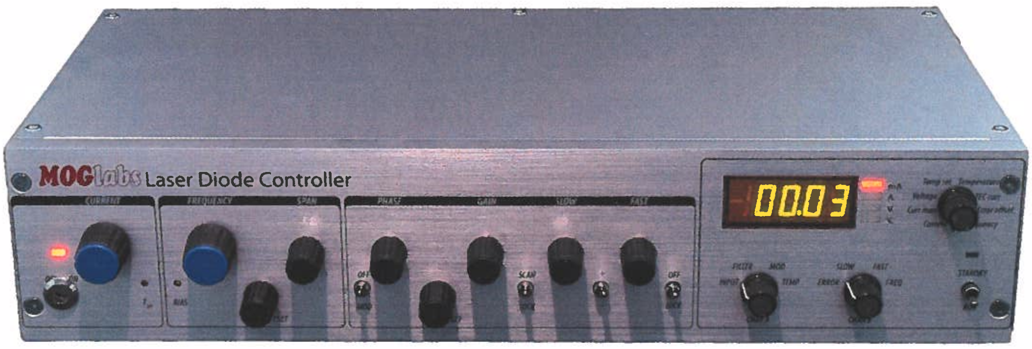
MOGlabs
Melbourne Optics Group

External Cavity Diode Laser Controller



Revision 1.05

Contents

Preface

Diode lasers can be wonderful things: they are efficient, compact, low cost, high power, low noise, tunable, and cover a large range of wavelengths. They can also be obstreperous, sensitive, and temperamental, particularly external cavity diode lasers (ECDLs). The mechanics and optics needed to turn a simple \$10 120 mW AlGaAs diode laser into a research-quality narrow-linewidth tunable laser are fairly straightforward,[1,2] but the electronics is demanding – and, until now, not available commercially from a single supplier, let alone in a single unit.

The MOGlabs range of ECDL controllers change that. With each MOG unit, we provide everything you need to run your ECDL, and lock it to an atomic transition. In addition to current and temperature controllers, we provide piezo drivers, sweep ramp generator, modulator for ac locking, lock-in amplifier, feedback servo system, laser-head electronics protection board, even a high-speed low-noise balanced photodetector.

We would like to thank the many people that have contributed their hard work, ideas, and inspiration to MOG, especially Lincoln Turner, Karl Weber, and Jamie White, as well as those involved in previous controller designs, in particular Mirek Walkiewicz and Phillip Fox.

We hope that you enjoy using MOG as much as we do. Please let us know if you have any suggestions for improvement in MOG 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.

Robert Scholten and Alex Slavec,
MOGlabs, Melbourne, Australia
http://www.moglabs.com

Safety Precautions

Please note several specific and unusual cautionary notes before using MOG, in addition to the safety precautions that are standard for any electronic equipment or for laser-related instrumentation.

CAUTION Please ensure that the unit is configured for the correct voltage for your AC mains supply before connecting. The supply must include a good ground connection.

WARNING The internal circuit boards and many of the mounted components are at high voltage, with exposed conductors, including the power supply circuitry at mains supply voltage, and the high-voltage piezo driver circuitry. The unit should not be operated with covers removed.

WARNING The rear-panel connector for the laser is similar to standard DVI (Digital Video Interface) plugs as used for LCD displays. The pins on this connector can be at high potential (up to 120 V). These can be hazardous to life and should be protected by connection of the correct cable to the laser. Under no circumstances should a standard DVI device such as an LCD display be connected to this socket!

WARNING If using a Zeeman coil modulator as described in appendix B, the secondary potential can easily be hundreds of volts! Please ensure that your coil and balance capacitor do not have exposed connections, and that all components have sufficient voltage rating.

NOTE MOG is designed for use in research laboratories. It should not be used for consumer or medical applications.

Chapter 1

Introduction

MOG can be used in various configurations, including simple current/temperature controller, passive frequency controller with internal or external sweep/scan, and as a complete system for active frequency stabilisation with ac, dc or external locking signal. Here we just give a quick outline of some modes of operation, so that you can connect and go as quickly as possible. Details are provided in chapter 3.

1.1 Simplest configuration

In the simplest application, MOG will be used to control the diode injection current, and temperature. Thus MOG must be connected to the diode, a thermoelectric (TEC) Peltier cooler, and a temperature sensor.

All connections between MOG and the laser head are via a single cable (part #MOG-C-20). A laser head interface board (part #MOG-HC), located as close as possible to the laser itself, includes protection relay and passive protection filters, a laser-on indicator, and MOLEX connectors for the diode, TEC and sensor (either 10 k thermistor, or AD590, or AD592). See appendix D.2 for details.

The front-panel display selector switch can be used to monitor the diode current, current limit, diode dropout voltage, temperature and temperature setpoint, and TEC current; see figure 1.2.

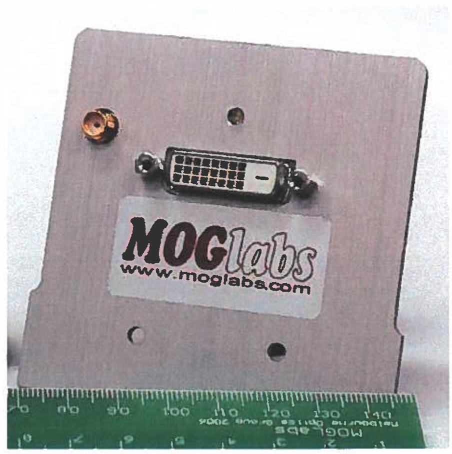


Figure 1.1: MOG is readily connected to a laser diode, temperature sensor and thermo-electric cooler via the provided laser head board.

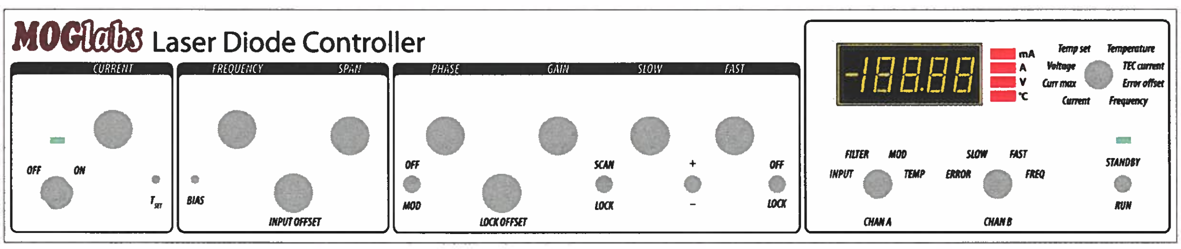


Figure 1.2: MOG front panel layout.

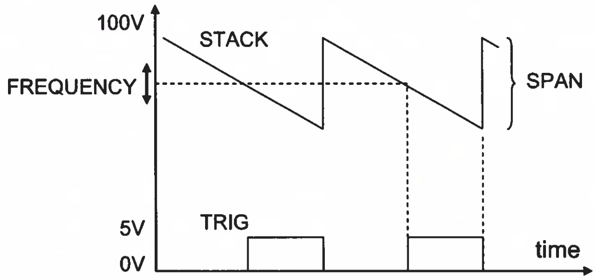


Figure 1.3: Stack output voltage and trigger pulse, when scanning.

1.2 Passive frequency control

MOG includes high voltage (100 V) outputs for controlling piezo electric actuators, designed to control the frequency of an ECDL. The actuators should be connected to the laser head board via the provided MOLEX connectors.

One or two piezo elements can be controlled. Typically, only a single "stack" actuator, such as the Tokin AE0203D04 (available from Thorlabs, `www.thorlabs.com`), will be required. The single stack actuator allows frequency scanning and frequency offset selection, and active slow (up to $\approx$ 100 Hz) feedback. A second actuator, typically a disc, can be added for faster active feedback control (described below).

In normal (SCAN) mode, a sawtooth is supplied to the stack (or equivalent actuator). The output is a high-to-low ramp, at frequency of 4 to 20 Hz; see figure 1.3. At the midpoint of the sweep, a trigger (low to high) pulse is output via the rear panel TRIG connection, for synchronising to an oscilloscope or external experiment.

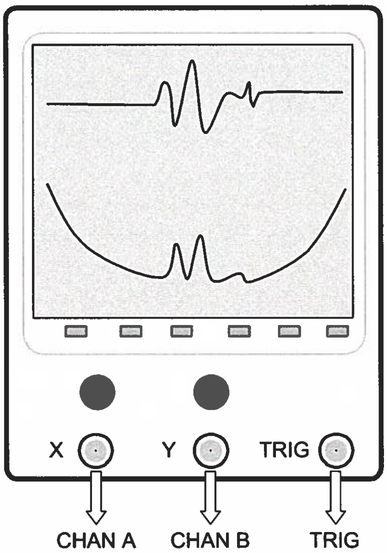


Figure 1.4: MOG connection to oscilloscope.

