Fabry-Perot Cavity

FP1-A
INSTRUCTOR'S MANUAL

A PRODUCT OF TEACHSPIN, INC.

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INSTRUCTOR'S MANUAL INDEX

Instruction Manual for TeachSpin's Fabry-Perot Cavity

Introduction

The Fabry-Perot Interferometer is a "resonant cavity" for light which has many uses in the world of optics. TeachSpin's Fabry-Perot Cavity was designed specifically to calibrate the frequency scale of a tunable laser. It can be used with any tunable laser operating in a wavelength range of 740 - 820 nm.

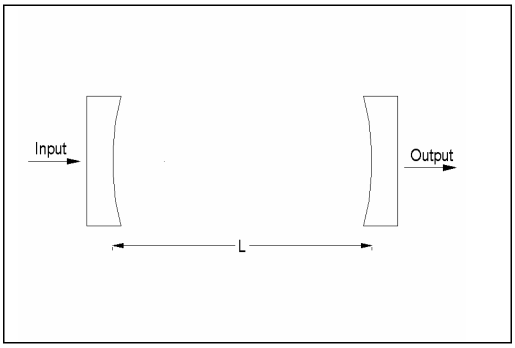
As an appendix, we have included a manual written by California Institute of Technology Professors Kenneth Libbrecht and Eric Black of the California Institute of Technology, with whom TeachSpin collaborated in building both our Diode Laser Spectroscopy apparatus and this Fabry-Perot cavity. In it, you will find a detailed discussion of the physics of this instrument, as well as descriptions of a variety of student experiments.

Here we offer a brief *Overview of the Physics* of a Fabry-Perot Cavity, instructions for *Unpacking the Instrument* and detailed instructions for *Setting Up the Fabry-Perot Cavity for the First Time*.

Overview of the Physics

A Fabry-Perot cavity is created by mounting a matched pair of highly reflective mirrors at either end of a tube. As seems logical, light aimed at the back of the near end mirror is, generally, reflected immediately and not transmitted through its length and out the other end. However, as the analysis in the appendix explains, at certain "resonant" frequencies, monochromatic laser light is actually transmitted.

The distance between the mirrors mounted at the two ends of a Fabry-Perot cavity determine its resonant frequencies. A detector just past the far end monitors the transmission. Non-resonant light is scarcely transmitted. As the frequency of a tunable laser is swept through the resonant frequencies of the cavity, distinct maxima in transmission occur.



For a properly adjusted cavity, the resonant frequencies are given by:

$$f_j = j\frac{c}{4nL} \qquad \text{1-1}$$

In this equation, j is an integer, c is the vacuum speed of light, L is the distance between the two mirrors defining the cavity, and n is the index of refraction of the air inside the cavity.

When the frequency of a tunable laser is scanned in time, a series of peaks in the transmitted light's intensity occur at

$$f_j = \ldots (j\text{-}1)\ \frac{c}{4nL},\ \ j\frac{c}{4nL},\ \ (j+1)\ \frac{c}{4nL}, \ldots \qquad \text{1-2}$$

As the series in equation 1-2 indicates, for any integer j, the transmission maxima will be equally spaced in frequency. The difference between adjacent maxima is defined as the *free spectral range* or FSR.

$$FSR = \Delta f = \frac{c}{4nL} \qquad \text{1-3}$$

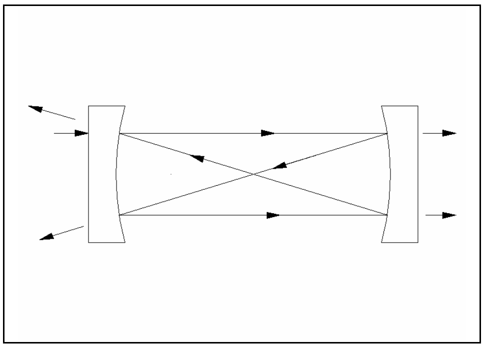
For the TeachSpin cavity, the adjusted length, L, will be near 20 cm, which will give a free spectral range of about 0.38 GHz or 380 MHz.

The transmission maxima, of course, will not be perfect spikes. The narrowness of a peak is described in terms of its full width, in frequency units, at half the peak height of the signal. For a properly adjusted Fabry-Perot cavity, the width in frequency of the maxima peaks (δf) will be much smaller than the spacing between the maxima (Δf). The ratio $\Delta f/\delta f$ is called the *finesse* of the cavity, and you should be able to achieve a finesse of over 100.

