moglabs
a santec company

Combined tapered amplifier and linear cavity doubler

Model MSHG

Revision 1.00

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Preface

The MOGLabs MSHG combines an external cavity diode laser (ECDL), a MOA tapered amplifier and an MSL linear cavity doubler into a single self-contained system. The MSHG can provide up to 1.5 W of frequency-doubled light in the range of 370–650 nm, for applications including optical lattice clocks, atom cooling, Bose-Einstein condensation, ion trapping, and quantum technology.

The linear second harmonic generation (SHG) cavity is inherently stable and insensitive to vibration, with no adjustability of the cavity alignment required. SHG conversion efficiencies of up to 60% can be achieved with freespace input from the tapered amplifier beam. Fibre coupling is available for both harmonic and secondary seed laser output, with typical fibre coupling efficiencies for the harmonic wavelength of 70% or higher.

The ECDL seed provides a robust, stable, low linewidth and highly tunable laser system, and a secondary output is included for monitoring or external locking of the seed laser fundamental frequency. The MOA then allows for amplification of the laser output power by up to 400 times (+26 dB) while maintaining the linewidth and optical spectrum of the seed input.

The MOGLabs MSHG includes the internal MOGLabs mLC electronics for spanning and locking the SHG cavity to resonance. Standard locking is using a piezo modulation and demodulation method (FM-demod), but Pound-Drever Hall locking is also available.

Please let us know if you have any suggestions for improving our products or this document, so that we can make life in the lab better for all.

MOGLabs, Melbourne, Australia
www.moglabs.com

Safety Precautions

Your safety and the safety of your colleagues depends on careful attention to proper operation of this product. Please read the following safety information before attempting to operate. Also please note several specific and unusual cautionary notes before using the MOGLabs MSHG, in addition to the safety precautions that are standard for any electronic equipment.

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

Light output from the MSHG can be dangerous. Please ensure that appropriate hazard minimisations have been implemented for your environment, such as laser safety goggles, beam blocks, and door interlocks.

- Avoid direct exposure to beams from the seed laser. tapered amplifier or the harmonic output. Avoid looking directly into any of these beam.
- The laser chassis should be in good electrical contact to the optical table or other surface, which in turn should be connected to the mains power supply electrical ground.
- Note the safety labels (examples shown in figure below) and heed their warnings.
- The MOGLabs MSHG is designed for use in scientific research laboratories. It should not be used for consumer or medical applications.

Label identification

The International Electrotechnical Commission laser safety standard IEC 60825-1:2023 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. Figures 1 and 2 show examples of these labels and their location on the MSHG.

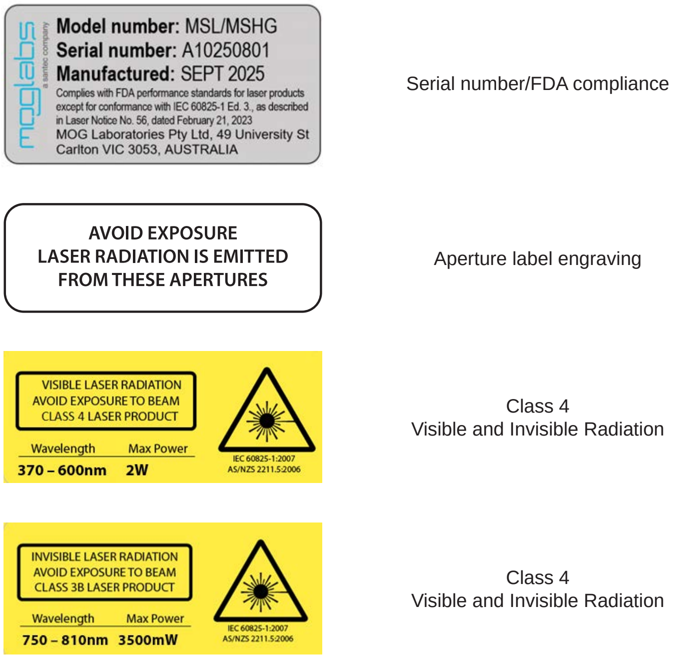

Figure 1: Warning advisory and US FDA compliance labels.

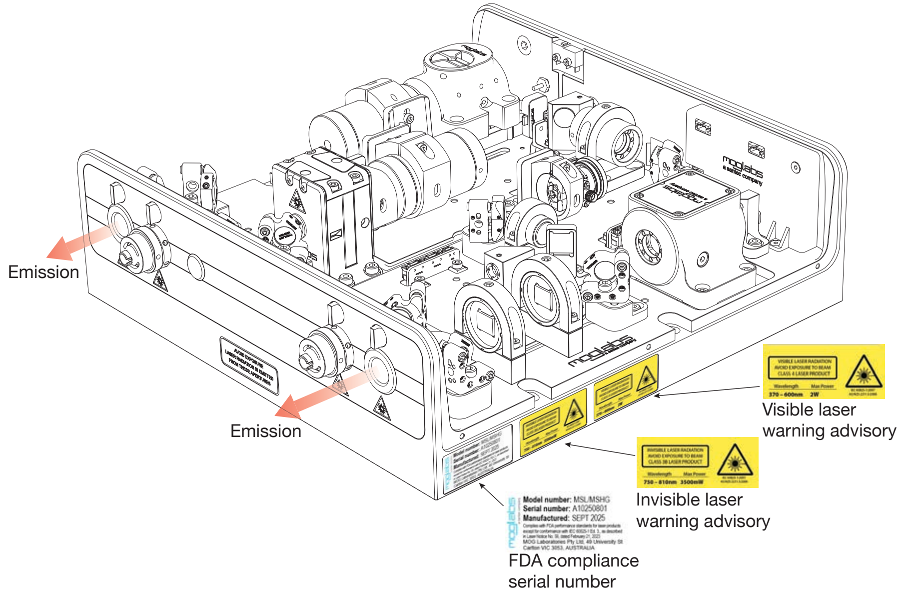

Figure 2: Schematic showing location of warning labels compliant with IEC 60825-1:2023 and the US FDA, and engraved emission warning.

Contents

1. Introduction

The MOGLabs MSHG combines an external cavity diode laser (ECDL), a MOA tapered amplifier and an MSL linear cavity doubler into a single self-contained system.

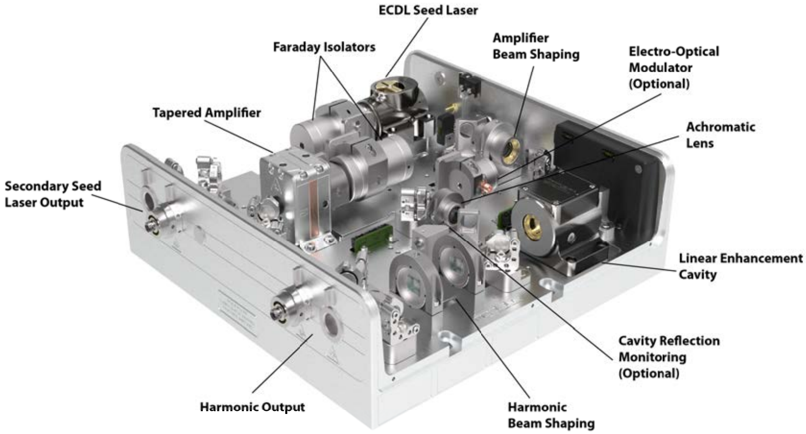

Figure 1.1: Render of the MSHG with ECDL seed, tapered amplifier and linear enhancement cavity. Beam-shaping on amplifier output and an achromatic lens on cavity input ensure optimal mode-matching between the amplifier beam and the linear enhancement cavity. An electro-optical modulator and pickoff mirror/photodiode for monitoring the cavitry reflection may optionally be included for locking the cavity via a Pound-Drever-Hall method. Beam-shaping lenses on cavity output are used to collimate the harmonic beam and correct for astigmatism. Harmonic output of the cavity and secondary seed laser output can be configured for freespace, fibre-coupled or dual-output schemes.

1.1 Seed laser

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. 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. An *external* cavity is constructed by placing a reflective optic in the beam path which then provides feedback into the laser diode.

A MOGLabs ECDL uses either a cateye reflector (MOGLabs CEL) or grating (MOGLabs LEL) to provide this external feedback, and the MSHG can be configured with either of these seed laser designs. When the external feedback is greater than that of the front diode facet, the external cavity determines the lasing wavelength. As shown in Figure 1.2, the net gain is the product of semiconductor gain, grating or filter response, and internal and external cavity interference.

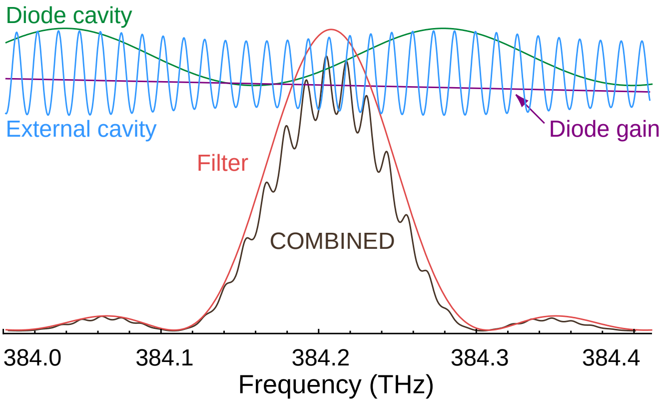

Figure 1.2: Schematic representation for the various frequency-dependent factors of a CEL, adapted from Ref. [1], for wavelength $\lambda = 780\,\mathrm{nm}$ and external cavity length $L_{\mathrm{ext}} = 15\,\mathrm{mm}$. Note that for a MOGLabs LEL a grating is used to provide wavelength selectivity instead of a filter.

1.2 Tapered amplifier

The TA diode is mounted in a block (U-chassis) with aspheric input and output lenses in flexure $x - y$ translation stages (Figure 1.3). The flexure mounts control the transverse positions of the input (focusing) and output (collimation) lenses, providing precise lens alignment with mechanical stability. Finely threaded tubes control the lens positions along the axis of propagation. The U-chassis allows simple user replacement of the TA diode; please contact MOGLabs support for further information about this process if required.

The TA diode emits from both input and output facets. Emission from the input-side waveguide can be used for seed laser alignment. A tapered engraving on the side of the U-chassis shows the TA diode orientation, with the small area ridge waveguide on the input side and large area tapered waveguide on the output side. The input lens focuses the seed laser onto the input waveguide of the TA diode. The output lens collimates the amplified TA laser beam emitted from the output waveguide.

For detailed background information on tapered amplifier diodes, please see Refs. [2, 3].

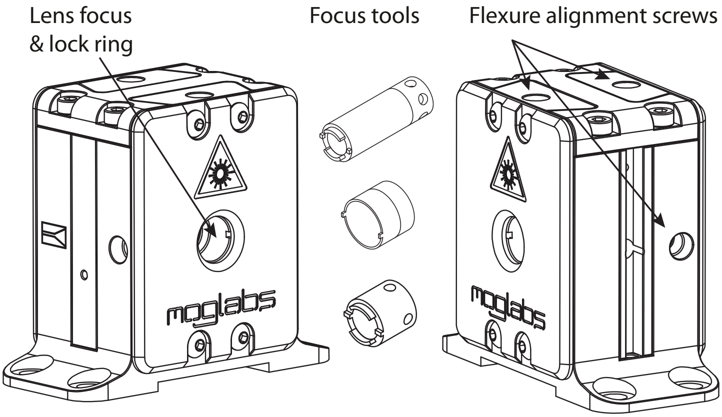

Figure 1.3: TA diode block (U-chassis), showing flexure alignment and focus adjustments for input and output lenses and tools for focus adjust and locking.

