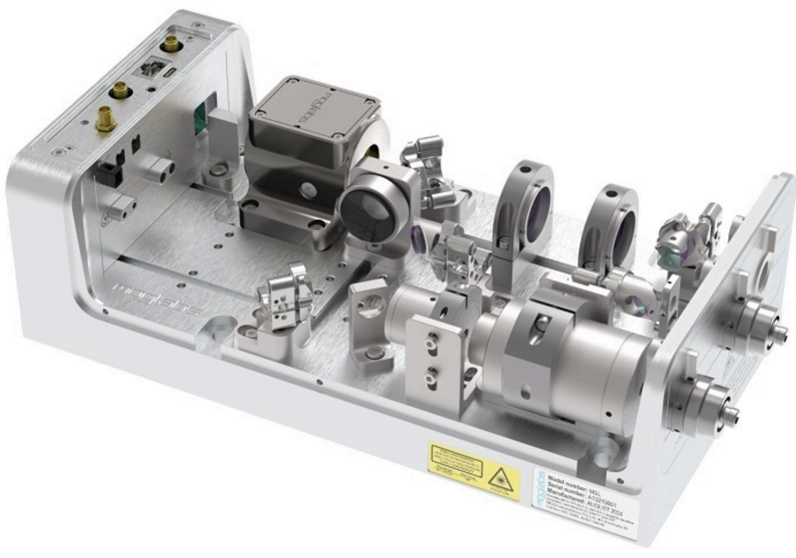
moglabs
a santec company

Linear frequency doubling cavity

Model MSL



Revision 1.08

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Preface

The MOGLabs MSL frequency doubler can provide more than 1 W of output with efficiency of up to 85%, for applications including optical lattice clocks, atom cooling, Bose-Einstein condensation, ion trapping, and quantum technology.

Compared to more traditional bow-tie doublers, the linear enhancement cavity is inherently stable and insensitive to vibration, with no adjustability of the cavity alignment. The fundamental cavity mode is non-astigmatic and circular, enabling near-perfect mode matching of the input light to the cavity, and the highest possible conversion efficiency.

The MOGLabs MSL is versatile and can be configured to work with fundamental wavelengths from 740 to 1300 nm. The range of wavelengths for a given configuration of mirrors and lenses is up to 70 nm for the input, and doubling crystals are available with similar range. Astigmatism correction is standard on the harmonic output, and fibre coupling is also available with typical fibre coupling efficiencies above 70%.

The MOGLabs MSL includes the internal MOGLabs mLC electronics for spanning and locking the cavity to resonance. Standard locking is using a piezo modulation and demodulation method (FM-demod). Hansch-Couillaud or Pound-Drever Hall locking are also available.

Please let us know if you have any suggestions for improvement of our products or of 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 MSL, 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

The MOGLabs MSL is a frequency-conversion device, not a laser. It is the responsibility of the user to ensure that the fundamental input laser meets the required laser safety specifications.

Light output from the MSL 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, both from the fundamental input and the harmonic output.Avoid looking directly into either 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 MSL 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 60825-1:2007 mandates warning labels that provide information on the wavelength and power of emitted laser radiation, and which show the aperture where laser radiation is emitted. Figures 1 and 2 show examples of these labels and their location on the MSL.

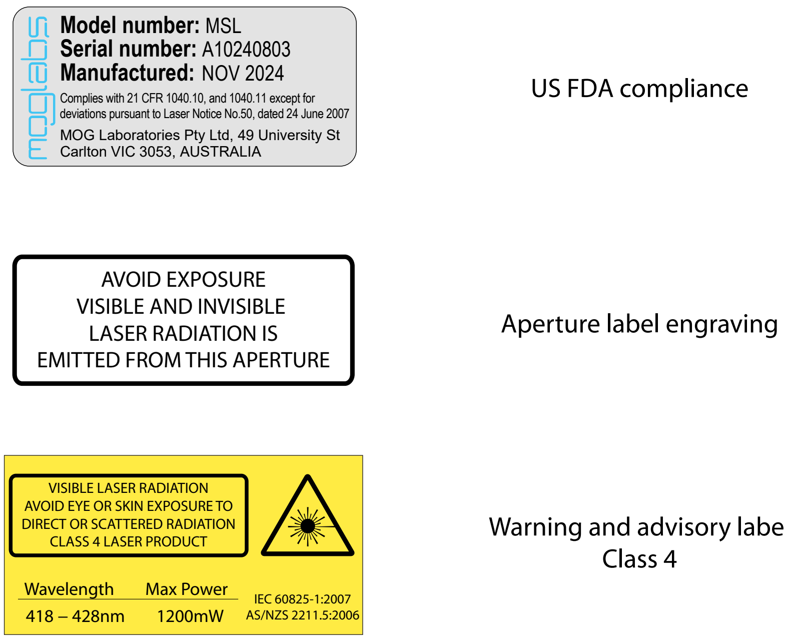


Figure 1: Warning advisory and US FDA compliance labels.

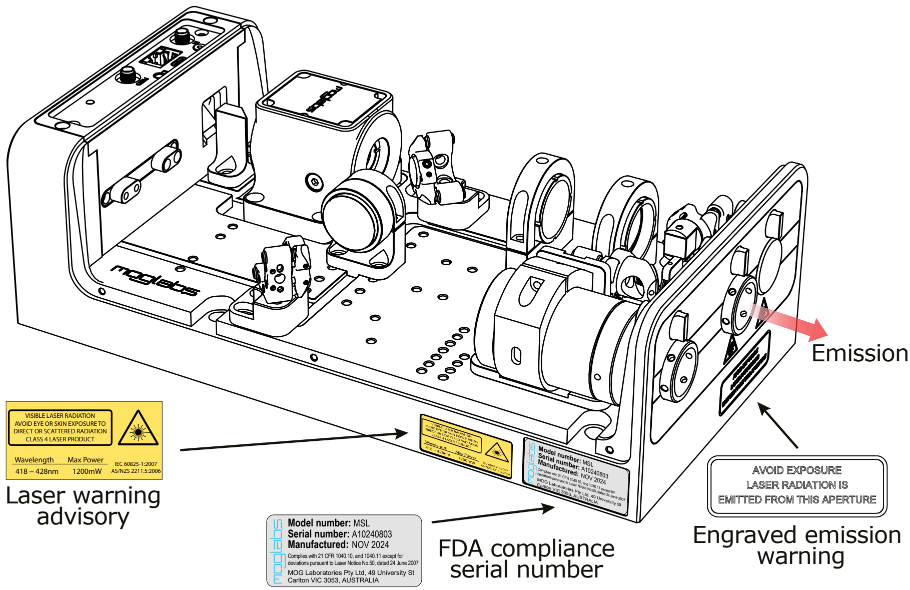


Figure 2: Schematic showing location of warning labels compliant with IEC 60825-1:2007 and the US FDA, and engraved emission warning.

