply connect the output of the function generator to the modulation input on the current driver and the sync output to the oscilloscope. Also connect the photodiode to the oscilloscope.

Try to get a signal similar to the one shown in Figure 26. By changing the laser diode current (offset) you can move the position of the elbow in the curve.

To measure the actual threshold, just change the current offset, so that the elbow is in the middle of the modulation period (think about what you see on the picture and find out where the middle of the modulation period is) and turn off the modulation. The value of the laser diode current shown on the driver now is the threshold current!

3.15.2 405nm ECDL

Optimizing the feedback in a 405nm ECDL follows the same procedure, but can be done very well by eye due to the human eye’s sensitivity to blue light. The best possible feedback via a well-aligned cavity is the most critical feature ensuring single mode operation through as large a current range as possible. Optimal feedback is achieved through an iterative process of adjusting diode, filter and lens positions.

1. Using the back face of the collimation lens mount as a guide, adjust the tightness of the screws holding the heat sink and diode mount, so that the diode is nicely aligned in the vertical and horizontal directions.

2. Plug in the diode mount thermistor and check proper operation. Set the temperature to somewhere near room temperature, and switch on the diode. Make sure that light is being emitted, and increase the current to just above threshold. Gauge the centring of the uncollimated beam on the out-coupling assembly. Adjust if necessary.

3. Attach the collimation lens mount and adjust its position so that the beam is nicely centered on the out-coupling assembly. This is easily visible by observing the output beam very close to the second cat’s-eye lens. The beam need not be collimated at this point. The diode mount
position will require numerous adjustments in order to have the beam nicely centered on the out-coupler. With some luck, feedback will be visible at this point and optimization will be possible by working to reduce the threshold current.

4. Once the diode position appears to be as well-optimized as possible, roughly optimize lens positions: First, collimate the beam inside and outside the cavity. Then adjust cat’s-eye lens 1 to reduce the threshold. Finally, re-collimate the beam outside the cavity using cat’s-eye lens 2.

### 3.16 Interference filter

The interference filter is the wavelength-selective element in the laser. Assemble it according to the following steps:

1. Use tweezers to place the filter into the notch in the barrel.

2. Fix the filter’s position with a Thorlabs PM1 prism mount (Fig. 18). Make sure it is nicely centered in the notch and aligned vertically.

3. Glue the filter in place with two very small glue points on the sides.

4. Let it cure overnight.

5. Wrap some teflon tape around the bottom of the barrel. This makes the angle alignment easier due to the increased resistance, once the filter is sitting in it’s round notch in the cavity.

6. Place the interference filter in the cavity. It should require a small amount of force to insert the mounted filter, however if the required force seems excessive, reduce the amount of teflon tape wrapped around the barrel.
3.17 Saturation Spectroscopy

3.17.1 Fluorescence

**767nm ECDL**  With the angle of the interference filter one can coarsely tune the wavelength of the laser. The following steps can be very hard, since you may need very good feeling in your fingers. Make sure the teflon tape provides enough turning resistance to be able to rotate the filter barrel through very small angles. With too much resistance the barrel ”jumps” from angle to angle, which is also bad.

Rotate the filter and watch the wavelength changing on the wavemeter. The goal frequency for the potassium line is $\sim$391015GHz. Try to rotate the filter so that the 391015GHz is in the middle between the two mode jumps of the internal cavity. Since the free spectral range of the internal cavity is about 40GHz, mode jumps should occur at 391035GHz and at 390995GHz. Simply vary the temperature on the laser diode to find these mode jumps. Now the filter transmission maximum should be centered right at the potassium line.

After adding the interference filter to the cavity, the threshold current gets less. But usually you can optimize the threshold slightly again. Just modulate the current around the threshold again and turn the cat’s eye lens to optimize it.

The idea with the symmetric mode jumps holds for centring the filter transmission maximum to any frequency.

Now that the frequency is coarsely aligned, the next step uses the laser diode temperature or the laser diode current to do some finer tuning.

