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# A modular, reconfigurable-cavity, pulsed dye laser for the advanced undergraduate laboratory

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The modular pulsed dye laser described is extremely easy to build, is quickly reconfigurable into different laser cavity designs, and is usable for experiments in spectroscopy. The laser can be constructed with readily available optical components and simple hand tools. This laser is designed primarily to illustrate the performance differences of three different dye laser cavity designs: the Littrow grating (Hänsch) cavity, and both the single- and double-grating grazing incidence cavities. In the double-grating configuration, the laser's linewidth of 0.007 nm is on the order of ten times narrower than many commercially available pulsed dye lasers. Thus the laser also has excellent performance as a spectroscopic tool. Construction, typical performance, and application details are described. © *1997 American Association of Physics Teachers.*

## I. INTRODUCTION

Dye lasers, a common tool in spectroscopy laboratories, are occasionally found in advanced undergraduate laboratories. Hilborn[1] and Alfrey[2] have described the construction of homemade dye lasers that are appropriate for undergraduate use. Several manufacturers[3] produce compact, rugged, and relatively inexpensive dye lasers suitable for undergraduate spectroscopy experiments. In this paper, we describe a "modular" dye laser that was designed both for experiments in laser physics and in spectroscopy. Use of standard, commercially available, optical components makes this dye laser extremely simple to build. The modular approach allows a student to rearrange the optical components into different laser cavity configurations in a matter of minutes. The performance of the laser is better than many commercially available models, thus this dye laser is also suitable for undergraduate research.

Many advanced laboratory experiments can be accomplished with dye lasers. Brandenberger[4] has edited conference proceedings describing the usefulness of laser/optics laboratory experiences for undergraduates. Included in the proceedings are several applications of dye lasers such as Raman scattering, laser-induced fluorescence, and the excitation of sodium Rydberg states. Arnett *et al.*[5] describe a simple optogalvanic spectroscopy experiment. Several laser manufacturers also provide lists of potential experiments.[6–8]

Like the lasers described by Hilborn and Alfrey, this laser can be used for spectroscopy. As a spectroscopic tool, this laser is appropriate for all the experiments referenced above. When assembled in the double-grating grazing incidence dye laser configuration, the laser delivers research quality performance, producing a linewidth that is on the order of ten times narrower than many commercially available dye lasers.

Our primary goal was to design a laser specifically for experiments on laser cavity physics. Because of its modular design, students can quickly configure this laser's cavity into at least three different designs. Students then compare and contrast the efficiency, linewidth, and stability of the different laser cavities. Thus the system provides not only an excellent introduction to dye laser design, but to the function of lasers in general.

This laser system, as described, can initially be built in less than two days using mostly ''off-the-shelf'' components. The few remaining components are easily constructed with a drill press and hand tools. The total cost of this dye laser was less than $3,300, nearly an order of magnitude less expensive than most commercial dye lasers. Once the initial construction and preassemblies are complete, upper-division students can assemble and operate this laser in less than an hour. Finally, with the addition of a few more components, further laser design experiments (e.g., other cavity designs, amplification stages, etc.) can be made available to the students.

## II. BACKGROUND

An impressive array of literature is available on all aspects of lasers. A delightful and thorough introduction to the physics, designs, techniques and applications of lasers has been presented by Schewe.[9] Another good starting point is O'Shea and Peckham's[10] Resource Letter on lasers. The basic theory of dye lasers in particular has been described in detail by Hilborn.[1] (Ganiel[11] has performed a more rigorous treatment for the advanced reader.)

Dye lasers require the standard components of any laser—an energy source (the pump laser), an active medium (the laser dye), and a resonant cavity. In addition, dye lasers require a method of isolating a narrow range of wavelengths out of the broad range over which the laser dye will allow lasing to occur. Almost universally, a diffraction grating is introduced into the laser cavity to disperse unwanted wavelengths, allowing amplification of only the desired wavelength. There are only two orientations in which diffraction gratings are commonly used: the Littrow mount and the grazing incidence configuration. Of the three cavities described in this paper, the first uses the Littrow mount, the second uses the grazing incidence configuration, and the third uses a combination of the two.

Several performance characteristics of each laser cavity configuration can be readily measured by students. We chose to measure the linewidth, the background noise (amplified spontaneous emission), the mode structure and the efficiency.

### A. The pump laser

The pump laser acts as the power supply for a dye laser. There are two requirements for the pump laser: the wavelength must be shorter than the desired output wavelength of the dye laser and the pump laser must be powerful enough to drive the dye laser above the lasing threshold.

While nearly any medium- to high-power laser can be used as the pump, in practice pulsed lasers are easier to use than continuous lasers. For pulsed light sources the average power remains low while the peak power can be quite high, easily into the megawatt range. Good candidates for the pump laser are the nitrogen-ion, Nd:YAG, and the excimer. The pump laser can be either purchased or constructed.

The excimer laser is probably not a good choice for a student laboratory because of the toxic and expensive gases needed. (A single mistake can rapidly pump $500 worth of xenon into the atmosphere.) Building your own is not really a viable option; although conceptually straightforward, excimer lasers are constructed from materials inert to the excited halogen gases used to create the excimer molecules. The advantages of the excimer laser are: high repetition rates, high peak power output, easy operation, and simple maintenance.

Nd:YAG lasers are not easy to build and require some expertise to maintain. However, Yang[12] *et al*. have described a homemade Nd:YAG laser. One advantage of this type of pump laser is that the output can be either green (532 nm) or ultraviolet (either 355 or 266 nm). The green output has the advantage of being easier to see. This makes it easier to control stray beams for the sake of eye safety. Also, many red laser dyes are more efficient when pumped with 532-nm light than with UV light. Finally, the beam quality of Nd:YAG lasers is generally very high.

Probably the best choice for the undergraduate laboratory is the nitrogen ion laser. The $N_2^+$ laser is easy to operate and maintain, and comparatively inexpensive to purchase or build. Hilborn,[13] and others,[14–16] have described many designs for homemade $N_2^+$ lasers. (It should be noted that careful attention must be paid to the choice and design of the capacitors, if you choose to build your own nitrogen laser.[17,18]) An inexpensive, albeit relatively low power, nitrogen laser is manufactured by Laser Science, Inc. (model VSL-337). More powerful nitrogen lasers are available from Photon Technology International, Inc. and Laser Photonics, Inc., among others. A more comprehensive listing of suppliers may be found in the annual buyers guide edition (August) of *Physics Today*.

If you are comfortable with possibly having to repair a laser, there are several dealers of used lasers.[19,20] The nitrogen laser is an especially good choice for this because of its simplicity and ease of maintenance. Both of our nitrogen pump lasers are secondhand and have worked well for us with only minor repairs.

On the other hand, a pump laser is not completely necessary. Dye lasers can also be pumped with high intensity flash lamps such as the one described by Alfrey.[2] While we have not tried it, it is conceivable that one could construct a flash lamp powered dye laser using the modular cavity approach described in this paper.

### B. General cavity configurations

#### *1. The Littrow mount laser*

Hänsch[21] describes a narrow-linewidth dye laser that is typical of the Littrow mount cavity. This basic design, still used by many dye lasers on the market today, is shown in Fig. 1. In general, the diffraction grating's light dispersion can be described as

$$m\lambda = a(\sin\,\theta + \sin\,\phi), \tag{1}$$

where $m$ is the diffraction order (typically between 1 and 4), $\lambda$ is the peak wavelength, $a$ is the spacing of the lines on the grating, $\phi$ is the angle from the normal to the incoming light, and $\theta$ is the angle from the normal to the outgoing light. In the Littrow configuration the angles of the incoming and outgoing light are the same for one of the diffraction orders. Thus, with $\theta = \phi$ we obtain

$$m\lambda = 2a\,\sin\,\theta. \tag{2}$$

Effectively, the diffraction grating behaves as a wavelength-specific end mirror. A particular wavelength can be selected by rotating the diffraction grating about an axis perpendicu-

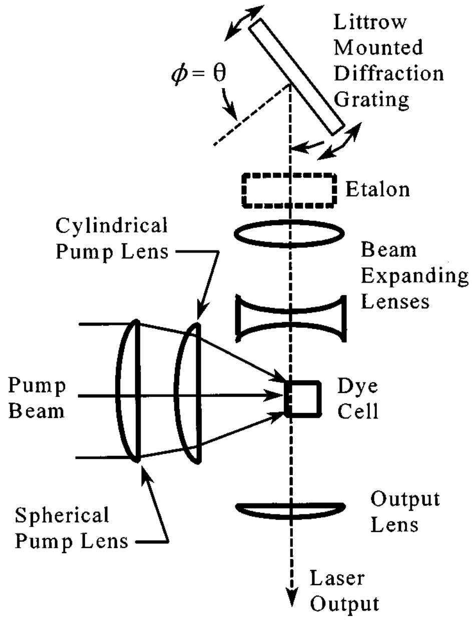


Fig. 1. The standard Hänsch design dye laser cavity configuration. Rotating the grating changes the laser's output wavelength. Hänsch used the etalon to narrow the laser's linewidth. Common practice is to not use the etalon. The first surface reflection from the Plano side of the output lens functions as the cavity's end mirror. The output lens also collimates the beam.