Contents

1. Introduction

The MOGLabs MSL 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). A Faraday isolator on the input prevents optical feedback to the input fibre facet and optical source laser. Fibre coupling options are available for the harmonic output.

1.1 Linear cavity

The MOGLabs MSL 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. Near-perfect mode matching to the beam from the input fibre is easily achieved.
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.

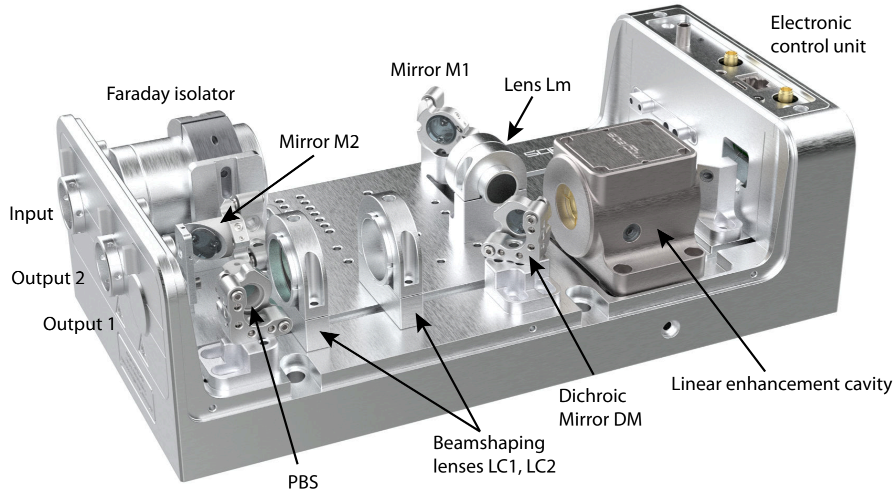


Figure 1.1: Render of the MSL with linear enhancement cavity. Steering mirror M1, mode-matching lens Lm, and dichroic mirror DM are used to align and focus the input light into the cavity. A beam pickoff may be added for directing light into one of the photodetectors to generate a cavity locking error signal. Lenses LC1 and LC2 are used to collimate the SHG output and correct for astigmatism, and the PBS (polarising beam splitter) ensures good linear polarisation. For systems with fibre out, the PBS and mirror M2 are adjusted to align into the output fibre coupler.

1.2 Optical layout

The standard MSL configuration is shown in figure 1.2. In normal operation the fundamental input light is delivered by single-mode polarisation maintaining fibre. It exits the fibre through a collimation lens and through the input Faraday isolator and a half-wave retarder to rotate the polarisation to vertical. The half-wave retarder is typically attached to the isolator on the input side but may be attached on the output side, or mounted separately to the chassis.

The beam reflects from mirror M1, propagates through mode-matching lens Lm, and reflects from dielectric mirror D1 to a waist at the flat cavity mirror. Light transmitted by the cavity is used for alignment and FM-

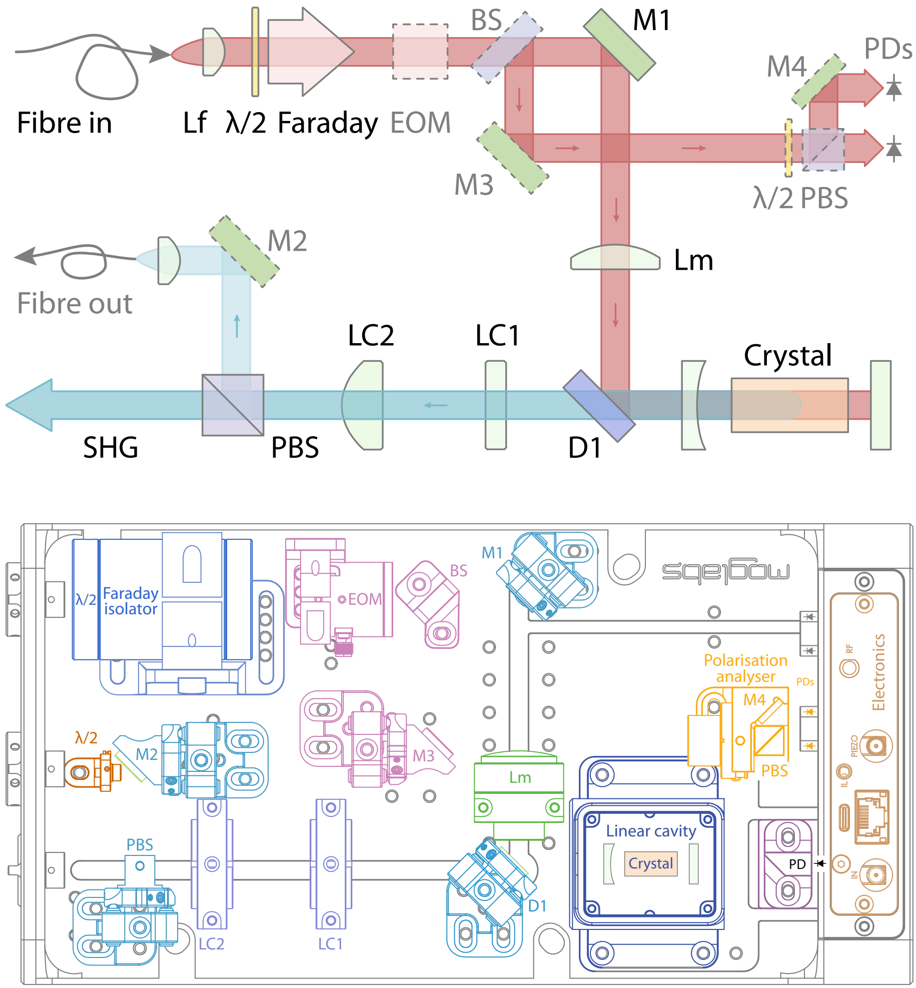


Figure 1.2: Schematic and layout of the MSL with fibre input, collimation lens Lf, half-wave retarder, Faraday isolator, and mode-matching lens Lm. Mirrors M1 and dichroic D1 direct the input into the cavity and separate the second harmonic output. Cylindrical lenses LC1 and LC2 collimate the SHG output and correct for astigmatism. Photodetector PD detects modulated transmission for locking the cavity to resonance. Options include fibre-coupled output (mirror M2), PDH locking (BS, M3 and EOM) or HC locking (BS, M3, and polarisation analyser).

demod locking.

