Video Article

Construction and Characterization of External Cavity Diode Lasers for Atomic Physics

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Abstract

Since their development in the late 1980s, cheap, reliable external cavity diode lasers (ECDLs) have replaced complex and expensive traditional dye and Titanium Sapphire lasers as the workhorse laser of atomic physics labs[1,2]. Their versatility and prolific use throughout atomic physics in applications such as absorption spectroscopy and laser cooling[1,2] makes it imperative for incoming students to gain a firm practical understanding of these lasers. This publication builds upon the seminal work by Wieman[3], updating components, and providing a video tutorial. The setup, frequency locking and performance characterization of an ECDL will be described. Discussion of component selection and proper mounting of both diodes and gratings, the factors affecting mode selection within the cavity, proper alignment for optimal external feedback, optics setup for coarse and fine frequency sensitive measurements, a brief overview of laser locking techniques, and laser linewidth measurements are included.

Video Link

The video component of this article can be found at https://www.jove.com/video/51184/

Introduction

Measuring and manipulating the quantum state of atoms is at the heart of atomic physics and requires the ability to address specific transitions between atomic electronic states. For example consider rubidium, a typical and much used alkali atom. Here, the wavelength of light coupling the ground and first excited electronic state is ~780 nm (384 THz) and the excited state lifetime due to spontaneous emission is ~26 nsec giving an absorption linewidth of 6 MHz [4]. Thus, a light source with frequency stability of at least one part in 108 is required to reliably address this transition.

Before the development of ECDLs, dye lasers and Titanium Sapphire lasers were typically used for atomic physics. These are large, expensive, complex systems that offer optical gain over a large bandwidth and thus can be tuned to overlap an atomic transition. The potential to replace these gain media with a cheap, simple diode laser engineered with a bandgap matching the desired wavelength was recognized in the early 1980s[1,2]. Simple, easy to build designs which achieve 100 kHz linewidths were well understood and common place by the early 1990s[3,5,6]. Many different configurations and designs have been demonstrated each with advantages and disadvantages. Probably the most common configurations are the Littrow[3,5,7,8] and Littman 9 configurations. This discussion focuses on the simplest, the Littrow configuration shown in **Figure 1A**.

A number of tuning mechanisms are simultaneously used to achieve a high precision in the laser frequency. Firstly, a diode is required with a bandgap producing sufficient gain at the desired wavelength at an achievable operating temperature. The typical laser diode will have gain over several nanometers (THz). Secondly, a reflective diffraction grating is angle tuned to provide optical feedback into the diode at the desired wavelength. Depending on the grating, the diode, the focusing lens used and their alignment, the grating will select a frequency range of typically 50-100 GHz. The laser will oscillate at a wavelength resonant with the external laser cavity (between the diode rear facet and the grating). Tuning this cavity length across a wavelength allows the laser to be tuned across a free spectral range ($c/(2L)$) around the grating gain peak where c, is the speed of light and L, is the cavity length, typically 1-5 cm (*FSR* 3-15 GHz). When two cavity modes are a similar wavelength from the peak grating feedback wavelength the laser may run multimode. As the oscillating cavity mode is tuned further from the gain peak than its neighboring mode the laser will mode hop limiting the tuning range. The behavior of the cavity modes with respect to the grating mode can be seen in **Figure 3**. The mode hop free tuning range is a key performance metric for an ECDL. By simultaneously tuning the grating angle and the cavity length it is possible to continuously tune across many free spectral ranges without mode hops, making locating and locking to spectral features much easier[8]. Electronic tuning of the optical path length of the cavity for locking may be achieved by a combination of tuning the grating angle/position using a piezo actuator (**Figure 1A**) (scanning bandwidth ~1 kHz) and tuning the diode current which primarily modulates the refractive index of the diode (scanning bandwidth ≥100 kHz). Using laser diodes rather than anti-reflection (AR) coated gain chips for the gain medium adds the additional complication of adding the laser diode internal cavity response which may have a typical free spectral range of 100-200 GHz. In this case the cavity must be temperature tuned to match the response from the grating. Using a laser diode rather than an AR coated gain chip will dramatically reduce the mode hop free tuning range unless there is a means to synchronously tune the diode current or temperature. Finally, to achieve a linewidth better than 100 kHz careful attention must be paid to eliminate other noise sources. This requires careful mechanical design of the mounts to minimize acoustic vibration, *mK* level temperature stabilization, *rms* current stability of the diode at the ≤30 nA level and careful tuning of the gain of all locking loops[10]. Selecting the proper electronics for the application is just as important as the laser and optics design. A list of diode controllers and specifications can be found in **Table 1**.

Once stable lasing has been achieved, the next requirement is to lock the laser frequency to a reference such as an atomic transition, an optical cavity or another laser. This removes the effects of slow drifts such as small temperature fluctuations, essentially eliminating noise for frequencies within the bandwidth of the locking loop. There are a myriad of locking techniques that have been developed for obtaining an error signal, each suited for a particular reference system. An error signal for phase locking two lasers can be obtained by mixing the two lasers on a beam splitter. Pound-Drever hall[11] or tilt-locking[12] can be used to lock to a cavity. To lock to an atomic absorption line DAVLL[13] or saturated absorption spectroscopy[3,14] in combination with current modulation[10], Zeeman modulation[10], or tilt-locking[15] may be used.