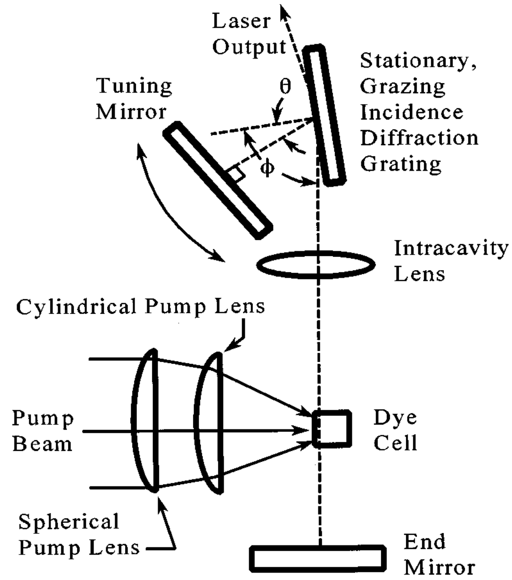


Fig. 2. The single-grating, grazing incidence dye laser cavity configuration. Rotating the tuning mirror around the diffraction grating changes the laser's output wavelength. The intracavity lens collimates the beam. The zeroth diffraction order is the output beam.

lar to the cavity and parallel to the rulings of the grating.

The linewidth, $\Delta\lambda$, of a diffraction grating is inversely proportional to the product of the number of grating lines illuminated, $N$, and the diffraction order,[22] specifically,

$$\Delta\lambda = \frac{\lambda}{mN}. \tag{3}$$

The total number of lines that are illuminated is $N$, which is equal to the number of lines per unit length of the diffraction grating (a fixed quantity) times the length of that portion of the grating that is illuminated. The purpose of the beam-expanding telescope inside a Littrow mount dye laser is to increase the number of lines on the diffraction grating that are illuminated, thereby increasing the spectral resolution of the laser. The beam-expanding telescope also serves to collimate the diverging beam leaving the dye cell. This ensures that the rays striking the diffraction grating are approximately parallel.

In most commercial Littrow mount dye lasers a system of two or more prisms is used in place of the beam-expanding telescope. This allows the beam to be expanded in only one dimension thus making the laser more efficient. A prismatic beam expander is substantially more expensive and more challenging to design. For our purposes we decided that the additional output power was not worth the added expense.

### *2. The single-grating grazing incidence dye laser*

The grazing incidence dye laser uses a stationary diffraction grating oriented with the grating normal at approximately 89° to the axis of the laser cavity as shown in Fig. 2. The grazing incidence dye laser does not need an intracavity beam expander because the orientation of the diffraction grating intrinsically maximizes $N$.

For the grazing incidence dye laser (hereafter referred to as the GIDL) the wavelength is determined from Eq. (1) as

$$m\lambda = a(\sin\theta + \sin\phi) \approx a(\sin\theta + 1), \tag{4}$$

where we have approximated $\sin\phi = \sin(89°) \approx 1$. Tuning of the laser wavelength is accomplished by rotating a flat mirror about an axis oriented perpendicular to both the laser cavity and the grating normal and through the center of the surface of the grating.

### *3. The double-grating grazing incidence dye laser*

The third laser design that students can easily configure our system into is a common modification of the GIDL where the flat tuning mirror is replaced with a second diffraction grating in a Littrow mount configuration. A closeup of this change is shown in Fig. 3. With two diffraction gratings in the cavity, the dispersion of unwanted wavelengths is substantial.

## C. Laser linewidth

Iles[23] has performed a theoretical analysis of the linewidth for each of the three cavities described in this paper. We can characterize the diffraction gratings by defining $\alpha$ (for the Littrow mounted grating) and $\beta$ (for the grazing incidence grating) as the ratios of the diffraction order to the grating line spacing. That is, $\alpha = m_1/a_1$ and $\beta = m_2/a_2$, where $m$ is the diffraction order and $a$ is the grating line spacing. Correcting for several typesetting errors in Iles paper, we can estimate the linewidths for the various cavities. For the Hänsch laser, Iles predicts the linewidth to be

$$\Delta\lambda_H = \frac{4\sqrt{2}\lambda}{\pi L\alpha}, \tag{5}$$

where $L$ is the length of the illuminated portion of the diffraction grating. For the single diffraction grating GIDL. Iles predicts the linewidth to be half that of a comparable Hänsch laser, i.e.,

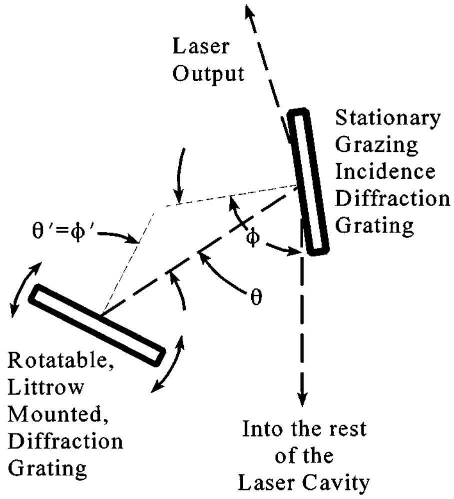


Fig. 3. The double-grating, grazing incidence dye laser (GIDL) cavity configuration. This figure shows only the differences from the single-grating GIDL. Rotation of the Littrow mounted grating controls the wavelength.

$$\Delta\lambda_s = \frac{2\sqrt{2}\lambda}{\pi L \beta}. \tag{6}$$

The double diffraction grating configuration is more complicated. Iles' result is

$$\Delta\lambda_D = \frac{2\sqrt{2}\lambda}{\pi L\left(\alpha + \frac{\beta}{2}\left[\frac{2\alpha\lambda - \alpha^2\lambda^2}{1-\left(\frac{\beta\lambda}{2}\right)^2}\right]^{1/2}\right)}. \tag{7}$$

This is roughly equivalent to the single diffraction grating situation but with an additional term in the denominator that accounts for the extra dispersion generated by the second diffraction grating. Using the parameters for our laser cavities, the predicted linewidths are 0.034, 0.0068, and 0.0023 nm, respectively.

Obtaining an accurate measurement of the linewidth is most easily done with an etalon.[24,25] The result of the measurement, $\Delta\lambda_{\text{meas}}$, is actually the convolution of the laser's actual linewidth, $\Delta\lambda_{\text{laser}}$, and the instrument's resolution, $\Delta\lambda_{\text{etalon}}$. This is approximately described as

$$\Delta\lambda_{\text{meas}} = \sqrt{(\Delta\lambda_{\text{etalon}} + \Delta\lambda_{\text{laser}})^2}. \tag{8}$$

Optimally, the resolution will be fine enough to not affect the measurement significantly. The resolving power of the etalon is the free spectral range (FSR) divided by the finesse. At $\lambda = 540$ nm, our etalon has a finesse of 40 and a FSR of 0.058 nm. Thus, the resolving power of this etalon is approximately 0.058 nm/40=0.0015 nm. For the double-grating GIDL cavity, the linewidth, as measured by the etalon, was 0.0072(2) nm. (The uncertainty is statistically determined from fitting the peak to a Gaussian line shape.) Using Eq. (8), we find that the actual linewidth of the laser is 0.0070(2) nm. Since this is within the uncertainty, we conclude that we don't need to routinely correct our measurements for the effect of the instrument.

Another method for measuring the linewidth is to drive an atomic transition with the laser. This can be done by setting up any of a number of experiments as mentioned above. We used a Ne hollow cathode discharge tube (HCDT) and the optogalvanic effect.[14] The primary broadening source in the atomic lines in a HCDT is from the Doppler effect. A reasonable estimate of the temperature inside the discharge is 400 K from which we can estimate the Doppler broadening to be approximately 0.002 nm. Our narrowest measurement of the Ne line was 0.0059(2) nm, this deconvolves to 0.0056(2) nm. Note that this error is greater than the fitting uncertainty.

The linewidth disagreement in the etalon and HCDT measurements is likely due to inaccuracies in curve fitting and systematic sources of error in the measurements. One such source of error is the physical size of the photodiode used to measure the etalon fringes. Another potential source of error is deviations from linearity (for signal versus intensity) in the photodiode or HCDT.

### D. Amplified spontaneous emission (ASE)

Lasing occurs when an initial spontaneous photon propagating along the axis of the laser cavity starts the chain reaction of stimulated emission that we know as laser light. For most lasers this is the end of the discussion, but for dye lasers the situation is different. Laser dyes are designed to support lasing over a bandwidth of tens of nanometers. Dye laser cavities must reject all but a very narrow bandwidth of photons for amplification. For example, the cavity for the grazing incidence dye laser typically reduces the emission bandwidth of the dye by four orders of magnitude. ASE is the result of spontaneous photons being amplified by either a single pass through the cavity or feedback from unwanted internal reflections. ASE is essentially broadband background noise in the laser output.

Completely eliminating ASE is impossible, but it can be reduced. For example, simply orienting the sidewalls of the dye cell exactly perpendicular to the axis of the laser cavity can quickly demonstrate serious ASE. Internal reflections from the sides of the dye cell will form a broadband resonant cavity. The effect can be readily observed by monitoring the laser output with a diffraction grating, or by observing a single slit diffraction pattern. With the slit, all fringe contrast will be washed out when broadband lasing occurs. For the diffraction grating, the output spot will spread over a much larger region. The effect is so strong, when the laser linewidth changes from 0.006 to 60.0 nm, that even a simple prism will detect it. ASE caused by internal reflections in the dye cell is easy to resolve; simply rotate the dye cell a few degrees about an axis parallel to the pump beam so that the laser cavity axis is not perpendicular to the faces of the dye cell.

