External Cavity Diode Laser

LDL Littrow

Revision 2.07

Limitation of Liability

Copyright

Contact

For further information, please contact:

MOG Laboratories P/L	MOGLabs USA LLC	MOGLabs Europe
49 University St	419 14th St	Goethepark 9
Carlton VIC 3053	Huntingdon PA 16652	10627 Berlin
AUSTRALIA	USA	Germany
+61 3 9939 0677	+1 814 251 4363	+49 30 21 960 959
info@moglabs.com	info@moglabsusa.com	info@moglabs.eu
www.moglabs.com	www.moglabsusa.com	www.moglabs.eu

Preface

Semiconductor laser diodes can provide an energy-efficient, compact, low cost, high power, low noise, tunable source of coherent light over a large range of wavelengths. With wavelength-dependent feedback from an external cavity, they can be very narrow in linewidth, but also very sensitive to vibration and frequency drift caused by environmental changes. The MOGLabs LDL Littrow design offers excellent passive stability with low sensitivity to vibration by avoiding common ECDL weaknesses, in particular springs and flexures.

We hope that the MOGLabs LDL works well for you. Please let us know if you have any suggestions for improvement in the laser or in this document, so that we can make life in the laser lab easier for all, and check our website from time to time for updated information.

MOGLabs, Melbourne, Australia
www.moglabs.com

Safety Precautions

Safe and effective use of this product is very important. Please read the following laser safety information before attempting to operate the laser. Also please note several specific and unusual cautionary notes before using MOGLabs lasers, in addition to the safety precautions that are standard for any electronic equipment or for laser-related instrumentation.

CAUTION – USE OF CONTROLS OR ADJUSTMENTS OR PERFORMANCE OF PROCEDURES OTHER THAN THOSE SPECIFIED HEREIN MAY RESULT IN HAZARDOUS RADIATION EXPOSURE

Laser output from the LDL can be dangerous. Please ensure that you implement the appropriate hazard minimisations for your environment, such as laser safety goggles, beam blocks, and door interlocks. MOGLabs takes no responsibility for safe configuration and use of the laser. Please:

- Avoid direct exposure to the beam.
- Avoid looking directly into the beam.
- Note the safety labels (examples shown in figure below) and heed their warnings.
- When the laser is switched on, there will be a short delay of two seconds before the emission of laser radiation, mandated by European laser safety regulations (IEC 60825-1).
- The STANDBY/RUN keyswitch must be turned to RUN before the laser can be switched on. The laser will not operate if the keyswitch is in the STANDBY position. The key cannot be removed from the controller when it is in the clockwise (RUN) position.

- To completely shut off power to the unit, turn the keyswitch anti-clockwise (STANDBY position), switch the mains power switch at rear of unit to OFF, and unplug the unit.
- When the STANDBY/RUN keyswitch is on STANDBY, there cannot be power to the laser diode, but power is still being supplied to the laser head for temperature control.

WARNING The internal circuit board and piezoelectric transducers are at high voltage during operation. The unit should not be operated with covers removed.

CAUTION Although the LDL is designed and priced with the expectation that the end-user will tweak the alignment, some components are fragile. In particular the piezo actuator behind the grating, and the grating itself, are very easily damaged. Please take care of these items when working inside the laser.

Do not attempt to clean the diffraction grating. Finger prints and blemishes usually do not impact the laser performance.

NOTE MOGLabs products are designed for use in scientific research laboratories. They should not be used for consumer or medical applications.

Label identification

The International Electrotechnical Commission laser safety standard IEC 60825-1:2007 mandates warning labels that provide information on the wavelength and power of emitted laser radiation, and which show the aperture where laser radiation is emitted. Figure 1 shows examples of these labels and figures 2 and 3 show their location on the LDL laser and large-chassis CEF version.

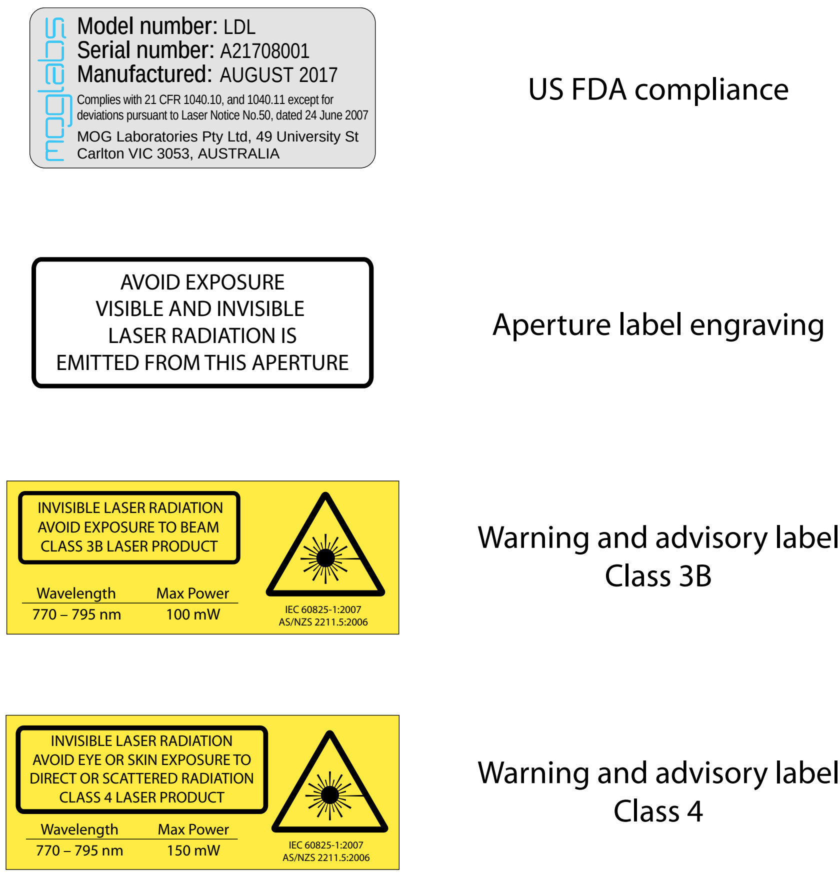

Figure 1: Warning advisory and US FDA compliance labels.

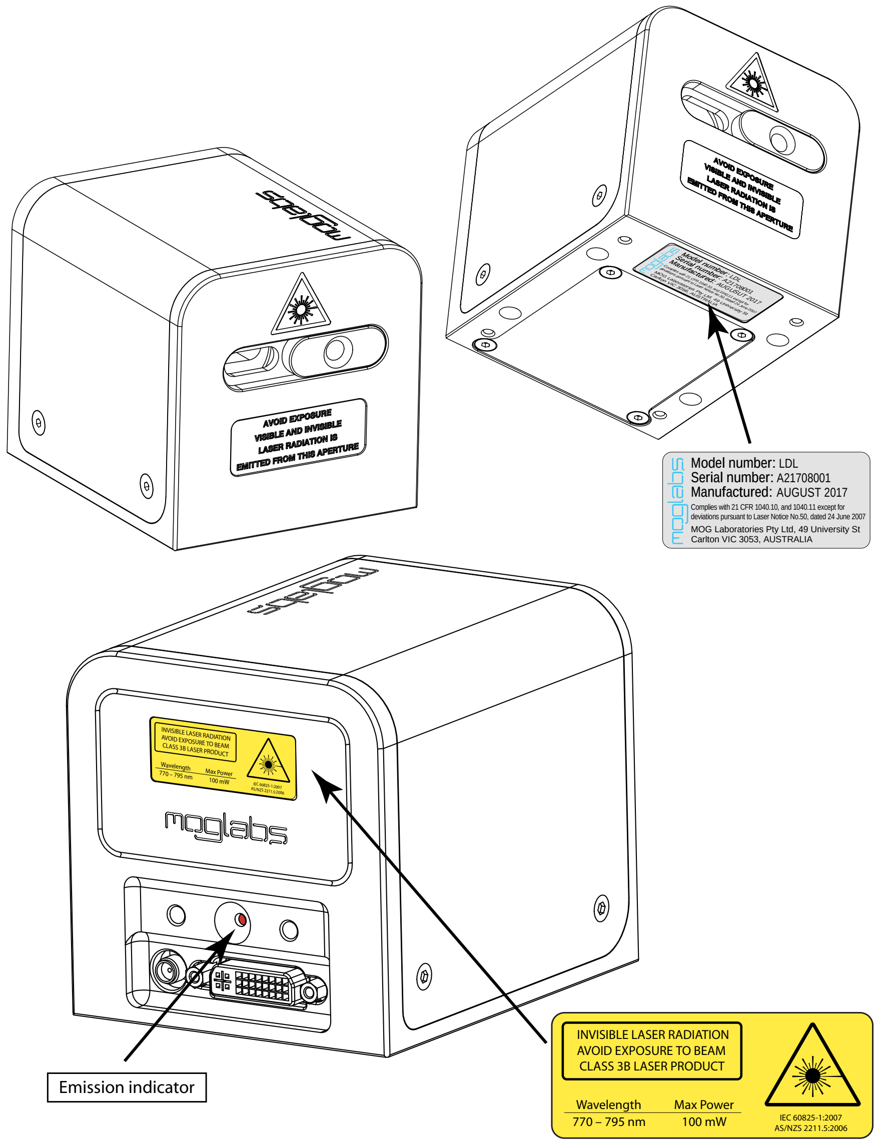

Figure 2: Schematic showing location of laser warning labels compliant with International Electrotechnical Commission standard IEC 60825-1:2007, and US FDA compliance label. Aperture label engraved on the front of the laser near the exit aperture; warning advisory label on the rear and compliance label beneath.