The locking of an ECDL to a rubidium transition using Zeeman modulation of saturated absorption in a vapor cell will be described here. If a low intensity beam passes through a rubidium vapor cell at room temperature and the frequency is tuned in the vicinity of the 780 nm atomic transition a number of Doppler broadened absorption features ~500 MHz wide will be observed rather than the 6 MHz wide natural linewidth (calculations for natural and Doppler linewidths can be found in Foot[16]). If, however, this beam is retro reflected, the second pass will have less absorption on resonance as atoms with a zero longitudinal velocity have already been partially excited by the first pass[17]. Other frequencies will be absorbed by different velocity populations on each pass and therefore absorption will not be saturated. In this way an apparent transmission feature overlaid on the Doppler broadened absorption at transitions with a width about the natural linewidth can be obtained. This provides a sharp absolute frequency reference to lock to. The frequency of the atomic transition may be modulated using the Zeeman effect by dithering the magnitude of a magnetic field in the reference cell. A suitable homogeneous magnetic field may be produced using a solenoid setup as shown in **Figure 5**. Electronically mixing the modulated waveform with the saturated absorption transmission generates an error signal which can be used to adjust the diode current and integrated to adjust the piezo voltage. Thus, the laser may be locked to the transition without needing to modulate the laser frequency.

The linewidth of an ECDL is generally measured by interfering two frequency locked lasers of the same type on a beam splitter[18]. The beat frequency between the lasers is then measured using a fast photodiode and an RF spectrum analyzer. The noise spectrum beyond the locking loop bandwidth is then fitted to a Voigt (convolution of a Gaussian and Lorentzian) profile. The noise from the different lasers add in quadrature. In the case of two equivalent lasers this gives a fitted linewidth of $\sqrt{(2)}$ times the single laser linewidth. If a laser is available with a known linewidth significantly smaller than that expected from the ECDL and it is within the tuning range of the ECDL, then that could be used instead. Another method commonly used for measuring linewidth is the delayed self homodyne technique[19,20] where part of the beam is sent along an optical delay line such as a fiber and then mixed on a beam splitter with the laser. This technique relies on the delay being longer than the coherence length of the laser under measurement. This works well for noisy lasers but for a 100 kHz linewidth laser the coherence length is around 3 km, which begins to become impractical. Alternatively, an atomic transition in a saturated absorption cell or a Fabry-Perot cavity can be used to provide a frequency reference for laser linewidth measurement. In this system the laser frequency will need to sit at a linear portion of ether a saturated absorption or Fabry-Perot resonance rather than allowed to scan in frequency. By measuring the signal noise on a photo diode and knowing the resonance linewidth, the frequency noise can be found. The lower limit of the linewidth measurement is then limited by the slope of the transmission resonance.

The presence of higher order lasing modes may be checked for by looking at intensity noise at the frequency of the free spectral range using an RF spectrum analyzer or by using a scanning Fabry-Perot or an optical spectrum analyzer with a resolution better than the free spectral range of the ECDL. The coarse tuning range may be measured by measuring the power as a function of wavelength (using a wavemeter, monochromator, or optical spectrum analyzer) while tuning the laser across its limits using the grating. The mode hop free tuning range is generally measured using a scanning Fabry-Perot cavity where a mode hop can be detected as a discontinuous jump in frequency.

Protocol

1. Component Selection

1. Select a diode at the appropriate wavelength for the atom of interest. It is critical that the selected diode be single mode (sm and has sufficient power for the application. An anti-reflection coated diode is ideal. These diodes will not lase without the addition of an external cavity and they are designed explicitly for ECDL operation. They have significantly better performance, particularly for applications where scanning the wavelength of the laser is important. The laser diode used here is listed in List of Materials).
   As in MacAdam *et al.*[3], the ECDL must be designed to tightly fit the diode and a collimating lens. Mechanical stability and thermal contact are critical for good operation of the laser. For ease of construction, and minimal machining, success has been had using a diode laser mount with integrated lens tube (List of Materials).
2. Select a lens to collimate the diode. It is important that the numerical aperture be comparable or larger than the numerical aperture of the diode otherwise there will be substantial losses. Most diodes have a high numerical aperture (>0.5) and require aspheric lenses, otherwise aberrations will result in very low feedback efficiency. Make sure the lens is anti-reflection coated at the operating wavelength, choose a lens with a long focal length to increase the beam size on the grating and a design wavelength near the operating wavelength to reduce aberration. Refer to List of Materials for the lens used in the demonstrated system.
3. Select the appropriate external grating for the laser diode's frequency range and the grating tuning arm central angle. The wavelength of light diffracted into the first order, Littrow configuration, is given by $\lambda = 2d\sin(\theta)$, where d is the grating line spacing, θ is the grating angle of incidence and λ the wavelength[21] (**Figure 1B**). There are two main types of diffraction grating, holographic and ruled, and both may be blazed or not. Depending on the type of grating the diffracted power may vary substantially. Aim for a holographic grating with a diffraction efficiency of between 20-30%. Refer to List of Materials for the grating used in the demonstrated system.
4. Use the simplest design manageable - complexity often means instability. There are a vast number of ECDL designs but the simplest is the Littrow[3,5,7,22]. Read the papers and decide whether a large mode hop free range (the frequency range over which the diode can continuously tune without suddenly jumping to a different frequency), a very narrow linewidth or reduced pointing variation is of greatest importance for

the application. Obtain as much information as possible before beginning ECDL design. Often the grating ECDL is more than adequate for applications in atomic physics.

