Fabry-Perot Interferometer

Introduction

The Fabry-Perot Interferometer is a high-resolution instrument that has been used extensively to study closely spaced components of spectral lines. It also forms the optical cavity employed in nearly all lasers. In this experiment a student model Fabry-Perot is first studied to illustrate the principles of operation and then it is used to measure the mode structure of the laser sources.

References:

1. Hecht, *Optics (5th ed.)*, Section 9.4.2, Mirrored Interferometers (the Fabry-Perot shares many aspects with the Michelson interferometer; Section 9.6, Multiple-Beam Interference (the math beind the Airy function; 9.6.1, The Fabry-Perot Interferometer; Section 13.1.3 The Laser (and laser modes).

2. Burleigh Instruments, Inc., *Fabry-Perots*, Instruction Manual for RC-10, -40, and -50. (Posted on class website.)

WARNING:

The Fabry-Perot mirror coatings are extremely fragile and will be permanently damaged by any contact whatsoever with the mirror surfaces. The mirrors are expensive, costing $\sim$ \$1,000 per pair. Do not, under any circumstances, touch or contact in any way either the front or back surfaces of the mirror pieces.

Summary of Fabry-Perot Theory

To effectively use a Fabry-Perot (FP) interferometer as a spectroscopic tool, you need to understand the concepts of **finesse** and **free spectral range**. This section presents these concepts in a descriptive form with emphasis on the underlying physics; see Hecht (references above) for the mathematical details.

The Fabry-Perot interferometer uses the phenomenon of multiple beam interference that arises when light shines through a cavity bounded by two reflective parallel surfaces. Each time the light encounters one of the surfaces, a portion of it passes through to the other side, and the remainder is reflected back; the net effect is to break a single beam into multiple beams which interfere with each other. If the additional optical path length traveled by a (multiply) reflected beam is an integer multiple of the light's wavelength, then the reflected beams will interfere constructively. Conceptually, the multiple reflections in the cavity interfere with each other in the same way that beams from a multiple-slit grating do: as the number of beams (or reflections) becomes higher, the interference maxima become sharper.

With this in mind, consider the arrangement shown in Fig. 1. The He-Ne laser produces a (nearly) monochromatic beam of light. The beam passes through the microscope objective which causes the beam to diverge. The diverging rays encounter the FP cavity where they undergo multiple reflections, and the light leaving the cavity creates an interference pattern on the screen. The

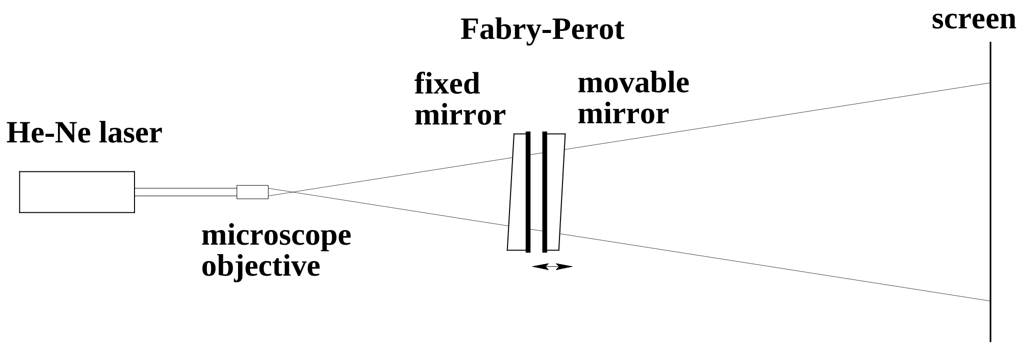

Figure 1: Basic setup for Fabry-Perot interferometry.

additional phase δ acquired by a beam reflecting once from each mirror surface before leaving the cavity depends on the mirror spacing d, the wavelength λ and the angle from the optical axis θ:

$$\delta = \frac{4\pi d \cos\theta}{\lambda} \ . \tag{1}$$

Under the ideal conditions of no absorption (all of the light either transmitted or reflected), perfect mirror flatness, and no diffraction limiting, the intensity of the light transmitted by the cavity I_t will follow the mathematical form of an Airy function:

$$I_t \propto \mathcal{A}(\theta) \equiv \frac{1}{1 + F\sin^2(\delta/2)} \ . \tag{2}$$

The quantity F is a parameter given the somewhat confusing name *coefficient of finesse* (it is not quite the same as "the *finesse*", but they are related, see below). If you examine Eq. (2) a moment, you can see that the Airy function equals 1 whenever $\delta/2$ is a multiple of π; otherwise the function is less than one. When the coefficient of finesse F is large, the function is sharply peaked at those multiples of π. The size of F increases with the number of reflections between the two mirrors, that is, if the mirrors have reflectance R, then $F = 4R/(1-R)^2$.

