Physics 408

Optics Laboratory

Department of Physics & Astronomy
UBC

2023/2024 Winter Term 2
(Last edited January 4, 2024 by V. Milner)

Chapter 1

Rules and Resources

1.1 Safety Rules – READ THIS IN FULL!

Please do not be apprehensive of these labs. If you are careful, the danger involved in working with laser beams used here is extremely minimal. However, if you fail to heed the following warnings, bad things may happen. Because of the importance of these safety rules, we will be penalizing (subtracting marks!) those who don't follow them.

Do Not enter the lab without permission

Even if you have card access, you are not allowed in the Optics Lab without one of the lab supervisors, i.e. one of the TAs, Dr. Van Dongen or Dr. Milner being present! No supervisor - no entry, no exceptions!

Do Not enter a curtained section without permission

If you see that the curtain around a particular section is closed, do not poke your head in! The occupants might be either doing some sensitive data collection, which requires darkness, or they may be aligning their laser beam and send it inadvertently towards the curtain. Either way, you will ruin their data or your eyes, so always ask from outside before entering.

Do Not touch the high voltage electrodes in the HeNe lab

There is a plastic casing surrounding the laser tube, there is no reason for you to remove this casing or to place your hands within the confines of it. People have died by mishandling laser power supplies. You won't, but there is no reason to test this theory.

Do Not stare into the laser beam

In this lab we use class 3R (1-5 mW) and 3B (5-500 mW) HeNe lasers. If for some reason the beam does impact near the area of your eyes your "blink reflex" should be enough to protect you for a very short exposure. That being said, you should never place your head/eye in the path of the beam to see where it is going or for any reason at all. This might also happen by accident if, for example, you bend down to the beam level or an optic is being moved or removed with the laser not being blocked. A small index card (provided) is a much better means of observing the path of the beam. It is also important to watch for stray reflections off of mirrors or other reflective surfaces. This means that any **watches, rings, or bracelets should be removed** before beginning this experiment.

If you do get a laser beam or scatter in your eye please warn your partner and do not try to repeat the process to figure out what happened. If possible block the beam or turn off the laser and report the incident to lab staff. If you want to check for laser scatter one method is to put your BACK to the experiment. With the room lights off place a white sheet of paper in FRONT of you where you would like to check if the laser light is hitting the paper.

Laser goggles are provided and should be used when you are aligning the optical components in your setup. If you feel uncomfortable with the light intensity or anything else laser related, please seek out assistance. Curtains and doors are provided to protect others from your laser equipment. Please be mindful to appropriately block out access to random bystanders so they do not have direct line of sight to your optical equipment.

Do Not touch any optical surface

It does not take many impurities on the optical surfaces (e.g. scratches, fingerprints, and even dust) to prevent lasing action from occurring in the HeNe lab, to ruin the cavity mode in the Cavity lab, to mess up the interference pattern in the Michelson lab, or to destroy the Fourier image in the Fourier lab. Either hold optical elements by their mounts or on their edges as applicable.

Do Not eat or drink in the lab rooms

If you must eat, do so in the hallway.

Do Not move optics mounts or other hardware fixed to the bench with screws painted in red

These are elements that are already in their proper place and moving them will make doing the lab impossible. If you don't have a tool to loosen a screw, you probably shouldn't be trying to move that component. If you do move an optical element held with red screws or suspect that such an element is not in its proper place, please immediately contact the lab TA or professor to help you reset this element - obtaining good data and completing the lab may depend on it.

Do Not place foreign objects close to the optical setup

It feels very convenient to place your laptop, or your paper notebook, right by your setup and type/write your report as you work. Do not do it! A computer monitor or a pen can easily scatter light into your eyes and cause serious injuries. Plastic covers, e.g. in the HeNe lab, were not designed or tested to hold extra weight and will easily brake if used as desk surfaces.

1.2 Logistics and Resources

How will the labs be marked?

All questions in the lab manual labeled with red upper-case letters, e.g. (A), (B), (C), etc., are for marks. Those which are labeled with blue lower-case roman numerals, e.g. (i), (ii), (iii), etc., are for bonus points. Although the weights of each point may be slightly different, you may expect that all of them will be pretty similar.

Working with lab desktop computers

Although you are welcome to bring and use your own laptop computer, you will need lab desktop computers for data collection. After you login to the lab computers with your CWL account, you will be able to store your files and data under `C:\Users\yourUsername\Desktop\yourFolders`. Please be mindful of the (relatively) limited space on the local hard drive and clean after yourself when you are done with a particular lab.

On every lab desktop, you will also see the following folders with read-only files:

- `C:\Users\public\Desktop\labName`
- `C:\Users\public\Desktop\hardware`
- `C:\Users\public\Desktop\software`

The `labName` directories, with `labName`=**Cavity**, **HeNe**, **Michelson** or **Fourier**, contain useful materials pertaining to each particular lab, including this manual and videos explaining the relevant optical alignment procedures.

The `hardware` folder contains subdirectories with technical spec sheets and manuals of all electronic, optical and opto-mechanical components. These are useful for various calibration procedures, which you are asked to do in these labs. Computer communication protocols can also be found in these folders.

For several experiments in this course you will use the Raspberry Pi CCD cameras to capture images or movies – please read Appendix A for details on how to operate these cameras in real time.

Finally, the `software` directory contains a number of examples of MATLAB scripts, demonstrating the way you can communicate with the hardware components used in all four labs, e.g. `raspiCamera.m` for capturing images and movies with a Raspberry Pi camera or `thorlabsStage.m` for controlling the position of a Thorlabs translation stage.

Feel free to copy these files (especially MATLAB scripts) to your own folders and modify them for your own purposes.

Pacing yourself

If you find yourself spending more than 10 or 15 minutes trying (unsuccessfully) to get the proper alignment of any element in any part of any experiment, you should seek the advice of a TA or lab instructor (or a friend!) to get you past this hurdle. The point of the lab is both to learn lab techniques (such as optical alignment) and to perform a certain set of experiments. Make sure you don't spend too much time on any given task since you are expected to complete each experiment (typically, up to six separate experimental tasks).

File sharing platform and feedback

As you work on each experiment within your lab, you will collect experimental data. To share the data with your lab partner, as well as with your TA, who may provide you with important feedback, we will use the Microsoft Teams platform. Look on Canvas for the link to your lab Team, appropriately called 'PHYS 408 L2X 2012W2 Optics', where X=A,B,C or D. Inside your Team, you will find multiple channels. The main public channel called 'General' will be used for general announcements, notifications and all labs related discussions within your section. On top of that, you and your lab partner will have a private channel with a name similar to 'Lab1_Cavity_Optics3' or 'Lab2_Fourier_Optics5', where the first part 'LabX' (X=1,2 or 3) says whether this is your first, second or third lab in this course; the second part is the type of the lab; and the third part 'OpticsYY' (YY=1,...,12) is the name of the desktop which serves the specific setup you are working on. These private channels will be pre-set by your TA and used for storing and sharing data within your group (the files are stored on your UBC OneDrive and can be accessed from anywhere), as well as for seeking feedback from your TA by showing your intermediate results and asking questions pertaining to your specific lab and group.

Lab report format and submission

As you work on each experiment in your lab, it is critical to keep a detailed and organized *electronic* lab notebook. Since the provided examples of communicating with experimental hardware and acquiring data are written in MATLAB (see `C:\Users\public\Desktop\software` on your lab desktop), and because MATLAB is an extremely powerful tool for data processing available to every UBC student, you are encouraged to use MATLAB "Live Scripts" as a means of keeping your electronic notes[1]. In the course of each lab, keep your electronic notebook in your private MS Teams channel, where it will be accessible to your TA and used for giving you feedback on your progress, providing help and guidance. At the end, you will submit your final lab report as a pdf file on Canvas. It is your responsibility to keep track of the deadlines, outlined on the main Canvas page.

1.3 Collaborations and academic integrity

Although you and your partner will be working in the lab together, and although we do encourage scientific collaboration among students working on the same project, it goes without saying that everybody is expected to complete their work independently. Most data acquisitions are relatively quick; hence, you and your partner should be using distinct data sets (probably, taken one after another) in your individual lab reports. If for some reason you want to share data with your partner (e.g. due to the very long data collection time), please get

[1]Python scripts and Jupiter notebooks will be accepted as well

an approval from your TA first. Close similarities between any two lab reports will be considered as plagiarism and will be treated with utmost seriousness following an official UBC policy on academic misconduct.

Chapter 2

The HeNe Laser

2.1 Objective

The helium-neon (aka HeNe) laser was among the first lasers ever constructed, and has since proved to be among the most popular. In this lab you will investigate the principles of operation and general properties of the HeNe laser. By observing and changing its operating conditions, you will learn how a laser works and what determines its output characteristics, both in the spatial and frequency domains. Specific objectives are:

1. Investigate the dependence of the cavity stability on the radius of curvature of the cavity mirrors.
2. Observe and identify the laser field distribution in different transverse spatial modes, and measure the size of these modes inside the laser cavity.
3. Understand the polarization properties of the laser output.
4. Investigate the spectral properties of the gain medium, and determine the effect of lasing on the output spectrum, using the technique of lock-in amplification.

2.2 Pre-lab Study

Before you start this lab, familiarize yourself with the following material from the course textbook, “Fundamentals of Photonics” by Saleh & Teich, which provides essential background for completing the required experimental tasks. Note that all this material has been covered (or will be covered - depending on your lab schedule), in class before (or after) your completion of this lab. In the latter case, you do not need to understand every single detail in the text (this will be thoroughly discussed in lectures), but you should form the general conceptual picture and become familiar with the mathematical tools used in the relevant topics. The following list refers to the **Third Edition (2019)** of the textbook.

- **Experiment 1:** Chapter 11.2A on the stability of optical resonators.

