A visible extended cavity diode laser for the undergraduate laboratory

R. S. Conroy, A. Carleton, A. Carruthers, B. D. Sinclair, C. F. Rae, and K. Dholakia
J F Allen Physics Research Laboratories, School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife KY16 9SS, Scotland, United Kingdom

We demonstrate how to construct a simple single-frequency extended cavity diode laser (ECDL) for the undergraduate laboratory using mainly standard opto-mechanical components. This ECDL is operated with both 635 and 670 nm laser diodes. We present three experiments that can be performed using this ECDL, namely spectroscopic studies of iodine, second harmonic generation, and an optical heterodyne experiment using the ECDL with a helium–neon laser. © *2000 American Association of Physics Teachers.*

I. INTRODUCTION

Recent years have witnessed dramatic advances in diode laser technology. These compact devices have found applications in many optical systems, including bar-code scanners and optical data storage. They also have strong potential for studying atomic and molecular transitions. However, for high-precision atomic spectroscopy, free-running, commercially available diode lasers do not possess the required spectral characteristics.[1] Thus, in practice, it may be difficult for the user to locate the atomic or molecular transition of interest and tune smoothly around this region. Ideally, a high-quality spectroscopic laser source would be continuously tunable in wavelength as well as possessing a narrow linewidth. Though diode lasers can run in a single longitudinal mode, they usually have a linewidth of the order of ~50 MHz for near infrared (IR) wavelengths and several hundred megahertz for visible wavelengths.

The wavelength of a diode laser is determined primarily by the bandgap of the semiconductor material though there is also a dependence on diode temperature and current density. Temperature influences both the optical path length of the cavity and the gain curve of the semiconductor material. The temperature dependencies of both these parameters are different, however. This results in discontinuities in the graph of output wavelength versus temperature. Changing the current changes the diode temperature as well as the carrier density in the diode (which changes the index of refraction) and the wavelength. These discontinuities are mode jumps between longitudinal cavity modes and represent a major problem when using diode lasers for high precision spectroscopy.

Sending light back into the laser diode has a dramatic effect on its lasing frequency due to a number of factors.[1] While this may be a problem for some arrangements, this optical feedback may also be used to one's advantage. To convert free-running diode lasers, with their inherent undesirable tuning characteristics, into narrow linewidth tunable laser sources, one may exploit this susceptibility to optical feedback. This may be performed by the use of a diffraction grating as an extended feedback mirror. This can dramatically reduce the linewidth of a diode laser by two orders of magnitude due to the higher quality factor of the cavity. In what is termed the ''Littrow'' geometry, light from the diode is sent onto a blazed diffraction grating and the first diffracted order is fed back into the laser cavity. The zeroth order provides the output coupling for the laser. The diode lases on an extended cavity consisting of the back facet of the diode laser and the diffraction grating. This is known as an extended-cavity diode laser (ECDL). Recent work by MacAdam and co-workers[2] has demonstrated how to construct near infrared extended cavity diode lasers and use them for studying resonance transitions in rubidium and caesium. Such systems have found widespread use in high-precision spectroscopy, notably the cooling and trapping of atoms.

Visible laser diodes have lagged behind the development of their near infrared counterparts and generally exhibit poorer spectral characteristics. Importantly, when run in an extended cavity they usually require antireflection coatings to make them tune smoothly in wavelength. In this paper we demonstrate how to construct extremely simple, inexpensive, and versatile extended cavity diode lasers at both 635 and 670 nm using mainly widely available opto-mechanical components. This system is simpler than previous systems developed[2,3] for the undergraduate laboratory but yet offers equivalent performance. We present a detailed discussion of the construction of the laser system and discuss the procedure for alignment of this laser. The ECDL we have developed is at a fraction ($\sim\frac{1}{10}$) of the cost of commercially available systems yet offers comparable performance. We discuss three major experiments using these ECDLs. We have successfully used this ECDL system in a number of undergraduate projects in our laboratory and it has proved to be a versatile device for student use.

One major motivation for developing an ECDL operating at ~635 nm is to exploit the existing teaching laboratory equipment designed for the 633 nm helium–neon (He–Ne) laser. Furthermore, the study of visible beams is both more visually expressive and ''safer'' than their near infrared counterparts. We have also realized this laser at 670 nm where diode lasers are less expensive than those at 635 nm. Many undergraduate laboratories have iodine vapor cells. The ECDL at both 635 and 670 nm is powerful enough to study diatomic spectra in this molecule. Molecular spectroscopy using these lasers is discussed in a later section. We use this laser additionally to study optical second harmonic generation in ammonium dihydrogen phosphate (ADP). Finally we perform a heterodyne experiment between this ECDL and a standard laboratory helium–neon laser to determine the linewidth of the ECDL. Details are presented for conducting all of these experiments.
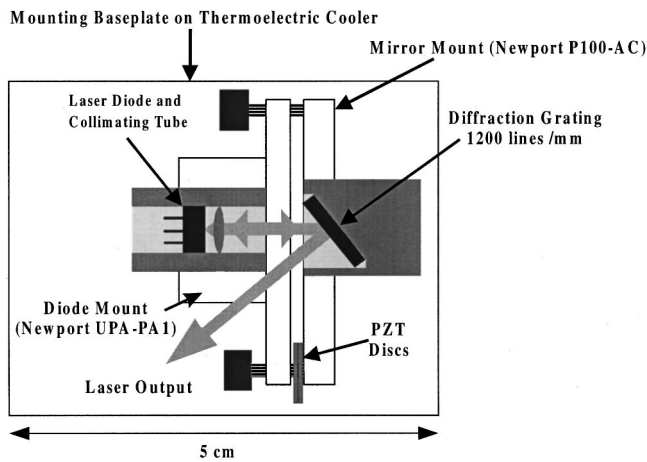
Fig. 1. Diagram of the extended cavity diode laser (ECDL) system.