The dependence of δ on θ, along with the axial symmetry of the setup, produces a ring pattern on the screen. Each ring in the pattern corresponds to a change in the optical path length by one wavelength of light, or one *order*. If the mirror spacing d were such that exactly m half wavelengths of light fit between them, then along the axis ($\theta = 0$) the phase parameter δ would equal $2m\pi$, and one would see a bright spot at the center of the screen. This spot would correspond to order m. As θ increases from 0, δ decreases (since $\cos\theta$ decreases), and at a certain angle, say θ_1, the phase would have decreased by 2π to become $2(m-1)\pi$, and one would see a bright ring, corresponding to order $m-1$. More generally, the order of the pth ring out from the center has order $m-p$. A small-angle approximation for $\cos\theta$ gives the angular location θ_p as

$$\theta_p^2 = \left(\frac{r}{L}\right)^2 = 2 - (m-p)\frac{\lambda}{d} \ , \tag{3}$$

where r is the radius of the ring on the screen and L is the distance between the screen and the focal point of the microscope objective.

The usual way to use an FP to make measurements is to vary the spacing between the mirrors in a controlled manner while measuring the light intensity at the very center of the ring pattern. This technique is called *central spot scanning.* For monochromatic light, the transmission will peak once every time the distance between the mirrors moves by $\lambda/2$: in central spot scanning, $\theta = 0$ and $\delta/2 = 2\pi d/\lambda$, so a change in d by a half wavelength changes δ by 2π. Since d is proportional to δ, a steady change in d will produce a graph of evenly spaced peaks.

Instrument Finesse

The sharpness of the peaks in a central spot scan depends on a number of physical conditions: the reflectivity of the mirrors, the flatness of the mirrors, diffraction from apertures in the optical path, and the angular acceptance of the central-spot detector. A practical measure of the peak sharpness from a real instrument is called the *instrument finesse* or simply *finesse.* It is defined as follows:

$$\text{Finesse} \equiv \mathcal{F} = \frac{\text{Peak separation}}{\text{Peak width}} \; . \tag{4}$$

In the ideal conditions that would allow a real instrument to obey Eq. (2), one would obtain a finesse dependent only on the mirror reflectivity. This is called *mirror finesse* $\mathcal{F}_m$, and a simple calculation shows that it depends on the parameter F, and thus, the mirror reflectance R:

$$\mathcal{F}_m = \frac{\pi}{2}\sqrt{F} = \frac{\pi\sqrt{R}}{1-R} \; . \tag{5}$$

To show this, simply find the change in δ, $\Delta\delta_m$ that allows $\mathcal{A}(\theta)$ to drop by 1/2 compared to the value of δ that separates two peaks, i.e., $\delta = 2\pi$.

A real instrument has a finesse typically much lower than this limit. To estimate the contribution of a couple of other imperfections, assume for a moment that the mirror finesse is infinite, that is, for a monochromatic source, a central-spot scan would produce delta-function peaks at every point that d equals a half-wavelength multiple.

If the mirror surfaces are not exactly flat over the aperture that contains the light beam, then the phase of the light reflected between the mirrors will also vary—our hypothetical delta function at $d = m\lambda/2$ would be smeared out over a variation in mirror separation Δd, which would produce a variation in phase $\Delta\delta_f = 4\pi\Delta d/\lambda$. The quality of mirror flatness is usually given in terms of a "mirror figure" M defined according to the fraction of a wavelength that the surface departs from flatness, that is, $\Delta d = \lambda/M$. This would make the phase variation $\Delta\delta_f = 4\pi/M$, and since the phase change between peaks is 2π, the so-called *figure finesse* $\mathcal{F}_f$ would be

$$\mathcal{F}_f = \frac{M}{2} \; . \tag{6}$$

The mirrors in our student-grade FP setup have a flatness of $\lambda/20$ over their entire surface. However, this number should be taken as a worst-case value since the area of the mirrors which produce the central spot is considerably smaller than the size of the mirror itself.