5. It is important to realize that the performance of an ECDL is most strongly rooted in the electronics that drive the diode current and stabilize the temperature of the laser. Without a good set of electronics the mechanical design will under-perform. Included is a comparison of different current and temperature controllers in **Table 1**. The lower the current noise, the better the laser will perform[23].

2. Assembly

1. For the purposes of this paper the starting point for the ECDL assembly will be a complete ECDL mechanical system mounted on a thermoelectric cooler (TEC) without the frequency selecting components (*i.e.* grating and laser diode).
2. Begin by placing the laser diode in its respective mounting hole and secure it using its mounting ring. Be careful not to over-torque the mounting ring. It should be snug but not tight.
3. Before connecting the laser diode to the current supply, check the diode specification sheet for the anode, cathode and ground pin assignments. This varies from diode to diode and putting the current through the diode backwards will destroy it.
    1. Laser diodes are low voltage devices, typically 5-10 V maximum, and care must be taken to ensure no static is discharged to them. It is good practice to wear a grounding strap when handling diodes and install a protection circuit (*e.g.* **Figure 2**) across the laser diode pins to prevent high voltages. The diode can and ground pins should be permanently grounded and the use of thin wires can aid in reducing the coupling of mechanical vibrations.
4. Set the maximum and minimum temperatures and the maximum diode and TEC current limits on the diode controller according to the values in the diode specification sheet. If the minimum operating temperature is below dew point for the lab then use a minimum temperature of ~ 2 °C above dew point. This will avoid condensation.
5. The diode specification sheet usually has a wavelength vs. temperature figure at a given diode current. Use this figure as a reference to initially set the diode temperature (and current) to match the wavelength of interest. If a temperature vs wavelength graph is unavailable adjust the set temperature to room temperature.
6. Turn the temperature controller on and allow the temperature to stabilize.
7. Turn ON the diode and turn the current up so that the output beam may be clearly observed with a viewing card. Use an IR card to view the beam.
8. Insert the aspheric collimating lens and collimate the laser diode by adjusting the separation between the diode and the lens. In order to ensure good collimation make sure the beam has a clear path, ideally >3 m, and adjust the lens position until the beam diameter just after the ECDL and at the end of the beam path are the same, being sure to check that the beam is not focusing at any point along the path.
9. Check the polarization from the diode laser is in the desired plane for the diffraction grating (S or P). In most cases the polarization of the diode is along the short axis of the elliptical beam shape but it is good practice to check the polarization axis using a polarizing beam splitter.
    1. If the beam axis is not in the desired plane, loosen the diode mounting ring and rotate the diode until the proper orientation is achieved. Some ECDL designs allow this to be done with the laser on and connected to the current source and others do not. If the current supply wires must be removed to rotate the diode, turn off the current supply at the control box and remove the wires. The ECDL temperature control can remain on during this process. Remember to always wear a grounding strap when handling the diode.
    2. If it was necessary to reposition the diode repeat the previous step to recollimate the diode.
10. The diffraction plane of the grating is usually labelled by the manufacturer with an arrow perpendicular to the grating lines and in the direction of the blazed reflection. Double check this by observing the reflection from a broad-band light source, such as a light bulb, as a function of angle.
    1. If the grating is held with the arrow pointing back towards the observer and a broad band light source over head, the reflected light will change in color as a function of grating angle.
    2. Mount the grating so that the arrow points back towards the diode and thus adjusting the grating angle varies the wavelength reflected back into the diode (**Figures 1A** and **1B**).
11. Once the grating orientation has been confirmed glue the grating on the ECDL tuning arm using fast setting glue such as Loctite.

3. Feedback Alignment

1. Place a viewing card aligned to the ECDL output beam. This will be used to monitor the laser power as adjustments are made to the pointing of the diffracted beam. A power meter could also be used but is slower in its response.
2. Adjust the set current on the diode control box to just *below* the threshold current for reflective front facet diodes and 1/3 the maximum current for AR coated diode gain chips. Reflective front facet diodes will have a threshold current on their specification or data sheets while AR coated gain chips do not.
3. Adjust the angle of the grating arm both horizontally and vertically, to steer the diffracted beam back into the diode, effectively making an external feedback cavity. When the beam is directed into the laser diode there will be a significant increase in the output power, observable as a marked increase or bright flash on a viewing card or a dramatic increase of power when measured using a power meter or photodiode.
    1. A viewing card is not a very quantitative measure of power so it may be necessary to incrementally lower the laser diode current and readjust the feedback beam until the above behavior can be seen at the lowest possible current.
    2. Adjusting the collimation lens focus or axial position to optimize focusing at the diode facet can further lower the threshold and increase output power after which it will be necessary to reoptimize the grating angle horizontally and vertically.

