Physics 408

Applied Optics Laboratory

Department of Physics and Astronomy
UBC

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Contents

Chapter 1

The HeNe Laser

Note: you will need to adjust the horizontal and vertical tip and tilt of the external mirror in the lab but please do not adjust the height of the mirror or remove the mirror post from the post holder for any reason. Any alignment of the mirror should be done with the adjustment knobs with the mirror mount left in place. If you suspect that the mirror mount height has been changed, please contact a TA to correct this problem.

1.1 Objective

In this lab you will construct a HeNe laser. By observing and investigating its fundamental properties and operating conditions, you will learn how a laser works and what determines its output characteristics. Specific objectives are:

1. Investigate the dependence of the cavity stability on the radius of curvature of the cavity mirrors
2. Observe and characterize properties of the laser output (for example, the transverse spatial mode, spectrum and polarization).
3. Measure the beam radius at different locations inside and outside the cavity and compare with the expected size given the chosen cavity length and mirrors.

1.2 Introduction

The helium-neon (HeNe) laser was among the first lasers ever constructed, and has since proved to be among the most popular. In general, a laser consists of two basics elements: (1) a gain medium to provide optical gain and (2) an optical element (here a two-mirror resonator) to send the light emitted by the gain medium back into the gain medium thus providing optical feedback.

In this lab, you will build a laser using a gas mixture of helium-neon as the gain medium. A high-voltage power supply is used to supply the energy by exciting the gas mixture confined in a glass tube. These atoms exist in the gain medium, which is a glass tube filled with a helium-neon gas mixture. The optical resonator is constructed using one fixed, very high reflectivity mirror and a second adjustable *output coupler* mirror. This mirror allows a small fraction of the photons in the laser to exit the resonator (normally around 1%). A schematic of the laser cavity is shown in Fig. 1.1.

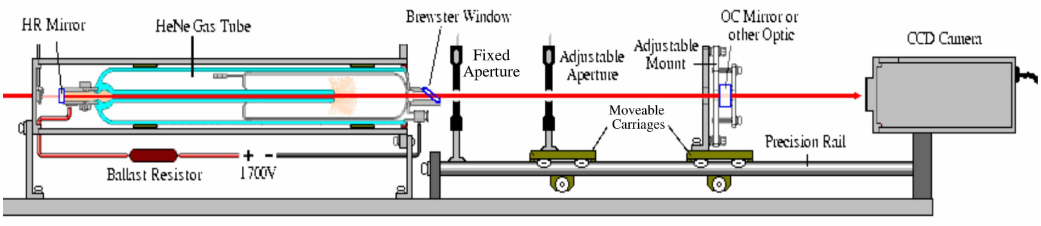

Figure 1.1: Open Frame HeNe Laser cavity. This is a schematic of the HeNe laser cavity that you will align in this lab.

The laser resonator you will build is capable of supporting more than one transverse spatial mode and more than one longitudinal mode. Each of these modes has associated with it a specific optical frequency and intensity distribution and only occur for certain configurations of mirror curvatures and separation.

The transverse mode of the laser refers to how the laser spot looks and is determined by the electric field distribution of the laser mode. These modes are labeled by TEM_{lm} (TEM stands for, not surprisingly, Transverse Electromagnetic), where l and m correspond to the number of electric field nodes along the x and y axis respectively.

It is typical in gas lasers such as the HeNe for the gain to be concentrated near the axis of the tube. As a consequence, any modes that have an electric field maxima on this axis tend to extract the most energy from the gain medium and thus dominate. However, if a small object (such as a thin wire) is placed such that it impedes the gain at the axis center, then only those modes with a node (zero) occurring at the location of the object will lase. Thus by translating the object laterally across the profile of the beam it is possible to change and control the spatial mode generated by the laser.

