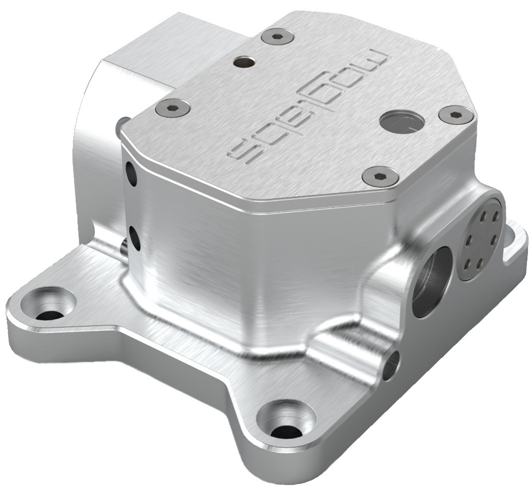
External Cavity Diode Laser

LDL Littrow Enhanced



Revision 1.03

Limitation of Liability

MOG Laboratories Pty Ltd (MOGLabs) does not assume any liability arising out of the use of the information contained within this manual. This document may contain or reference information and products protected by copyrights or patents and does not convey any license under the patent rights of MOGLabs, nor the rights of others. MOGLabs will not be liable for any defect in hardware or software or loss or inadequacy of data of any kind, or for any direct, indirect, incidental, or consequential damages in connections with or arising out of the performance or use of any of its products. The foregoing limitation of liability shall be equally applicable to any service provided by MOGLabs.

Copyright

Contact

For further information, please contact:

MOG Laboratories P/L
49 University St
Carlton VIC 3053
AUSTRALIA
+61 3 9939 0677
info@moglabs.com

MOGLabs USA LLC
419 14th St
Huntingdon PA 16652
USA
+1 814 251 4363
www.moglabs.com

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.

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.

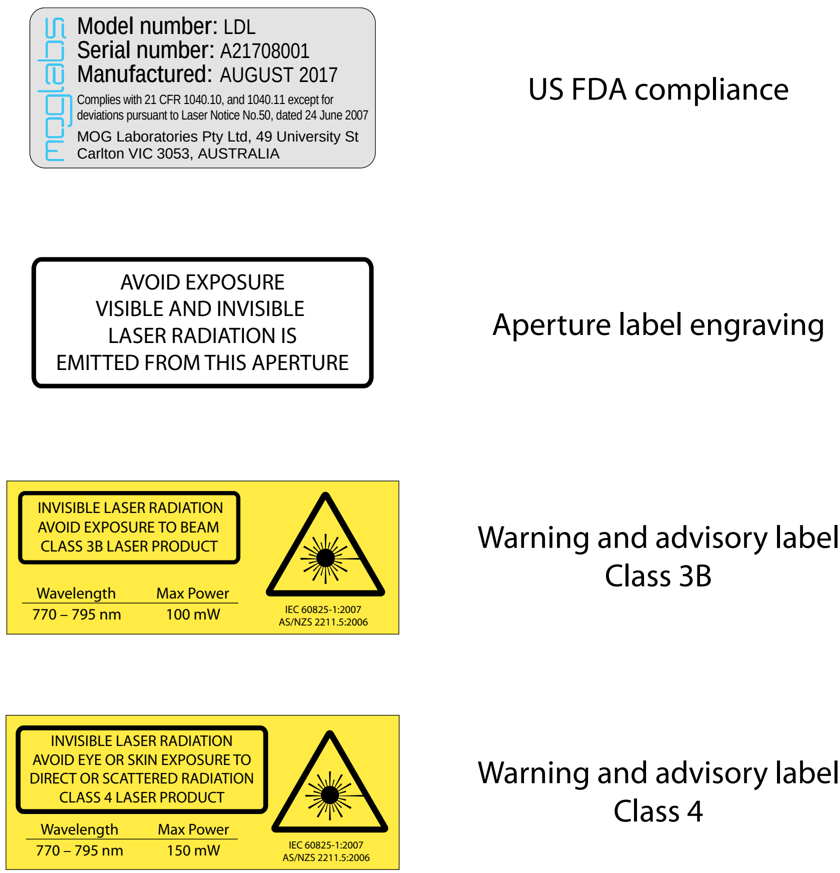


Figure 1: Warning advisory and US FDA compliance labels.

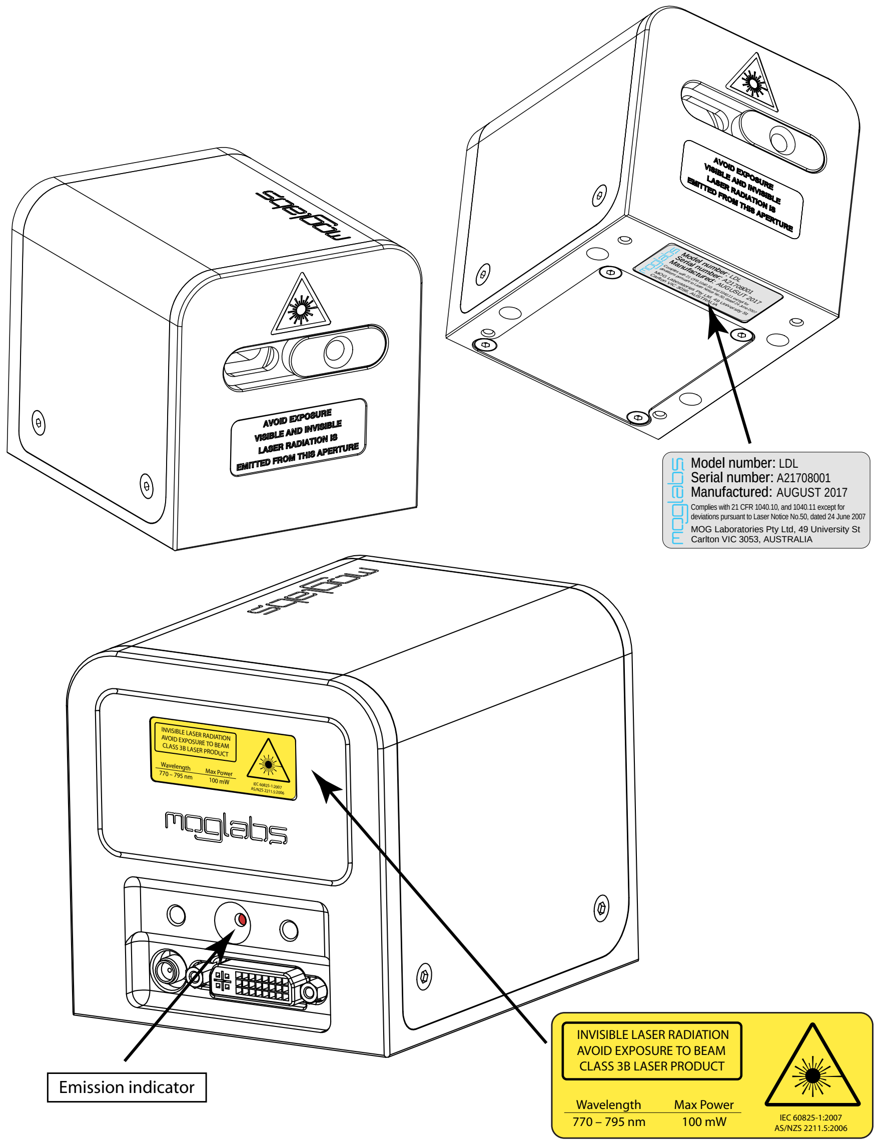


Figure 2: Schematic showing location of laser warning labels compliant with International Electrotechnical Commission standard IEC 60825-1:2007, and US FDA compliance label. Aperture label engraved on the front of the laser near the exit aperture; warning advisory label on the rear and compliance label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