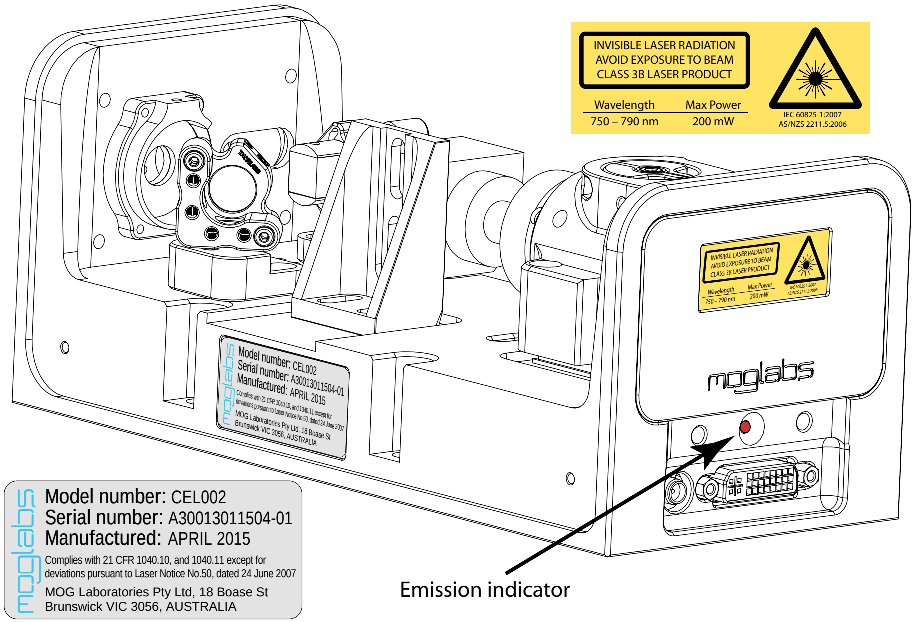

Figure 3: Schematic showing location of laser warning labels for the large-chassis CEF version of a MOGLabs laser.

Protection Features

MOGLabs lasers includes a number of features to protect you and your laser.

Protection relay When the power is off, or if the laser is off, the laser diode is shorted via a normally-closed solid-state relay at the laser head board.

Emission indicator The MOGLabs controller will illuminate the emission warning indicator LED immediately when the laser is switched on. There will then be a delay of at least 2 seconds before actual laser emission.

Interlock It is assumed that the laser power supply is keyed and interlocked for safety. In some cases, the laser head board provides connection for an interlock (see appendix B), if used with a power supply which does not include such an interlock.

RoHS Certification of Conformance

MOG Laboratories Pty Ltd certifies that the MOGLabs External Cavity Diode Laser does not fall under the scope defined in *RoHS Directive 2002/95/EC*, and is not subject to compliance, in accordance with *DIRECTIVE 2002/95/EC Out of Scope; Electronics related; Intended application is for Monitoring and Control or Medical Instrumentation*.

MOG Laboratories Pty Ltd makes no claims or inferences of the compliance status of its products if used other than for their intended purpose.

Extending laser diode and piezo lifetime

At night, switch to standby:

1. If using the LDL to seed an amplifier, first turn the amplifier off.
2. Switch the laser diode current off.

   If using a MOGLabs DLC controller, don't adjust the current, just switch the toggle up (off).
3. Switch from RUN to STANDBY.

For a MOGLabs DLC controller in standby mode, the temperature controller will continue to operate, so the laser is ready for quick startup the next day. But the laser diode current and piezo voltage will be zero, extending their operating life.

In the morning, switch back on:

1. Switch from STANDBY to RUN.
2. Switch the laser diode toggle down (on).

   You don't need to adjust the current, just wait a few minutes for the diode temperature to equilibrate.

You should switch your MOGLabs DLC into STANDBY mode at nights and weekends and whenever the laser is not being used for more than a few hours. Most lasers need to operate only 40 hours during a 168 hour week; thus switching to standby mode can extend the diode and piezo lifetime by a factor of four.

Contents

1. Introduction

Semiconductor laser diodes are compact, efficient and low-cost, but usually have poor wavelength control, linewidth and stability. The addition of an external frequency-selective cavity allows control of the operating wavelength over a few nm range, with sub-MHz linewidth and stability. The MOGLabs LDL (see Fig. 1.1) is machined from a solid aluminium block, so that the laser is stable, robust, and insensitive to vibration. The cavity is hermetically sealed for additional suppression of environmental fluctuations and drift.

The MOGLabs LDL is a Littrow design (see Fig. 1.2) in which an external cavity is formed between the rear reflecting surface of the semiconductor diode, and a diffraction grating at several centimetres from the diode. Many references describe designs and design considerations [1–6].

The output beam from a laser diode is collimated with a high numerical aperture (NA) lens and incident on a diffraction grating. The grating is angled such that the first order reflection is directed back into the laser

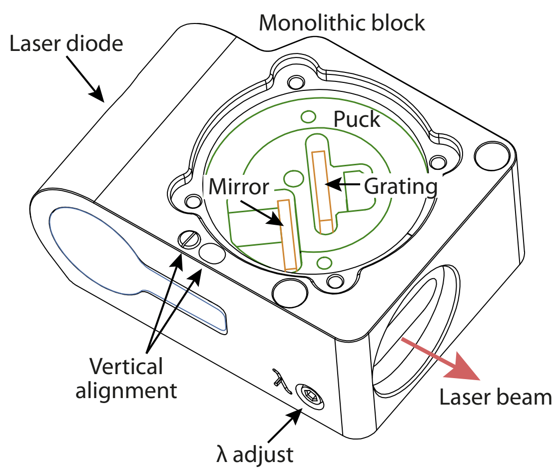

Figure 1.1: Sketch of MOGLabs LDL monolithic block external cavity diode laser.

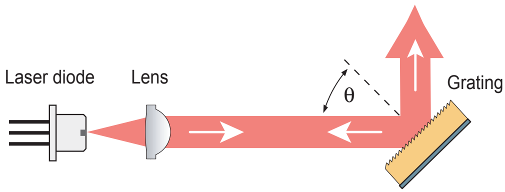

Figure 1.2: Schematic of a Littrow configuration external cavity diode laser (ECDL). The external cavity, formed by the rear facet of the laser diode and the grating, determines the laser wavelength. One longitudinal cavity mode is selected by dispersive feedback from the grating.

diode. This feedback has a wavelength centered around $\lambda = 2d\sin\theta$ where d is the grating line spacing and θ is the angle with respect to the the grating normal.

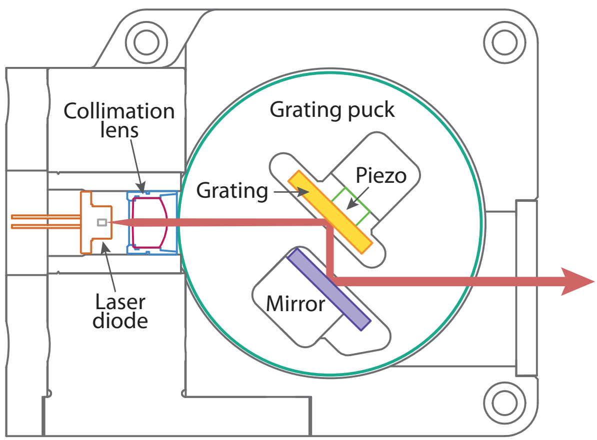

Figure 1.3: Cross-section of MOGLabs LDL Littrow laser, showing arrangement of laser diode, collimation lens, grating, piezoelectric transducer and fold mirror. The grating angle and hence wavelength is adjusted by rotating the central cylinder (the grating puck) which forms a rigid mount for grating and mirror.

1.1 External cavity

Semiconductor laser diodes normally have a high reflectivity rear facet and a front facet with reflectivity of only a few percent. The diode cavity is called the intrinsic or internal cavity. The *external* cavity is formed by the diffraction grating and the diode rear facet, and because the feedback from the grating is generally greater than that of the front facet, the external cavity determines the lasing wavelength. The external cavity is typically around 20 mm long, with cavity mode spacing (FSR) of $c/2L = 7.5\,\text{GHz}$.

The laser diode and collimating lens are held rigidly in a focusing tube. The grating (usually sinusoidal holographic) is fixed to a precision mechanical mount which can be adjusted to optimise feedback of the first order diffraction back into the laser diode, and the zeroth order (direct reflection) becomes the laser output beam. An optional fold mirror cancels angular deviation of the output beam as the laser wavelength is tuned [3]. Variation of the grating angle is used for coarse selection of the wavelength, within the gain bandwidth of the laser diode.

1.2 Mode competition

As the wavelength is varied, competition between the frequency determined by the internal and external cavities, and the dispersion of the grating diffraction, leads to *mode hops*. From figures 1.4 and 3.3, the net gain (combined product of semiconductor gain, diffraction dispersion, internal and external cavity interference) can be very similar at adjacent external cavity modes. A small change in the internal cavity mode, or the grating angle, can lead to the overall gain being greater at a mode adjacent to the mode in which the laser is oscillating, and the laser then hops to that higher-gain mode. See Ref. [1] for a detailed discussion.

1.3 Piezo-electric frequency control

Small changes to the laser frequency are achieved by controlling the external cavity length with a piezo electric actuator. For the MOGLabs LDL, the grating is mounted to a multilayer piezoelectric "stack". The cavity length

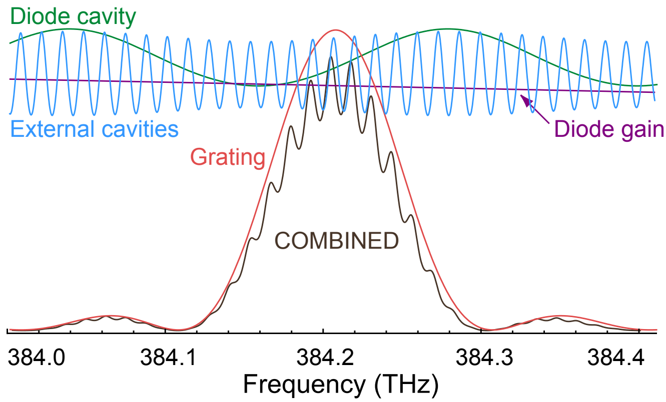

Figure 1.4: Schematic representation for the various frequency-dependent factors of an ECDL, adapted from Ref. [1], for wavelength $\lambda = 780$ nm and external cavity length $L_{ext} = 15$ mm.

variation is about 10 nm per volt, producing a frequency shift of 250 MHz/V with a range of 25 GHz for 100 V drive voltage. The bandwidth is limited by mechanical resonances, typically at a few kHz.

1.4 Temperature and current

The laser frequency also depends on temperature and current; the sensitivities are typically 3 MHz/μA and 30 GHz/K [7]. Thus, low-noise stable electronics, such as the MOGLabs DLC external cavity diode laser controller, are essential [2] to achieve sub-MHz linewidth and stability.

An important aspect of an ECDL is temperature control of the cavity, since the laser frequency depends on the cavity length and hence on the thermal expansion coefficient of the cavity material [1]. The cavity can be machined from materials with low thermal expansion coefficient but even then the passive stability is inadequate for research applications. Active feedback of the cavity temperature combined with cavity length control provide a flexible and stable approach. The MOGLabs LDL uses a negative temperature coefficient (NTC) thermistor to sense the cavity temperature and Peltier thermoelectric cooler (TEC) to heat and cool the cavity material.

