Physics 408

Optics Laboratory

Department of Physics & Astronomy
UBC

2021/2022 Winter Term 2
(Last edited January 10, 2022)

Chapter 1

Rules and Resources

1.1 Safety Rules

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.

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

This is not a high power laser beam; if for some reason the beam does impact near the area of your eyes your 'blink reflex' should be enough to protect you. This does not mean you should place your head/eye in the path of the beam to see where it is going. 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. Laser goggles are provided.

Do Not Touch Any Optical Surface

It does not take many impurities on the optical surfaces to prevent lasing action from occurring in the HeNe lab. Scratches, fingerprints, and even dust on the cavity elements can prevent a laser or a cavity from working.

No food or drink is allowed 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.

1.2 Logistics and Resources

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. If you decide to write your own code (e.g. in Python) to communicate with any particular piece of hardware, 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 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

You should do your best to fully answer all questions posed in the lab manual. 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] Python scripts and Jupiter notebooks will be accepted as well

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 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 Optical Cavity

2.1 Objectives

In this experiment the goal is to explore the spatial and temporal characteristics of the transverse and longitudinal modes of a two-mirror optical resonator. This resonator is similar to the resonators inside multiple lasers (e.g. inside the HeNe laser used in this lab), except that there is no gain element in the cavity and it is therefore a "passive" device. Specific objectives are:

1. Learn how to characterize optical elements and light beams.
2. Explore the concepts of resonance, spatial mode matching, and resonator stability using the TEM_{00} transverse mode of a Helium-Neon laser and an external two-mirror optical cavity.
3. Investigate the dependence of the cavity finesse, linewidth and free spectral range on cavity length.
4. Use the cavity to measure the linewidth of the HeNe laser source.

2.2 Introduction

One of the most common methods used in the characterization of laser light involves sending that light into an external optical resonator (i.e. cavity). A passive linear optical cavity with highly reflective end mirrors is known as a Fabry-Perot cavity. When such a cavity, of length d, is illuminated with light at a specific wavelength, λ, the intensity of light inside the cavity is periodic in cavity length:

$$I(d) = I_{max} \frac{1}{1 + (2\mathcal{F}/\pi)^2 \sin^2(2\pi d/\lambda)}. \tag{2.1}$$

The parameter $\mathcal{F}$ is called the *finesse* and depends on the combined mirrors' reflectivity r:

$$\mathcal{F} = \frac{\pi\sqrt{r}}{1 - r}. \tag{2.2}$$

For high values of the finesse the lineshape in Eq. 2.1 is Lorentzian. In a typical setting, and in this lab in particular, the cavity length is a lot longer than the

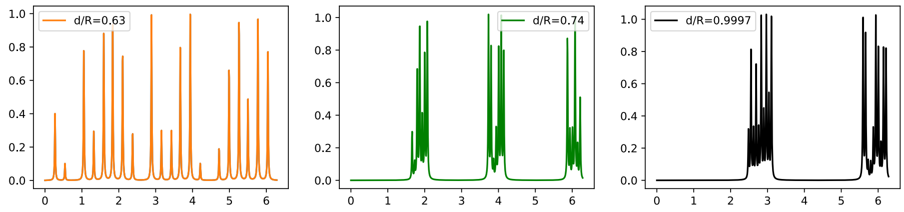

Figure 2.1: The simulated distribution of 20 modes with distinct values of $(1 + l + m)$ within a single Free Spectral Range is plotted for three different cavity lengths. The panel on the left has an arbitrarily chosen length. The middle and right panels correspond to the cavity lengths which nearly produce $\zeta(d) = \pi/3$ and $\pi/2$, and in those panels the modes are beginning to cluster into 3 or 2 groups of lines. There are the same 20 modes shown in all three panels. In general $\zeta(d) = \pi/n$ results in n clusters of modes.

wavelength, meaning the the Fabry-Perot order is rather high:

$$N = \frac{2d}{\lambda} \approx \frac{2 \times 10\text{cm}}{633\text{nm}} \approx 3 \times 10^6. \tag{2.3}$$

Eq. 2.1 was written for a plane wave. The cavity you will use has one flat mirror and one spherical mirror, and so the light within the cavity will be in a Gaussian mode whose radius of curvature matches that of the mirror,

$$R_{\text{mirror}} = d\left[1 + \left(\frac{z_0}{d}\right)^2\right], \tag{2.4}$$

where z_0 is the mode's Rayleigh length. Notice that z_0 is real only if $R/d \geq 1$, which coincides with the domain of stable cavity operation.

A TEM_{lm} mode acquires an extra phase shift along the optical axis and across the focal plane at $z = 0$, called the Gouy phase:

$$\Delta\phi(z) = (1 + l + m)\zeta(z), \text{ where } \zeta(z) = \tan^{-1}(z/z_0). \tag{2.5}$$

Cavity resonance requires that a round trip within the cavity, including $2(1 + l + m)\zeta(d)$, is $2N\pi$, so the effect of the Gouy phase is to shift slightly the resonant cavity lengths for light in different transverse modes. In general, the effect might look like the left-hand panel of Figure 2.1, where one free spectral range is plotted for an arbitrary cavity length populated with 20 distinct values of $(1 + l + m)$. The amplitudes of each of these 20 modes has been chosen at random for illustrative purposes. What you see as you scan the length of a Fabry-Perot cavity across a free spectral range is the round trip phase shift modulo 2π. What this means is that for several special cavity lengths where the Gouy phase is an integer fraction of π, namely $\zeta(d) = \pi/n$, the round trip Gouy phase mod 2π clusters at an integer number of locations within a free spectral range. See the middle or right hand panels of Fig. 2.1. For more details, see also Appendix D.

2.3 Experimental Procedures

SAFETY WARNING: This lab has a 20 mW laser which is much more powerful than the lasers used in the other experiments. Please be especially careful with this laser not to reflect any portion of it into your eye. Be aware of beam scatter, especially from shiny metal surfaces. Because of that scatter, you should remove all unnecessary objects from your hands, e.g. watches or rings. Goggles are provided for this lab and should be worn when moving and adjusting optical components. The laser beam can be seen through the goggles when it is incident on a piece of paper provided. Several pieces of paper are provided for checking the location of the beam in this manner. As a general safety rule in an optics lab, never bend down to the level of the experimental table!

2.3.1 Mirror reflectivity

Let's start by characterizing the mirrors of the cavity.

1. Measure the reflectivity and transmission of both cavity mirrors. Do your reflectivity and transmission coefficients add to unity? Should they?
2. Calculate the finesse that you expect your cavity to have.
3. Given this finesse, for a cavity with length L=15 cm, what do you expect the cavity linewidth and free spectral range to be? Express your answer in MHz and nm. Which do you think is a better unit of measure in this context?
4. What would happen to the cavity characteristics if the low reflectivity sides of the mirror faced each other?

2.3.2 Beam radius measurement

Now let's proceed with the characterization of the input laser beam. There are two lenses available to optimally couple (that is, mode match) the light into the TEM_{00} mode of the optical cavity. Unfortunately, none of them are the exact lens you require. For this section, we recommend that you choose the 50 cm focal length lens.

1. Sketch the beam shape and phase fronts of the cavity mode. Where is the focus of this beam? Hint: What boundary condition applies to the eigen-modes of the cavity?
2. At what location should the beam come to a focus in order to best mode match into the cavity?
3. Measure the minimum beam width (i.e. the beam waist) at the focus using a knife-edge measurement, described in detail in Appendix F.
4. What beam waist should you have in order to best mode match into the cavity? Hint: Your answer might depend on the length of your cavity. Be sure to specify what length (or lengths) you have decided to use.
5. Given your answer for the ideal beam waist, what would be the ideal focal length lens to use? How far from the M1 mirror should it be placed?