Other sources of ASE, for example, surface reflections from optical components inside the laser cavity, are not as easy to control. Rotating all the optics a few degrees so that no first surface reflections can be amplified is one solution. However, this also causes astigmatism in the laser beam. We require that the students deliberately orient at least one optical component such that a stray reflection is amplified. The students then rotate the component slightly while monitoring the beam quality.

### E. Cavity mode structure

No laser is truly monochromatic. Beyond the issue of a finite bandwidth, most lasers contain several closely spaced emission lines arising from longitudinal modes inside the cavity. For a typical resonant cavity with plane mirrors, the

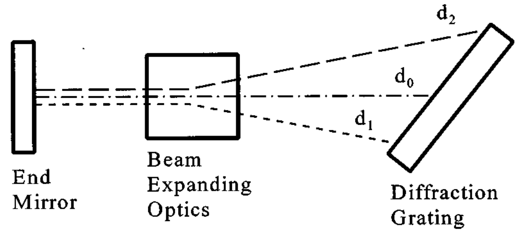


Fig. 4. A simplified diagram of a typical dye laser cavity. Notice the different cavity lengths, $d_0$, $d_1$, and $d_2$. A poorly defined cavity length is only one of the complications involved in calculating the cavity mode structure for a dye laser. A Hänsch laser is shown, but the problem is even more pronounced in the grazing incidence cavities.

spacing between modes is described by $\Delta\lambda = \lambda^2/(2nd)$, where $n$ is the index of refraction and $d$ is the cavity length. (The mode spacing is a direct result of the requirement that an integral number of half-wavelengths fit inside a resonant cavity.) Unlike most lasers, the cavity length is not a well-defined quantity for dye lasers. This is because of the tipped ''mirror'' formed by the diffraction grating (see Fig. 4). Other complexities arise because the active medium (the optically pumped laser dye) is only a small part of the cavity; thus neither the index of refraction nor the laser gain is constant inside a dye laser.[26]

An etalon will readily display the modes of a dye laser if the laser modes are more closely spaced than the free spectral range of the etalon. It turns out that the mode structure of a dye laser is far more dependent on careful alignment than on cavity length. In use, a dye laser is usually scanned in wavelength; therefore, the optical alignment must be robust throughout the tuning range of the laser. Each of the three laser cavities described in this paper have different behavior with respect to cavity modes. Typical results are reported below.

### F. Laser safety

There are two primary safety concerns for dye laser users: light and laser dyes. It is not the purpose of this article to address these issues at length. However, there are a few easy precautions that all dye laser users should follow.

An excellent overview of laser hazards and safety has been written by Weichel *et al.*[27] The Optical Society of America's Laser Safety Committee[28] has addressed specifically the issues related to ultraviolet laser light such as the lasers used for optically pumping the dye laser. Moseley[29] has written a more current and extremely detailed review article on both ultraviolet and laser radiation safety.

In addition to retinal damage from direct exposure to laser beams, the lens tissue can also be damaged by the UV pump laser. The 337-nm laser light from an $N_2^+$ pump laser is right at the edge of the range that causes cataracts. Additionally, with UV light, skin exposure should also be avoided as much as is practical. Skin effects include erythema (sunburn), accelerated aging of the skin and photocarcinogenisis (skin cancer).

Because the laser light is pulsed, the average power may be only a few milliwatts, yet the peak power can be quite high. The pump laser can easily exceed 1 MW and the dye laser's peak power can be in the range of 10 kW. Common sense is the best first defense, but careful planing can help. You should have an adequate supply of UV blocking laser safety goggles. All stray laser beams should be monitored, preferably blocked. Be alert to first surface reflections from laboratory equipment and furniture, e.g., glass cabinet doors and windows. It is good laser laboratory practice to keep all laser beams in a single horizontal plane. Then, make sure that no chairs are available that would place an occupant's eyes on the same level as the laser beam plane. The general direction of the laser beams should be away from doors or other traffic areas. Access doors must have warning lights and signs.

Laser dyes introduce a hazard not present with other laser types. The dyes themselves have not generally had complete tests done on the toxilogical and mutagenic properties. (The current test results[30] indicate that many laser dyes are generally safe, though be aware that some laser dyes are known mutagens.) All liquid laser dyes use solvents. Usually the solvents, e.g., methanol, are easy to handle. However, some laser dyes require solvents such as DMSO. DMSO is difficult to handle without risking the direct absorption of laser dyes into the body. Since dyes requiring DMSO are easy to avoid, we recommend that they not be used in the undergraduate laboratory. All laser dyes should be mixed in a fume hood or other area with adequate ventilation. Gloves and eye protection should be worn whenever dyes are handled. Premixed dye solutions should be kept tightly capped. The laser dye powder often gets spilled in minute amounts and seems to get everywhere, hence the mixing area should be carefully wiped down after each use.

## III. BUILDING AND USING THE LASER

### A. Components

We have attempted to minimize the use of parts requiring specialized machining. This laser can be constructed almost completely from off-the-shelf optical components. The minimum tools needed to manufacture the specialized components are a hacksaw, a drill press, and an 8-32 tap. A complete listing of parts and suppliers is in Appendix A. The dye laser (sans the pump laser) can be built for less than \$3,300 and will outperform lasers costing more than \$20,000.

Most of the optical components need only be of standard student laboratory quality. The only exceptions are the dye cells, pump beam lenses and diffraction grating(s).

For the dye cells, spectrometer cuvettes, commonly used in chemical analysis equipment, are readily available and work well. Most campus chemistry department stock rooms stock these. If you are using UV light for the pump then you will want a quartz dye cell. A glass dye cell might also work since the optical path thickness is small enough that the UV absorption and reflection losses should be about 25%. (The quartz dye cell will have about an 8% loss.) If your pump laser is powerful enough then this loss will probably not be critical. (We have not tried glass cells.) We found that plastic dye cells will not work due to strong absorption of the UV pump beam. Additionally, some of the laser dyes stain the plastic aggressively. The dye cell must have a securely sealing top to reduce evaporation of the dye solvent.

An improvement to the system is to use a flowing dye cell or a dye cell stirrer. This will allow for higher repetition rates without saturating the laser dye. We found that a simple, unstirred dye cell provides stable operation at ten pulses per second (pps) but becomes unstable at 15 pps. Lower pump power will likely offset this limitation.

The pump beam lenses should be constructed of UV transparent material such as silica. The cylindrical lens is the most expensive. Some laser manufacturers might have overstock and/or damaged cylindrical silica lenses on hand that can be purchased at a reduced price. A small chip in the lens will not affect its use unless it is near the vertex.

For the grazing incidence dye laser, purchasing a diffraction grating that is blazed for this purpose is best. However, we found that any high quality grating with 1200–2400 lines/mm can be used, although the efficiency will be less. Good potential sources of free, high quality diffraction gratings are chemistry and geology departments. For example, we obtained several top quality diffraction gratings (and other optics) from an atomic absorption instrument that was being surplused as scrap by our chemistry department.

The optics mounts should be as sturdy as possible. However, we deliberately shook each mount and found that only the dye cell, tuning mirror/grating and diffraction grating mounts really needed to be of the highest quality.

Being able to scan the dye laser wavelength with a stepper motor is extremely useful. The step sizes must be small enough to provide five or more steps across the full width at half-maximum of the laser linewidth. We found that elaborate gearing systems were much more difficult to use than a microstepping circuit for the stepper motor. Microstepping circuits are commercially available that can be controlled by transistor–transistor logic (TTL) digital input–output (I/O) signals from a computer data acquisition card.

Many moderately priced rotation stages have substantial lateral motion of the control knob while rotating the stage. These stages will work if the stepper motor drive linkage can adapt to this. We successfully used a chain and sprocket drive train along with a microstepper circuit. This was substantially easier than earlier attempts that used flex shafts and universal joint couplings.

### B. Assembly

The components we used are listed in Appendix A along with a note describing the position of that component. Because the goal of this project was to have a laser that students could quickly reconfigure, we have placed every optical component in its own permanent mount. Students can safely bolt down the components that they do not need off to the side on the breadboard. Permanently mounted components also lessen the potential for damage to the optical components. Unfortunately, the current design requires direct handling of the most delicate element—the diffraction grating. Currently, this is done only with the instructor present.

In Appendix A we have described which mounts hold which optics for the initial assembly. Once the optical components are mounted, students can shuffle them around on the breadboard to match the cavity configurations shown in Figs. 1, 2, and 3. Appendix B gives an outlined approach to setting up each individual laser cavity. Figure 5 is a photograph of the optical components arranged for the double-diffraction grating GIDL. The black baseplate was removed, and the spacing between the optics increased, for photographic clarity.

The effects of the pump beam include the eventual breakdown of the laser dye caused by photochemical interactions. Some laser dyes will only last for a few hours of use. There is no visual way to know when the laser dye is exhausted since the dye will still fluoresce. So, if your attempts at lasing fail for no apparent reason, try using fresh laser dye.