2. First light

Initial installation of the laser is typically a matter of mounting it to an optical table and connecting to a MOGLabs controller. Mounting holes can be accessed by removing the cover, so that the M6x16 socket head cap screws provided can attach the laser to the optical table. The hole spacing also allows direct mounting to imperial tables for non-metric countries (Burma, Liberia and the USA).

The laser includes a water cooling channel for laser operation at unusually high or low temperatures, or in laboratories with high or unstable air temperature. For most applications, water cooling is not required; dissipation to the air and/or optical table is sufficient.

The performance of an external cavity diode laser is strongly dependent on the external environment, and in particular acoustic vibrations. Very small changes in the external cavity length have a large effect on the laser frequency, typically 25 MHz per nanometre length change. The monolithic block construction of the MOGLabs LDL reduces the influence of vibrations on the cavity length, but some elasticity remains. The LDL is hermetically sealed to substantially reduce the effects of acoustic disturbances in the cavity air gap.

Active feedback to the laser frequency, via piezo translation and current modulation, reduces external influences, but some simple measures to minimise coupling to environmental variations and vibration sources may be warranted. For example, a surrounding box to reduce air movement and accidental bumping of the laser, mounting the laser to a heavy support, and isolation from the optical table with an intermediary breadboard which is separated from the main optical table with viscoelastic polymer (e.g. Sorbothane™).

Once the laser is mounted appropriately, the laser can be powered on. It is assumed that a MOGLabs DLC controller has been provided with your laser and that the temperature and current limit have been set appropriately.

If an alternative supply is used, please set a current limit according to the maximum safe operating current stipulated in the test data provided with your laser. Also note that $+5\,\mathrm{V}$ must be provided on pin 15 of the headboard connector to open the protective relay; see appendix B for connection details.

2.1 Temperature

The preferred diode temperature will depend on the diode, the required wavelength, and the ambient room temperature. For example, typical AlGaAs diodes used for data storage applications (CD-R burners) have a nominal wavelength of $\lambda = 784\,\mathrm{nm}$ at 25°C, with a $d\lambda/dT$ slope of $-0.3\,\mathrm{nm}/°\mathrm{C}$, implying an optimum temperature of about 12°. Depending on the humidity, low temperatures may induce condensation on the diode and collimation lens. The grating feedback will determine the final wavelength, and the feedback is generally sufficient to "pull" the wavelength by $\pm 5\,\mathrm{nm}$, and thus in this example a sensible set temperature would be about 17 to 18°C.

2.2 Current

The output of semiconductor laser diodes follow a nominally linear power *vs.* current (PI) relationship, once the current is above a device-specific threshold (see Fig. 2.1). Initially the current should be set above threshold, but well below the nominal maximum operating current, until the laser is fully aligned.

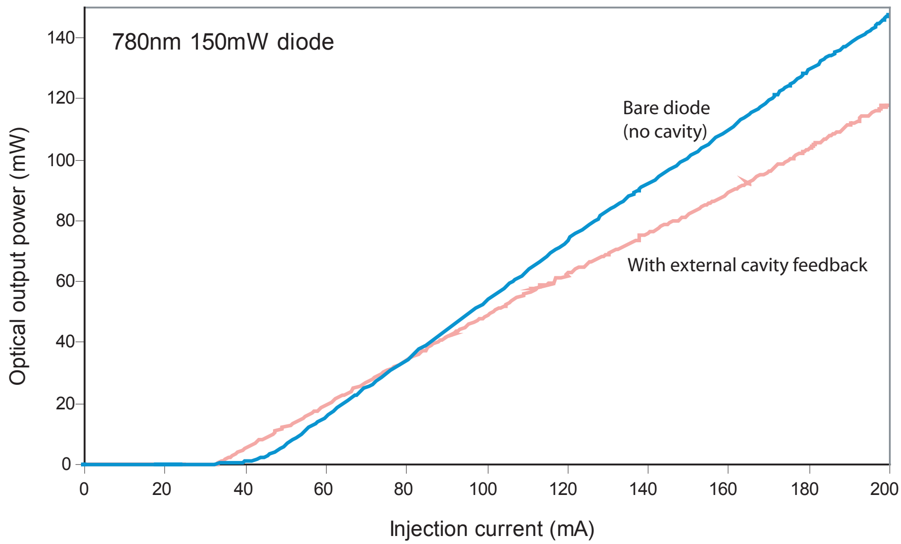

Figure 2.1: Sample laser diode power-current *PI* characteristic curves, with and without an external cavity. The external cavity feedback reduces the threshold current, and also the apparent power/current slope because the measured power with feedback is not the power from the bare diode, but the output beam reflected from the grating. The slope with feedback in this example is 75% of the bare diode output slope, consistent with the grating direct reflectivity.

3. Operation

Figure 3.1 is a schematic of the laser. Normal operation of the laser is usually a matter of selecting the correct wavelength, and adjusting the parameters to achieve the maximum possible mode-hop free scan.

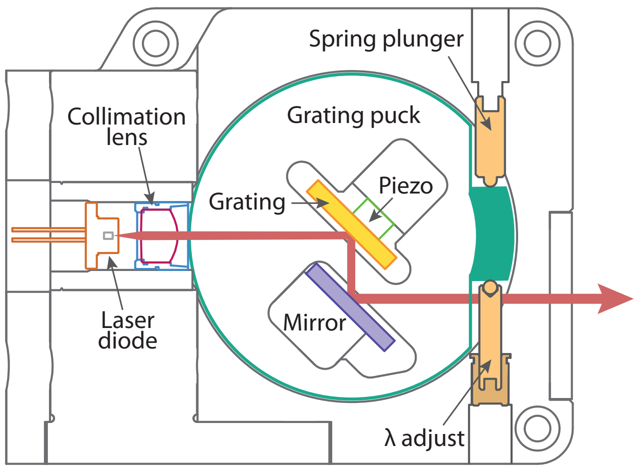

Figure 3.1: Cross-section sketch of the MOGLabs LDL, showing the cylindrical grating mount (puck), piezo-mounted grating, fold mirror, and wavelength adjustment. The grating mount can be rotated using the tangential λ fine adjustment screw. A counteracting spring-plunger should be released to allow rotation.

3.1 Wavelength

The primary control of wavelength is the grating angle, which can be adjusted while the laser is operational. A wavemeter [8], high-resolution spectrometer, or similar is almost essential, although with patience it is possible to find an atomic reference by carefully adjusting the grating angle while scanning the laser.

Note that the wavelength is quite sensitive to grating angle. For example, with the standard $\lambda = 780$ nm, $1/d = 1800$ l/mm grating, the angular dependence is about 14 nm per degree of grating angle. With the LDL, that is 8 nm per full turn of the wavelength adjustment screw.

Set the laser current so that the output power is sufficient, ensuring that the internal cavity power is below the maximum rated for the diode (see Fig. 2.1). Then change the grating angle to adjust the wavelength. The laser will hop between external cavity modes, as the wavelength is adjusted, through cycles of dim and bright output. Adjust the angle to one of the bright modes nearest the optimum wavelength, and then adjust the laser current and piezo voltage to achieve the exact wavelength required.

It may then be necessary to adjust the vertical alignment slightly; follow the flash procedure outlined previously. That is, set the injection current just below threshold, and adjust the vertical alignment until the laser flashes, and repeat until the threshold current is minimised.

3.2 Scanning, mode-hops, and bias

Mode-hops are a frequent occurrence with external cavity diode lasers. A mode-hop is a discontinuity when tuning or scanning the laser wavelength. As the laser wavelength is varied, usually by changing the cavity length with a piezo, competition between the wavelength determined by the different wavelength-dependent cavity elements can lead to a *mode hop*: a jump in laser wavelength to a different external cavity mode. Wavelength-dependent elements include the external cavity, the laser diode internal cavity between the rear and front facets of the diode, the filter transmission, and the gain bandwidth of the laser diode.

The different wavelength-dependent characteristics are shown schematically in figure 3.2. The net gain is the combined product of semiconductor gain, filter transmission, internal and external cavity interference. The net gain can be very similar at adjacent external cavity modes. A small change in the internal cavity mode, or the filter angle, can lead to the overall gain being greater at a mode adjacent to the mode in which the laser is oscillating, and the laser then hops to that higher-gain mode. See Ref. [1] for a detailed discussion.

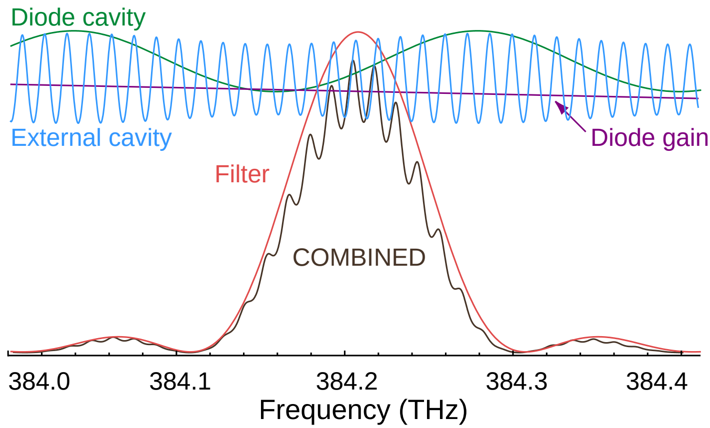

Figure 3.2: Schematic representation for the various frequency-dependent factors of an ECDL, adapted from Ref. [1], for wavelength $\lambda = 780\,\text{nm}$ and external cavity length $L_{\text{ext}} = 15\,\text{mm}$.

3.3 Scanning

The external cavity length is usually controlled by piezo actuators moving the output coupler. The cavity length changes with piezo voltage, and for a large change, the laser will usually hop to a neighbouring cavity mode. Figure 3.3 is a schematic of the net gain variation with laser frequency, showing two adjacent modes of very similar gain. Figure 3.4 is a measurement of the frequency of a laser scanning properly, and with a mode-hop at one edge of the scan.

The mode-hop-free scan range (MHFR) can be optimised by careful adjustment of the injection current, which affects the refractive index of the diode and hence the frequency of the cavity mode.