2.3.3 Mode coupling

In this section, you will align the optical cavity (see Appendices and the video in the appropriate desktop folder for details on the alignment).

Suppose, for the moment, that the laser light is purely monochromatic and has a TEM_{00} beam profile. The laser light will pass into the external cavity if the cavity length were stabilized and if the frequency of the laser light were resonant with the frequency of one of the modes of the cavity. For ideal coupling of the light into the cavity, the transverse mode profile of the laser light should match the transverse profile of the cavity mode with which it is resonant. So, if the laser light propagates in a TEM_{00} mode (by which we mean the fundamental transverse mode of the laser resonator), then we would want it to match the fundamental transverse mode (TEM_{00}) of the external cavity. Such mode matching does not occur automatically since the fundamental mode of the external cavity will have its own beam shape (i.e. spatially varying beam width and radius of curvature) set by the cavity mirrors, and this will be independent of the beam shape of the laser. To mode match the laser TEM_{00} mode to that of the external cavity mode, lenses (or, in this case, one lens) must be used to shape the incoming beam so that the parameters of the input beam match those of the resonant cavity mode.

As usual, the experimental situation is more complex than the ideal case. If the laser beam is not perfectly aligned and mode-matched to the external cavity, the input beam will partially couple to many different transverse modes of the cavity as the cavity length is changed and these modes come into resonance with the frequency of the laser output (the mode of the input beam can be described as a superposition of external cavity eigenmodes- such as the Hermite-Gaussian modes). The light that exits the cavity will resemble whatever cavity modes happen to be excited rather than resembling the spatial profile of the original input beam. Since the cavity length in this lab is not stabilized, microscopic vibrations of the optical bench will change its length and the coupling of the laser beam to the longitudinal and transverse cavity modes will change with time, and the light patterns that are observed exiting the cavity will fluctuate with time, revealing a time-dependent coupling of the laser beam to many different high-order Hermite-Gaussian modes. Figure 2.2 shows a schematic of the setup you will use in this lab. The cavity consist of two mirrors: one flat, and one with a radius of curvature of 30 cm. The output of the HeNe laser has a beam diameter of 1.2 mm.

The general idea of the beam coupling mechanism is illustrated in Figure 2.3. To form a perfect match, we would need to choose a new external coupling lens for each passive cavity length, matching the input z_0 to that of the cavity. If you have not done that, there will be many modes which can survive, depending on the cavity length.

As you setup the cavity, answer the following questions:

1. When only one mirror (M1) is placed in the beam path, what effect does it have on the transmitted light?

2. When you place the second mirror (M2) in the setup, what is the net effect on the light transmitted through both mirrors? Does it depend on whether or not the cavity is correctly aligned?

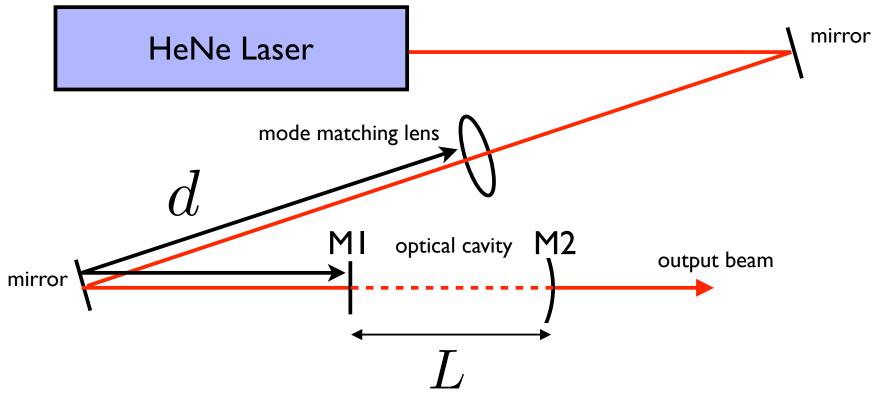

Figure 2.2: Cavity setup. The length of the cavity is the distance between M1 and M2 (L), and the distance from the mode matching lens to the input coupler of the cavity (M1) is denoted d.

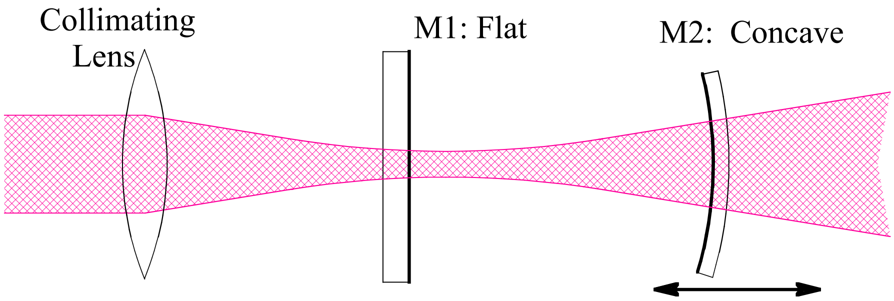

Figure 2.3: An external 500 mm FL lens is used to focus a laser beam on the reflective surface of a flat mirror defining one end of a cavity, producing a beam waist there.

When you think you have the cavity aligned correctly (the first time), get a TA to check.

2.3.4 Cavity observations

Once the cavity is aligned, observe the transmitted beam pattern using the CCD camera while slowly scanning the piezo voltage by hand. As an alternative approach, you can turn the function generator to about 0.1 Hz and with a smaller amplitude sweep slowly through the modes.

Use a web browser to observe the output from the CCD camera in real time. Try to stabilize the cavity length on a particular mode by adjusting the length of the cavity using the piezo driver manual adjust knob. When the coupling is optimal and the cavity is very well aligned, you will probably see that most of your higher order modes are circularly symmetric - i.e. Laguerre-Gaussian instead of Hermite-Gaussian modes (a few examples are shown in Figure). See how many different pure Laguerre and/or Hermite-Gaussian modes you can isolate and identify for a given length. Record your results using your own software script (see `raspiCamera.m` in the `Software` folder for examples on how to do it), clearly indicating the different transverse mode structures of output beams. What is the largest transverse mode (TEM_{lm}) you can observe as you adjust the cavity length? What is the brightest mode? Which mode should be brightest if the cavity is properly aligned and mode matched?

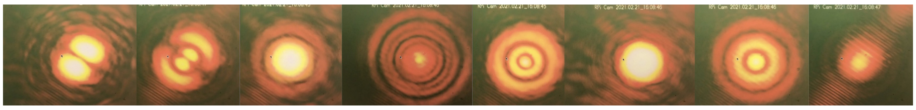

Figure 2.4: Snapshots taken from a video (recorded with a RasPi camera) of a single scan of the Fabry-Perot cavity length. The piezo scan rate was turned down by a facor of 1,000 to capture this image, from the normal 100 Hz to a period of 10s.

Given your observations, answer the following questions:

1. Does the long or short cavity have more visible transverse modes? Why? Hint: What is the size of the beam at the M2 mirror? You can determine this both experimentally (i.e., look at it) and theoretically (i.e., calculate the beam radius at the position of M2 given what you know about the cavity).

2. Why do you see multiple peaks that repeat periodically, rather than just one? Which cavity mode likely corresponds to the largest transmission peak?

3. Why do different transverse modes occur at different cavity lengths?

2.3.5 Cavity finesse

In this part of the lab, you will determine the finesse of your cavity by measuring the free spectral range of the cavity and the width of the transmission peaks.