4. Initial Frequency Selection

1. For the initial frequency alignment of the laser an absolute measurement of wavelength with a precision of <1 nm and ideally <0.1 nm is ideal. This coarse frequency measurement will make it much easier to tune the laser frequency onto an atomic transition in a later step. There are many options including using a wavemeter, an optical spectrum analyzer, spectrometer, or a monochromator with a camera. Make sure a calibrated accurate device is used or check its calibration for example, using a HeNe laser. Alternatively, the coarse frequency adjustment can usually be accomplished by walking the grating angle and current while the laser is scanning until an absorption or fluorescence signal from a vapor reference cell can be seen.
    1. Generally a secondary beam picked off from the main beam, using a glass wedge prism or $\lambda/2$ waveplate and polarizing beam splitter, will be used as an input for the wavemeter. This optics setup is seen in **Figure 1D**. Refer to List of Materials for materials used in this demonstration.

2. Adjust the ECDL until the desired output wavelength is obtained. The diode driving current, temperature, grating angle and external cavity length will all affect the laser frequency[24] (**Figure 3**).
    1. Begin by adjusting the grating angle, either by hand or using the piezo. Secondly, adjust the diode current.
    2. If the desired frequency is to the blue of the grating sweep range, the diode temperature should be decreased and vice versa if the desired wavelength is to the red.

5. Fine Frequency Adjustments and Frequency Locking

1. Set up saturated absorption spectroscopy on the ECDL output using the configuration in **Figure 1F** [3,14,17]. The use of an optical isolator immediately after the laser is essential (**Figure 1C**). It is important to avoid back reflection into the laser, which can cause instability. Saturated absorption spectroscopy using a reference cell, containing the atom of interest is a simple way to lock a laser to a narrow atomic transition[25].
    1. Ensure the reference cell is on an angle to avoid back reflections and that the mirror retro reflects the beam back through the vapor cell with maximum overlap. The double pass transmitted power may be monitored using the photo diode as the ECDL wavelength is scanned.

2. Most diode controllers will have a built in scan function that will scan the wavelength by adjusting the grating piezo voltage and hence the grating angle and external cavity length or by modulating the diode current. The width, scan offset and laser temperature and current should be adjusted until an absorption signal can be viewed on a scope connected to the photo detector. When the laser is scanning over the atomic transition it should be possible to see the laser beam path in the vapor cell fluoresce or flash with the naked eye or through an IR viewer.
3. The power per unit area in the reference beam for saturated absorption spectroscopy must be at or above the saturation intensity for the atomic transition. Use the $\lambda/2$ wave plate before the polarizing beam splitter to increase the power until a clear absorption signal can be seen. Calculations of saturation intensities can be found in Foot[16].
4. With the laser scanning over the 780 nm Rb atomic transition, a wide Doppler broadened absorption signal should be seen, ~5 GHz width, with several sharp transitions ~10 MHz burned in Foot[16] (**Figure 4**). Minimizing the power used for generating the saturated absorption signal is necessary to reduce power broadening and produce a sharper feature to lock to.
5. In order to lock the ECDL frequency, an error signal is needed. By placing coils around the reference cell as in **Figure 5**[10] and oscillating the magnetic field, the Zeeman levels and thus the frequencies of the transitions are modulated. In this case the current passing through the Zeeman coils is modulated at around 250 kHz with a magnitude of ~1 G.
6. Mix the absorption signal from the saturated absorption photo detector with the modulation signal from the function generator. When the output from the mixer is viewed on a scope it should be an error signal similar to **Figure 4**. The magnitude of the error signal will depend on the relative phase between the two mixed signals. Rotate the $\lambda/4$ beam splitter before the vapor cell to adjust the phase.
7. Progressively reduce the scan range and adjust the offsets to center the scan over the transition of interest with no other transitions present.
8. A proportional-integral-derivative (PID) circuit (for example see MacAdam *et al.*[3]) may then be used to lock the ECDL wavelength using the error signal. The PID gain should be reduced below the point at which ringing is observed by looking for the presence of modulation in the error signal (*e.g.* using a spectrum analyzer or Fourier transform of the error signal trace).

6. Linewidth Measurement

1. In order to attain an accurate linewidth measurement it is necessary to have either a known narrow linewidth source (another laser with linewidth significantly less than the ECDL), two of the same ECDLs or a delay line long compared with the coherence length of the ECDL. Here two ECDLs will be interfered to measure linewidth. Alternatively, it may be easier to lock to a resonance produced by an atomic transition or a Fabry-Perot cavity and fit to the noise above the bandwidth of the locking loop.
2. Lock the two lasers to different hyperfine transitions, ideally around 100 MHz offset. This will minimize the impact of electronic noise.
3. Mode, power and polarization match the two beams and interfere them together using a 50/50, nonpolarizing beam splitter. Align the resulting beam on a photo detector. The signal output on the photo detector should be a sine wave with a frequency of the two laser's frequency offset. It may be necessary to attenuate or defocus the resulting beam so as not to damage or saturate the photodiode.
    1. The overlap of the two beating beams will determine the fringe contrast as viewed on a scope during the linewidth measurement. If the fringe contrast is poor, spend additional time improving the mode matching and overlap of the beams on the beam splitter and detector. A good method is to overlap the two beams using two iris', or pin holes, separated by a relatively large distance, ~1 m.

4. It will be difficult to resolve the frequency fluctuations on a scope. For the best measurement use a spectrum analyzer, which will give a Voigt profile centered on the beat frequency with a linewidth Δf, equal to the convolved laser linewidth (**Figure 6**). To a good approximation the trace can be fit to a Gaussian and the linewidth obtained from the fit. The measured noise or linewidth will depend on the acquisition or

integration time, which may be set by adjusting the resolution bandwidth on the spectrum analyzer. For this reason it is important to quote the integration time when quoting the measured linewidth.