The second harmonic generated (SHG) in the non-linear crystal is transmitted by the curved input coupling mirror. The SHG beam is collimated by orthogonal cylindrical lenses LC1,2 which allow correction of astigmatism and ellipticity.

For fibre coupled output, the harmonic is reflected by a polarising beam splitter (PBS) and mirror M2 into a fibre coupler. Depending on user-requirements, the PBS can be replaced with a mirror or partially reflective mirror.

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 MSL 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 MSL 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 aperture should be blocked with a suitable power meter or beam dump.

5. 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 comms and USB-C power delivery.

6. Run the MOGLabs mLC application[2] and connect to the controller.

7. Connect the laser using appropriate polarisation-maintaing single-mode end-capped fibre. Check the input fibre specification against that specified in the MSL factory test report.

[1] For safety reasons, please contact MOGLabs before using an alternate power supply.
[2] Check the MOGLabs website for firmware and app updates.

2.2 First light

The fundamental input has been aligned in the factory to the cavity and only very minor adjustments should be required. Before operating the laser system at high power, verify that the fundamental is well coupled to the cavity and the alignment was not perturbed during transport.

1. Run the `mLC` app and ensure the temperature setpoint matches the value in the MSL test report and activate the temperature controller by sliding the switch to the right (see fig. 2.1).
2. Switch the `mLC` display window to the logging window (fig. 2.1) and ensure that the cavity temperature stabilises to the desired set point.
3. Engage the piezo controller. Set the span to the typical ‘full free spectral range’ value listed in the test report and engage the piezo

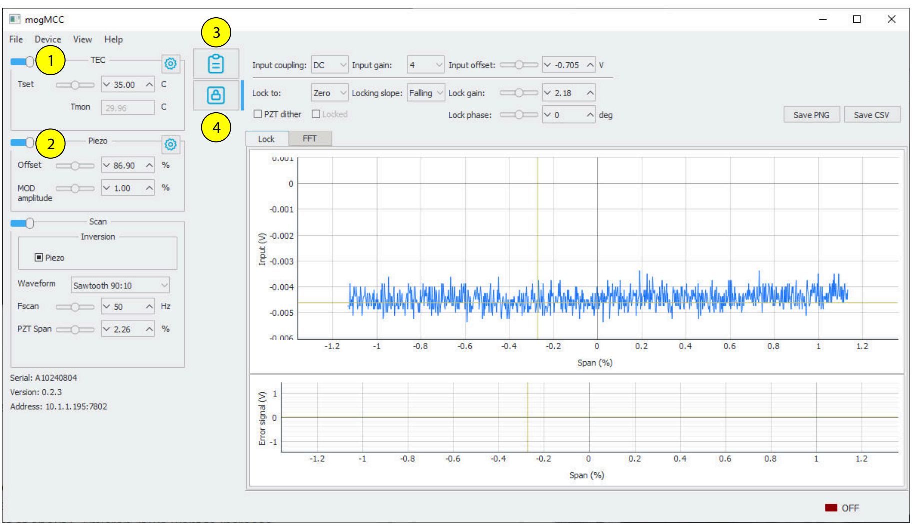


Figure 2.1: The `mLC` app. Horizontal sliders activate the (1) temperature and (2) piezo controllers. The cavity temperature setpoint and piezo scan parameters can be adjusted. Pushbuttons allow switching between (3) logging and (4) photodiode signal.

controller, as indicated in figure 2.1 Toggle the mLC display window back to the lock screen.

4. Measure the fundamental power before and after the input isolator and compare the isolator transmission efficiency to the MSL test report. Verify that the input beam is centred on the isolator. If the transmission is considerably lower than expected and the beam is well centred, the polarisation of the fundamental may not be aligned to that of the isolator. If this is the case, rotate the half wave plate on the input of the isolator. If this does not improve the transmission, contact MOGLabs.

5. Using a fluorescent IR card, trace the beam path through the chassis. Ensure the beam is well centred on the mode-matching lens and on the input coupler of the doubling cavity. Note that if the chassis is configured for PDH or HC locking, there will be a reflection of a few percent of the input light off the wedged pickoff that will be directed out of the chassis. Ensure there is an appropriate beam dump for this reflection whenever the chassis lid is removed.

   If there is any concern that the system alignment has been disturbed in shipping, please contact MOGLabs.

6. Increase the input power to 100 mW, and monitor the transmitted

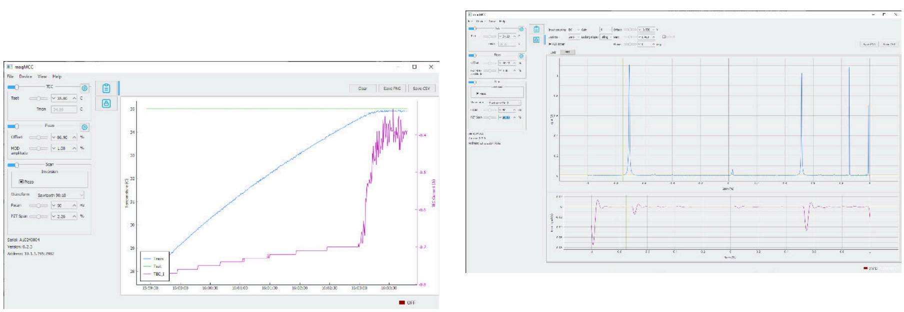


Figure 2.2: The logging window, displayed on the left, showing the temperature converging to the setpoint, and the photodetector signal window, displayed on the right, showing a typical transmission signal for a well aligned cavity.

photodetector signal on the mLC software. Compare the signal to your MSL test report.

If the alignment is good you should see a few distinct sharp peaks with no small peaks in between (fig. 2.3). Small misalignment is apparent from additional smaller peaks between the main resonances. These are higher-order transverse spatial modes. If the alignment is very poor, there may not be any particularly large resonance peaks.