Watch the vapour cell with an infrared camera and tune the frequency around the 391015GHz using the current and/or the temperature till you can see fluorescence on the IR camera. The fluorescence should occur right where the beam is going through the cell. Write down all settings!

**405nm ECDL**  It is assumed that the ECDL has been placed in an optical setup where the beam can simultaneously be sent to the Ocean Optics spectrometer, a potassium vapour cell, and if possible a reference cavity to confirm that the laser is operating in a single mode.

With the laser off, turn the interference filter to a small angle ($\sim$5°). Turn the laser on and optimize threshold using cat’s-eye lens 1 and the collimation lens, ”walking” through the 2D parameter space to find the minimum laser threshold.

Collimate the output beam using cat’s-eye lens 2, and couple the beam into a fiber leading to the spectrometer. Rotate the interference filter until the observed spectrum is as close as possible to the shape and position of Fig. 28, which was captured using the same spectrometer while near the fluorescence maximum. Keep a close eye as well on the vapour cell for any signs of fluorescence.

If no fluorescence has been observed and the spectrum is as close as possible to Figure ??, begin experimenting with piezo voltage, laser diode current and temperature. Piezo voltage provides the finest control by changing the position of the external cavity modes (on the order of 1 GHz or $\sim$0.002nm), followed by laser diode current and temperature which each change the position of the diode gain curve on the order of tenths of nanometers. Start with small adjustments, and try to
avoid adjusting the temperature a large amount, as this can cause ongoing temperature oscillations as the TEC PID control finds a new set point.

With some luck, fluorescence will be visible after minimal adjustment of laser diode current and piezo voltage.

3.17.2 Observing saturation spectroscopy signal

Modulate the piezo voltage a sawtooth of frequency 50-200Hz an amplitude of approximately $10V_{pp}$ ($10V_{pp}$ should be on the piezo, think about gain of modulation input of the driver!).

Connect the sync output of the function generator to the oscilloscope and trigger the photodiode signal to it. Use AC coupling for the photodiode signal. Now one should see a drop in intensity on the AC photodiode signal at some point of the modulation period and little peaks next to it (see Figure R). If not, use the piezo voltage offset knob to scan "left" and "right" of the spectrum for it. Once it has been found, center it in the spectrum and have fun identifying the little peaks you see :) To improve the visibility of the peaks in the saturation spectroscopy signal, you can heat up the vapour cell to 40C or 50C.

Using the saturation spectroscopy signal, one can play around with different parameters (laser diode current, piezo voltage, temperature) to get a feeling for the mode hop and wavelength tuning behaviour of the laser.

4 Laser Characterization

4.1 767nm ECDL

4.1.1 Output power

The output power has been measured using a power meter.

Figure 19 shows the temperature dependence of the output power of Laser 1. With lower temperatures the output power seems to increase. This could be an intrinsic property of the diode. Other than that, it could be that due to the temperature change, the modes and the emitted frequency are changing. The modes at the edge of the FWHM of the IF (near a mode jump) have a lower gain and are therefore expected to have less output power. But this effect would average out, since with the current, also the wavelength gets tuned! However, the effect could be observed during the measurements, that near mode jumps the slope of the curve gets smaller. This can be nicely seen at high diode currents currents in the black curve, that the output power slope goes down every $\sim 20mA$ (what corresponds to the current needed to scan over the free spectral range of the internal cavity - see section 4.1.3).

Comparing the output powers of all the laser systems tested (Fig. 19), one can see the following:

The output power of laser 1 is higher than the output power of laser 2, even the OC reflectivity is smaller. One explanation could be the fact that the feedback of laser 2 was maybe not optimal.
Figure 19: Output power vs laser diode current for the laser setup with $R_{OC} = 10.9\%$ (Laser 1) for different laser diode temperatures.

Another explanation could be that with the $R=8\%$ mirror, the region of decreasing output power, when decreasing $R$ is reached (when $R$ gets too small, the properties of the bare diode dominate, what leads to lower output power when decreasing $R$).

