To get the most out of your in-lab experience, you must come to Lab prepared (makes life easier for you and the TA and minimizes your time in the Lab). Thus, you should go through this Lab manual, complete the Pre-Lab Exercises, and answer all the Pre-Lab questions BEFORE entering the Laboratory. In your lab notebook record data, explain phenomena you observe, and answer the questions asked. Remember to answer all questions in your lab notebook in a neat and orderly fashion. No data are to be taken on these laboratory sheets. Tables provided herein are simply examples of how to record data into your laboratory notebooks. Expect the in-lab portion of this exercise to take about 3 hours. Please note that a formal written report is required for this Laboratory Exercise.

PRE-LAB EXERCISES

PL7.1 – Get Prepared to Start the Laboratory Exercises

Read the entire laboratory handout, and be prepared to answer questions before, during and after the lab session. Determine all the equations and constants that may be needed in order to perform all the laboratory exercises. Write them all down in your laboratory notebook before entering the Lab. This will ensure that you take all necessary data while in the Lab in order to complete the lab write-up. This preparatory work will also count toward your Lab Exercise grade.

PL7.2

Design a lens system that would convert the beam from a typical diode laser to a circular shape as is done in laser pointers. Remember that diode lasers typically have an emission area with a rectangular cross section. The beam exiting a laser diode can be described by two spatially independent Gaussians (in x and y). The total beam is the result of the multiplication of these two Gaussians. One Gaussian will have much greater divergence than the other (so the intensity pattern will look like an oval, instead of a circle).
IN-LAB EXERCISES

7.1 Specific Laser Systems

(a) In this exercise, we want you to examine and identify the key components within a variety of commercial and homemade laser systems. These include:

1. He-Ne laser
2. Argon-ion laser
3. Homemade CO₂ laser
4. Nd:YAG laser
5. Visible semiconductor diode laser
6. Infrared semiconductor diode laser (from Newport fiber-optics kit)

Specifically, you should look for things such as, output wavelength, gain medium material, length of the cavity, type of mirrors used, Brewster windows, pumping mechanism, typical out power, typical input electrical power, wall-to-light efficiency, mode locking or Q-switching mechanisms (describe their operating principles), expected coherence length, and cost.

For each of the six lasers, write brief comments on each of the characteristics listed in the above paragraph. As an example, you would fill in the missing information in the table below with text or numbers as appropriate for the chemical laser. Hint: go to the manufacturer’s website, Photonics Buyer’s Guide, or Laser Focus Buyers Guide.

<table>
<thead>
<tr>
<th>Chemical Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating wavelength:</td>
</tr>
<tr>
<td>Approximate Cavity length:</td>
</tr>
<tr>
<td>Approximate length of gain medium:</td>
</tr>
<tr>
<td>Type of mirrors used:</td>
</tr>
<tr>
<td>Type/configuration of Brewster windows:</td>
</tr>
<tr>
<td>Pumping mechanism:</td>
</tr>
<tr>
<td>Typical optical output power:</td>
</tr>
<tr>
<td>Electrical power requirements:</td>
</tr>
<tr>
<td>Wall to light efficiency:</td>
</tr>
<tr>
<td>Mode-locking mechanism:</td>
</tr>
<tr>
<td>Q-switching mechanism:</td>
</tr>
<tr>
<td>Expected coherence length:</td>
</tr>
<tr>
<td>Approximate cost:</td>
</tr>
<tr>
<td>Manufacturer:</td>
</tr>
</tbody>
</table>

(b) For the open-cavity He-Ne laser, observe the light emitted from the side of the laser tube with the spectroscope. Describe your observations and their implications in terms of what you know about lasers and about the He-Ne laser system in particular. Add your description and analysis to your table in (a) for the He-Ne laser.
(c) What are blue semiconductor lasers made of?

(d) What kinds of lasers are used to weld automotive parts together?