7. If necessary, 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, refer to section 4.1 to optimise the alignment.

8. Increase the fundamental power to a few hundred milliwatts so that the second harmonic is clearly visible at the output of the cavity.

9. 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, verify that the 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 persst, it may be necessary to adjust the crystal angle as described in section 4.2.

10. Lock the cavity as described in the following chapter.

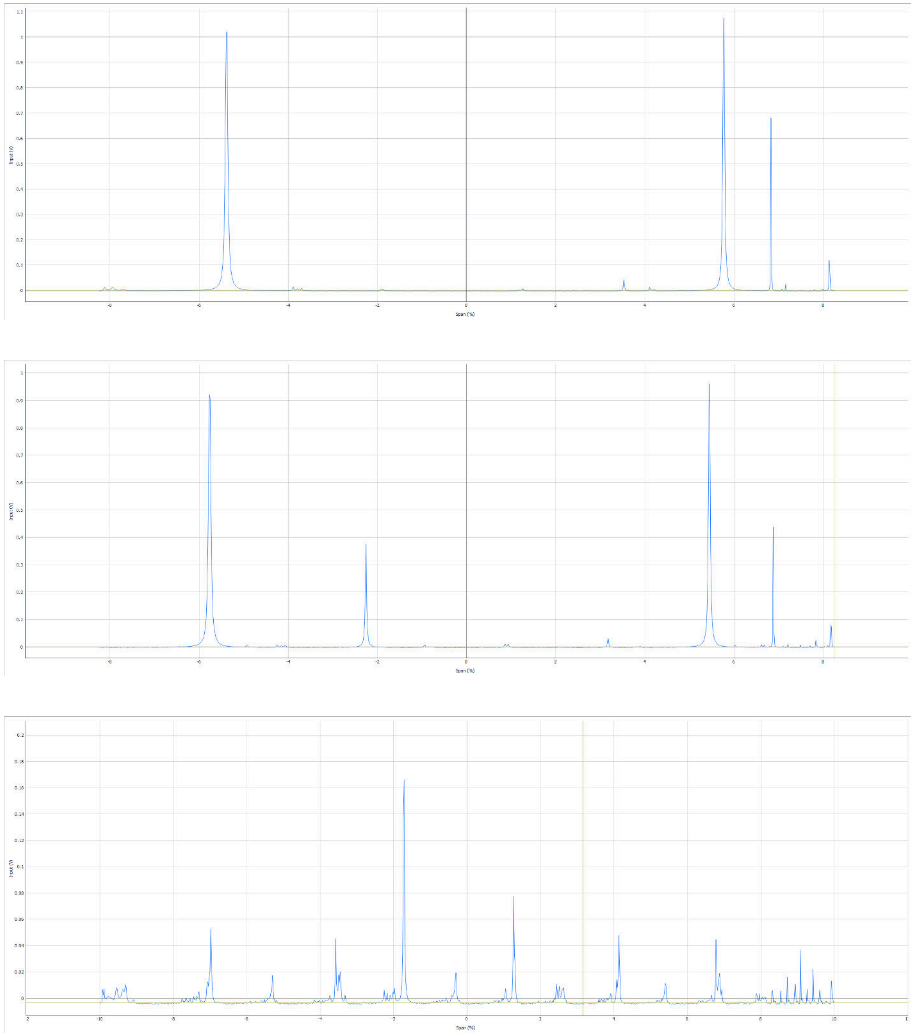


Figure 2.3: Cavity spectra for good alignment(top), small misalignment(middle), and very poor alignment(bottom).

3. Cavity locking

The MOGLabs MSL can be configured to lock the resonance frequency of the enhancement cavity to the frequency of the input light using any of three techniques:

1. Frequency modulation/demodulation (FMDM)
2. Hänsch-Couillaud (HC)
3. 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.

3.1 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 is 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.

3.1.1 Using FMDM

FMDM can be activated by checking the *PZT dither* tick box in the mLC app (fig. 3.1). 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 relating to FMDM locking specifically:

Phase Set the scan range to <5% of full span and adjust phase to maximise the slope of the error signal.

Gain Analogue gain of the photodetector signal.

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.

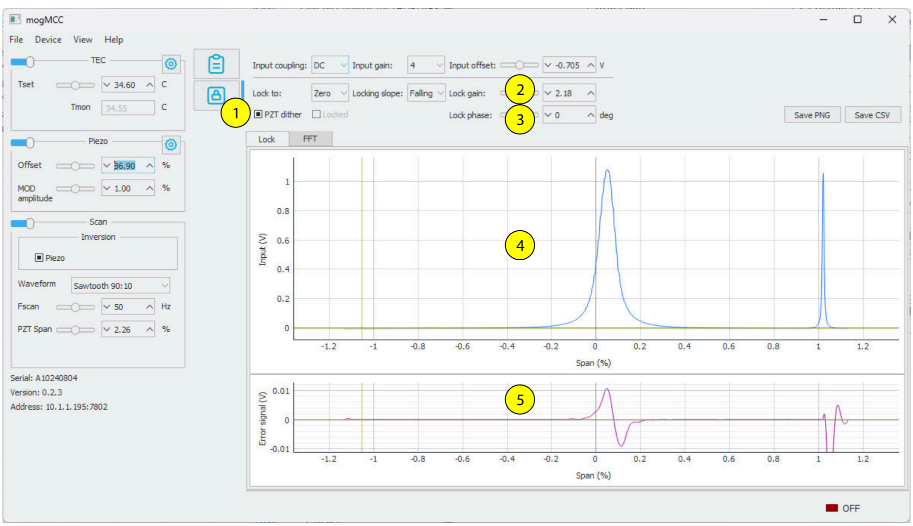


Figure 3.1: The mLC main application window when configured for FMDM locking, showing the location of (1) PZT dither enable, (2) input gain adjust, (3) phase adjust, (4) cavity transmission and (5) error.

3.2 Optimising the cavity lock

Additional locking control parameters apply to all locking techniques:

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.