Surprisingly laser 3 ($R=22\%$) has a higher output power than laser 4 ($R=17\%$). This and the result described before, could indicate that in laser 4 (which uses the same setup as laser 2) is maybe something intrinsically worse than in the other setup. It could be just that the laser diode properties are different or that the optics are better in one setup (or less dirty). Also the laser diode in one setup (which provides the back mirror of the cavity) could have more of an angle to the z-axis than in the other setup, due to imperfections in the mechanical elements or during the gluing process of the diode.

The threshold currents of laser 4 and 1 indicate that the feedback in the two setups could be different (Table 3).

However, with all lasers output powers of 40mW are possible below a diode current of 120mA, for laser 1, 3 and 4 even below 100mA, which is only half of the maximum diode current!

The limitation on the diode is according to the spec. sheet an extracavity power of 100mW, but no information is given about the feedback of the external cavity, which determines the intracavity power (the one that could kill the diode!). Just for safety I would recommend the diode not to run at more than 100mW intracavity power, so depending on the OC reflectivity one should set limitations to the current.

### 4.1.2 Beam profile

Using the Beam’R the beam profile of the four laser setups has been measured. The pictures are in the Appendix B. According to a gaussian fit, all lasers are estimated more than 90% TEM$_{00}$ mode. The further away you measure, the better the beam quality gets. For example laser 4, the at a
Threshold currents for all laser setups measured with the technique explained in section REF (except the bare diode). (*maybe not optimized feedback due to not nicely collimated intracavity beam)

<table>
<thead>
<tr>
<th>ROC</th>
<th>$I_{th} \text{ with IF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8%</td>
<td>$33\text{mA} \pm 1\text{mA}$</td>
</tr>
<tr>
<td>11%</td>
<td>$26\text{mA} \pm 1\text{mA}$</td>
</tr>
<tr>
<td>17%</td>
<td>$27\text{mA} \pm 1\text{mA}$</td>
</tr>
<tr>
<td>22%</td>
<td>$25\text{mA} \pm 1\text{mA}$</td>
</tr>
<tr>
<td>bare diode</td>
<td>$65\text{mA} \pm 1\text{mA}$</td>
</tr>
</tbody>
</table>

distance of 13cm (Fig. 20) the profile looks really crappy, but at a distance of 125cm (Fig. 20) the beam profile looks really nice! At short distances I expect effects like reflections of apertures and the fluorescence of the laser diode (that is still there and has a broad angle distribution) to mess the beam profile up.

The beam coming out of the laser diode is usually elliptic, but the external cavity seems to clean the mode profile. The ratio of vertical to horizontal FWHM of the intensity is always measured to be $0.9 < \text{FWHM} < 1.1$. The FWHM does not change significantly, by changing the laser output power.

Due to an astigmatic beam, it is not possible to collimate the output beam in both the horizontal and vertical direction. It seems, that collimating it in the vertical direction is somehow not nicely doable. So the light was always collimated in horizontal direction.

The collimation has been done using an IR card, which might not be the perfect tool to do that, due to saturation effects.

### 4.1.3 Wavelength tuning

As described in section 4.1.1, the fine tuning of the laser frequency is mainly done using the laser diode current and the piezo voltage.

To find out what the frequency sensitivities, as well as the mode hop free tuning ranges are for the piezo voltage and the diode current, the setup in Figure ON was used. The measurement results are shown in Table 3.

Actually all measurements are limited by the 100MHz resolution of the wavemeter. Especially for the current tunability within one external mode, this limits pretty much the measurement accuracy! (the error bars are just the standard deviation taken for an average of 2 values!)