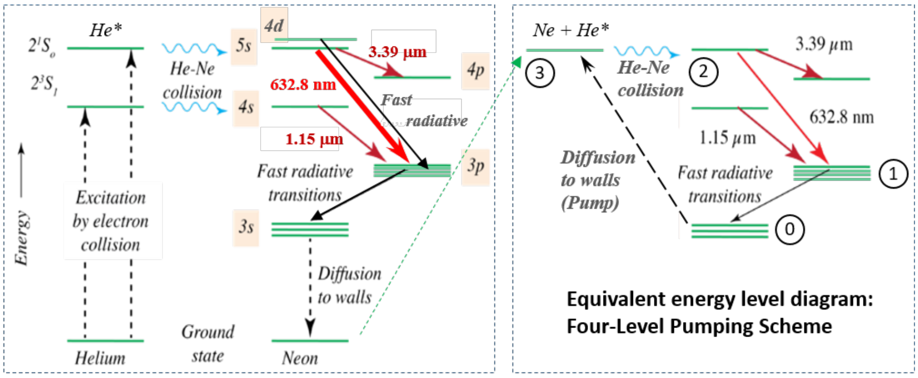

Figure 2.1: Left: Energy levels of Helium and Neon, involved in the lasing process. A population inversion is established in Neon by collision with Helium. The He atoms linger in the 2s state because radiative transitions from 2s to the ground state are very slow. The energy of Helium in 2s state is very close to the energy of Ne in either 5S or 4d state. The small energy difference between these states is easily available from kinetic energy in a warm gas, which enables the collisional energy transfer from He (2s) to Ne (in either 5s or 4d). (Image was edited from `https://en.wikipedia.org/wiki/File:HeNe_Laser_Levels.png`) Right: a slight re-arrangement of the energy levels connects them to the standard diagram for a Four-Level laser, found in the textbook. The highest energy level ③ corresponds to the ground state neon atom and a helium atom in the excited 2^1S_0 state.

- **Experiments 2:** Chapter 3.1 on the basic properties of Gaussian beams, and Chapter 3.3 on Hermite-Gaussian beams.
- **Experiments 3:** Chapter 6.2 on the polarization of reflected and transmitted light.
- **Experiment 4:** Chapter 14.1A on the atomic energy levels, Chapter 14.3 on the interaction of light with atoms, Chapters 15.1A and 15.2 with a focus on Four-Level Pumping scheme, which characterizes the HeNe laser. Refer to Figure 2.1 to make a connection between the standard level notation for the Four-Level laser and the actual energy levels of a HeNe laser.
- Appendices A, B, C, D, E.

2.3 Experiments

2.3.1 Laser Alignment and Stability

You are provided with the ingredients of a HeNe laser on an optical bench, as illustrated in Fig 2.2: a HeNe gain cell with one fixed high-reflector (HR) mirror,

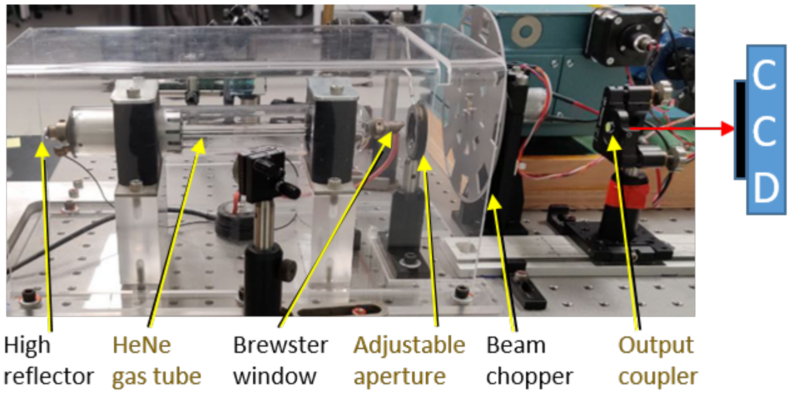

Figure 2.2: Picture of the HeNe tube in your experimental setup, together with a few important surrounding optical elements (looking from the back wall towards the center of the lab).

a Brewster window, and a partially reflecting mirror (known as an "output coupler", OC) on a moveable, adjustable mount. The linear optical resonator (or cavity) is created by the HR mirror on one side, and OC mirror on the other side. A high-voltage power supply is used to supply the energy via discharge in the mixture of He and Ne gases confined in a glass tube.

IMPORTANT NOTE: A laser is a much more delicate and sensitive device than a passive cavity. Therefore, as you work with the HeNe laser, there are some important rules to follow! Do not touch any of the optical surfaces – a single fingerprint scatters enough light to overcome the gain of a round trip, and the laser might never start. Do not change the height of the adjustable OC mirror or remove it from its post. It is a manageable problem to search in three dimensions (z, θ_x, θ_y) to get the system aligned, but if you add two more dimensions by moving the mirror center with respect to the optic axis, you may never finish this experiment! Before the start of this lab, the laser has been pre-aligned, so whatever you do, do not introduce big changes, and whenever in doubt – ask your TA.

Turn on the discharge in the gain cell. Rotate the spinable chopper by hand so that one of its windows is roughly centered at the optical axis of the laser. For your first output coupler, use the planar mirror and place it such that the cavity length is < 50 cm. Use the fixed aperture to help align the fluorescence from the HeNe tube back onto itself (watch the videos in the `HeNe` directory for the demonstration on how it's done). Finally, make small adjustments to the two control knobs on the OC mirror mount until you see a bright red glow on the mirrors. Your laser is lasing! Now, let's investigate how robust this laser action is with respect to the cavity length.

(A) Use the planar mirror (radius of curvature $R = \infty$) to determine the ROC of the fixed HR mirror. *Hint: scan the cavity length and employ the theoretical stability condition.*

(B) Replace the planar OC mirror with the provided concave mirror $(R < 0)$

and find the radius of curvature of that mirror, again by measuring the stability regions of the laser. How does your measured region of stability compare with what you expected, given the information gathered in the previous step? Present your results in a simple table for comparison, and plot theoretical expectations. What are the reasons for possible disagreement?

(i) 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?

2.3.2 Transverse Laser Modes

The laser resonator which you are investigating is capable of supporting more than one transverse spatial mode and more than one longitudinal mode. Each of these modes has a specific optical frequency associated with it and, similarly, a specific intensity distribution (that is, how the laser spot looks like in a transverse plane). Each mode can occur only for certain configurations of mirror curvatures and separations. The 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. In the following experiments, use one of the curved mirrors as an output coupler and set the cavity length to around 40 cm.

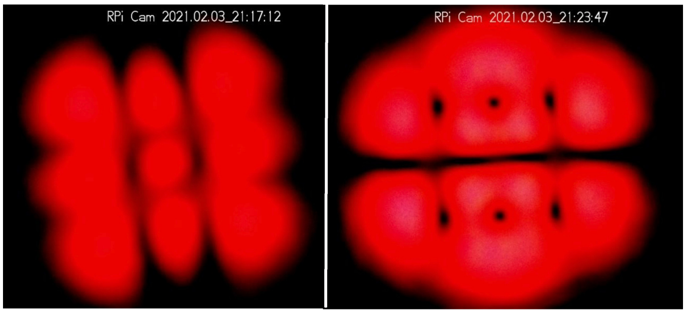

Figure 2.3: Two modes found in a two-dimensional search of external cavity mirror alignment. The one on the left is a Hermite-Gaussian TEM_{22} mode. The one on the right is not so easily classified and is a combination of more than one TEM mode occurring simultaneously.

(A) Use the curved mirror and continue adjusting it, while looking at the mode profile on a camera. Capture some of the mode patterns and copy them to your lab book (a couple of examples are shown in Fig. 2.3). For each, explain and label their mode structure (don't forget to mention the cavity length at which the mode was observed!). What is the highest order mode you could see?

(B) 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.

(i) Do you usually see only one transverse spatial mode at a time or a few co-existing modes? Try explaining your observations. *Hint: do all Ne atoms provide gain at the same single frequency or different atoms may resonate at different frequencies?*

Looking at the camera image, it is easy to determine the size of the laser beam *outside* of the laser cavity, but how can we do it *inside* the cavity. It turns out it can be done by placing a small object (such as a thin wire) inside the laser. With that obstacle in place, only those modes with a node (zero) occurring at the location of the obstacle will not experience losses and will continue lasing. Thus by translating the object laterally across the profile of the beam it is possible to measure the distance between the nodes of a particular spatial mode, effectively measuring its size.

(C) Place the wire (mounted on a translation stage) 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 the observed behavior.

(D) Tweak 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). *Hint: If you are having difficulty, try making the cavity length large but still within its stability range (e.g. 65-70 cm). Place the wire near to the output coupler mirror and ensure that the wire can be translated through the laser beam. Optimize the output coupler alignment and the wire position horizontally so that a TEM_{10} mode is seen. Move the wire in either direction to see if a TEM_{20} mode appears. Note that the camera is rotated so that vertical nodes appear as horizontal on the web interface!*

    TEM_{30} or TEM_{40} are also possible, but harder to achieve. Once you think you have this alignment correct, please check with a TA. 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. Present your measurements results in a simple table. 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?

(E) From the experimentally determined positions of the nodes and the theoretical expression for the intensity of a Hermite-Gaussian beam [Equation (3.3-12) from the chapter on Hermite-Gaussian Beams in Saleh & Teich], calculate the waist size $w(z)$ at the location of the wire, $z = z_{\text{wire}}$.

(F) Given all the known parameters of your cavity, i.e. the ROC of both mirrors and the distance between them, calculate the Rayleigh length z_0 and the position of the focus ($z = 0$) relative to the output coupler. You will need to consult Section 11.2.B "Gaussian Modes" of Saleh & Teich from the chapter on Resonator Optics.

(G) From the result of the calculations above, what is the position of the wire with respect to the focus, i.e. what is the value of z_{wire}? Finally, using this value, calculate the expected beam waist at the position of the wire and compare it with the one you found experimentally. Discuss reasons for possible disagreement.

To double-check that your experimental measurements of the beam waist inside the cavity are consistent with the theoretical predictions, you might want to repeat the same exercise outside the cavity.

(ii) Place the camera somewhere along the rail and take a picture of a TEM_{10} and a TEM_{20} mode at this location. From the pictures, determine the distance between the nodes of each mode. *Hint: read Appendix A for the proper determination of the camera's effective pixel size.*

(iii) Similarly to what you have done in point (G) above, determine the position of the camera (z_{cam}) with respect to the focus of the mode ($z = 0$) and compare the observed waist size $w(z_{\mathrm{cam}})$ with the expected one.

(iv) Plot the theoretical beam radius as a function of position, $w(z)$, and overlay it with the beam radius measurements that you obtained experimentally (both inside and outside the cavity). 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.

2.3.3 Polarization of Laser Light

In this part you will explore the polarization properties of your laser, and explain the mechanisms behind them.

(A) What does it mean for the laser to be polarized? Check the polarization of the HeNe laser beam using the provided polarizer.

(B) 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?

2.3.4 Spectral Properties of Emitted Light

So far, we have explored the physical characteristics of the laser beam and the laser cavity. Another really important consideration is how stimulated emission at a specific wavelength, in our case 633 nm, occurs. This section takes you through the steps to understand why the HeNe laser is lasing at 633 nm. The key point to understand is that any lasing always requires population inversion between two energy levels - keep that in mind when working on various tasks in this section.