Now return, mentally, to our ideal FP set with an infinite finesse, but imagine that our detector has an pinhole aperture of diameter D. If we start with the condition that a spot is present at the center of the detector, the phase parameter $\delta = 4\pi d/\lambda$, and we will record a peak in transmission from our detector. Now let the mirror separation increase. The spot will grow into a sharp ring, but the detector will continue to record a peak until this ring reaches the edge of the detector pinhole. At this point, the phase parameter has changed by an amount $\Delta\delta_p$ so that $\delta + \Delta\delta_p = (4\pi d/\lambda)[1 - \theta^2/2]$ (using the small-angle approximation for $\cos\theta$), consequently the variation in phase that still allows a peak to be seen is $\Delta\delta_p = 2\pi d\theta^2$ where, in this case, $\theta = D/(2L)$, the angular acceptance of the pinhole. Thus, the *pinhole finesse* $\mathcal{F}_p$ is given by

$$\mathcal{F}_p = \frac{4\lambda L^2}{D^2 d} \,. \tag{7}$$

In order to combine the contributions of each effect into a single estimate for the instrument finesse, note that the consequence of a finite finesse is to introduce an error $\Delta\delta$ into the phase parameter δ. Since each effect (pinhole size, mirror flatness, and mirror reflectivity) is independent of the other, it is reasonable as a first approximation to add the errors due to each effect in *quadrature*, that is, the total fractional error in δ, $\Delta\delta/\delta$ is found by assuming $(\Delta\delta/\delta)^2 = (\Delta\delta_m/\delta)^2 + (\Delta\delta_f/\delta)^2 + (\Delta\delta_p/\delta)^2$, or in terms of finesse,

$$\frac{1}{\mathcal{F}^2} = \frac{1}{\mathcal{F}_m^2} + \frac{1}{\mathcal{F}_f^2} + \frac{1}{\mathcal{F}_p^2} \,. \tag{8}$$

Free Spectral Range

Up to this point the discussion has assumed that the light entering the FP cavity is perfectly monochromatic. Now consider what you would see if light of two different colors were used. For each wavelength, you would see a different spacing of the rings in the ring pattern, corresponding to the different values of λ in Eqs. (1) and (3), for a given mirror separation d. For example, the spacing between rings of red light would be larger than the spacing between rings of green light since the longer wavelength of red light would require $\cos\theta$ to change more in order to have the same change of δ in Eq. (1).

Now imagine that the two colors are very close to each other, for example, two slightly different shades of green. The ring pattern would be composed of "doublets": pairs of closely-spaced rings. Which ring in a given pair corresponds to which wavelength? The answer is a bit counter-intuitive, given that the longer-wavelength light must produce more widely-spaced rings. The *larger* diameter ring in a doublet corresponds to the *shorter* wavelength light. To see why this is true, consider how δ changes as λ changes, with d and θ held constant. As λ shrinks, δ must grow, and this pushes all of the rings *outward*. Moreover, as the rings themselves become larger, the spacing between successive rings shrinks; one can see this by taking differentials of Eq. (3). Let $\Delta\theta_p$ be the difference in angles between two rings. From Eq. (3), we get

$$\Delta\theta_p = \frac{\lambda}{2d\theta_p}\Delta p \,. \tag{9}$$

So for larger rings (larger θ_p), the ring spacing $\Delta\theta_p$ is smaller.

In a central-spot scan, with d increasing, the rings would expand from the center, and the shorter-wavelength light would make a peak a bit before the longer-wavelength light would, as the next order of the shorter-wavelength light would come into the pattern before the corresponding order of the longer-wavelength light. In a very long scan, however, the peaks would separate (since the spacing between the longer-wavelength rings must be greater), until one would see the the shorter-wavelength peak coming *before* the longer-wavelength peak; indeed, the two peaks would eventually overlap! What is happening in this case is that the *orders* of the two peaks at a particular separation d are different: the mth order of the longer-wavelength light is making a peak at the same time as the $(m + 1)$th order of the shorter-wavelength light.

If the scan were run in the opposite direction, with d decreasing, the rings would collapse toward the center. In this case, the longer-wavelength peak would be recorded before the shorter-wavelength peak. In a long scan the peaks would get closer together, but they would overlap completely only at $d = 0$. However, because the finesse is not infinite in a real instrument, one would record a single peak well before zero separation.

One may ask the question: what wavelength difference $\Delta\lambda$ would cause the "order mixing" to occur at a particular separation d? The answer to this question is called the *free spectral range* of the FP cavity.