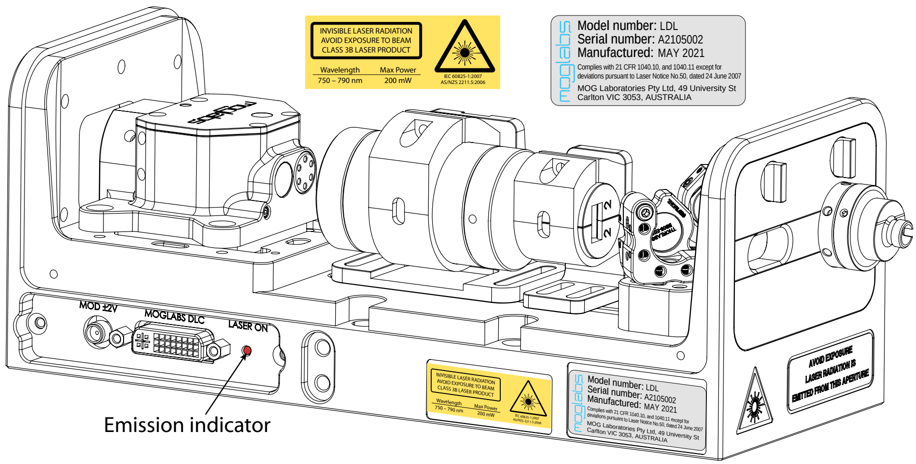


Figure 3: Schematic showing location of laser warning labels for the large-chassis version of a MOGLabs laser.

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 and hermetically sealed so that the laser is stable, robust, and insensitive to vibration and air pressure fluctuations.

The MOGLabs LDL is a Littrow design 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 from a laser diode is collimated and incident on a diffraction grating in the Littrow configuration, where the first order diffracted light is directed back into the laser diode. The feedback has wavelength centered at $\lambda = 2d \sin\theta$ where d is the grating line spacing and θ is the angle with respect to the the grating normal.

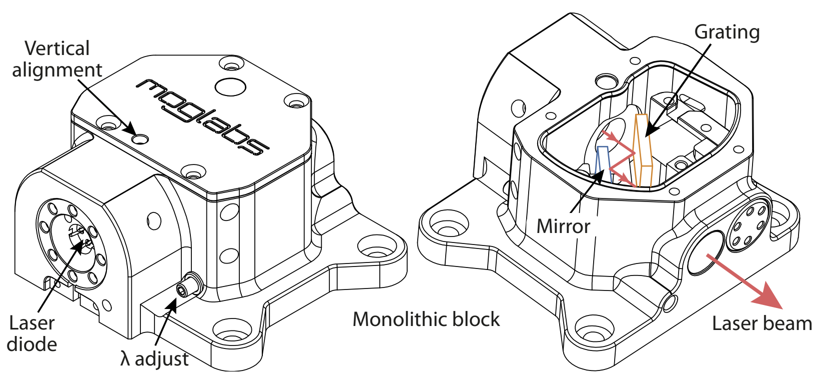


Figure 1.1: Sketch of MOGLabs LDL monolithic block external cavity diode laser.

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 about 15 mm long, with cavity mode spacing (FSR) of $c/2L = 10$ GHz.

The laser diode emission is collimated by a high numerical aperture lens in an x, y translation flexure mount. The laser diode can be moved along the beam direction z to adjust the focus. The grating is fixed to a piezo-electric transducer, or to a dual-piezo flexure to allow simultaneous translation and

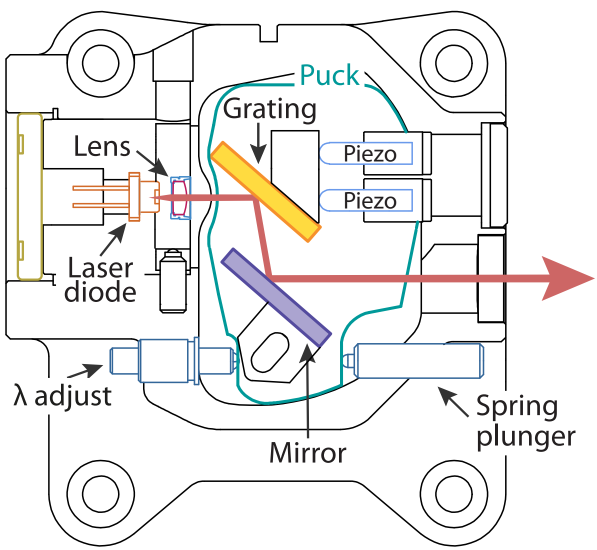


Figure 1.2: Cross-section of MOGLabs LDL Littrow laser, showing arrangement of laser diode, collimation lens, grating, piezoelectric transducers and fold mirror. The λ-adjust screw acts tangentially on the puck, rotating it and thus the grating to change the wavelength. The puck forms a rigid mount for grating and mirror, maintaining a fixed direction of the output beam for all wavelengths.

rotation of the grating. The first-order diffracted light returns back to the laser diode, and the direct reflection from the grating becomes the laser output beam. A fold mirror redirects the output parallel to the input beam, and cancels angular deviation of the output beam as the laser wavelength is tuned [3]. The grating and fold mirror are on a rotating puck to allow variation of the diffraction angle for coarse selection of the wavelength, within the gain bandwidth of the laser diode.

1.2 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 frequency change is about 40 GHz over the full 120 V range applied to the piezo. The bandwidth is limited by mechanical resonances, typically 25 kHz.

1.3 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 to achieve sub-MHz linewidth and stability [2].

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 a 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.

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 your laser test report and note that +5 V must be provided on pin 15 of the headboard connector to open the protective relay; see appendix B for connection details.

2.1 Standby/Run

Please first check that the MOGLabs DLC has been set to the correct mains supply voltage by inspecting the red voltage selector above the rear panel IEC power inlet. Then turn the main power switch on. Make sure that the laser diode CURRENT knob is turned fully anti-clockwise, that the OFF/MOD, SLOW and FAST lock switches are off (up), and then turn the keyswitch from STANDBY to RUN. The LED status indicator should be yellow indicating that the thermistor and TEC elements are connected.

2.2 Current

Turn the laser diode CURRENT adjust to zero (fully anti-clockwise). Note that it is not recommended to turn the current to zero when turning off the laser: the soft-start function of the DLC ensures that the current is ramped up slowly and safely to the required current. When first aligning the laser to your experiment, it is important to set the laser output power to a low value for safety.

Adjust the diode current to 5 – 10 mA and check that the diode voltage (VOLTAGE selection on main control knob on DLC) is the same as listed in the diode data sheet. If in doubt, please contact MOGLabs before continuing.

The laser threshold current is defined as the current at which the output is 1 mW. Adjust CURRENT to achieve 1 mW output, and if the threshold differs from that in the test report by more than 10 mA please refer to chapter 4.