A monochromator has been provided to allow measurements of the spectrum of light produced in the gas discharge, as well as the laser light – see Figure 2.4. A mirror assembly (bottom right corner in the figure) and a focusing objective lens are used to form a vertical image of the horizontal gas discharge tube on the input slit of the spectrometer (thick orange lines in the figure). Together with two additional mirrors, the laser light "leaking through" the high reflector can also be sent towards the spectrometer (thin red lines in the figure). Here, you will record and compare the spectra of both sources. The setup is already close to being properly aligned, so only minor adjustment of the mirror knobs should

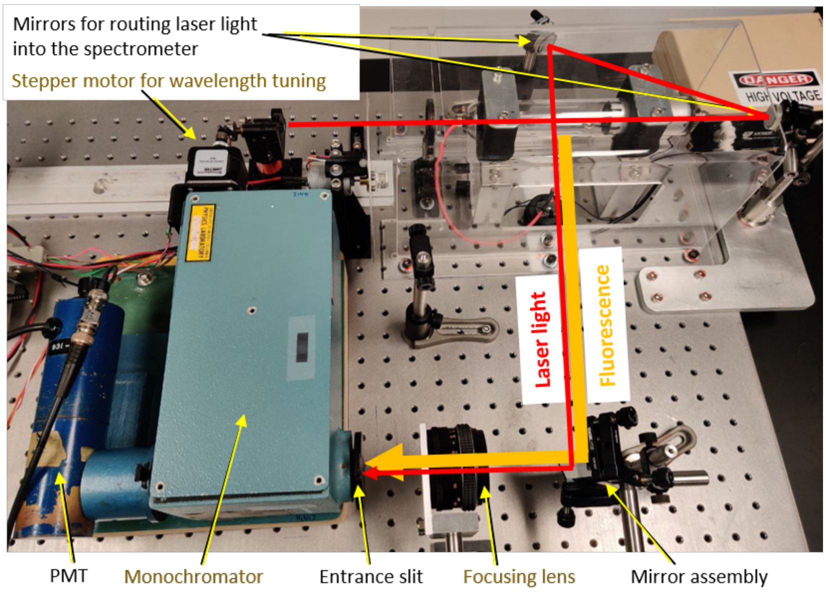

Figure 2.4: Picture of the setup from above, with the important components labeled. Note that the fluorescent light escapes the HeNe tube from the side, whereas the laser light "leaks through" the HR mirror and gets routed to the monochromator by two additional mirrors.

be necessary for optimization once a signal is obtained. Please do not unscrew the mirrors and the lens from the table! **SAFETY NOTE**: the adjustable mirror located near the fixed high reflector of the HeNe tube should not be adjusted at all, hence at no time should you have your hands near the high voltage ends of the laser!

Scanning the monochromator is executed by rotating its diffraction grating, located inside the monochromator, with a stepper motor (upper left corner in Figure 2.4). You control the stepper motor via the digital inputs and outputs on the Raspberry Pi board. The Raspberry Pi board also has an MCC118 analog-to-digital (A2D) data acquisition hat from Measurement Computing. Take a look at the example of a MATLAB script `raspiA2D.m` in the `Software` folder, which shows you how to initiate the wavelength scan. Please note that this code is not meant to just be run as is, since it accomplishes multiple purposes. You will need to select the appropriate task to perform. Also, please do not interrupt the code while a scan or search is occurring, as this could leave Raspberry Pi in a confused state. Notice that the scan is performed in the units of motor's *step counts* rather than *nanometers*. To convert the step count C to wavelength, use the following formula:

$$\lambda[\text{nm}] = a - b \cdot C[\text{count}], \tag{2.1}$$

with the calibration constants a and b, which depend on the number of your lab station (as written on the desktop monitor):

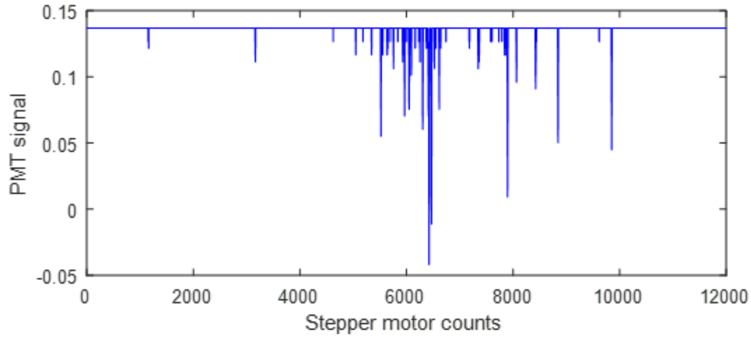

Figure 2.5: Typical raw signal from the PMT collected during the wavelength scan. Note the horizontal units which have to be converted to nanometers. Note also the negative polarity of the signal, meaning that *brighter* light will result in *lower* (i.e. more negative) signal.

- **OPTICS 1**: $a = 959.4, b = 0.05794$
- **OPTICS 4**: $a = 971.8, b = 0.06190$
- **OPTICS 6**: $a = 930.4, b = 0.05978$

These calibrations may change slightly with time and should be used as a starting point for your analysis. The wavelengths should be fine-tweaked based on the comparison of your spectra with the values from NIST.

As you scan the wavelength, the A2D board enables you to simultaneously acquire the voltage signal from the photomultiplier tube (PMT), which is proportional to the light intensity at that wavelength. Before turning the PMT on, please read Appendix D about the working principles of a photomultiplier tube. You can easily damage the PMT by exposing it to bright light. Therefore, do not turn it on unless it is properly mounted in the monochromator and the input slit is in place (neither the PMT nor the slit should ever be removed from the monochromator!). To be on a safe side, it is a good idea to collect spectra with the room lights off and curtain closed (please be mindful of tripping or hitting sharp corners in a dark environment!). If you want to operate with the room lights on, cover the photomultiplier with the provided thick cloth. The black gain knob on the PMT should not be adjusted. Finally, always turn the PMT voltage up in steps, while watching the output signal on the oscilloscope and making sure it does not exceed a few hundred millivolts as its base level. The operating PMT voltage is 1 kV.

For the rest of this lab, please operate the laser well within its stability region and optimize the output coupler mirror to give the brightest looking mode possible, typically the large one with a complex looking profile.

(A) First, investigate the spectrum of the fluorescence alone. Refer to Figure 2.1 and your pre-lab studies for the interpretation of your observations. Block the laser light from going towards the monochromator, e.g. by attaching a sticky note on the back side of the laser's plastic shield. Carry out your first scan with the lasing process inhibited by the chopper

Observed Wavelength Air (nm)	Rel. Int. (?)	g_kA_{ki} (s^{-1})	Acc.	Lower Level Conf., J	Upper Level Conf., J
616.35937	10000	4.38e+07	B+	$2s^22p^5(^2P°_{1/2})3s$ 0	$2s^22p^5(^2P°_{1/2})3p$ 1
618.21460	1500	1.86e+07	B+	$2s^22p^5(^2P°_{3/2})3p$ 3	$2s^22p^5(^2P°_{3/2})5s$ 2
620.57775	1000	4.56e+06	C+	$2s^22p^5(^2P°_{3/2})3p$ 0	$2s^22p^5(^2P°_{3/2})4d$ 1
621.38758	1500	8.55e+06	B+	$2s^22p^5(^2P°_{3/2})3p$ 2	$2s^22p^5(^2P°_{3/2})5s$ 1
621.72812	10000	1.91e+07	B+	$2s^22p^5(^2P°_{3/2})3s$ 2	$2s^22p^5(^2P°_{3/2})3p$ 1

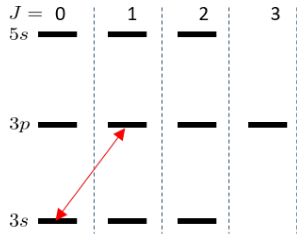

Figure 2.6: An example of the table retrieved from the NIST database (left). Energy levels, which are relevant to any particular radiative transition, can be (partly) identified by the quantum state of the excited electron (e.g. $3s, 3p$ or $5s$) and the total electronic angular momentum J. For instance, the transition at ≈ 616.4 nm is between $3p(J = 1)$ and $3s(J = 0)$, as indicated by the red boxes in the table. The corresponding transition is also marked on the energy level diagram (right).

wheel, and plot the PMT signal as a function of wavelength. Now enable lasing by rotating the chopper wheel out of the laser beam's path. Keep the laser beam blocked from entering the monochromator. Record the fluorescence spectrum again. Compare the two spectra. Do all the peaks "react" to the lasing action similarly, or are there differences? If the peaks react, do they become stronger or weaker? *Hint: Take a note about what these "changing" lines are, without spending too much time in analysis. Later in part E we will use a sophisticated piece of equipment, called a lock-in amplifier, that will give much more detailed information about how the Neon transition intensities are affected by the presence or absence of the lasing action.*

(B) Identify the major observed spectral peaks by comparing your data to known atomic lines, available from `https://physics.nist.gov/PhysRefData/ASD/lines_form.html`. When using the NIST website, type `‘‘Ne I’’` under `Spectrum` (meaning that you are interested in the neutral Ne) and limit the wavelength range from 570 nm to 650 nm. *Hint: to avoid being swamped by enormous number of possible spectral lines, you might want to retrieve only the strongest ones, applying "relative intensity minimum" under the* `Show Advanced Settings > Optional Search Criteria`. For instance, try putting 1.0e+06 as the "Minimum Transition Strength" and 3000 as a "Relative intensity minimum". An example of the NIST table is shown in Figure 2.6. To simplify the analysis, focus your attention on the quantum state of the excited electron and the total angular momentum J. What are the electronic energy levels producing the strongest fluorescence peaks? Make a sketch of the relevant energy level diagram, similar to the one shown in Fig. 2.6 (though you may expand it with at least one more relevant quantum state – remember to consult Fig. 2.1) and indicate the transitions involved with the corresponding wavelengths of the emitted light. In your diagram include the energy level values E_i and E_k given in the NIST database. Identify those transitions which share an energy level with the lasing transition at 632.8 nm.

(C) Now unblock the laser beam and observe it being focused close to the monochromator's entrance slit. DO NOT touch the mirrors in an attempt to bring the laser beam closer to the center of the slit, since that may send the laser beam upwards towards your eyes! Instead, attach a small piece of scotch tape to the entrance slit of the monochromator (ask your TA for guidance). The tape works as a light diffuser (scatterer), allowing both the laser light and the fluorescence light to enter though the slit and into the monochromator (even if they are not perfectly focused on the slit). Record the spectrum with and without the laser blocked, and explain your observations: how many laser lines do you see and why? Do they coincide with any particular peaks in the fluorescence spectrum and which one?