Mathematical derivations of the free spectral range are given in Hecht and other texts. Here is a derivation based on a mental picture. What we are after is the change in wavelength $\Delta\lambda$ necessary to make the mth order of the longer-wavelength light happen at the same separation d as the $(m + 1)$th order of the shorter-wavelength light. Assume for a moment that d is such that only one-half wavelength of the longer-λ light fits between the mirrors; in other words $m = 1$. The wavelength would have to shrink by a factor of 2 to fit the next order of the shorter wavelength in the same space: $\Delta\lambda$ would equal $\lambda/2$. See the upper picture in Fig. 2. As the separation d is increased, the wavelength change needed to fit the next order between the mirrors decreases; note that the change needed to go from $m = 5$ to $m = 6$ in Fig. 2 is about $\lambda/6$. Typically the mirror separation d is much larger than λ—many orders fit between the mirrors. One can see that for large m, $\Delta\lambda = \lambda/m$ (since there's not that much difference between m and $m + 1$). Because there are m half-wavelengths which fit between the mirrors, $m = d/(\lambda/2)$, so in terms of d, the free spectral range is

$$\Delta\lambda_{FSR} = \frac{\lambda^2}{2d} \,. \tag{10}$$

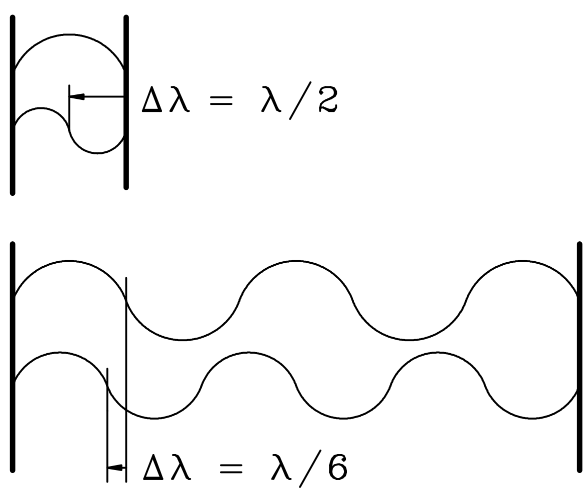

Figure 2: Illustration showing that the free spectral range $\Delta\lambda_{FSR}$ decreases with increasing mirror separation.

In many instances, the free spectral range is given in terms of the change in frequency of the light, rather than the change in wavelength. It is easy to show, using the well-worn relation $\nu = c/\lambda$ that

$$\Delta\nu_{FSR} = \frac{c}{2d} \,, \tag{11}$$

which has the advantage that the free spectral range can be given without specifying a particular wavelength λ.

Knowledge of the free spectral range allows one to use a central spot scan to measure wavelength shifts in a spectroscopic measurement. For example, in the Zeeman effect, the application of a magnetic field to a gas of atoms emitting light causes the emission lines to separate into components of slightly different wavelengths. The amount of wavelength separation is proportional to the applied field. If the light is passed through an FP cavity, these separations can be resolved into different peaks. The distance between *different-wavelength* peaks in a scan is directly proportional to the free spectral range. Since, by definition, the wavelength change of an amount *equal* to the free spectral range is given by the distance between the peaks of two successive orders of the same wavelength, one can use this distance, along with the free spectral range calculated from the known value of d to make a conversion factor.

For example, suppose the mirror separation is 4 cm. By Eq. (11), $\Delta\nu_{FSR} = 3.74$ GHz for this separation. A scan is made of some light source, and it is found that the distance between peaks of the *same wavelength* is 6 cm, and that two *different-wavelength* peaks are separated by 2 cm. The conversion factor would be (3.74 GHz)/(6 cm) = 0.623 GHz/cm. So the frequency separation between the two different-wavelength peaks would be 1.25 GHz.

Two final notes on the use of FPs for spectroscopy: First, the minimum resolvable difference in wavelengths depends, of course, on the instrument finesse. You can estimate this by using the free spectral range and the width of the (monochromatic) peaks in your scan. Second, watch out for peaks which appear to move a lot with respect to the others as the scan runs from order to order; such peaks may have significantly different wavelengths than the one used for calibration of your scan. The estimate of wavelength differences from fractions of the free spectral range is only valid when those differences are indeed less than the free spectral range.

1 *Instrument Alignment*

1.1 Laser alignment

Be sure to perform this procedure before setting up the Fabry-Perot mirrors. We will first work with the red HeNe laser ($\lambda = 632.8$ nm), so make sure that it is in place and secured to the table top. With no mirrors in the beam path, check that the laser beam is parallel to the table surface at a height of 6 inches. This is done by shining the beam directly from the laser onto one of the target screens, all of which have a horizontal line at 6 inches height. Start with the screen as close to the laser as possible. If the beam does not hit the screen on the 6 inch line, adjust the front positioning screws (on the underside of the laser mount, toward the beam end of laser) so that the beam hits the line. Now move the screen several feet from the laser. If the beam does not hit the screen on the 6 inch line, adjust the rear positioning screws (toward the power line end of laser) so that it does. Repeat this procedure (screen close to laser, screen far away from laser) until the beam hits the 6 inch line at all distances from the laser.