3.3.1 BIAS optimisation

This shift of cavity mode frequency allows for compensation of the mismatch of tuning responses. The diode injection current can be “automatically” adjusted as the laser frequency is changed, using a “feed-forward” or cur-

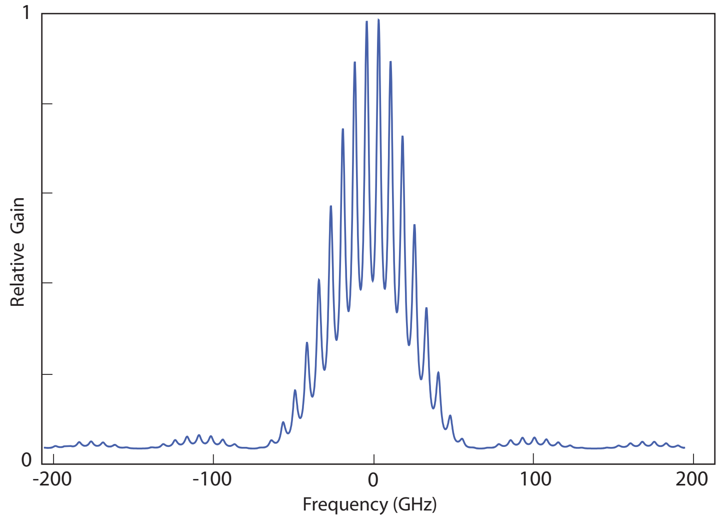

Figure 3.3: Combined gain for an external cavity diode laser, including the internal and external modes, the diode laser gain, and the filter response. The broad feature is the frequency selectivity of the filter, and the smaller peaks are the external cavity modes (see fig. 3.2). A small relative shift of the external cavity mode relative to the filter frequency will cause the laser to jump to another external cavity mode where the net gain is higher.

rent bias which changes as the piezo voltage is changed. Feed-forward current bias adjustment is a feature of MOGLabs DLC controllers. Adjustment is straightforward. With the laser frequency scanning, the current bias control is adjusted until the maximum mode-hop-free scan range is observed. Small changes to the injection current optimise the scan range near the nominal centre frequency. Detailed instructions follow. A Fizeau wavemeter, an atomic absorption spectroscopy signal, or a Fabry-Perot cavity is required, to monitor the actual laser frequency while varying the different control parameters.

1. Make sure that BIAS is enabled (DIP switch **4**).
2. Set the FREQUENCY knob to approximately 0V (use monitor display Frequency on the 8-position selector switch).

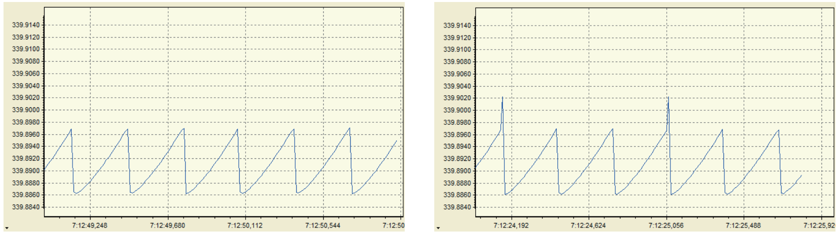

Figure 3.4: Frequency of a laser scanning properly (left) and with a mode-hop at one edge (right).

3. With SPAN set to max, adjust the BIAS trimpot to zero amplitude as see on monitor CHAN B Current output.
4. Adjust the laser diode CURRENT so that the laser wavelength and power are correct. Use the values provided in the original factory test report as a guide.
5. If the wavelength is close but not quite correct, small adjustments of either CURRENT or FREQUENCY may be required to find a better lasing mode. If more significant wavelength adjustment is required, either mechanically rotate the filter of the laser, or for changes of less than 0.2 nm, adjust the temperature set-point by 0.2 to 0.5°C. Note that the response to adjustment of the temperature setpoint is slow, and you should wait several minutes for the temperature to equilibrate.
6. If the wavelength is within a few pm (GHz) of your target, increase the SPAN while observing the Fizeau wavemeter Long Term measurement (or spectroscopy scan or FP cavity transmission on an oscilloscope), as shown in fig. 3.4.
7. As the SPAN is increased, you will at some point observe a mode hop. For spectroscopy scans it is easier to observe mode hops using the AC error signal from the MOGLabs DLC, if current modulation is enabled.

   The mode hop should be at one edge of the scan; if so, adjust the FREQUENCY so that the scan no longer 'clips' this mode hop (i.e. the scan is free of mode hops), and continue adjusting in the same direction until a mode hop is observed on the other edge of the scan.

8. Adjust the FREQUENCY to the mid-point between the two extremes.

9. Increase SPAN further, until a mode hop is again apparent, and readjust the FREQUENCY to the mid-point.

10. Repeat until mode hops are observed at both edges of the scan.

11. Adjust the diode CURRENT by small amounts to try to remove at least one of these mode hops, then attempt to increase the SPAN further.

12. If the mode hops are at both edges of the scan and cannot be removed by FREQUENCY or CURRENT adjustments, turn the BIAS trimpot either clockwise or counterclockwise to remove one of both of the mode hops. If one trimpot direction only makes the mode hops worse, try the other trimpot direction. If both mode hops are removed, repeat the steps above (increasing SPAN) until no further improvements can be made to the MHFR.

13. If the MHFR is substantially less than expected (refer to the factory test report), it may be advisable to change mode by increasing or decreasing the CURRENT to find a nearby single-mode current, to rotate the filter slightly to alter the net gain so that one cavity mode has higher gain than those adjacent.

4. Alignment

Alignment of the laser may be required, for example if the laser diode is replaced, or perhaps initially after shipping if the laser has been mishandled, or after making significant changes to the laser wavelength. The process is straightforward and normally takes only a few minutes.

For long-wavelength lasers, an infra-red upconversion card or video camera can be very helpful. Common low-cost security cameras, computer USB cameras, and home movie or still cameras are also good options, although they may have an infra red blocking filter which must be removed.

Diodes are very sensitive to electrostatic discharge. Please make sure you are electrically grounded, ideally with a wrist ground strap. If you do not have a proper wrist ground strap, at least be sure you are not wearing woolen clothing, and touch something grounded from time to time (e.g. a soldering iron tip, the earth of a power supply, the MOGLabs DLC controller).

4.1 Pre-alignment of lens tube and diode

1. Insert the laser diode into the lens tube (see fig. 4.1). Ensure that the V-notch in the base flange of the diode can is *not* aligned with one of the radial alignment screws.

2. Add the retaining threaded ring, and tighten gently, enough such that the diode does not move but not so much that it cannot move.

3. Approximately centre the diode using the alignment adjustment screws and two 0.9 mm hex keys.

4. Insert the collimation lens, taking care to ensure that the lens does not contact the diode. Also ensure the lens is tight; if not, use PTFE tape on the lens threads. One or two layers of thick tape (90 μm as used for gas plumbing) is usually sufficient.

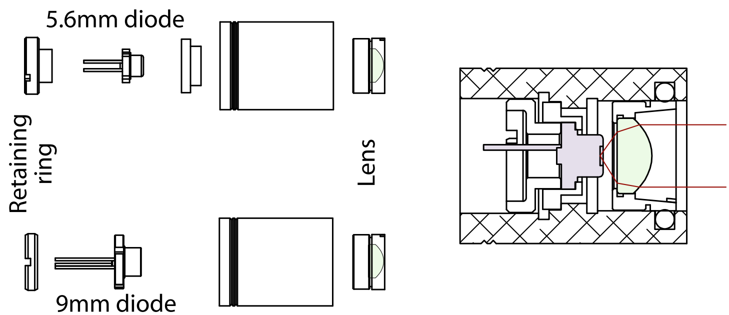

Figure 4.1: Lens tube assembly, showing diode, lens, and mounting hardware. The same tube can be used for 5.6 mm and 9 mm diodes.

Figure 4.2: Image showing collimation tubes with alignment adjustment screws.

5. Mount the lens tube in a holder or mount that allows rotation of the entire assembly around the long axis.
6. Apply power to the diode, above threshold but well below the maximum permissible current.
7. Approximately focus at several metres distance. It may be helpful to reflect it from a mirror and back so that you can adjust the alignment and see the effect nearby. You should adjust focus until you see a clean symmetric ellipse at this distance.
8. Rotate the collimation assembly and adjust the alignment screws until the beam remains reasonably well on-axis.

9. Adjust the alignment to optimise the laser beam spatial profile even at the expense of maintaining concentric alignment. The profile should be a symmetric ellipse with Gaussian profile along each axis.

10. Tighten the retaining ring (hard) and re-check that the beam profile remains uniform and symmetric.

11. Focus the collimation lens such that the laser focuses to a spot at some significant distance, more than 4 m. The laser stability and modehop free range can be better if the laser output is weakly converging [2].

4.2 Initial diode test

1. Inspect the beam profile for diffraction fringes. If the lens has been screwed in too far and made contact with the diode (particularly for 5.6 mm diodes), the lens can become scratched or stressed, leading to poor performance. Fringes can be an indication of such scratches (or an indication of a poor diode).

2. On the MOGLabs DLC controller, make sure DIP switch 4 (Bias) is OFF, the span is set to zero (fully anti-clockwise), and the frequency knob is at zero (middle of range; set the display selector to Frequency and adjust to zero volts).

3. Measure the power/current (*PI*) curve for the bare collimated diode. This provides a useful benchmark for comparison when optimising the threshold lowering with feedback.

4.3 Orientation and polarisation of the output beam

The output from the diode is a widely diverging *elliptical* beam. The grating dispersion (i.e. frequency selectivity) increases with the number of rulings illuminated by the light: $\Delta\lambda/\lambda \propto 1/N$ where N is the number of grating lines illuminated. The ellipse is therefore typically oriented with the major axis perpendicular to the grating rulings. For the MOGLabs LDL, the grating rulings are vertical and so the elliptical beam should have the

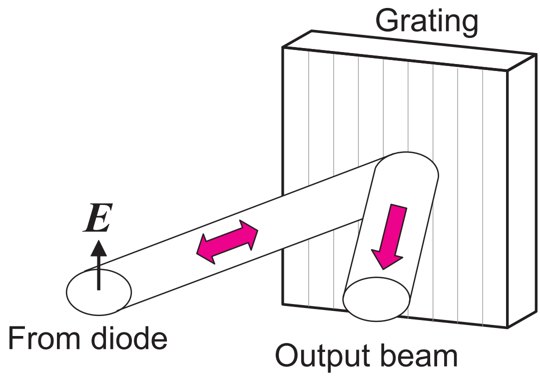

Figure 4.3: Orientation of the diode laser beam ellipse with respect to the diffraction grating.

major axis horizontal (see Fig. 4.3), for most laser diodes which operate in TE mode.