Above threshold, the laser power *vs.* injection current is well approximated by a linear curve function (see Fig. 2.1). Initially the current should be set above threshold, but well below the maximum operating current, until the laser is fully aligned with your experiment.

2.3 Temperature

The optimum temperature has been set by MOGLabs and should not require adjustment. Refer to your test report to verify that the set point temperature is correct. Once the diode current is set, allow 5 minutes for the temperature to reach equilibrium. When the laser is not needed for extended periods, for example overnight, turn the laser diode off and the keyswitch to STANDBY. In standby mode, the temperature controller remains active, so that stable operation can be achieved more quickly than when the DLC is powered off. It is not necessary to change the CURRENT setting when turning the laser diode on and off.

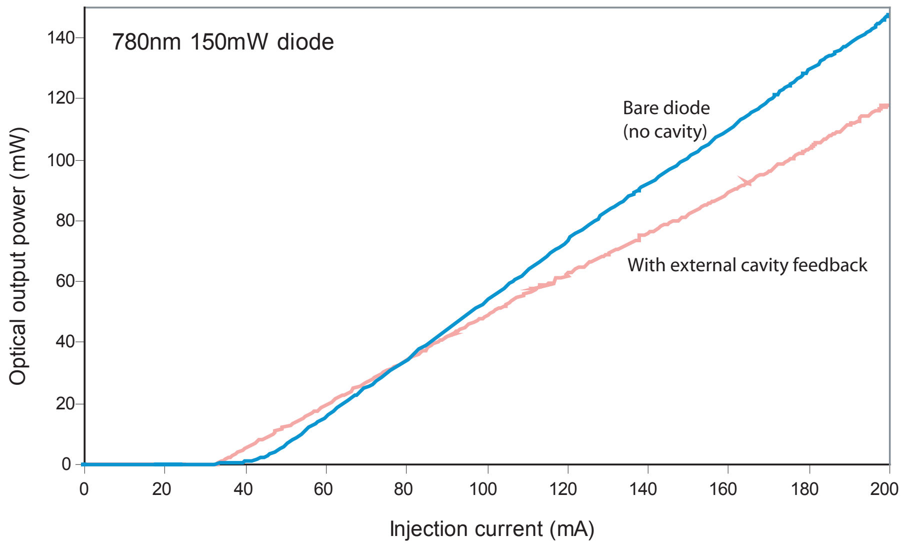


Figure 2.1: Sample laser diode power-current *PI* characteristic curves, with and without an external cavity. The external cavity feedback reduces the threshold current, and also the apparent power/current slope because the measured power with feedback is not the power from the bare diode, but the output 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

Your laser has been carefully tuned to the specifications provided in the laser test report. In most cases, the laser will perform as expected once the current, temperature and piezo settings are adjusted to those in the test report.

Figure 3.1 is a schematic of the laser showing the key components affecting performance.

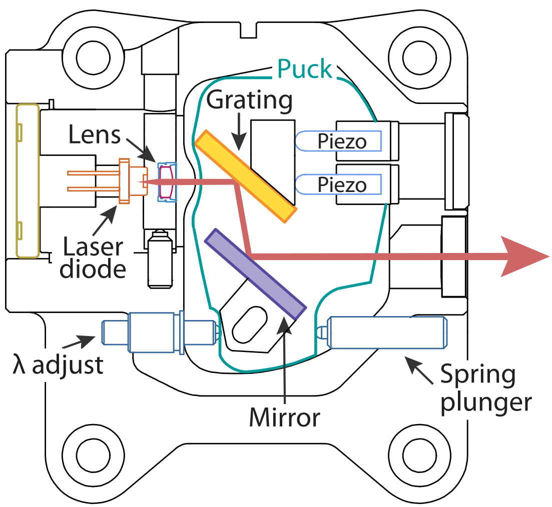


Figure 3.1: Cross-section of MOGLabs LDL Littrow laser, showing laser diode, collimation lens, grating, piezoelectric transducers and fold mirror. The grating can be rotated using the tangential λ fine adjustment screw. A counteracting spring-plunger should be released to allow rotation.

3.1 Power

Adjust CURRENT and compare the output power to the PI curve provided on the first page of your test report. The threshold current and slope above threshold should be similar; if not, refer to chapter 4.

3.2 Wavelength

Once the power measured is comparable with the test report, the wavelength can be adjusted with reference to a wavemeter or spectrometer. Increase CURRENT to the value recorded in the laser test report. If the measured wavelength is within 0.1 nm of the desired wavelength, the current and piezo (FREQUENCY) can be used to make small changes. If the precise wavelength cannot be reached with current and piezo adjustments, then the wavelength should be adjusted using the λ adjustment screw (see figure 3.1). Before adjusting , make sure that the spring plunger is not locked against the grating puck by rotating the screw 18 of a turn anticlockwise using a 1.3 mm driver.

Note that the wavelength is quite sensitive to grating angle. For example, for $\lambda = 780$ nm and $1/d = 1800$ 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.

For large changes in wavelength, it may be necessary to adjust the vertical alignment slightly using the vertical translation screw on the laser diode collimation lens. Set the injection current just below threshold, and adjust the vertical alignment until the laser flashes, and repeat until the threshold current is minimised. See chapter 4 for more a more detailed discussion.

3.3 Mode-hops

There are typically four wavelength-dependent elements in an external cavity diode laser that constrain the laser to a single ferquency:

1. The gain bandwidth of the laser diode, which determines the broad tuning range of the ECDL.
2. The coarse wavelength adjust mechanism: a grating, which narrows the range of wavelengths that are coupled back into the laser diode. Typical bandwidths are on the order of 50 – 250 GHz.

3. The laser diode internal cavity formed by the front and rear facets of the laser diode, with free spectral range of 20 – 50 GHz.

4. The external cavity formed by the rear facet of the laser diode and the grating. The external cavity free spectral range is typically 9 GHz.

The wavelength-dependent characteristics are shown schematically in figure 3.2. The net gain is the product of semiconductor gain, grating response, and internal and external cavity interference. Normally the gain at one external cavity mode is greater than for all others, and the laser will operate at that frequency. If the net gain is very similar at two or more external cavity modes, the laser can jump between those modes or even oscillate at several frequencies simultaneously. Small changes in the laser cavity optical path length, the diode internal cavity mode frequency, or the grating angle can change the product of gains such that a different mode becomes dominant: the laser mode-hops. See Ref. [1] for a detailed discussion.

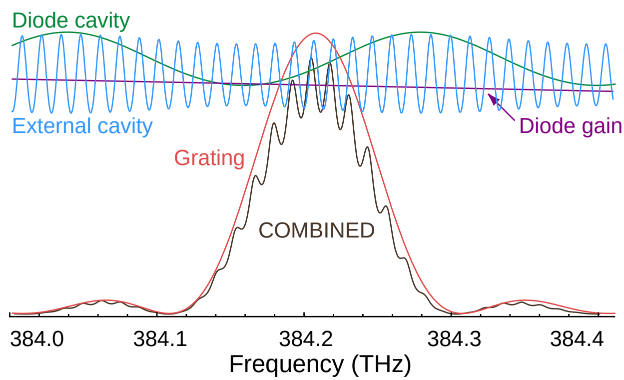


Figure 3.2: Schematic representation for the various frequency-dependent factors of an ECDL, adapted from Ref. [1], for wavelength $\lambda = 780\,\text{nm}$ and external cavity length $L_{\text{ext}} = 15\,\text{mm}$.