1.2 Mirror alignment

Mirror alignment is all important for proper operation of the FP interferometer. Even a finesse of 20 requires that mirrors be aligned (made parallel to each other) to within $\lambda/40$ over the area of the beam that traverses the FP cavity. To achieve the best possible alignment and best possible results from the FP, it is helpful to approach the alignment procedure methodically and patiently.

The experimental setup is shown schematically in Fig. 1. **Again, do not touch or contact in any way either the front or back surfaces of the mirror pieces. Doing so will permanently damage the mirror coatings.**

First position the fixed mirror assembly about 40 cm from the front of the laser so that beam passes approximately through the center of the mirror and the brightest spot of those reflected from the mirror back onto the laser is as close to the laser exit aperture as possible. Clamp the base to the table (flip the lever on the base). Make sure that the base does not rock on the table top after engaging the magnetic clamp. If it does, reposition the base slightly along the beam path and try again. After clamping the base, use the horizontal adjust screw (lower one, marked H) and the vertical adjust screw (upper one, marked V) on the mirror mount to center the brightest reflected spot on the laser aperture. The knob marked with red tape is clamped down and is not adjustable.

Perhaps you are wondering why there are multiple reflected spots (see the front of the laser) coming from this mirror. It turns out that the glass substrate on which the mirror coating is deposited is wedge-shaped, with the result that light reflected from the surface opposite the mirror is reflected at an angle to the light reflected at the mirrored surface. It is the light reflected (and transmitted!) in the cavity defined by the mirrored surfaces which is at the heart of the operation of the FP interferometer. If the light reflected from other surfaces were not deflected, those surfaces would form additional (solid) cavities and create undesired patterns superposed on the one from the mirrored cavity.

Next adjust the micrometer drive so the movable mirror is near the center of its travel, that is, somewhere around the 12-13 mm mark on either the black or red scale. (Travel is from 0 to 25 mm with 1 complete turn of the thimble producing 0.5 mm of travel. Each small division on the thimble of the micrometer represents 0.002 mm of travel.)

For the initial measurements you are to work with a mirror spacing or approximately 3 mm (0.12"). The mirrors are slightly recessed in the mirror mounts so that when the mirror mounts are separated by 3 mm the mirrors are separated slightly more than 3 mm. Don't worry about this as the spacing is not critical. It's the parallelism that counts.

Now position the movable mirror assembly to achieve the desired mirror separation of approximately 3 mm and align the assembly coarsely by hand to bring the brightest series of spots on the screen as close together as possible. Clamp the base to the table, again making sure that it does not rock after it is clamped. The brightest spot on the screen will now be deflected downward slightly from the six inch level due to the mirror substrates being wedge-shaped. After clamping the movable mirror assembly, use the vertical and horizontal adjust screws on this mirror mount to bring the spots on the screen into coincidence. Now use the calipers to measure the separation between the mirror mounts. It should be approximately 3 mm (0.12"). The graduations on the outer green scale of the calipers are 0.01". Adjust the separation, if necessary, by turning the micrometer handle, being sure to keep the micrometer reading between 10 and 15 mm at all times. It is important to **measure and record the separation** before performing the final alignment of the mirrors, as even the light contact between the calipers and the mirror mounts can shift the position of the mounts sufficiently to disrupt the alignment.

After measuring the mirror mount separation, use the vertical adjust screw (upper one) on the movable mirror to create a series of spots several mm apart, starting at the bright spot and progressing upward. Use the horizontal adjust screw (lower one) to orient the series of spots so that they are at or near vertical. Now use the vertical adjust to bring the spots into coincidence, then continue until the spots trail downward. As the spots move from above to below the center spot, they should lie on a straight line (as best you can tell by eye) and there should be no streaking of light to either side as the spots go through coincidence. If you haven't achieved these conditions on the first try, turn the horizontal adjust knob slightly and use the vertical adjust knob to run the spots through coincidence and to the opposite side again. When the spots above and below form a straight line and there is no observable streaking when they pass through coincidence, you are ready for final alignment. Make the final alignment by using the vertical adjust knob to bring the spots into coincidence, with the goal of achieving the smallest possible spot size, and no obvious streaking in any one direction. When you get close to good alignment, you may see faint rings surrounding the central spot; very slight adjustments of the H and V screws can be used to bring the circles concentric with the central spot.