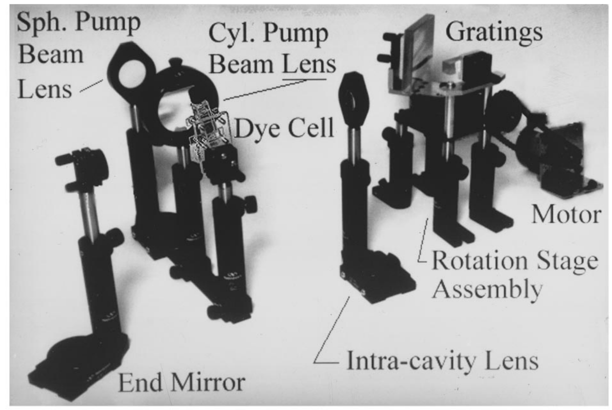


Fig. 5. The double-grating grazing incidence dye laser. For clarity, the black baseplate was removed for the photograph. Students can reconfigure the laser into the different cavity designs by simply rearranging the optical assemblies. Only the rotational stage assembly requires direct handling of the optical components. The motor is used to scan the laser's output wavelength by rotating the stage.

### C. Measurement

The primary goal of this work is for the student to be able to change the cavity design quickly, then measure the effects of that change. A secondary goal is to have a laser that is useful for projects in spectroscopy. Both goals require measurement equipment. The cost of measurement equipment can easily exceed the cost of the laser, although several ways exist to reduce that expense.

Laser parameters that students might measure include the linewidth, ASE, efficiency, polarization, and beam divergence. Since diffraction gratings produce polarized light, all dye lasers are polarized. The beam divergence depends primarily on the adjustment of the output lens, or, for the GIDL, on the intracavity lens. Therefore, beam divergence depends less on the laser cavity and more on careful adjustment.

The linewidth can be measured with an etalon, by scanning an atomic transition, or by using a high resolution spectrometer. By far the easiest and fastest choice is the etalon. An etalon also aids in final adjustment of the laser. A student quality Fabry–Perot interferometer will work but ours was not nearly as efficient as a high quality etalon. We also attempted to use a Michelson interferometer but the resolution was completely inadequate. Etalons typically cost several thousand dollars; however, Perkalskis and Freeman[25] describe the construction of a homemade etalon for a fraction of this cost. Dye laser manufacturers sometimes have etalons available that are obsolete stock or over-stock accessories that they will sell for a reduced price. The etalon also provides a simple and accurate method for measuring the ASE, as is described below. Etalons are useful for other experiments too, e.g., measuring the Zeeman effect can be easily done with an etalon.

One of the easiest ways to scan an atomic transition is by using neon in a hollow cathode discharge tube (HCDT). Arnett *et al.*[31] have described the technique in detail. HCDTs cost about a tenth that of an etalon. We obtained ours for no cost from the chemistry department; while the HCDT no longer functioned for their atomic absorption instrument, it worked well for our purposes. Try to obtain several tubes since not all tubes have a stable discharge current. Of the three tubes we obtained only two were usable.

Table I. Comparison of the three cavity configurations for the homemade dye laser and a commercial dye laser. The results reported are ''typical,'' not ''best.''

| Laser cavity | Linewidth[a] (nm) | Efficiency (%) | Noise[b] (%) | Stability[c] |
|---|---|---|---|---|
| Hänsch | 0.16(3) | 5 | 15 | poor |
| single-grating GIDL | 0.011(5) | 2 | 10 | good |
| double-grating GIDL | 0.0073(2) | 2 | 4 | excellent |
| commercial laser[d] | 0.050(2) | N/A[e] | 10 | fair |

[a]Measured using an etalon except the Hänsch configuration that was measured with a 0.25-m spectrometer.
[b]Defined as the fraction of amplified spontaneous emission (ASE) in the total output power.
[c]Defined subjectively as ease of setup, alignment, and smoothness when scanned in wavelength.
[d]Photon Technology International, South Brunswick, NJ, model PL202. This is a single-grating GIDL with the addition of an amplifier stage.
[e]This dye laser has an amplifier stage built in. Thus a direct comparison cannot be made with the homemade laser.

Schreiber *et al.*[32] describe a homemade, high resolution Ebert spectrometer that is precise enough for measuring laser linewidths. We did not complete ours in time for this project but did use a low resolution, 0.25-m, commercial scanning spectrophotometer for measuring the Hänsch dye laser.

Amplified spontaneous emission can be measured with an etalon by measuring the laser power at a fringe peak, at a minimum between fringes, and with the beam blocked. Using the blocked beam reading as the zero power level, the percent ASE is simply obtained from the ratio of the fringe minima to the fringe maxima. Lacking an etalon, a reasonable estimate of the ASE can be made by using a diffraction grating or prism. Disperse the output beam and then measure the power with the lasing portion alternately blocked and unblocked. If you are using a photodiode for power measurement, you will need to add a lens to focus the dispersed beam onto the photodiode.

Efficiency measurements are best accomplished with a laser power meter. An inexpensive alternative is a photodiode. Since you should measure the power of the pump beam, make sure your photodiode will measure in that frequency range. Most photodiodes use glass windows that start to cut off transmission at about 350 nm, so, the 337-nm nitrogen laser output is slightly attenuated.[33] Many photodiode suppliers provide sample circuit diagrams. Photodiode circuits are typically very simple, often involving less than five components.

## IV. TYPICAL RESULTS

The dye laser proved to be extremely stable and easy to assemble. The dye laser demonstrated clear differences between three cavity designs. The results presented here are not the best data obtained, but are typical of what should be obtained by students setting up the laser for the first time. We made measurements of the linewidth, the ASE level, and the efficiency. These are compared with that of a commercially made dye laser used as a baseline reference. The results are summarized in Table I.

Optomechanical stability and durability are excellent. The components are generally robust, except for the surface of the diffraction gratings. Aggressive tapping on, and wiggling of, the optical components produced little or no effect in the beam quality with the exception of the mounts for the diffraction grating, tuning mirror/grating, and dye cell.

With practice, we could obtain good laser performance within 15 min when starting with a completely disassembled system. An experienced technician with no formal background in optics or physics was able to obtain excellent laser performance within an hour on the first try. He simply followed a detailed set of instructions on the laser's alignment. Choosing optical mounts that are easy to adjust is advantageous. Several early designs using low-end optical mounts were adequate but much slower to adjust. In particular, mounts with stationary baseplate slots forced one to adjust several degrees of freedom at once for each mount. Being able to slide the optical mount around on the breadboard without rotating the optical component proved to be a significant advantage.

Because students typically approach optical alignment very haphazardly, we have found that they require a detailed procedure. An outline of the alignment procedure is provided in Appendix B.

Based on Iles theoretical analysis, the linewidth of the Hänsch laser should be 0.034 nm, the single-grating GIDL should be 0.0068 nm, and the double-grating GIDL should be 0.0023 nm. With quick alignments, we obtained typical values of 0.175, 0.009, and 0.007 nm, respectively. (With extreme care in the alignment we can obtain values much closer to the theoretical predictions.) The main cause of the increased linewidth was multimode operation. By comparison, the commercial dye laser (Photon Technology International, model PL202) using a single-grating, grazing incidence design produced a linewidth of 0.044(1) nm that, while consistent with their specifications, is much broader than Iles' predictions.

Figures 6, 7, 9, and 10 show typical results for the laser linewidths and tuning stability. For ease of comparison all wavelength axes use the same scale except Fig. 6. A bar on the wavelength axis of Fig. 6 shows the wavelength range of the other figures. The raw data are shown with symbols, and the lines are the results of nonlinear curve fitting to approximately the top half of each peak to a Gaussian. The measured linewidths and uncertainties are all full width at half-maximum (FWHM) and are obtained from the Gaussian curve fit.

Figure 6 was obtained by combining spectrophotometer scans of the neon spectrum from the HCDT and of the laser. The spectrophotometer's resolution is 0.052(4) nm as determined by measuring the neon line. Figure 6 is interesting because it shows that the laser is operating on at least three separate paths within the laser cavity. Other attempts at aligning the Hänsch laser cavity resulted in one or two peaks. Overall, this cavity required more care than the other designs to obtain the best operation. Linewidths on the order of 0.2 nm, as shown for the three peaks in Fig. 6, were typical for this cavity even when operating with a single peak. Hänsch added an intracavity etalon to narrow the linewidth substantially (shown by a dashed box in Fig. 1). This is still common today in many commercial Hänsch design, dye lasers.

The ASE level shown in Fig. 6 is misleading. Since these data were taken with a spectrometer, the correct method to determine the ASE level would be to integrate the area under the curve (excluding the laser lines) rather than reading the instantaneous level as can be done with measurements using

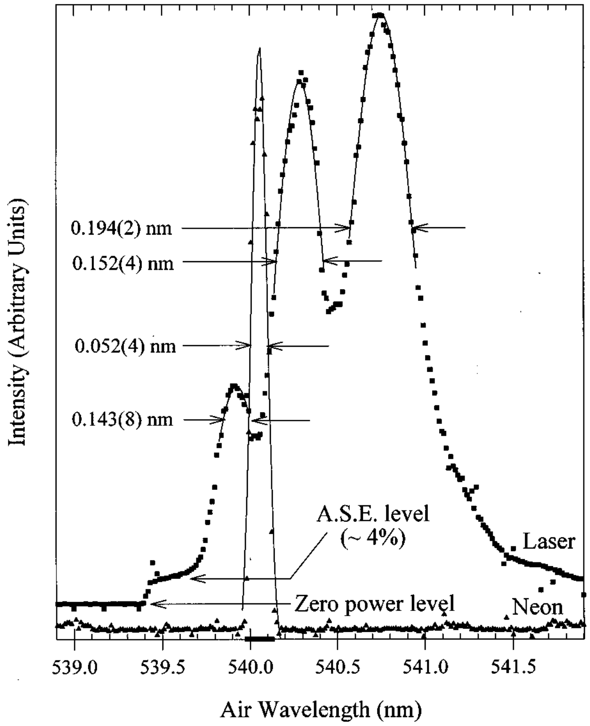


Fig. 6. The laser's spectral output when configured as a Hänsch dye laser, measured using a 0.25-m spectrometer. The neon spectral line was scanned separately for calibration and to determine the resolution of the spectrometer. The amplified spontaneous emission (ASE) level indicates the amount of broadband noise in the laser's output. The horizontal bar on the wavelength axis near 540.0 nm indicates, for comparison, the spectral range covered in Figs. 7, 9, and 10.