Fig. 2. Workshop diagram of the holder for the diffraction grating.

II. CONSTRUCTION OF THE EXTENDED CAVITY LASER DIODE

Near-IR diode lasers may be used ''off-the-shelf'' in an extended cavity. However, diode lasers at 635 nm typically require antireflection coatings on their front facet to allow them to tune smoothly in wavelength. One may build a general coating apparatus as detailed by Libbrecht and co-workers[3] to coat laser diodes in-house. However, there are now a number of companies that will apply antireflection coatings to laser diodes. We have used one such manufacturer (Sacher Lasertechnik, Germany) who has coated a 635 nm 15 mW laser diode (SDL-7501-G1) at a modest cost.[4] At 670 nm, we used a similar AR-coated laser diode manufactured by Hitachi (HL6714G) specified at 10 mW and again coated by Sacher Lasertechnik.

In previous setups[2,3] extended cavity diode lasers have been mounted in purpose-built machined holders and systems. However, if there are not elaborate machining facilities available, it is important to be able to construct such a laser from off-the-shelf components. The details presented here will allow construction of the ECDL system from simple opto-mechanical components. The system described here for 635 and 670 nm is very similar to one that we regularly use in our research laboratory with 780 nm laser diodes for trapping and cooling atoms, a stringent test of the characteristics of an ECDL.[5] Other similar designs exist for ECDLs that offer equivalent performance.[6] Our system has important attributes in that it is inexpensive, very easily assembled, and reliable. We note that the use of similar components from manufacturers other than those we have quoted may offer equivalent performance.

Figure 1 shows a diagram of our laser diode arrangement. There are two major parts to the system: a package for mounting and collimating the laser diode and a separate diffraction grating. The use of commercially available collimating laser diode tubes[7] simplifies the alignment of the diode and mount as well as the collimating procedure compared to the arrangement detailed in Refs. 2 and 3. The diode fits into the back of the tube and is immediately centered with respect to the accompanying (antireflection coated) aspheric collimating optic (supplied with the tube). An adjustment spanner (see Ref. 7) allows one to adjust the position of the collimating lens with respect to the diode. The ECDL we use is based around a standard op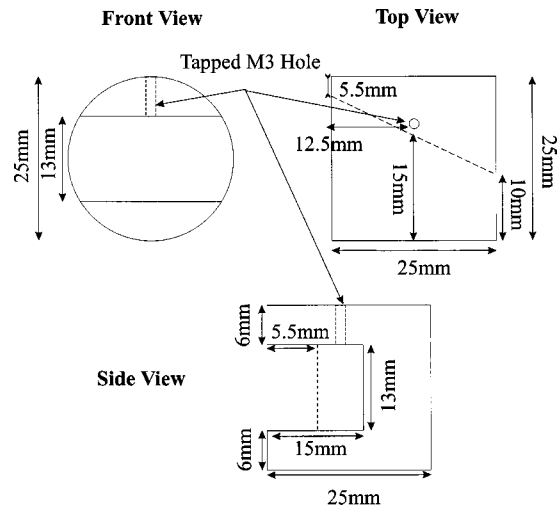en-quadrant design kinematic mirror mount (Newport P100-AC). A hole is drilled into an associated adaptor (Newport UPA-PA1) to accommodate the tube and a screw holds the tube in place. To mount the diffraction grating, we machine a cylindrical holder with a slot at the Littrow angle. This holder resides in the mirror mount where one would normally place the mirror substrate. The choice of blaze wavelength of the diffraction grating influences the amount of light sent back into the laser (in the first-order beam). This dictates the tuning range of the ECDL. We have used the ECDL with a $\frac{1}{2}$ in. square 1200 lines/mm grating[8] blazed for 300 nm. The Littrow angle is simply determined from the grating equation:

$$a(\sin \theta_m - \sin \theta_i) = m\lambda. \tag{1}$$

Here θ_i and θ_m denote the angle of incidence and the angle of reflection, respectively, and a is the spacing between successive rulings on the diffraction grating. In the Littrow configuration, $\theta_i = -\theta_m$. For our grating at 635 nm, this gives a Littrow angle of 22.5°. The reflectivity into the first order for our choice of grating is around 20% at 635 nm and 15% at 670 nm.

A workshop diagram for this holder is shown in Fig. 2. The grating is placed in the holder with its lines oriented vertically. The geometry immediately realizes an ECDL with a short cavity length of around 20–30 mm.