Surprisingly the piezo mode hop free tuning range is bigger than the mode spacing of the external cavity modes. This is due to the fact that the internal cavity modes are very weak. The advantage of having such a big mode hop free tuning range is at the cost of stability: Imagine the laser starts at the optimal position. Assume the external cavity mode gets shifted by more than the free spectral range without a mode jump. Then the neighboured mode is in this optimal position and should have the highest gain, but the laser is still emitting in the other mode! One explanation
Figure 20: 767nm ECDL 4 beam profile: upper picture 13cm distance, lower picture 125cm distance.
Contribution of driver noise to linewidth

4.1.4 Noise and linewidth

and therefore “restarting” the laser without changing any of the relevant parameters. You could be done is just blocking the beam in the laser with a piece of paper for a short time and if the frequency gets turned down, the internal cavity modes could be. That tuning a running laser is different compared to tuning a ”not running” laser. In the running laser there are already many photons in the cavity and if the frequency gets tuned adiabatically, the total gain is not only determined by the cavity modes, but also by how many photons are already in the cavity, using the population inversion for their frequency!

One could test this instability by tuning more than the free spectral range, turning off the laser and turning it on again to see if it is lasing at the same frequency or at the one having the ”new” optimal frequency. Unfortunately if the laser current gets turned down, the internal cavity modes get shifted what changes the hole situation and it is not clear how reversible this process is.

What could be done is just blocking the beam in the laser with a piece of paper for a short time and therefore ”restarting” the laser without changing any of the relevant parameters.

4.1.4 Noise and linewidth

**Contribution of driver noise to linewidth** The piezo voltage driver has a noise level of 9.9mV_{pp} and 1.5mV_{RMS} [9] (no information about the frequency of the noise), tested without an external load connected. Adding a capacitive load, such as a piezo will decrease the noise, since the capacitance will create a low pass filter with the output resistance. So these numbers should be seen as an overestimated upper limit. The frequency sensitivity of the piezo is d\nu/dV_{piezo} = 0.053GHz/V according to the measurement in 5. Therefore the overestimated expected frequency noise, caused by the noise of the piezo driver, would be \Delta \nu_{RMS} \lesssim 80kHz respectively \Delta \nu_{pp} \lesssim 520kHz.
Table 5: Typical frequency scales of noise

<table>
<thead>
<tr>
<th>Noise source</th>
<th>Typical time scale</th>
<th>Typical frequency scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature drifts</td>
<td>≥1 s</td>
<td>≤1 Hz</td>
</tr>
<tr>
<td>Mechanical vibrations</td>
<td>10ms-50μs</td>
<td>100Hz-20kHz</td>
</tr>
<tr>
<td>Electrical noise</td>
<td>~1μs</td>
<td>~1 MHz</td>
</tr>
</tbody>
</table>

The current driver for the laser diode has a noise level of < 1.5μA_RMS (ripple: 50/60Hz & noise without ripple 10Hz-10MHz) [10]. The frequency sensitivity is dν/dI ≈ 170MHz/mA and therefore the expected frequency noise Δν ≲ 250kHz.

**Noise spectrum**  In order to find out at what frequencies the dominant noise contributions are, the noise spectrum has been measured. The trick is to turn fluctuations in the laser frequency into intensity fluctuations, using the saturation spectroscopy signal. This can be done by tuning the laser frequency to the edge of the crossover peak (red marked region in Fig. 22). At this point the intensity is very sensitive to small movements in frequency, what can be measured using a photodiode (PDA36A, 17MHz bandwidth). By connecting the photodiode to a spectrum analyzer (HP 3585B, 20Hz-40MHz), the noise spectrum can be obtained.

Since the lasers are free running, I checked once in a while that the frequency is not drifting away from the slope.

After turning off the sweep for the sat-spec signal, the function generator was unplugged from the piezo driver input, to avoid noise caused by the function generator (that gets multiplied by 15 at the input of the piezo driver).

The noise spectra are pretty similar for all laser setups. An example is shown in Figure 23 and Figure 24.

There are some noise peaks in the region around a kHz. This is the spectral range of sound waves and mechanical vibrations.

Lowering the noise caused by mechanical vibrations could be done by setting the laser on a rubber pad, to decouple it vibrationally from the laser table.