Critical MOG signals can be monitored using the CHAN A and CHAN B outputs on the rear panel, synchronised to the TRIG trigger output. These signals should be connected to a two-channel oscilloscope as shown in figure 1.4. The particular signals are selected from the front-panel CHAN A and CHAN B selector switches. The signals are described in detail in the following chapter.

1.3 DC locking to an atomic transition

Figure 1.5 shows one possible configuration in which a MOG is used to lock an ECDL to an atomic transition. Locking is to the side of an absorption peak in a vapour cell; see for example Demtröder[3] for more information on spectroscopy. The passive configuration of section 1.2 is extended with the MOG photodetector (part #MOG-PD, see appendix D), and an atomic vapour absorption cell (not supplied). Alternately, a Fabry-Perot optical cavity or other reference based on intensity variation, could be used.

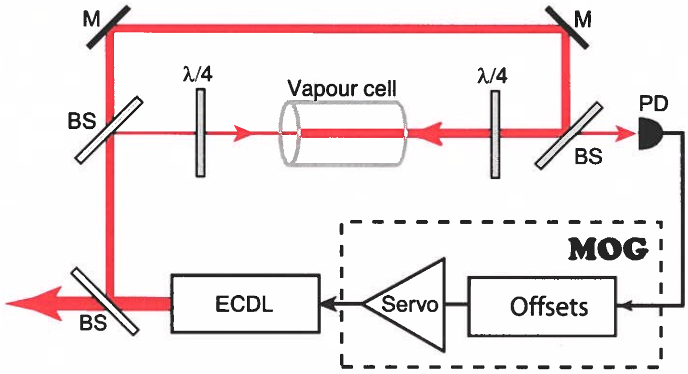


Figure 1.5: Schematic setup for dc locking to an atomic transition. PD is the MOG photodetector. BS beamsplitter, M mirror, $\lambda/4$ a quarter-wave retarder.

The schematic shows a saturated absorption spectroscopy arrangement, but often simply locking to the side of a Doppler-broadened absorption peak will be adequate. The photodetector can be used in single channel mode (default) or with balanced differential inputs, for example to subtract a Doppler background from a saturated absorption spectrum; see fig. 1.5.

The lock frequency is determined by the zero-crossing point of the photosignal. The photosignal offset is adjusted via the INPUT OFFSET and LOCK OFFSET controls. Feedback can be via one or both piezo actuators, the diode injection current, or all three.

1.4 AC (heterodyne) locking to an atomic transition

AC locking locks to a peak centre, and offers the advantage of inherently lower noise. The setup for ac locking is similar, but modulation of the laser frequency, or the reference frequency, is required. MOG provides a high-power internal 250 kHz oscillator which can directly drive an external modulator. In particular, it is designed to drive a Zeeman-shift modulation coil surrounding the atomic reference vapour cell; see appendix B.

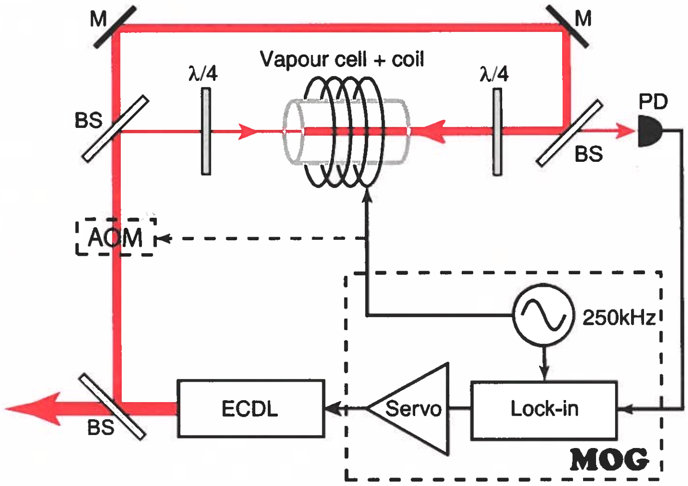


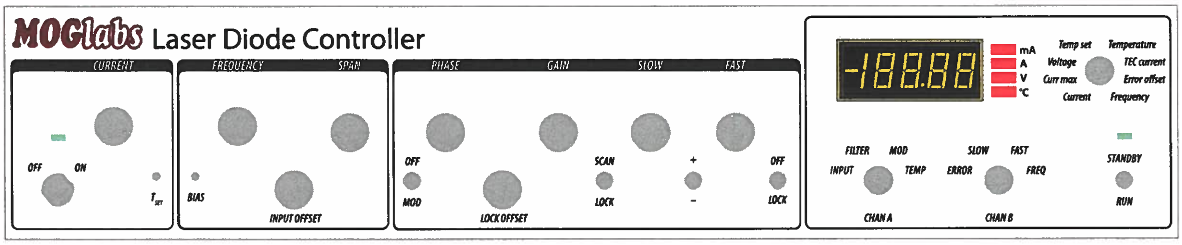
Figure 1.6: Schematic setup for ac locking to an atomic transition. PD is the MOG photodetector. BS beamsplitter, M mirror, $\lambda/4$ a quarter-wave retarder.

Figure 1.6 shows a simplified ac locking setup, for either a coil to Zeeman modulate the reference, or an acousto-optic modulator (AOM) for modulating the frequency of the beam through the atomic reference cell. If required, the modulator drive output can be connected to the MOG internal piezo or current modulation inputs (see section 2.5), but this approach is not actively supported. Feedback can again be via one or both piezo actuators, the diode injection current, or all three.

Chapter 2

Connections and controls

2.1 Front panel controls



STANDBY/RUN	In STANDBY mode, MOG maintains the laser temperature, but powers down all other components including high-voltage piezo power, and the main on-board low-voltage power.
OFF/ON	Key to switch power to the diode. The STANDBY/RUN switch should first be on RUN and the associated indicator must be green. **Troubleshooting** If the diode fails to power on, check: • SCAN/LOCK and OFF/LOCK should be up (SCAN and OFF) • External interlock and laser head interlock • Cable continuity • Diode failure
CURRENT	Diode injection current, 0 to 200 mA.
FREQUENCY	Laser frequency. The laser frequency will normally be controlled via a piezo-electric actuator, STACK. This controls the offset voltage applied to that actuator, from 20 to 100 V.
SPAN	Frequency scan range, from 0 to 100 V. The span may be limited by the maximum voltage that can be applied to the actuator, 100 V.
PHASE	When ac locking, MOG demodulates the signal from the modulated light intensity. This control adjusts the relative phase between the internal reference modulator and the detected signal, from 0 to 360°.
GAIN	Overall error signal gain, 0 to 40 dB.
SLOW	Additional gain for feedback to the slow (DISC) actuator, 0 to 40 dB.
FAST	Additional gain for fast feedback to the diode current, 0 to 40 dB.
T_{set}	Temperature set point.
BIAS	Feed-forward bias current. As the laser frequency is scanned via the piezo actuator, the current can also be scanned. This trimpot controls the change in current. It can be positive or negative.

INPUT OFFSET	Offset to input light intensity, 0 V to −10 V.
OFF/MOD	Modulator enable.
LOCK OFFSET	MOG will lock such that the error signal plus LOCK OFFSET is zero, allowing for small adjustment so that the zero of the error signal is at the desired frequency.
SCAN/LOCK	Switch from scanning mode to lock. When switching from scan to lock, MOG will reset the scanning actuator (STACK) to the offset voltage at the centre of the scan; that is, the voltage at which the external trigger transitions to active. Thus, MOG will lock to the frequency at the centre of the scan.
+/−	Sign of fast (current) feedback. The sign of the slow feedback can be changed with the PHASE control for ac locking, and by reversing the photodetector for dc locking.
OFF/LOCK	Enable fast feedback.

2.2 Front panel display/monitor

Display selector

MOG includes a high-precision 4.5 digit LED display with four unit annunciators and 8-channel selector switch.

Current	Actual diode current (mA)
Curr max	Current limit (mA) Note: (−) sign indicates limit rather than actual current
Voltage	Diode voltage (V)
Temp set	Temperature set point (°C)
Temperature	Actual temperature (°C)
TEC current	Current to thermoelectric (Peltier) cooler (A)
Error offset	Error offset voltage (V)
Frequency	Slow piezo (STACK) offset voltage (V)

CHAN A

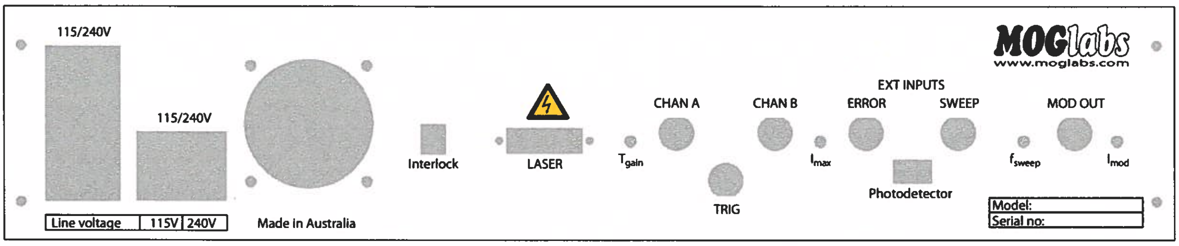
Several important signals can also be monitored externally with an oscilloscope via the rear connectors CHAN A, CHAN B and TRIG. The outputs to these can be selected with the CHAN A and CHAN B selectors.