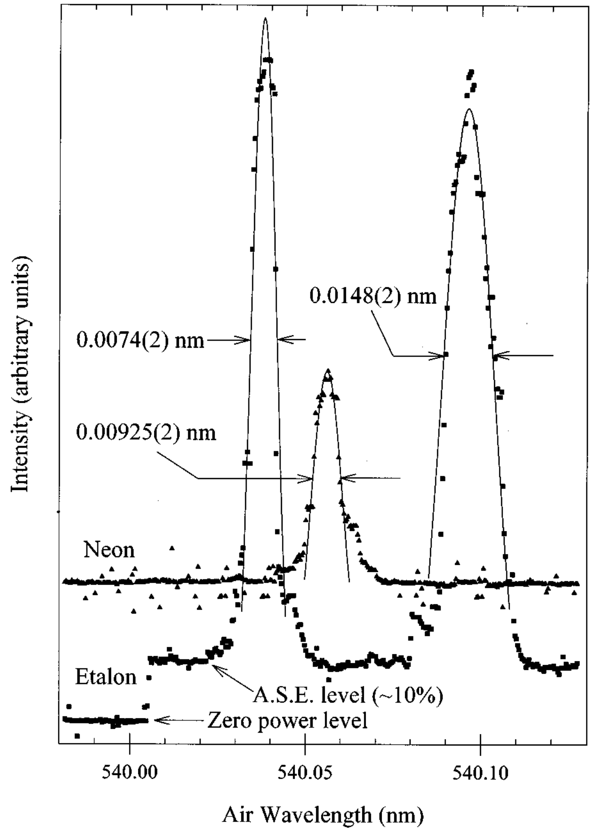


Fig. 7. The spectral output from the laser when configured as a single-grating, grazing incidence dye laser. The etalon fringes and optogalvanic spectra were simultaneously measured while the laser was scanned in wavelength. Note the progression in linewidth as the laser mode structure changes.

the etalon. However, the approach used in Fig. 6 does provide a sense of the level of the background noise in the laser output.

Figures 7, 9, and 10 are simultaneous measurements of the etalon fringes and optogalvanic effect in the HCDT while scanning the laser wavelength. For the sake of clarity, we have plotted only every other data point. We scanned the laser with a microstepping stepper motor providing more than 30 steps within the FWHM of the laser line. (A later version of the drive circuit reduced this resolution by a factor of 2. The reduced resolution is still more than adequate and has improved the data collection rate.) At the start of each scan, we blocked the laser beam into the etalon to determine a zero power level. The ASE is then determined as described in the previous section.

The single-grating GIDL performance is shown in Fig. 7. Note the progression in linewidth as the laser scanned upward in wavelength. Changes in the mode structure caused this. At the start of the scan, the cavity was lasing predominantly on one or two adjacent longitudinal modes. [Typical etalon fringes for this situation are shown in Fig. 8(a).] At the second etalon fringe, at 540.97 nm, the cavity is lasing on multiple adjacent modes. [Figure 8(b) shows typical etalon fringes when the laser is running on multiple modes.] By the next etalon fringe (not shown in Fig. 7) the linewidth was back to 0.007 nm and the cavity was again running nearly single mode. This is a common problem with narrow linewidth lasers when they are being scanned. The phenomenon is known as ''mode hopping.''

The added spectral dispersion provided by a second diffraction grating significantly improved the stability of the laser cavity, as is shown in Fig. 9. Longer scans with this design proved much more stable than similar scans with the single diffraction grating GIDL. This laser cavity routinely provided the easiest alignment for the highest quality resolution. The 60% reduction in ASE compared with the single grating design is an additional benefit of the extra dispersion contributed by the second grating.

The commercial dye laser's performance is shown in Fig. 10. Notice the noise in the peaks caused by instability in the mode structure. Students can easily see this by looking at the etalon fringes. Each fringe consists of many fine fringes all with unstable intensity levels. This is manifested as noise in the neon peak in Fig. 10. (Because of an equipment failure, Fig. 10 is actually the result of combining two scans obtained a few minutes apart. Thus, the noise peaks do not line up between the two signals.)

The laser efficiency is determined by taking the ratio of the output power of the dye laser to the input power from the pump laser. Again, using typical results rather than ''best'' results, we found that the Hänsch design yielded 5% efficiency. Both the single and double grating GIDLs ran at approximately 2% efficiency. At first glance it would appear that the Hänsch dye laser is the most efficient. This is misleading, however, since often what is important is the spectral energy density. Since the GIDLs operate with on the

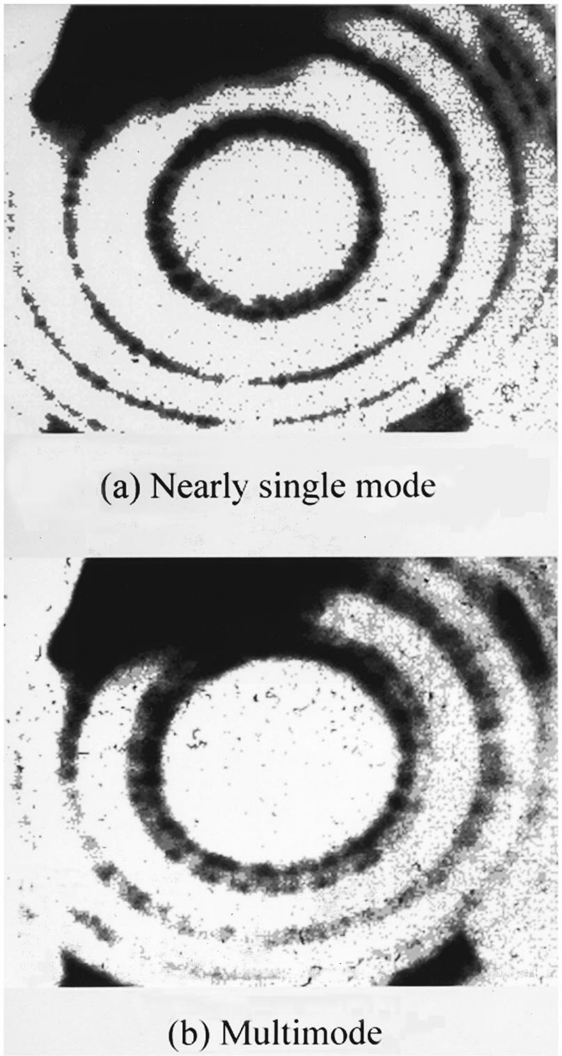


Fig. 8. Final adjustments to the laser are most easily made while monitoring the output with an etalon. In (a) the fringes are crisp and narrow indicating a well defined, narrow linewidth. In (b) the laser cavity is operating on at least two cavity modes resulting in multiple etalon fringes.

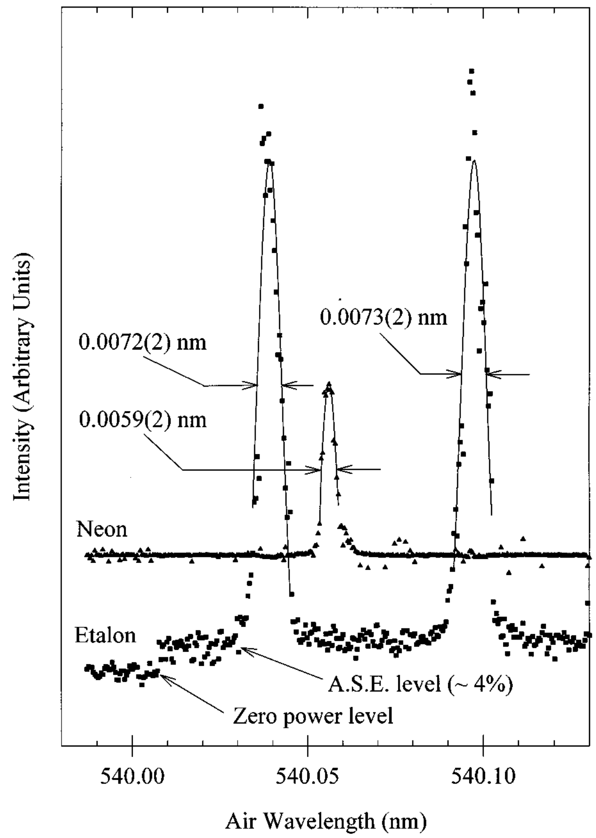


Fig. 9. The spectral output from the laser when configured as a double-grating, grazing incidence dye laser. Data were collected as in Fig. 7. Note the stable, narrow linewidths. Note also the reduction in amplified spontaneous emission (ASE) as compared with Fig. 7.

order of 20 times narrower linewidths, the actual useful energy density is nearly 10 times greater for the GIDLs than for the Hänsch laser.