The system uses the vertical and horizontal adjustment screws of the mirror mount for exact alignment of the first-order diffracted light from the diffraction grating back into the laser diode. The inclusion of a PZT element is crucial in the laser to allow changes in the laser cavity length for tuning the laser frequency. As used by MacAdam and co-workers[2] (for their quite different geometry), we use a similar PZT disk inserted between the horizontal positioning screw of the mirror mount and its main body. The disk is about 1 in. in diameter with a brass backing onto which a silver-plated piezoelectric section is attached. Two such disks are lightly soldered together with their brass sections back to back to increase the displacement for an applied voltage.[2] The advantages of these PZT disks are not only that they are very inexpensive, but also they can be driven from a standard laboratory signal generator (that can generate a triangular output waveform) obviating the need for purchasing a relatively expensive high-voltage piezo driver. To protect

the laser from air currents we place the system inside a simple metal box with a transparent plastic lid.

III. DIODE CURRENT SUPPLY AND TEMPERATURE STABILIZATION

The laser diode requires a stable low-noise current supply for operation. One could construct one in-house if suitable electronics expertise exists. Details for suitable current sources may be found elsewhere.[1,2] We use a commercial diode driver to perform this task.[9] We run the 635 nm diode at approximately 70 mA and achieve an output power of about 10 mW from our extended cavity geometry. The 670 nm diode laser gives us an output power of around 7 mW at an input current of 82 mA.

The whole assembly is placed on an aluminum plate and a Peltier thermoelectric cooler element $(30 \times 30 \text{ mm}^2)$[10] is used between this plate and a larger slab of aluminum, which acts as a heatsink. A negative temperature coefficient thermistor[11] is placed in a small hole drilled in the mirror mount close to the diode laser collimating tube. We find that one Peltier cooler driven by a temperature controller is sufficient to maintain the diode temperature to within a fraction of a degree ($\sim$mK) using a relatively inexpensive commercial temperature stabilizer.[12] We run the ECDL at around 20 °C. Again, one can build such a unit in-house using circuits described elsewhere if desired.[1,2]

IV. SYSTEM ALIGNMENT

All diodes are susceptible to electrostatic problems. Suitable precautions are required when mounting these devices and the use of a personal earth strap is recommended. Once the diode is placed in the collimating tube and current supplied (at a value of a few mA below threshold), the output collimation may be adjusted using the spanner while observing the fluorescent (spontaneous emission) output of the device several meters away. We find that adjustment of the lens position is critical, and true collimation requires rotational accuracy of the lens position to a degree or so. The output beam of the laser is linearly polarized ($>$99%) in the vertical direction and is elliptical in nature with an aspect ratio of around 4:1 with the major axis being 5 mm in length. The tube is rotated such that the major axis is horizontal and perpendicular to the lines of the diffraction grating. Once the collimation has been performed, and while the laser is still below its threshold current setting, the grating, in its holder, may be inserted in front of the diode laser. To achieve the extended cavity lasing, the first-order diffracted beam from the grating must be sent directly back into the diode. Initially, when one is close to the alignment of the extended cavity, two fluorescent spots are observed on a piece of card placed at the output. One is the zeroth-order output off the grating and the other is a faint reflection of the first-order diffracted beam off the front surface of the collimating lens. By adjusting both horizontal and vertical alignment screws on the mirror mount one can overlap these two spots and lasing action, indicated by a sudden increase in brightness, should be witnessed. We find that lasing action is more sensitive to the vertical adjustment screw. The horizontal adjustment screw of the mirror mount may be adjusted over a larger range and allow a study of discontinuous tuning of the laser system. This behavior is expected due to the orientation of the grooves of the diffraction grating in the system.
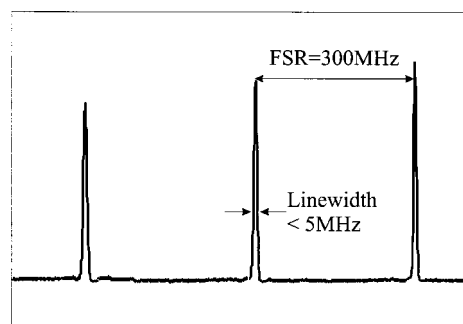

Fig. 3. Single mode operation of the 635 nm ECDL showing a linewidth of $<$5 MHz on our spectrum analyzer (free spectral range = 300 MHz). Similar data at 670 nm were recorded.

V. PERFORMANCE

We observed the output of the laser on a Technical Optics Spectrum analyzer (part no. 13SAE005) and found that the laser operated on a single longitudinal mode (Fig. 3) at both 635 and 670 nm. This spectrum analyzer is a scanning Fabry–Pérot etalon with a free-spectral range of 300 MHz and a finesse of 200. The linewidth of the laser was measured to be under 5 MHz for both laser diodes. The student may compare the linewidth of a free-running diode laser with that of a diode in an extended cavity arrangement with this spectrum analyzer by simply measuring the width of the transmission peaks. If such a spectrum analyzer is not available, a heterodyne ''beating'' experiment can be performed on a fast photodiode to determine the instantaneous linewidth of the ECDL. We discuss such an experiment later in this manuscript. However, the use of such a spectrum analyzer or similar Fabry–Pérot etalon is useful to allow the student to observe that the laser is indeed running in a single longitudinal mode. Furthermore, it would allow the student to observe the rate of change of frequency with PZT voltage and to determine the maximum range of continuous frequency tuning. The voltage ramp required on the PZT element for tuning may be observed by placing the output of the signal generator driving the PZT element on an oscilloscope.