INPUT	Photodetector signal
FILTER	Filtered photodetector signal (40 kHz low pass)
MOD	Modulator output current (1 V = 1 A)
TEMP	Temperature (10 mV/°C)

CHAN B

ERROR	Feedback error signal
SLOW	Feedback to slow actuator (DISC)
FAST	Feedback to diode current
FREQ	Output to frequency scanning actuator (STACK)

2.3 Rear panel controls and connections



IEC power in/out	MOG should be preset for the appropriate voltage for your country. The output IEC connector is a direct connection to the input after the mains filter circuitry. This should be used only to power a monitoring oscilloscope. It is provided to minimise ground-loop noise problems.
Fan	The fan is temperature-activated and will not normally run when MOG is in standby.
Interlock	MOG will not power on the laser unless the pins on this connector are shorted. A standard 2.5 mm dc plug is provided.
LASER	Connection to laser head. This connector provides diode current, two piezo drives, temperature sense, and TEC current. **WARNING:** The piezo drive signals can be lethal.
T_{gain}	Temperature control feedback gain. Increase this if the response time is too great or if the temperature error is large. Reduce this if the temperature oscillates.
CHAN A	Monitor output; connect to two-channel oscilloscope, channel 1.
CHAN B	Monitor output; connect to two-channel oscilloscope, channel 2.
TRIG	Oscilloscope trigger; connect to external trigger on two-channel oscilloscope.
I_{max}	Diode current limit.
ERROR	Input for externally derived feedback error signal. Applies in lock mode.
SWEEP	Input for externally generated frequency control. Applies in scanning mode.
Photodetector	Connection to photodetector unit.
f_{sweep}	Scan rate.
MOD OUT	Connection to external modulator, 0 to ±500 mA. Current output; that is, if a voltage is required, connect across an external resistor.
I_{mod}	Modulation current amplitude.

2.4 Internal switches and adjustments

See appendix E for the location of relevant internal components.

DIP switches

	OFF	ON
1	See below	
2	See below	
3	ac lock	dc lock
4	Single photodiode	Dual photodiode
5	Current bias disabled	Feed-forward current bias
6	Internal error	External error
7	Internal sweep	External sweep
8	STACK normal	STACK via HD1
9	DISC normal	DISC via HD1
10	Current normal	Current via HD7

Switches 1, 2 can be set for several different configurations of feedback to two different piezo actuators. It is assumed that STACK is a wide-range but slow device, such as an NEC-Tokin AE0203D04 stack, while DISC is faster but with smaller range, such as a piezo-electric disc.[1,2]

Switch 1	Switch 2	Operation
OFF	OFF or ON	STACK fast, DISC fixed
ON	OFF	STACK fixed, DISC fast (preferred)
ON	ON	STACK slow, DISC fast

Feedback to the slow actuator STACK can be very slow, to compensate for slow temperature-related drifts, with fast primary feedback to a faster piezo disc. Alternately feedback to STACK can be fast, to provide primary locking feedback. Usually the latter is adequate, and feedback to a second fast piezo is not required.

The last four switches are designed to allow the measurement of separate actuator response functions, using the external error and sweep inputs, or the internal connections described below.

Temperature controller internal adjustments

RT10: Adjust to calibrate active sensors (AD590, 592); located near the $\mathbf{T}_{\text{gain}}$ external trim-pot (see appendix E).

RT12: Maximum TEC current; located near the rear right corner of the main circuit board (see appendix E).

Phase lead

RT9: Adjusts phase-lead of current feedback servo filter.

2.5 Internal connections

HD1	Piezo sweep in
HD7	Current sweep in

These inputs allow direct external drive to the piezo and current channels, nominally for measuring actuator response functions. They are disabled unless DIP switches #9, #10 are on. The external piezo signal is added to the internally generated signal, so that the laser can be locked on the slow channel, while the fast (current) response is measured. Switching DIP switch #10 on, however, disables the internal current feedback. Current modulation can be added, while the laser current is feedback controlled, using the laser head SMA direct input.

Chapter 3

Operation

3.1 Simplest configuration

In the simplest application, MOG will be used to control the diode injection current, and temperature. Thus MOG must be connected to the diode, a thermoelectric (TEC) Peltier cooler, and a temperature sensor (fig. 1.1).

All connections are via the single cable (part #MOG-C-20). A laser head interface board (part #MOG-HC) includes protection relay and passive protection filters, a laser-on LED indicator, and MOLEX connectors for the diode, TEC and sensor (either 10 kΩ thermistor, AD590 or AD592). The laser head board can be fitted to the supplied laser head panel (part #MOG-HP), which replaces the matching panel on Toptica DL100 lasers, or which can be cut to suit other lasers. See appendix D.2 for further information.

To operate in passive configuration:

1. Connect the diode, TEC and sensor to the laser head board (figure 1.1) using the provided Molex 2- and 3-pin connectors. Please note the polarities.
2. Adjust the temperature setpoint: first select **Temp set** on the display selector, then adjust T_{set} via the front-panel trimpot.
3. Ensure the power is on, and the STANDBY/RUN switch is on STANDBY. In this mode, MOG will switch all electronics off, including most of the main internal board, low and high voltage DC supplies, piezo and diode outputs etc. Note that on first power-up, the STANDBY indicator will be red; this is normal. The switch should be set to RUN to initiate temperature control.
4. Switch from STANDBY to RUN. The indicator should change from red (if just powered up), or orange, to green. If the indicator is not green, the TEC or sensor is not correctly wired. In RUN mode, all electronics will be powered up, except for the diode injection current supply.
5. If MOG is switched back to STANDBY, all electronics will be powered down, *except for the temperature controller*, which will continue to operate normally.
6. It may be helpful to adjust the temperature controller response time; that is, the integrator gain, via the rear-panel trimpot labelled T_{gain}, while monitoring the temperature error via CHAN A output and the front panel CHAN A selector switch set to **Temp**.
7. Adjust the current control knob to minimum (fully anti-clockwise).
8. Set the diode maximum current: select **Curr max** on the display selector, then adjust the maximum allowed diode injection current via the rear panel I_{gain} trimpot. Note that with the display set to **Curr max**, a negative sign ($-$) provides a visual reminder that the limit is being displayed rather than the actual current.

9. Switch the laser on with the keyswitch. The indicator on the laser head board should illuminate, and the front-panel indicator above the keyswitch should turn green.

Note that the SCAN/LOCK and fast-channel OFF/LOCK switches must be set to SCAN and OFF respectively. Other protection features will prevent current to the diode, including main cable disconnect, and open circuit on the rear-panel or laser head interlocks.

3.2 Laser frequency control

MOG includes high voltage (100 V) outputs for controlling piezoelectric actuators, designed to control the frequency of an ECDL. These should be connected to the laser head board via the provided MOLEX connectors.

One or two piezo elements can be controlled. Typically, only a single "stack" actuator, such as the Tokin AE0203D04 (available from Thorlabs, www.thorlabs.com), will be required. The single stack actuator allows frequency scanning and frequency offset selection, and active slow (up to $\approx$ 100 Hz) feedback. A second actuator, typically a disc, can be added for faster active feedback control (described below).

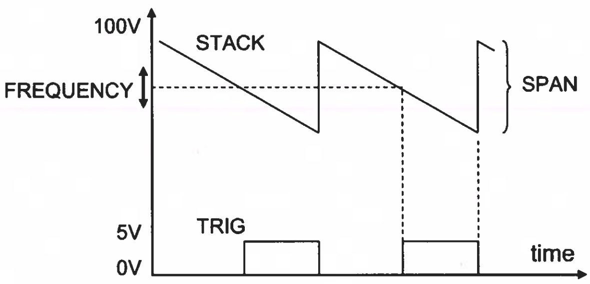


Figure 3.1: Stack output voltage and trigger pulse, when scanning.

In normal (SCAN) mode, a sawtooth is supplied to the the stack (or equivalent). The output is a high-to-low ramp, at frequency of 4 to 20 Hz; see figure 3.1. At the midpoint of the sweep, a trigger (low to high) pulse is output via the rear panel TRIG connection, for synchronising to an oscilloscope or external experiment. Several adjustments are possible:

SCAN/LOCK	The SCAN/LOCK switch should be on SCAN.
FREQUENCY	Sets the mid-point voltage of the ramp.
SPAN	Sets the peak-to-peak height of the ramp. Note that the ramp may saturate at zero or 100 V (see figure 3.1).
BIAS	The BIAS front-panel trimpot controls a feed-forward bias injection current which follows the ramp. The bias current allows wider mode-hop-free scans; see figure 3.1. The bias can be adjusted in a trial-and-error manner to achieve the widest possible scans. BIAS is disabled unless internal DIP switch #5 is ON.
f_{sweep}	The rear-panel f_{sweep} trimpot adjusts the ramp rate from 4 to 20 Hz.