Finally, we varied the length of the laser cavity for the GIDL designs. No significant effect was detected, just as was predicted by Iles. It seems that longer cavities offset the closer longitudinal mode spacing with higher extinction of unwanted frequencies due to the angular dispersion caused by the diffraction gratings. This analysis fails for extremely short cavities that can operate on a single mode.

## V. CONCLUSION

Because of the ease of assembly, stability, and educational value of this experiment, it will become a standard laboratory exercise for our Applied Optics course. Additionally, the laser is visually ''pretty'' to view and has attracted much attention and excited many students.

Due to the dye laser's modular design, this system can easily provide future expandability. With the addition of a few optical parts, students can study other laser cavity designs, e.g., the DiMauro[34] laser. Planned future improvements include the addition of an amplifier stage and adding dye cell stirring or a flow through dye cell. Amplifier stages are extremely efficient, often as high as 35%. Stirring will allow for higher repetition rates. Even without additional improvements, the laser is already useful for spectroscopic work and outperforms many commercial dye lasers.

Purchasing off-the-shelf optics both reduced the development time and added to the ease of assembly. Standard, off-the-shelf optical mounts later replaced several mounts originally manufactured in-house. Given the comparatively low cost of high quality optical mounts, we do not feel it is worth the labor to make your own.

## ACKNOWLEDGMENTS

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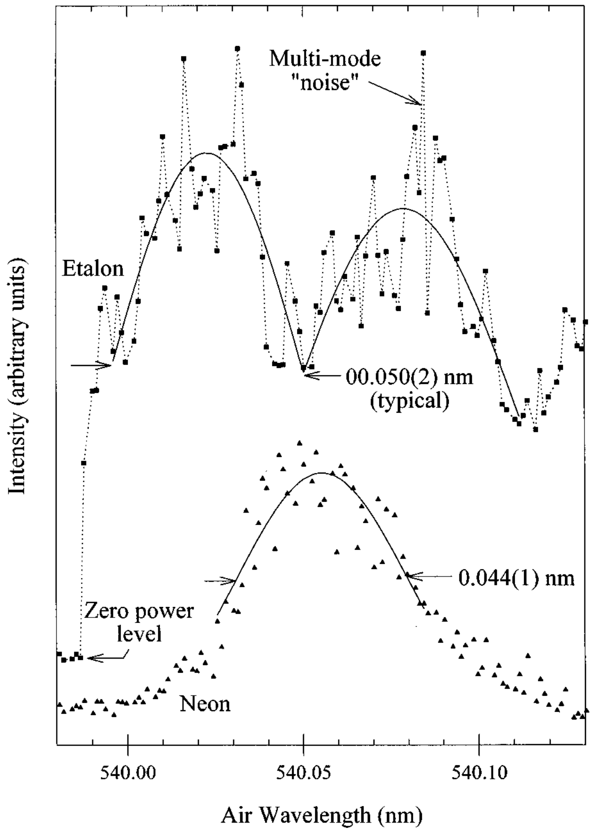


Fig. 10. The spectral output from a commercial dye laser that uses the single-grating grazing incidence design. Data were acquired using the same methods as for Figs. 7 and 9. An ASE measurement is not possible with this data because of our choice of free spectral range for the etalon. (An ASE level of 10% was determined using an external diffraction grating.) Unstable mode structure inside the laser cavity causes the noise in the data.

## APPENDIX A: PARTS LIST AND INITIAL ASSEMBLY

A detailed list of all items used to construct this laser system is shown in Table II. Of course, any comparable products will work, we have listed specific suppliers for reference only. Prices are dynamic and are also listed for reference only. The height of the laser cavity above the breadboard is chosen to match the pump laser's beam height. Changing the length of the support posts (items with part number prefixes ''SP-'') and post holders (part numbers starting with ''VPH-'') can easily adapt the height of the dye laser to any pump laser. No values (focal lengths, grating constants, etc.) are critical. Costs can be reduced by several hundred dollars by: using lower quality lenses (except the pump beam lenses), using a glass dye cell, substituting the less convenient B-05 style base for the BUP-2 base, choosing not to build the Hänsch cavity, using cheaper optics mounts (except as noted in the text), and/or building most of the components in-house.

Several simple homemade adapters are used for attaching optics to the rotation stage. Construction details are described below, while Fig. 11 shows these various adapters in use. The sprocket (see Fig. 11) was bored out to fit the rotation stage knob. Two set screws keep the sprocket from slipping when the motor is running the stage.

The diffraction gratings and tuning mirror can be secured to the mounting plates (see Fig. 12) with either epoxy or double-back sticky tape. (Do not use foam-based tapes.) We made the mounting plates from aluminum measuring $0.25 \times 1.0 \times 1.0$ in. A 0.25-in.-diam, 0.5-in. long pin was glued into a matching hole centered in the plate. This pin was inserted until flush with one side of the plate. No dimensions are critical, except the pin diameter. The pin must be chosen such that it will fit into the MM-1, or equivalent, mounting hole.

We hold the grazing incidence diffraction grating above the rotation stage with the support plate shown in Fig. 13. The plate is attached with two 2.50-in.-long 8-32 screws through two standoffs to two of the support posts that hold the stage; see Fig. 11. (The standoffs are made from 0.375-in.-diam rods, with 8-32 clearance holes drilled lengthwise through the axes.) The standoffs hold the support plate above the stage. The third hole in the plate is for attaching the mounting that holds the diffraction grating.

The tuning optic, Littrow mount diffraction grating or tuning mirror, is attached to the rotation stage with the bracket shown in Fig. 14(a). The baseplate holes match the surface of the rotation stage and the mount for the tuning optic is attached with the vertical spacer shown in Fig. 14(b).

We attach the dye cell to the MM-1, or equivalent mount, with the holder shown in Fig. 15. As was done for the diffraction grating mount (Fig. 12), the dye cell holder has a 0.50-in.-long pin glued into the 0.25-in. hole. Except for the pin, we constructed this holder of plastic so that the dye cell will not be scratched. The dye cell is sandwiched between the clamps [Fig. 15(a)] and the main holder [Fig. 15(b)] with four 8-32 screws.

The cylindrical pump beam lens does not completely fit inside its mount. We attached it to the LH2-150R holder with two spots of hot glue.

## APPENDIX B: LASER ALIGNMENT

An orderly approach to alignment cannot be over-stressed. Following is an overview to the typical alignment procedure. We have assumed that the assemblies mentioned in Appendix A have already been completed.

For all laser cavity designs:

(1) Wear UV laser safety goggles. For an UV light detector, use a business card or other white paper stock: the UV light will cause the card to fluoresce in the blue.
(2) Insert the spherical pump beam lens.
(3) Insert the cylindrical pump beam lens.
(4) Insert the dye cell with laser dye, tip the dye cell away from vertical a few degrees about the optical axis of the pump beam. Make sure the dye cell front surface is perpendicular to the pump beam by verifying that the first surface back-reflection is centered on the pump beam lenses.
(5) Adjust the pump beam lenses such that the dye cell width is completely illuminated and the focus of the line is as sharp as possible. Rotate the cylindrical lens about the optical axis until the fluorescence beams exiting the sides of the dye cell are horizontal.

For the GIDL cavity designs:

(1) Insert the intracavity lens. Adjust the lens such that the output is collimated and centered on the original fluorescence spot on a distant screen.

Table II. Parts list for the reconfigurable, homemade dye laser and support equipment.