3.4 Selecting a particular mode

To tune an ECDL to a particular wavelength, all four wavelength selection mechanisms must be aligned at the desired wavelength. The different mechanisms are coupled, so that tuning one also affects the others.

3.4.1 Tuning the gain bandwidth

The gain peak wavelength of the diode depends on the semiconductor temperature, which depends on the diode current, and to a small extent on the temperature of the laser body. For typical red and infrared diodes, the effects are about $0.25\,nm/K$ and 0.06 nm/K, both small compared to the gain bandwidth which is at least a few nm. Changing the temperature is therefore not useful unless the desired wavelength is near the edge of the gain curve.

3.4.2 Tuning the coarse wavelength adjustment

The primary wavelength control is by rotation of the grating, using the fine pitch wavelength adjustment screw, and the piezo is then used to make small changes. To optimise the mode-hop-free range (MHFR) of the piezo tuning relative to the desired central wavelength:

1. Set the laser near the desired operating current and monitor the wavelength/frequency with a wavemeter.
2. Slowly decrease the laser current until the laser frequency abruptly changes (hops). Note the approximate frequency change and the new frequency. Typically the laser frequency will decrease with decreasing current, and a typical hop will be 8 GHz. That frequency jump is an approximate measurement of the free spectral range of the external cavity.
3. Continue decreasing the current until the laser frequency hops multiple times and record these frequencies.

4. The laser frequency will eventually hop by a larger amount and increase in frequency rather than decrease. The typical size of this hop will be on the order of 25 to 50 GHz, which is the free spectral range of the cavity formed by the front and rear facets of the laser diode semiconductor chip. Note the new frequency after the laser hops.

The highest and lowest frequencies during this procedure indicate the highest and lowest frequenc lasing modes permitted by the coarse wavelength adjustment mechanism. The average of these two frequencies gives an approximate indication of the central frequency of the coarse wavelength adjustment.

Typically the exact angle of the coarse wavelength adjustment mechanism is not critical to achieving a desired wavelength. To maximise the gain at the desired wavelength, and in particular maximise the mode hop free scan range about that given frequency, the coarse wavelength adjustment should be precisely tuned.

3.4.3 Tuning the intrinsic diode cavity

The frequency at which the intrinsic diode cavity is resonant is determined by the optical path length of light between the front and reaf facets of the diode. The optical path length is the physical path length multiplied by the refractive index of the semiconductor material. The temperature of the diode affects the physical length, in proportion to the thermal expansion coefficient of the semiconductor.

Two factors affect the temperature of the laser diode: the temperature of the laser body, and the laser diode current. The response time constants are very different: tens of seconds forchanges to the body temperature, and microseconds for current changes.

The diode current also affects the refractive index of the semiconductor. The effect is opposite in sign to the thermal response, and much faster (sub-nanosecond), but is much smaller in magnitude and can be ignored for normal operation.

To achieve a particular laser frequency, once the coarse wavelength adjustment mechanism is optimised, slowly adjust the laser diode current until the laser hops to the frequency that is closest to the desired lasing frequency, which should be within half of the free spectral range of the external cavity determined above.

If a specific output power and thus diode current are preferred, the laser body temperature can be tuned a small amount instead to bring the laser diode cavity into resonance with the desired frequency at a particular current. Start with temperature changes should be of order 0.1°C or less, wait a few minutes for the temperature to stabilise, and repeat the steps in section 3.4.2. Repeat until the central wavelength is optimised.

3.4.4 Tuning the external cavity

For a specific grating angle and intrinsic diode cavity mode, there will be one external cavity mode within half an external cavity free spectral range. That mode will have the highest overall gain, and the laser will operate at that mode frequency. The external cavity length and thus lasing frequency can be precisely controlled by adjusting the voltage applied to a piezo-electric actuator. The piezo and high-voltage driver have picometre precision, corresponding to kHz control of the laser frequency.

3.5 Scanning mode hop free

For large changes in piezo voltage, corresponding to a large fraction of the free spectral range of the external cavity, the laser will usually hop to a neighbouring external cavity mode. The hop occurs because the piezo voltage changes the external cavity mode frequency but the diode cavity mode is fixed. The gain of the lasing mode decreases as the external cavity mode is no longer resonant with the peak of the diode cavity. The gain of a neighbouring external mode then increases as it tunes more closely to the diode cavity mode, leading to a jump between the two modes.

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 probability of jumping to an adjacent exter-

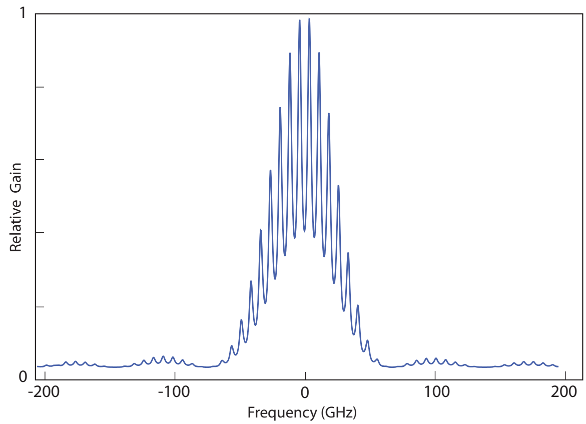


Figure 3.3: Combined gain for an external cavity diode laser, including the internal and external modes, the diode laser gain, and the grating response. The broad feature is the frequency selectivity of the grating, and the smaller peaks are the external cavity modes (see fig. 3.2). The laser will easily hop between the two highest external modes with similar net gain.

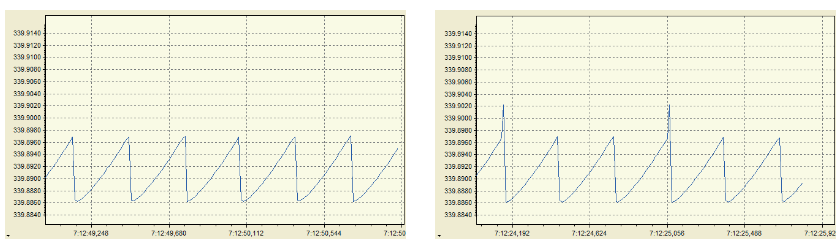


Figure 3.4: Frequency of a laser scanning properly (left) and with a mode-hop at one edge (right).

nal cavity mode can be reduced by simultaneously changing the frequency of the intrinsic diode mode using feed-forward current bias. Changing the diode current changes the diode mode frequency as described above (§3.4.3). Optimising current bias to maximise the mode-hop-free scan range is described in the next section.

3.5.1 BIAS optimisation

Ideally the frequencies of the external cavity mode and the intrinsic laser diode mode are identical (see fig. 3.2). The external mode frequency is controlled by the piezo. The intrinsic diode mode frequency can be controlled by adjusting the laser diode current.

The diode injection current can be "automatically" adjusted as the laser frequency is changed, using a "feed-forward" or current bias which changes as the piezo voltage is changed. Feed-forward current bias adjustment is a feature of MOGLabs DLC controllers. Each laser requires a different change in diode current for a given change in piezo, and the ratio can be adjusted with the BIAS trimpot on the DLC controller.