Critical MOG signals can be monitored using the CHAN A and CHAN B outputs on the rear panel, synchronised to the TRIG trigger output. These signals should be connected to a two-

channel oscilloscope as shown in figure 1.4. The particular signals are selected from the front-panel CHAN A and CHAN B selector switches.

3.3 External scan control

An external source can be used to control the laser frequency while in SCAN mode.

1. Connect the external frequency control (ramp, or dc) signal to the rear-panel SWEEP external input.
2. Select the external signal by setting internal DIP switch #7 to ON.
3. Set SCAN/LOCK to SCAN. The FREQUENCY and SCAN knobs will be inactive.

3.4 Locking to an atomic transition: dc

Figure 3.2 shows how a MOG can be used to lock an ECDL to an atomic transition as determined from absorption in a vapour cell. The basic configuration described in section 3.2 is extended with the MOG photodetector (part #MOG-PD), and an atomic vapour absorption cell (not supplied). Alternately, a Fabry-Perot optical cavity or other reference based on intensity variation, could be used.

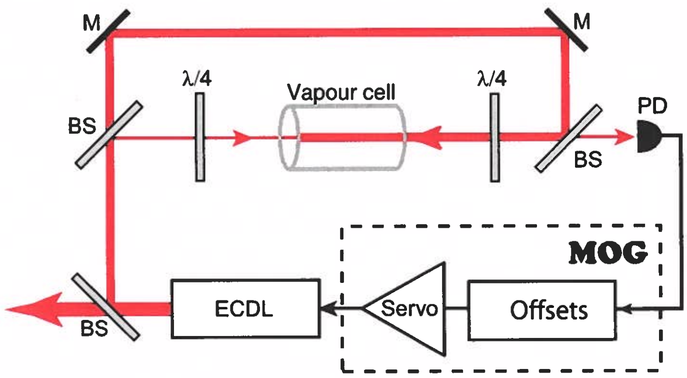


Figure 3.2: Schematic setup for dc locking to an atomic transition. PD is the MOG photodetector. BS beamsplitter, M mirror, $\lambda/4$ a quarter-wave retarder.

The photodetector can be used in single channel mode (default) or with balanced differential inputs, for example to subtract a Doppler background from a saturated absorption spectrum.

Sample oscilloscope traces obtained in dc locking mode are shown below, for wide and narrow spans. These traces were obtained with an 8 cm long Rb vapour cell at room temperature, using a Zeeman modulation coil as described in appendix B.

To operate in dc locking configuration:

1. Select dc locking by setting internal DIP switch #3 to ON.
2. If using differential inputs, set internal DIP switch #4 to ON.
3. Connect the diode, TEC and temperature sensor as above. Also connect a two-channel oscilloscope, as in figure 1.4.
4. Connect the MOG photodetector module using the supplied cable.

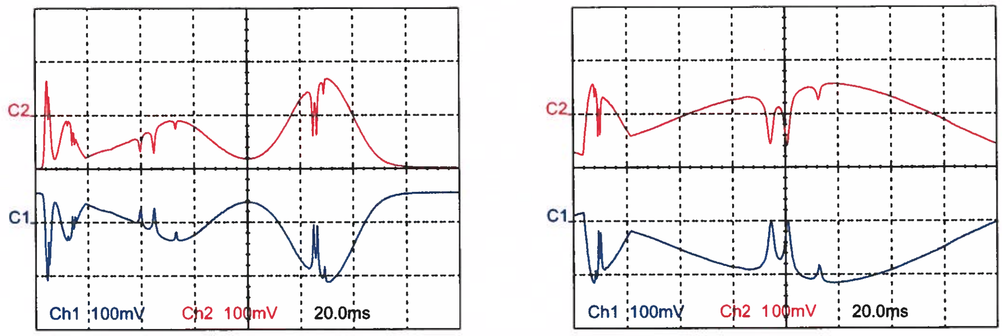


Figure 3.3: Examples of spectra for dc locking, for wide and narrow spans.

5. Using an optical beamsplitter, a stray reflection, or by other means, deflect a fraction of the laser output through the vapour cell. MOG is designed to operate best with about 250 μW incident on each of the Si-PIN photodiodes. MOG is normally supplied with lensed and filtered photodiodes which remove most background light, but best results will be obtained if light from incandescent or fluorescent lamps is minimised.
6. If using balanced inputs, the second light beam should illuminate the second photodiode.
7. Find appropriate absorption feature(s).
8. Adjust front-panel INPUT OFFSET and LOCK OFFSET to obtain a zero-crossing ERROR signal at the desired frequency. Note that the slope should be positive. If it is necessary to lock to a negative slope, the photodetector must be reversed to invert the locking signal.
9. Switch SCAN/LOCK to LOCK.
10. Switch OFF/LOCK to LOCK.
11. Increase SLOW and FAST gains to minimise the error signal, ideally using an external audio spectrum analyser. The gains should be increased until the onset of oscillation, and then reduced.

3.5 Locking to an atomic transition: ac

Figure 3.4 shows a typical setup for ac locking. MOG is particularly designed for Zeeman modulation as described in appendix B. A broad range of modulators can be used instead, for example an external acousto-optic modulator configured as a frequency shifter. In that case, the modulation current drive output should be converted to a suitable potential using a resistor. The current sense resistor is $1\,\Omega$. Thus connecting a $50\,\Omega$ resistor across the modulation output, and adjusting the modulation current (CHAN A set to MOD) to ± 20 mA will produce a voltage of ± 1 V.

Sample oscilloscope traces obtained in ac locking mode are shown below, for wide and narrow spans. These traces were obtained with an 8 cm long Rb vapour cell at room temperature, using a Zeeman modulation coil as described in appendix B.

To operate in ac locking configuration:

1. Select ac locking by setting internal DIP switch #3 to OFF.

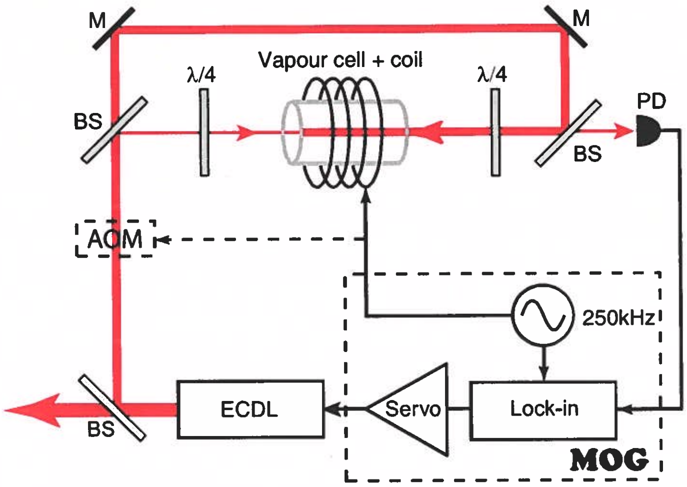


Figure 3.4: Schematic setup for ac locking to an atomic transition. PD is the MOG photodetector. BS beamsplitter, M mirror, $\lambda/4$ a quarter-wave retarder.

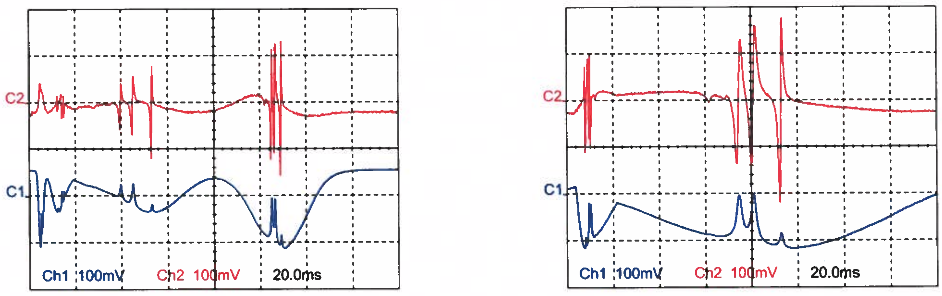


Figure 3.5: Examples of spectra for ac locking, for wide and narrow spans.