The diode laser polarisation is *usually* parallel to the *short* (minor) axis of the ellipse. Thus, for the orientation described above, the polarisation is parallel to the grating rulings. However, the grating feedback efficiency is larger when the polarisation of the incident light is *perpendicular* to the grating rulings, so for the arrangement shown, the diffraction efficiency is small (typically around 15%). While low efficiency might seem undesirable, 15% is usually sufficient for single-mode operation of the laser, and the high percentage of non-diffracted light is directly reflected to provide the maximum possible power in the output laser beam.

4.4 Alignment

The horizontal and vertical angles of the grating, and the lens focus, must be adjusted so that the diffracted beam propagates back into the exit facet of the diode, so that the external cavity dominates the optical feedback. When aligned, the external cavity feedback overrides the feedback from the front facet of the diode itself, so that the laser frequency is determined by the external cavity. The feedback alignment is optimised by setting the diode current just below threshold, and then adjusting the vertical alignment until the output suddenly flashes brightly, indicating effective feedback which tends to lower the overall gain threshold.

The feedback is optimised by aligning the beam from the laser diode, to the grating and back to the diode. The vertical angle of the beam is adjusted to minimise the lasing threshold current.

The laser diode tube is mounted into a rotatable cylindrical mount (see fig. 4.4). A fine adjustment screw is used to adjust the vertical tilt angle of the laser diode, against a spring plunger that pushes the tilt arm downwards. Two locking screws at the rear clamp the cylinder; these can be released slightly to make adjustments, and tightened when satisfactory alignment is achieved.

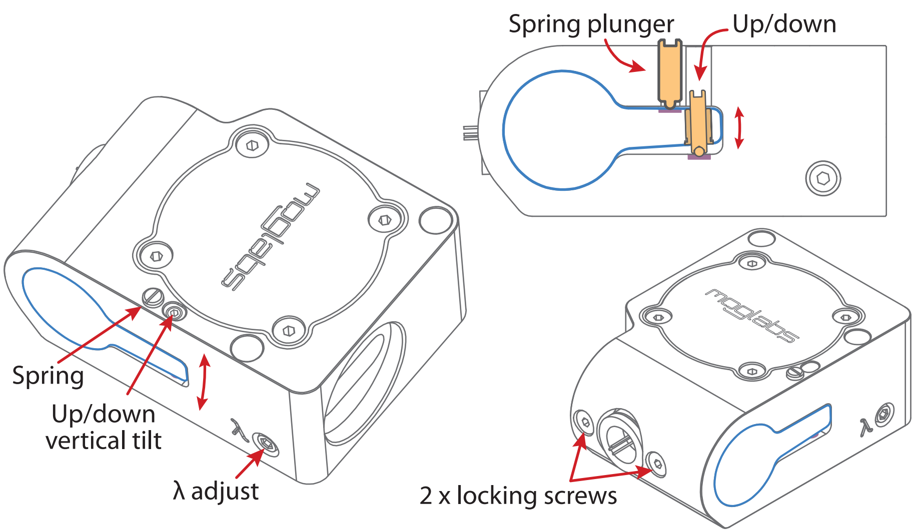

Figure 4.4: Sketch showing location of vertical alignment adjustments: a fine adjustment screw to push the laser diode beam upwards, and a spring plunger that pushes downwards.

The sequence is as follows:

1. Insert the lens tube into the laser cavity.
2. Project the output beam onto a piece of black card at a distance of about 30 cm from the laser. Monitor this beam spot using a video camera such as a webcam.
3. Rotate the lens tube so that the elliptical profile of the output beam is horizontal (for TE polarised laser diodes).
4. Adjust the diode current well above threshold, and search for a secondary output beam caused by the diffracted light propagating back into the diode and then reflecting from the rear of the diode back to the screen. Try adjusting the vertical alignment to see a spot moving up and down "faster" than the main output beam.
5. Align the reflection of the return beam so that the two spots are centred horizontally, but displaced vertically.
6. Adjust the vertical alignment until the secondary beam is colinear with the primary. The laser should significantly brighten or "flash" when the grating feedback is aligned back into the diode.
7. Adjust the injection current to just below threshold.
8. Adjust the vertical alignment and grating angle (wavelength) until flash (i.e. lasing).
9. Iterate reduction of the injection current, following by alignment until lasing occurs, until the minimum threshold is achieved.

   The grating wavelength (horizontal angle) should then match the diode free-running wavelength.
10. If the threshold is not significantly lower (at least a few mA), remove the lens tube and adjust the focus of the collimation lens, being careful not to touch the surface of the lens. Usually the lens should be moved slightly closer to the diode, clockwise when viewed from

the lens side, if the lens was previously set to focus some distance from the laser.

11. Iterate until threshold lowering is significant.

    Note that there is a compromise here. At minimum threshold, feedback is optimised giving the narrowest linewidth. However, then the overlap of the back-reflected beam with the laser output facet is quite critical, which can reduce the mode-hop-free scan range and make the laser more sensitive to acoustic vibrations. It is generally easier to have a weakly focusing beam.

12. Increase the current to well above threshold, check the laser wavelength, and adjust the grating angle if required. The wavelength adjustment is about 0.1 turns per nm, and clockwise to increase wavelength.

    Note that if the wavelength of maximum gain is far from the desired wavelength, it may be a good idea to change the operating temperature to reduce that gap, before proceeding.

13. Adjust the vertical alignment to minimise the threshold.

14. If possible, scan the laser through an atomic resonance and view the absorption on an oscilloscope. With current bias disabled (DIP 4 on a MOGLabs controller) and full span, the pattern should repeat several times as the laser scans over a short range and then mode-hops. A Fabry-Perot etalon or a fast high-resolution wavemeter (e.g. MOGLabs MWM) can also be used to optimise the mode-hop-free range.

15. Adjust the alignment and grating angle, and the injection current, to optimise the scans so that you see the maximum number of repeats and the deepest signals.

16. Check that there is only one significant output beam spatially and, if available, use a Fabry-Perot to check for single frequency.

17. Check that the saturated absorption traces are clean. Noisy spectra indicate multi-mode operation, or high linewidth, which may be due

to weak feedback. The feedback depends on the collimation lens focus. The lasing threshold is a good diagnostic: lower threshold indicates better feedback and consequently lower linewidth, at the expense of sensitivity. A noisy spectrum can also be due to extreme sensitivity to acoustic disturbance, or to external feedback.

A scanning Fabry-Perot is a very useful diagnostic tool to check for single-mode operation.

18. Measure the laser output power as a function of diode injection current, and plot the power/current response as in Fig. 2.1.

19. Switch the current bias (DIP switch 4) back on, and adjust the bias to optimise the mode-hop-free scan range.

The laser should now be operating with grating controlled feedback near the desired wavelength of the diode. The threshold current should be significantly lower than without feedback (2 to 5 mA for uncoated 780 nm diodes). Record the output power and threshold characteristics for subsequent reference.

4.5 CEF extended chassis

The laser can be supplied in a very compact form, or with optional extended chassis (option CEF) which allows internal mounting of Faraday isolator, and also the addition of a fibre coupler (see fig. 4.5).

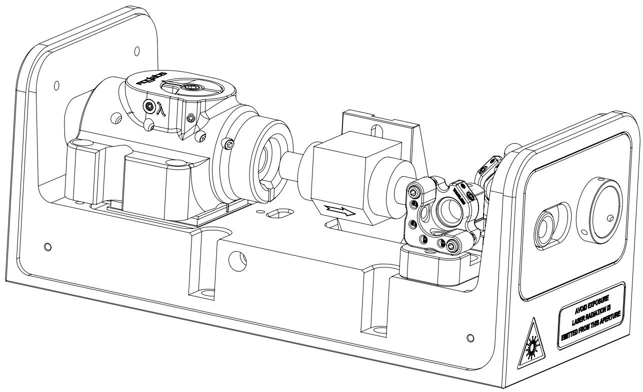

Figure 4.5: Extended chassis CEF option, shown here with CEL cateye installed.

4.5.1 Faraday isolator alignment

Faraday isolators are almost always required for external cavity diode lasers. The very high gain of the semiconductor diode and low optical feedback of the external cavity mean that even very low power external feedback can have a significant effect on the laser frequency stability. Generally 30 dB of isolation is needed; that is, the optical feedback into the ECDL should be less than 0.1% of the output power.

The extended chassis version of a MOGLabs laser allows internal mounting of a Faraday isolator (see figure 4.6). Alignment is straightforward: the isolator should be concentric with the exit beam of the laser, and rotated axially so that the first polarisers is parallel to the polarisation of the laser beam. The power of the laser should be measured before inserting the isolator, and then the isolator position and rotation adjusted to maximise the transmission. Depending on wavelength, the transmission varies from

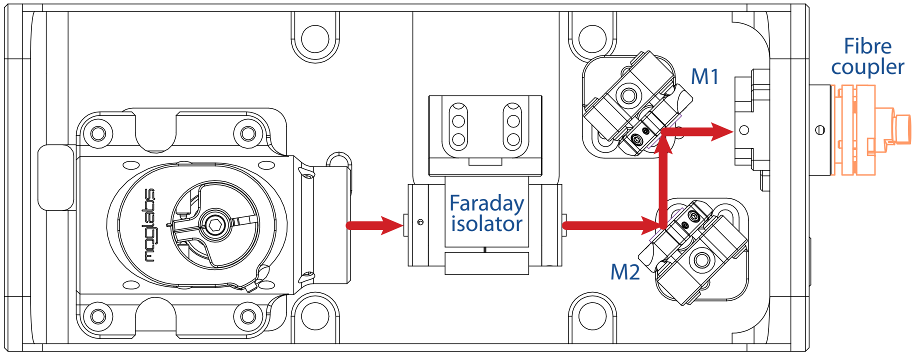

Figure 4.6: Schematic of the extended chassis laser showing Faraday isolator, and two mirrors used for aligning the beam to a single-mode fibre.

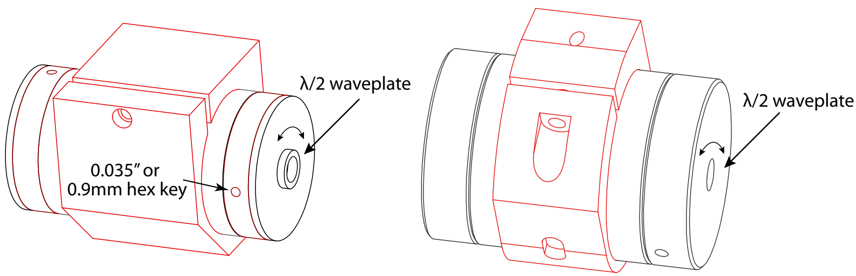

Figure 4.7: Two types of Faraday isolator. Each can be supplied with exit $\lambda/2$ waveplate inside one end-cap. The waveplate can be rotated to rotate the plane of polarisation of the exit beam, for example to optimise coupling into polarisation maintaining fibre, or to adjust the ratio of exit beams for lasers fitted with a polarising beamsplitter instead of mirror M2.

about 70% to 95%, with 90 to 92% typical at 780 nm.