Although it’s not really clear yet where this noise is coming from or over what channel it is brought to the cavity (base plate vibrations, cable vibrations, or just sound waves hitting the resonator at a mechanical resonance).

In the region higher than 1.4kHz no measurable noise could be found (maybe limited by the noise floor of the spectrum analyzer)

The noise peak at 1.4kHz does not change when the casing of the laser is opened, so its not a soundwave resonance property of the casing.

**Beat note measurements**  Several beat note measurements have been taken using the spectrum analyzer HP E4402B (9kHz-3GHz) and the photodiode ET 2030 FC (30kHz-1.2GHz). The photo-
Figure 22: Saturation spectroscopy signal: on the edge of the cross over peak, the intensity is very sensitive to frequency fluctuations (steepest slope).

Figure 23: Left: noise spectrum of laser 4, right: noise floor without signal in the range of (a) 10Hz-2kHz and (b) 10Hz-50kHz.
diode was used without using a fiber, to avoid back reflections from the fiber facet. But still the fiber coupling input of the photodiod was used with the bare beams.

For total sweep times of 50ms and 1s over a span of 15-16MHz, 20-30 single sweep measurement were made.

Since the lasers are not locked, the beat note frequency moves around on the order of several hundreds of kHz (beat note frequency) over a few seconds. To compensate for that, all measurements have been recentered. To compensate for the fact that the jittering in some measurements broadens the line due to a movement in the scan direction and sometimes narrowing it due to a movement opposite to the scan direction during the measurement, an average is made over 4-5 single measurements (average in the linear scale!).

The choosing of the single sweep measurements is kind of arbitrary, one could only choose the narrowest ones in order to get better data. I tried to choose narrow ones as well as broader ones. I tried to not choose asymmetric ones and ones that are obviously messed up by mechanical or acoustic disturbances like hitting a table, slamming a door or Dylan talking and hitting the 1.4kHz resonance (see section 4.1.4) with his voice.

Examples of the beat notes are shown in Figure 25. All other measurements look quite similar. The low frequency noise (around the peak) is due to technical frequency noise of the drivers and therefore has a gaussian distribution. The high frequency noise, is due to intrinsic limitations (for example the linewidth of the laser transition) and is thus given by a Lorentzian distribution. Both regions has been fitted, translating these distributions into logarithmic scales. For the Lorentzian fit the boundary condition of matching the peaks value was chosen.

Linewidths measured for 1s, 50ms sweep time, as well as the instantaneous one (Lorentzian fit of the wings), are getting smaller, with higher OC reflectivities. The Gaussian linewidth difference for the 1s and the 50ms sweep time indicates, that there is noise in the frequency region between 100Hz and 2kHz an addition in linewidth of 21kHz, respectively 14kHz is picked up. In this region the main two main noise peaks could be observed (see section 4.1.4).

By not perfectly recentering the beat note measurements and taking the average, the linewidth could be broadened.
### Table 6: Beat note measurement results.

<table>
<thead>
<tr>
<th>Laser pair</th>
<th>low R</th>
<th>high R</th>
<th>low R</th>
<th>high R</th>
</tr>
</thead>
<tbody>
<tr>
<td>sweep time, span</td>
<td>1s, 15MHz</td>
<td>1s, 16MHz</td>
<td>50ms, 15MHz</td>
<td>50ms, 16MHz</td>
</tr>
<tr>
<td>linewidth $\Delta \nu_{\text{Gaussian}}$</td>
<td>214 ± 27</td>
<td>193 ± 13</td>
<td>153 ± 7</td>
<td>139 ± 10</td>
</tr>
<tr>
<td>linewidth $\Delta \nu_{\text{Gaussian}}$</td>
<td>24</td>
<td>12</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>range for fit $</td>
<td>\nu - \nu_0</td>
<td>_{\text{Gaussian}}$</td>
<td>&lt; 0.7MHz</td>
<td>&lt; 0.5MHz</td>
</tr>
<tr>
<td>range for fit $</td>
<td>\nu - \nu_0</td>
<td>_{\text{Lorentzian}}$</td>
<td>&gt; 2MHz</td>
<td>&gt; 2MHz</td>
</tr>
<tr>
<td>sweeptime over $\Delta \nu_{\text{Gaussian}}$</td>
<td>~ 10ms</td>
<td>~ 0.5ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>contributing noise [kHz]</td>
<td>&gt; 0.1</td>
<td>&gt; 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 25: Upper picture: Beat note measurement: average over 5 single sweeps, 1s sweep time for laser 3 & 4; Lower picture: Beat note measurement: averaged over 5 single sweeps, 50ms sweep time for laser 3 & 4.](image-url)
Figure 26: Characteristic curve for the 20% out-coupled 405nm laser with AR-coated diode.