2. Connect the diode, TEC and temperature sensor as above. Also connect a two-channel oscilloscope, as in figure 1.4.
3. Connect the MOG photodetector module and optimise the photosignal on CHAN A. MOG is designed to operate best with about 250 μW incident on the Si-PIN photodiode. MOG is normally supplied with lensed and filtered photodiodes which remove most background light, and when ac locking at 250 kHz modulation frequency, any remaining photocurrent from background lighting should not be a problem.
4. Adjust the INPUT OFFSET such that saturated absorption trace is near zero.
5. Switch the modulation on with OFF/MOD.
6. Find appropriate absorption feature(s) and observe the dispersive error signal with CHAN B set to ERROR.
7. Optimise the error signal (usually for maximum slope) by adjusting the front panel PHASE. The error signal slope should be positive at the desired frequency.
8. Adjust front-panel LOCK OFFSET such that the error signal is crossing zero at the desired frequency.
9. Switch SCAN/LOCK to LOCK.
10. Switch OFF/LOCK to LOCK.

11. Increase SLOW and FAST gains to minimise the error signal, ideally using an external audio spectrum analyser (see chapter 4). The gains should be increased until the onset of oscillation, and then reduced.

3.6 Locking using an external signal

MOG can be used for Pound-Drever-Hall[5] or offset locking[7,8], or indeed using a wide variety of externally generated dispersive signals. See appendix C for examples.

To operate with externally generated locking signal:

1. Connect the external error signal to the rear-panel ERROR external input.
2. Select the external locking signal by setting internal DIP switch #6 to ON.
3. Follow the procedure above for dc locking.

Note that actually the external error signal is *added* to the internal error signal, so it may be advisable to switch off the MOG modulator.

3.7 External control of lock frequency setpoint

It is often useful to have external control of the lock frequency setpoint, for example to suddenly change the detuning of a laser.

The rear-panel ERROR external input is *added* to the internally generated error signal. Thus MOG can be used to lock a laser, even with external error enabled via DIP switch #6 ON; see above.

Chapter 4

Optimisation

Laser frequency stabilisation is a complex and ongoing research topic. A thorough treatment would require extensive discussion of control theory, actuator response, mechanical design, laser-atom interactions and electronics. Here we consider the problem from a pragmatic perspective.

The laser is assumed to be moderately stable, operating close to a nominal laser frequency, with a linewidth of a few MHz averaged over a typical measurement time of about one second. The very short-term linewidth is determined by the Schawlow-Townes (S-T) limit, which is probably about 100 kHz. MOG will stabilise the laser frequency to an external reference, usually an atomic absorption feature, and reduce the linewidth as close as possible to the S-T limit.

Achieving the best frequency locking stability and linewidth reduction requires careful optimisation of the signal-to-noise ratio (SNR) of the frequency discrimination signal obtained from the saturated absorption or other reference. Then the phase and gain settings must be optimised, preferably by measuring the feedback error signal spectrum.

4.1 Frequency reference

The frequency reference is critical to MOG performance: MOG cannot reduce the laser frequency noise without an appropriate frequency-dependent reference signal.

MOG has been designed to work with a saturated absorption reference, as shown in figures 3.4 and 3.5. Users should familiarise themselves with saturated absorption spectroscopy, for example as described in Demtröder.[3]

The frequency discriminator ("ERROR") SNR should be optimised to produce large, clear (low-noise) dispersive error signals as shown in the upper trace of fig. 3.5. Factors to consider include:

Probe power The probe power should be about 250 μW. Higher power will increase the photosignal, but the detector saturates at about 1 mW.

Probe intensity The probe intensity should be low to reduce power-broadening. Thus, the probe beam should be expanded to 5 or 10 mm diameter, to allow high power and low intensity (irradiance).

Polarisation The frequency discriminator (ERROR) signal is sensitive to the pump and probe polarisations. Good polarisers and careful alignment can be very helpful.

Coil design The Zeeman modulation coil is discussed in appendix B.

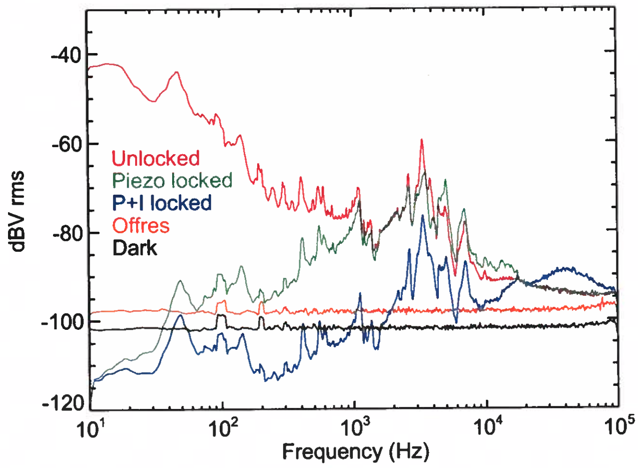


Figure 4.1: Error signal spectra, with laser unlocked, locked with SLOW (piezo) feedback only, and with SLOW and FAST (piezo+current) feedback). The off-resonance and dark noise spectra provide information on the effective noise floor.

Shielding The Zeeman coil produces substantial magnetic fields, oscillating at 250 kHz. These fields can readily induce problematic potentials and currents in the laser head and/or MOG. In particular, it is quite possible to produce a larger frequency modulation from induced currents in the laser diode than from the Zeeman modulation of the reference. It is vital that the coil be located far from MOG and the laser, or that it be shielded. A layer of high-permeability material (soft iron or mu-metal) is probably adequate. To test this, simply reverse the polarity of the coil connection. If the error signal is also reversed, but otherwise similar, then the shielding is probably adequate.

4.2 Noise spectra

The master, slow and fast gains can be set as described in chapter 3, increasing them until the onset of oscillation, and then reducing slightly. If possible, an audio frequency spectrum analyser can be used to provide better guidance. A generic computer sound card with spectrum analysis software gives reasonable results up to 20 kHz. A good sound card (24-bit 200 kHz, e.g. Lynx L22 or E-Mu 1212m) provides low-cost noise analysis up to 100 kHz with 140 dB dynamic range, surpassing most standalone audio spectrum analysers. Connect the spectrum analyser to the CHAN B output, and set the CHAN B selector to ERROR.

You should see curves similar to those shown in figure 4.1. The noise spectra with laser unlocked, and off-resonance, were obtained with MOG operating in scan mode, but with zero span, and the frequency carefully set to an atomic resonance (the highest saturated absorption dip in fig. 3.5), and far off resonance. The latter gives the frequency discriminator noise floor: it is meaningless to try to reduce the laser frequency noise below this level.

With SLOW feedback enabled, the noise for low Fourier frequencies is drastically reduced. A double-integrator is used for slow feedback, such that the suppression is 40 dB/decade. The SLOW gain adjusts the 0 dB gain point; in the figure, this reaches approximately 1 kHz. Higher gains result in oscillation at a frequency corresponding to a pole in the piezo actuator response (i.e. a mechanical resonance).

If MOG is configured to work with the stack actuator only (see section 2.4), then the SLOW feedback will be very slow indeed, suppressing noise only to a few Hz.

FAST feedback adds an additional 20 dB/decade suppression, with 0 dB gain beyond 20 kHz, even as high as 40 kHz, depending on the diode, optical feedback, the frequency discriminator noise floor and other details. Typically we find that the laser diode itself has a 90° phase lag at 15 to 25 kHz. MOG partially compensates for that phase lag with a phase lead compensator.

Ideally, the SLOW and FAST gains should be adjusted to minimise the integrated noise (roughly, the area under the error spectrum). The data in figure 4.1 show a clear "Bode bump" at around 40 kHz, indicating excessive current gain, leaving the laser marginally stable. For lower FAST gain, the Bode bump will be reduced, at the expense of reduced suppression of the mechanical resonance noise peaks around 3 kHz.

Note that the frequency discriminator SNR is only a few dB at higher Fourier frequencies, above 20 kHz. Improvements to the reference, for example using a Fabry-Perot etalon rather than saturated absorption spectroscopy, can provide much greater SNR and correspondingly greater laser frequency noise suppression.