1.3 Linear doubling cavity

The SHG component of the MSHG combines a non-linear crystal with a linear enhancement cavity to efficiently generate frequency-doubled light. The cavity length is adjusted with a piezoelectric transducer, for scanning the cavity and to lock the cavity resonance to the input laser wavelength using the built-in photodetector and servo electronics. The cavity temperature is stabilised with a thermistor sensor and Peltier thermoelectric cooler (TEC). Fibre coupling options are available for the harmonic output.

The MOGLabs MSHG optical enhancement cavity uses a linear rather than traditional bow-tie configuration, for five key reasons:

1. The linear cavity consists of only two mirrors rather than four, reducing mirror-related losses.
2. Optical alignment is less critical, and kinematic adjustment of the mirrors and crystal are not required.
3. The absence of kinematic mounts makes the cavity insensitive to vibration and mechanical disturbance.
4. The cavity is rotationally symmetric, so the fundamental cavity mode is circular and non-astigmatic.
5. The cavity is very compact, with a large free spectral range and cavity linewidth compared to a conventional bow-tie design. The large linewidth improves locking stability and reduces amplitude noise.

1.4 Optical layout

The standard MSHG configuration is shown in Figure 1.4. In normal operation, the seed laser should provide a collimated beam which propagates through a Faraday isolator (we recommend $\geq$ 60dB isolation) and is deflected by mirrors M1 and M2 into the TA diode. M1 is a fixed beam splitter (or polarising beam splitter (PBS) with a half-wave plate before the PBS) to pick off a fixed (or variable) secondary seed laser output, which can be used for locking to a frequency reference or monitoring the seed laser.

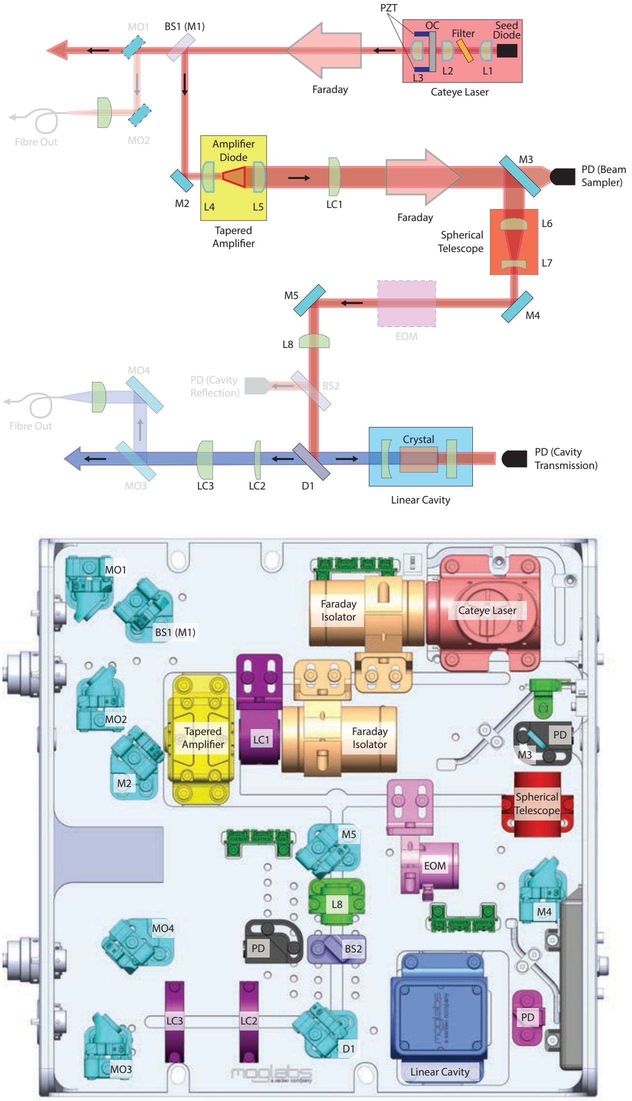

Figure 1.4: Schematic (top) and layout (bottom) diagrams of the MSHG, showing all Faraday isolators, mirrors (M), optional mirrors (MO), beam-splitters (BS), lenses (L), cylindrical lenses (LC) and photodiodes (PD). Further descriptions of the role of each component can be found in the text. Note that these diagrams show a CEL seed laser, but the MSHG can also be configured with a MOGLabs LEL seed.

Mode-matching between seed laser beam and TA diode is optimised by ensuring that the reverse propagating TA beam, emitted from the small area ridge waveguide side of the TA back towards M1 and M2, is overlapped with the seed beam propagating towards the TA. Lens L4 on TA input is optimised such that seed and reverse propagating TA beams have similar beam size along their paths, and a half-wave plate on output of the first Faraday isolator for matching seed polarisation to the TA diode.

Cylindrical lens LC1 provides an astigmatism correction for the TA output, and a second Faraday isolator (we recommend $\geq$ 60dB isolation) protects the TA diode from high-power reflections from the linear enhancement cavity. A photodetector (PD) mounted behind M3 monitors the TA output to ensure that the amplifier diode is properly seeded at high operating currents (see Chapter 4 for further information).

A spherical telescope (L6 & L7) and achromatic lens (L8) shape and focus the amplifier output beam to optimise mode-matching with the fundamental resonant mode of the linear cavity. The incoming beam reflects from dichroic mirror D1 to a waist at the flat cavity mirror. A PD positioned behind the cavity monitors light transmitted through the cavity, which is used for cavity alignment and frequency modulation-demodulation (FMDM) locking.

The second harmonic generated (SHG) in the non-linear crystal is transmitted by the curved cavity input coupling mirror. The SHG beam is collimated by orthogonal cylindrical lenses LC2 & LC3 which allow correction of astigmatism and ellipticity.

Fibre coupling for both the harmonic and secondary seed output can be installed upon request, using mirror pairs MO1 & MO2 and MO3 & MO4 respectively with fibre couplers installed at the relevant output ports. MO1 and MO3 can also be replaced with partially-reflective mirrors or beamsplitters for dual output configurations.

Cavity locking using a Pound-Drever-Hall (PDH) scheme is also available upon request, using an electro-optical modulator (EOM) installed between M4 and M5. In this locking configuration, a pickoff beamsplitter (BS2) is installed between M5 and D1, which allows for the reflected cavity to be monitored upon an additional PD.

Cavity scanning, locking and temperature are controlled by the MOGLabs mLC electronics fully contained within the MSL chassis. A USB-C port provides power for the MSL system, which is operated through the USB-C or the twisted-pair LAN (TCP/IP) port.

2. First light

2.1 Basic setup

1. The MSHG should be firmly mounted to an optical table or other stable surface. Mounting holes can be accessed by removing the cover, then M6 (or 1/4-20) socket head cap screws can fix the device to the optical table. The hole spacing allows direct mounting to metric and imperial tables.

2. The MSHG chassis should be in good electrical contact to the optical table or other surface, which in turn should be connected to the mains power supply electrical ground.

3. If necessary, connect water cooling using the quick-fit connections provided (for 4 mm OD tubing by default and 6 mm OD on request). For most applications, water cooling is not required, but may be helpful if operating at unusually high or low temperatures, or in laboratories with poor temperature regulation.

4. The exit apertures for both harmonic and secondary seed laser output should be blocked with suitable power sensors or beam dumps.

5. Connect the seed laser head to a MOGLabs dDLC controller and the amplifier head to a MOGLabsLDD controller.

2.2 Seed laser

1. Turn on mains power to the MOGLabs dDLC controller. Briefly wait for the controller to initialise, and then turn the keyswitch from STANDBY to RUN. The LED status indicator should initially be yellow (indicating that the thermistor and TEC elements are connected), then change to green when set to RUN. Wait for the seed laser temperature to stabilise to the setpoint, which should match the specified setpoint value in the seed laser test report.

   - If the LED status indicator does not turn green, or if the temperature does not stabilise within 5 minutes, please contact MOGLabs support.

2. Set the seed laser injection current to a very low value (5-10mW), and enable the seed current (push-button on the dDLC). Check the diode voltage (found under the ”Laser” menu on the dDLC display) and ensure that it is below the ”Maximum compliance voltage” specified in the seed laser test report.

   - If the voltage measured by the controller exceeds the specified maximum, check that all connections between dDLC, laser headboard (DVI nuts in particular) and diode are secure. If all connections are secure and the diode voltage remains abnormally high, please contact MOGLabs support.

3. Insert a power sensor between the seed laser barrel and the first Faraday isolator. Set the seed laser injection current to 10mA above the laser threshold (the injection current at which 1mW output occurs) specified in the seed laser test report, and measure the output power of the seed laser. Verify that the measured threshold of the seed laser matches the value specified in the test report within ±10mA.

   - If the measured laser threshold differs from the value specified in the test report by more than 10mA, please refer to the ”Threshold Optimisation” procedure specified in the seed laser operating manual. If the expected threshold cannot be restored after following these instructions, please contact MOGLabs support.

4. Increase the seed laser injection current to the ”tuned wavelength set current” specified in the seed laser test report. Measure the laser output power immediately before and after the Faraday isolator on seed output, and confirm that these values match (within ±5mW) the powers expected at this injection current specified in the test report.

- If the measured laser power at the set current differs from the test report data by more than ±5mW, please contact MOGLabs support.

5. **Fibre coupled seed output only:** At the set laser current, measure the seed laser power immediately before the seed output fibre coupler. Insert the appropriate fibre patchcord into the seed output fibre coupler, and measure the output power from the other end of this fibre. Confirm that the ex-fibre output power matches (within ±5mW) the value specified in the MSHG test report.

    - If the ex-fibre seed laser power differs from the test report data by more than ±5mW, please refer to the ”Fibre Coupling Realignment” procedure specified in Chapter 7 of this manual. If the expected ex-fibre power cannot be restored after following these instructions, please contact MOGLabs support.

6. Couple the secondary seed laser output into a wavemeter (if available) and measure the wavelength of the seed laser. Verify that the measured operating wavelength of the seed laser matches the specified value in the seed laser test report within ±0.1nm.

    - If the measured vacuum wavelength of the seed laser differs from the value specified in the test report by more than ±0.1nm, please refer to the ”Wavelength adjustment” procedure specified in the seed laser manual. If the expected operating wavelength cannot be restored after following these instructions, please contact MOGLabs support.
    - If the measured vacuum wavelength of the seed laser differs from the value specified in the test report by less than ±0.1nm but a higher degree of precision is required, adjust the seed laser injection current. Slight adjustments of 2-3mA will allow the laser to “mode-hop” to a different operating wavelength. Refer to the ”Mode selection” section of the seed laser manual for more information on this process.

2.3 Tapered amplifier

1. Turn on mains power to the MOGLabs LDD controller. Briefly wait for the controller to initialise, then turn the keyswitch from STANDBY to RUN and enable the temperature controller (push-button on the LDD labeled “TEC”). The LED status indicator should initially be yellow (indicating that the thermistor and TEC elements are connected), then change to green when set to RUN. Wait for the seed laser temperature to stabilise to the setpoint, which should match the specified setpoint value in the seed laser test report.

    - If the LED status indicator does not turn green, or if the temperature does not stabilise within 5 minutes, please contact MOGLabs support.