The isolator rotates the polarisation of the laser beam by 45°. For lasers ordered with fibre coupling, or with dual beam output (using a PBS polarising beamsplitter cube), the isolator can in most cases be ordered with internal half-wave retardation waveplate. The waveplate is mounted inside the end-cap of the isolator (see figure 4.7). On older (EOT) isolators, the waveplate is in the final silver-coloured metal element of the retarder.

The waveplate angle may need adjustment, for example to vary the power ratio for the two beams exiting the PBS or to align the polarisation to a more convenient horizontal or vertical axis for experiments, or to align to a polarisation preserving fibre. To adjust the waveplate angle, loosen the radial set screw holding the waveplate, rotate, and restore set screw tension. For older isolators use a 0.035″ or 0.9 mm hex key; for MOGLabs isolators, a 1.5 mm hex key.

A second waveplate holder is available, which mounts inside the exit face of the laser (see figure 3). A standard 25.4 mm waveplate can be inserted, to align the polarisation of the reflected exit beam to match to an external experiment or to a polarisation preserving fibre, independent of the direct output beam.

4.6 Fibre alignment

The extended chassis is most often used when coupling to a single-mode otpical fibre. Two mirrors are used to align the beam to the fibre coupler: a common and familiar arrangement for optical scientists (see figure 4.6). The arrangement conveniently allows splitting the output into two beams, using a PBS as the first reflector.

Given the 8% Fresnel loss from entrance and exit facets of the fibre, the maximum theoretical efficiency for single-mode fibre coupling is 92%. The stainless steel kinematic mirror mounts are stable and easy to use, and coupling efficiency of over 70% is easily attained at 780 nm.

Alignment requires first adjusting the mirrors so that the beam exits the laser chassis in the centre of the fibre coupling port, and parallel to the long axis of the chassis. The fibre coupler can then be installed, without fibre, and the mirrors adjusted so that the beam is clearly transmitted by the coupler (see below for detailed instructions).

For Schäfter-Kirchhoff 60FC fibre couplers, detailed instructions on optimising the coupling efficiency are provided via their website:
CouplingSMS.pdf.
An eccentric key is provided for adjusting the lens focus.

4.6.1 Reverse beam: using a visual fault locator

A *visual fault locator* is a very useful device for quickly achieving initial coupling of the laser beam to the fibre. A visual fault locator (see fig. 4.8) is a low-power red laser that injects a beam into the *exit* end of the fibre patchcord, thus propagating visible light backwards along the fibre and then into free space, forming a beam back into the laser cavity. These devices are very low in cost (search on eBay for *visual fault locator*; they are typically less than $20).

Figure 4.8: Fibre laser pen, or visual fault locator. Injects visible laser beam into fibre, which allows basic alignment and mode matching.

Aligning the MOGLabs laser beam to the fibre is then simply a matter of adjusting the mirrors so that the MOGLabs laser beam and the visual fault locator beam overlap inside the laser. It will be easier if the Faraday isolator is temporarily removed.

4.6.2 Mirror adjustment

To maximise the fibre coupling efficiency, the angle and location of the laser beam at the fibre coupler must be optimised by walking the mirrors.

Let M1 be the mirror closest to the fibre coupler, and M2 be closest to the laser (see figure 4.6).

1. Adjust the laser current so that the output power is around 5 to 10 mW.
2. If some power is detected exiting from the fibre, skip to step 9 below.
3. If the fibre coupler is not yet installed, first coarsely adjust the mirrors so that the beam exits through the centre of the fibre coupler

mount, and parallel to the long axis of the laser chassis. Then install the coupler.

4. If some power is detected exiting from the fibre, skip to step 9 below.

5. With fibre patchcord removed, adjust the mirrors so that the beam exits from the fibre coupler cleanly. You should be able to observe a bright beam centred in the circle of a shadow of the fibre coupler.

6. Measure the power just before the fibre coupler and record the power meter reading.

7. If not already installed, connect the fibre.

8. If a visual fault locator is available, use that to inject a backwards-propagating beam, and adjust the mirrors so that the MOGLabs laser and visual fault locator beams are coincident along their paths. The visual fault locator can then be removed: a measurable transmitted beam should be evident at the fibre exit.

9. Fix the power meter to monitor the output power exiting from the optical fibre. Make sure background light is not affecting the reading.

10. For the horizontal axis first, find the maximum output power by adjusting the mirror M1, closest to the fibre (furthest from the isolator), and record the output power.

11. Adjust the horizontal axis of mirror M2 furthest from the fibre (closest to the isolator) clockwise such that the output power drops by no more than 25%. If the efficiency is over 50%, drop the power by only 5 to 10% or less. Take note of roughly how many degrees rotation were required, so you can easily return to the original position.

12. Adjust the horizontal axis of mirror M1 and maximise for output power. Compare the new maximum output power to the output power obtained at step 10.

13. Repeat steps 10 to 12 if the power is increasing, or repeat but with reversed direction of adjustment if the power is decreasing.

14. Once horizontal alignment is optimised, repeat the procedure but using vertical adjustments.

15. Iterate horizontal and vertical alignment until power is fully optimised. As optimum coupling is approached, the adjustments should be reduced at each step.

16. If the coupling efficiency is less than expected, focus adjustment may be required (see instructions from Schäfter and Kirchhoff). Focus adjustment is not normally needed unless severe shock has moved the lens, or if a new diode has been installed in the laser, leading to change of beam waist location.

17. Once optimised, record the input power to the fibre coupler, maximum output power, and the laser current.

18. Increase the laser current to the desired operating current and optimise if needed.

19. Use the factory test results for your laser as reference. Degradation may indicate facet damage on the fibre patchcord. Reversing or replacing the fibre patchcord may be helpful.

A. Specifications

Parameter	Specification
Wavelength/frequency	
370 – 1620 nm	Diode dependent. Please contact MOGLabs for availability.
Linewidth	Typically $<$ 200 kHz FWHM
Grating	Standard: 1800 l/mm holographic Au
Tuning range	Up to 100 nm, depending on diode
Sweep/scan	
Scan range	40 GHz typical
Mode-hop free	$>$ 10 GHz; up to 40 GHz (780 nm, uncoated diode)
Piezo stack	3 μm @ 150 V, 100 nF typical
Cavity length	25 – 30 mm
Optical	
Beam	3 mm × 1.2 mm ($1/e^2$) typical
Polarisation	Vertical linear 100:1 typical

Parameter	Specification
Thermal	
TEC	±14.5 V 3.3 A $Q = 23$ W standard
Sensor	NTC 10 kΩ standard; AD590, 592 optional
Stability at base	±1 mK (controller dependent)
Cooling	4 mm diam quick-fit connectors
Electronics	
Protection	Diode short-circuit relay; cover interlock connection; reverse diode
Indicator	Laser ON/OFF (LED)
Modulation input	Active (AC and DC coupled) or RF bias tee
Connector	MOGLabs DLC Diode Laser Controller single cable connect
Mechanical & power	
Dimensions	110 × 90 × 90 mm (L×W×H), 1 kg
Beam height	58 mm
Shipping	420 × 360 × 260 mm (L×W×H), 3.1 kg

A.1 Compact LDL mechanical

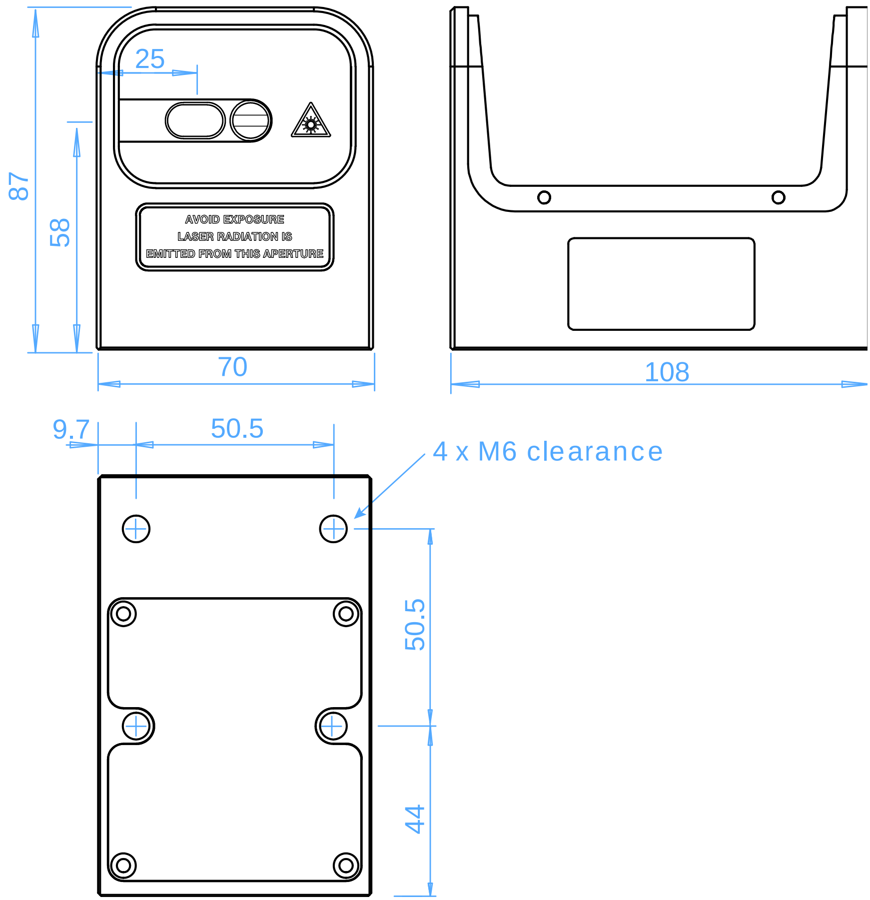

Figure A.1: Dimensions of compact LDL laser head.