4.2 405nm ECDL

4.2.1 Output power

The output power of the 405nm ECDL was measured with a Thorlabs power meter for a range of currents up to the operating current of approximately 44mA (Fig 26).

The AR-coated diode used in this laser has an original rating of 120mW, and is rated by the distributor (Sacher Lasertechnik) to 30mW at $I_{LD} \approx 75$mA in an external cavity configuration. In order to preserve the lifetime of the diode, the diode was run at currents not more than 50mA, producing output power up to $\sim 16$mW.

4.2.2 Beam profile

The profile of the 405nm ECDL was measured using the Beam’R at approximately 65cm and 140cm, showing a marked increase in Gaussian fit quality (Fig. 27). The apparently poor TEM$_{00}$ fit at short distances is likely due to the significant amount of spatially incoherent light emitted by the laser diode in addition to the beam, which has not yet diverged sufficiently to be excluded from the profile.

4.2.3 Mode and linewidth

The ability of the 405nm ECDL to remain single mode even through mode hops is strongly dependent on the quality of feedback and thus the alignment of the cavity. The low resolution of the Ocean Optics spectrometer (Fig. 28) necessitated the construction of a Fabry-Perot interferometer (Fig. 29), to observe the spectrum in detail and in real-time.

The home-built Fabry-Perot interferometer is a confocal reference cavity constructed from two Thorlabs lenses (part number LC1054), custom coated with Thorlabs’ broadband dielectric mirror.
Figure 27: Beam profile for 405nm ECDL at (a) 65cm and (b) 140cm, showing an increase in TEM$_{00}$ fit quality at greater distances.
coating. Unfortunately, the radius of the lenses was mistakenly chosen too small, creating a very small reference cavity with a large free spectral range. The free spectral range $\Delta f$ of a confocal cavity is given by

$$\Delta f = \frac{c}{4d} \quad [5]$$

For the home-built cavity, $d = 12.9\text{mm}$ and thus $\Delta f = 5.81\text{GHz}$. The finesse $F$ of a Fabry-Perot cavity is a parameter related to the ”sharpness” of the resonance, given by

$$F = \frac{\pi \sqrt{R}}{1 - R} \quad [2]$$

Estimating a reflectivity of the mirrors $R=99\%$ [11], the finesse of the home-built cavity is approximately 310. With these two parameters, the FWHM of the resonance in the Fabry-Perot cavity is found to be

$$\text{FWHM} = \frac{\Delta f}{F} \approx 19\text{MHz}$$

Despite the limited resolution of this Fabry-Perot cavity, the calculated FWHM and the measured cavity trace (Fig. 30) suggest that 19MHz represents an upper limit for the linewidth of the ECDL.

### 4.2.4 Saturation spectroscopy

A heated potassium vapour cell was set up in order to:

1. Tune the laser to fluorescence using filter position, current and temperature.
2. Observe the Doppler-broadened absorption of the potassium vapour.
3. Set up Doppler-free saturation spectroscopy to observe the hyperfine splitting of $^{39}\text{K}$ and (occasionally) $^{41}\text{K}$ (Fig. 31).
4. Set up frequency modulation transfer spectroscopy with a lock-in amplifier to generate and optimize an error signal (Fig. 32).
Figure 29: Home-built confocal reference cavity for (somewhat) high resolution spectroscopy of 405nm ECDL.