1.3 Transverse Laser Modes

For this section, use the planar mirror as the output coupler mirror, and place the mirror such that the cavity length is < 50 cm. Use the fixed apperature to help align the flourescence from the HeNe tube back onto itself. Next, make small adjustments to the x and y controls until you see a bright red glow on the mirrors. Your laser is lasing!

1. Continue to adjust the mirror, and look at the mode profile on a camera. Does the pattern change?

2. Capture some of these patterns and print them in your lab book. For each, explain their symmetry and label their mode structure. What is the highest order mode you could see?

3. With the laser lasing in any mode that is not the TEM_{00} mode, slowly open and close the iris near the Brewster window. What happens? Explain why.

4. Why do you usually see the laser has only one transverse spatial mode at a time?

1.4 Measuring Mirror Curvatures and Stability Regions

1. Use the planar mirror ($R = \infty$) to determine the ROC of the fixed cavity mirror.

2. Measure the stability regions of the laser using the curved output coupler mirror. How does your measured region of stability compare with what you expect (given the information gathered in the previous step)? Use your measurements to verify experimentally the advertised ROC of the curved output coupling mirror.

3. Could you use a convex ($R < 0$) mirror in this setup? If so, are there any constraints on the radius of curvature that this mirror could have?

1.5 Polarization

1. What does it mean for the laser to be polarized? Check the polarization of the HeNe laser beam.

2. Why might the output of the laser be polarized? Are there any elements in the laser that could cause the output beam to be polarized?

1.6 Spectral Output

Make sure the cavity is short enough that a second mirror can be placed outside the cavity in order to reflect light into the monochromator.

1. Measure the spectrum of the laser light from 580 nm to 640 nm.

2. Measure the spectrum of the fluorescence directly from the tube over the same range. Why are the results different?

1.7 Mode Control and Beam Radius Measurements

In this section, your goal is to measure the beam radius inside the cavity and in at least two locations outside the cavity. You will compare your measured beam radius with what you expect given what you know about the ROC of the mirrors and the cavity length. You should use the curved mirror for this section of the experiment. Note: Outside the cavity you can easily place a camera in the beam in order to make a measurement of the beam size. You cannot do this inside the cavity (as it will stop the lasing action). You will find section 3.3 of Saleh and Teich indispensable for the required analysis in this section.

1. Place the wire (mounted on a translation stage on a carriage) into the cavity, somewhere between the output coupler mirror and the iris. Describe what you see as you translate the wire through the location of the beam. Explain why you see this behavior.

2. Align your setup such that you can see at least the TEM_{10} and TEM_{20} modes as you translate the wire across the beam (at different locations of the wire, of course). Once you think you have this alignment correct, please check with a TA.

3. Starting with the wire on one side of the cavity, translate the wire across the center of the cavity and record the micrometer position where each mode occurs. You should see the TEM_{20} modes occur twice. Why is this? Which mode occurs when the wire is at the (transverse) center of the cavity?

4. Place the camera somewhere along the rail and take a picture of a TEM_{00}, TEM_{10} and TEM_{20} mode at this location. Repeat for at least one other camera position.

5. From your data, determine the beam radius at each location (i.e., inside the cavity at the location of the wire, and at the positions of the camera). Hint: the pixel size of the camera is 7.5 ± 0.2 μm.

6. Use your previous measurements of the ROC of the mirrors, and the length of the cavity to determine the theoretical beam radius as a function of position.

7. Plot the theoretical beam radius as a function of position, and overlay the beam radius measurements that you obtained (both inside and outside the cavity). Also include an indication of the position of the cavity mirrors on your plot. Comment on the agreement (or disagreement) between your data and the theory.

1.8 Additional Questions

1. Show that the allowable laser frequencies are given by

$$f_m = m\frac{c}{2L} \tag{1.1}$$

   where L is the length of the laser cavity, and m is the number of half-wavelengths that fit between the mirrors. Why can you only get red light out of this laser? In other words, Eq. 1.1 suggests that many frequencies should be possible, so why do you only see one color?