Optimisation is straightforward. With the laser frequency scanning, the 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. A fast Fizeau wavemeter, an atomic absorption spectroscopy signal, or a Fabry-Perot cavity can be used to monitor the laser frequency while varying the different control parameters.

1. Ensure that BIAS is enabled (DIP switch **4**).
2. With SPAN set to max, monitor CHAN A Freq and CHAN B Current on a dual-channel oscilloscope. Confirm that the peak-to-peak voltages on the two sawtooth outputs match the values specified in the laser test report.
3. Set the piezo to the middle of its range, with ramp off. On a MOGLabs DLC controller, set SPAN to zero and adjust FREQUENCY to zero.
4. Use a wavemeter, absorption spectroscopy, or scanning Fabry-Perot etalon to set the desired wavelength (§3.4.2).
5. Increase SPAN until a mode-hop is evident (fig. 3.4). If using absorption spectroscopy to monitor the laser wavelength, it can be helpful to observe the derivative, for example the demodulated error signal (CHAN B Error on a MOGLabs DLC).

The mode hop should be at one edge of the scan; if so, adjust 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.

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

7. Increase SPAN and adjust FREQUENCY mode hops are evident at both edges of the scan.

8. Adjust diode CURRENT by small amounts to suppress the mode hops. Increase SPAN and adjust CURRENT and FREQUENCY until the mode hops cannot be suppressed.

9. Adjust the BIAS trimpot to suppress the mode hops.

10. Repeat steps 5 to 9 above until no further improvements can be made.

11. If the mode-hop free ranage is substantially less than expected (refer to factory test report), it may be helpful to change to a different intrinsic diode mode by increasing or decreasing CURRENT. Alternately rotate the grating slightly to alter the net gain so that one cavity mode has higher gain than those adjacent.

3.6 Faraday isolator

The laser can be supplied in a very compact form, or with optional extended chassis (option LDX or LDF) which allows internal mounting of Faraday isolator, and also the addition of a fibre coupler (option LDF) (see fig. 3.5).

3.6.1 Faraday isolator alignment

Faraday isolators are critical to the stability of an external cavity diode laser: even very weak reflections from external optics can have a significant effect on the laser frequency. At least 30 dB of isolation is needed; that is, the optical feedback into the ECDL should be less than 0.1% of the output

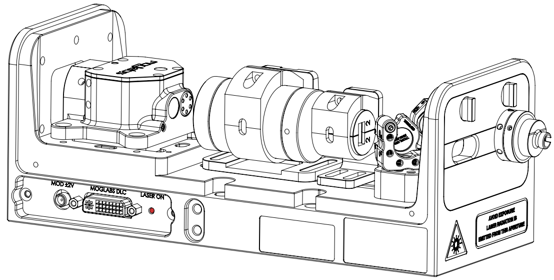


Figure 3.5: Extended chassis LDF option, shown here with LDL Littrow laser installed.

power. Double-stage isolators provide 60 dB or more of isolation which is necessary if locking to a high-finesse optical cavity.

The extended chassis version of a MOGLabs laser allows internal mounting of a Faraday isolator (see figure 3.6). Alignment is straightforward: the isolator should be concentric with laser beam, and rotated axially so that the first polariser is parallel to the polarisation of the laser beam. Depending on wavelength, the transmission varies from about 70% to 98%, with 90 to 95% typical at 780 nm.

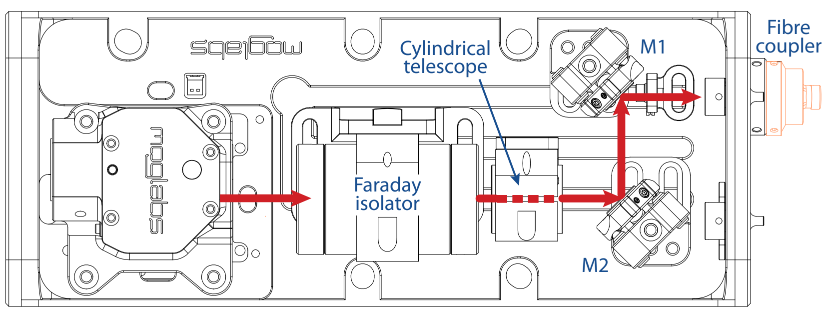


Figure 3.6: Schematic of the extended chassis laser showing Faraday isolator, and two mirrors used for aligning the beam to a single-mode fibre.

For lasers with fibre coupling, or those with dual beam output (using a PBS polarising beamsplitter cube), the isolator will in most cases have an internal half-wave retardation waveplate. The waveplate is mounted inside

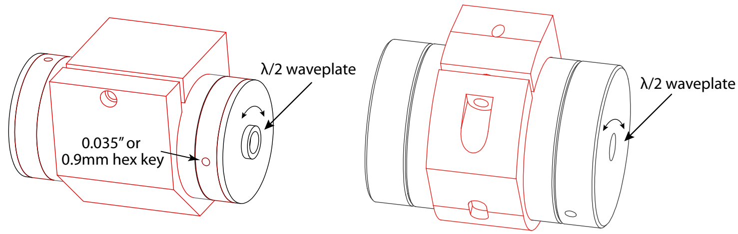


Figure 3.7: Two types of single-stage Faraday isolator. Each can be supplied with exit $\lambda/2$ waveplate inside one end-cap. The waveplate can be rotated to rotate the plane of polarisation of the exit beam, for example to optimise coupling into polarisation maintaining fibre, or to adjust the ratio of exit beams for lasers fitted with a polarising beamsplitter instead of mirror M2.

the end-cap of the isolator (see figure 3.7). 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. Older isolators use a 0.035″ or 0.9 mm hex key; newer MOGLabs isolators require a 1.5 mm hex key.

A second waveplate holder is available, which mounts directly before the exit face of the laser. The waveplate allows separate polarisation control for the beam reflected from M1.

4. Alignment

Alignment of the laser may be required, for example after shipping if the laser has been mishandled, or after changing laser diode or 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 (IR) blocking filter which must be removed.

4.1 Vertical grating/diode alignment

WARNING The vertical and horizontal adjusters have only a very small translation range. Use only tiny adjustments with minimal force. The horizontal adjustment should not, in general, be adjusted as it is factory-set and irreversible damage can be done if excessive force is applied.

When aligned, the external cavity feedback dominates 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 the free-running current threshold, and then adjusting the vertical collimation lens alignment until the output flashes brightly, indicating effective feedback to lower the overall gain threshold. The laser diode collimator focus can also be adjusted to optimise the spatial mode matching of the external cavity feedback to the laser diode output. The horizontal collimation lens adjustment is factory set and will not, in general, need user adjustment.

The vertical alignment of the diode output direction is controlled by vertical shift of the collimation lens. A focus ring adjusts the laser diode to collimation lens distance (see fig. 4.1). The collimation lens can also be moved in the horizontal direction to change the output beam direction, but this is not recommended as a general adjustment, only under specific direction from MOGLabs support. In addition to the risk of irreversible damage to the horizontal adjuster, the grating angle and lasing wavelength will also be affected by the horizontal adjustment and are not straightforward to recover.