Appendix A

Specifications

Parameter	Specification
Current regulator	
Output current	0 to 200 mA
Maximum diode voltage	5 V
Display resolution	±0.01 mA
Noise	< 200 nA (10 Hz – 1 MHz, rms)
Ripple component (50/60 Hz)	TBA
Stability	Warmup time: 15 minutes
External modulation	SMA 50 Ω, 160 kHz – 500 MHz
BIAS	±10 mA over full sweep
Temperature controller	
TEC current max	±2 A
TEC voltage max	±6 V
TEC power max	12 W
Stability	±5 mK/°C
Sensor	NTC 10 kΩ, AD590, AD592; autodetected
Range	10–30° standard; extended range optional
Display resolution	±0.01°
Piezos	
STACK	0 to 100 V for FREQUENCY stack
DISC	100 ± 20 V feedback
Scan rate	4 to 20 Hz
Photodetector	
Photodiodes	Si-PIN, IR filtered 740 nm – 1100 nm, 1 × 1 mm sensor Lensed, ±10 ° field of view Options: unfiltered 400 nm – 1100 nm, ±20 °, ±70 °
Coupling	ac and dc, single or differential
Diode separation	10 mm
Bandwidth	1 MHz
Dimensions	25 × 25 × 60 mm

Parameter	Specification
Feedback system	
MOD OUT	250 kHz, ±10 V, ±250 mA via I_{set} rear-panel trimpot Current output (1 Ω sense)
PHASE	0 to 360° (min)
INPUT OFFSET	0 to −10 V
LOCK OFFSET	±0.5 V
GAIN	MASTER ±20 dB SLOW MASTER ±20 dB FAST MASTER ±20 dB
Bandwidth (gains all at midpoint)	SLOW 0 dB at 700 Hz FAST 0 dB at 80 kHz
Protection and status	
External interlock	2.5 mm dc power plug (provided)
Laser head enclosure interlock	2-pin molex connector (provided)
Key switch interlock	Diode current OFF/ON
Delayed soft-start	1 s delay + 0.5 s ramp
Open circuit detect	Laser cable, TEC
Diode current limit	Rear panel trimpot I_{max}
STANDBY/RUN LED	RED AC mains power on ORANGE Standby (temperature controller on) GREEN Fully operational (piezo, current,ramp)
STATUS LED	RED Start sequence error or fault (usually SCAN/LOCK on LOCK, or current lock OFF/ON is on) ORANGE Ready GREEN Diode running
Mechanical & power	
DISPLAY	4.5 digit LED; standard colour yellow
FAN	12 V dc ball-bearing Temperature controlled (45° on, 40° off)
IEC input	110, 120, 220, 230, 240 V, 50 to 60Hz
IEC output	Common ground with power input Intended for oscilloscope; 1 A max
Dimensions	Standard 2U 19", WxHxD = 422 × 84 × 200 mm
Weight	4.3 kg (excluding cables, laser head board, photodetector) 7 kg shipping

Appendix B

Modulation coils

MOG is designed to lock to an atomic transition, particularly using ac locking where the atomic reference is modulated. This can often be achieved at low cost using a solenoid coil wrapped around an atomic vapour cell, as shown in the photo below.

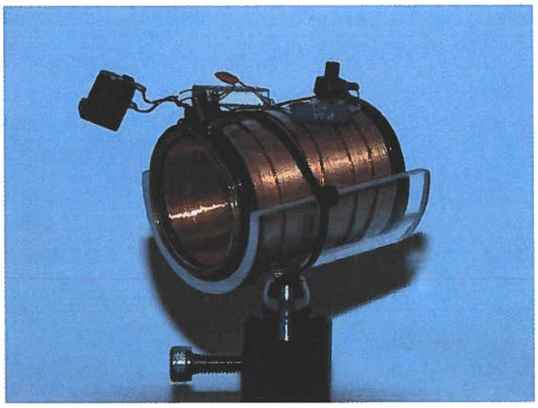


Figure B.1: Vapour cell, Zeeman coil, and primary excitation coil.

B.1 Field requirements

Ideally the Zeeman dither coil should produce a frequency shift of about half the peak width, typically a few MHz. Atomic "stretched" state transitions will be Zeeman shifted by one Bohr magneton:

$$\mu_B = e\hbar/2m_e = 1.4\,\mathrm{MHz/Gauss} \tag{B.1.1}$$

so we need fields of around one Gauss (10^{-4} Tesla). The magnetic field inside a long solenoid is

$$B = \mu_0 n i \tag{B.1.2}$$

where n is the number of turns per unit length and i the current. For wire diameter 0.4 mm, $n = 2500\,\mathrm{m}^{-1}$, and the current requirement is only $22\,\mathrm{mA/MHz}$.

B.2 Coil impedance

However, driving an oscillating current through a coil is problematic because the impedance grows with the frequency. The impedance is given by $X_L = \omega L$ where ω is the radial frequency and L the inductance. The inductance for a long solenoid is

$$L = \mu_0 n^2 A l \tag{B.2.1}$$

where A is the cross-section area of the coil (πr^2 for a circular cross-section) and l is the coil length. In practice, the inductance will be less (e.g. see Wheeler[4]):

$$L_{\text{Wheeler}} = \frac{N^2 r^2}{228r + 254l} \qquad \text{(mH)} \tag{B.2.2}$$

where N is the total number of turns, r is the coil radius in metres, and l is the length in metres ($l > 0.8r$). We have found that for dimensions typical of coils wound around vapour cells, these two formulae agree within a factor of two.

Note that the inductance increases with n^2 (or N^2) whereas the magnetic field and hence modulation depth grows with n; thus for our purposes, we generally prefer small n and large currents. On the other hand, the driving voltage requirement (the "back emf") is given by

$$\epsilon = -L di/dt \qquad \epsilon_{\text{max}} = L i_0 \omega \tag{B.2.3}$$

for a sinusoidal current of amplitude i_0. The required output slew rate is

$$dV/dt = -L d^2 i/dt^2 \qquad \text{Max} \equiv L i_0 \omega^2. \tag{B.2.4}$$

MOG operates at $\omega = 250\,\text{kHz}$. For a cell of length 8 cm, 0.4 mm wire, and 20 mA, we find $L_{\text{Wheeler}} \approx 650\,\mu\text{H}$, and $\epsilon_{max} = 20\,\text{V}$, and the maximum slew rate is $32\,\text{V}/\mu\text{s}$.

MOG does not have that direct output capability. Reducing n helps: inductance, and thus ϵ and dV/dt fall with n^2 while the frequency modulation depth falls with n. Thus a coil of about 40 turns ($500\,\text{m}^{-1}$) and current amplitude of 150 mA should result in a modulation depth of 1.3 MHz. However, we prefer to use a two-coil impedance matching arrangement to increase the modulation depth at smaller currents.

B.3 Impedance matching

MOG can drive up to ± 0.25 A and ± 10 V, with a slew rate of $6\,\text{V}/\mu\text{s}$. This can be impedance-matched to a high current coil using a transformer, or quite effectively by directly winding a primary on the main Zeeman coil, as shown in the photo above.

For the main Zeeman coil, we typically use 0.4 mm or 0.6 mm diameter wire wound around our vapour cell, about 120 to 200 turns. The coil is "balanced" for the MOG modulation frequency of $\omega = 250\,\text{kHz}$ using a capacitor. The coil is excited inductively by a primary, about five to ten turns, connected directly to MOG (see figure).

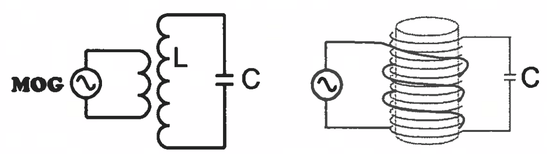


Figure B.2: Circuit diagram for Zeeman coil and excitation coil. Typically the primary is 5 to 10 turns, and the secondary 120 to 200 turns.

The capacitor should be chosen such that the capacitive impedance equals the inductive impedance. That is,

$$\omega L = \frac{1}{\omega C} \qquad C = \frac{1}{\omega^2 L}. \tag{B.3.1}$$

Using the long-solenoid equation for inductance, we can predict

$$C \approx \frac{2}{\omega^2 \mu_0 n^2 A l} \tag{B.3.2}$$

although in practice we find that about half that value is closer, typically about 1 to 2 nF. with this arrangement, energy is stored in the inductor-capacitor "tank", and MOG need only drive a small current (e.g. 50 mA peak-to-peak) to compensate for losses.

WARNING! The potential across the secondary Zeeman coil can easily be hundreds of volts! Please ensure that your coil and capacitor do not have exposed connections! Also be sure to use capacitors with adequate voltage rating.

B.4 Tuning

To maximise the current in the secondary, the capacitor should be chosen to tune the circuit to the MOG modulation frequency. Drive the coil with a function generator and measure the magnetic field with another independent coil (e.g. 20 turns of fine wire on a 1 cm diameter former) connected to an oscilloscope. Adjust the capacitor by adding or removing small capacitors in parallel, until the field is maximum at 250 kHz.

Again, be sure to use capacitors with sufficient voltage rating: you can measure the voltage when the primary is driven by MOG at high current.

In some cases the Q of the circuit may be *too* high, such that a series resistor of about 0.5 ohm (as seen in photo B.1) can result in increased current at 250 kHz, and reduced sensitivity to frequency drifts.

B.5 Shielding

Large magnetic fields oscillating at 250 kHz can readily cause problematic electromagnetic interference (EMI). Induction in the laser head or the cable to the laser head can easily produce substantial diode current modulation. The coil (and vapour cell) should be located far from the laser and from MOG, or shielded with soft iron or a high permeability alloy such as mu-metal or Conetic. We find that a tube made from thin (0.25 mm) sheet mu-metal, about 50% longer than the cell and coil, is adequate.