2. Set the amplifier injection current to a very low value (<50mA), and enable the injection current (push-button on the LDD labeled “Current”). Check the diode voltage (found under the ”Laser” menu on the LDD display) and ensure that it is below the ”Maximum compliance voltage” specified in the tapered amplifier test report.

    - If the voltage measured by the controller exceeds the specified maximum, check that all connections between LDD, amplifier headboard (DVI nuts in particular) and diode are secure. If all connections are secure and the diode voltage remains abnormally high, please contact MOGLabs support.

3. Position a power sensor at the exit of the TA U-chassis, before LC1. Set the sensor at a slight angle to minimise any reflections from the sensor back into the amplifier diode. Measure the unseeded amplifier power up to 100mW output OR the maximum safe current specified in the tapered amplifier test report, whichever occurs first. Verify that the unseeded output power of the amplifier matches (within ±10mW) the ”output facet of the bare amplifier diode” data in the tapered amplifier test report.

    - If the unseeded power from the output facet of the amplifier diode differs from the test report specifications by more than

±10mW, please contact MOGLabs support.

4. Enable seed laser injection current, and set to the set current recommended in the seed laser test report (if not already enabled). Insert a power sensor immediately before the tapered amplifier input, and measure the seed laser power incident upon the TA. Verify that this value corresponds (within ±2mW) to the "Recommended seed power" specified in the tapered amplifier test report.

   - If the seed power before amplifier differs by 2–5mW at the seed laser set current, adjust the seed laser injection current to bring the before amplifier seed power back to the recommended value.
   - If the seed power before amplifier differs by >5mW at the seed laser set current, please contact MOGLabs support.

5. Insert pickoff mirror in front of linear cavity (this comes installed within the MSHG chassis in a different location; see Figure 2.1 for details), and position a power sensor such that the input tapered amplifier beam is deflected onto the sensor. Set the TA injection current to the maximum unseeded safe current, and measure the seeded output power of the TA before the linear cavity. Ensure that this value corresponds (within ±10%) with the value reported in the "Before Cavity" power listed in the MSHG test report.

6. Increase the amplifier injection current to the "Maximum Current" value listed in the TA test report. Measure the before-cavity output power of the amplifier, and confirm that this value corresponds (within ±10%) with the value reported in the "Before Cavity" power listed in the MSHG test report.

   - If the seeded TA output power before the linear cavity differs by more than 10% (at either the maximum unseeded safe current or the maximum injection current), please refer to the "Amplifier seeding alignment" procedure specified in Chapter 3 of this manual. If the expected before-cavity TA power cannot be restored after following these instructions, please contact MOGLabs support.

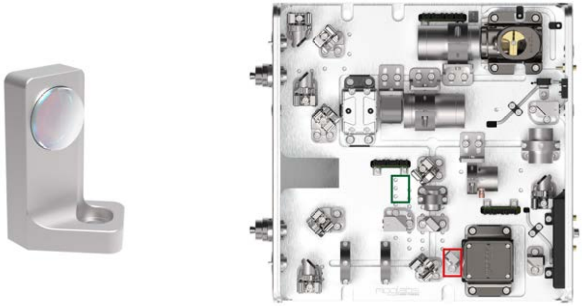

Figure 2.1: Left: Pickoff mirror used for deflecting tapered amplifier beam out of chassis. Right: Birds-eye view of the MSHG, showing the pickoff mirror installed in front of the linear cavity (outlined in red) and the location in the chassis where the pickoff mirror is installed for shipping (outlined in green).

7. Reduce the amplifier injection current to the maximum unseeded bare diode current. On the LDD, navigate to “Settings/Interlock”, and record the PD voltage reading. Verify that this is at least 0.3V higher than the “PD cutout voltage” value listed in the TA test report.
    - If the PD voltage reading is less than 0.3V above the PD cutout voltage, please refer to the “Photodiode cutout adjustment procedure” in Chapter 4 of this manual. If the PD voltage still cannot be increased to the expected level after following these instructions, please contact MOGLabs support.

2.4 Linear cavity

1. Power on the MOGLabs mLC by connecting it to the USB-C power supply provided[1] and connect via LAN. The USB-C port can also be used for communication, but please contact MOGLabs if you experience difficulties with combined communications and USB-C power

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[1] For safety reasons, please contact MOGLabs before using an alternate power supply.

delivery.

2. Run the MOGLabs mLC application[2] and connect to the controller. Ensure the temperature setpoint matches the value in the MSHG test report and activate the temperature controller by sliding the switch to the right (see fig. 2.2).

3. Switch the mLC display window to the logging window (Figure 2.2) and ensure that the cavity temperature stabilises to the desired set point.

    - If the temperature does not stabilise within 5 minutes, please contact MOGLabs support.

4. Engage the piezo controller using the horizontal slider in the mLC app (Figure 2.2), and toggle the display back to the lock screen. Set the span to the typical 'piezo span' value listed in the MSHG test report.

5. Adjust the TA injection current such that the input power to the cavity is approximately 100 mW, and monitor the transmitted photodetector signal on the mLC software. Compare the signal to the "Transmitted photodetector signal when the cavity is well aligned" data shown in the MSHG test report. If the cavity input is well-aligned you should see a few distinct sharp peaks with no small peaks in between (Figure 2.3, top). Small input misalignment is apparent from additional smaller peaks between the main resonances (Figure 2.3, middle). These are higher-order transverse spatial modes. If the alignment is very poor, there may not be any particularly large resonance peaks (Figure 2.3, bottom).

    - If the cavity is slightly misaligned, make small adjustments to the horizontal and vertical actuators of the dichroic mirror D1 to maximise the height of the dominant resonance peaks. If suppression of the smaller spatial modes below a few percent of the main peak heights cannot be achieved through this method, or if

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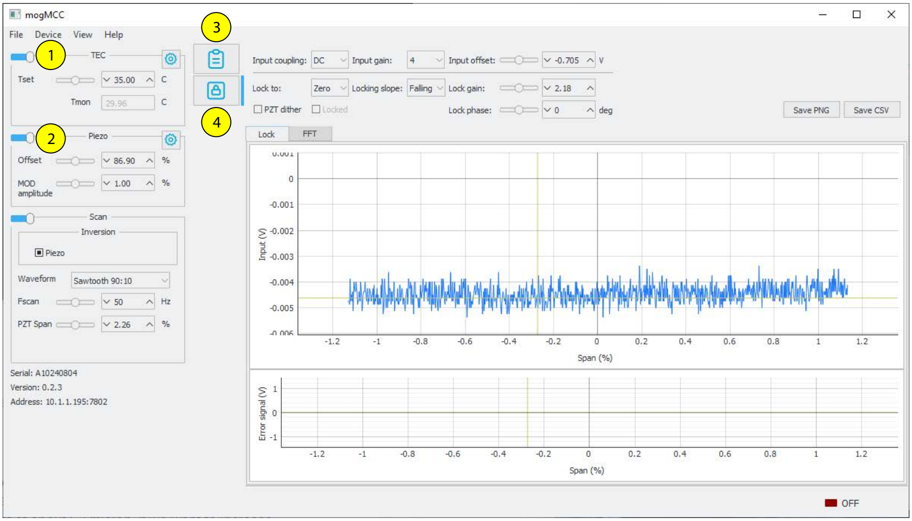
[2] Check the MOGLabs website for firmware and app updates.



Tset 35.00 C
Tmon 29.96 C
Offset 86.90 %
MOD amplitude 1.00 %
☒ Piezo
Waveform Sawtooth 90:10
Fscan 50 Hz
PZT Span 2.26 %
Serial: A10240804
Version: 0.2.3
Address: 10.1.1.195:7802
Input coupling: DC
Input gain: 4
Input offset: -0.705 V
Lock to: Zero
Locking slope: Falling
Lock gain: 2.18
☐ PZT dither
☐ Locked
Lock phase: 0 deg

Figure 2.2: The mLC app. Horizontal sliders activate the (1) temperature and (2) piezo controllers. The cavity temperature setpoint and piezo scan parameters can be adjusted. Pushbuttons allow switching between (3) logging and (4) photodiode signal.

the cavity alignment appears very poor, refer to Chapter 5 to optimise this alignment. However, **please contact MOGLabs support before proceeding to a full cavity realignment**.

6. Increase the TA injection current to maximum. The second harmonic should clearly be visible at the output of the cavity.
7. Place a card after the LC2 cylindrical beam shaping lens. A single clear circular output beam profile should be observed, possibly with a small halo of light to one side.
    - If multiple lobes are apparent in the harmonic beam profile, verify that the linear cavity is at the operating temperature specified in the test report and also that the source laser is single mode and at the correct wavelength. If problems persist, please follow the instructions outlined in Chapter 5.2 of this

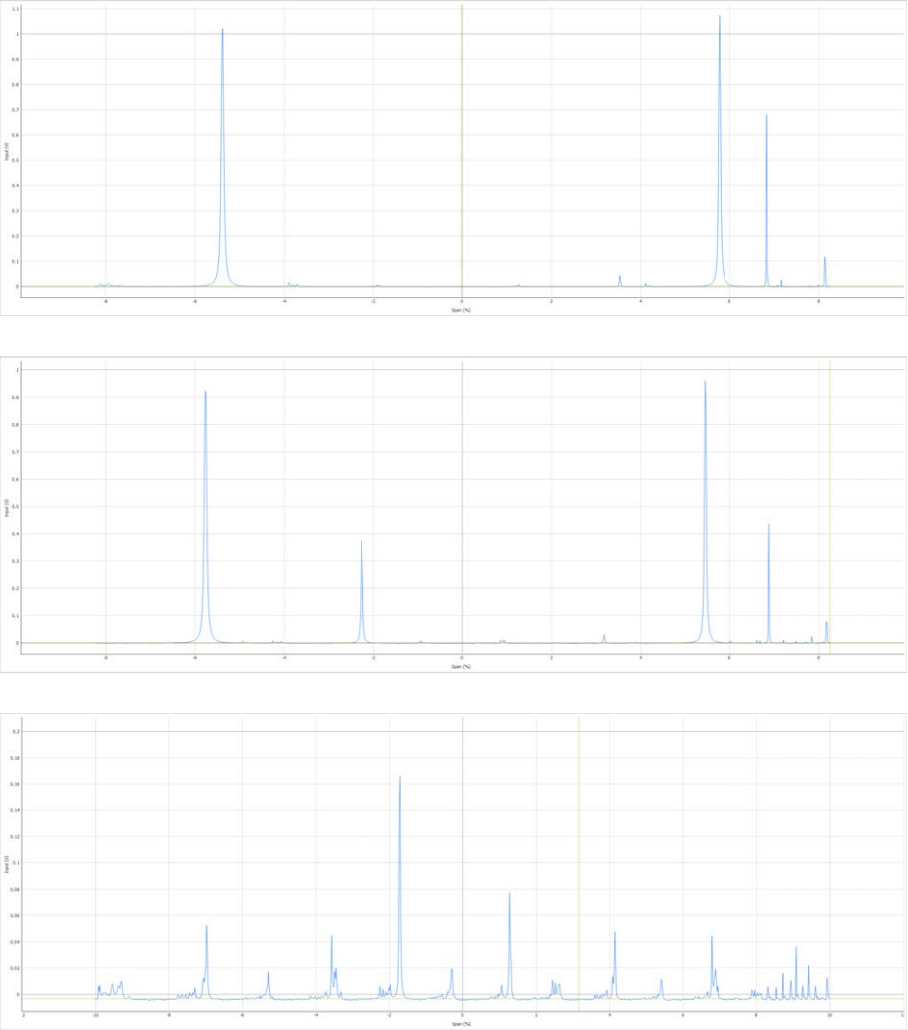


Figure 2.3: Cavity spectra for good alignment(top), small misalignment(middle), and very poor alignment(bottom).

manual to adjust the crystal angle.