Fine adjustments of the length of the cavity are produced by applying a voltage to the piezoelectric actuator ("piezo" for short) behind the M2 mirror. Voltage is supplied to the piezo by a high voltage supply, which has a manual adjustment knob and an external input. The external input is connected to a ramp generator. Note that the high voltage supply has a gain of 10x on the external input when the voltage range is set to 100. The input multiplier changes depending on the voltage limit indicated by the green LED. The distance the actuator moves given a certain voltage change can be found on the actuator datasheet.

To start, the function generator can be set at 100 Hz, 2 V peak-to-peak amplitude, and with an offset of 2 V. The phase can be set to 0. When the external input (`EXT INPUT`) of the MDT694A piezo controller is unplugged, the voltage output should be about 60 V. Please note that the external input of the piezo controller should only have positive voltages from 0 to 10 V max.

A plain glass optical flat is placed in the output beam and oriented to reflect a few percent of the intensity to a RasPi camera, whereas the rest of the light is directed to a photodiode (Thorlabs PDA10A), which is connected to an oscilloscope (Tektronix TDS1002B). You will control this oscilloscope programmatically (see an example of a MATLAB script in the 'Software' directory) and use it to capture photodiode signals as you scan the cavity length. Your typical scan may look like that shown in Figure 2.5.

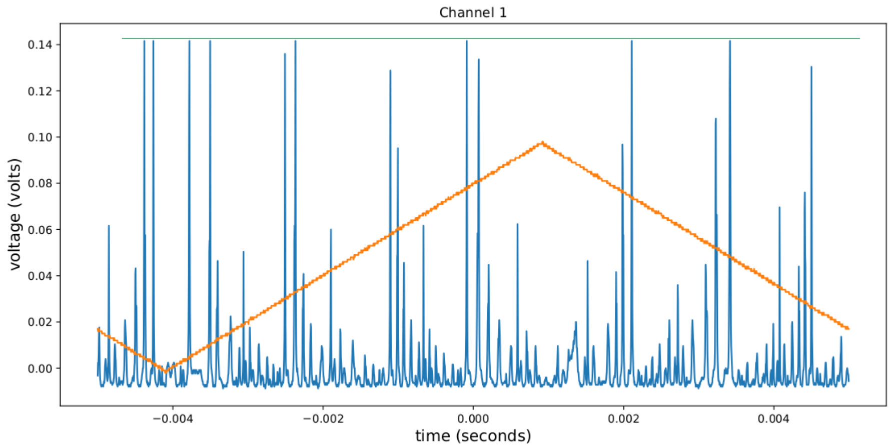

Figure 2.5: Data from the oscilloscope showing the triangle-wave voltage controlling the piezo-electric mirror mount and the voltage from the Si photodiode. These traces were collected with a script similar to `tektronixScope.m` in the `Software` folder. The piezo drive voltage was adjusted so as to scan across several times the free spectral range. The voltages on the vertical scale in this plot refer to the Si photodiode signal (blue). The scale for the piezo driving voltage (orange) is very different; that signal is a few volts at the oscilloscope and is amplified to be a few tens of volts at the mirror.

1. Measure the free spectral range, linewidth and finesse of your cavity as a function of cavity length. Be very clear about the units of your measurements. Hint: The free spectral range and linewidth of the cavity should be on the order of 10 to 100s of MHz.

2. Plot the cavity finesse and cavity linewidth as a function of cavity length. On the same figure, plot the expected cavity finesse (you found this earlier) and the expected cavity linewidth (given the expected finesse). Do your results agree or disagree with what you expect?

3. From these results, what can you say about the spectral linewidth of the HeNe laser?

4. What is the Q-factor of your cavity?

5. Consider a tuning fork oscillating at 440 Hz (this is what musicians often use to tune their instruments). How long would the tuning fork ring given it had the same Q-factor as your optical cavity? Is this reasonable?

2.3.6 Cavity stability

In this final part, you will investigate the region of stability of an optical cavity.

1. For what range of lengths is the cavity stable?
2. What is the cavity distance L where the geometric factors drop out (i.e. $g_1 g_2 = 0$) and you can see the modes becoming degenerate?
3. Align your cavity near this length, and slowly vary the cavity length using the M1 translation stage, while scanning it by hand along the optical axis. Record the transmission spectrum as you approach the length where the modes become degenerate.
4. What happens to the transmitted power as you move the cavity length beyond the length over which it is stable?

2.4 Useful Readings (chapters from Saleh & Teich)

- Section 1.4 Matrix Optics [A,B,C,D], Condition for Periodic Trajectory (8 pages),
- Read the last subsection of Section 2.5 Interference, this part discusses the Interference of an Infinite Number of Waves of Progressively Smaller Amplitudes and Equal Phase Differences,
- 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-D,
- Appendices A,B,C, D, E, F.

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

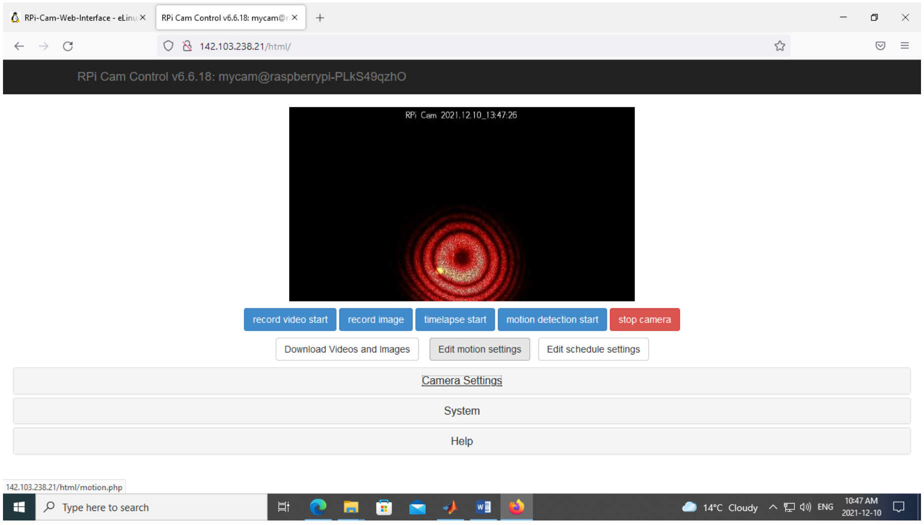

Figure A.1: An example of the web interface for operating Raspberry Pi cameras in real time.

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/.

Appendix B

Thorlabs Advanced Positioning Technology (APT) Software

In Cavity and Michelson labs, we have translation stages whose position can be controlled by software. The motorized actuators which change their length are either Z825B or Z625B from Thorlabs. The controllers that are used to interface from a computer to the actuators are either the TDC001 or the OptoDC Driver (ODC001) from Thorlabs. These controllers have a USB connection to the lab computer that controls it.

There are two ways to control the motor length, and therefore translation stage position. First, there is a software GUI provided by the Thorlabs company called the APT (for Advanced Positioning Technology) User software. The second means of communications is by programming using, for example, MATLAB to send custom Active X Control commands to do things such as set the desired speed or position of the motor actuator. This Appendix will explain how to use the APT user software and will briefly discuss the programming through MATLAB.

APT GUI

To open the APT user software click on the APT User icon on the desktop or go to the Start Menu and to the Thorlabs option and click on APT user. You should see a GUI show up as shown in Figure B.1 below.