7.2 Semiconductor Diode Laser Characterization

(a) Using the Tektronix 576 curve tracer, the Sanyo DL3147-021 diode laser or the Hitachi HL 6320G 10mW visible laser, connect the purple and white leads to the collector and emitter slots of the curve tracer. Make sure to set the base terminal to “open.” Also, set the vertical scale to 50mA/div and set the horizontal scale to 500 mV/div. The laser has a peak wavelength of 632 nm with maximum and minimum wavelengths of 640 nm and 625 nm respectively.

(i) Record the i-v characteristics of the laser diode.

(ii) Direct the output light from the laser onto the silicon photodetector. Slowly increase the current into the laser diode, being careful not to saturate the detector or destroy the laser diode, and plot the output intensity-vs.-current characteristic for the laser.

(iii) Estimate the threshold current from your plot.

(b) Using the HL 6320G or the Sanyo DL3147-021 semiconductor diode laser, record a picture of the output beam shape using a diffuser and the digital camera.

(c) Measure the divergence angles of the output beam.

(d) Use your measurements of Part (b) to estimate the cross-sectional dimensions of the laser cavity.

(e) Coherence Length Measurement

The setup shown below is a Michelson Interferometer that can be excited simultaneously by both a He-Ne laser and the Melles-Griot Model# 561CS153/HS diode laser whose coherence length we want to measure. In this experiment, both laser beams are collimated before they reach the interferometer. As the He-Ne laser has a much longer coherence length than the diode laser, the main purpose of the He-Ne laser is to establish interferometer alignment at all times.

(i) With the two arms of the interferometer unequal by about 20 cm, align the system so that a spatial fringe pattern is formed on the screen by the He-Ne laser. Make a sketch of and comment on the fringe pattern you have produced (perfect alignment is not necessary). Now block the light from the He-Ne laser so it no longer excites the interferometer. With the diode laser turned on, observe its spatial interference pattern (if any) on the screen. Make a sketch of and comment on the fringe pattern owing to the diode laser. Compare the two interference
patterns - comment on their similarities and differences. Record the positions of the two mirrors of the interferometer.

(ii) Translate the movable mirror to new position, realign the system with the He-Ne laser beam, and repeat part (i).
(iii) Repeat part (ii) as necessary until you have enough information to get a rough estimate of the coherence length of the diode laser. Show you data for each position you tried.

(iv) Describe how you arrived at your estimate of the coherence length.

![Michelson interferometer setup to estimate the coherence length of a diode laser.](image)

**7.3. Spectral Analysis of the HeNe Laser**

(a) The small, 2mW, He-Ne lasers in the modern optics lab are NOT monochromatic. Unfortunately the 1/2m Jarrel Ash grating spectrometer in laboratory does not have sufficient resolution to resolve the fine structure of the laser output.
Although we know the He-Ne laser employs curved mirrors, for convenience in this exercise we will model its resonator as a Fabry-Perot interferometer (see Fig. 2). The laser resonator (cavity) modes (high Q) naturally select the output frequencies for the laser.

Lasing action thus occurs under the gain curve, \( g(\nu) \), only at a discrete set of frequencies. However, in order to sustain laser oscillation, the gain per round trip in the cavity must be greater than the loss, and so no laser action occurs at Fabry-Perot transmission bands, which fall near the wings of the gain curve. The laser output therefore looks like that shown in the Fig. 3. These are the so-called longitudinal modes of the laser.

The scanning Fabry-Perot spectrometer is an instrument that can resolve the fine structure of the laser output. Its principle of operation is described in Chapter 3 of the Class Notes. You will be using this instrument to study the light output of our small He-Ne lasers. It is also called an optical spectrum analyzer.

The MOL has an “Optical Spectrum Analyzer” made by Spectra Physics Corp. Although it is actually a spherical Fabry-Perot interferometer in the confocal mirror arrangement we will approximate it operation by assuming a parallel-plate Fabry-Perot configuration. The free
The spectral range of the etalon is given to be equal to 2 GHz. A description of the scanning mode in which the device operates is given below:

(a) The output of our 2-mW He-Ne laser consists of a number of closely spaced “modes.” Given that the gain bandwidth of the lasing medium (assume it is equal to the “Doppler width”) is approximately 1500 MHz, how many modes would you expect to be present in the laser output? (See Fig. 4).