2. Do you see that the laser only lases for specific mirror separations, as predicted by Eq. 1.1? Why or why not? It might be useful to know that the FWHM of the gain medium in the HeNe laser is about 1 GHz.

Final Question

What was the most challenging part of this lab? Is it what you thought it would be (i.e., what you wrote in your outline)? Comment (i.e., write more than yes or no).

1.9 Useful Readings

- Section 3.1 The Gaussian Beam
- Section 3.2 Transmission through Optical Components (Beam Shaping and Beam Focusing)
- Section 3.3 Hermite-Gaussian Beams
- Section 10.1 Planar-Mirror Resonators
- Section 10.2 Spherical-Mirror Resonators (including parts A and B
- Section 13.3 Interactions of Photons with Atoms
- Section 15.1 Theory of Laser Oscillation
- Section 15.2 Characteristics of the Laser Output (especially part C on Spatial Distribution and Polarization and part D on mode selection)
- Appendices: A,C,D,E

Appendix A

The Monochromator and Photomultiplier

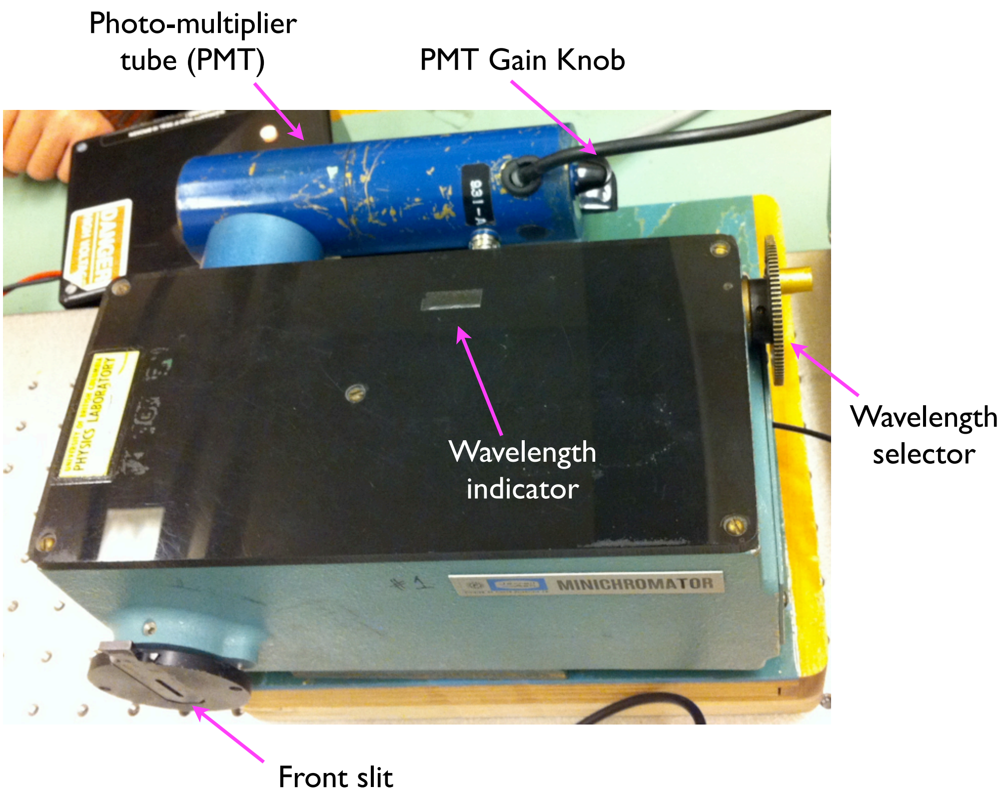

Figure A.1: The mini-monochromator available in the lab.