8. Lock the cavity using FM modulation/demodulation on the transmitted cavity signal. Refer to Chapter 6 for detailed instructions on how to achieve this.

9. Position a power sensor at the harmonic output port of the MSHG chassis (**Freespace output**) or before the output fibre coupler (**Fibre coupled output**), and measure the SHG output power. Compare this measured value to the power listed in the MSHG test report, and verify that the two values match within ±10%.

   - If the measured output harmonic power is more than 10% lower than the expected value from the MSHG test report, make small adjustments to the horizontal and vertical actuators of the dichroic mirror D1 to attempt to recover the output power.
   - If adjusting D1 does not recover the power, make a minor adjustment to the crystal angle (see Chapter 5.2) to recover the output power.
   - If neither of the above are successful in restoring the expected harmonic output power, please contact MOGLabs support.

10. **Fibre coupled harmonic output only:** Measure the seed laser power immediately before the seed output fibre coupler, preferably at a relatively low power (reduce the TA injection current while the cavity remains locked). Insert the appropriate fibre patchcord into the harmonic output fibre coupler, and measure the output power from the other end of this fibre. Confirm that the ex-fibre output power matches (within ±10%) the value specified in the MSHG test report.

    - If the ex-fibre harmonic laser power differs from the test report data by more than ±10%, please refer to the ”Fibre Coupling Realignment” procedure specified in Chapter 7 of this manual. If the expected ex-fibre power cannot be restored after following these instructions, please contact MOGLabs support.

3. Amplifier seeding alignment

WARNING
Do not operate the tapered amplifier above the ***Maximum current, unseeded*** without an appropriately coupled input seed. Operation exceeding that condition can cause fatal structural degradation of the TA diode. Refer to the ***Maximum current, unseeded*** specified in the amplifier test report.

WARNING
The isolators contain very strong magnets - much stronger than expected. Do not bring any e.g. steel objects within 50 mm of the isolators.

3.1 Small adjustment to seed alignment

After initial setup (Chapter 2), an MSHG system may require a small adjustment to the amplifier seeding alignment. With reference to Figure 3.1, optimise the seeding alignment using the procedure outlined below.

1. Ensure proper seed laser operation according to the instructions provided in the MOGLabs seed laser user manual.
2. Take note of the *Maximum current, unseeded* listed in the TA test report and the maximum expected output power at this injection current.
3. Install the pickoff mirror before linear cavity, and terminate the TA output beam path with a power sensor rated to at least the *Maximum current, unseeded* at location *D* in Fig. 3.1.
4. Power on the TA diode with an injection current of 100 mA less than the *Maximum current, unseeded*. Adjust the seed laser current/power so that at position *B* in Fig. 3.1 it matches the recommended seed input power for the TA.

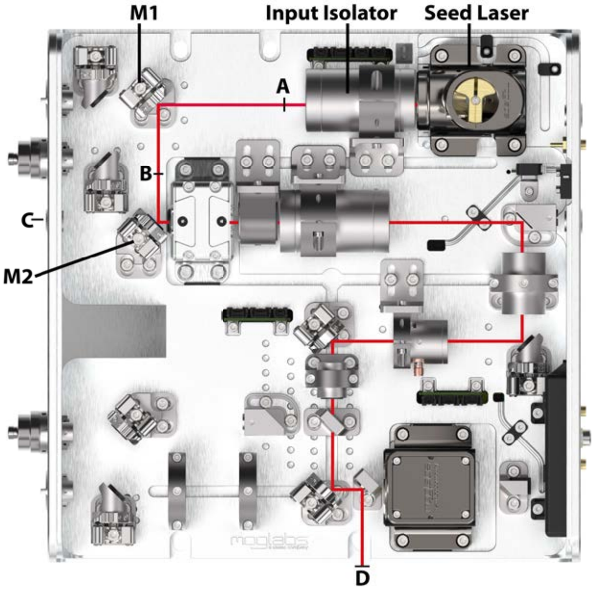


Figure 3.1: Location of major components and positions of relevance in the MSHG when measuring or adjusting the TA seeding.

5. Slightly adjust mirror M2 first horizontally, then vertically, to achieve the maximum possible TA power, P_{REF}. The measured power should be close to the value in the plot of "Before Cavity" TA power in the MSHG test report.

3.1.1 Abbreviated walking procedure

(a) Measure the TA output power while making small (e.g. $\frac{1}{16}$ turn) adjustments to the *horizontal* axis of M1 until the output power is maximised.

(b) Adjust only the horizontal axis of M2 to further optimise P_{REF}.

(c) Repeat above two steps until P_{REF} is optimised.

(d) Repeat the above steps for the vertical axis of M1 and M2 until P_{REF} is optimised.

6. Compare the recorded power of the TA with the appropriate value from the test report. A variation of 5% is acceptable.

7. Record a TA power vs. TA current curve of the seeded TA diode as a future reference for comparison if system performance changes.

If the TA output power is far below the factory measured output indicated in the MSHG test report, proceed to section 3.2.

3.2 Substantial adjustment to seed alignment

Please *do not* proceed with the alignment steps below unless instructed to do so in the previous section, there has been substantial seed misalignment, the TA diode has been replaced or under instruction by MOGLabs support.

To obtain effective seeding of the TA diode:

1. Take note of the *Maximum current, unseeded* listed in the TA test report and the maximum expected output power at this TA current.

2. Install the pickoff mirror before linear cavity, and terminate the TA output beam path with a power sensor rated to at least the *Maximum current, unseeded* at location *D* in Fig. 3.1.

   NOTE: Ensure that the TA output propagates through the output isolator and all other optical components without clipping. If the beam is observed to clip on any components between the TA and location *D* in Fig. 3.1, please refer to Chapter X for details on realigning the amplifier output beam.

3. Power on the TA diode with an injection current less than the *Maximum current, unseeded*. Adjust for a few mW in the reverse propagating TA beam at location *B* in Fig. 3.1.

4. Adjust the seed laser current/power so that at position *B* in Fig. 3.1 it matches the recommended seed input power for the TA. The seed

laser should be stable in power and frequency, i.e. not near a mode-hop and not ramping the piezo.

5. The divergence of seed reverse propagating TA beams should be matched. Observe the secondary seed output beam after M1, or use a pickoff mirror to deflect the seed beam out of the chassis. Check the collimation of the seed laser using a shear plate (shearing interferometer) or M^2 beam profiler and if necessary adjust the focus of the seed laser to achieve collimation (refer to the seed laser operating manual). If a shear plate or M^2 beam profiler is unavailable, the spot size of the seed laser beam should be minimised at 5 m distance from the seed laser.

6. The reverse propagating TA beam is collimated with an input lens mounted in a flexure translation mount. Remove M2 and the TA input chassis plug (*C* in Fig. 3.1), and allow the reverse propagating beam to propagate about 5 m. Adjust the reverse propagating beam divergence by rotation of the TA input lens mount using the supplied lens tube spanners (see Fig. 1.3 and Fig 3.2). There is an outer tube spanner for loosening the retaining lock ring and an inner tube spanner for adjusting the lens focus. Make sure to tighten the retaining ring once the lens position has been adjusted. The beam spot size should be as small as possible at about 5 m propagation distance.

7. Using the flexure alignment screws (see Fig. 1.3), adjust the input lens $x-y$ position so that the reverse propagating beam exits parallel to the MSHG chassis horizontal plane and parallel with the MSHG chassis long edge.

Figure 3.2: Lens tube spanners for adjusting TA collimation lenses.

NOTE: The TA diode injection current should not be more than *Maximum current, unseeded*. Do not allow the TA reverse propagating beam to propagate into the seed laser without a seed isolator installed; it could damage the seed laser diode.

8. Re-install M2, ensuring the incident beams are centred on the mirror and are at 45° angle of incidence.
9. Pre-align the seed laser beam and the reverse propagating TA beam using M1 and M2. The beams should be collinear and overlapping at locations *A* and *B* in Fig. 3.1.
10. Measure the transmission efficiency of the input Faraday isolator(s). If the amplifier configuration has two input isolators, the isolator close to the seed laser should be installed first. Compare the isolator efficiency with the efficiency value specified in the system test report. If the value from the test report and the measured efficiency are different by more than 10%, contact MOGLabscustomer support.
11. Remeasure the seed laser power before the TA diode (after the input isolator) and adjust the seed laser current to achieve the same power specified in the system test report. The seed laser should still be stable, not near a mode-hop.
12. The TA injection current should now be set to *Maximum current, unseeded* or just below this value.
13. Using M1 and M2 accurately align the seed laser beam with the TA reverse propagating beam using the following *walking* procedure:
    (a) Make sure the seed laser is incident and centred on the TA block input aperture by adjusting M1 and M2.
    (b) Install the pickoff mirror before linear cavity, and terminate the TA output beam path with a power sensor rated to at least the *Maximum current, unseeded* at location *D* in Fig. 3.1.
    (c) For the *horizontal* axis first, adjust M2 to achieve maximum output power from the TA. Call this value P_{REF}.

(d) Make a small adjustment to the *horizontal* axis of M1 in a clockwise direction such that the output power drops by no more than 25%. Take note of how much adjustment was made e.g. $\frac{1}{16}$ turn clockwise.

(e) Next adjust only the horizontal axis of M2 to maximise the output power from the TA. The adjustment range should be less than half a turn of the actuator at this step, and this range should reduce upon iteration.

(f) If the new measured power is greater than P_{REF}, this higher power is the new reference power P_{REF}. Iterate steps 13d and 13e until P_{REF} is maximised. It will be necessary to drop the output power by less than 25% as the alignment improves, e.g. 10% or 5%.

(g) If the new measured power after step 13e is instead lower than P_{REF}, readjust the horizontal axis of M1 anti-clockwise to return to the original angle (as noted at step 13d), then reoptimise the horizontal axis of M2 to return to P_{REF}. Now iterate steps 13d and 13e with an *anticlockwise* adjustment at step 13d.

(h) Once P_{REF} is maximised, iterate steps 13d through 13g for the *vertical* direction.

(i) Iterate the horizontal and vertical alignment procedures above until P_{REF} is maximised.

14. Check that the seed laser power before the TA (position B in Fig. 3.1) has not changed during the adjustment procedure and corresponds to the seed power from the system test report. If it has changed, again adjust the seed laser current so that the power at position B matches the recommended seed power in the TA test report. Iterate the walking procedure from step 13 again (with very small adjustments).

15. Once P_{REF} is optimised, adjust the orientation of the half-wave plate mounted in the endcap of the input isolator (see Fig. 3.3) by first loosening the set screw indicated. Rotate the half-wave plate to maximise power out of the TA diode, then re-tighten the set screw.

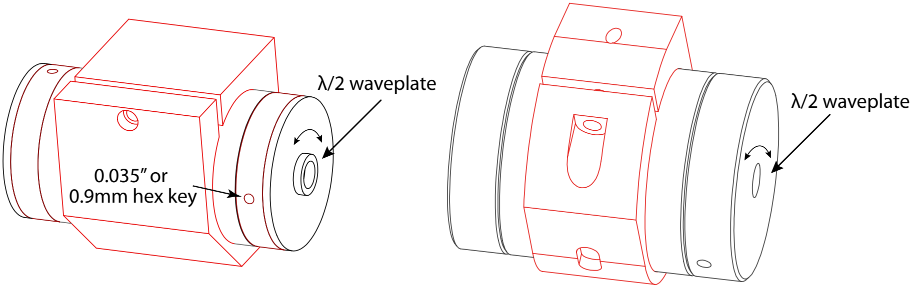


Figure 3.3: Schematic diagram showing location of half-wave plate in isolator endcaps. Ensure set screw is loosened before rotating endcap.