Representative Results

There are 5 main steps involved in aligning, frequency locking and characterizing the linewidth of the ECDL. These are: obtaining feedback from the grating and using this to set the coarse ECDL frequency measured on a wavemeter, observing laser absorption in the reference cell, viewing the atomic transition with a resolution around the natural linewidth in a saturated absorption spectroscopy setup, obtaining an error signal around the desired transition and locking to it, and finally observing the beat note of two lasers and measuring the laser linewidth. Step one is successfully completed, fairly trivially when the wavelength as read on the wavemeter corresponds to the atomic transition of interest. When attempting to achieve absorption in the reference cell, florescence can be seen along the beam path in the cell with an IR viewer when the transition is hit. If the ECDL is scanning the cell will flash. A saturated absorption signal may be difficult to spot when first aligning because the transmission lines may be very small compared to the Doppler absorption peak. When peaks, similar to those shown in **Figure 4**, can be seen, the saturated absorption system is working properly. By adjusting the phase and scan parameters an error signal similar to that shown in **Figure 4** should be obtained. In order to measure the ECDL linewidth it is necessary to obtain a beat signal between two beams. As the beams become more and more overlapped a sine wave will begin to appear, as seen on a scope from a photo detector. Keep aligning until the contrast between the nodes and anti-nodes is largest. When the beat signal is then passed through an electronic spectrum analyzer a signal similar to **Figure 6** should be seen. The laser linewidth can be measured from this signal. The complete optics setup can be seen in **Figure 1**.

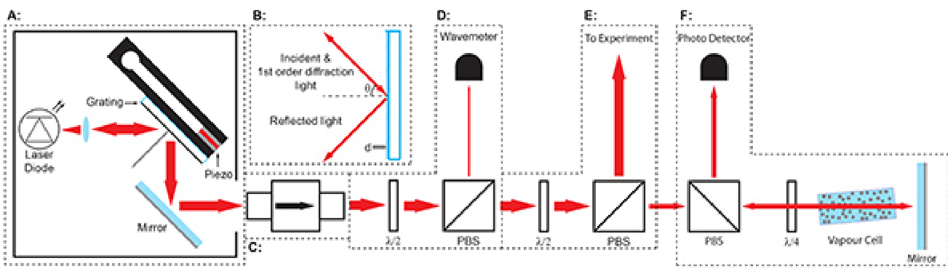

Figure 1. Complete optics setup. This is an example of a complete optics setup for the ECDL system discussed. **A:** This shows the Littrow configuration of an ECDL. A percentage, typically 20-30%, of the beam incident on the grating is diffracted back into the diode. The diffraction angle and reflection angle are equal. The grating is mounted to a tuning stage which uses a piezo to control the grating angle. **B:** The output beam from the laser diode is incident on the grating at angle θ with the 0th order reflecting off and the 1st order diffraction being sent back along the incident beam path. The wavelength of diffracted light is given by $\lambda = 2d\sin(\theta)$ in Littrow configuration. **C:** Position, and orientation of the optical isolator to reduce unwanted feedback to the laser diode. **D:** The output beam from the laser box passes through a $\lambda/2$ waveplate and PBS and is aligned to the wavemeter. The power in the reflected and transmitted beams can be adjusted by rotating the waveplate. **E:** Beam line used for experiment. This line will contain the majority of the laser's power. **F:** Pass a reference beam at or above saturation intensity through a PBS, $\lambda/4$ waveplate, reference gas cell, and retro reflect it back onto the PBS. It is important that the two beams are well overlapped to get proper saturation spectroscopy. The waveplate will ensure the polarization of light on the retro reflected beam will be rotated 90° from the incident beam allowing it to exit the opposite port of the beam splitter. Click here to view larger image.

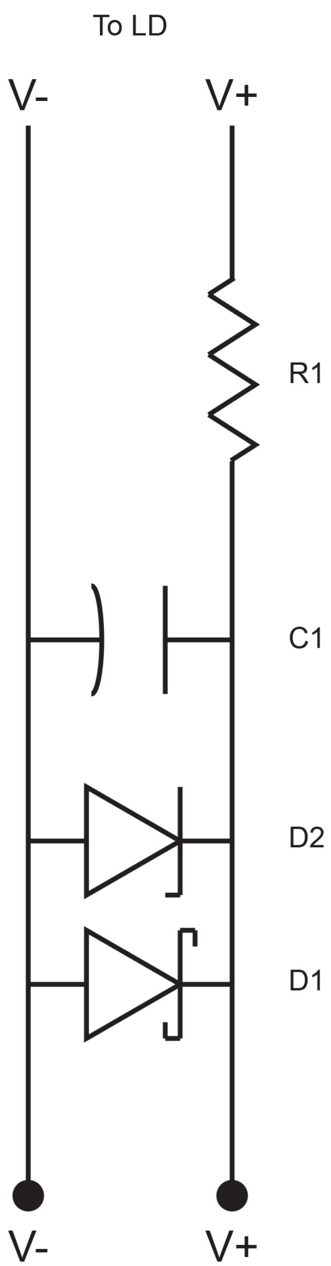

Figure 2. Laser diode protection circuit. Example protection circuit for the laser diode current. *R*1 and *C*1 form a basic RC circuit and will filter out high frequency noise. *D*1 and *D*2 are Schottky and Zener diodes respectively. The Schottky diode, which has a fast response time, is in place to protect against reverse voltages, and the Zener diode, which has a slower response time, is designed to allow current to pass if above the laser diodes maximum operating voltage, thereby avoiding damage to the laser diode. Typical values for the components will be *R*1 = 1 Ω, *C*1 = 1 mF, *D*1 = 30 V, *D*2 = 6 V. The values chosen for R1 and C1 will limit the current modulation bandwidth of the diode. This may be less than ideal if a error signal is being produced via current modulation instead of the Zeeman modulation discussed.