Now place the microscope objective in the beam path about 15 cm from the fixed mirror, and center its optical axis along the beam. The ring pattern you see on the screen should be centered near where the bright spot was. Adjust the height and orientation of the objective so that the ring pattern is uniformly illuminated. Look closely at the ring pattern, if necessary, with a magnifying glass. If the pattern is not symmetric in sharpness (rings fuzzier or streaked or disappear toward one side), make very slight adjustments to the H and V knobs on the fixed mirror to bring the rings into uniform symmetry.

2 *Fabry-Perot Instrument Function*

2.1 Measure the Ring Pattern

First, you want to measure the diameters of a number of rings so that you can later determine the mirror separation. Start by taping a piece of the provided target paper on the back (non-white) side the large, 12" x 12" screen. The crossed lines on the target paper should be centered on the ring pattern. Mark the position of the diameters of a number of rings (at least 5) on one of the lines.

Measure and record the distance between the screen and the point of focus of the microscope objective (5 mm from the end of the objective). Estimate and record the distance between the mirrors with calipers, being careful not to touch the mirror surfaces.

To analyze the ring pattern measurements, look again at Eq. (3). Each ring corresponds to a different value of $m - p$. We don't know (very well) what m should be, but it does not matter: rewrite Eq. (3) in terms of the diameters $2r$ versus p:

$$(2r)^2 = p\left(\frac{4\lambda L^2}{d}\right) + \text{const.}\,, \tag{12}$$

where the constant is equal to $4L^2(2 - m\lambda/d)$. This says that a plot of $(2r)^2$ versus p should yield a straight line. Make such a plot and fit the line to obtain the slope. Then use the slope along with your values of L and $\lambda = 632.8$ nm (red laser) to find d.

Include your calculations and results in your report. Compare the value you derive for the mirror separation to the value determined with the calipers. High precision is not required here, but you should *estimate how well you have determined the separation by the ring measurement method. Remember to propagate the errors correctly!*

2.2 Make a Central Spot Scan

In most applications, the ring pattern is recorded by holding the wavelength and angle of incidence constant and varying the mirror separation. The intensity of each ring is recorded as it collapses to a central spot, and this technique is called, not surprisingly, *central spot scanning.* For research instruments such as the Burleigh FP, the separation of the mirrors is varied by piezoelectric stacks on which one mirror is mounted, and that change their length with the application of an electric field. With piezoelectric stacks, the separation can be changed both precisely and rapidly. For the student FP, mirror separation is changed with a geared down AC motor which drives a 100:1 worm gear, which drives the micrometer thimble on the movable mirror mount.

The diameter of the pinhole is denoted by the colored tape on the cap (see pinhole box for color key). Use the 0.010" diameter pinhole. Move the detector assembly along the rail (note the clamping screw on the carriage) so that the pinhole is horizontally centered on the ring pattern, and adjust the height of the detector (by turning the large ring on the vertical translation stage) so that the pinhole is at the center of the ring pattern.

To vary the mirror separation, place the rubber O-rings on the worm gear output shaft gently but firmly against the *large diameter, knurled part of the micrometer thimble* and clamp the base of the motor/worm gear drive to the table. See Fig. 3 for the proper setup of the clock-motor drive relative to movable mirror micrometer thimble. Check that the O-rings are snug against the knurled

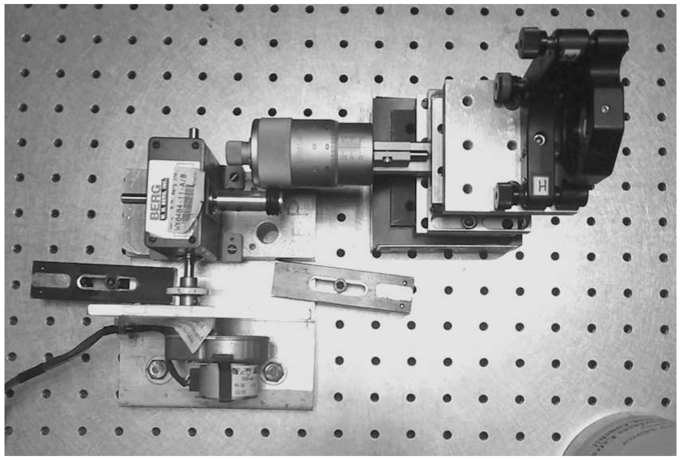

Figure 3: Motor-drive placement relative to adjustable-mirror control. Make sure that the magnetic base is fully "ON," the gently press the the O-ring shaft against the *large diameter* part of the micrometer knob. While holding it, check that the micrometer knob does not slip, and tighten the hold-down clamps. Turn on the motor drive (decreasing separation) and let it run for a while (3–4 minutes minimum) before collecting any data.

knob by checking that the knob does not turn (easily) by hand. Check that the ring pattern is still centered on the pinhole, and adjust the mirror alignment and detector position if necessary.