Figure 30: Cavity trace for 405nm ECDL using the home-built Faby-Perot reference cavity. The finesse of the cavity is not especially high (~310) due to incorrectly chosen mirrors, contributing to the poor resolution of the signal. Still, it is sufficient to distinguish whether or not the laser is operating in a single mode.
Figure 31: Saturation spectroscopy signal for 405nm ECDL. Peaks for $^{39}\text{K}$ F=1 and F=2 states are visible, as well as the large central crossover peak.

The length scale of the saturation spectroscopy signal is set by the known 461.72MHz hyperfine splitting of the $4S_{1/2}$ F=1 and F=2 states of $^{39}\text{K}$ [12]. Fitting a Gaussian using MATLAB (Fig. 31a), the FWHM of the Doppler-broadened absorption was found to be

$$\text{FWHM}_{\text{Doppler}} = 2\sqrt{2}\ln 2 \sigma \approx 985\text{MHz (meas.)}$$

Which compares reasonably well with the theoretical FWHM given by the Maxwell speed distribution:

$$\text{FWHM}_{\text{Doppler}} = \sqrt{\frac{8k_B T \ln 2}{mc^2}} f_0 \approx 1.02\text{GHz (theor.)}$$

Subtracting the Gaussian fit from the Doppler-broadened absorption spectrum, the crossover peak for the F=1, F=2 transition was fitted with a Lorentzian profile of $\approx 8$ GHz (meas.).

The lock-in amplifier and lock-box were incorporated into the 405nm ECDL setup, and used to generate an error signal (Fig. 32). The resulting signal was very noisy and inconsistent, but due to the lock-in amplifier’s unreliable nature it was difficult to establish whether or not this noise was present in the laser, caused by air currents, or due to faulty electronics. One suggestion that the noise is due to faulty electronics is the very similar error signal obtained by John Simpson from the same lock-in amplifier in his Summer 2010 report [13].

Assuming that a portion of the noise present in the error signal is cause by the ECDL itself, the most likely cause appears to be acoustic noise. It is recommended that in the future the 1/4”-20 screws holding the laser to the table be replaced by 8-32 screws, connected to the optics table with Thorlabs AE8E25E thread adapters.
Figure 32: Error signal of the $^{39}$K F=1, F=2 crossover peak obtained using frequency modulation transfer spectroscopy. A significant amount of noise is present in the signal, likely due in part to acoustic coupling of the ECDL to the optical table.

5 References


6 Appendix

6.1 Notes for future 405nm ECDLs

There are a number of features of the particular design of IF-stabilized ECDL that posed problems for single-mode operation of a 405nm ECDL. The following brief list summarizes those that were found most in need of modification.

- It is likely that single-mode operation would be possible at higher currents of the laser diode (and thus higher output power), with a shorter laser cavity. I therefore suggest that in a future design, the interference filter be placed as close to the collimation lens as possible, with the first cat’s-eye lens immediately thereafter.

- Heat-sinking was an issue for the 405nm laser diodes, which require a larger voltage drop across their terminals (thus generating more power as heat for the same output power). While this problem was solved by modifying a Home-Hardware heat sink to fit the cavity, obviously a more standard solution would be preferable.