A.2 Older LDL mechanical

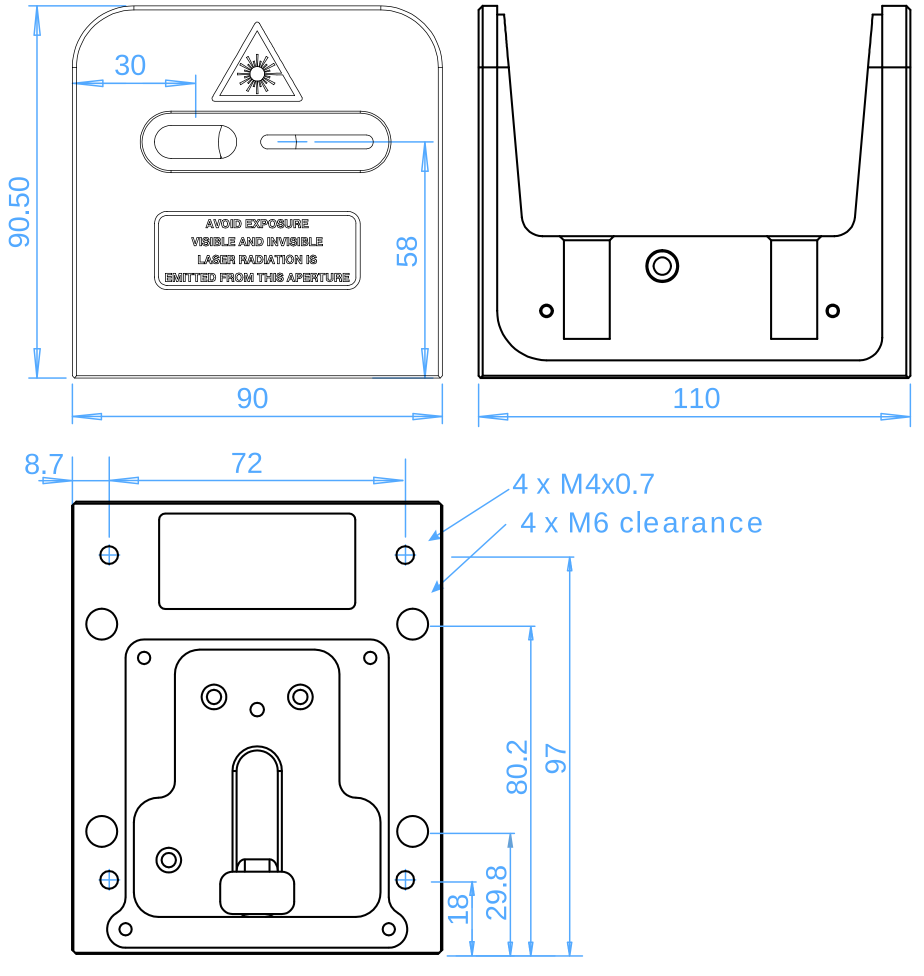

Figure A.2: Dimensions of previous generation LDL laser head.

A.3 CEF mechanical

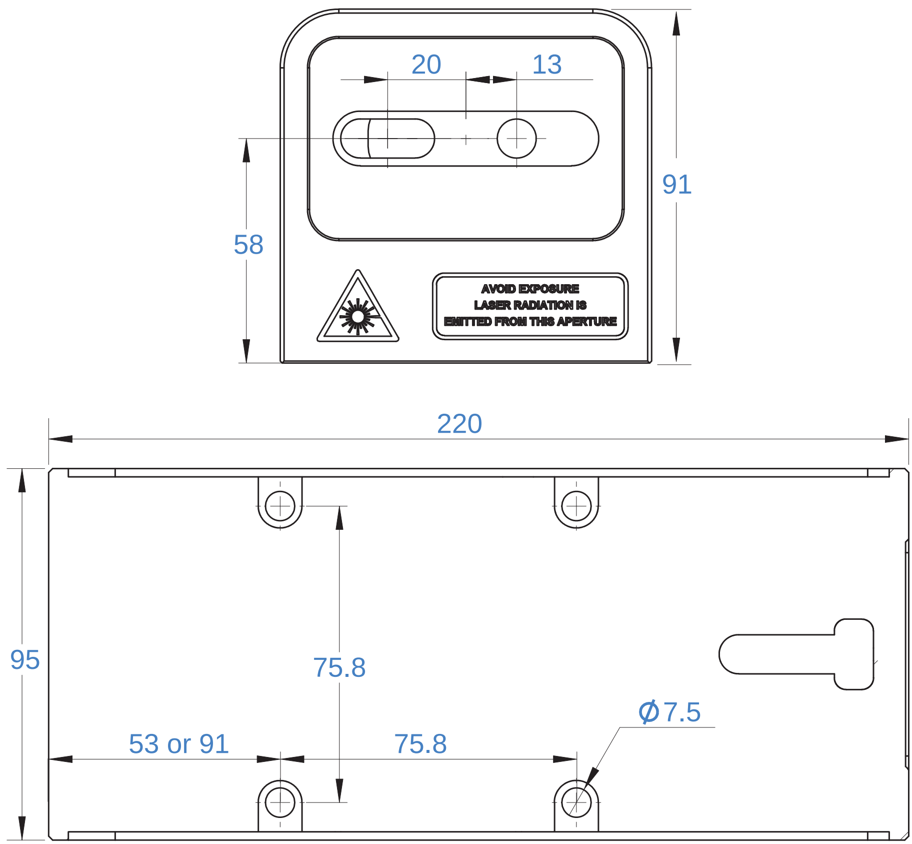

Figure A.3: Dimensions of CEF laser head.

B. Laser head board

The laser head interface board provides connection breakout to the laser diode, TEC, sensor, piezo actuators, and laser head interlock. It also includes a protection relay and passive protection filters, a laser-on LED indicator, and an SMA connection for direct diode current modulation.

Several versions of the laser headboard are available.

MOGLabs lasers are built with a T-shaped headboard, using Hirose DF59 "swing-lock" wire-to-board connectors (Digikey H11958-ND and H11957CT-ND plug and crimp pin). The B1047 headboard provides high bandwidth active current modulation for wide bandwidth frequency stabilisation and linewidth narrowing, for example using a high finesse optical cavity or polarisation spectroscopy. Higher bandwidth is provided by the B1240 headboard which further increases bandwidth and reduces phase delay, to allow sub-Hz linewidth narrowing. The B1240 is limited to low compliance voltage laser diodes (red and infrared); the B1047 must be used for blue diodes. B1045 and B1046 headboards provide RF modulation via an RF bias tee allowing modulation up to 2.5 GHz, for example to add sidebands for repumping, or to add noise for coherence control.

In all cases, there is no provision for the internal photodiode in many consumer-grade laser diodes.

B.1 B1045/1046 headboard

The B1045 and B1046 provide connection to one or two piezos (slow high-range multi-layer stack and fast disc), and either passive NTC thermistor or active AD590/592 active temperature sensor. Note only one temperature sensor should be connected, not both. They provide an SMA input for direct diode modulation via an RF bias tee (see B.1.1 below).

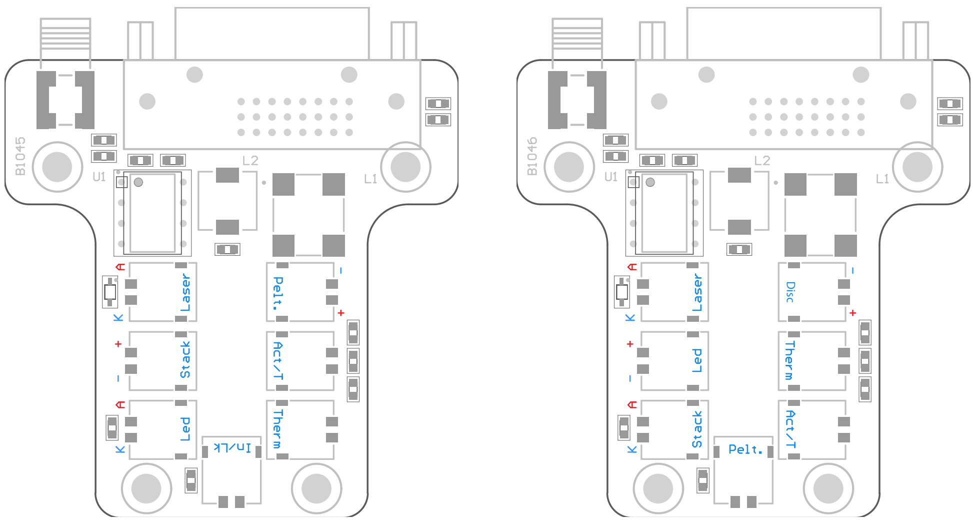

Figure B.1: MOGLabs B1045 and B1046 laser head boards showing connectors for laser diode, piezo actuator, temperature sensors, TEC and head enclosure interlock. Connectors are Hirose DF59.

B.1.1 RF coupling

For the B1045/1046 headboard, the SMA connector allows high-frequency current modulation via a bias-tee. The RF input is AC coupled, with low- and high- frequency limits of about 30 kHz and 2.5 GHz (see fig. B.2). Capacitor C4, either 47 nF or 100 pF, can be changed to adjust the low-frequency cutoff. For higher bandwidths, use an external bias-tee such as the Mini-Circuits ZFBT-4R2GW-FT between the head board and the diode.

The input impedance is 10 k. The sensitivity depends on the diode impedance but is typically around 1 mA/V.

WARNING: The RF input is a direct connection to the laser diode. Excessive power can destroy the diode, which is separated from the head board relay by an inductor. Thus the relay does *not* provide protection from high frequency signals.

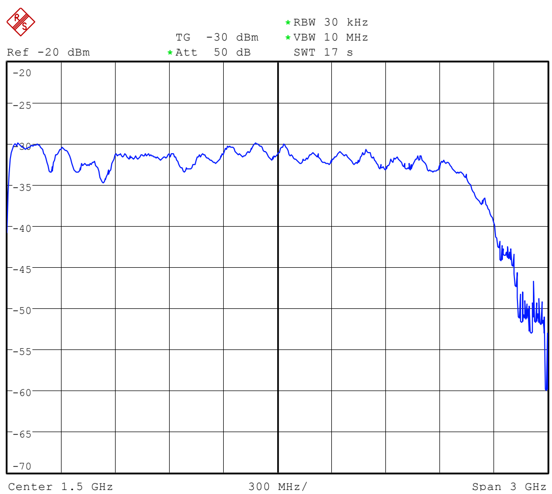

Figure B.2: RF response, SMA input on laser headboard to diode SMA output.