16. Verify optimum seed alignment by again walking the M1,M2 mirror pair according to step 13 (with very small adjustments).

17. Record the final TA output power, P_{REF}, along with the seed power and injection current. Temporarily block the seed beam and record the unseeded amplifier output power. Compare the measured P_{REF} with the plot of "Before Cavity" TA power in the MSHG test report.

18. If there is still more than 10% difference from the report value, slightly adjust the TA input lens focus (z) position to achieve better mode-matching and repeat step 13. It may take a number of iterations to maximise P_{REF}.

19. Measure TA output power as a function of injection current at location D in Fig. 3.1, and compare to the "Before Cavity" TA power in the MSHG test report.

20. If the measured and factory curves still differ by more than 10%, contact MOGLabs customer support.

4. Amplifier beam sampler

For MOGLabs MSHG laser systems used with the LDD controller, a photodiode monitors the TA output to ensure the seed is properly coupled at high operating currents. If the output power is measured low when the TA injection current is above the photodiode safety cutout *interlock current*, for example because the seed input has been blocked, the TA current will be switched off to prevent TA diode damage. The interlock current is set using the LDD menu under Settings → Interlock → Interlock Current. Please refer to your TA test report for the recommended interlock current, specified as *Maximum current, unseeded*.

When operating the TA above the interlock current, the photodiode reading (LDD menu item Settings → Interlock → PD reading) must exceed the photodiode setpoint (LDD menu item Settings → Interlock → PD setpoint). The *PD setpoint* is set to about 85% of the typical output power expected at the interlock current, **when the recommended seed laser power is well coupled to the TA**. The *PD setpoint* can be adjusted using the LDD menu item. Please refer to your system test report for the recommended *PD setpoint* specified at item *Photodiode safety cutout*.

The *PD reading* is affected by TA output power, beam shape and mechanical alignment of the photodiode assembly. Large changes to the seed wavelength will result in substantially different TA power output at a given current due to the wavelength-dependent gain response of the TA diode, requiring recalibration of the *PD setpoint*. If the output beam shaping has been adjusted or the incident polarisation after the TA output isolator has changed, this can also result in a different measured power at the photodiode for the interlock current. In these circumstances, the photodiode gain can be optimised as follows:

4.1 Photodiode cutout adjustment procedure

1. With seed power at the recommended input value, ensure the seed coupling is optimised and TA output power agrees with the system test report (see Chapter 3)

2. Set the TA current to the *Maximum current, unseeded* specified in the system test report. Check *PD reading* is within the range of 0.5–2.0V.

3. Block the seed beam, and record the *PD reading* while the TA is unseeded. Verify that the difference in *PD reading* between seeded and unseeded operation is at minimum 0.3V; if this is not the case, contact MOGLabs support.

4. In the LDD menu (Settings → Interlock → PD setpoint), adjust the PD cutoff setpoint to 85% of the *PD reading* while operating at the *Maximum current, unseeded* when the TA diode is seeded

5. Unblock the seed beam. Increase the TA injection current to the maximum operating current. Check *PD reading* is between 4 to 4.8 V (note that 4.94 V is the saturation voltage).

6. If *PD reading* is saturated, adjust the gain trimpot so the *PD reading* is between 4 to 4.8 V (see fig. 4.1). If trimpot adjustment is required, return to steps 2–4.

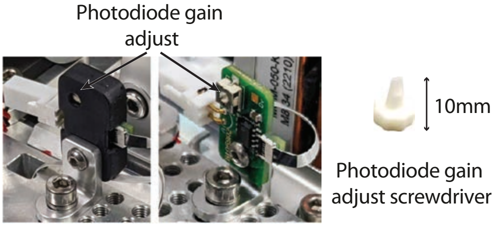


Figure 4.1: Examples of B1059 photodiode adjustment PCBs showing location of photodiode gain adjust and photodiode gain adjust screwdriver.

5. Linear cavity alignment

Full alignment of the cavity input beam consists of (1) coupling the fundamental TA input beam to the enhancement cavity, followed by (2) alignment of the crystal to the cavity. This chapter describes realignment of both of these aspects; **however, please contact MOGLabs support before proceeding to a full cavity realignment**.

5.1 Cavity alignment

Coupling into the high finesse cavity is similar to coupling a free-space laser beam into a single mode optical fibre. A few tools can make the process much less tedious:

1. A white card for tracing beam paths, particularly one with a small hole. Then the card can be placed so that the beam passes through the hole, and back-reflected beams can be seen on the reverse side of the card.
2. An IR fluorescent card for tracing the path of the fundamental light.
3. A camera (CCD or CMOS) to observe the mode structure of the light transmitted by the cavity.

5.1.1 Coarse cavity alignment

1. Adjust the TA injection current such that there is about 100 mW fundamental power before cavity.
2. Trace the fundamental beam with an IR fluorescent card from TA output to cavity input, ensuring the beam is centered on all optics and is not clipping anywhere.
3. Centre the input beam on the back mirror of the cavity. First adjust the horizontal actuator on dichroic mirror D1 until you see the beam

clip on one side of the cavity, then adjust the actuator in the opposite direction until you see the beam clip on the opposite side, then centre the beam between these two positions. Repeat with the vertical actuator.

4. Using the IR card, look for the back reflection off the cavity, first between M4 and M5 (see Figure 1.4). If no reflection can be found then try closer to the cavity, for example in front of lens L8.
5. Make small adjustments to dichroic mirror D1 until the back reflection is aligned with the input beam between M4 and M5.
6. Verify vertical polarisation of the input beam before the linear cavity, using a polariser with a known transmission axis. If this polarisation requires correction, do so by adjusting the rotation of the half-wave plate on the last Faraday isolator in the system before the cavity.
    - If the half-wave retarder is fixed to the output end of the isolator, rotate the retarder to correct the polarisation.
    - If the retarder is on the input side, first rotate the isolator to correct the polarisation, then rotate the retarder to optimise power after the isolator.
7. Connect to the mLC controller and set the piezo scan range to $\approx 50\%$.
8. On the front face of the photodetector mechanics there is a small mirror that will direct the cavity transmitted beam horizontally out of the chassis. Place a camera sensor (without lens) in the path of this reflected beam.
9. Observe the light transmitted by the cavity using the camera. Set the camera exposure time to greater than the cavity sweep time; for example, if the cavity sweep rate is 20 Hz, set the exposure time to 100 ms to ensure the exposure is integrated over one full piezo scan.
10. It can be instructive to stop the piezo scanning, and slowly adjust the piezo offset through the various cavity modes (or tune the fundamental laser frequency with piezo fixed). Resonance peaks of vary-

ing height indicate resonances with different non-degenerate spatial modes (fig. 5.1).

5.1.2 Spatial modes

Visualisation of the spatial modes of the cavity is very helpful for optimising cavity alignment. With the camera exposure time greater than the sweep time, the transmitted image is an integration over all the spatial modes excited for the different incident laser frequencies. Ideally, all the power is coupled only to the fundamental Gaussian TEM$_{00}$ mode, and only a Gaussian profile will be observed on the camera. With imperfect alignment and focus, some of the incident power is coupled into higher-order transverse modes:

- **Hermite-Gaussian** (HG) modes (Fig. ??, left) are not rotationally symmetric, excited when the incident light is not centred on the radius of curvature of the first cavity mirror, or the beam is not propagating parallel to the cavity axis.

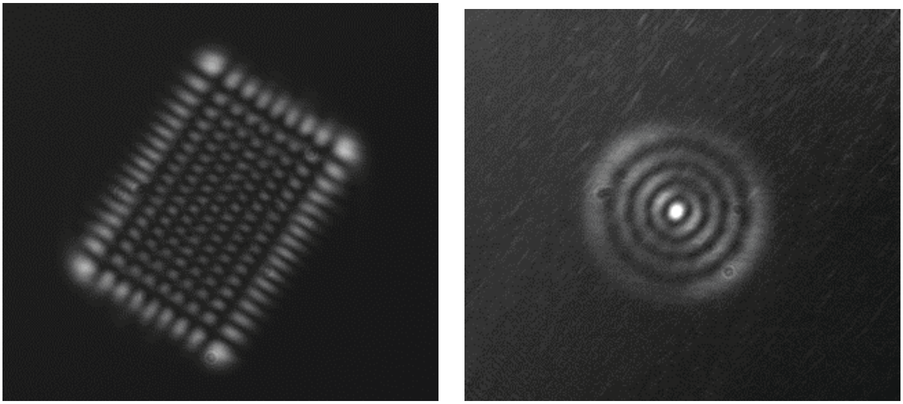


Figure 5.1: Images of light transmitted by the linear cavity, for higher order spatial modes. Left: Hermite-Gaussian. Right: Laguerre-Gaussian.

- **Laguerre-Gaussian** (LG) modes (Fig. **??**, right) are rotationally symmetric, coupled when the incident light is not focussed on the flat mirror of the cavity.

Figure 5.2 shows examples of images captured as the cavity is scanned. Initially a rectangular structure is expected (Fig. 5.2, left), corresponding to excitation of many higher order HG modes caused by poor alignment. Small adjustments to the dichroic mirror D1 horizontal actuator will correlate to expansion or contraction of the image along the horizontal direction (Fig. 5.2, middle).

Similarly adjustment of D1 in the vertical direction is used to reduce the spread vertically (Fig. 5.2, right). When both axes are optimised, the image should rotationally symmetric.

Finally, adjustment of the spherical telescope (with minor correction of the horizontal and vertical adjustment of D1) reduces the overall spread of the centred Gaussian TEM_{00} transmitted beam.

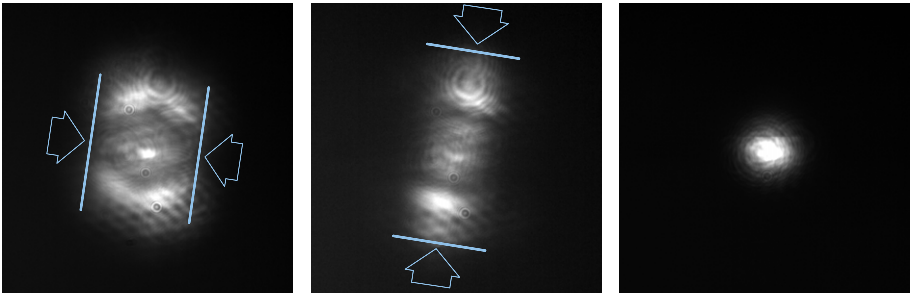


Figure 5.2: Images of the light transmitted by the cavity. Left: Poorly aligned, appearing as a rectangle. Middle: Adjustment in the horizontal alignment collapses the image to a line. Right: After vertical alignment the image is rotationally symmetric.

5.1.3 Fine cavity alignment

The photodetector signal from cavity transmission provides additional insight into how light is coupled into different spatial modes. After the coarse alignment steps above, the `mLC` photodetector plot should show distinct peaks separated by the free spectral range of the cavity, with intermediary smaller secondary peaks (Fig. 5.3, top). The largest peaks correspond to the fundamental Gaussian mode of the cavity, and the secondaries are from higher-order spatial modes. Maximum conversion efficiency is achieved when all of the light is coupled into the primary Gaussian mode.