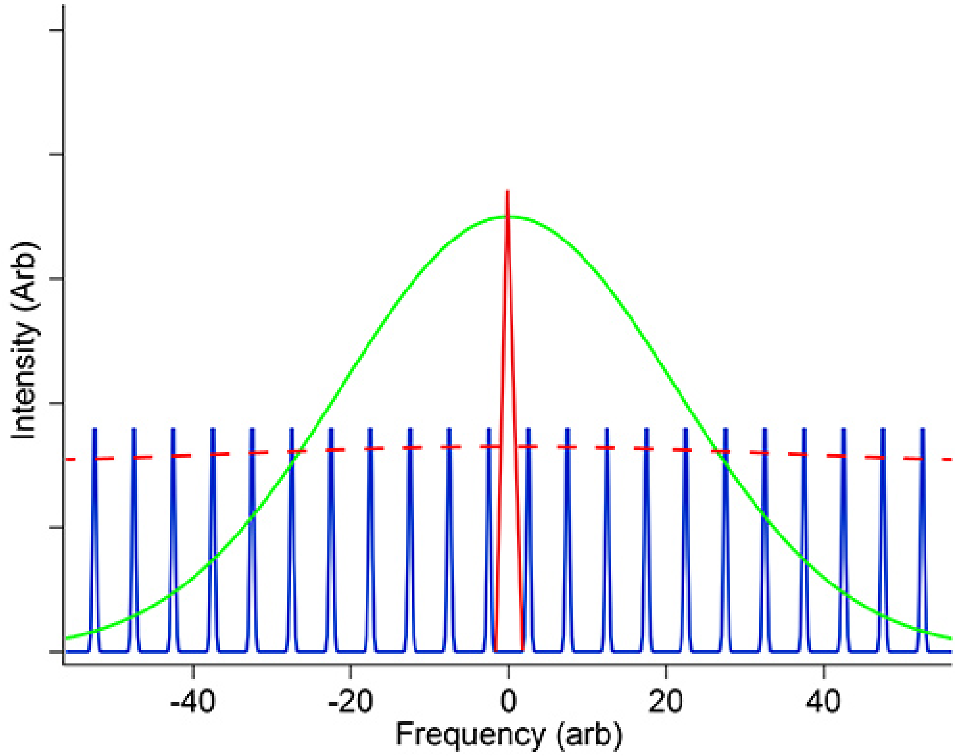

Figure 3. Competing modes in an ECDL. Green: Line width of grating diffraction order ≈50 GHz depending on the grating. **Red solid:** The Internal cavity mode of a laser diode with a line width ≈10 MHz and free spectral range ≈80 GHz. **Red dash:** The internal cavity of an anti-reflection coated diode. These diodes will have a line width in the nm range. **Blue:** External cavity modes with a line width of ≈500 kHz and a free spectral range of ≈5 GHz. From a 3 cm long external cavity. Adjusting the grating angle will shift the center of the green curve and simultaneously change the external cavity length in turn shifting the blue curve as well. Adjustment of the diode current and temperature will shift the red curves.