On this GUI the position of the motor is shown with a value between 0 and 25 mm. Pressing the Home button will make the motor go to its home position which is 0 mm. If you click inside the box where the position is shown, in our case 11.0000 mm, then a box will appear where you can type in the position you would like the motor to go to. If, while you are moving, you want the motor to stop - press the Stop button.

There are two ways the motor can move, either by being told as mentioned above to go to a certain position, or by performing a ‘jog’. A jog means the motor moves by a certain pre-set amount from its current position. The jog button up and down arrow will increase or decrease the motor position by an

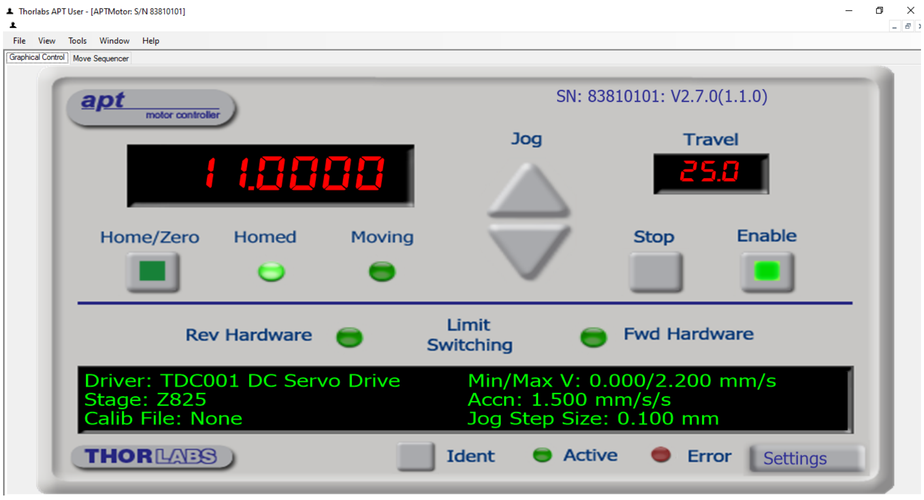

Figure B.1: The APT User Software GUI.

amount set by the 'Jog Step Distance'. That Step Distance can be set by clicking on the Settings tab on the bottom right and a window will appear as shown in Figure B.2.

The most useful setting in the Motor Driver Settings window is the 'Max Vel' input box at the top left under 'Moves - Velocity Profile'. This is the speed at which the motor will move when you input a specific position to go to as described earlier by clicking in the position indicator box and inputting the desired position. The other settings in this Motor Driver Settings window are of less importance and should not necessarily be played with. In addition, the 'Stage/Axis' and 'Advanced' tabs are not recommended to be altered. To re-iterate, the main usage of this Motor Driver Settings window is to set the maximum velocity the motor moves at when a new position is asked of it.

Troubleshooting of the APT User GUI: If the APT user software stops working it may be needed to unplug the power supply of the controller from the wall, wait for about five seconds and then plug it back in. PLEASE DO NOT UNPLUG THE POWER OF THE CONTROLLER BY DISCONNECTING THE POWER CONNECTOR PLUGGED INTO THE CONTROLLER FROM THE CONTROLLER. The controller can be damaged by doing that. Leave the power connector plugged into the controller and unplug the power supply from the wall instead.

When the controller has been power cycled, it will read a zero position when the APT user software is reopened. This is an incorrect reading since the motor position is still at wherever it was when the power was turned off. To fix this press the Home button on the APT User GUI and watch the position just before it goes to home and resets itself to zero. It may say something like negative 11.5 mm which means that it had to travel back approximately 11.5 mm to get home. Then, to get back to the approximate position where you started, type in for example 11.5 mm into the position window and it will go back to the last position before the power was cycled. If all of this confuses you, please ask one

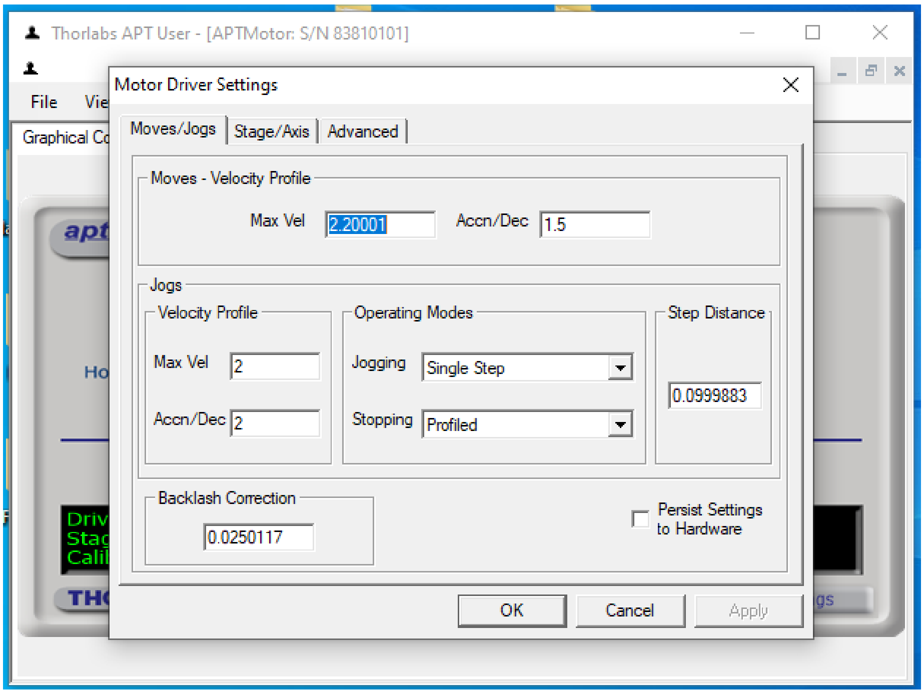

Figure B.2: The Motor Driver Settings window in which the velocity at which the motor moves to a new position can be set as well as other settings.

of the instructors for help before you destroy something!

Note: Please, properly close the APT User software when you are finished using the computer and properly sign out of the computer. This will help the next user to not have troubles due to existing unclosed connections.

MATLAB control of the motor

The second way to move the motor is by sending commands to the controller using MATLAB. The possible commands are many and complex and are fully documented in the `thorlabsStage_ProgrammingManual.pdf` posted in the `Hardware/Thorlabs Translation Stage` folder. The commands that you will need are given in the `thorlabsStage.m` MATLAB script as an example. This script gives example of how to initiate a connection to the controller, how to set the speed and position of the motor actuator, and finally how to cleanly close the connection to the controller and the motor. In the optical cavity lab, you are asked to combine commands from the `thorlabsStage.m` script with commands that record data from an oscilloscope in order to perform the "knife edge" scan. In the Michelson interferometer lab, you are asked to combine commands from the `thorlabsStage.m` script with commands found in `raspiCamera.m` script to collect data from the Raspberry Pi camera at the same time as the motor is being controlled.

Note 1: If you run the `thorlabsStage.m` script (or any script that you create) that controls the motor, please first close any APT User GUI window that you have open. If you desire to have a Figure B.1 window appear as When you control the motor by command in MATLAB, a window looking similar to Figure B.1 will appear as a MATLAB figure. Please be aware that it is NOT the APT User GUI window, so please do not click in it to control the motor. That window shows up just so you can see what is happening with the motor position as your script is running and that window should be closed when you are done running your script.