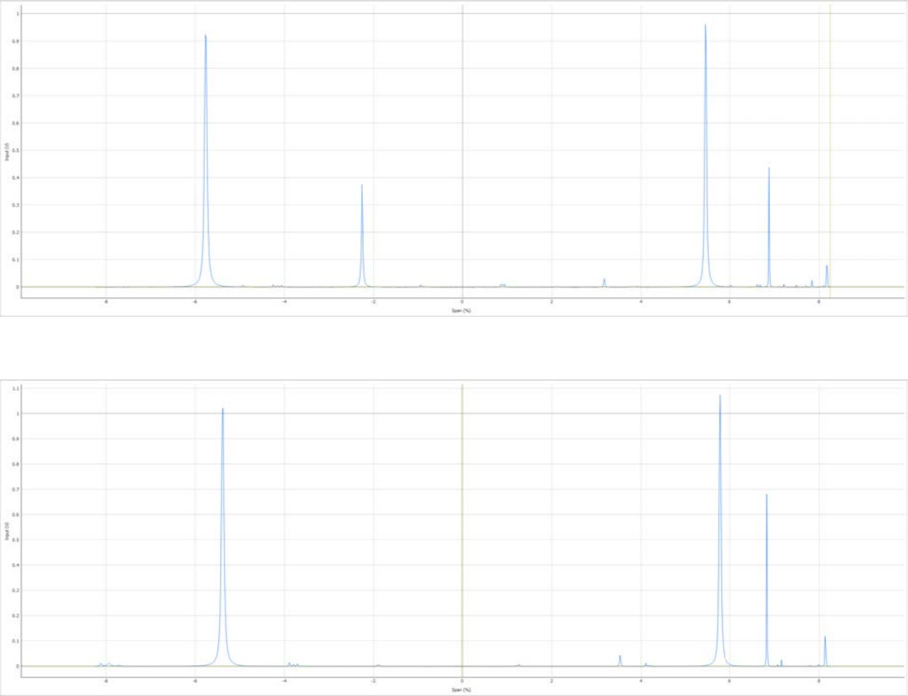


Figure 5.3: Top: cavity spectrum for a reasonably well aligned cavity. Polarisation, alignment and focus modes are present, but not particularly large. Below: spectrum after optimising the different alignments, showing greater power coupled into the fundamental Gaussian mode, and almost non-existent coupling to other modes.

The test report provided with the MSHG will include a plot similar to Figure 5.3, with the following secondary modes identified:

Polarisation: Arise from slight misalignment of the fundamental light polarisation into the cavity. The crystal in the cavity is birefringent, therefore the optical path length of the cavity is polarisation-dependent, creating polarisation-dependent resonances. When close to optimal alignment, only the Gaussian mode associated with the wrong polarisation will be significant.

Alignment: Related to small rotational assymmetry of the cavity, so that the horizontal and vertical couplings are not degenerate. The coupling of the fundamental into these two transverse modes are strongly affected by alignment into the cavity. Slowly scanning the cavity shows they are associated with the lowest order Hermite-Gaussian modes.

Focus: Again related to non-degeneracy of horizontal and vertical alignment, in this case due to imperfect focus (of the spherical telescope or coupling lens L8). These modes are rotationally symmetric, low-order Laguerre-Gaussian modes.

To optimise coupling into the cavity:

1. Reduce the piezo span to one free spectral range of the cavity; that is, only two large peaks are displayed, with intermediary small secondary peaks. The MSHG test report has suggested settings for the span value, but some adjustment of the piezo offset will be needed so that the two fundamental peaks are at the edges of the scan.

2. Adjust the half-wave rotator on the output of the isolator to minimise the polarisation mode

3. Adjust the horizontal actuator of D1. Referring to the MSHG test report, one of the modes identified as alignment-related will grow rapidly.

4. Verify which other mode (secondary peak) is affected by the vertical actuator.

5. Once the alignment modes are identified, walk the dichroic mirror D1 and mirror M5 pair in the horizontal direction to minimise the peak height of the horizontal alignment mode.

6. Walk D1 and M5 in the vertical direction to minimise the vertical alignment mode.

7. Repeat horizontal then vertical walking until no further reduction in peak heights is possible. By the end of this process the alignment mode peak heights should be 1–2% of the main peak height and it remains to optimise the focus.

8. Make a small (5°) clockwise adjustment to the brass ring on the spherical telescope. This may may affect horizontal or vertical alignment. Adjust only the horizontal and vertical actuators on the dichroic mirror D1 to reduce these modes.

9. Adjusting the telescope should have increased the height of the focus mode peaks. Adjust the position of lens L8 to minimise these peak heights.

10. If steps 8–9 have caused the focus mode peak heights to decrease, continue to iterate the focus in the same direction until minimised. If the peak height has increased, rotate the telescope focus adjustment anti-clockwise and repeat steps 8–9 until the focus mode peak heights are minimised. The MSHG test report shows the expected secondary peak height that can be achieved, typically 1–2% of the main peak height.

11. Revisit steps 6–7 as some small walking may be necessary after optimising the telescope and lens positions.

12. Record the final spectrum for future reference. In the top right corner of the mLC main application window there are two options 'save CSV' and 'save PNG'. Record an image and the CSV data. If there is

some discrepancy with the results in the MSHG test report, contact MOGLabs support with this data (both csv and image) for further advice.

5.2 Crystal alignment

Efficient second harmonic generation requires phase matching between the fundamental and harmonic fields, which is controlled by angle-tuning or temperature-tuning of the crystal.

5.2.1 Angle tuning

Angle tuning, also known as critical phase matching, can be used with uniaxial or biaxial crystals. When the crystal is not at the optimal angle relative to the cavity, SHG still occurs, but parallel to the ideal phase matching angle rather than the cavity axis, leading to multiple low-power exit beams.

The MOGLabs MSHG provides crystal angle adjustment of ±2°, corresponding to a wavelength range of up to ±20 nm of the harmonic. Figure 5.4 shows the location of the fine threaded actuator that adjusts the crystal angle, and the spring plunger that provides a restoring force to the actuator. When making adjustment of the crystal angle, please note:

1. The plugs that cover the angle adjustment actuator and spring plunger should be reinstalled after adjustments to seal the cavity.
2. The crystal should rotate smoothly. If there is an increase in tension the spring plunger may have run out of travel or the puck may have reached its limit of rotation. Back off the spring plunger then test the tension on the wavelength adjustment. If the tension has reduced, then the angle adjustment can be continued; if not, contact MOGLabs support. **Please do not apply excessive force if the crystal rotation is not smooth; this can irreversibly damage to the fine-adjust screw or the puck mechanic.**

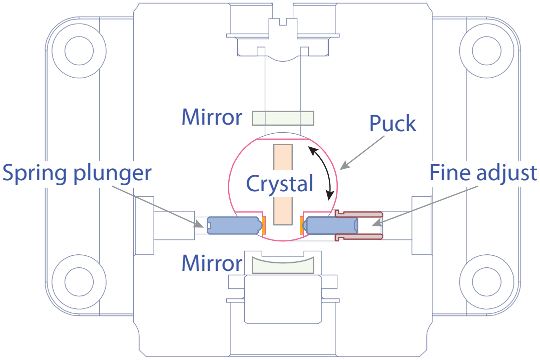


Figure 5.4: Cross section of enhancement cavity at the plane of the crystal adjustment screws, as seen from above. The crystal angle is controlled by the fine threaded actuator (right) pushing against the spring plunger (left).

5.2.2 Temperature tuning

Temperature tuning can be used to fine tune the phase matching condition. The effect is small: 50° change in crystal temperature is roughly equivalent to 1° change in angle. Note that the MSHG crystal temperature should be limited to the range $25-60°$C, and ideally around 30°. Do not allow the crystal temperature to fall below the dew point.

5.2.3 Optimising phase matching

1. Set the cavity temperature to the value specified in the MSHG test report.
2. Ensure the cavity is well aligned to the fundamental input (section 5.2).
3. Tune the wavelength of the fundamental to the desired wavelength for SHG. Ensure that the seed laser is operating on a stable single mode.
4. Adjust the TA injection current such that the before-cavity fundamental power is a few hundred milliwatts.

5. Set the piezo scan to span several free spectral ranges of the cavity.
6. Position a white viewing card after dichroic mirror D1. Some SHG output should be apparent on the card (Figure 5.5, left). If no SHG is visible, please contact MOGLabs support: the crystal angle may have changed dramatically and the cavity may need to be opened to restore operation.
7. Make small adjustments to the crystal angle. Adjustment in one direction will bring the multiple SHG output beams closer together, and the other direction will cause them to diverge. Adjust the crystal angle until they overlap as one bright beam (Fig. 5.5, right).
8. If a large adjustment to the crystal angle has been made then the cavity coupling will change. Re-optimise alignment as in section 5.1.

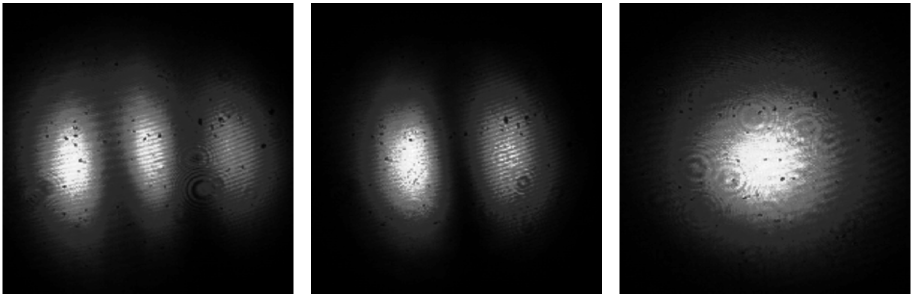


Figure 5.5: Left to right: output beam profile of the harmonic for poor crystal alignment, improved alignment, and optimum alignment.

5.2.4 Crystal translation and rotation

The crystal can be translated to expose different regions of the crystal as it ages and therefore increase its useful lifetime.

The SHG crystal is bonded to a crystal mount which sits within the crystal puck. Note that the ends of the crystal overhang the crystal mount slightly to allow easy access for cleaning the crystal facets. The crystal mount can be pushed to either side of the puck to access two different spots on the crystal face, or rotated 180 degrees to access two new paths through the crystal.

Translation or rotation of the crystal requires opening the linear cavity, which should only be attempted in a clean dust-free environment with low humidity. Please wear optics grade powder free gloves for this process, and ensure that both seed laser and TA are powered off.

Crystal translation

1. Using a 2 mm driver, remove the four screws that hold the lid onto the cavity.
2. Lift off the cavity lid by inserting a small flat head screwdriver into the notch on the side.
3. Remove the wave washer on top of the crystal puck.
4. Using a 2 mm driver remove the two screws that hold the lid onto the crystal puck.
5. Remove the puck lid from the cavity.
6. Using tweezers, gently slide the crystal mount from one side of the puck to the other, being very careful that the crystal and mount to not touch the back cavity mirror.
7. Gently place the puck lid back on top of the crystal mount and tighten in place with the two screws that were removed.
8. Restore the wave washer back on top of the puck lid.
9. Fix the cavity lid back on top of the cavity with the four screws that were removed.
10. Follow the procedure in section 5.2 to re-optimise the puck angle for maximum harmonic output.