Turn on the motor controller in the "decreasing mirror separation" direction. When first starting the motor, there is typically some slack in the drive system and it may take some minutes before the ring pattern begins to change smoothly. In fact, you may see the pattern change in the wrong direction before all of the slack is taken up!

The connections from the detector to the PDA-700 amplifier, through the switchbox, and into the National Instruments data acquisition interface should already be set up.

Start up the computer-based LabVIEW Chart Recorder application on the computer with the National Instruments interface box attached to it.

After the Chart Recorder application starts, click on the tabs at the top left to set the scan parameters. The following settings should produce a nicely visible set of traces (if the setting is not specified, the default value is acceptable):

Channel 1 Check Enable Ch 1.

Sample Clock The sample clock controls how often a measurement is recorded by the interface box. We will use a little signal averaging to reduce noise. Check Pre-bin samples and set Bins/Read-cycle to 10.

Go back to the Scan Controls tab, click TAKE SCAN, and see what you get. *You may need to click more than once. The Chart Recorder application is new as of Spring 2023, and has a number of small bugs when this set of instructions was written. It does collect accurate data, but its controls need some work.*

Allow your scan to run until you get 4–5 full peaks Time your scan stop and start so that you capture only one direction. You can save a scan in local memory to look at it later by clicking

RETAIN SCAN. If you give the scan a name (in Scan Name) it will save this name with the scan. Otherwise it will use the default. Subsequent RETAIN SCANs will save more scans with the assigned name and a number.

A scan you want to save permanently should be saved to disk by clicking SAVE TO FILE. It is recommended to use the file extension `.wfm`, which indicates that it is a LabVIEW "waveform" file (a binary format). You can also load old scan files into the application to study and manipulate them.

You can filter noise with the Low Pass Filter settings. Do not be to aggressive with these filters! You do not want to distort the underlying signal, just remove the "fuzz" that may be obscuring the important response to the varying light intensity.

Don't forget to RETAIN and then SAVE TO FILE your best scans before stopping the application. Please check with the TA or instructor to get the latest information on the chart recorder application along with tips on its use.

One unfortunate feature of the hardware in this experiment is that the motor/worm gear/micrometer thread combination does not always produce a uniform translation of the mirror over a given time interval. (The requirements on the mechanical system are extreme! No research instrument uses a system like ours to change mirror separation.) This problem shows up in uneven spacing between the peaks of successive orders as recorded on the X-Y recorder. To measure the quantities of interest in this experiment, one needs to have equal spacing between the peaks associated with successive orders. It is a good idea to quickly check the peak spacing after recording a scan, and before moving on in the experiment. If the spacing is not even, record another scan until a succession of at least 2-3 evenly-spaced peaks is obtained.

It is important to be careful not to lean on the optical table or disturb it in any way once a scan is begun. The strain or vibration introduced in the tabletop will substantially alter the transmission through the Fabry-Perot if it changes the mirror separation or parallelism by a small fraction of a wavelength. Check it out. Before you start a scan, try pressing on the table near the mirror assemblies and observe how the ring pattern changes.

[Note: The current generated by the light falling on the photodiode is very small, typically $\sim$ a nanoampere. Transient currents of this magnitude can easily be generated by touching or moving the signal cables, or just waving your hands near cables or instruments! These transient signals will show up as undesirable glitches on the X-Y recorder output. To avoid this, it is recommended that you stand away from the measuring and recording instruments while a scan is in progress.]

2.3 Determine the Finesse

From your X-Y recorder plot determine the finesse, according to Eq (4). You may extract information from the plot with the "record cursor" tool. Ask for help on how to use the tool. With the information, obtain the full-width at half-maximum of a few peaks, and the separation of those peaks, both in units of time.

For your report, calculate the expected contributions to the instrument finesse from mirror reflectivity, mirror flatness and pinhole diameter, by using Eqs. (5), (6), (7), and (8). The manufacturer claims that the reflectance of the mirrors has been measured to be 0.89 at 633 nm (also 0.89 at 545 nm), and the flatness is specified to be $\leq \lambda/20$ at 633 nm over the entire surface of the mirror. You will need to know the distance L from the point of focus of the microscope objective (5 mm from the end of the lens) to the pinhole.