To optimise the lock performance:

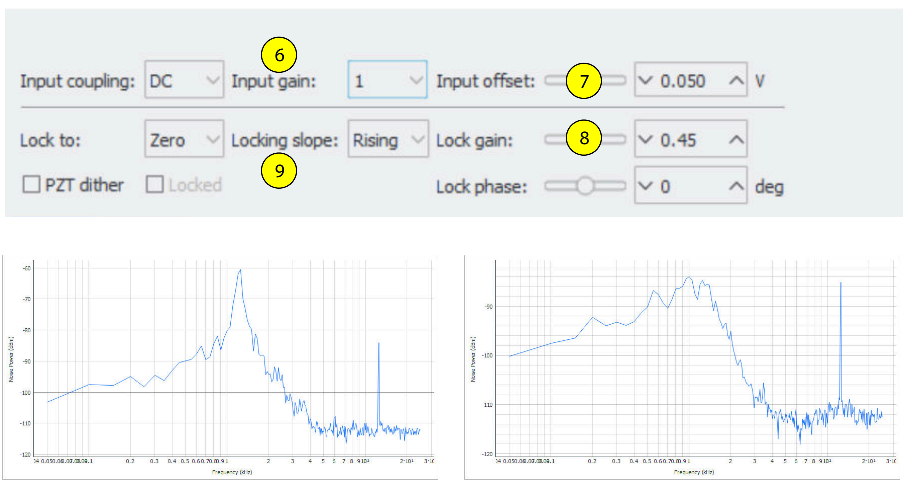


Figure 3.2: mLC locking controls: (6) input gain, (7) input offset, (8) lock gain, (9) locking slope, and error signal spectrum when the control loop gain is too high (lower left) and optimal (lower right).

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.
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.

[1] Figure 3.2 shows two example noise spectra, one of a control loop with too much gain and one with optimal gain.

3.3 Hänsch-Couillaud

Hänsch-Couillaud [1] (HC) locking uses frequency-dependent polarisation changes in the light reflected by the cavity. HC locking is a DC technique, without modulation, and hence there is no modulation on the amplitude or frequency of the output light. The primary advantage of HC is the large capture range, which can be many times larger than the cavity linewidth, allowing for a very robust lock. The trade-off is that, as with all DC locking techniques, the lock point can drift due to the influence of many external effects including variations in the power, polarisation, alignment, and wavelength of the input light, as well as temperature variations changing the birefringence of any of the optics in the signal generation path.

The overall conversion efficiency is inherently reduced because a pickoff (BS in figure 1.2) must be inserted in the incident beam path to monitor the reflected signal, and the input polarisation must be misaligned from optimum because both components of polarisation are required to generate the error signal. Increased misalignment of the input polarisation increases the signal-to-noise ratio of the error signal, but reduces harmonic conversion efficiency because the misaligned polarisation does not contribute to SHG. The input polarisation to the cavity is set by the output of the isolator and the half-wave retarder. The optimal polarisation misalignment is set at MOGLabs, and should not be adjusted without consultation.

3.3.1 HC error signal generation

The optical configuration for HC locking is shown in figure 1.2 with optional components added to the default FMDM setup: a beamsplitter (BS) samples the *reflected* beam, and M3 directs that light through a polarisation analyser (PBS and M4). The error signal is the difference in signals from the two photodetectors.

A waveplate on the input of the polarisation analyser can be adjusted to control the shape and zero-crossing of the error signal which determins the locking frequency. Figure 3.3 shows the HC error signal for two angles of the waveplate. The crosses indicate the optimal lockpoint for harmonic generation. For the non-optimal orientation, the capture range is reduced, but the error signal offset can be adjusted to achieve the same SHG conversion efficiency and output power.

The error signal for HC locking is complex. For each spatial mode of the cavity, there are two zero crossings with opposite slopes, corresponding to the two different polarisations that are present within the cavity. As the doubling crystal within the cavity is birefringent, this leads to slightly different frequency resonant conditions for the two different polarisations and thus two zero-crossings.

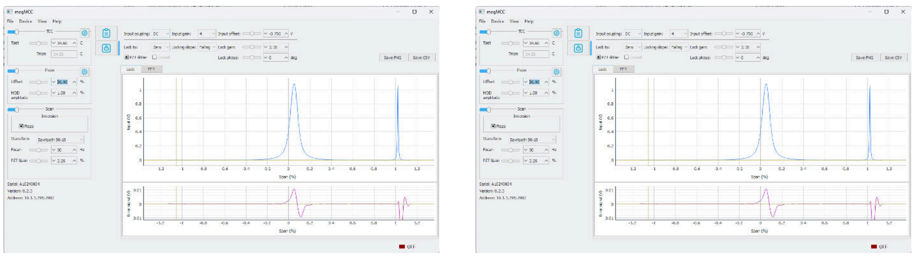


Figure 3.3: The HC error signal changes shape with variation of the waveplate in the polarisation analyser. Left: Optimised HC polarisation and alignment; the crosses show the optimal lockpoint, and the dashed lines indicate the capture range. Right: Imperfect waveplate angle.

3.3.2 Waveplate optimisation

For HC locking, the waveplate rotation controls the shape of the error signal, and is typically optimised for largest capture range.

1. With `mLC` app error *Offset* set to zero, rotate the waveplate so that the error signal is approximately centred about zero.
2. Lock the cavity with the current `mLC` error signal and measure the harmonic output power.
3. Apply small offsets to the error signal in the `mLC` app to maximise the harmonic output power.

4. Unlock the cavity, and rescan the piezo and note the optimal lock point; that is, the frequency at which the error signal crosses zero.

5. If the optimal lockpoint is centred (as in fig. 3.3(a)) then no further optimisation is needed.

6. If the optimal lockpoint location is closer to the turning points of the error signal (as in fig. 3.3(b)) make a small adjustment to the waveplate angle.

7. Relock the cavity to the fundamental and then reoptimise the output harmonic power by adjusting the error signal offset.

8. Once reoptimised, unlock and scan. If the zero crossing is closer to the centre of the error signal slope, continue with another iteration of rotating the waveplate as before. If worse, try rotating the waveplate in the opposite direct.

9. Iterate the above steps until the optimal lock point is well centred on the slope of the error signal.

3.3.3 Polarisation analyser alignment

Changes to the input beam alignment will affect alignment of the reflected signal into the polarisation analyser and distort and diminish the HC error signal. To realign the polarisation analyser:

1. Ensure the fundamental is well aligned to the cavity.

2. Remove the polarisation analyser optomechanics (fig. 1.2).

3. Use mirror M3 (fig. 1.2) to optimise the alignment of the reflected beam onto the photodetector directly behind the polarising beam splitter (PBS). To optimise the alignment, maximise the absolute value of the photodetector signal.

4. Reinstall the polarisation analyser mechanics and block the first photodetector, e.g. with a narrow strip of business card.