Crystal rotation

1. Using a 2 mm driver, remove the four screws that hold the lid onto the cavity.
2. Lift off the cavity lid by inserting a small flat head screwdriver into the notch on the side, and remove the wave washer on top of the crystal puck.
3. Remove one of the two screws that hold the lid onto the crystal puck, using a 2 mm driver.
4. Screw one of the long screws that held the cavity lid on into the now free tapped hole in the crystal puck, again with a 2 mm driver.
5. Loosen both the spring plunger and fine angle actuator away from the puck, using a 1.5 mm driver.
6. Remove the crystal puck from the cavity with a gloved hand. The puck should slide out easily; if there is resistance, do not force it. Contact MOGLabsfor advice if necessary.
7. Take a photo of the crystal mount from above to provide a record of how far forward the crystal sits relative to the puck.
8. Using tweezers, gently slide the crystal mount out of the puck so that it is more easily accessed.
9. Rotate the crystal mount by 180 degrees along the long axis, so the crystal is suspended in its mount, and place back within the crystal puck. Push it against one side of the puck and ensure the crystal extends out from the puck as before, with reference to the photo acquired before rotation.
10. Place the puck lid back on top of the crystal mount and tighten in place with one of the two short screws that were removed, and one of the long screws.

11. Using a gloved hand, slowly lower the puck back into the cavity, return the wave washer back to the top of the puck lid, place the cavity lid back on top of the cavity and fix in place with the four screws that were removed.
12. Follow the procedure in section 5.2 to re-optimise the puck angle for maximum harmonic output.

6. Cavity locking

The MOGLabs MSHG can be configured to lock the resonance frequency of the enhancement cavity to the frequency of the input light using one of two techniques:

1. Frequency modulation/demodulation (FMDM)
2. Pound-Drever-Hall (PDH).

The capture range of a particular locking technique is defined as the frequency range over which the lock will be able to recover, determined by where the error signal is above the noise with correct polarity.

6.1 Frequency modulation/demodulation

The default method is frequency modulation and demodulation (FMDM). A very small high-frequency modulation is applied to the piezo to modulate the cavity resonance frequency and hence transmitted photodetector signal. The photodetector signal is then demodulated and the resultant error signal provides the dispersive response needed for locking.

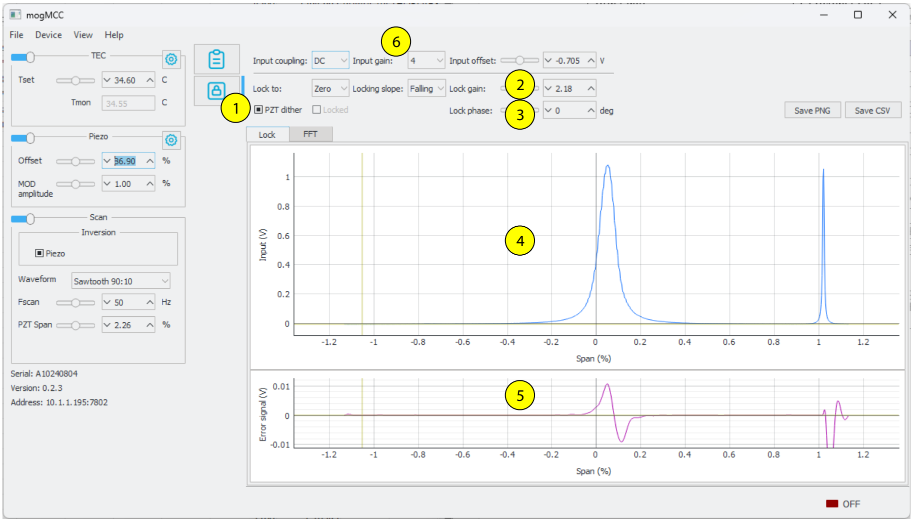
FMDM is an AC technique which is insensitive to variations of the input laser power, alignment, and wavelength, and requires no additional optics. The modulation occurs at frequencies well above the piezo response bandwidth, where background noise is low and a clear signal can be extracted even with very small modulation amplitude. The capture range of this technique is limited to the cavity linewidth.

6.1.1 Using FMDM

FMDM can be activated by checking the *PZT dither* tick box in the mLC app (Figure 6.1). When active, the generated error signal will be displayed. For large scans, spurious oscillations may appear in the error signal display. They are related to under-sampling and should disappear for reduced scan ranges.

Key parameters for FMDM locking:

Phase	Set the scan range to <5% of full span and adjust phase to maximise the slope of the error signal.
Input gain	Analogue gain of the photodetector signal.
Lock gain	Master gain of the PID loop.
MOD amplitude	The modulation amplitude (depth) will be set at MOGLabs and should not require adjustment.
Frequency	The modulation frequency will be set at MOGLabs and should not require adjustment.



TEC
Tset 34.60 C
Tmon 34.55 C

Piezo
Offset 36.90 %
MOD amplitude 1.00 %

Scan
Inversion
☒ Piezo
Waveform Sawtooth 90:10
Fscan 50 Hz
PZT Span 2.26 %

Serial: A10240804
Version: 0.2.3
Address: 10.1.1.195:7802

Input coupling: DC
Input gain: 4
Input offset: -0.705 V
Lock to: Zero
Locking slope: Falling
Lock gain: 2.18
☒ PZT dither
☐ Locked
Lock phase: 0 deg

Figure 6.1: The mLC main application window when configured for FMDM locking, showing the location of (1) PZT dither enable, (2) lock gain adjust, (3) phase adjust, (4) cavity transmission signal, (5) error signal and (6) photodetector gain adjust.

The following additional locking control parameters apply to all locking techniques, and Figure 6.2 shows the location of these controls on the mLC application:

Input gain	Increase the gain until the signal is about two thirds of saturation.
Control gain	Increase until the control loop oscillates, then reduce by about one third.
Offset	The error signal *Offset* can be adjusted so that the desired lock point occurs where the shifted error signal crosses zero. Typically the *Offset* is adjusted to optimise the SHG output.
Slope	In some cases it might be useful to lock to the rising edge of an error signal.

Input coupling: DC

Input gain: 1

Input offset: 0.050 V

Lock to: Zero

Locking slope: Rising

Lock gain: 0.45

☐ PZT dither ☐ Locked

Lock phase: 0 deg

Figure 6.2: mLC locking controls: (6) input gain, (7) input offset, (8) lock gain, (9) locking slope, and error signal spectrum when the control loop gain is too high (lower left) and optimal (lower right).

6.1.2 Optimising the cavity lock

To optimise the lock performance:

1. Adjust the fundamental power to the typical operating power.
2. Ensure the error signal crosses zero.
3. Decrease the piezo span until the cavity resonance fills ≈10% of the span, and is approximately centred.
4. Adjust the phase of the demodulation to give the largest falling slope on the error signal.
5. Engage the lock by double clicking on the lock feature in the error signal window.
6. Observe the output power. If SHG is clear, then the *Slope* polarity is correct. If not, try swapping polarity and re-engaging the lock.
7. Once the cavity is locked, allow 30 seconds for the cavity to stabilise.
8. Adjust the offset by small amounts, typically in steps of 0.01, to maximise the harmonic output power.
9. Once the offset is optimised, switch to the error noise spectrum tab in the `mLC` application.
10. Observe the noise spectrum while adjusting the control gain. Increasing gain should suppress noise at low frequencies, and increase noise at higher frequencies[1].
11. Increase the control gain until the onset of control loop oscillation, apparent from sharp resonances at high frequencies.
12. Decrease the control gain until the resonances have disappeared.

---

[1] Figure 6.2 shows two example noise spectra, one of a control loop with too much gain and one with optimal gain.

13. Adjust the cavity set temperature in small steps of 0.01° to optimise the SHG output power. Some patience is required because of the slow thermal response.

6.2 Pound-Drever-Hall

Pound-Drever-Hall (PDH) locking [4] uses interference of two frequency sidebands that are imposed on the fundamental light. The phase shift imparted on the light reflected from the cavity depends on whether the fundamental is above or below resonance. As the cavity scans across resonance, the two reflected sidebands (which are not resonant with the cavity) interfere with one another to produce the error signal.

As with FMDM locking, PDH is an AC technique, insensitive to variations in ambient conditions. Remnant modulation in the SHG output can be much smaller than with FMDM because the modulation frequency is higher than the cavity linewidth, typically 5 to 20 MHz. Since they are well outside the cavity resonance, the sidebands will not be enhanced by the cavity. $1/f$ noise is lower at higher frequencies, allowing smaller modulation for a given signal to noise in the extracted error signal. As for HC locking, the beam sampler reduces the input into the cavity and the overall conversion efficiency is reduced.

External electronics are required to generate the high modulation frequency, to demodulate and low-pass filter the detected signal and to adjust the relative phase between modulation and demodulation. The fundamental laser can be modulated either directly via current modulation of the laser diode, or using an electro-optical phase modulator (EOM).

6.2.1 PDH error signal generation

The optical configuration for PDH locking is shown in Figure 1.4). A beamsplitter (BS2) samples the *reflected* beam and directs that light to a photodetector. The fundamental must be phase-modulated, either by injecting an RF signal into the fundamental laser, or with the addition of an electro-optic phase modulator (EOM). The error signal is generated by demodulating the signal from the photodetector, typically with a double-balanced mixer and low-pass filter (see details in MOGLabs application note *AN002: Pound-Drever-Hall Locking*, `https://www.moglabs.com/support/appnotes`).

7. Fibre coupling

The free-space harmonic output beam of an MSHG is almost diffraction limited, enabling fibre coupling efficiencies of 70–80% (despite 8% Fresnel losses at the two fibre facets). Astigmatism correction is included on cavity output, but for SHG wavelengths >530 nm the benefits are marginal. The secondary seed laser output beam is generally more elliptical and therefore more difficult to fibre couple, with coupling efficiencies of 55–60% generally observed.

MOGLabs recommends using polarisation-maintaining (PM) fibre patchcords for both seed laser and harmonic output beams, and using end-capped fibres if the free-space power is over 500 mW or the wavelength is below 500 nm.

Some instruments and tools are helpful for quickly achieving optimum coupling efficiency:

1. Suitable single mode fibre patchcord.
2. Fibre laser pen or fibre visual fault locator (see Fig. 7.1).

Figure 7.1: A fibre laser pen or visual fault locator injects visible laser light into a fibre, allowing basic alignment and mode matching.

3. OD3 neutral density filter.
4. Power meter and sensor head.

Note that silicon photodiode power sensors easily saturate below their maximum power when the full sensor is not illuminated, giving false readings. Integrating sphere sensors are recommended to avoid saturation.

7.1 Fibre alignment

Seed laser and cavity outputs should be well collimated: the collimation and astigmatism correction will be set at MOGLabs. The optimum fibre alignment and focus are weakly power-dependent, and may need to be adjusted if the operating laser power is changed.