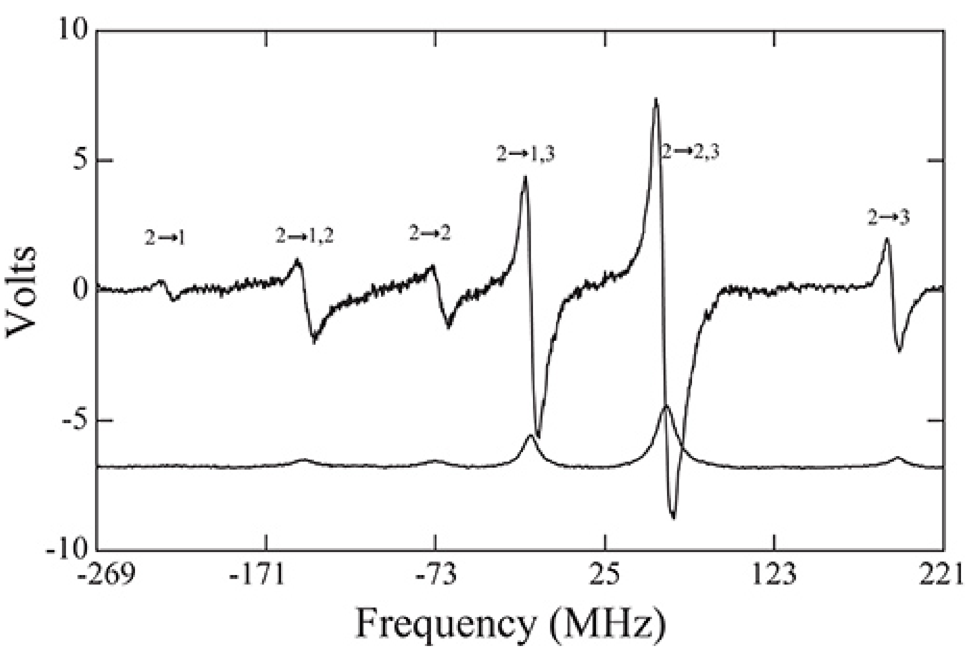

Figure 4. Saturated absorption spectroscopy and corresponding error signal. For Rubidium 87. Lower Curve: Saturated absorption peaks on the much broader Doppler absorption peak formed from Doppler free spectroscopy. Upper Curve: Error signal for the corresponding saturated absorption system. The labels above the error signal correspond to the atomic transition (*F→F'*).

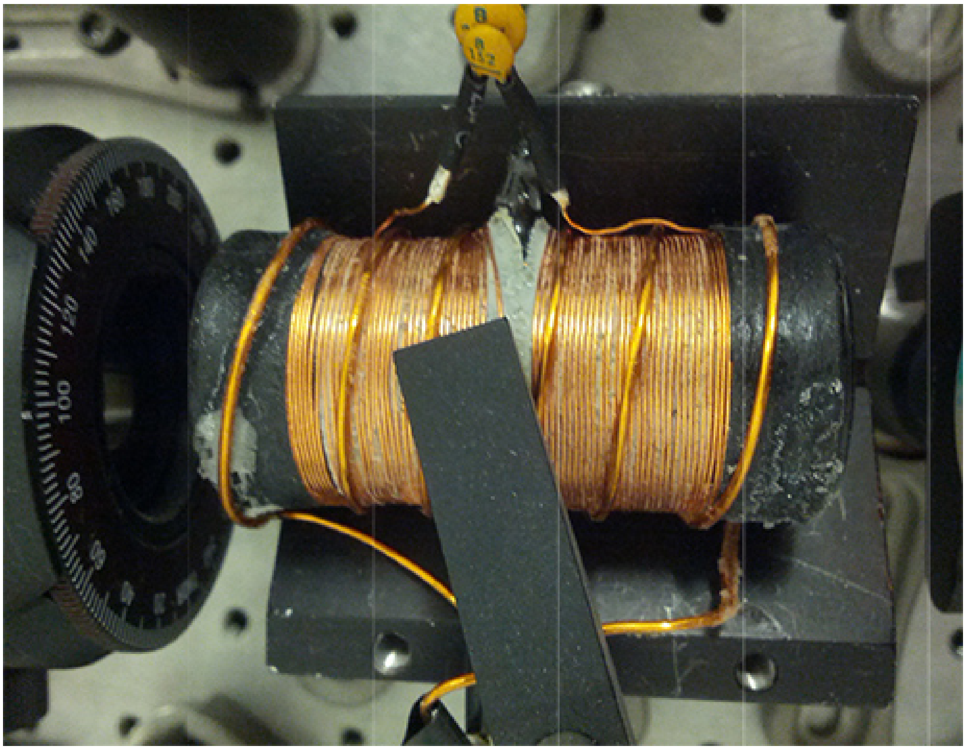

Figure 5. Zeeman Coil. Coil wrapped around a rubidium vapor cell used in Zeeman modulation.

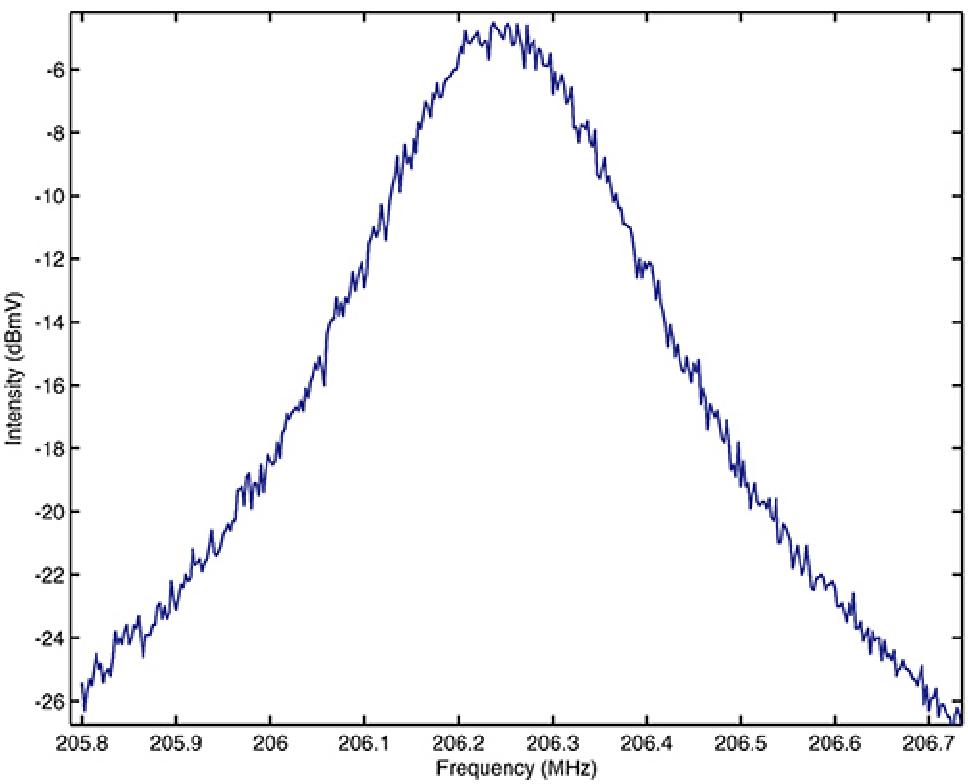

Figure 6. Laser linewidth. Signal acquired from a spectrum analyzer of the beat note formed by two similar lasers. From the figure, the beat has a frequency of 206.24 MHz and a linewidth of 0.3 MHz with an integration time of 20 msec.