Note 2: Please, be aware that the serial number found on the controller must be correctly input by hand into either the `thorlabsStage.m` script or any script you write yourself. In the `thorlabsStage.m` script, this is the line that looks like this:

```
   % Motor serial number (specific to each station)
>> motorSN=83810101;
```

Appendix C

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). And 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. C.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. C.2). They are written in cylindrical coordinates using Laguerre polynomials

Ince-Gaussian modes

the Ince–Gaussian beams (see Fig. C.3 and Fig. C.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.

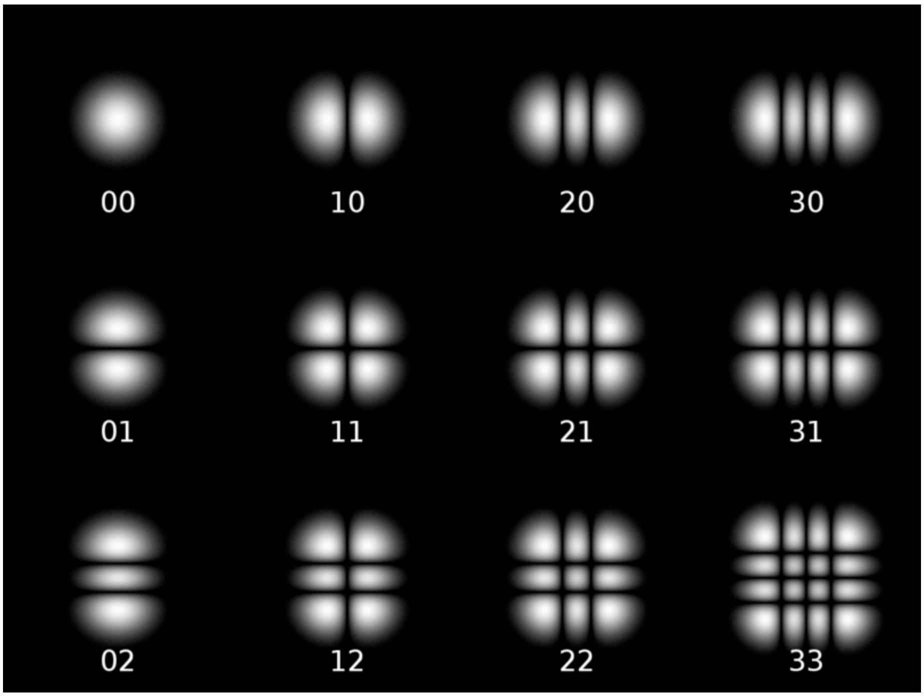

Figure C.1: Hermite–gaussian modes.

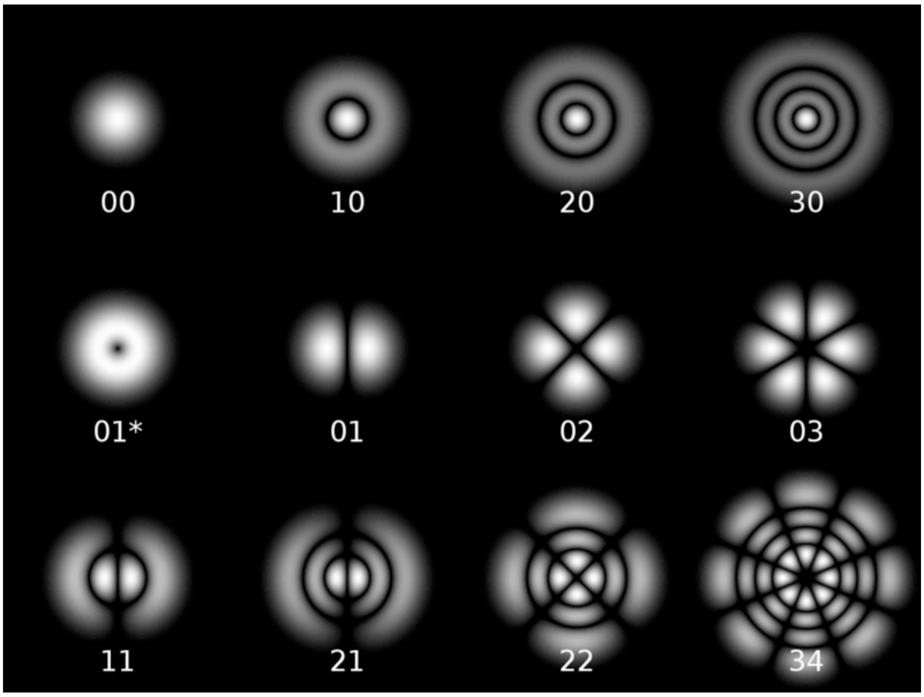

Figure C.2: Laguerre–gaussian modes.

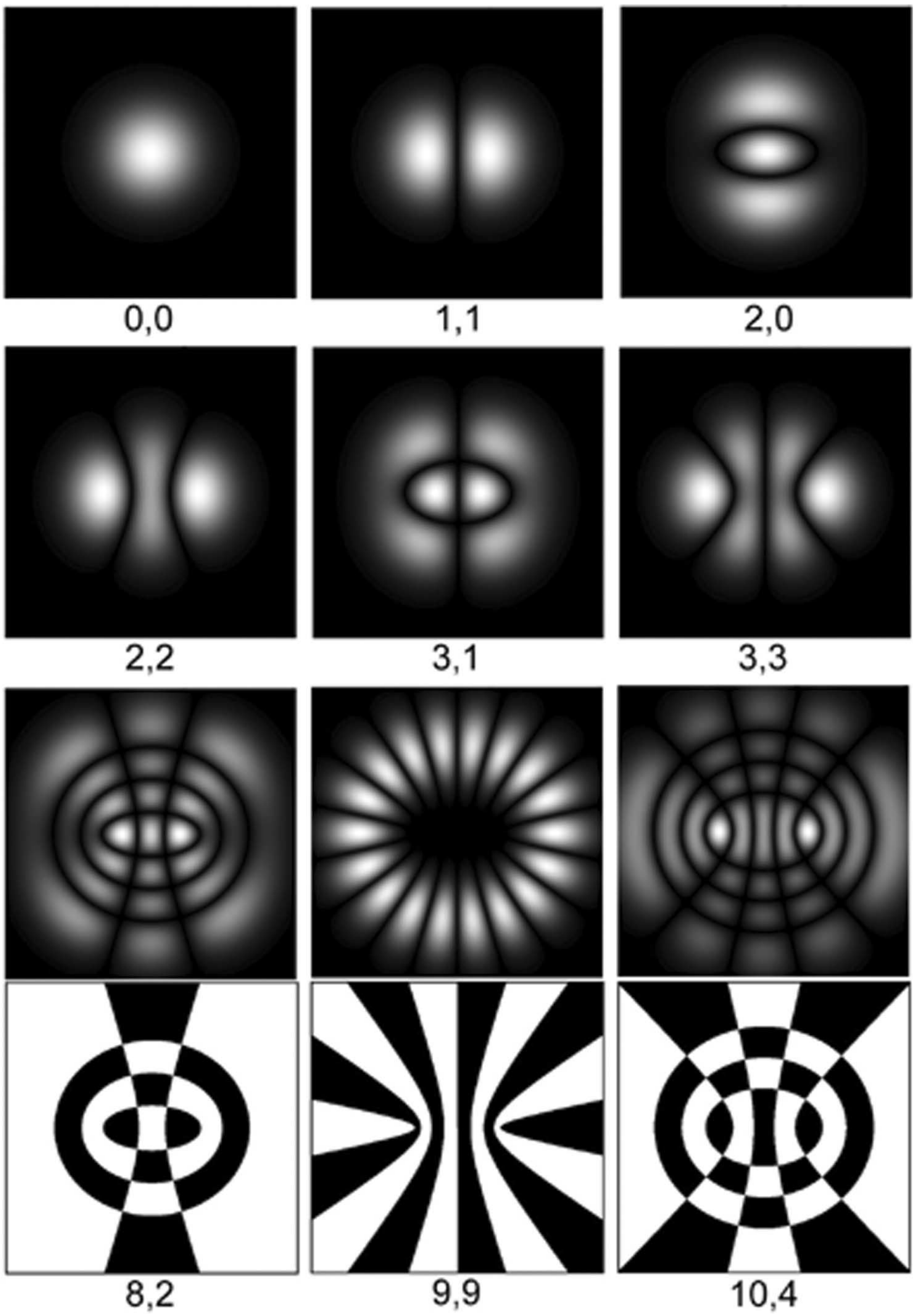

Figure C.3: Transverse field distributions of some even Ince–Gaussian beams. Plots in the bottom row correspond to the phase structures of the modes displayed in the row immediately above them. Figure from Opt. Lett. 29, 144 (2004).