5. Rotate the polarisation analyser mechanics to optimise the signal on the second photodetector. The signal will have the opposite sign to the first photodetector signal.

6. Unblock the first photodetector and rotate the waveplate in front of the PBS to balance the photodetector signals. That is, with *Offset* set to zero in the mLC software, the error signal should be centred about zero.

7. Further optimise the waveplate alignment as described in the previous section.

3.4 Pound-Drever-Hall

Pound-Drever-Hall (PDH) locking [2] 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).

3.4.1 PDH error signal generation

The optical configuration is similar to that for HC locking, as shown in figure 1.2). A beamsplitter (BS) 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 in fig. 1.2). 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`).

4. Full realignment

Full alignment consists of coupling the fundamental input beam to the enhancement cavity, followed by alignment of the crystal to the cavity.

4.1 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 visual fault locator (fig. 5.1).
2. 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.
3. An IR fluorescent card for tracing the path of the fundamental light.
4. A camera (CCD or CMOS) to observe the mode structure of the light transmitted by the cavity.

4.1.1 Initial alignment

Typically the MSL will be used with infrared light which is difficult to see. In that case, it can be helpful to instead align using light injected from a visual fault locator. Ignore any divergence or convergence which can be related to chromatic shift of the fibre coupler collimating lens at the visual fault locator wavelength (typically 650 nm) rather than the fundamental wavelength.

1. Connect the fault finder to the input fibre.

2. Trace the beam through the input isolator and onto the first mirror, ensuring the beam is not clipping. If the beam is clipping, check with the fundamental light to ensure the clipping is related to the chromatic aberration mentioned above.

3. Adjust mirror M1 so that the beam is centred on the cavity and on the focussing lens, and check that it is not clipping on the dichroic mirror.

4. Adjust the dichroic mirror D1 until the beam is transmitted by the cavity.

5. Centre the beam on the back mirror of the cavity. First adjust the horizontal actuator on the dichroic mirror 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.

6. Using a small white card, look for the back reflection off the cavity, first near the output of the input isolator. If no reflection can be found then try closer to the cavity, for example in front of the focussing lens. To help identify the back reflection, make very small adjustments to the dichroic mirror (D1) to see the reflection move around.

7. Make small adjustments to the dichroic mirror until the back reflection is aligned with the input beam at the entrance of the input isolator.

8. On the front face of the photodetector mechanics there is a small mirror that will direct the cavity transmitted beam vertically, out of the chassis. Place a camera sensor (without lens) in the path of the reflected beam.

9. Replace the fault finder with the fundamental laser and trace the beam using an IR card and/or imaging camera or nightvision camera. Ensure that the fundamental light is not clipped.

4.1.2 Coarse cavity alignment

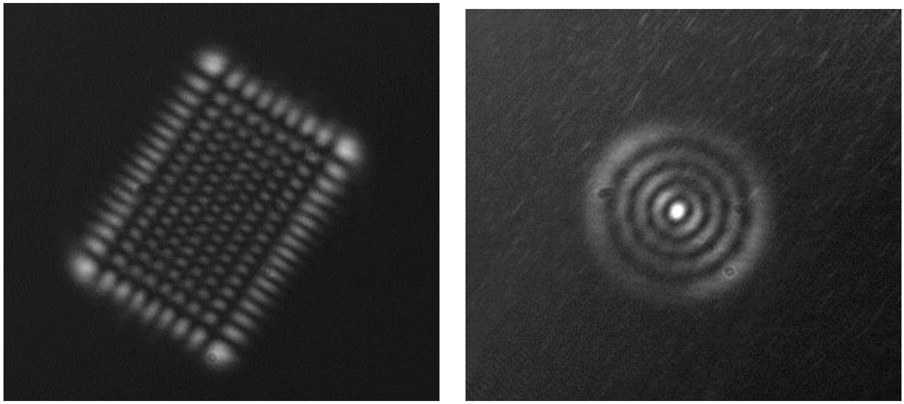


Figure 4.1: Images of light transmitted by the cavity, for higher order spatial modes. Left: Hermite-Gaussian. Right: Laguerre-Gaussian.

1. Adjust the fundamental laser such that about 100 mW is injected into the MSL.

2. Verify vertical polarisation after the isolator, using a polariser with a known transmission axis. 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.

3. Connect to the `mLC` controller and set the piezo scan range to $\approx 50\%$.

4. 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.

5. 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. 4.1).

4.1.3 Spatial modes

Visualisation of the spatial modes of the cavity is very helpful in guiding optimisation of the 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 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.

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

Figure 4.2 shows examples of images captured as the cavity is scanned. Initially a rectangular structure is expected (fig. 4.2, 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. 4.2, middle).

Similarly adjustment of D1 in the vertical direction is used to reduce the spread vertically (fig. 4.2, right). When both axes are optimised, the image should rotationally symmetric.

Finally, adjustment of the fibre coupler focus (with minor correction of the horizontal and vertical adjustment of the dichroic) reduces the overall spread of the centred Gaussian TEM_{00} transmitted beam.

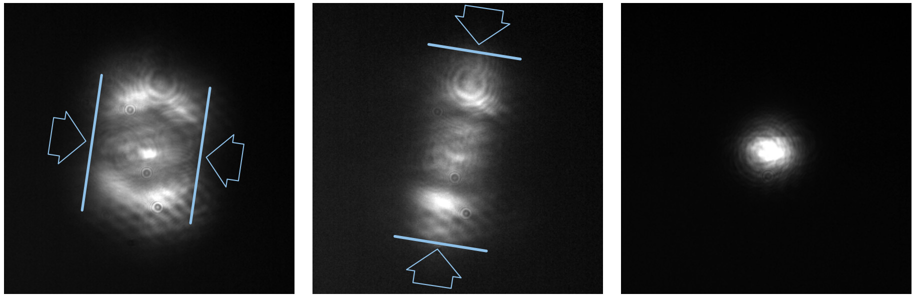


Figure 4.2: Images of the light transmitted by the cavity. Left: Poorly aligned, appearing as a rectangle. Middle: Adjustment in the horizontal alignment collapses the image to a line. Right: After vertical alignment the image is rotationally symmetric.

4.1.4 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. 4.3, left). 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.