Current Controls	**Range**	**Noise**
Thor Labs:		
LDC200CV	0-20 mA	<1 µA (10 Hz -10 MHz)

LDC201CU	0-100 mA	<0.2 µA (10 Hz -10 MHz)
LDC202C	0-200 mA	<1.5 µA (10 Hz -1 MHz)
LDC205C	0-500 mA	<3 µA (10 Hz -1 MHz)
Moglabs:		
DLC-202	0-200 mA	<300 pA/√Hz
DLC-252	0-250 mA	<300 pA/√Hz
DLC-502	0-500 mA	< 300 pA/√Hz
Stanford Research Systems:		
LDC500	0-100 mA	< 0.9 µA RMS (10 Hz -1 MHz)
LDC501	0-500 mA	< 4.5 µA RMS (10 Hz -1 MHz)
Toptica:		
DCC 110/100	0-100 mA	200 nA RMS (5 Hz-1 MHz)
DCC 110/500	0-500 mA	1 µA RMS (5 Hz-1 MHz)
Temperature Controllers		
Thor Labs:		
TED200C	-45 to 145 °C	±2 mK
Moglabs:		
DLC-202	-40 to 50 °C	±5 mK
DLC-252	-40 to 50 °C	±5 mK
DLC-502	-40 to 50 °C	±5 mK
Stanford Research Systems:		
LDC500	-55 to 150 °C	±2 mK
LDC501	-55 to 150 °C	±2 mK
Toptica:		
DTC 110	0-50 °C	±2 mK

Table 1. Diode Current and Temperature Controllers. Various companies' diode current and temperature controllers with their ranges and noise levels.

Discussion

This publication has shown how to move from a disassembled ECDL through the alignment and frequency locking to produce a measurement of the laser linewidth. The mechanical design and the design of the electronics such as PID servos, diode drivers and temperature controllers is too specialized to be discussed here but have been comprehensively discussed in referenced publications[1,3,5].

Although diode ECDL's have become a staple in atomic physics labs, the species and transitions that these devises can reach is limited. Much progress has been made in broadening the wavelength range from diode based lasers however currently many gaps remain especially in the UV. Power limitations of ECDL systems continue to restrict their applications. Bare single mode diodes range in power from µWatts to 100's of mWatts. Additionally, tapered amplifiers can be added to an ECDL system to increase the single mode total laser power up to the Watt level. If single mode powers much greater than a Watt or other wavelengths are required alternative laser architectures are required. These include fiber lasers[26], solid state lasers[27] such as TiSaph lasers or they may rely on nonlinear frequency conversion processes[27] such as Raman lasers, four wave mixing, sum frequency generation, or an optical parametric oscillator.

This publication focuses on a locking mechanism that is dependent on an atomic vapor cell. For many applications in atomic physics a simple glass vapor cell, as discussed here, may not be available, such is the case for species like Yb. Many other techniques for obtaining a reference sample with a variety of species have been demonstrated such as, hot atomic beams, discharge lamps, buffer gas cells, iodine cells, and sputtering cells.

This laser system design is inherently limited to linewidths of ≈30 kHz [28] and typically closer to 100 kHz. If the application requires a narrower linewidth other stabilization techniques or alternative laser designs[26] are required.

Whenever working with optical systems, cleanliness is of the utmost importance. It is good practice when first being introduced to and handling optics that gloves be worn to prevent accidentally touching the optical surface. If an optic is scratched it should not be used in a laser system. In most cases optics with finger prints or dust can be cleaned with acetone or compressed air respectively. Any imperfection in an optical surface can and will introduce loss and potentially noise into the system. Optics mounts should be fixed to the optics bench at all times and should be firmly bolted down once in place.

When aligning optics such as waveplates and polarizing beam splitters, ensure the light is incident near perpendicular to the optical surface while avoiding reflections back into the laser. As the incident angle deviates from 90° the behavior of these optical elements becomes further and further from ideal. To minimize aberration and maximize numerical aperture beams should always travel through the center of lenses and be normal to the lens. In contrast, a vapor cell should be placed at a slight angle to the incident beam to avoid etalon effects. For this reason many vapor cells are manufactured with nonparallel end facets.

The lasers used here are class 3B. Even stray reflections have the potential for eye damage. Work with lasers of this type should only be undertaken by trained personnel familiar with the hazards of lasers. Laser safety goggles should be worn at all times. Never look directly down the path of any laser for optical alignment and take particular care to avoid generating hazardous specular reflections off optical components. Always positively terminate beam lines using a beam dump.

Disclosures

The authors have nothing to disclose. Specific product and company citations are for the purpose of clarification only and are not an endorsement by the authors.

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