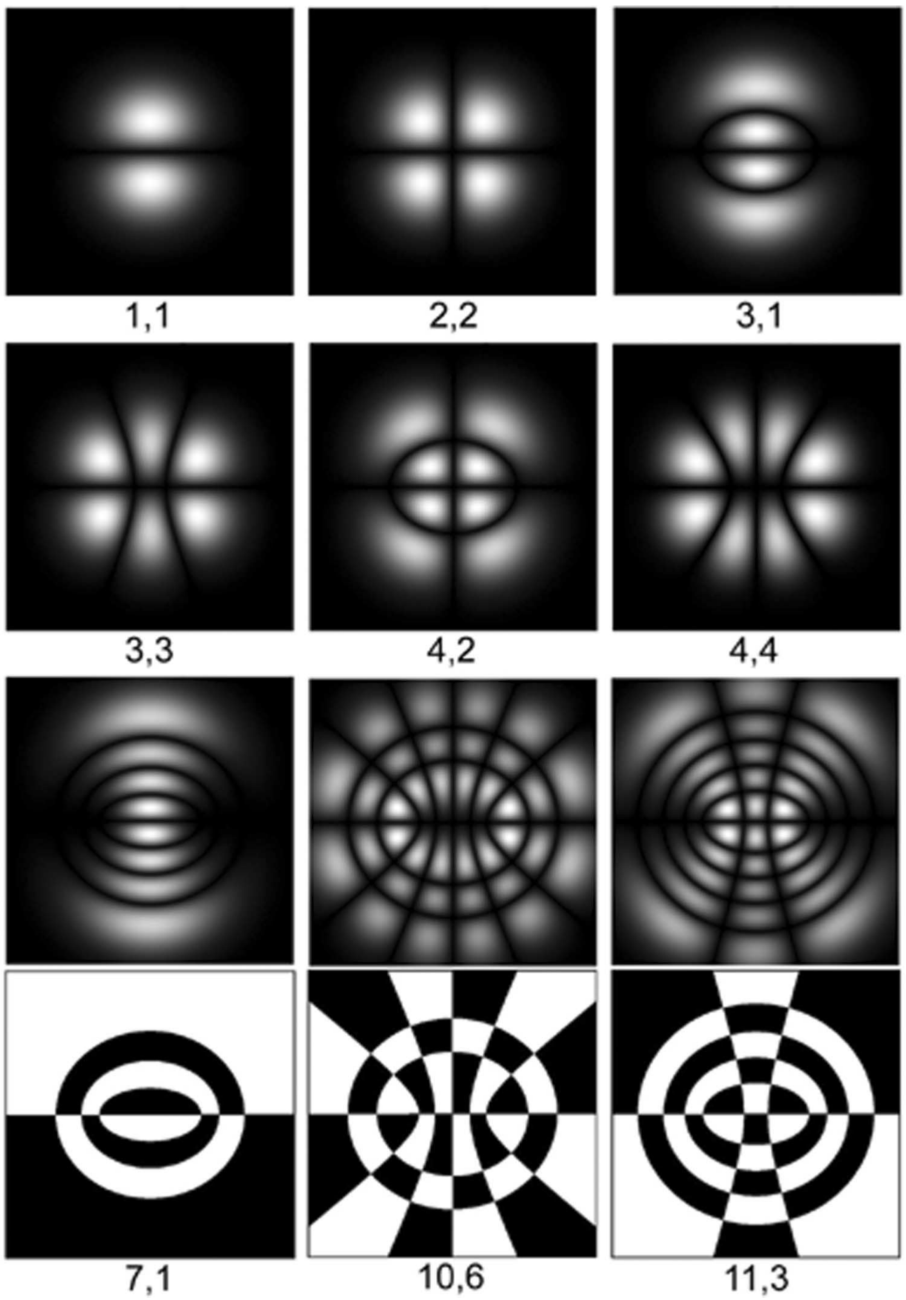

Figure C.4: Transverse field distributions of some odd Ince–Gaussian beams. Plots in the bottom row correspond to the phase structures of the modes displayed in the row immediately above them. Figure from Opt. Lett. 29, 144 (2004).

Appendix D

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;

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

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 ***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. You should record this derivation in your lab book. A good starting point for this analysis in located in your text book (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

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

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

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

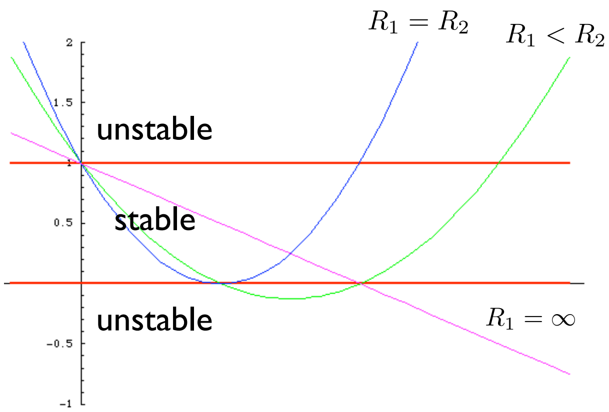

Figure D.1: Plot of the middle term in expression (D.1) as a function of the mirror separation, d, for various mirror combiations (i.e. values of R_1 and R_2). The cavity is stable at all locations, d, for which the value of the term is between 0 and 1 (denoted by red lines).

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 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

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

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

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

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 D.2 shows a schematic of these cavity resonances and how they change when the cavity length is changed, and the shape of the cavity transmission is shown in Fig. D.3.

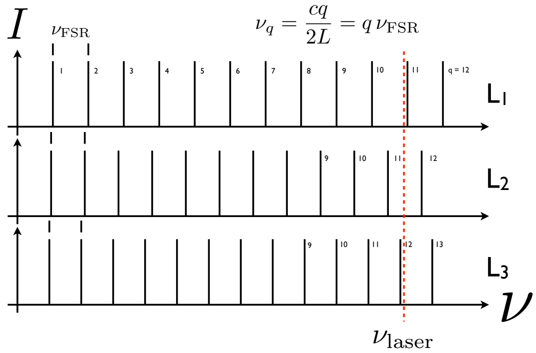

Figure D.2: This figure shows the set resonance frequencies $\nu_q = q\,\nu_{\rm FSR}$ for the cavity (with the resonances labeled here by the q value) for three slightly different lengths ($L_1 < L_2 < L_3$). As the length of the cavity **increases**, the free spectral range ($\nu_{\rm FSR}$) **decreases** and the $11^{\rm th}$ and $12^{\rm th}$ resonant mode are at first above the laser frequency ($\nu_{\rm laser}$) 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 wavelengths that fit inside L - that is $q = L/\lambda$.