(b) Measure the modes separation and compare your results with the estimate in part (a). How many free-spectral ranges (each equal to 2 GHz) does the scan of the interferometer cover? What is the separation between the two mirrors in the scanning Fabry-Perot interferometer?

(c) Increase the dispersion by expanding the horizontal scale of the oscilloscope trace and measure the half-width of a single peak. Since the bandwidth of a single mode from the laser is much beyond the resolution of the Fabry-Perot, the measured width gives directly the resolution of the instrument. Calculate the finesse, \( F \), for the instrument.
(d) Observe the effect of placing a linear polarizer in the unpolarized laser beam on the mode structure. Note the results for various orientations of the polarizer. Try to explain the observed behavior.

(e) Adjust the micrometers of the Fabry-Perot angular mount so as to direct reflected light from the interferometer back into the He-Ne laser. What would you expect? (Good alignment is critical).

7.4. Second Harmonic Generation in a KDP Crystal

7.4.1 Introduction to SHG

Second Harmonic Generation (SHG) or frequency doubling is just one of the manifestations of non-linear optical phenomena. To generate SHG, we require a material in which the atomic polarization has a strong component that depends on the square of the electric field of the light passing through the material (in addition to the traditional linear term). That is, at high electric field strengths (high intensity), the second order component of the polarization is significant. That is, we can write the

\[ P(E) = \varepsilon_0 \chi^{(1)} E + \varepsilon_0 \chi^{(2)} E^2 + \ldots \]

For the crystal to convert energy from the fundamental to the second harmonic frequency, first we would want the crystal to be transparent at both the fundamental and the second harmonic wavelengths. Secondly, we would need to set a resonance condition in the crystal such that the momentum of two fundamental frequency photons can add vectorially to produce the momentum of the second harmonic photon as illustrated in Fig. 5. Specifically we want all three photons to have the same propagation direction and "see" the same refractive index. Since the wavelengths of the fundamental and the second harmonic are very different, the only way to accomplish this task is to exploit the birefringence of the crystal by propagating one beam as an ordinary wave and the other as an extraordinary wave. The final challenge is to find a suitable non-transparent crystal in which there is a unique direction of propagation through the crystal such the ordinary and extraordinary rays "see" the same refractive index. This condition is called angle phase matching.

![Figure 5: Geometry for type I second harmonic generation in a negative uniaxial crystal. Adapted from Boyd [1].](image-url)
In this Lab, we have employed a laser-diode pumped Nd:YAG laser (1.06 um wavelength) as the fundamental pump source. For this chosen wavelength, we will use Potassium DiHydrogen Phosphate (KDP) as the frequency doubling crystal. KDP has a KH$_2$PO$_4$ as its chemical formula, is a birefringent material with a tetragonal lattice, happens to have a large second-order non-linear coefficient and satisfies all the required conditions. A non-centrosymmetric crystal structure (which KDP exhibits) is necessary for the existence of its second-order non-linear optical properties. A centrosymmetric crystal (such as one with cubic structure) cannot have second-order effects to its electric susceptibility, which is the foundation of second harmonic generation. To see why this must be true, consider the second-order polarization. If the crystal were centrosymmetric, reversing the polarity of the electric field would reverse the polarity of the induced dipole, which is not possible given the above equation. Therefore only non-centrosymmetric crystals may have the properties required for frequency doubling.

Given this material, the requisite angle for phase-matching can be calculated from a knowledge of the refractive index dispersion curves for KDP. Values for the ordinary and principal extraordinary index taken from Zernike [2] reveal that the desired angle of propagation through the KDP crystal is about 41.2° as measured from the c-axis of the crystal. This is in agreement with the crystal manufacturer’s quoted value [3].