(i) Does the laser line correspond to the strongest fluorescence peak? Why do you think that is?

Let's investigate the effect of the lasing action on the fluorescence spectrum in greater details than our first attempt in task (A). For completing this study, make sure to read Appendix E on the principles of lock-in amplifier. We will use this device to produce an output signal proportional to the difference between the PMT voltage signal when the laser is blocked and unblocked. This will help determine which transitions are involved in making your HeNe laser function. Consult with your TA on the proper operation of the lock-in amplifier.

(D) Keep the laser beam unblocked and hitting the diffuser (scotch tape) in front of the monochromator. Turn on the lock-in amplifier. Tune the monochromator to the laser wavelength (the strongest peak in your spectrum) by calling the `vsearch.py` script from within your MATLAB code (see an example in `raspiA2D.m` in the `Software` folder) and performing a short scan around 632.8 nm. Now turn on the motorized chopper and the chopper reference source. The spinning wheel will alternately block and unblock the laser optical cavity at a frequency between 100 Hz and 200 Hz (verify this by putting the output of the chopper reference box on the oscilloscope!). The discharge will keep producing fluorescence, but the lasing action will be modulated with the chopper. Confirm that the monochromator is indeed "parked" on the laser line by observing the PMT signal on the oscilloscope - it should be clearly modulated with the frequency of the chopper. *Hint: this is a good time to improve the alignment of your laser. Carefully tweak the output coupler to increase the modulated signal on the scope. Also, if you need to run `vsearch.py` again for any reason, turn the chopper off.* Now feed this signal to the lock-in amplifier. Find the reference phase for which the lock-in signal is zero, and then maximum. What is the phase difference between the two cases and why? What happens when the phase is flipped by 180°? Document and explain your findings.

Figure E.4 in Appendix E on Lock-in Amplifier is helpful for answering the above questions. A lock-in amplifier essentially takes the signal input, multiplies it by an internally generated waveform at the reference frequency and with a controllable phase. The result of that multiplication is then averaged in time, producing a measure of how strongly the input signal is modulated at that frequency and a given phase.

(E) Set the reference phase for the maximum positive lock-in signal (while the monochromator is still tuned to the laser line) – this means that a positive lock-in signal for other spectral lines will correspond to the increase of light intensity when the lasing is enabled, whereas a negative lock-in signal will indicate the increase of intensity with the lasing inhibited. Before leaving the 632.8 nm line block the laser light going to the monochromator and take off the diffusing tape from the monochromator. You are now looking only at the spontaneously emitted 632.8 nm light. Did the signal from the lock-in amplifier change sign? Why or why not?

(F) Now feed the signal from the lock-in amplifier to the Raspberry Pi A2D board (since CH0 is taken by the PMT signal, use CH1 for the lock-in). Initiate the wavelength scan again, now recording both CH0 and CH1 signals. Focus on the same spectral lines you identified earlier and discuss the qualitative differences between the PMT and the lock-in signals. Using this scan, analyze which transitions are affected by the lasing action. Are they affected the same way? Why or why not? Please remember to convert the lock-in signal output voltage to the proper value based on its range settings. The lock-in amplifier may give a 3 V output signal on a 100 mV range. This means that the actual modulation signal is 30 mV. How strongly a line is modulated is expressed by the modulation amplitude, given by the lock-in amplifier, relative to the strength of the PMT signal.

Hint: refer to the energy level diagram you made in point (B). Remember that (a) the strength of any fluorescence line depends on the population of the corresponding excited state (i.e. the number of atoms occupying that state and (b) the stimulated emission decreases/increases the population of the upper/lower level faster than the spontaneous emission between the same two levels – accordingly, do you expect those populations to change as a result of the lasing action?

(ii) Remember that the laser cavity supports only certain optical frequencies given by the following expression (see Appendix C for details):

$$\nu_q = q\frac{c}{2L}, \tag{2.2}$$

where L is the length of the laser cavity and q is the mode order, equal to 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. 2.2 suggests that many frequencies should be possible, so why do you only see one color?

(iii) Do you see that the laser only lases for specific mirror separations, as predicted by Eq. 2.2? 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.

Appendix A

Raspberry Pi Camera Operation

For several experiments in this course you will use the Raspberry Pi CCD cameras to capture images or movies. While you will be taking your final data using Matlab (or Python) scripts (see an example in the `Software` directory), it is often convenient to look at the camera image in real time, e.g. when you search for various cavity modes or optimize the interference pattern. For a real time view of the raspberry pi camera it is useful to use the Raspberry Pi Camera Web Interface. This interface simply needs a web browser and to see the interface type in the web url: `http://142.103.238.21/html/` where the IP address is different for different desktop stations and can be found on the corresponding monitor.

If you want to view the camera on your laptop, then you need to be connected to UBC VPN. The web interface has many configurable options but for us there are only a few to be concerned with. When you first open the page, it will look similar to the one shown in Fig. A.1.

On this page the items of interest are:

1. The stop camera/ start camera button. You must press the stop camera button to free up the camera when you want to take images with MATLAB instead. Press the start camera button when you want to use the web interface again.

2. Record image or record video start. These will record an image or video saved on the raspberry pi.

3. Download Videos and Images will allow you to see images or videos you have taken and you can download them to the computer you are using the web interface on. You can also use this to delete picture files saved on the raspberry pi. **Please clean up after yourself as the RasPi memory is limited!**

4. The Camera Settings menu provides many options which we will refer to later in this document.

5. The System menu has options. **Please do not touch any of those except the Reset Settings button!** The reset settings button can

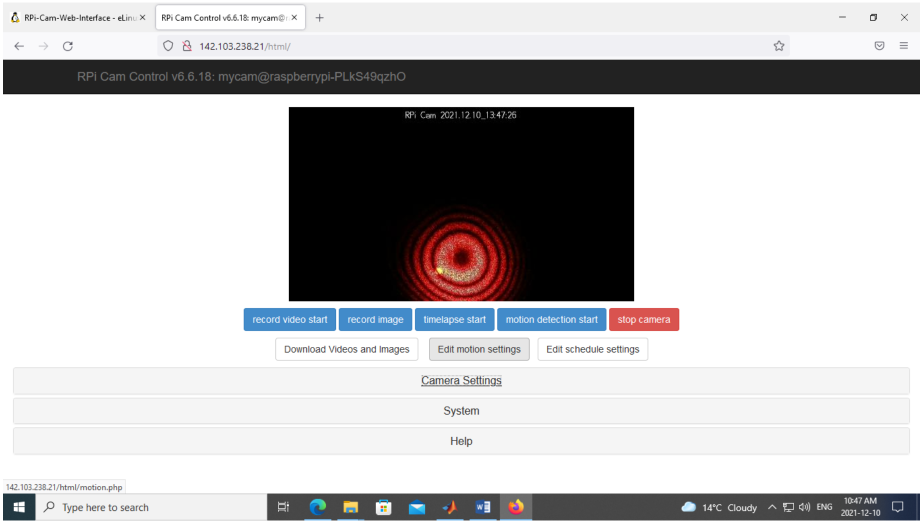

Figure A.1: An example of the web interface for operating Raspberry Pi cameras in real time.

help if the web interface is left in an odd state or if you want to return to the default settings. The web interface saves the last used settings even if the web browser is closed.

Please note that more than one person can have a web interface open at the same time to see the camera but it is not advisable to be tweaking settings on different computers at the same time.

Camera Settings Menu. There are many many options in the camera settings. You do not need to and should not play with most of them. The main settings of use are:

1. Exposure mode to ‘off’ or ‘auto’. ‘Off’ allows you to set the shutter speed yourself.

2. Shutter speed (in micro seconds) can be set when the exposure mode is set to off. Note that a shutter speed of 0 is auto exposure regardless of the exposure mode setting.

3. White Balance to ‘off’ of ‘auto’. This is useful when you want to correctly collect the red pixel values for data analysis. For the most part we are using HeNe lasers whose wavelength is red (633 nm) so it makes sense to set the white balance to ‘off’, for example, for taking cross sections of images where the red pixel value only is needed.

4. Other settings such as ISO may be useful. Sharpness, contrast, brightness, saturation can be played with but typically the shutter speed is the most valuable.

5. Image quality changes the amount of image compression and is mildly useful.

6. If you want truly uncompressed data for analysis, for example, for cross section analysis then the raw layer can be set to 'On'. The raw Bayer information is appended to the end of the jpeg image file and must be extracted. This option makes the file size large so only use if needed for analysis.

7. Annotation and size can be changed if you want to have a descriptor written on your image.

We do not recommend altering other settings unless you have a very good reason to. If you find that the camera view is strange, first try resetting the settings. If buttons are not working at all or the preview is updating only sporadically, the web interface will need to be reinstalled on the raspberry pi. **Please ask for assistance if that is the case and do not do that on your own.**

Resources for more information: `https://elinux.org/RPi-Cam-Web-Interface`, which is based on the picamera module urlhttps://picamera.readthedocs.io/en/release-1.13/.

Raspberry Pi High Q camera image resolution and effective pixel size. It is important to realize that the effective pixel size of the RasPi camera changes depending on the image resolution specified. The specifications for the Raspberry Pi High Q camera are given as:
`Sony IMX477R stacked, back-illuminated sensor, 12.3 megapixels, 7.9 mm sensor diagonal, 1.55` μ`m` $\times$ `1.55` μ`m pixel size.`

The maximum resolution of this camera is 4056×3040 pixels. Just to make sense of these numbers it means that there are more pixels along one direction than another which you can tell from looking at the rectangular shape of the CCD chip. If we multiply (4056×3040) we get 12330240 total pixels which agrees with the 12.3 megapixel specification. Each physical pixel is 1.55 μm $\times$ 1.55 μm in size which gives us an approximate 7.9 mm diagonal, as shown in Fig. A.2.

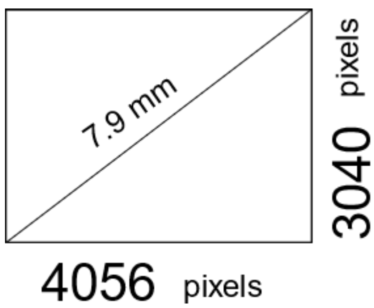

Figure A.2: The CCD chip of the raspberry pi high Q camera has 4056 by 3040 pixels with a 7.9 mm diagonal dimension.