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

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

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 $T_{\rm max}/2$ (i.e. when $\sin^2(\Delta\phi_{\rm rt}/2) = \left(\frac{\pi}{2F}\right)^2$) are given by $\Delta\phi_{\rm rt} = 2\sin^{-1}(\pi/2F)$. 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 $\delta_{\rm HM} \simeq \pm(\pi/F)$. And thus the full width of the resonances at half maximum is $\delta_{\rm FWHM} = 2\pi/F$ 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:

$$\nu_{\rm FWHM} = \frac{\nu_{\rm FSR}}{F} \tag{D.7}$$

$$L_{\rm FWHM} = \frac{\lambda}{2F} \tag{D.8}$$

$$\lambda_{\rm FWHM} = \frac{1}{2LF} \tag{D.9}$$

Fig. D.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.

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

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. D.4 shows the transmission of the cavity at different values of the finesse.

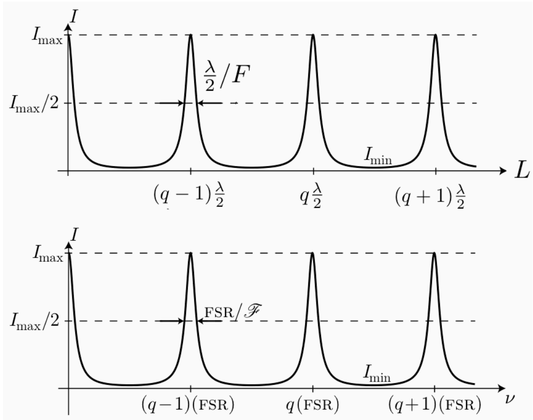

Figure D.3: Transmission of cavity.

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

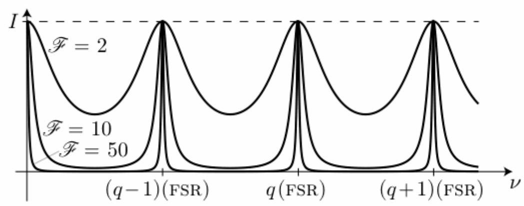

Figure D.4: Transmission of cavity for various values of the finesse.

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 $\Delta\phi_{\mathrm{rt}} = 2kL$, and the resonance condition for the cavity is given by Eqn. D.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 D.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.

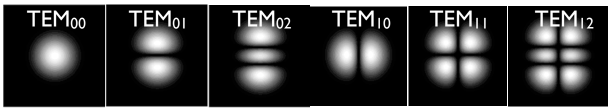

Figure D.5: Transverse intensity pattern of a $\mathrm{TEM}_{l,m}$ Gaussian beam. The mode is specified by the numbers l and m corresponding to the number of nodes along x and y respectively.

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

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

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. 10.2-33 in your textbook. Note that for $l = m = 0$ we recover Eqn. D.4, the original result for a plane wave. **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. **??** 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. D.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

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

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

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

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

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

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

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

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

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

Appendix E

Images of Components for Cavity Lab

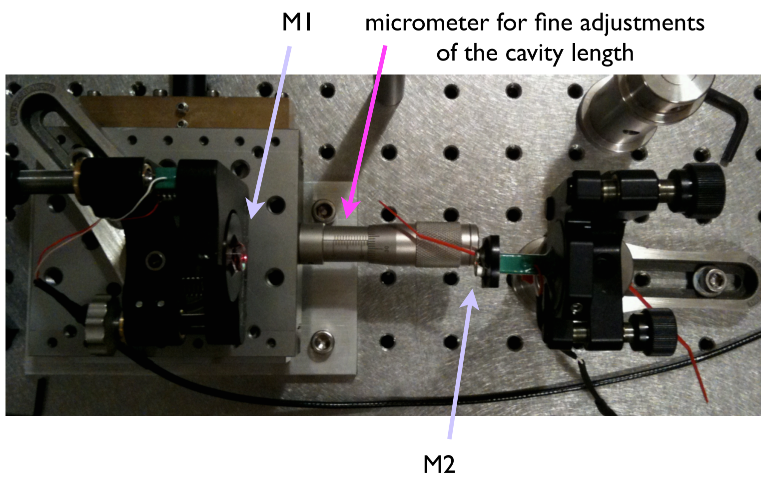

Figure E.1: Image of the cavity showing M1 and M2.

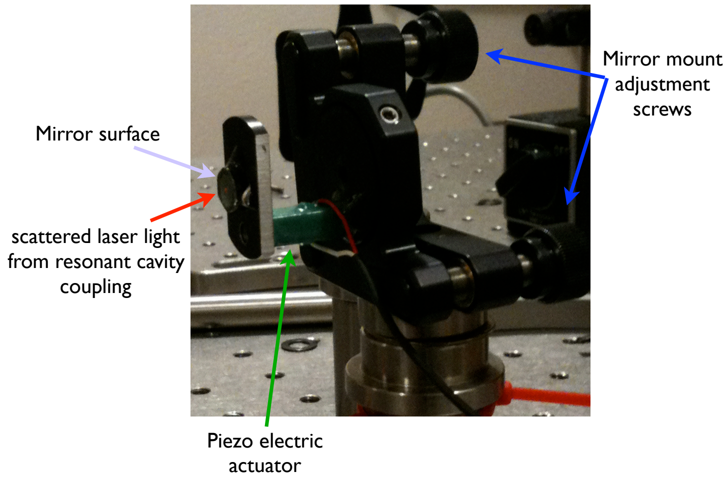

Figure E.2: Close-up image of the mirror M2 showing the piezo actuator. When the cavity is resonant with the input laser light, the optical power inside the cavity is very large and scattered light from the mirrors becomes clearly visible.

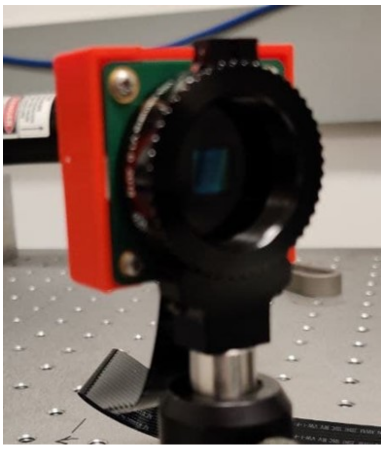

Figure E.3: Image of the Raspberry Pi CCD camera.

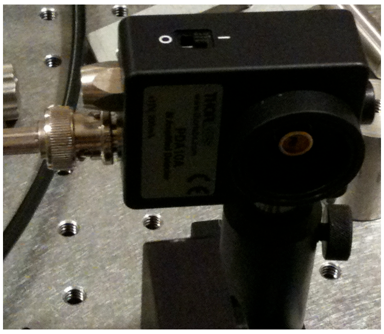

Figure E.4: Close-up image of the photodiode. The active area of the sensor is a tiny (< 1 mm^2) square centered in the area bordered by the gold ring.

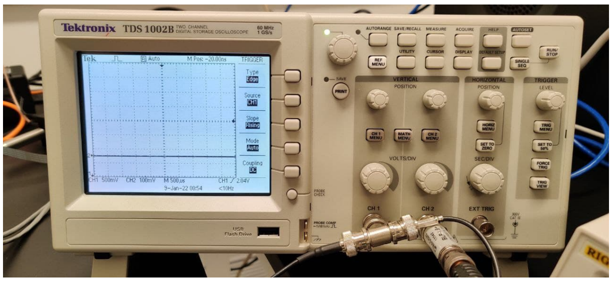

Figure E.5: Tektronix oscilloscope, which is used to monitor the transmission signal through the cavity (provided by the photodiode) as a function of time.