| Qty | Description | Part number | Function | Our supplier[a] | Unit cost[b] |
|---|---|---|---|---|---|
| 1 | breadboard | SA-12 | 1 ft×2 ft baseplate, mounting holes on 1-in. centers | Newport Corp., Irvine, CA | $427.00 |
| 1 | 6-in. rail | MRL-6 | pump optics mounting for focus slides | Newport | 38.00 |
| 2 | rail carrier | MCF | pump optics rail slides (focus adjustment) | Newport | 20.00 |
| 1 | rotory stage | 481-A-S | for wavelength tuning, holds Figs. 9 and 10 | Newport | 360.00 |
| 4 | base | B-05 | supports rotation stage | Newport | 8.50 |
| 4 | post holder | VPH-3 | supports rotation stage | Newport | 13.00 |
| 4 | support post | SP-3 | supports rotation stage | Newport | 7.00 |
| 6 | post holder | VPH-4 | supports for dye cell, end mirror, all lenses | Newport | 15.00 |
| 6 | support post | SP-4 | supports for dye cell, end mirror, all lenses | Newport | 8.00 |
| 4 | base | BUP-2 | supports for dye cell, end mirror, all lenses | Newport | 63.00 |
| 1 | lens mount | LM-2R | rotatable for 2-in. cyl. pump beam lens | Newport | 39.00 |
| 1 | lens holder | LH2-150R | holds cyl. pump lens in above mount | Newport | 26.00 |
| 1 | lens holder | LH-150 | mounting for spherical pump beam lens | Newport | 21.00 |
| 4 | mirror mount | MM-1 | for both gratings, dye cell, end mirror | Newport | 44.00 |
| 1 | mirror holder | MM-1H | GIDL end mirror holder, fits into MM-1 | Newport | 7.00 |
| 1 | lens holder | MM2-1A | for Hänsch output lens | Newport | 54.00 |
| 2 | lens holder | LH-100 | mounting of Hänsch beam expander lenses | Newport | 18.00 |
| 1 | mirror mount | MM-2 | for 2-in. GIDL tuning mirror | Newport | 51.00 |
| 1 | UV lens | A115100 | spherical pump lens 38 mm diam., $f=254$ mm | Esco Products, Oak Ridge, NJ | 146.00 |
| 1 | UV lens | B115030 | cyl. pump beam lens, 38 mm, $f=76.2$ mm | Esco Products | 174.00 |
| 1 | biconvex lens | KBX058 | GIDL intracavity lens, 1-in. diam., $f=75.6$ mm | Newport | 27.00 |
| 1 | planoconvex | KPX082 | Hänsch lens/end mirror, 1-in., $f=50.2$ mm | Newport | 29.00 |
| 1 | biconcave lens | KBC046 | Hänsch beam expander, 1-in., $f=-25.0$ mm | Newport | 30.00 |
| 1 | biconvex lens | KBX070 | Hänsch beam expander, 1-in., $f=150.0$ mm | Newport | 24.00 |
| 1 | dye cell | 23H-10 mm | polished on four sides with stopper | NSG precision Cells, Inc., Farmingdale, NY | 118.00 |
| 1 | 1-in. mirror | 10D20BD.1 | GIDL end mirror | Newport | 98.00 |
| 1 | 2-in. mirror | 20D20BD.1 | GIDL wavelength tuning mirror | Newport | 217.00 |
| 1 | grating | 135.2400D21 | GIDL diffraction grating, 2400 lines/mm (This grating is blazed for use in GIDLs) | American Holographic, Fitchburg, MA | 265.00 |
| 1 | grating | unmarked | Littrow mount grating, 1440 lines/mm | scavanged (Perkin–Elmer) | 0.00 |
| 1 | laser dye | C540A, 1 g | almost any laser dye will work | Exciton, Dayton, OH | 44.00 |
| 1 | drive circuit | 7100-DB | for microstepper control of stepper motor (Kit form, you supply box and power.) | Am. Sci. Instrument Corp, Smithtown, NY | 175.00 |
| 1 | stepper motor | M061-CS02 | remote control of wavelength scanning | Slo-Syn | 110.00 |
| 1 | sprocket | 25B21 | 21 tooth, drill out to fit rotation stage knob | U.S. Tsubaki | 5.34 |
| 1 | sprocket | 25B10 | 10 tooth, for stepper motor shaft | U.S. Tsubaki | 4.02 |
| 1 | 16-in. chain | | connect motor and stage sprockets | U.S. Tsubaki | 5.60 |
| 1 | screw kit | SK-25A | screws for attaching mounts to baseplate | Newport | 46.00 |
| 3 | mounting | Fig. 12 | adapts optics to MM-1 mounts (see Fig. 11) | homemade | 0.00 |
| 1 | support | Fig. 13 | holds gazing incidence grating (see Fig. 11) | homemade | 0.00 |
| 2 | spacers | | support plate spacers (see Fig. 11) | homemade | 0.00 |
| 1 | bracket | Fig. 14 | holds tuning optics (see Fig. 11) | homemade | 0.00 |
| 1 | holder | Fig. 15 | dye cell holder, fits into MM-1 mount | homemade | 0.00 |
| The following items are not specifically part of the dye laser but are useful or required support items: | | | | | |
| 6 | Ne–N goggles | G-LGS-NN | safety goggles | Newport | 196.00 |
| 1 | etalon | EA201-7S1-7S2 | linewidth testing | TecOptics, Merrick, NY | 4,487.00 |
| 1 | HCDT | | neon spectrum | surplus | 0.00 |
| 2 | integrator | SR250 | data acquisition and averaging | Stanford Research Systems, Sunnyvale, CA | 2,990.00 |
| 1 | nitrogen laser | UV-1000 | pump source | Molectron (now Laser Photonics) Orlando, FL (used laser) | $4,001.00 |

[a]Part numbers and suppliers are listed for reference only, any roughly equivalent component will work.
[b]Prices were accurate at time of submittal.

(2) Install the end mirror and adjust it such that its reflected spot is centered on the previous spot.
(3) Mount the diffraction grating such that the rulings are as perpendicular to the laser cavity as possible. (This is a one time adjustment.)
(4) Insert the rotation stage/diffraction grating assembly such that the diffraction grating intersects the collimated fluorescence beam at about 89° from the grating normal. Part of the beam will spill past the surface. The second spot is the zeroth diffraction order. Adjust the angle of the diffraction grating such that the angle between the spilled beam and the diffracted beam is 2°. Take care to illuminate the diffraction grating as uniformly and completely as possible.
(5) Attach either the Littrow mounted diffraction grating or the tuning mirror to the rotary stage. Position the optic to

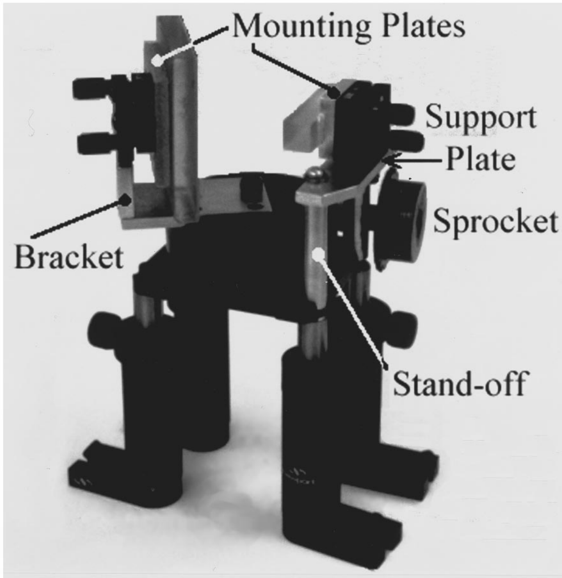


Fig. 11. A closeup view of the rotational stage assembly. The diffraction gratings and tuning mirror are glued to the mounting plates. The standoffs (two are required) and the support plate are only used for the grazing incidence laser cavity.

retroreflect the brighter of the two first-order diffraction lines from the grazing incidence diffraction grating.

(6) While monitoring the remaining first-order diffraction line from the grazing incidence diffraction grating, adjust the tuning optic such that laser speckles appear both in this diffraction order and in the output beam.

(7) Use an etalon or other measuring method to make minor adjustments to optimize the laser cavity alignment.

For the Hänsch dye laser cavity design:

(1) Insert the negative focal length beam expanding lens. Adjust the lens such that the output is centered on the original fluorescence spot on a distant screen. Rotate the lens about a vertical axis just enough that any first surface reflections do not return through the dye cell for unwanted amplification. (Skew lenses cause astigmatism, do not rotate any of the lenses more than needed.)

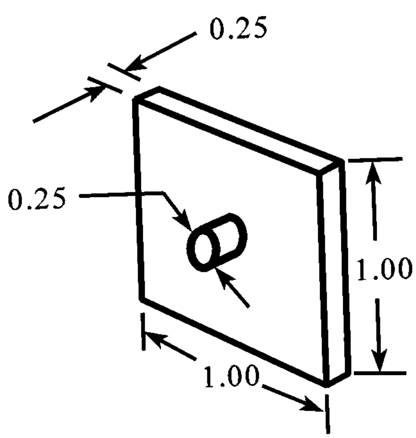


Fig. 12. The aluminum mounting plate (three required) used to hold the diffraction gratings and tuning mirror to the adjustable optical mounts. The protruding pin inserts into the adjustable optical mount.

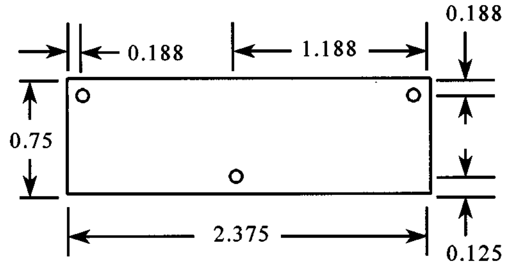


Fig. 13. The support plate for the grazing incidence diffraction grating. The plate is constructed from 0.25-in.-thick aluminum. Figure 11 shows the support plate in use.

(2) Insert the positive focal length beam expanding lens. Adjust the lens such that the output is collimated and centered on the previous fluorescence spot on a distant screen. Again, rotate the lens slightly to keep reflections out of the active region of the dye cell.

(3) Install the output lens/end mirror and adjust it such that its back reflected spot is centered on the previous spot. This lens should be installed with the Plano side toward the inside of the laser cavity.

(4) Mount the diffraction grating such that the rulings are as perpendicular to the laser cavity as possible. (This is a one time adjustment.)

(5) Rotate the diffraction grating such that a specific wavelength reflects back into the laser cavity. (The Littrow mount condition.) The laser should be operating now.

(6) While monitoring the quality of the output, make small adjustments to optimize the alignment.