Note that the image resolution can be specified by the user. For example, the web interface we use to collect raspberry pi images has a default image resolution of (2592×1944). This means that images collected have 2592×1944 elements so that the effective pixel size has increased in comparison to the 1.55 μm $\times$ 1.55 μm size of the physical pixel elements. In that case the effective pixel size is instead 2.42 μm $\times$ 2.42 μm as calculated by:

$$\begin{aligned}(4056/2592) \times 1.55\,\mu\text{m} &= 2.42\,\mu\text{m}, \\ (3040/1944) \times 1.55\,\mu\text{m} &= 2.42\,\mu\text{m}.\end{aligned}$$

This is important for the HeNe lab where you are asked to measure the beam diameter with a camera. In that case it is important to know the separation distance between the elements in your image array. You need to take into account your image resolution used when saving your images to calculate the correct beam diameter.

Appendix B

Modes of a Spherical Resonator

A spherical mirror resonator (like the one in the Cavity lab or the HeNe lab) support (i.e. resonate) with certain transverse mode patterns. These are the patterns corresponding to the exact solutions of the free-space paraxial wave equation. When the system has Cartesian symmetry, the solutions are the Hermite–Gaussian beams (or modes) composed of a 2D Hermite polynomial times a 2D Gaussian function. These are probably the most familiar to you, but there are others of importance (including the Laguerre gaussian modes and the Ince modes). You may run across these other modes in the lab, so we provide a short discussion below as well as some pictures of the mode patterns for your reference.

Hermite-Gaussian Modes

The Hermite-Gaussian modes (see Fig. B.1) are particularly common, since many laser and/or resonator systems have Cartesian reflection symmetry in the plane perpendicular to the beam's propagation direction.

Laguerre-Gaussian Modes

If the laser or resonator cavity is cylindrically symmetric, the natural modes are Laguerre-Gaussian modes (see Fig. B.2). They are written in cylindrical coordinates using Laguerre polynomials

Ince-Gaussian modes

The Ince–Gaussian beams (see Fig. B.3 and Fig. B.4) form the third complete family of exact and orthogonal solutions of the paraxial wave equation. They constitute the continuous transition modes between HGBs and LGBs, and are natural resonating modes in stable resonators. In particular, if the laser or resonator cavity has an elliptical symmetric, the natural modes are Ince–Gaussian modes. The transverse distribution of these fields is described by the Ince polynomials and has an inherent elliptical symmetry.

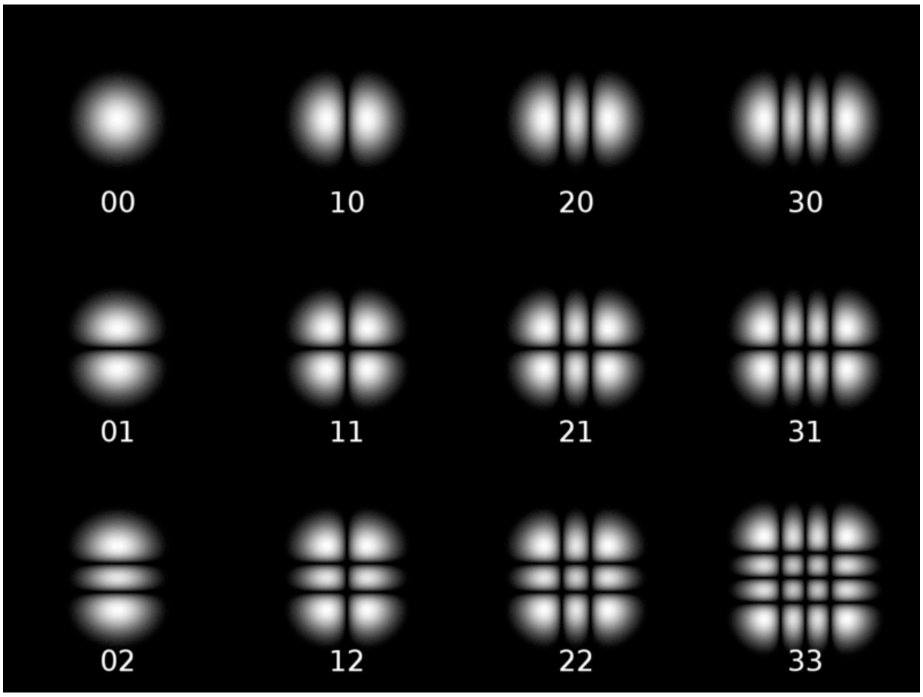

Figure B.1: Hermite–gaussian modes.

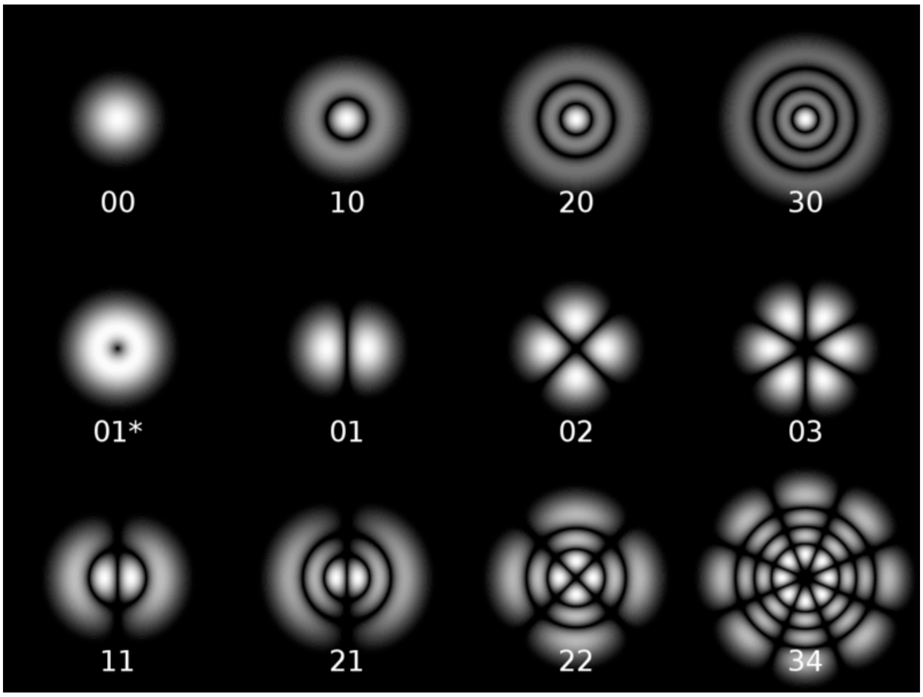

Figure B.2: Laguerre–gaussian modes.

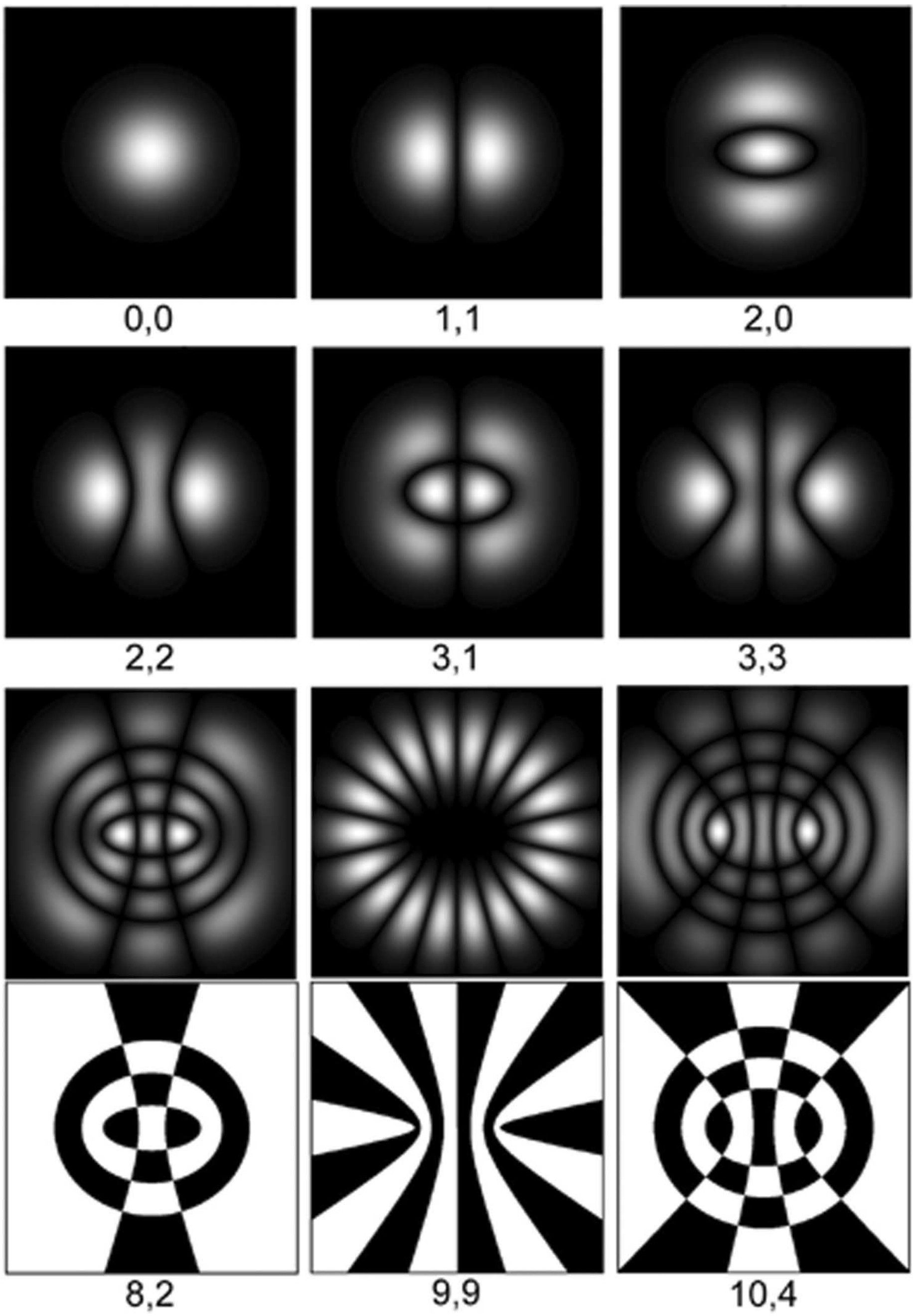

Figure B.3: Transverse field distributions of some even Ince–Gaussian beams. Plots in the bottom row correspond to the phase structures of the modes displayed in the row immediately above them. Figure from Opt. Lett. 29, 144 (2004).