Appendix C

External modulators and injection current modulation

MOG is designed for ac locking a laser to an external reference such as an atomic resonance or an optical cavity. In many cases it is convenient to use the MOG internal modulator driver, and Zeeman modulation of an atomic transition, as described in appendix B. Zeeman modulation is not always possible (e.g. if the reference is an optical cavity), or desirable (e.g. due to magnetic interference). MOG can dither the laser diode injection current via the SMA connector on the laser head board, or drive an external phase modulator, such as an electro-optic modulator (EOM) or acousto-optic modulator (AOM).

C.1 Coupling circuit

MOG provides a current-controlled modulation output. Normally some impedance-matching will be needed to drive an external modulator, and typically a dc level shift. The circuit below provides these functions, specifically for rf amplifiers used for AOMs such as the D323B from ISOMET.

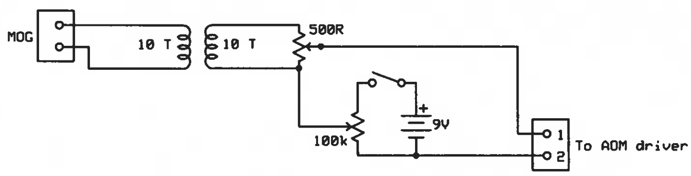


Figure C.1: Coupling from MOD OUT to an external modulator.

The ISOMET D323B rf driver has a frequency control input with 4 to 17 V range. We ac couple MOG using a simple 10T:10T ferrite bead transformer. Primary and secondary were wound with 10 turns of PVC-insulated hookup wire around a ferrite bead approximately 15 mm diameter. A 500 Ω potentiometer allows control of the modulation amplitude, and a 9 V battery and 100 kΩ potentiometer provide a dc shift to set the centre modulator frequency. The latter allows frequency offset control of the modulated light beam.

C.2 Injection current modulation

The circuit above can be connected directly to the SMA modulation input on the laser head board, though further attenuation (e.g. 50 dB) will make it easier to adjust the dither amplitude. Use a resistive divider or simply add more turns to the MOG primary. Note that the SMA input is ac coupled and hence the dc offset is superfluous.

MOG can also be used with high frequency modulation (e.g. 10 MHz) to achieve very narrow linewidths, for example for phase locking two lasers. The diagram below shows an arrangement that we have used to demonstrated relative linewidths below 20 kHz.

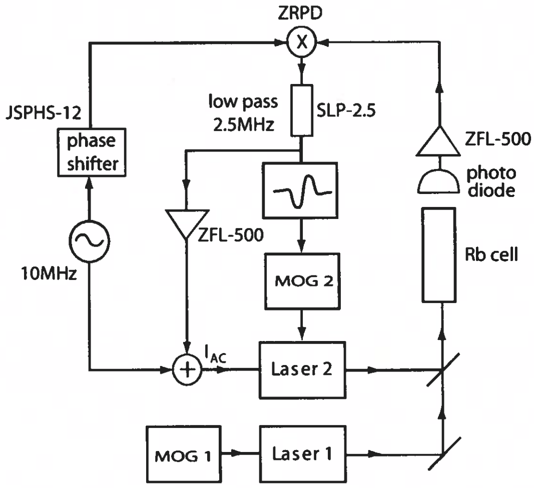


Figure C.2: High bandwidth locking based on PDH sideband demodulation.[5] Laser 2 is locked with high bandwidth, relative to laser 1, using electromagnetically induced transparency as a dispersive reference.

Laser 1 is locked to the $5^2S_{1/2}F = 3 \rightarrow 5^2P_{3/2}F = 3$ transition of ^{85}Rb using Zeeman modulation, as in section 3.5. Laser 2 is tuned to the $F = 2 \rightarrow F = 3$ transition and modulated at 10 MHz. The two lasers copropagate through a Rb vapour cell and onto a photodiode. An electromagnetically induced transparency provides a dispersive reference. A frequency error signal is obtained by Pound-Drever-Hall demodulation[5]. The error signal is returned to the external error input on MOG 2, which locks the laser with bandwidth up to about 40 kHz. The error signal is also combined with the 10 MHz modulation using a passive bias tee, and directly injected into the SMA modulation input, to provide feedback bandwidth up to at least 100 kHz.

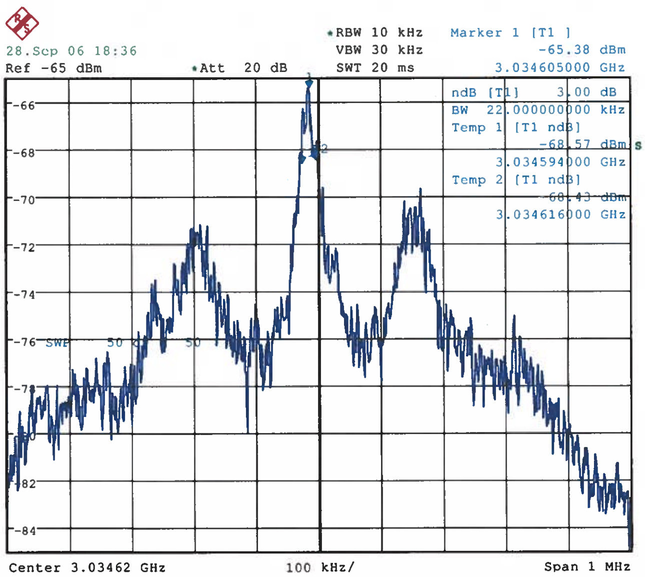


Figure C.3: rf beatnote from two MOG-locked lasers. The -3 dB peak width is 22 kHz with a spectrum analyser RBW setting of 10 kHz.

Appendix D

Photodetector and laser head board

D.1 Photodetector

The MOGlabs photodetector is shown in the images below. It can be used as a single detector (left photodiode, seen from front), or as a differential pair, via internal MOG DIP switch #4. The photodetector is connected to MOG via the rear socket and cable provided. It will normally be mounted with a standard post to the M4 or 8-32 thread on the bottom.

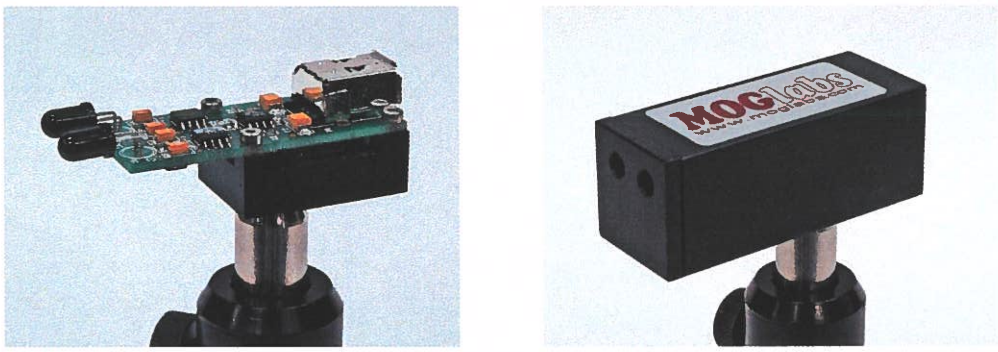


Figure D.1: MOG balanced differential photodetector.

The detector can also be mounted vertically to conserve bench space, using the M4 thread just below the socket at the rear of the detector. To use in the latter configuration, it may be preferred to drill two 5 mm diameter holes in the side of the shell opposite the mounting holes, and bend the photodiode leads to reorient the diodes appropriately (see figure D.2).

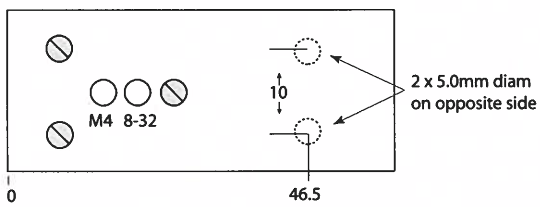
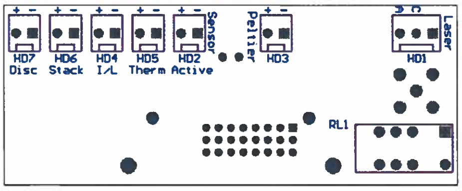


Figure D.2: Location of M4 and 8-32 mounting holes, and suggested location of photodiode holes for vertical mounting.

D.2 Laser head board

The laser head interface board (part #MOG-HC; image below) provides convenient 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.

MOLEX connectors are supplied for the diode (3-pin), TEC and sensor (either 10 kΩ thermistor, AD590 or AD592), interlock, and piezo actuators (2-pin). The laser head board can be fitted to the supplied laser head panel (part #MOG-HP), which replaces the matching panel on Toptica DL100 lasers, or which can be cut to suit other lasers.