If the laser is far from alignment, for example after a change of laser diode:

1. Project the output beam onto a piece of black card at a distance of about 30 cm from the laser. For wavelengths outside the normal visible range, monitor this beam spot using a camera such as a webcam or CCD.

2. Adjust the diode current well above threshold but below the maximum safe current when operating without feedback (refer to the laser test report for these values).

3. 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. First try adjusting the vertical alignment (e.g. 1/8th of a turn of the screw in either direction) to

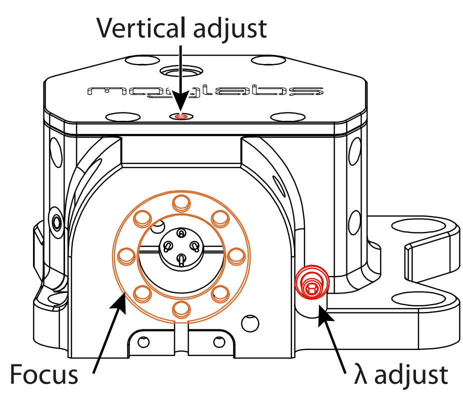


Figure 4.1: Location of vertical collimation lens adjuster and laser diode focus ring. WARNING: make only small changes to the vertical adjustment screw, which has very limited travel range.

see a spot moving up and down "faster" than the main output beam. Never apply force to the vertical adjustment screw - it should easily rotate with light finger adjustment.

4. Align the reflection of the return beam using the wavelength adjustment screw, so that the two spots are centred horizontally but displaced vertically.

   A secondary spot is not always visible; in that case, set the current close to threshold and search for lasing as in the following step.

5. The laser should significantly brighten or "flash" when the grating feedback is aligned back into the diode. For maximum precision, insert the short arm of an L-shaped allen key into the adjustment screw, rather than a ball driver. Use a power sensor to monitor the output power and look for a global power maximum as you make small adjustments to the vertical alignment screw. It can be helpful to reduce the current and start with a power of 1 mW incident on the sensor, then make gentle vertical adjustments towards higher power.

When the laser is partially aligned, to optimise:

1. Adjust the injection current to just below threshold.

2. Adjust the vertical alignment until flash; that is, lasing, or recovering to 1 mW output power.

3. Iterate reduction of the injection current, followed by vertical alignment until lasing occurs, until the minimum threshold is achieved (minimum current to achieve 1 mW output).

   The grating wavelength (horizontal angle) will now likely be close to the diode gain curve centre and require adjustment to the specific desired target wavelength.

4.2 Focus

1. If the threshold is not significantly lower than the bare diode threshold, by at least a few mA, the focus may need adjustment. If the laser

beam is initially converging to a focus at some distance from the laser, then rotate the focus ring clockwise to move the focus further from the laser, until the beam is fully collimated. "Collimated" output can be achieved by using a scanning beam profiler, or approximated by adjusting the focus such that a beam waist (smallest spot size) occurs at a distance of about 4 m from the laser chassis output.

2. Iterate the vertical alignment steps of section 4.1 until the threshold is minimised. If the threshold current is still a few mA or more higher than the value specified in the laser test report, repeat the focus adjustment and reflashing process.

   Note that there is a compromise here. At minimum threshold, feedback is optimised giving the highest output power and narrowest linewidth. The back-reflected beam diameter is then matched to the laser diode waveguide mode diameter, but small changes in alignment will then have a dramatic effect on that mode-matching. Defocusing slightly, by rotating the focus adjust anti-clockwise a little so that the output beam is weakly focusing, can improve stability and the mode-hop-free scan range.

4.3 Wavelength

1. Increase the current to well above threshold but below maximum current, and adjust grating angle to achieve the desired wavelength. Monitor the laser with a wavemeter, or scan the laser through an atomic reference and search for the absorption spectrum on an oscilloscope. The wavelength adjustment is about 0.1 turns per nm, clockwise to increase wavelength. Ensure that the spring plunger is not locked against the arm of the grating spindle when adjusting the wavelength.

2. Again adjust the vertical alignment (section 4.1) to minimise the threshold.

3. With current bias disabled (DIP 4 on a MOGLabs controller) and full span, the time-dependent wavemeter trace or the absorption spec-

trum should repeat several times as the laser scans over a short range and then mode-hops.

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

5. Measure the laser output power as a function of diode injection current, and plot the power/current response as in Fig. 2.1. If very different to the laser test report, contact MOGLabs for advice.

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

4.4 Fibre coupling

Lasers with extended chassis can be fitted with a fibre connector to allow coupling the free-space laser beam into a single-mode optical fibre. Two mirrors on kinematic mounts allow precise alignment of the position and angle of the laser beam into the fibre coupler: a common and familiar arrangement for optical scientists (see figure 3.6). The arrangement can also be configured to allow 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).

An eccentric key is provided for adjusting the coupling lens focus. Please contact MOGLabs if your fibre coupling efficiency is much lower than stated in your laser test report.

4.4.1 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 figure 4.2) 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 4.2: 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.

4.4.2 Mirror adjustment

To maximise the fibre coupling efficiency, the incident 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 3.6).

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. Locate a power meter sensor to monitor the output power exiting from the optical fibre. Ensure that the reading is not affected by background light. We strongly recommend using integrating sphere sensors to avoid errors due to saturation of the detector.

10. For the horizontal axis first, find the maximum output power by adjusting 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 much rotation was 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 coupling efficiency 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 at `https://www.sukhamburg.com/documents/Adjustment_SMS.pdf`). 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	Rotation 38° to 60°
Tuning range	Up to 100 nm, depending on diode
Sweep/scan	
Scan range	40 GHz typical
Mode-hop free	$>$ 10 GHz; up to 100 GHz (dual piezo)
Piezo stack	3 μm @ 150 V, 100 nF typical
Cavity length	10 – 15 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