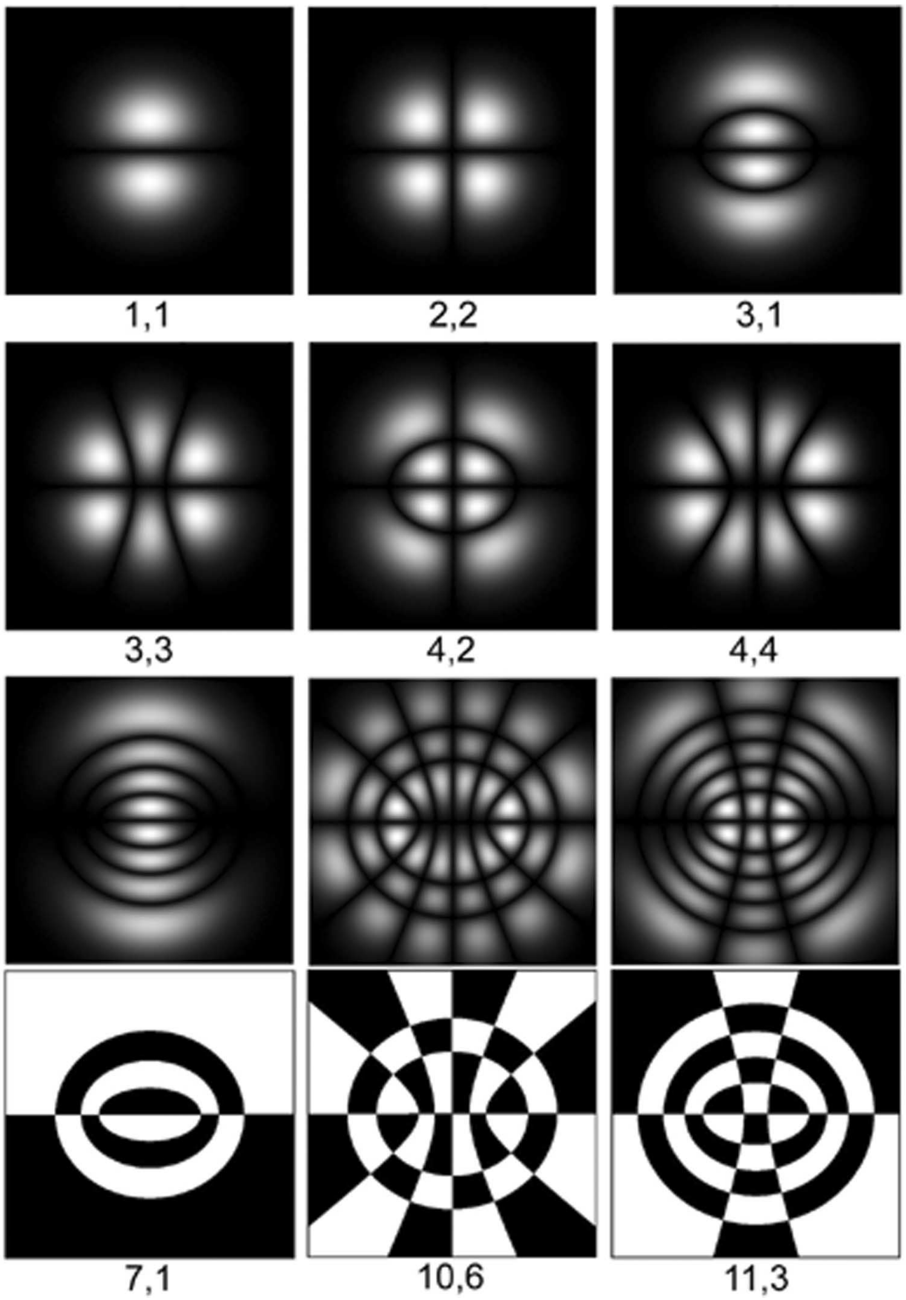

Figure B.4: Transverse field distributions of some odd Ince–Gaussian beams. Plots in the bottom row correspond to the phase structures of the modes displayed in the row immediately above them. Figure from Opt. Lett. 29, 144 (2004).

Appendix C

Resonator Theory

Spherical-Mirror Resonators

An optical resonator composed of two planar mirrors ($R_1 = R_2 = \infty$) is stable for any mirror separation so long as they have been perfectly aligned. The difficulty with this arrangement is that in practice planar mirrors are extremely sensitive to misalignment; they must be perfectly parallel to each other and perfectly normal to the incident light rays. This sensitivity can be reduced by replacing the planar mirrors with spherical ones. The trade off, however, is that spherical-mirror resonators are only stable for specific geometric configurations. These mirrors can be either concave ($R < 0$) or convex ($R > 0$).

Limiting yourself to ray optics, and specifically to the methods of paraxial matrix-optics, it is possible to determine that the region of stability for any spherical-mirror resonator is given by;

$$0 \leq \left(1 + \frac{d}{R_1}\right)\left(1 + \frac{d}{R_2}\right) \leq 1 \tag{C.1}$$

where d is the optical cavity length, and R_1 and R_2 are the radii of curvature for the two mirrors. Typically, the two middle terms are written in terms of the $\boldsymbol{g}$ **parameters**

$$g_1 = 1 + \tfrac{d}{R_1} \quad \text{and} \quad g_2 = 1 + \tfrac{d}{R_2}$$

It is left as an exercise to demonstrate that this result is valid. A good starting point for this analysis in located in your textbook (Saleh and Teich, *Fundamentals of Photonics*).

The transmission function of the optical resonator in this lab (which is a Fabry-Perot interferometer) depends on the *quality* (or Q-factor) of the resonator (equivalently the *finesse*) and the spectrum of the laser light. For a laser input with an infinitely narrow optical spectrum, the cavity transmission is

$$T = \frac{T_{\max}}{1 + \left(\frac{2F}{\pi}\right)^2 \sin^2(\Delta\phi_{\mathrm{rt}}/2)} \tag{C.2}$$

where $T_{\max}$ is the maximum transmission (depending on the mirror reflectivity), F is the cavity *finesse* and $\Delta\phi_{\mathrm{rt}}$ is the round trip optical phase. The finesse is defined by

$$F = \frac{\pi\sqrt{r}}{1 - r} \tag{C.3}$$

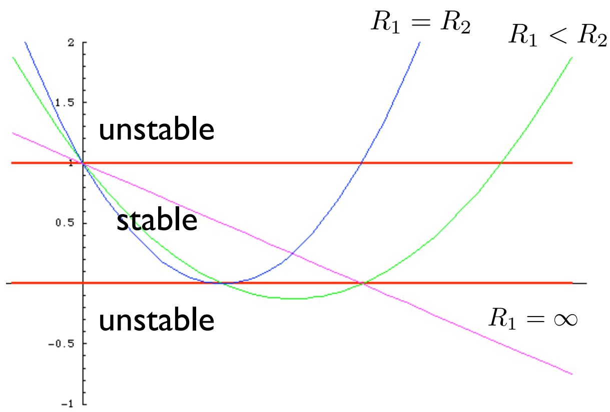

Figure C.1: Plot of the middle term in expression (C.1) as a function of the mirror separation, d, for various mirror combinations (i.e. values of R_1 and R_2). The cavity is stable at all locations, d, for which the value of the term is between 0 and 1 (denoted by red lines).

where the amplitude of the wave is reduced by a factor r on each round trip. Given intensity reflection coefficients R_1 and R_2, we have that $r = \sqrt{R_1 R_2}$. For a plane wave inside a cavity of length L made of planar mirrors, $\Delta\phi_{\mathrm{rt}} = 2kL$, where $k = n2\pi/\lambda$ and n is the index of refraction of the material inside the cavity. The cavity transmission is maximum when $\Delta\phi_{\mathrm{rt}}/2 = q\pi$ where q is an integer or equivalently when $2kL = 2\pi q$.

Okay, here's the main point: the resonance condition is then $L/\lambda = q/2$ (where $q = 1, 2, 3 \ldots$). That is, the cavity length must be an *integer multiple of half the wavelength of the input light*! That means that monitoring the resonance of optical cavities is a great way to detect small changes (on the order of λ) in the cavity length. This is the principal of operation for LIGO, the cosmic gravitational wave detectors run by MIT and Caltech. **Notice**: since we can *either* vary the input **laser frequency** (i.e. wavelength) OR the **cavity length** to move the laser and the cavity into resonance, we get *two conditions on the positions of the resonances*. For a **fixed cavity length**, the resonance condition on the wavelength or frequency of the input beam is

$$\lambda_q = \frac{2L}{q}; \quad \nu_q = \frac{cq}{2L} = q\,\nu_{\mathrm{FSR}} \tag{C.4}$$

where the so-called "free-spectral range" is $\nu_{\mathrm{FSR}} = c/2L$ and the speed of light in the cavity is $c = c_0/n$ where c_0 is the speed of light in a vacuum. The time it takes a photon to travel from M1 to M2 and back to M1 (the round trip time) is simply $\tau_{\mathrm{rt}} = 1/\nu_{\mathrm{FSR}}$. From this, we see that the cavity transmission is periodic in the input laser frequency with period ν_{FSR}. On the other hand, for a **fixed laser frequency**, the resonance condition on the length of the cavity is that it must be an integer number of half wavelengths

$$L_q = q\frac{\lambda}{2}. \tag{C.5}$$

This implies that for a fixed input frequency, the cavity transmission is periodic in the length L of the cavity with period $\lambda/2$. Figure C.2 shows a schematic of these cavity resonances and how they change when the cavity length is changed. The shape of the cavity transmission is shown in Fig. C.3.

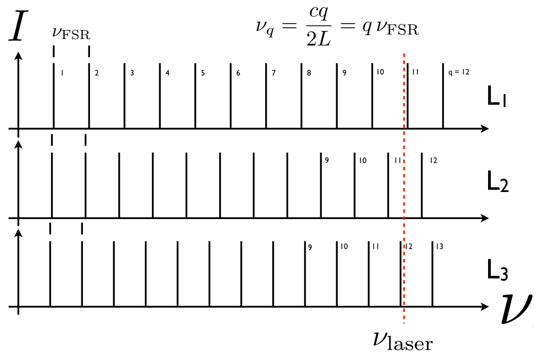

Figure C.2: This figure shows the set of resonance frequencies $\nu_q = q\,\nu_{\mathrm{FSR}}$ for the cavity (with the resonances labeled here by the q value) for three slightly different lengths ($L_1 < L_2 < L_3$). As the length of the cavity **increases**, the free spectral range (ν_{FSR}) **decreases** and the 11$^{\mathrm{th}}$ and 12$^{\mathrm{th}}$ resonant mode are at first above the laser frequency (ν_{laser}) for a cavity length of L_1 and then they both move below it for a cavity length of L_3. Ramping the cavity length from L_1 to L_3 would then produce two identical transmission peaks. Note: this figure is only a schematic since the typical value of q is on the order of 10^5 to 10^6 and not 11 or 12. The value of q is simply the number of half-wavelengths that fit inside L - that is $q = 2L/\lambda$.