The test report provided with the MSL will include a plot similar to figure 4.3, with five different 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 the 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 fibre coupler or coupling lens Lm). 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 MSL 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, unless using HC locking in which case about 2 to 3% of secondary polarisation should be retained.
3. Adjust the horizontal actuator of the dichroic. Referring to the MSL 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 M1 pair in the horizontal direction to minimise the peak height of the horizontal alignment mode.
6. Walk D1 and M1 in the vertical direction to minimise the vertical alignment mode.
7. Repeat horizontal then vertical walking until no further reduction in peak heightrs is possile. By the end of this process the alignment mode peak heights should be 1 or 2% of the main peak height and it remains to optimise the focus.

8. Make a small (5°) clockwise adjustment to the input fibre coupler focus (see section 5.2).

9. Adjusting the fibre coupler focus may affect horizontal or vertical alignment. Adjust only the horizontal and vertical actuators on the dichroic mirror D1 to reduce these modes.

10. If the focus mode peak height has decreased, continue to iterate the focus in the same direction until minimised. If the peak height has increased, rotate the fibre coupler focus adjustment anti-clockwise.

    The MSL test report shows the expected secondary peak height that can be achieved, typically 1 to 2% of the main peak height.

11. Revisit the alignment coupling as some small walking may be necessary, iterating the optimisation procedure above.

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 MSL test report, contact MOGLabswith this data (both csv and image) for further advice.

4.2 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. Understanding phase matching in non-linear optics is not required for successful operation of the MSL, but if interested, a quick web search will unearth many good explanations.

4.2.1 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

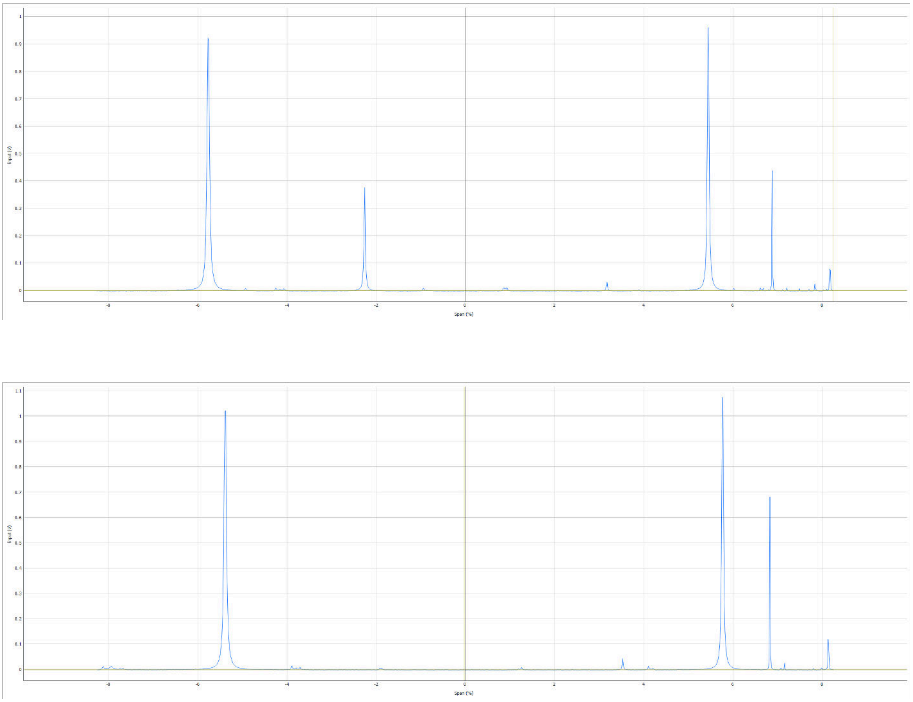


Figure 4.3: Top: cavity spectrum for a reasonably well aligned cavity. Polarisation, alignment and focus modes are present, but not particularly large. Below: spectrum after optimising the different alignments, showing greater power coupled into the fundamental Gaussian mode, and almost non-existent coupling to other modes.

matching angle rather than the cavity axis, leading to multiple low-power exit beams.

The MOGLabs MSL provides crystal angle adjustment of ±2°, corresponding to a wavelength range of up to ±20 nm of the harmonic. Figure 4.4 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 screws 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.

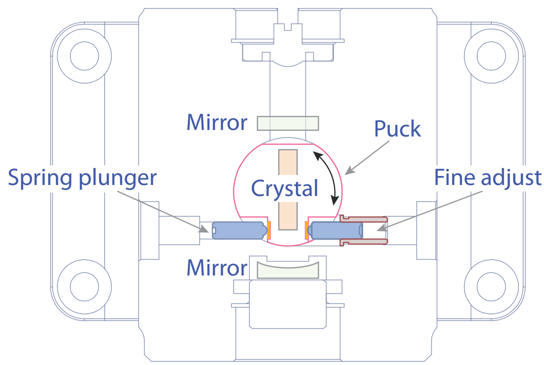


Figure 4.4: Cross section of enhancement cavity at the plane of the crystal adjustment screws, as seen from above. The crystal angle is controlled by the fine threaded actuator (right) pushing against the spring plunger (left).

4.2.2 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° chane in angle. Note that the MSL 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.

4.2.3 Optimising phase matching

1. Set the cavity temperature to the value specified in the MSL test report.

2. Ensure the cavity is well aligned to the fundamental input (section 4.2).

3. Tune the wavelength of the fundamental to the desired wavelength for SHG. The fundamental laser should be single mode.

4. Increase the fundamental power to a few hundred milliwatts.

5. Set the piezo scan to span several free spectral ranges of the cavity.

6. Some SHG output should be apparent (fig. 4.5, left). If no SHG is visible, please contact MOGLabs: the crystal angle has probably 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. 4.5, 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 4.1.

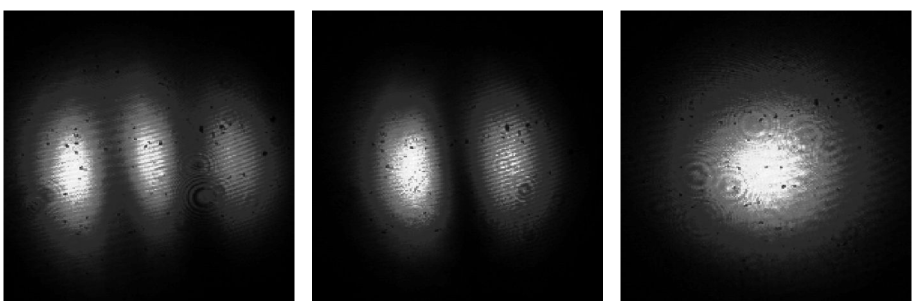


Figure 4.5: Left to right: output beam profile for poor crystal alignment, improved alignment, and optimum alignment.