The discontinuous tuning range of the laser may be readily determined with the use of a low-resolution monochromator ($\sim$1 nm resolution). By adjusting the horizontal control of the mirror mount (and thus the angle and distance between the diode and the grating) one can tune the laser typically over 5 nm. The choice of diffraction grating here dictates the tuning range. Choosing a grating that reflects a larger fraction of light back into the laser results in a broader discontinuous tuning range at the expense of reduced output power. Typical data that we have obtained for the discontinuous tuning range at both 635 and 670 nm are shown in Fig. 4. If carefully aligned, the laser can be made to tune **continuously** by up to 8 GHz by changing the voltage to the PZT element, though typically 4–6 GHz is achieved. This is an important attribute for spectroscopy. A spectrum analyzer is very useful for observing the tuning range in this study.

VI. SPECTROSCOPY OF MOLECULAR IODINE

This ECDL system described is a very useful spectroscopic source. For the undergraduate laboratory, one can use this source to access transitions in molecular iodine. Iodine exhibits various rotational–vibrational bands in the visible
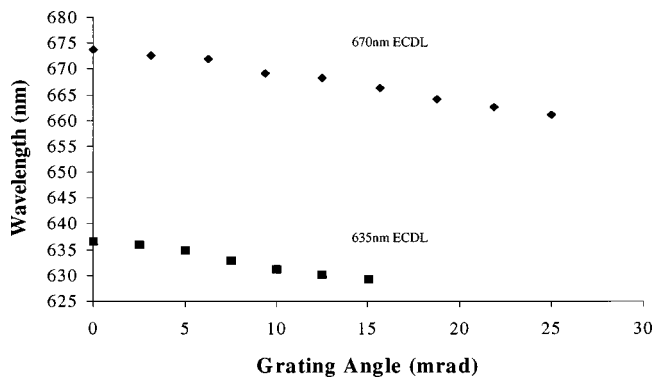
Fig. 4. Discontinuous tuning graph for both the 635 nm ECDL and the 670 nm ECDL. The laser was found to jump to each of the wavelengths as shown when the horizontal control mirror mount was adjusted.

range of the spectrum. These bands have been central in the development of molecular spectroscopy using laser sources. Furthermore, the absorption lines of the $I_2 B-X$ bands are commonly used for the frequency stabilization of many laser systems, most notably He–Ne lasers operating at 632.8 nm.[13] The B level is the first excited level and the X level is the ground state.

Absorption experiments have been performed using He–Ne lasers,[14] though here one is reliant on fortuitous co-incidences between iodine lines and the laser frequency. The ECDL presented here offers the student the opportunity to access a variety of lines in iodine by tuning the ECDL frequency and utilizing the scanning ability of the laser. The experimental arrangement for iodine spectroscopy is shown in Fig. 5. The ECDL output is sent through a 5 cm long iodine cell with Brewster cut windows. Initially, to locate iodine lines we manually adjust the horizontal adjustment screw of the ECDL mount and scan the laser over a few GHz. Generally, one is able to locate a line within a few minutes. In a darkened room we are able to observe iodine fluorescence in the cell with the naked eye. To record the spectra we place a photodiode (see Ref. 2 for a suitable photodiode and amplifier circuit) above the cell and scan the laser in frequency. The use of a calibrated monochromator is also very useful, especially one of high-resolution (~0.05 nm) as one can then identify exactly the iodine peak located by the laser. Spectra we have recorded using this technique using both 635 and 670 nm ECDLs are shown in Fig. 6. By using a standard iodine atlas[15] students can check their data
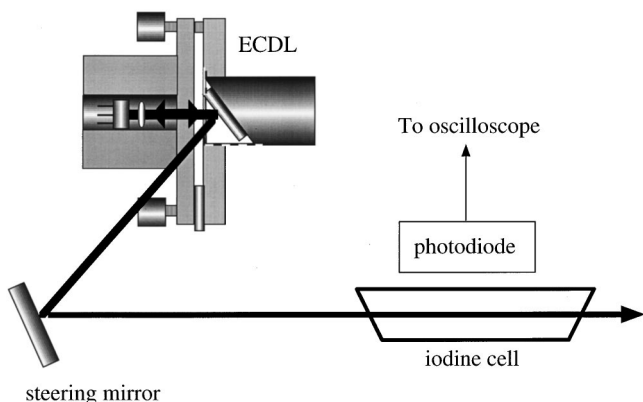

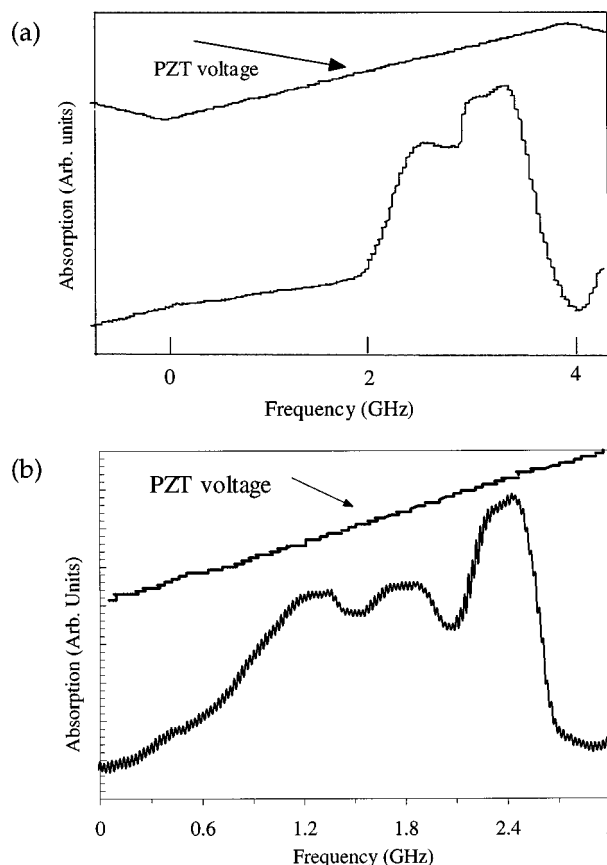Fig. 5. Experimental setup for iodine spectroscopy.