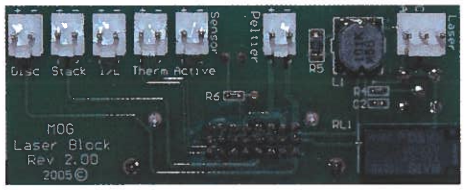
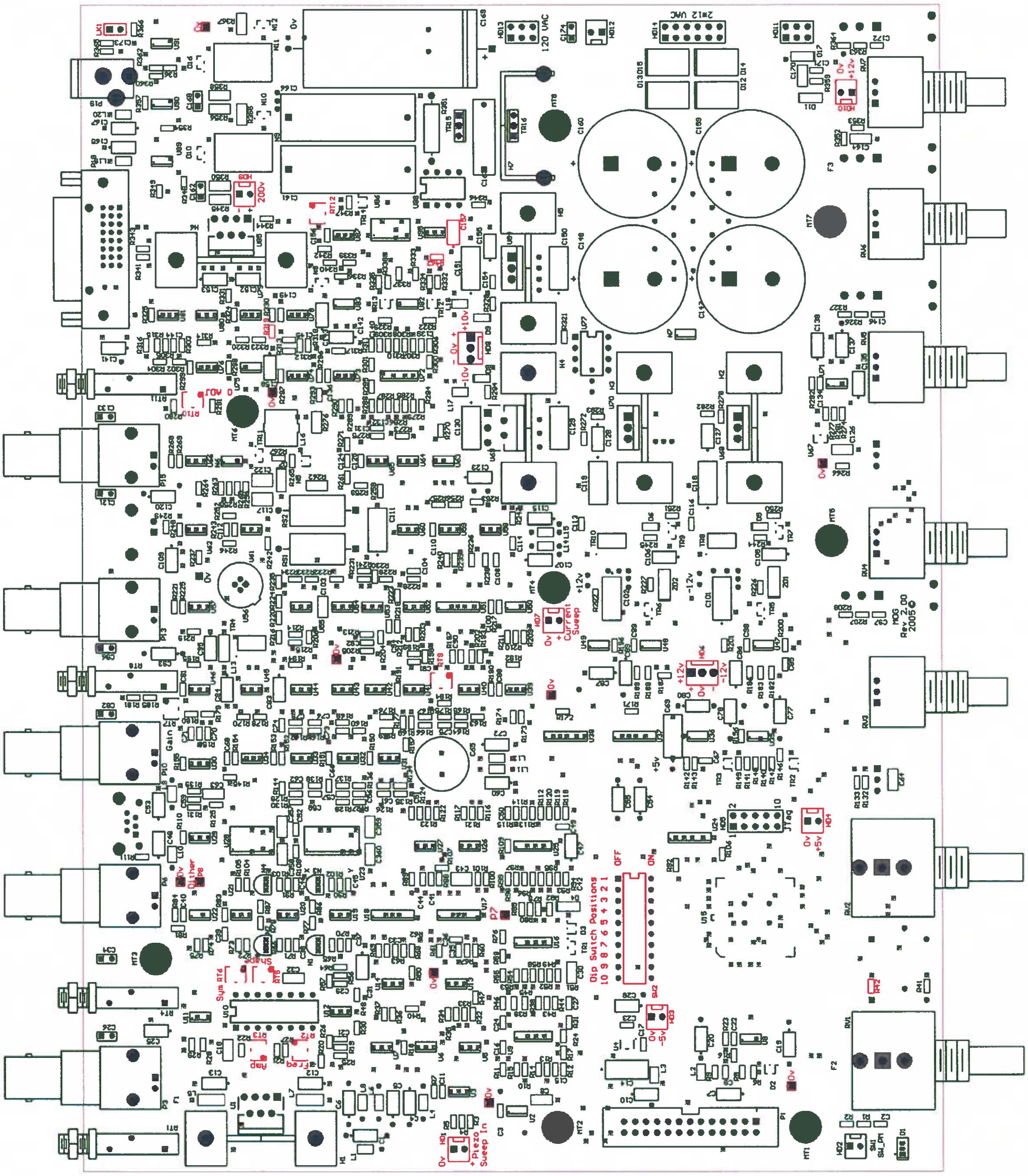


Figure D.3: MOG laser head board showing headers for connection of laser diode, piezo actuators, temperature sensor, TEC and head enclosure interlock.

Appendix E

PCB layout



Appendix F

Known limitations

dc lock polarity MOG was designed for ac locking, where the slope of the error dispersion curve can be reversed using the PHASE control. When dc locking, or when using an externally generated lock signal, PHASE has no effect, and there is no control to change the polarity of the SLOW feedback. Thus locking is possible on a positive slope only. To lock to the other side of a peak, it is necessary to reverse the light beams to the two photodiodes on the photodetector when using it in differential mode, or use the other photodiode if operating in single-photodiode mode, or invert the externally generated lock signal.

Piezo polarity It is assumed that the stack actuator (STACK) increases the external cavity length with increasing voltage, while the disc actuator (DISC) will reduce the cavity length, and that the laser frequency increases with shorter cavity. The ramp only operates high-to-low voltage for scanning, corresponding to increasing frequency.

When operating with three-channel feedback, using both piezo actuators, the relative polarity of the two piezo elements cannot be altered. If the actuators are not "opposite" in their effect, only one piezo can be used for locking.

Current limit The current limit adjust, I_{set} should not be used as a current control. As the actual diode current approaches the limit, the current can become unstable, oscillating between set current and the limit (but does not exceed the limit). In addition, the display reading of the current limit will change as the actual current approaches the limit. Thus, to operate the diode at, say, 140 mA, the current limit should be set to 150 mA or higher.

Appendix G

User modifications

Temperature controller

To increase the setpoint range from the default 10 – 30°C, adjust R41 and R42.

R41: Normally 10 k; can be short-circuited to allow temperature setpoint up to 50°C.

R42: Normally 4k99; can be short-circuited to allow temperature setpoint down to 0°C.

RT10 should be adjusted to calibrate active sensors (AD590, 592). Set the sensor to a known temperature and adjust **RT10** such that the temperature reads correctly.

RT12 should be adjusted to set the maximum TEC current. Standard MOG units can drive up to approximately 1.8 A if RT12 is set to the maximum (fully CW).

R312: PID proportional gain resistor, nominally 1 M; reduce to 10 k for lasers with large thermal capacity, e.g. those using the Toptica (Ricci/Hänsch) design.[2]

R319: PID integrator feedback resistor, nominally 470 k. Charges a 10 μF feedback capacitor; increase to 1 M for lasers with large thermal capacity, e.g. those using the Toptica (Ricci/Hänsch) design.[2]

Current feedback

The feed-forward current bias of older versions of MOG had limited (1 mA) range. The range was increased to 10 mA, but in some versions the current feedback saturated at too low a value.

For correct 10 mA feed-forward bias range, and full current saturation limit, the following resistor values are required:

Resistor	Old value	Correct value
R216	10 k	1 k
R220	10 k	1 k
R230	100 k	10 k

To reduce the range of piezo scan while maintaining the feed-forward bias, a resistive divider can be added. For example, a 5 k resistor from pin 3 of of U13 to ground.

Fan temperature setpoint

The MOG cooling fan is triggered by the temperature of an LM56 sensor, U63, located near the main heatsinks H1 and H2. The trip temperature is determined by resistors R426,7, originally both 10 k (though the LM56 datasheet recommends that the sum of the two is nominally 27 k). Note that these resistors are on the bottom side of the main board.

The resistors can be determined from

$$R_{426} = R_{\text{sum}}(0.0062T + 0.395)/1.25V_T$$
$$R_{427} = R_{\text{sum}} - R_{426}. \qquad \text{(G.1.1)}$$

Temperature	R426	R427
37°C	13.5 k	13.5 k
"	10.0 k	10.0 k
45°C	11.8 k	10.0 k
60°C	16.6 k	10.4 k
"	12.3 k	7.7 k

Piezo and current signal outputs

The final current feedback signal, including bias feed-forward and error servo, can be measured at pin 7 of U53.

Test point P7 provides the ramp voltage, via an opamp buffer.

The fast feedback error signal is output on pin 7 of opamp buffer U52.

The slow feedback is pin 1 of opamp buffer U14 but should be accessed only after R37, a 43 R resistor.

The final stack voltage (ramp during scanning, or error when locked), is on pin 6 of U90, which also then goes through a 43 ohm resistor, R360.

rf modulation

The SMA input on the laser headboard can be used for modulation up to 500 MHz. The input impedance becomes too large at high frequencies, in large part because of the PCB layout and materials.

The low-frequency limit is determined by the ac impedance of the diode (typically 100 to 300 Ω), and the series capacitor C2 on the headboard, originally 10 nF (160 kHz) and later, 100 pF (16 MHz). If C2 is shorted, take care that the modulator does not present a dc load which will draw current away from the diode.

We sometimes use 1 μF (1.6 kHz) when adding external PDH feedback (appendix C), though this might be better replaced with 33 nF (16 kHz with 300 ohm diode impedance).

Interlock

Link LK1 (rear right of main board) can be shorted internally to avoid requirement for external interlock.

Phase lead

The current feedback servo filters include a phase lead component which can be adjusted via **RT9**.

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