- Any method of weakening the acoustic resonance characteristics of the laser cavity would be ideal, for example placing an acoustic-damping anti-static foam inside the free space in the cavity (leaving the optical axis clear, of course).
### 6.2 Project timeline for 405nm ECDL

<table>
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<tr>
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<td>25-29</td>
<td>1-5</td>
<td>8-12</td>
<td>15-19</td>
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- **Building shelves & optics table walls**
- **Part orders**
- **Webcam profiler**
- **Imaging for Chip Experiment**
- **Reference cavity**
- **Report writing**
- **Located Matthias’ drawings**
- **Inventor drawings**
- **Machine shop**
- **ECDL assembly**
- **Heat-sinking**
- **Laser optimization**
- **Feedback breakthrough**
- **Testing assorted diodes, optimization**
- **Joseph orders AR-coated diode**
- **AR-coated diode installed**
- **Error signal**
- **ECDL characterization**
6.3 Complete parts list

Table 7: Parts fabricated in U of T machine shop

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<tr>
<th>ITEM</th>
<th>DESCRIPTION</th>
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<td>base plate</td>
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<tr>
<td>back plate</td>
<td>aluminum</td>
</tr>
<tr>
<td>main cavity</td>
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<tr>
<td>collimation lens mount</td>
<td>brass</td>
</tr>
<tr>
<td>cat’s-eye lens 1 mount</td>
<td>brass</td>
</tr>
<tr>
<td>cat’s-eye lens 2 mount</td>
<td>brass</td>
</tr>
<tr>
<td>collimation lens mount mount</td>
<td>aluminum</td>
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<tr>
<td>diode mount</td>
<td>copper</td>
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<tr>
<td>cylinder for heat conduction</td>
<td>copper</td>
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Estimated cost: $1176.00

Table 8: Controllers

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<thead>
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<th>ITEM</th>
<th>COMPANY</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>PRICE</th>
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<tr>
<td>LD current driver</td>
<td>Thorlabs</td>
<td>LDC202C</td>
<td>$I_{\text{max}} = 200\text{mA}$</td>
<td>$950.00$</td>
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<td>base TEC controller</td>
<td>Thorlabs</td>
<td>TED200C</td>
<td>$I_{\text{max}} = 2\text{A}$</td>
<td>$968.00$</td>
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<tr>
<td>LD TEC controller</td>
<td>Thorlabs</td>
<td>TED200C</td>
<td>$I_{\text{max}} = 2\text{A}$</td>
<td>$968.00$</td>
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<td>piezo voltage driver</td>
<td>Thorlabs</td>
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<td>$712.00$</td>
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### Table 9: Optics & Electronics

<table>
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<tr>
<th>Item</th>
<th>Company</th>
<th>Part Number</th>
<th>Description</th>
<th>Price</th>
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<tbody>
<tr>
<td>laser diode</td>
<td>Sacher Lasertechnik</td>
<td>SAL-405-030</td>
<td>$\lambda=403\text{nm}, \quad P_o=120\text{mW}$</td>
<td>$$6800.00$</td>
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<tr>
<td>collimation lens</td>
<td>Thorlabs</td>
<td>C230TME-A</td>
<td>$f=4.51\text{mm, NA}=0.55$</td>
<td>$$87.00$</td>
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<tr>
<td>cat’s-eye lens 1</td>
<td>Thorlabs</td>
<td>352280-A</td>
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<td>cat’s-eye lens 2</td>
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<td>352220-A</td>
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<td>LD socket*</td>
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<td>HPS9500/10-5/5</td>
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<td>LD TEC*</td>
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<td>CH-41-1.0-0.8</td>
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<td>$$22.50$</td>
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<tr>
<td>out-coupler</td>
<td>CVI Melles-Griot</td>
<td>PR1-405-11-0512</td>
<td>$R=20%$, $30%$ purchased</td>
<td>$$205.00$</td>
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<td>heat sink</td>
<td>Home Hardware</td>
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<td>interference filter</td>
<td>Iridian</td>
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<td>$\lambda_{max}=406.4\text{nm, }2\sigma=0.39\text{nm}$</td>
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<td>thermistors*</td>
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<td>optical isolator</td>
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<td>IO-5-405-LP</td>
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<td>$$1975.00$</td>
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</tbody>
</table>

*Indicates items remaining in stock from construction of 767nm ECDLs.

**Estimated total cost:** $\$14640.18$

#### 6.4 Mechanical drawings