The minimum cavity transmission is achieved when $\sin^2 \Delta\phi_{\mathrm{rt}}/2 = 1$ and is

$$T_{\mathrm{min}} = \frac{T_{\mathrm{max}}}{1 + \left(\frac{2F}{\pi}\right)^2}. \tag{C.6}$$

The minimum intensity only goes to zero in the limit of large finesse - that is when the *mirror reflectivity becomes nearly perfect* ($r \to 1$). As a way to characterize the width of the resonances, we can find the full width at half maximum of the transmission peaks. The points at which the transmission falls to $T_{\mathrm{max}}/2$ (i.e. when $\sin^2(\Delta\phi_{\mathrm{rt}}/2) = \left(\frac{\pi}{2F}\right)^2$) are given by $\Delta\phi_{\mathrm{rt}} = 2\sin^{-1}(\pi/2F)$. The width of a resonance is really only a sensible concept in the limit of large finesse, when the resonances are well resolved. In this limit, we can write the half-maximum intensity phases as $\delta_{\mathrm{HM}} \simeq \pm(\pi/F)$. And thus the full width of the resonances at half maximum is $\delta_{\mathrm{FWHM}} = 2\pi/F$ or equivalently $L/\lambda = 1/(2F)$. Again, since we can either vary the input **laser frequency** OR the **cavity length** to move the laser and cavity through resonance, we get the following conditions on the width of the resonances:

$$\nu_{\mathrm{FWHM}} = \frac{\nu_{\mathrm{FSR}}}{F} \tag{C.7}$$

$$L_{\mathrm{FWHM}} = \frac{\lambda}{2F} \tag{C.8}$$

$$\lambda_{\mathrm{FWHM}} = \frac{1}{2LF} \tag{C.9}$$

Fig. C.3 shows the transmission (or intensity inside the cavity) as a function of the cavity length given a *fixed laser frequency* and as a function of the input frequency ν given a *fixed cavity length* L. From this, it is clear that the cavity finesse can be obtained experimentally by taking the ratio of the cavity periodicity and dividing this by the width of the transmission peaks.

$$F = \frac{\nu_{\text{FSR}}}{\nu_{\text{FWHM}}} = \frac{\frac{\lambda}{2}}{L_{\text{FWHM}}} \tag{C.10}$$

Alternatively, if the mirror reflectivity (thus finesse) and cavity length L are known, the frequency or length resolving power of the cavity can be computed. Fig. C.4 shows the transmission of the cavity at different values of the finesse.

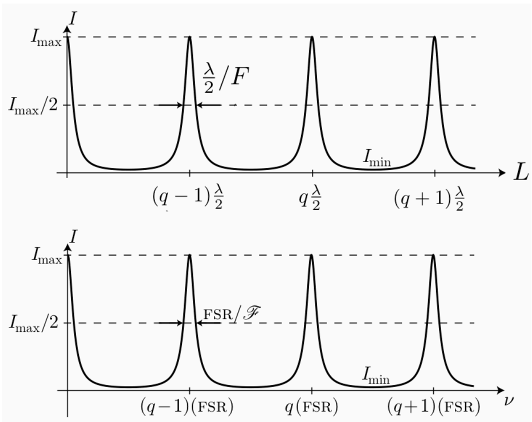

Figure C.3: Transmission of cavity.

As the finesse is increased, the resonances become more and more sharp and the transmitted light off of resonance becomes smaller and smaller.

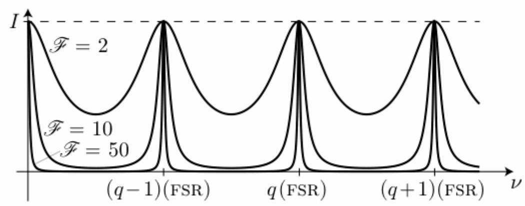

Figure C.4: Transmission of cavity for various values of the finesse.

Cavity resonances for different spatial modes

So far, we have assumed that we have a plane wave inside a cavity of length L. In this case, the round trip phase of the wave is $\Delta\phi_{\text{rt}} = 2kL$, and the resonance condition for the cavity is given by Eqn. C.4. However, the optical wave inside the cavity is actually a Gaussian beam and it may have transverse mode structure (i.e. curves or lines along which the electric field and intensity vanish).

Note: the round trip phase is slightly *different* for each mode! Figure C.5 shows example plots of the intensity pattern of a $\mathrm{TEM}_{l,m}$ Gaussian beam with different transverse mode numbers l (the number of nodes along the x axis) and m (the number of nodes along the y axis). The beam is assumed to be propagating along z.

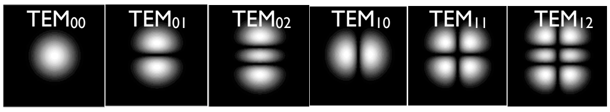

Figure C.5: Transverse intensity pattern of a $\mathrm{TEM}_{l,m}$ Gaussian beam. The mode is specified by the numbers l and m corresponding to the number of nodes along x and y respectively.

For a $\mathrm{TEM}_{l,m}$ mode, the resonant condition (Eqn. C.4 is modified by the additional phase associated with the transverse mode

$$\nu_q = q\nu_{\mathrm{FSR}} + (l + m + 1)\frac{\Delta\xi}{\pi}\nu_{\mathrm{FSR}} \tag{C.11}$$

where $\Delta\xi$ is the phase retardation of this Gaussian mode relative to a plane wave (otherwise known as the accumulated Gouy phase). Think of it as if the different modes traverse slightly diagonal trajectories in the cavity and they therefore experience slightly different cavity lengths. For a rigorous explanation, see the discussion surrounding Eqn. (11.2-33) in your textbook. Note that for $l = m = 0$ and $\Delta\xi = 0$ we recover the original result for a plane wave in Eqn. C.4. **The main point** here is that different transverse modes are resonant with the cavity at slightly different frequencies ν_q. Equivalently, a laser at fixed frequency will resonantly excite different modes of the cavity at slightly different cavity lengths (which control ν_{FSR}). This is why in Fig. C.3 we see a series of distinct transmission peaks at slightly different cavity lengths occurring periodically as the cavity length is increased by $\lambda/2$ (or one free spectral range). Each distinct peak corresponds to a different $\mathrm{TEM}_{l,m}$ mode and it is excited when the cavity length is just right so that the laser frequency is equal to the cavity resonance frequency for that mode given by Eqn. C.11.

Photon survival time and Q-factor

A photon in the cavity completes one round trip every $\tau_{\mathrm{rt}} = 1/\nu_{\mathrm{FSR}}$ seconds. Over this round trip, it has a probability $P_{\mathrm{s}} = R_1R_2$ of surviving the trip (i.e. not being lost from the cavity). Here R_1 and R_2 are the intensity reflection coefficients. Therefore the lifetime of a photon inside the cavity is

$$\tau_{\mathrm{p}} = \frac{\tau_{\mathrm{rt}}}{1 - P_{\mathrm{s}}} = \frac{1}{\nu_{\mathrm{FSR}}(1 - P_{\mathrm{s}})} \tag{C.12}$$

The finesse also depends on the mirror reflectivity and can be written as

$$F = \frac{\pi P_{\mathrm{s}}^{1/4}}{1 - \sqrt{P_{\mathrm{s}}}}. \tag{C.13}$$

For large finesse (large survival probabilities), we can approximate $P_{\mathrm{s}}^{1/4} \simeq 1$ and $(1 - P_{\mathrm{s}}) \simeq 2(1 - \sqrt{P_{\mathrm{s}}})$ which allows us to rewrite the photon lifetime as

$$\tau_{\mathrm{p}} = \frac{1}{2\nu_{\mathrm{FSR}}(1 - \sqrt{P_{\mathrm{s}}})} = \frac{F}{2\pi\nu_{\mathrm{FSR}}} = \frac{1}{2\pi\nu_{\mathrm{FWHM}}} \tag{C.14}$$

and we get an “uncertainty relation” (analogous to the time/energy uncertainty principle in quantum mechanics) of

$$\tau_{\mathrm{p}}\, \nu_{\mathrm{FWHM}} = \frac{1}{2\pi} \tag{C.15}$$

The resonator *quality* or Q-factor is 2π times the ratio of the total energy stored in the cavity divided by the energy lost in a single cycle. We can write this as

$$Q = 2\pi\nu_q\tau_{\mathrm{p}} = \frac{\nu_q}{\nu_{\mathrm{FWHM}}} = qF. \tag{C.16}$$

Appendix D

The Monochromator and Photomultiplier

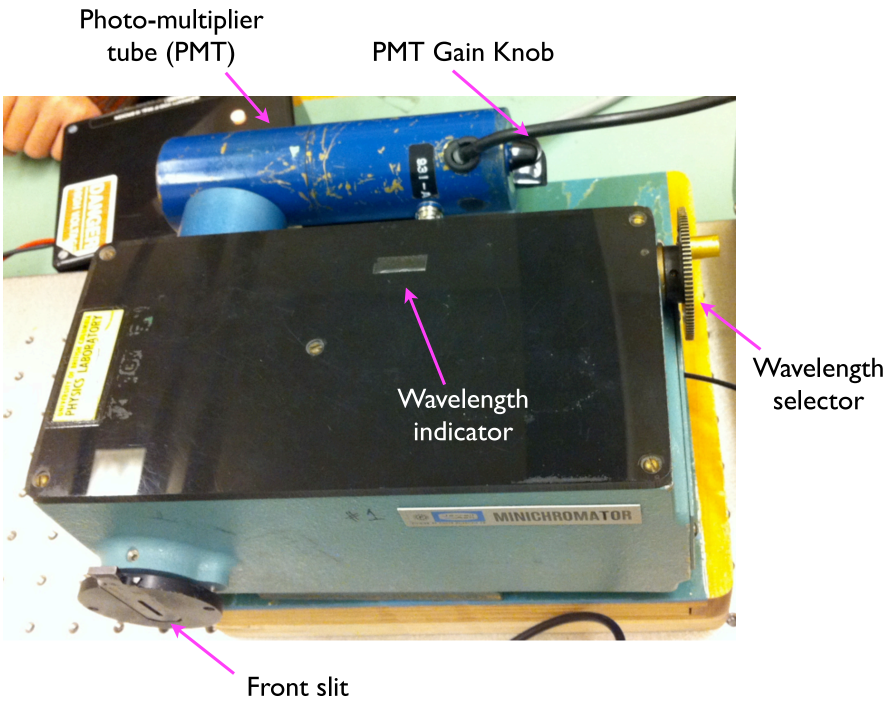

Figure D.1: The mini-monochromator available in the lab.