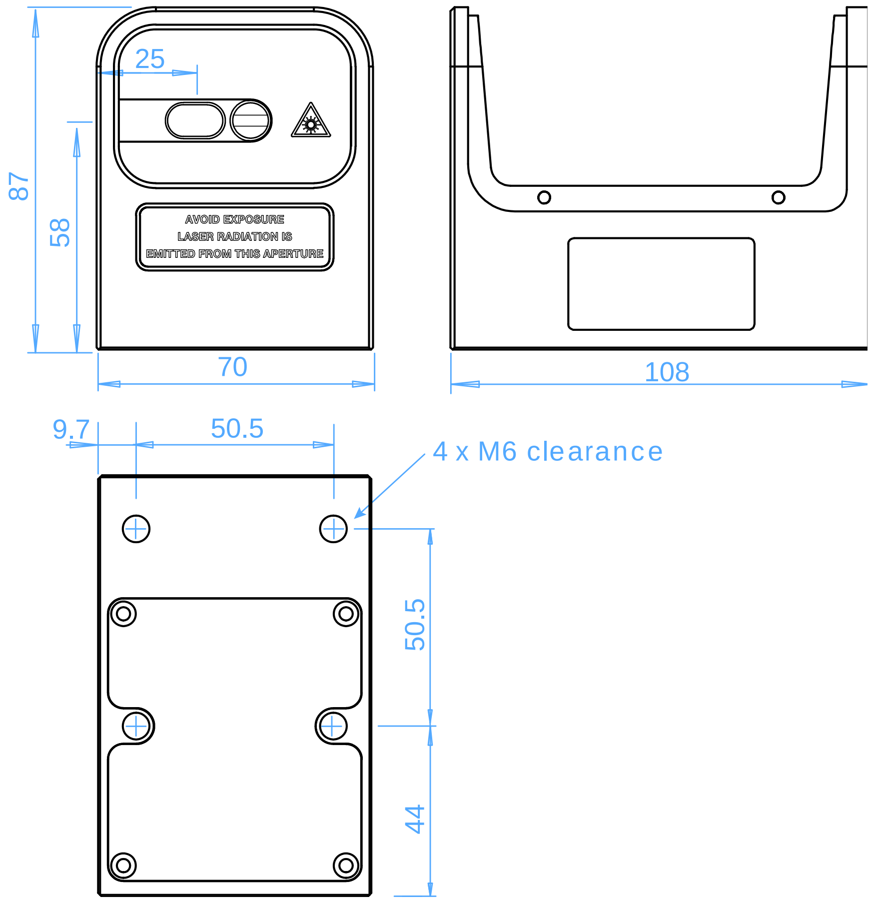


Figure A.1: Dimensions of compact LDL laser head.

A.2 Older LDL mechanical

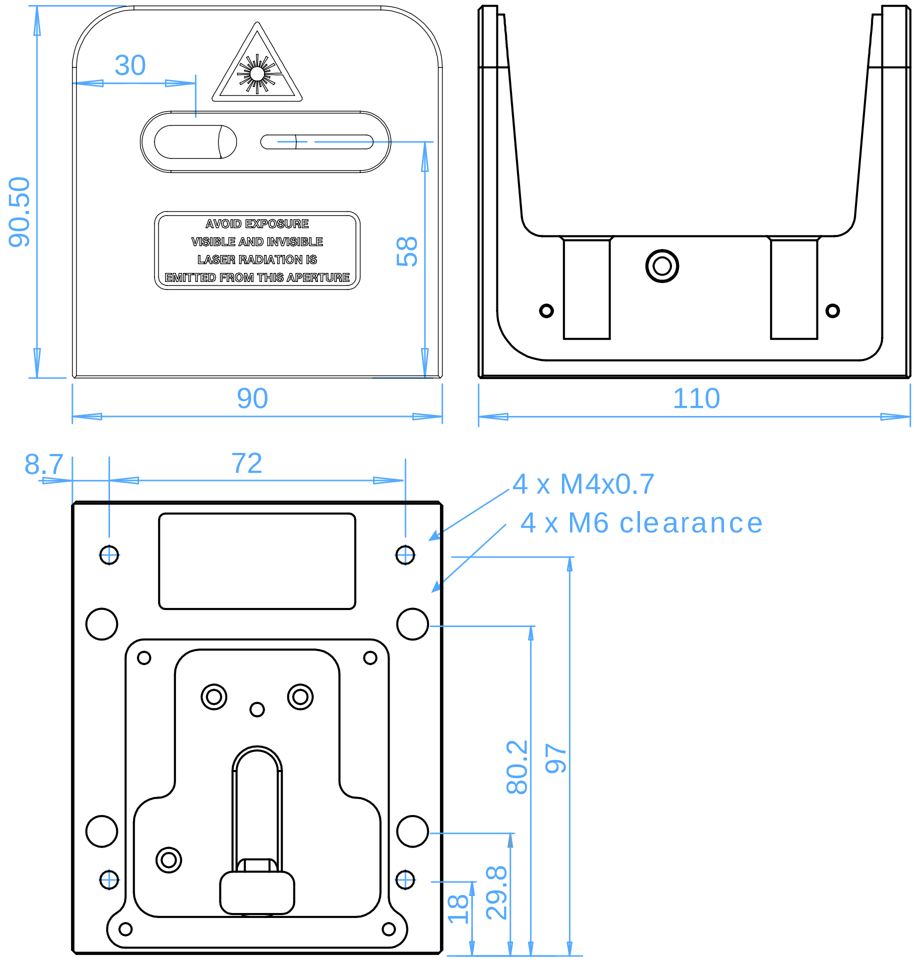


Figure A.2: Dimensions of previous generation LDL laser head.

A.3 LDX/LDF mechanical

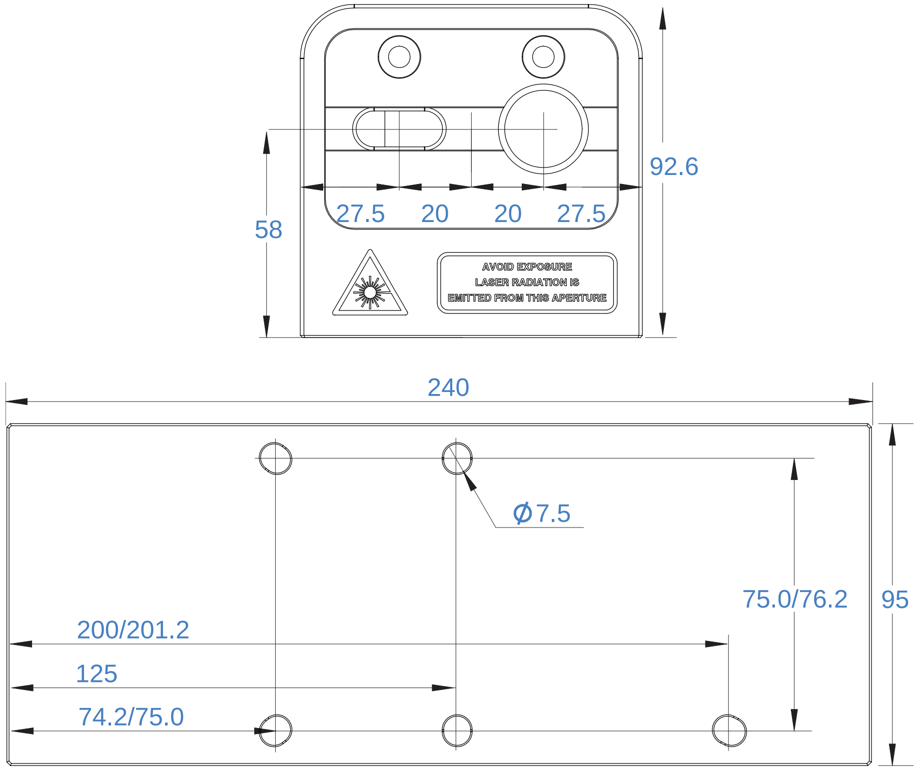


Figure A.3: Dimensions of LDX/LDF laser head.

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).