B.2 B1047/B1240 headboards

The B1047 and B1240 provide high-speed active modulation of the diode current. They use 500 MHz opamps and very low latency circuitry to reduce phase delay to around 12 ns for the B1240. The B1047 allows for closed-loop bandwidth of about 1.2 MHz while the B1240 can achieve about 4 MHz (in both cases, without phase advance). The latter makes it particularly easy to achieve sub-Hz linewidth reduction by locking to a high-finesse optical cavity. The B1240 also allows direct-ground connection or buffered; the latter is about 10% slower but reduces problems with ground-loop noise. The B1240 is not suitable for diodes with high compliance voltage, typically diodes with wavelength below 600 nm.

Note that connection to the SMA input will reduce the diode current, even if the input voltage is at zero.

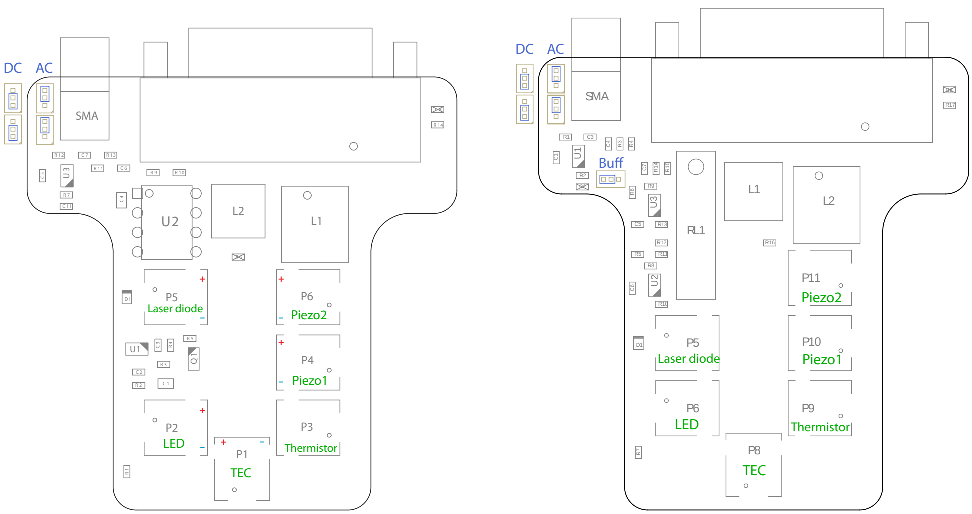

Figure B.3: B1047 (left) and B1240 (right) enhanced laser head boards. Jumpers at top left can be configured for AC or DC coupling. The B1240 has an additional jumper "Buff" for direct or buffered (differential) ground coupling, shown connected for differential coupling; change to pins 1 and 2 for direct. Modulation input via SMA connector, sensitivity 2.5 mA/V. Connectors are Hirose DF59.

B.2.1 SMA input

The B1047/B1240 SMA input provides AC or DC coupling to an active modulation circuit. Note that connection to the SMA input will reduce the diode current by about 1.6 mA (B1047) to 2.5 mA (B1240), with zero input voltage.

	B1047	B1240
Input range	±2.0 V max	±2.0 V max
Input coupling	AC/DC	DC (direct) AC/DC (buffered)
AC time constant	6 μs (25 kHz)	15 μs (10 kHz)
Phase delay	40 ns	$<$ 20 ns (direct) $<$ 30 ns (buffered)
Gain bandwidth (−3 dB)	3 MHz	20 MHz
Input impedance	5 k	1 k
Current gain	1 mA/V	1 mA/V
Laser diode voltage	10 V max	2.5 V max

B.3 Headboard connection to controller

Note The MOGLabs laser cable is a digital DVI-D DL (***dual link***) cable. There is a bewildering assortment of apparently similar cables available. Most *computer display* DVI cables will ***not*** work because they are missing important pins; see diagram below. Only high quality digital ***dual-link*** DVI-D DL cables should be used.

Pin	Signal	Pin	Signal	Pin	Signal
1	TEC –	9	DIODE –	17	DISC +
2	TEC +	10	DIODE +	18	DISC –
3	Shield	11	Shield	19	Shield
4	TEC –	12	DIODE –	20	STACK +
5	TEC +	13	DIODE +	21	STACK –
6	T_{sense} –	14	Relay GND	22	
7	T_{sense} +	15	Interlock out	23	NTC –
8		16	+5V in	24	NTC +

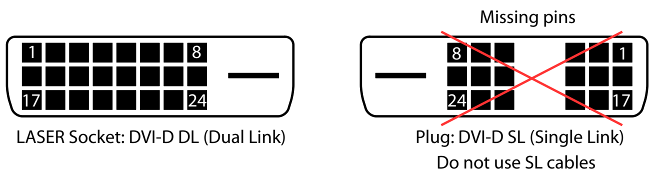

Figure B.4: Headboard connector. Note that the pinout is different to that of the matching connector on the rear of the DLC controller.

A 10 k thermistor should be connected to NTC+ and NTC–, but an AD590 or AD592 temperature sensor can be instead be connected to T_{sense}. Pin 16 should be connected to a +5 V supply. To activate the laser diode, relay GND (pin 14) should be grounded to open the relay that otherwise short-circuits the diode current. +5 V (pin 16) is internally connected to pin 15 (Interlock), normally with a permanent connection but on some headboards (see above), a connector is provided to allow connection to a cover-activated microswitch to disable the laser when the cover is removed.

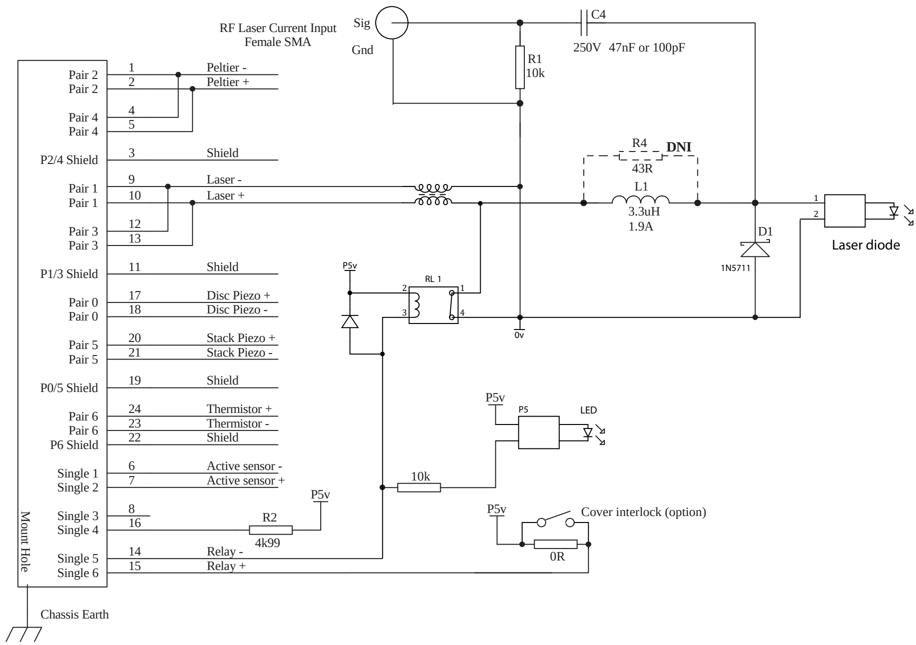

Figure B.5: MOGLabs DLC laser head board schematic (B1040/1045). The RF modulation low-pass cutoff frequency is determined by C4 and the diode impedance ($\sim 50\Omega$).

Bibliography

[1] S. D. Saliba, M. Junker, L. D. Turner, and R. E. Scholten, Mode stability of external cavity diode lasers, *Appl. Opt.*, 48(35):6692, 2009. 1, 3, 4, 10, 11

[2] S. D. Saliba and R. E. Scholten. Linewidths below 100 kHz with external cavity diode lasers. *Appl. Opt.*, 48(36):6961, 2009. 1, 4, 17

[3] C. J. Hawthorn, K. P. Weber, and R. E. Scholten. Littrow configuration tunable external cavity diode laser with fixed direction output beam. *Rev. Sci. Inst.*, 72(2):4477, 2001. 1, 3

[4] A. S. Arnold, J. S. Wilson, and M. G. Boshier. A simple extended-cavity diode laser. *Rev. Sci. Inst.*, 69(3):1236–1239, 1998. 1

[5] X. Baillard, A. Gauguet, S. Bize, P. Lemonde, Ph. Laurent, A. Clairon, and P. Rosenbusch. Interference-filter-stabilized external-cavity diode lasers. *Opt. Communic.*, 266:609, 2006. 1

[6] L. Ricci, M. Weidemüller, T. Esslinger, A. Hemmerich, C. Zimmermann, V. Vuletic, W. König, and T. W. Hänsch. A compact grating-stabilized diode laser system for atomic physics. *Opt. Communic.*, 117:541, 1995. 1

[7] H. Talvitie, A. Pietiläinen, H. Ludvigsen, and E. Ikonen. Passive frequency and intensity stabilization of extended–cavity diode lasers. *Rev. Sci. Inst.*, 68(1):1, 1997. 4

[8] P. J. Fox, R. E. Scholten, M. R. Walkiewicz, and R. E. Drullinger. A reliable, compact, and low-cost michelson wavemeter for laser wavelength measurement. *Am. J. Phys.*, 67(7):624–630, 1999. 9

[9] S. C. Bell, D. M. Heywood, J. D. White, and R. E. Scholten. Laser frequency offset locking using electromagnetically induced transparency. *Appl. Phys. Lett.*, 90:171120, 2007.

[10] G. C. Bjorklund. Frequency-modulation spectroscopy: a new method for measuring weak absorptions and dispersions. *Opt. Lett.*, 5:15, 1980.

[11] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward. Laser phase and frequency stabilization using an optical resonator. *Appl. Phys. B*, 31:97–105, 1983.

[12] M. Zhu and J. L. Hall. Stabilization of optical phase/frequency of a laser system: application to a commercial dye laser with an external stabilizer. *J. Opt. Soc. Am. B*, 10:802, 1993.

[13] M. Prevedelli, T. Freegarde, and T. W. Hänsch. Phase locking of grating-tuned diode lasers. *Appl. Phys. B*, 60:241, 1995.

[14] P. Feng and T. Walker. Inexpensive diode laser microwave modulation for atom trapping. *Am. J. Phys.*, 63(10):905–908, 1995.

[15] C. J. Myatt, N. R. Newbury, and C. E. Wieman. Simplified atom trap by using direct microwave modulation of a diode laser. *Opt. Lett.*, 18(8):649–651, 1993.

MOG Laboratories Pty Ltd
49 University St, Carlton VIC 3053, Australia
Tel: +61 3 9939 0677 info@moglabs.com