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.

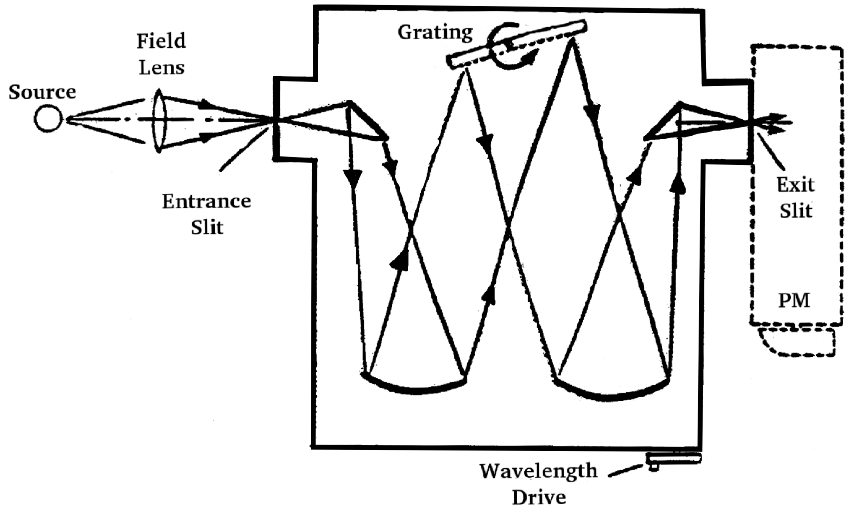

Figure D.2: The Czerny-Turner Monochromator (the field lens is optional).

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. D.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. D.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. D.3.

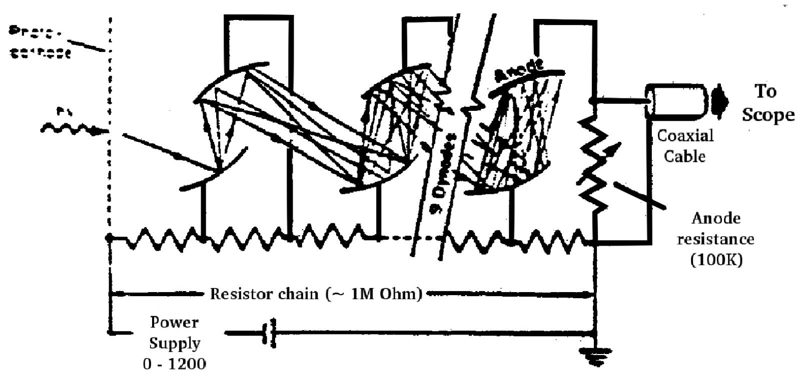

Figure D.3: Schematic of the RCA 931 Photomultiplier Tube.

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.

Spectral Response of the PM-Monochromator Combination

It was pointed out in Section D 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,

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

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 $R(\lambda)$.

Appendix E

The Lock-in Amplifier

Figure E.1: A Lock-in Amplifier.

A Lock-In Amplifier is a specialized tool you will use to measure the difference in intensity of various atomic lines as the laser operation is turned on and off rapidly by the chopper. Used properly it allows you to detect changes which are much too small to be measured slowly, which you might have thought to do by opening the shutter, measuring intensity , closing the shutter, measuring again and taking the difference. Lock-in amplifiers are widely used to perform low noise measurements, especially in settings where the effects under study can be modulated. The lock-in amplifier measures changes in the effect under study at the frequency of modulation, avoiding the low frequency noise present in most systems. Just to illustrate this approach, imagine you want to determine if a process you are studying heats up its container by 0.1°C. This small difference would be very hard to measure if you measured the temperature, turned the process off and came back the next day to measure another temperature. Changes in Room T would overwhelm the effect you are looking for. However, if you could turn the apparatus on and off at 100 Hz and had a reference signal indicating whether it was on and off, you might imagine that a 0.1°C temperature signal at 100 Hz can be measured at high signal-to-noise ratio.

The time constant of the output amplifier must be longer than the period of the chopped signal, of course. In fact, the longer the time constant is, the quieter and more reliable the signal will be. At the same time, you must keep the time constant shorter than the variations in the signal which you wish to see. In this experiment, τ must be shorter than the time which the spectrometer requires to scan across a single line.

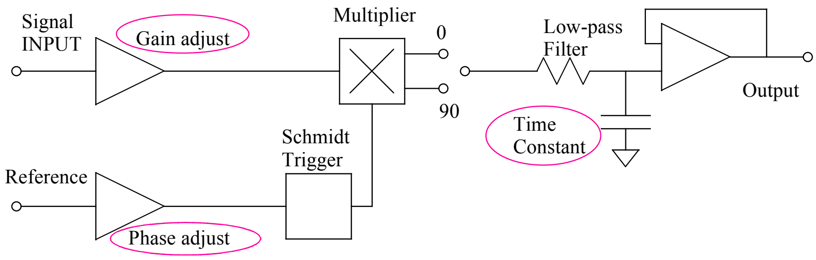

Figure E.2: A lock in amplifier schematic diagram. The signal under study is supplied to a tuned amplifier with variable gain –a sensitivity setting. A reference signal is used to generate a symmetric, signed square wave at the frequency of experimental modulation. The input signal and the reference square wave are multiplied and the product is averaged for a time much longer than the reference frequency. This square wave can be phase shifted to maximize or null the lock-in output. Typically facility is provided to switch the reference phase rapidly by 90° and by 180°. The items circled in red are the key adjustments of a lock-in: input **sensitivity**, reference **phase**, and output **time constant**. The centre **frequency** of the input tuned amplifier, not shown, is also adjustable.

Instructions on how to use

Goal: To measure the component of the PMT signal that is modulated at the chopper frequency.
Experimental setup:

- Input BNC: PMT signal.
- Output BNC: A voltage measurement of the modulated component of the input signal at the frequency of the external reference. This only gives a correct reading if the phase is set correctly (see 'Taking Measurements' section below).
- REF IN BNC: Put the output of the chopper circuit to this. This is a square wave signal which alternates between 5V and 0V depending if the infrared sensor is blocked by the chopper wheel or not.

Correct settings: Please have the INT/EXT/2f switch on 'EXT' for an external reference which in our case comes from the infrared sensor circuit that gives the frequency that the chopper wheel blocks the laser cavity.

- Dials: You do not use the zero suppress dial and the switch below the dial should be at the 'OFF' position.
- Frequency range selector: Please ensure you have the appropriate frequency range selected so you can measure an approximate 120-200 Hz signal.
- Frequency dial: You do not use this dial it is used when no external reference is supplied.

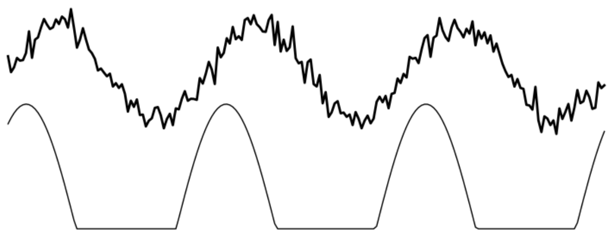

Figure E.3: The signal under study and a phase and frequency reference signal input to a lock-in amplifier. Due to details of the experimental setup and of the system used to generate the reference signal, the phase between the main signal and the reference is often arbitrary. In order that the diagram is clear, the signal-to-noise level is very high in this illustration compared to typical signals for which lock-in amplifiers are needed. In a typical use, the signal at the modulation frequency is not visible by eye.

- Time constant: The measurement speed is affected by this dial (as discussed at the beginning of this Appendix). If you choose a time constant that is too short the output will oscillate. In this experiment, the time constant of 40 mSec should work well.

Taking measurements: To take a measurement, start with a PMT signal where you can clearly see the square wave modulation in the PMT signal. To do that, you will have to tune the monochromator to one of the strong emission lines. Use an example MATLAB script `raspiA2D.m` in the `Software` folder to see how it's done programmatically.

Ensure you have the input signal and the external reference connected to the lock in amplifier, it is okay to have them also connected to the oscilloscope. Switch to a sensitivity scale that you think is appropriate. Then switch the 90 degree switch and/or the 180 degree switch until you can change the phase dial and set the output reading to zero. When you have set the output reading to zero with the phase dial, switch the 90 degree switch and now the output reading of the lock in will be correct.

NOTE: THE OUTPUT ALWAYS GOES FROM +/- 10V. What that output reading means depends on the sensitivity scale. For example, if you are on a 10 mV scale with the 'NORMAL' mode selected then 10 V output will correspond to a 10 mV reading. Similarly if you are on a 100 mV scale with the 'NORMAL' mode selected then 10 V will correspond to a 100 mV reading. If you are on a 0.1X mode and a 100 mV sensitivity, then a 10 V output reading will correspond to a 10 mV measurement. To summarize, the real measurement value is: (Sensitivity/10V)*(Scaling, e.g. 0.1, 1, or 10)*Output in V. In this experiment, the sensitivity range of 100 mV works well.

The overload light will come on if your input signal is above the sensitivity scale you are on, or it might come on if you do not have an input plugged in. Once you have a reading, if you switch the 180 degree switch the output reading should change sign. You can choose your first reading to be positive or negative but once you select it, leave it alone for the rest of the measurements. You

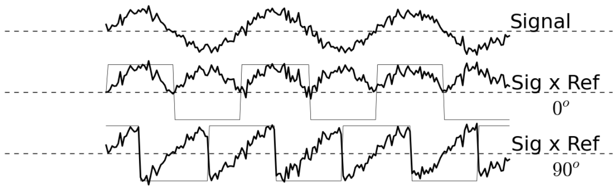

Figure E.4: A symmetric square wave is generated from the input reference and is phase shifted as needed. The three traces here illustrate an input signal, that signal multiplied by a reference signal with the phase correctly adjusted, and at bottom the same signal multiplied by a reference 90° out of phase. The average values of the bottom two traces are the lock-in amplifier output. When the phase is adjusted so that the 90° signal is 0, the 0° signal is maximized. **Why is there a phase difference between the signal and the reference in the first place?**

should not have to adjust the phase for the rest of the measurements. When you take Neon line data some lines will give a positive lock in amplifier reading and some might be negative. Think what it means and explain the difference in sign.