Fig. 6. (a) Scan (using 635 nm ECDL) at 15786 cm^{-1} in iodine. Lines 230 and 231 are recorded. (b) Scan (using 670 nm ECDL) at 15059.99 cm^{-1} in iodine showing line 154. The line numbers are those given to these features in the iodine atlas of Ref. 15.

and directly identify the iodine line located. For more advanced studies it is noted that the ECDL presented here offers sufficient output power to perform Doppler-free saturated absorption spectroscopy.

VII. SECOND HARMONIC GENERATION

In noncentrosymmetric optical crystals, nonlinear phenomena result due to dipoles in the medium responding nonlinearly to the oscillating E-field at frequency ω of an incident laser beam.

The electric polarization (P) of the medium may often be written as a power series where terms of order 2 and above represent the nonlinear terms:

$$P = \varepsilon_0 \chi_1 E_\omega + \varepsilon_0 \chi_2 E_\omega^2 + \varepsilon_0 \chi_3 E_\omega^3 + \cdots, \qquad (2)$$

where χ represents the susceptibility of the medium and ε_0 is the relative permittivity of free space. The first higher-order term for the polarizability may then be written as

$$P_2 = \varepsilon_0 \chi_2 E_\omega^2. \qquad (3)$$

This electrical polarization, which contains a term oscillating at twice the original frequency, is responsible for second harmonic generation (SHG). The advent of the laser and the higher intensity it offers has allowed the exploration of nonlinear optics. Nowadays, second harmonic generation offers a powerful technique to access wavelengths that are difficult to reach using standard laser transitions. In the context of
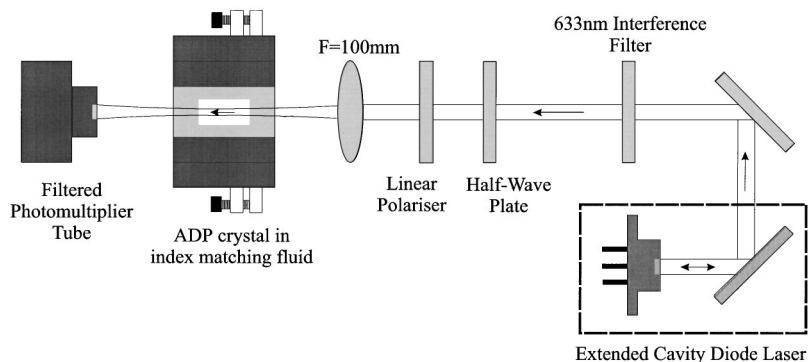
Fig. 7. Experimental setup for second harmonic generation.

undergraduate laboratory, it offers an excellent introduction to nonlinear optics.

The ECDL we present here offers a good quality laser source for studying second harmonic generation. A detailed discussion of second harmonic generation is outside the scope of this paper—more details can be found in a number of optics textbooks.[16,17] The experimental arrangement is shown in Fig. 7. The diode laser is focused into a 4 cm long nonlinear crystal of ADP (ammonium dihydrogen phosphate). This crystal may be both "angle tuned" and "temperature tuned" to achieve phase matching. Phase matching is a well-known prerequisite for efficient second harmonic generation. Dispersion means that light generated at a frequency 2ω and the incident light at frequency ω will generally travel at different speeds through the crystal. Thus the light generated at 2ω in one plane of the nonlinear crystal is not necessarily in phase with light at 2ω generated at some other plane within the crystal. Overall this leads to an interference effect within the crystal and an inefficient second harmonic process.[16,17] To overcome this we can offset the dispersion of the crystal material with the temperature and polarization dependence of the refractive index. The refractive index (and hence the velocity) of the extraordinary wave (e-ray) varies with propagation direction through the crystal. Thus one picks a direction such that this matches the refractive index of the ordinary wave (o-ray):

$$n_{2\omega}(\text{e-ray}) = n_{\omega}(\text{o-ray}). \tag{4}$$

This allows a coherent build-up of ultraviolet radiation (at 316 nm for doubling our ECDL tuned to 632 nm) to take place along the whole length of the crystal. For our ADP crystal, phase matching occurs when the fundamental light propagates at around $57°$ to the optic axis.[18] The crystal we use is in the type I phase-matching geometry[19] where the crystal is angle tuned to achieve "critical" phase matching at around 300 K. The ADP crystal we use is cut so that when light is incident perpendicularly on its end facets, this condition is satisfied. The crystal is housed in index-matching fluid in a thermal jacket with a simple heater to allow the temperature to be varied. The output is sent through a filter (Chance 9863) blocking out the fundamental (red) laser light. The UV light generated is transmitted, and then detected by a photomultiplier tube (Thorn EMI 9594QUB) which in turn is connected to a microammeter. The student may readily record a variety of sample data using this apparatus. The second harmonic power as a function of crystal angle and crystal temperature may be measured, for example. Data we have taken for this are shown in Fig. 8. These sample data show that for phase matching both the crystal angle and temperature are important.