The Lab’s sample of potassium dihydrogen phosphate is model 542-250 from Inrad Optics [3]. It is housed in a black box and surrounded by index-matched fluid making it impossible to actually see the crystal. The crystal itself is 15 × 15 × 30 mm. The diameter of the input aperture is 25.0 mm. Figure 6 is a diagram of the container’s dimensions. The KDP data sheet and laser data sheet can be found at references [3] and [4], which include URLs. The crystal was purchased off eBay and has one defect. There is a burn line which goes all the way through the crystal. Fortunately, the crystal is large enough that the damaged area is easily avoided.

![Figure 6: Dimensions of KDP crystal housing. Model number used is outlined in orange. Courtesy Inrad Optics [5].](image-url)
7.4.2 Experimental Setup and Procedure

The laser-diode pumped Nd:YAG laser is focused into the KDP crystal (to achieve maximum beam intensity) and then passed through the 45° apex of the right angle prism as shown in Figure 7. The laser is rated to have a maximum average power of 500 mW and output in the TEM00 mode. It operates in a passively Q-switched mode, for which the repetition rate varies between 5 and 20 kHz. It is assumed to be vertically polarized. The KDP crystal is oriented in its case to accept vertically polarized light for SHG operation.

![Optical setup](image)

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Fig. 7: Optical setup used to demonstrate second harmonic generation. φ₁ and φ₂ are the angles the KDP crystal and prism orientations, respectively, are offset from normal incidence. A baffle is used to absorb the unconverted IR light from the photodetector.

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![Photograph](image)

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Fig. 8: Photograph of the setup used to demonstrate second harmonic generation. The spot in the top left corner of the photograph is due to the unconverted IR light and is not visible to the naked eye. The camera used to take this photograph however captured it.
The laser first passes through a lens with a focal length of approximately 200 mm. A long focal length is desirable to keep the entrance angle across the beam as constant as possible while focusing to as small a spot as possible.

The KDP is fastened to the rotation stage such that the stage reads 0° when the laser is incident normally. Limited by the aperture size and length of the device, the crystal can be rotated about 42° in either direction from normal, allowing for almost the entire range of possible entrance angles. We define the angle the entrance face is offset from normal incidence as $\phi_1$ (see Fig. 7).

The prism is used to separate the fundamental from the second harmonic. Here we are using the region near one of the 45° apexes of a right-angle prism for this purpose. We define the offset angle of the prism hypotenuse as $\phi_2$ (see Fig. 7) making the true angle of incidence off the entrance surface of the prism of $(45° - \phi_2)$. The value of $\phi_2$ is not critical. About 10° will give sufficient spatial separation between the IR and green beams over a propagation distance of about 40cm to the screen/photodetector. A baffle has been used to absorb the 1064 nm light while the 532 nm light continues to the photodetector detector. The Lab photodetector recommended is a Thorlabs S130C silicon detector [5] which is sensitive at both 532 and 1064 nm with a range of 500 pW to 500 mW.

7.4.3 Experimental Results and Discussion
After all has been set up and roughly aligned as described above, the crystal is rotated very slowly until green output is observed. Then, the mirrors and rotation stages are fine tuned to maximize the power in the green second-harmonic beam.

With this system, second harmonic generation of 1064 nm light will be observed with an offset angle of the KDP crystal, $\phi_1$ of about 12.2°. Unfortunately the index matching fluid prevents us from directly measuring the incident angle relative to the optic axis, but we will assume that it must be close to the calculated value of 41.2°. Fig. 9 is a photograph of the green light on the screen showing successful SHG.

![Figure 9](image.png) Figure 9: The original light at 1064 nm at the right with its second harmonic at 532 nm to the left. The IR light is viewed with a fluorescent card.

The power in the fundamental beam after the prism is much lower than the laser power (500 mW) because of several loss mechanisms along the way. Power is attenuated approximately 4%
by both faces of the lens, 10% by both faces of the crystal housing, and another 20% is reflected off the incident face of the prism instead of passing through.

The power in the second harmonic had a maximum of $1.615 \pm 0.002$ mW. If we assume that the green light experiences the same losses by the prism as the IR light, we find that our SHG process is only about 0.8% efficient.

7.4.4 References