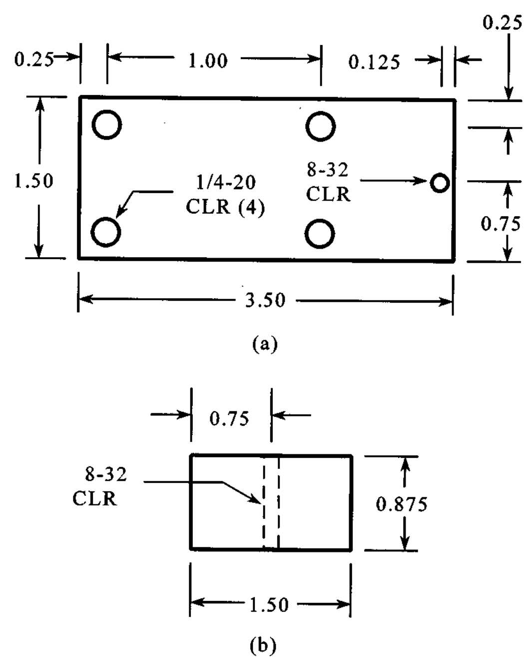


Fig. 14. This bracket holds the tuning optic (a diffraction grating or plane mirror) to the rotation stage. The base bracket (a) bolts to the surface of the stage and the vertical spacer (b) is used between the optical mount and the base bracket. Both items are constructed from 0.25-in.-thick aluminum. Figure 11 shows this bracket in use.

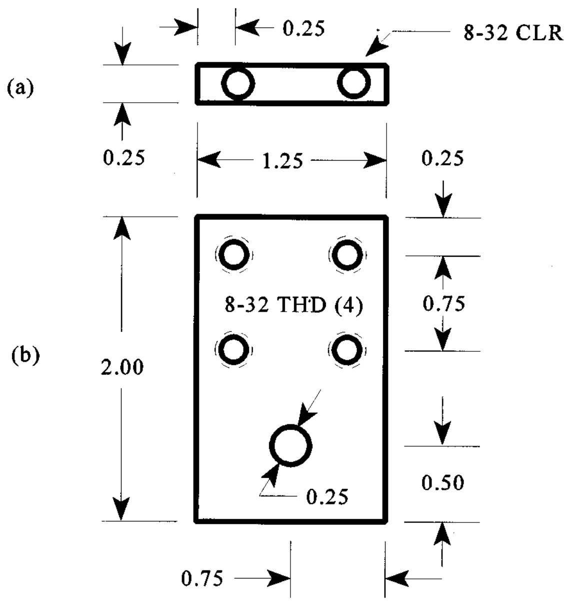


Fig. 15. The dye cell holder. This is constructed from 0.25-in.-thick plastic (we used Lexan). Two of the clamping pieces (a) are needed. The dye cell is sandwiched between the clamping pieces and the main holder (b) using four, 1-in.-long 8–32 screws. A 0.5-in.-long, 0.25-in.-diam pin is glued into the 0.25-in. hole on the main holder. This pin fits into the optical mount used to hold the dye cell assembly.


[1]R. C. Hilborn, ''Design and construction of simple, nitrogen-laser-pumped, tunable dye lasers,'' Am. J. Phys. **46**, 565–572 (1978).

[2]A. J. Alfrey, ''Flashlamp-pumped dye laser as an undergraduate lab project,'' Am. J. Phys. **49**, 776–781 (1981).

[3]Laser Science, Inc., 26 Landsdowne St., Cambridge, MA 02139, produces a small Hansch design dye laser. Reference the annual (August) Buyers Guide issue of Phys. Today for more manufacturers.

[4]J. R. Brandenberger, *Proceedings of Laser Physics and Modern Optics in Liberal Arts Colleges*, Appleton, WI, 22–23 June 1987 (Lawrence University Press, Appleton, WI, 1987).

[5]K. Arnett, R. Anderson, and R. Alexander, ''Modern spectroscopy with a spectrometer by the optogalvanic effect,'' Am. J. Phys. **49**, 767–772 (1981).

[6]H. P. Grieneisen, *The Nitrogen Laser-Pumped Dye Laser: An Ideal Light Source for College Experiments* (Laser Science, Inc., Cambridge, MA, 1984).

[7]F. H. Wirth, *Dye Laser Experiments for the Undergraduate Laboratory* (Laser Science, Inc., Cambridge, MA, no date given, approximately 1984).

[8]*Nitrogen Dye Laser Applications to Physics and Chemistry Courses in Colleges and Universities* (Laser Photonics, Inc., Orlando, FL, 1992).

[9]P. F. Schewe, ''Lasers,'' Phys. Teach. **19**, 534–547 (1981).

[10]D. C. O'Shea and D. C. Peckham, ''Resource Letter L-1: Lasers,'' Am. J. Phys. **49**, 915–925 (1981).

[11]U. Ganiel, A. Hardy, G. Neumann, and D. Treves, ''Amplified Spontaneous Emission and Signal Amplification in Dye-Laser Systems,'' IEEE J. Quantum Electron. **QE-11**, 881–892 (1975).

[12]D.-H. Yang, T. L. Breeden, and H. J. Metcalf, ''Home-built Nd-YAG laser for general laboratory use,'' Appl. Opt. **24**, 1899–1901 (1985).

[13]R. C. Hilborn, ''An inexpensive reliable, high power molecular nitrogen laser,'' Am. J. Phys. **44**, 1172–1176 (1976).

[14]R. S. Kunabenchi, M. R. Gorbal, and M. I. Savadatti, ''Simple nitrogen laser,'' Am. J. Phys. **50**, 568–569 (1982).

[15]M. Feldman, P. Lebow, F. Raab, and H. Metcalf, ''Improvements to a home-built nitrogen laser,'' Appl. Opt. **17**, 774–777 (1978).

[16]E. Armandillo and A. J. Kearsley, ''High-power nitrogen laser,'' Appl. Phys. Lett. **41**, 611–613 (1982). Of special note, they report peak power outputs in excess of 5 MW.

[17]G. J. Havrilla, R. B. Green, and T. O. Trask, ''Capacitor modification for the Schenck–Metcalf nitrogen laser,'' Appl. Opt. **17**, 3525–3527 (1978).

[18]A. Fried and C. W. Mathews, ''Ceramic capacitor failures in nitrogen lasers: A solution,'' Appl. Opt. **16**, 3077 (1977).

[19]Laser Resale, Inc., 54 Balcom Rd., Sudbury, MA 01776, 508-443-8484, http://www.laserresale.com

[20]OE Technologies, Box 703, LaMadera, NM 87539, 505-583-2482.

[21]T. W. Hänsch, ''Repetitively Pulsed Tunable Dye Laser for High Resolution Spectroscopy,'' Appl. Opt. **11**, 895–898 (1972).

[22]Eugene Hecht, *Optics* (Addison-Wesley, Reading, MA, 1987), p. 428.

[23]M. K. Iles, ''United Single-Pass Model of Linewidths in the Hänsch, Single- and Double-Grating Grazing-Incidence Dye Lasers,'' Appl. Opt. **20**, 985–988 (1981).

[24]An etalon is a Fabry–Perot interferometer with fixed mirrors, see any optics text, e.g., E. Hecht, *Optics* (Addison-Wesley, Reading, MA, 1987), pp. 368–371.

[25]B. S. Perkalskis and J. R. Freeman, ''Fabry-Perot interferometers for lecture demonstrations and laboratories,'' Am. J. Phys. **64**, 1210–1212 (1996).

[26]*Atomic, Molecular, & Optical Physics Handbook*, edited by G. W. F. Drake (AIP, Woodbury, NY, 1996), pp. 784–794.

[27]H. Weichel, W. A. Danne, and L. S. Pedrotti, ''Laser Safety in the Laboratory,'' Am. J. Phys. **42**, 1006–1013 (1974). Note: While this is an old article, it is still reasonably current and well worth posting in the laser laboratory.

[28]OSA Laser Safety Committee, ''Don't be ultraviolated!'' Opt. News **7**, 18–21 (1988).

[29]H. Moseley, ''Ultraviolet and laser radiation safety,'' Phys. Med. Biol. **39**, 1765–1799 (1994).

[30]Material Safety Data Sheets (MSDS) are available from the laser dye manufacturers. Dyes that cover the visible spectrum are available that have low biological hazard levels, e.g., Stilbene 420, Coumarin 481, Coumarin 540 A, Rhodamine 6G, and Kiton Red 620.

[31]K. Arnett, R. Anderson, and R. Alexander, ''Modern spectroscopy with a spectrometer by the optogalvanic effect,'' Am. J. Phys. **49**, 767–772 (1981).

[32]C. L. Schreiber, E. Y. Wong, and D. Johnston, ''Low-cost, high-resolution Ebert spectrographs for a teaching laboratory,'' Am. J. Phys. **39**, 1333–1336 (1971).

[33]Our measurements comparing a laser power meter with photodiode response at 337 and at 540 nm indicates that you can get reasonable efficiency estimates using a photodiode if you multiply the 337-nm photodiode reading by 4.1. This seems to take into account both the effects of the glass window and the declining responsivity of the silicon photodiode. N.B., This may be strongly dependent on your particular photodiode.

[34]R. Smith and L. F. DiMauro, Appl. Opt. **26**, 855–859 (1987).


## RENORMALIZATION

[Renormalization is] just a stop-gap procedure. There must be some fundamental change in our ideas, probably a change just as fundamental as the passage from Bohr's orbit theory to quantum mechanics. When you get a number turning out to be infinite which ought to be finite, you should admit that there is something wrong with your equations, and not hope that you can get a good theory just by doctoring up that number.

Paul Adrien Maurice Dirac, in *A Question of Physics: Conversations in Physics and Biology*, conducted by Paul Buckley and F. David Peat (Routledge and Kegan Paul, London, 1979), p. 39.