The student may also study the dependence of second harmonic output power on the power in the fundamental beam. Standard texts on optics[17] show how to solve the set of coupled equations for both the fundamental and second harmonic waves propagating in a nonlinear medium. We can approximate the ratio of the output (second harmonic) power $W_{2\omega}$ to the incident power W_{ω} to be

$$W_{2\omega} = A W_{\omega}^2 \frac{\sin^2(\Delta kl/2)}{(\Delta kl/2)^2}. \tag{5}$$

In this equation A is constant (geometry and crystal dependent), l is the length of the nonlinear crystal, and Δk is the phase mismatch between the waves. This equation is valid if there is negligible depletion of the fundamental beam and a plane wave is used. A quadratic relationship is thus expected between the fundamental and second harmonic power levels.
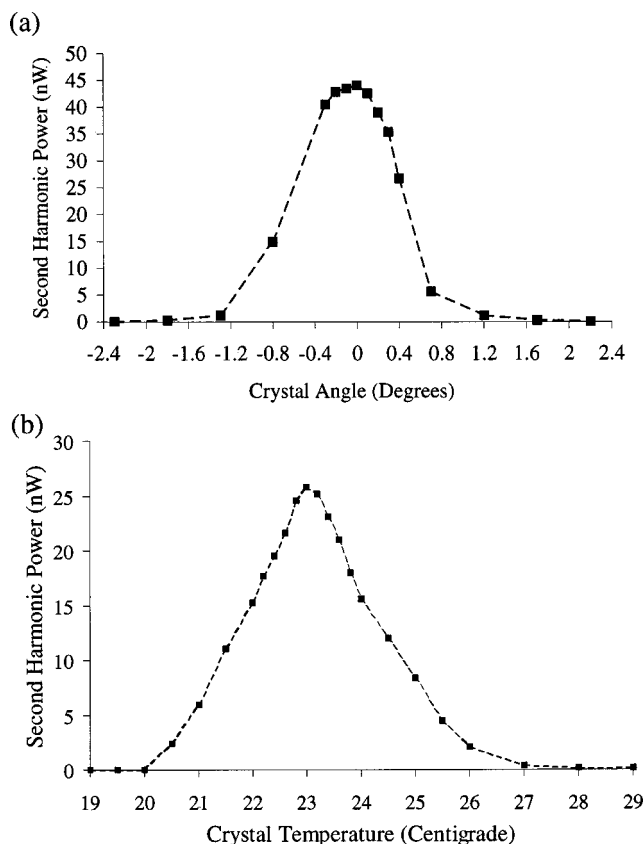

Fig. 8. (a) SHG output versus crystal angle. (b) SHG output versus crystal temperature.
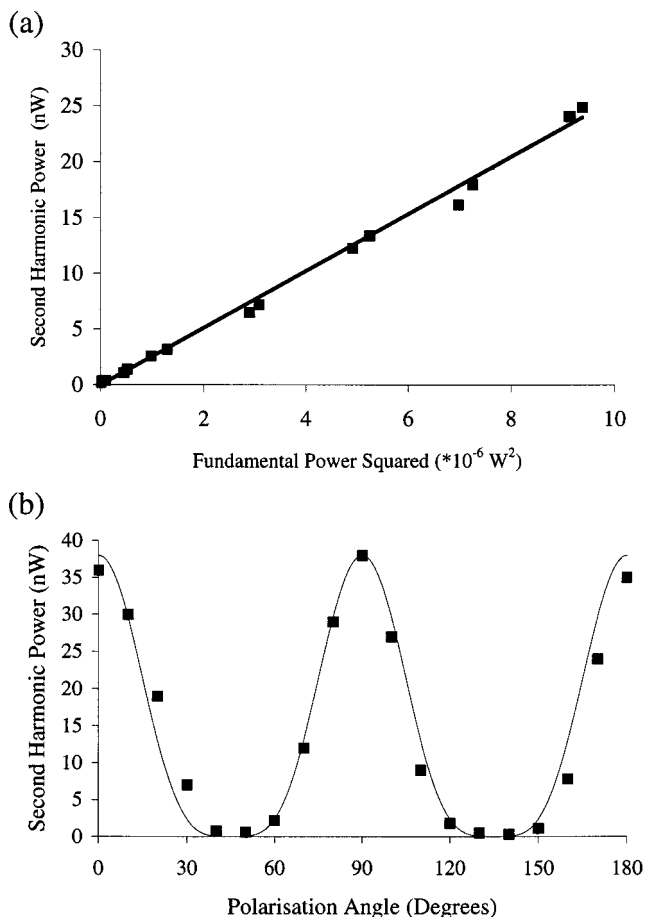
(a)

(b)

Fig. 9. (a) Graph showing second harmonic power versus square of the input power. A quadratic behavior is observed. (b) A plot of second harmonic power versus input polarization angle. The fit is in accordance with the theory in the main text and shows good agreement.