The easiest way to align the monochromator is to do this by eye (but don't do this with the laser - only with the pink light from the HeNe tube. So remove the OC from the HeNe laser). First, insure the PMT voltage source is OFF so you don't blind the PMT when you remove it from the monochromator. Next, direct your light source at the entrance slit and insure that it is propagating perpendicular to the slit plane. Then remove both the front and rear slit. Set the monochromator wavelength to about 500 nm. Adjust the light source with a turning mirror so that you can see the light through the monochromator. Put in the front slit and reoptimize. Then put the back slit in and re-insert the PMT. Plug the PMT output into the scope and turn on the PMT power supply. Set it to about 1000V and dial the wavelength selector until you see a signal.

Introduction

A monochromator is a device used to isolate a small wavelength interval of a spectrum. It consists of an entrance slit, a dispersive element (*e.g.* a grating), and an exit slit which allows only a selected portion of the spectrum to pass to a detector. The photon detector in this lab is a photomultiplier tube. The instrument can be used to study the wavelengths and intensities of spectral lines emitted by a source.

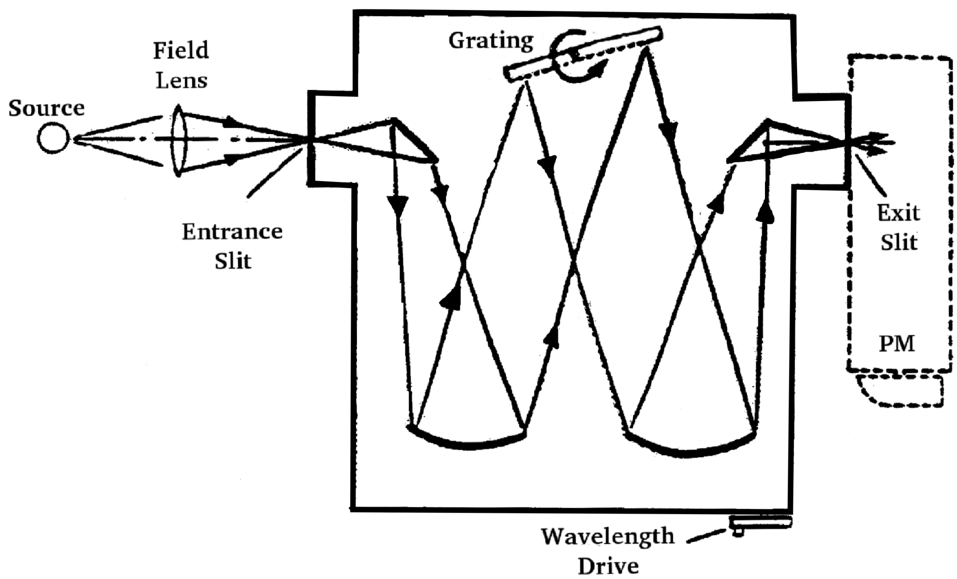

Figure A.2: The Czerny-Turner Monochromator (the field lens is optional).

The Czerny-Turner Monochromator

Although the particular model of monochromator used here is small, the design and operation is identical to that of larger models. This particular arrangement of mirrors, slits, and grating is referred to as the Czerny-Turner arrangement. The dispersive element is a diffraction grating.

The light path through the instrument is shown in Fig. A.2. The light from the source falls on the entrance slit. If necessary the light intensity can be increased with a field lens. A spherical mirror then collimates the beam of light and illuminates the grating. The grating disperses different wavelengths at different angles and one of these wavelengths is focussed onto the exit slit by the other spherical mirror. Since the slits are very narrow (typically 0.1mm or less), only a small range of wavelengths emerges from the exit slit. The instrument width of this monochromator is approximately 1nm, but for more expensive instruments a width of 10^{-2}nm is easily achievable.