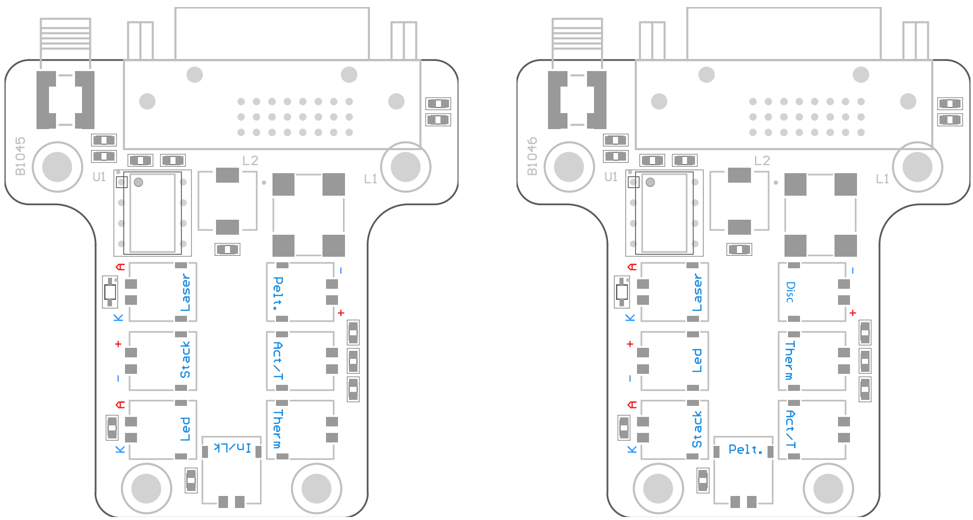


Figure B.1: MOGLabs B1045 and B1046 laser head boards showing connectors for laser diode, piezo actuator, temperature sensors, TEC and head enclosure interlock. Connectors are Hirose DF59.

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 figure 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 kΩ. 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.

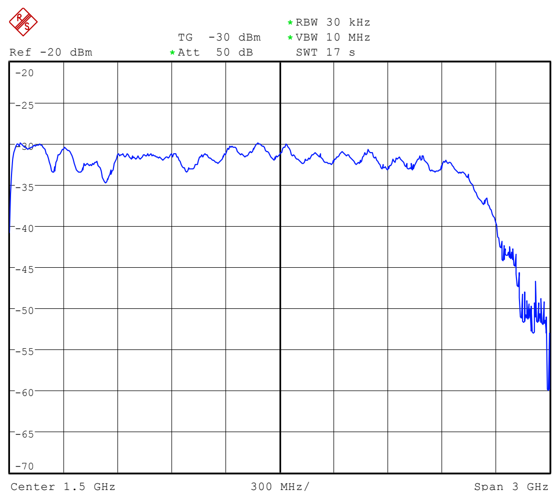


Figure B.2: RF response, SMA input on laser headboard to diode SMA output.

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), which is helpful in achieving 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 control voltage is at zero.

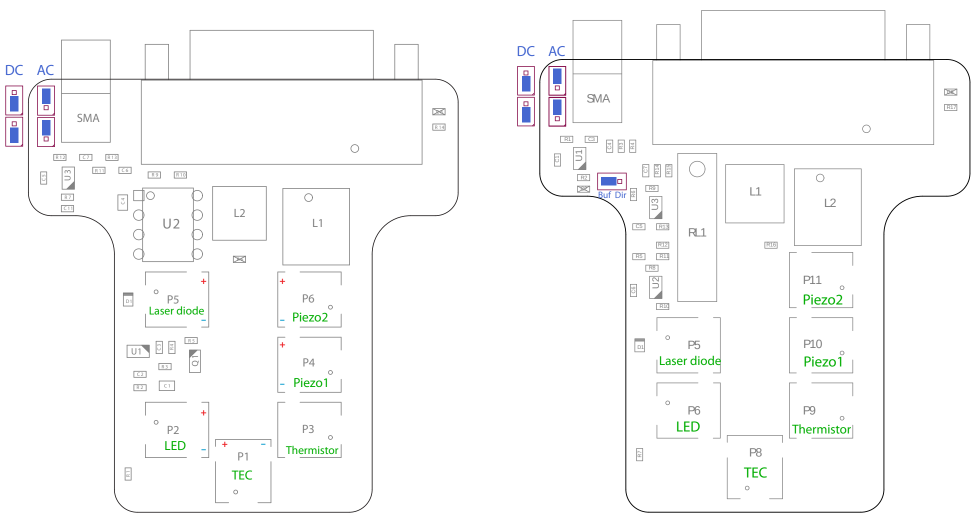


Figure B.3: B1047 (left) and B1240 (right) enhanced laser head boards. Jumpers at top left can be configured for AC or DC coupling. The B1240 has an additional jumper “Buf Dir” for buffered or direct input, shown connected for buffered; change to pins 1 and 2 for direct. Modulation input via SMA connector, 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	15 μs (10 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 kΩ	AC buffered: 1 kΩ at 10 kHz DC buffered: 1 kΩ Direct: 1 kΩ
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	+5V in	23	NTC –
8		16	Interlock out	24	NTC +

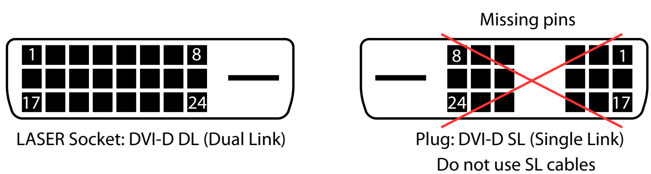


Figure B.4: Headboard connector. Note that the pinout is different to that of the matching connector on the rear of the DLC controller.

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 15 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 15) is internally connected to pin 16 (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.

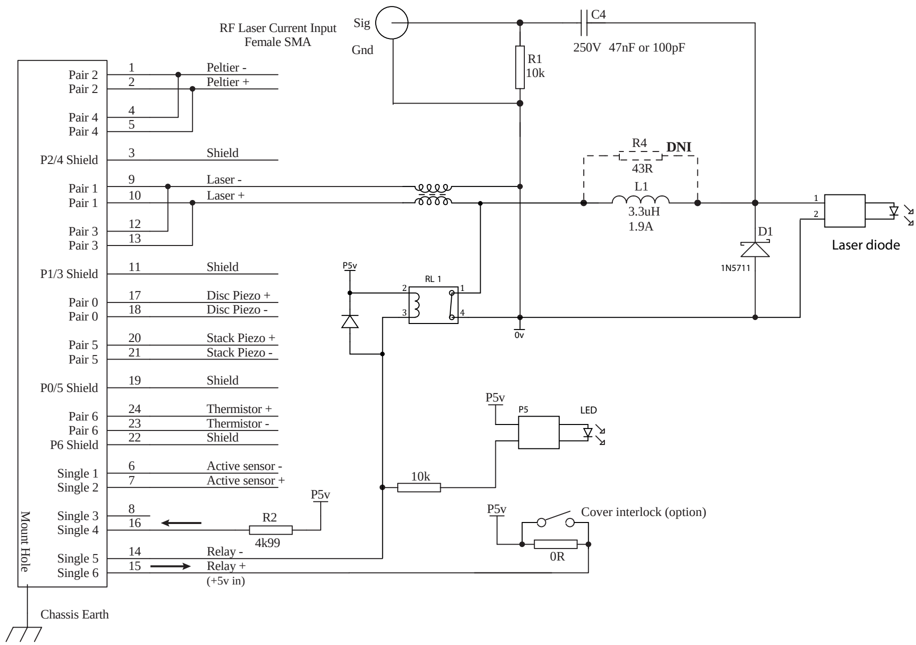


Figure B.5: MOGLabs DLC laser head board schematic (B1040/1045). The RF modulation low-pass cutoff frequency is determined by C4 and the diode impedance ($\sim 50\Omega$).

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, 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, 3

[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. 3

[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] 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