Data for this are shown in Fig. 9(a) and a good fit to this quadratic dependence is observed. It is worth noting that a deviation from the sinc^2 dependence in the above equation is observed experimentally due to the divergence of our focused beam. To vary the fundamental power in this part of the experiment the student can use a half-wave plate and a polarizer. In Fig. 9(b) we also show how the SHG process is affected by the variation of the input polarization of the light source. In this instance we introduce a half-wave plate between the crystal and the nonlinear crystal and thus rotate the plane of incident polarization. Only the component of the incident light falling on the crystal as an o-ray contributes to the SHG. The subsequent variation in power ($W_{2\omega}$) for this part of the experiment can be seen in the following way:

$$E_{2\omega} \propto E_{\omega l}^2,$$

but we can write $E_{\omega l} = E_\omega \cos\theta,$ \hfill (6)

$$W_{2\omega} \propto E_{2\omega}^2 \propto \cos^4\theta.$$

In the above θ is the angle between the direction of the E-field of the incident light and the axis of the crystal. The data in Fig. 9(b) are fitted to the above relationship and again good agreement is found.

The second harmonic experiment may be conducted using a He–Ne laser where the output beam is more circular than that from the ECDL. However, the ECDL we use has higher power than a standard He–Ne laser of similar cost. Furthermore, with a He–Ne laser one has to take care to filter out the spontaneously emitted UV in the He–Ne discharge so that it does not mask out the weak SHG signal.

VIII. HETERODYNE EXPERIMENTS WITH A He–Ne LASER

The extended cavity diode laser has a narrow linewidth (<5 MHz). We mentioned above the measurement of this linewidth using a high-finesse optical spectrum analyzer. However, if such a device is not available, there are alternative methods by which the ECDL linewidth may be determined.

To determine the instantaneous linewidth of the laser a heterodyne experiment may be performed. Normally, this involves the use of two similar lasers and one directs the outputs of both devices simultaneously onto a fast-response photodiode. If both lasers are close in frequency to one another (to within a few GHz), then a ''beatnote'' will be observed at the difference frequency of the lasers. For two similar laser systems, the width of this beatnote will be around twice the fluctuation observed in either laser and would allow the student to determine the short-term linewidth of either one of the lasers. If the lasers have dramatically different linewidths (as is the case here), then the width of the beatnote is essentially the linewidth of the broader of the two laser sources.

For simplicity in the undergraduate laboratory, we heterodyne our ECDL at 633 nm with a He–Ne laser (Hughes 3224 H-PC). This obviates the need to build a second ECDL and also removes the potentially difficult task of getting two ECDLs to be close enough in frequency to observe this heterodyne beat note. The use of a He–Ne laser here means we have two laser systems with vastly different linewidths. Indeed the instantaneous linewidth of the He–Ne laser is only a few kHz and the width of any beatnote we observe reflects the linewidth of the ECDL system. Initially we need to get the lasing frequency of the ECDL close (~ 1 GHz for the fast photodiode we use) to that of the He–Ne laser. The student may achieve this by using a combination of temperature and current tuning as well as grating tuning on the ECDL. The output of the He–Ne laser and the ECDL is placed on a fast photodiode.[20] It is important to ensure that the polarization direction of both lasers is the same. We look at the signal on an rf spectrum analyzer (Hewlett Packard HP 70000 system and HP 70206A system display). It is worth stressing that we need to overlap the light from both the He–Ne and ECDL very well for this experiment—we ensure that both beams are collinear and are overlapped over a distance of several meters. This can be achieved with the aid of simple pinholes in the optical beam path. In this process, one also has to take care not to allow any light from the He–Ne laser to reflect into the ECDL as this will effect the ECDL output due to its sensitivity to optical feedback. In practice, we have found that students have been able to achieve this without too much trouble. The He–Ne we have lases simultaneously on two or three longitudinal modes. Adjacent longitudinal modes are separated by around 430 MHz [Fig. 10(a)]. This is typical for such lasers.[21,22] In Fig. 10(b) we can see the resultant mode beating of the He–Ne laser and the ECDL. Several beatnote peaks are evident. One can measure the width of these peaks to find the linewidth of the ECDL, seen here to be around
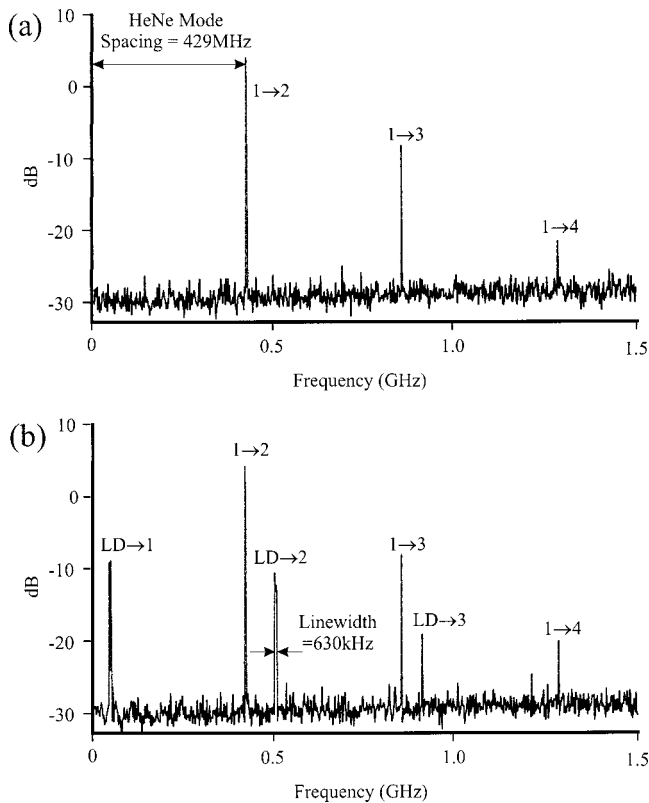
Fig. 10. (a) The self-mode beating of the He–Ne laser observed on the rf spectrum analyzer. (b) The mode beating observed between the He–Ne laser and the ECDL. Several peaks are observed. From the peaks due to the beating of the He–Ne with the ECDL (denoted LD on the figure) one can deduce the linewidth of the ECDL to be around 630 kHz.