4.2.4 Crystal translation and rotation

The crystal can be translated to expose different regions of the crystal as it ages and therewfore increate 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 should only be attempted in a clean dust-free environment with low humidity. Wear optics grade powder free gloves, and ensure the fundamental laser is 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. If need be, slide the crystal mount a few millimetres towards the input mirror before sliding the crystal mount to the other side of the puck Afterwards slide the crystal mount back towards the back cavity mirror, to within 1 mm.

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 4.2 to re-optimise the puck angle for maximum SHG.

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 4.2 to re-optimise the puck angle for maximum SHG.

5. Fibre coupling

The free-space output beam of an MSL is almost diffraction limited, enabling fibre coupling efficiencies of 70% to 80% despite 8% Fresnel losses at the two fibre facets. Astigmatism correction is included, but for SHG wavelengths >530 nm the benefits are marginal. MOGLabsrecommends 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. 5.1).

Figure 5.1: 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.

5.1 Fibre alignment

The cavity output 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 output fibre coupler.

2. Adjust the fundamental power so that the SHG output power is a few tens of milliwatts. Refer to the test report for a suitable input power.

3. Verify the doubled output is centred on the fibre coupler aperture and approximately normal to the end of the MSL chassis, by walking the PBS and M2 mirror pair.

4. Connect the fibre patchcord, 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 harmonic 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 harmonic. Ensure that the harmonic beam and the visual fault locator beam are well overlapped by walking the PBS, M2 mirror pair. Use the PBS adjustments to overlap the harmonic beam with the fault locator beam immediately in front of the fibre coupler, then use M2 to overlap the fault locator beam with the harmonic beam just in front of the dichroic mirror D1. 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 PBS, M2 mirror pair to optimise output power.

8. The astigmatism and ellipticity of the harmonic output beam are only very weakly dependent upon power. It should be possible to achieve

close to the specified fibre coupling indicated in the MSL test report (within 10%) even at low power.

The harmonic 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 5.2).

10. Increase the fundamental power slowly, verifying that the coupling efficiency remains high. Some PBS, M2 walking may be necessary at higher power.

5.2 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 MSL is at typical operating power, for the fibre core specified in the MSL 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 MSL 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 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 MSL. Contact MOGLabs for advice if coarse adjustment is needed.

A C-shaped spanner provided by MOGLabs(fig. 5.2) 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.

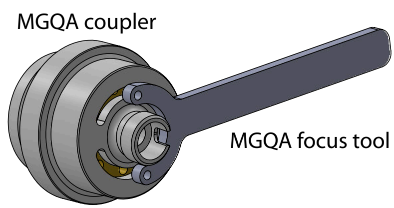


Figure 5.2: Fibre coupler and focus adjust tool.

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 M3, M4 mirror pair to optimise fibre coupling efficiency (see step 7). 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 M3, M4 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.

5.3 Polarisation control

The harmonic beam exiting the cavity is horizontally polarised. 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 30 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.

5.4 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.

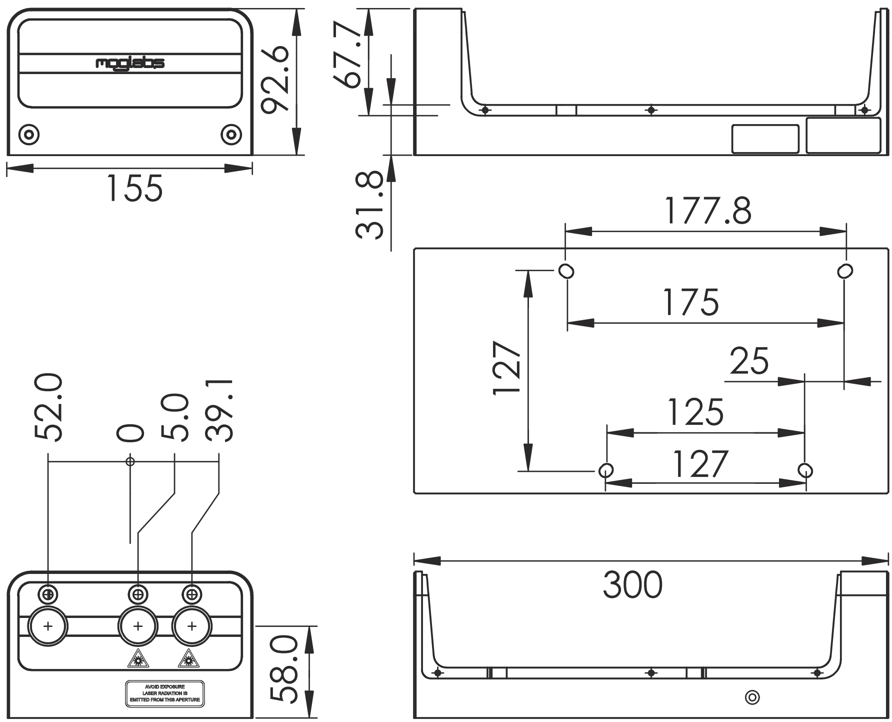
Another common problem is power-dependent variation in laser beam astigmatism and thermal misalignment. Changing the operating power of the MSL can cause small thermal drifts in the cavity output. Fibre coupling should be re-optimised at high power.

A. Specifications

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 90% demonstrated (1.1 W at 399 nm from 1.22 W at 798 nm)
Crystal	System-dependent, user-replaceable
Polarisation	Linear typically $> 200:1$
Residual infrared	TBD
RIN	$< 0.2\%$ rms
Input/output	
Input	FC/APC PM connector default
Input isolation	Single-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

Parameter	Specification
Cooling	M5x0.8 thread for 4 mm diam quick-fit connections (e.g. SMC KQ2S06-M5A). ***NOTE:*** Use distilled water only (not de-ionised). The 6061 aluminium chassis will react with many cooling additives.
Electronics	
Control system	Fully self-contained digital
Locking	FM demod standard; HC and 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 Interlock 3.5 mm stereo headphone style
Mechanical	
Dimensions	300 × 155 × 93 mm (LxWxH)
Weight	3 to 7 kg
Power	USB-C, 3.5 W typical
Operating temp	15 – 35°C, non-condensing

B. Chassis dimensions



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