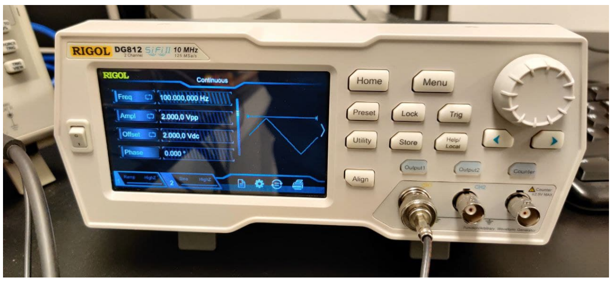

Figure E.6: Rigol function generator, which is used to provide the signal to the piezo stack (after being amplified) to scan the cavity length.

Figure E.7: High voltage (HV) amplifier (THORLABS model MDT694A). The display shows the output voltage. A voltage applied to the "EXT INPUT" on the front is amplified and that voltage is added to that set by the manual "OUTPUT ADJ" knob. The input multiplier changes depending on the voltage limit indicated by the green LED.

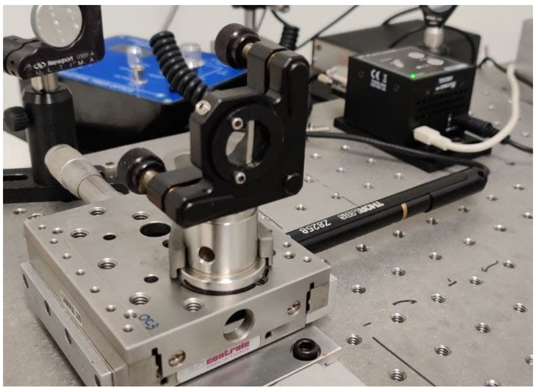

Figure E.8: The knife edge mounted instead of the input cavity mirror on the translation stage. Along the optical axis, the stage can be moved manually (silver handle in the back), and in the perpendicular direction via computer-controlled actuator (black cylinder on the right).

Appendix F

The Knife Edge technique

A common technique in the laboratory for measuring the beam waist parameter of a Gaussian beam is illustrated in Fig. F.1. A Gaussian beam is incident on an optical device, which registers the total transmitted power, like a power meter or (as in the case of this lab) a photo-diode connected to an oscilloscope. A knife edge can be translated in the transverse direction to block part of the beam (i.e., if the position of the knife edge is x_k, then the parts of the beam with $x < x_k$ is blocked from reaching the power meter).

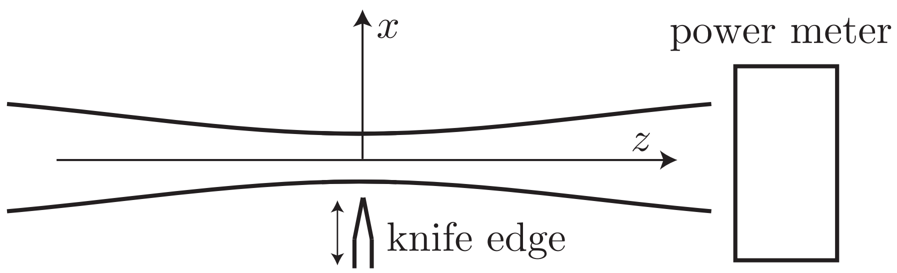

Figure F.1: An illustration of the "knife edge" technique. The beam power is recorded with the power meter as the sharp edge is moved into the beam.

Nothing happens in the y-direction, so we only need to consider the x-dependence of the Gaussian beam profile. Also, we will consider the intensity only at the z-position of the knife edge, so we will simply use w to denote $w(z)$. Then the intensity profile of the beam is:

$$I(x) = A \exp\left(-\frac{2x^2}{w^2}\right), \tag{F.1}$$

where A is a constant. The knife edge blocks the beam in the region $x < x_k$, so the fraction of the beam that makes it past the knife edge is:

$$\bar{I}(x_k) := \frac{\int_{x_k}^{\infty} I(x)dx}{\int_{-\infty}^{\infty}} = \frac{1}{2}\text{erfc}\left(\sqrt{2}\frac{x_k}{w}\right), \tag{F.2}$$

where the "complementary error" erfc function is defined as:

$$\mathrm{erfc}(z) := 1 - \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt, \tag{F.3}$$

and can be calculated using Matlab or any other software math package. By numerically fitting the measured normalized $\bar{I}(x_k)$ intensity dependence to the erfc function, the beam waist w can be extracted by means of Eq. F.2.

Instructions on how to execute

To measure the size of your laser beam with the knife-edge technique, first place the provided knife edge into a mount and attach it to the Thorlabs translation stage (see the picture of this setup in Appendix E). Confirm that by scanning the translation stage, which you can do by hand using an external control knob on a Thorlabs controller, the knife edge is moving perpendicularly to the optical axis of the laser beam. Place it close to the beam, but without blocking the beam at this point - this is the start position of your knife-edge scan.

Now remove the input cavity mirror (M1) and make sure that the light transmitted through the output mirror (M2) is entering the photo-diode detector. This should be confirmed by observing a non-zero signal on the Tektronix scope, which disappears when the laser beam is blocked. The scope should show a relatively steady signal, independent on the cavity length (because with M2 removed, there is no cavity).

Your task now is to scan the position of the knife edge across the laser beam, while recording the transmitted light intensity as measured by the photo-diode and registered on the scope. To do that, take a look at the example scripts `thorlabsStage.m` and `tektronixScope.m` in the `Software` folder. The scripts show how to move the stage and read out the signal from the scope. Write your own code to execute the two processes simultaneously. In general terms, your code should do the following:

- Initialize the stage and the scope, setting the appropriate hardware parameters, e.g. the time scale of the scope or the speed of the translation stage.
- Move the stage step by step (in a for loop) while pausing at each step and recording the waveform from the scope. The average value of that waveform (in Volts) is going to be proportional to the transmitted intensity at the current position of the stage.
- Clean up by closing the connections to both the translation stage and the scope.

At the end, the retrieved voltage as a function of the knife edge position should look similar to the one shown in Fig F.2 below.

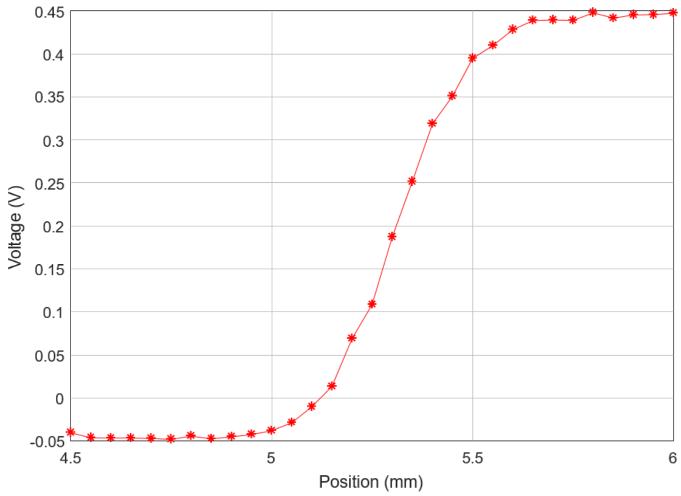

Figure F.2: An example of the signal, retrieved from the Tektronix oscilloscope and proportional to the transmitted light intensity, as a function of the position of the knife edge.