630 kHz. Tuning the ECDL cavity by varying the voltage to the PZT will cause these beatnotes to move in this spectrum.

IX. CONCLUSIONS

We have presented details for the construction and alignment of a particularly compact and inexpensive extended cavity diode laser assembled mainly from commercially available opto-mechanical components for the undergraduate laboratory. We have discussed the operation of the laser at both 635 and 670 nm. This system will allow the student to readily investigate the physics behind the extended cavity diode laser. The student may characterize the tuning of such a laser using readily available instruments in an undergraduate optics laboratory. Additionally, we have described three major experimental studies the student may undertake using this ECDL. The first involves a simple study of the molecular spectra of iodine. The second involves generating ultraviolet radiation using the basic nonlinear process of second harmonic generation. The third involves a heterodyne experiment of the diode laser with a He–Ne laser. We believe that this ECDL is a versatile device and offers an exciting array of experiments for the undergraduate laboratory.

[1]C. E. Wieman and L. Hollberg, ''Using diode lasers for atomic physics,'' Rev. Sci. Instrum. **62**, 1–20 (1991).

[2]K. MacAdam, A. Steinbach, and C. Wieman, ''A narrow band tunable diode-laser system with grating feedback and a saturated absorption spectrometer for Cs and Rb,'' Am. J. Phys. **60**, 1098–1111 (1992).

[3]K. G. Libbrecht, R. A. Boyd, P. A. Willems, T. L. Gustavson, and D. K. Kim, ''Teaching physics with 670 nm diode lasers—construction of stabilised lasers and lithium cells,'' Am. J. Phys. **63**, 729–737 (1995).

[4]Sacher Lasertechnik, Am Kähneplatz 8, D-35041 Marburg, Germany.

[5]M. A. Clifford, J. Arlt, J. Courtial, and K. Dholakia, ''High-order Laguerre-Gaussian laser modes for studies of cold atoms,'' Opt. Commun. **156**, 300–306 (1998).

[6]A. S. Arnold, J. S. Wilson, and M. Boshier, ''A simple extended cavity diode laser,'' Rev. Sci. Instrum. **69**, 1236–1239 (1998).

[7]Thorlabs USA, 435 Route 206, P.O. Box 366, Newton, NJ 07860-0366. 9 mm laser diode collimating tube and aspheric optic part no. LT-110P-B. Adjustment spanner part no. SPW301.

[8]Optometrics UK Ltd., Unit C6/Cross Green Gate, Leeds LS9 OSF, England, diffraction grating part no. 3-4130.

[9]Wavelength Electronics, P.O. Box 865, Bozeman, MT 59771. Laser diode driver model MPL-250.

[10]Melcor Corp., 1040 Spruce St., Trenton, NJ 08648. Peltier element part no. CP-1.4-127-06L.

[11]R. S. Components, P.O. Box 99, Corby, Northants NN17 9RS, UK. $10k\Omega$ n.t.c. thermistor, part no. 151–237.

[12]Wavelength Electronics, P.O. Box 865, Bozeman, MT 59771. Temperature stabiliser model MPT-2500.

[13]G. R. Hanes and C. E. Dahlstrom, ''Iodine hyperfine structure observed in saturated absorption at 633 nm,'' Appl. Phys. Lett. **14**, 362–364 (1969).

[14]E. L. Lewis, C. W. P. Palmer, and J. L. Cruickshank, ''Iodine molecular constants from absorption and laser fluorescence,'' Am. J. Phys. **62**, 350–356 (1994).

[15]S. Gerstenkorn and P. Luc, *Atlas du spectre d'absorption de la moleculde d'iode* (Centre Nationale de la Reserche Scientific, Paris, 1978).

[16]F. L. Pedrotti and L. S. Pedrotti, *Introduction to Optics*, 2nd ed. (Prentice–Hall, Englewood Cliffs, NJ, 1987), pp. 543–546.

[17]A. Yariv, *Quantum Electronics*, 3rd ed. (Wiley, New York, 1989), pp. 378–406.

[18]M. H. Dunn and F. Akerboom, in *Physics Experiments and Projects for Students, Volume 1*, edited by C. Isenberg and S. Chomet (Newman–Hemisphere, 1985), p. 87.

[19]W. Koechner, *Solid-State Laser Engineering*, 2nd ed. (Springer-Verlag, New York, 1988), pp. 484–485.

[20]Photodiode BPX65 (part no. 304-346) from R. S. Components (see Ref. 11).

[21]M. H. Dunn, S. T. Whittley, and J. R. M. Barr, ''Mode effects in second harmonic generation and their uses for laser stabilisation,'' Opt. Quantum Electron. **15**, 113–118 (1983).

[22]A. M. Lindberg, ''Mode frequency pulling in He–Ne lasers,'' Am. J. Phys. **67**, 350–353 (1998).