1. Ensure there is no fibre patchcord connected to the SHG or seed output fibre coupler.
2. Adjust the incident power before fibre coupler to a few tens of milliwatts. Refer to the test report for a suitable input power.
3. Verify that the incident beam is centred on the fibre coupler aperture and approximately normal to the end of the MSHG chassis, by walking MO1 & MO2 (seed output) or MO3 & MO4 (SHG output).
4. Connect the fibre patchcord to the fibre coupler, and the visual fault locator to the fibre output end, and switch the visual fault locator on.
5. The visual fault locator will emit a counter-propagating beam along the fibre which can be used to spatially match the incident beam with the fibre mode. Fibre couplers typically use chromatic aspheric lenses for coupling into the fibre, so the focal length is strongly wavelength dependent. The beam from the visual fault locator may be diverging or converging even though the fibre coupler focus is correctly adjusted for the operating wavelength. Ensure that the incident beam and the visual fault locator beam are well overlapped by walking the relevant mirror pair. Adjust MO1/MO3 to overlap the output beam with the fault locator beam immediately in front of the fibre coupler, then use MO2/MO4 to overlap the fault locator beam with the output beam just in front of the seed isolator (seed beam) or dichroic mirror D1 (SHG beam). Iterate until no improvement is possible.
6. Remove the visual fault locator from the output of the fibre, and attach a power sensor to allow monitoring of the fibre coupling efficiency.

7. Walk the relevant mirror pair to optimise output power out of the fibre.

8. The astigmatism and ellipticity of the output beam is only very weakly dependent upon power. It should be possible to achieve close to the specified fibre coupling indicated in the MSHG test report (within 10%) even at low power.

   When coupling the SHG beam, note that the output is strongly dependent upon the fundamental input power, and small fluctuations in the input can lead to much larger fractional changes in the output. It is important to check the input power to ensure it has not changed when calculating the fibre coupling efficiency.

9. If a fibre coupling efficiency of 50% is not achievable, check both ends of the fibre patch cord for contamination or damage with a fibre microscope. The fibre coupler collimation focus may also need some adjustment (see section 7.2).

10. Increase the fundamental power slowly, verifying that the coupling efficiency remains high. Some beam walking may be necessary at higher power.

7.2 Fibre coupler collimation

It will not normally be necessary to adjust the focus of the fibre coupler. The fibre coupler was optimised by MOGLabs for best efficiency when the MSHG is at typical operating power, for the fibre core specified in the MSHG test report. If a different fibre type is required, either different mode-field diameter or different end-cap, the procedure below can be used to optimise the focus.

The MSHG by default is configured with a MOGLabs fibre coupler, but in some cases a Schäfter-Kirchhoff fibre coupler may be used. If your system is configured with a Schäfter-Kirchhoff fibre coupler, you will have been provided with an eccentric key for focus adjustment. If you believe you need to adjust the focus, please contact MOGLabs first.

MOGLabs MGQA fibre couplers have both a coarse and fine adjustment mechanism. Coarse adjustment of the fibre collimator should not be necessary and can be difficult to achieve without the appropriate light source, as chromatic shift of the fibre collimator becomes significant at short wavelengths. It is recommended that if coarse adjustment of the fibre collimator is needed, then the harmonic output should be directed out of the chassis by insertion of a mirror in the beam path, and coupled externally into a fibre with an external fibre coupler. A high efficiency coupler is not necessary, only a small amount of light is needed in the fibre, so that fibre can then be used to inject light backwards into the main fibre coupler to allow focus adjustment at the exact wavelength of the MSHG. Contact MOGLabs for advice if coarse adjustment is needed.

A C-shaped spanner provided by MOGLabs(Figure 7.2) is used to adjust the fibre-collimator focus. The focus adjustment has approximately a half turn of adjustment. If screwed too far in (too much clockwise adjustment, viewed from the fibre side) it will reach an inbuilt stop in the mechanics, preventing damage. If screwed too far out (anti-clockwise) the focus ring will disengage and further adjustment will not change the lens position.

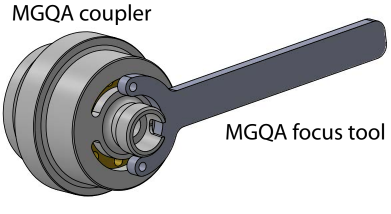


Figure 7.2: Fibre coupler and focus adjust tool.

If adjustment of the focus is necessary and the focus is far from the initial position set by MOGLabs, approximate collimation can be achieved by fully screwing in (clockwise) the focus adjustment ring until it stops, then backing out by a tenth of a turn.

1. Walk the relevant mirror pair to optimise fibre coupling efficiency

(see step 7 of 7.1 above). Note the efficiency achieved.

2. Adjust the collimation lens focus clockwise by a very small amount (a few degrees at most) using the adjustment tool provided.
3. Reoptimise the fibre coupling efficiency by walking the mirror pair again.
4. Iterate the above two steps, with clockwise or anti-clockwise rotations of the focus as required, until the maximum coupling efficiency is achieved.

7.3 Polarisation control

By default, the fibre coupler key will be oriented horizontally at the factory, and a half-wave plate installed before the fibre coupler will be adjusted to ensure good polarisation alignment with the fast axis of a polarisation maintaining fibre. The polarisation extinction ratio is typically greater than 25 dB, but always greater than 20 dB. Note that the fast axis of polarisation maintaining fibres can be misaligned by a few degrees from the fibre key, and therefore changing fibres may require a slight adjustment of the waveplate angle to optimise the extinction ratio.

7.4 Common fibre coupling issues

A frequent cause of low coupling efficiency with high powered laser systems is fibre facet damage. If the coupling is less efficient than expected, inspect the end facets of the fibre using a fibre microscope inspection tool, and clean and polish as necessary. Try reversing the fibre patchcord if the ends are symmetric, or a new patchcord.

Another common problem is power-dependent variation in laser beam astigmatism and thermal misalignment. Changing the operating power of the MSHG can cause small thermal drifts in the cavity output. Fibre coupling should be re-optimised at high power.

A. Specifications

A.1 General

Parameter	Specification
Mechanical	
Dimensions	300 × 300 × 93 mm (LxWxH)
Weight	X to X kg
Operating temp	15 – 35°C, non-condensing
Cooling	M5x0.8 thread for 4 mm diam quick-fit connections (e.g. SMC KQ2S06-M5A). ***NOTE:*** Use distilled water only (not deionised). The 6061 aluminium chassis will react with many cooling additives.

A.2 Seed Laser

Parameter	Specification
Wavelength/frequency	
Wavelength	760 – 1560 nm, diode dependent. Please contact MOGLabs for availability.
Linewidth	Typically < 100 kHz
Tuning range	Diode dependent; 5 nm to 50 nm
Sweep/scan	
Scan range	10 to 30 GHz
Mode-hop free	5 to 30 GHz
Piezo	$5 - 9\,\mu$m @ 150 V, 200-350 nF (typical) or $2.6\,\mu$m @ 150 V, 550 nF (typical)
Cavity length	$10 - 15$ mm (LEL), 22 mm (CEL)

Parameter	Specification
Output	
Output isolation	Double-stage Faraday isolator
Output	Free-space and/or FC/APC PM connector
Beam	3 mm × 1.2 mm ($1/e^2$) typical
Polarisation	Vertical linear 100:1 typical
Thermal	
TEC	±14.5 V 3.3 A $Q = 23$ W standard
Sensor	NTC thermistor 10 kΩ, $\beta = 3988$, standard AD590, 592 optional
Stability at base	±1 mK (controller dependent)
Electronics	
Protection	Diode short-circuit relay; cover interlock connection; reverse diode
Indicator	Laser ON/OFF (LED)
Connector	MOGLabs Diode Laser Controller single cable connect
Modulation input	Active (AC and DC coupled) or RF bias tee

A.3 Tapered Amplifier

Parameter	Specification
Wavelength/frequency	
Wavelength	760 – 1560 nm, diode dependent. Please contact MOGLabs for availability.
Linewidth	Determined by seed laser
Tuning range	Diode dependent; 10 nm to 30 nm

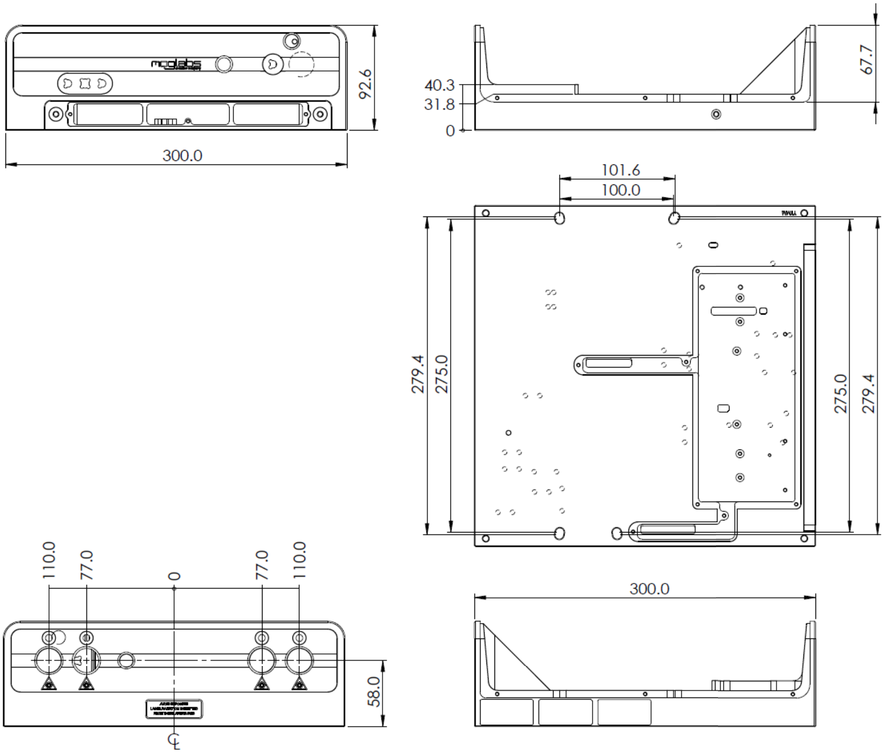
Parameter	Specification
Thermal	
TEC	±14.5 V 3.3 A $Q = 23$ W standard
Sensor	NTC thermistor 10 kΩ, $\beta = 3988$, standard AD590, 592 optional
Stability at base	±1 mK (controller dependent)
Electronics	
Protection	Diode short-circuit relay; cover interlock connection; reverse diode
Indicator	Laser ON/OFF (LED)
Connectors	MOGLabs Laser Diode Driver dual cable connect

A.4 Linear Doubling Cavity

Parameter	Specification
Doubling	
Wavelengths	370 nm to 445 nm; 445 nm to 510 nm; 510 nm to 560 nm. Others on request
Cavity range	Typically ±20 nm at harmonic
Crystal range	Typically ±10 nm at harmonic, larger range available on request
Piezo scan	Typically 30 GHz at 399 nm
Efficiency	Over 60% demonstrated (1.7 W at 422 nm from 2.7 W at 844 nm)
Crystal	System-dependent, user-replaceable
Polarisation	Linear typically $> 200:1$
Residual infrared	TBD
RIN	$< 0.2\%$ rms

Parameter	Specification
Input/output	
Input	Freespace coupling from TA
Input isolation	Double-stage Faraday isolator
Output	Free-space and/or FC/APC PM connector
Beam quality	Near diffraction limited, $M^2 < 1.05$
Piezo and TEC	
Piezo drive	150 V, 10 mA, digital + analogue PID servo
Piezo bandwidth	First resonance > 30 kHz
Temperature	7.5°C – 49.5°C ±0.001°C resolution
Stability	Better than ±1 mK/°C
TEC power	±2 A, ±12 V (24 W)
Sensor	NTC thermistor 10 kΩ
Electronics	
Control system	Fully self-contained digital
Locking	FM demod standard; PDH optional
Communications	USB-C, 10/100 ethernet
Software	SCPI-like text-based command interpreter; Windows GUI app
Connectors	2 x SMA 0 to 2.5 V piezo mod input and multipurpose input

B. Chassis dimensions



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