Compare your calculated finesse to the measured finesse, and discuss. Which contribution to the calculated finesse is the greatest? If your calculation gives a finesse less than the one you measured, can you say which contribution is overestimated? If your calculation gives a value much greater than the one you measured, can you explain what the additional source of instrument imprecision might be? Are any of the calculated contributions essentially negligible, and if so, why?

3 Laser Mode Structure

The most frequently encountered form of laser can be described as a Fabry-Perot cavity with an active medium inside. An active medium is one for which a light wave transiting the medium experiences a gain in amplitude. Within the range of frequencies for which the medium has sufficient gain, oscillations will occur for frequencies for which the cavity is resonant, i.e., an integral number of half wavelengths of the light fit between the ends of the cavity. These frequencies correspond to "modes", or, in this case, "longitudinal modes" of the FP cavity. From the description above, they differ in frequency by units of the free spectral range.

For gas lasers such as the HeNe laser, it is usually true that the medium exhibits sufficient gain to sustain oscillations over a frequency range that encompasses more than one mode. If so, several modes can oscillate at once and the output is said to be *multimode*. In practice, the amplitude of any one mode varies in time, and the cavity oscillation may pass rapidly from one mode to another, a process called *mode hopping*.

The object of this section is to measure mode separations for a red (632.8 nm) and, optionally, a green (543.5 nm) HeNe laser. The laser manufacturer states that the mode separation in the red laser is 687 MHz. (Does this make sense? How long is the laser?)

Again, be careful not to touch or contact in any way either side of the of the mirror pieces. Doing so will permanently damage the coatings.

Reposition the *fixed* mirror about 5–7 cm toward the laser, leaving the movable mirror engaged to the motor. You will need to measure the mirror separation for your analysis. Remove the microscope objective and realign the fixed mirror. Replace the objective and tune up the alignment. You will see that the ring spacing has become very small, and that the alignment will be very sensitive to any disturbance. When doing the final touch-up, try to make the central most ring as symmetrical as possible. To achieve a good measurement of the mode separation, it is very important that the ring pattern be well defined and have no obvious asymmetry or streaking. [Note: With this larger mirror spacing, the interferometer is much more sensitive to strains in the tabletop. Even walking around the table can induce strains that will show up on the recorded data. Once a scan is begun, it is best to not move around too much in the experiment area until the X-Y recorder has completed the scan.]

If you wish to measure the green laser, turn it on before recording the red-laser scans so it can warm up for 15-20 minutes. This will help stabilize the laser so that the output does not shift so rapidly from one mode to another.

Record a scan with 3 to 5 orders using the red laser. After yor scan, measure as well as you can the separation between the mirrors with the caliper, being careful not to touch the mirror surfaces.

To really get a good feel for how the FP resolves the modes, it is instructive to vary the mirror spacing and note the effect on the peak locations. Repeat your measurements of the red laser, but try mirror spacings of 3 cm on either side of the one you first used. For example, if your initial spacing was 6 cm, make another scan at a spacing of 9 cm and at 3 cm. Use these scans to derive further estimates of the mode spacing.

For your report, determine the mode spacing from your scan and the distance between the mirrors. Compare it to the claimed 687 MHz, and comment on any differences you see.

Hint: if you are careful, and do not set the y-axis gain too high, you can get all three scans on the same piece of paper.

3.1 Optional – Mode structure of the green laser

The mode separation in the green laser is stated to be 732MHz. Replace the red HeNe laser with the green one. You don't need to realign the mirrors if you are careful. See if you can set the green laser so that it makes a ring pattern in the same spot as the red. Record a scan with 3 to 5 orders, as before. Determine the mode spacing and compare it to 732 MHz.

[Note: The green laser is less powerful than the red laser (0.3 mW vs. 2 mW) and the photodiode sensitivity at the green wavelength is less than at the red wavelength. These factors lead to a much smaller photodiode current with the green laser. Increasing the PDA-700 sensitivity and/or Y axis sensitivity will help to make the trace a more reasonable size. Of course, any noise will also be more prominent!]

Shutdown

When you are finished taking data, be sure to turn the motor drive off, unclamp the drive assembly from the table, and move it back so the O rings are not in contact with the micrometer thimble. Turn off all electronics and log out of the computer with the Chart Recorder application. Cover all optics with their protective bags and the FP mirrors with their plastic cups.

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