The RCA 931A Photomultiplier Tube

The photomultiplier tube is a vacuum tube device used in industry to measure light signals, especially those from transient light sources. (A transient light source is one which only emits for a short period of time, such as a spark). The active element of a PM is the photo-cathode, which liberates electrons when struck by light. These electrons form a current pulse, which is amplified by a series of dynodes. Because the photon energy depends on the colour of the light, the energy (and number) of liberated electrons will also. This changes the dynode avalanche amplification which results in a current pulse amplitude dependent on the colour of the light. The last dynode is called the anode and is connected by an anode resistor to ground (see Fig. A.3). A voltage is therefore developed across the anode resistor which, in the ideal case, is proportional to the intensity of the incident light. The schematic construction and operation of the photomultiplier tube is shown in Fig. A.3.

The linearity of the PM response must be established before accurate intensity measurements can be made. This is done by plotting the amplitude of the PM signal as a function of the intensity of the incident light. Ideally the graph should be linear, but at large signals a deviation from linearity is usually observed.

Monochromator alignment

The transmission through the monochromator is highly dependent on the angle of the light with respect to the monochromator. To line up the monochromator, first make sure the gain and the supply voltage on the PMT are set

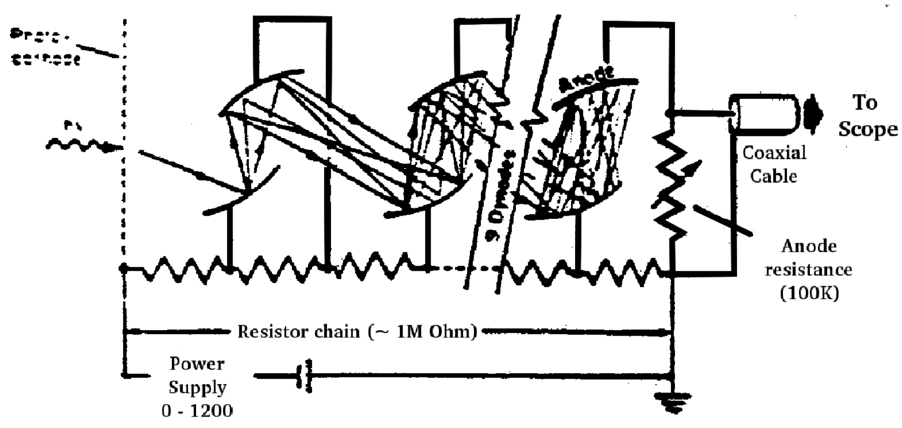

Figure A.3: Schematic of the RCA 931 Photomultiplier Tube.

to ZERO and remove it from the monochromator. Set the monochromator to 500 nm and then take the slits out the front and back and look in through the back of the monochromator (i.e. put your eye where the PMT would normally be). Move the light source around until you can see light through the monochromator and then put in the first slit and optimize the position of the lamp with this first slit in place. Put in the second slit and repeat the above step. When you are done, put the PMT back in place and turn the supply on and adjust the gain setting until you get a measurable signal (about 1V). The supply voltage to the PMT can be increased if more gain is needed, but do not exceed 1.2 kV. While you can use the voltmeter to measure the voltage output of the PMT, in most cases where the PMT output noise is high and you want a reliable measurement, you will need to use a fan to chop the light going to the monochromator, and you will use the oscilloscope to measure the PMT response to the dark and light periods.

Spectral Response of the PM-Monochromator Combination

It was pointed out in Section A that the photomultiplier does not respond equally to light of different wavelengths; neither does the monochromator. The combination of the two is very wavelength sensitive. For many experiments involving comparison of intensity measurements at various portions of the spectrum, it is necessary to know the spectral response of the entire system.

To measure this response, light from a known continuum source is passed through the system and the PMT signal, $S(\lambda)$, is measured at many wavelengths over the complete spectrum. If the intensity of the source, $I_w(\lambda, T)$ at a temperature of T, is known as a function of wavelength, λ, then the response of the system as a function of wavelength is given by,

$$R(\lambda) = \frac{S(\lambda)}{I_w(\lambda, T)} \tag{A.1}$$

Once the response function is known, the intensity of any other source at wavelength λ may be determined by measuring $S_2(\lambda)$ and dividing by $R(\lambda)$.