To have an idea of the sensitivity of this instrument, we can look at the three different frequency ranges involved. Writing them all in MHz will make them easier to compare. First, there is the frequency equivalent of the particular light we are investigating. For light of wavelength near 780 nm, the optical frequency is about 384,000 GHz or 384×10^6 MHz. We have calculated that Δf, the free spectral range, of our cavity is about 380 MHz. This means that, as we sweep the laser frequency, whenever the frequency of the transmitted light changes by *one part in a million*, you'll get another transmission maximum. Now, let's look at the transmission peaks themselves. Since the finesse of our cavity is around 100, having a FSR (Δf) of 380 MHz means that the frequency width of the peak itself, δf, will be on the order of 4 MHz. Since δf is measured half way up the peak, we can easily see changes ¼ as great. Thus a Fabry-Perot interferometer can be sensitive to frequency changes on the order of 1 MHz, out of an optical frequency of 400 *million* MHz.

The optical cavity of a Fabry-Perot interferometer is created by the pair of high reflectivity concave mirrors mounted at the two ends. The TeachSpin mirrors have a (power) reflection coefficient of $R > 0.995$ or 99.5%. The experiment must adjust the distance between the mirrors so that the focal points of the two mirrors coincide in space at the center of the cavity – in other words, the mirrors must be arranged to be 'confocal'. When properly aligned, these mirrors define a cavity mode that is stable against the otherwise inevitable transverse spreading of a beam that bounces back and forth between the mirrors for hundreds of round trips. The mirrors used in the TeachSpin cavity have radii of curvature 20 cm, so as concave mirrors they have focal lengths of 10 cm. Therefore, when properly adjusted, the mirrors are 20 cm apart. Part of your task will be to find the 'confocal condition' experimentally.

The 'ray diagram' for a confocal cavity is quite simple: any ray leaving either mirror, at any (paraxial) angle, and reaching the other mirror, will return to its original point of departure after two round trips, for a total distance traveled that's very near 4*L. If the incident light reaches the cavity parallel to, but laterally displaced from, the common axis of the mirrors, then the rays inside the cavity follow a 'bow-tie' pattern.



Emerging from the far end of the cavity are two transmitted rays, either of which will show the 'transmission maxima' you'll be studying. From the mirror at the input end of the cavity, there is also an immediate *reflection* from the cavity, which can be used in advanced applications of a Fabry-Perot interferometer. (At non-resonant frequencies, almost all of the light is reflected. At resonant frequencies, this immediate reflection reaches a minimum.)

Unpacking the Instrument

TeachSpin's Fabry-Perot Cavity comes with an iris for aligning the beam and a brass spanner wrench which can be used to remove the retaining ring if you wish to change or replace the mirrors.

The Fabry-Perot Cavity itself consists of an aluminum tube with a 0.5" ID. The tube is threaded at each end (0.535" by 40 threads per inch). These threads accept Thor Labs adjustable lens tubes (model SM05V05). High reflectivity curved cavity mirrors have been placed into each lens tube and are held in place with a threaded retaining ring. Both the lens tubes and the retaining rings have been shipped with the threads fully engaged and tightened. You will find removable plastic caps covering the ends of the lens tubes.

When you first unpack your cavity, remove the end caps and inspect the mirrors. Make sure the retaining ring has not become loose during shipping. (CAUTION: Do not scratch the mirrors with the retaining ring tool!) The lens tube should also be fully threaded in. The end caps should be used to protect the mirrors any time the instrument is not in use. You may want to keep them in place for the first part of the set up.

Setting Up the Fabry-Perot Cavity for the First Time

To set up the cavity, you will need to use the Diode Laser, the rubidium absorption cell and two photodiode detectors along with the Fabry-Perot system. Figure 1 shows a convenient layout. You are welcome to devise your own, but alignment will be simplified if you put the Fabry-Perot's input mirror close to the second steering mirror.

Before starting, be sure that the lens tubes are fully threaded in. This will mean that the cavity is set for its minimum length. The oscilloscope traces included in this manual were taken while a cavity was being set up for the first time. Because the photodiodes (PD) put out a negative voltage, both oscilloscope channels have been inverted. The transmission through the Fabry-Perot cavity (FP) is shown on Channel One. Channel Two, when displayed, indicates the light intensity of a beam passing through a rubidium absorption cell. This means that dips the trace on Channel Two show the rubidium D_2-line's absorption signals.

Select area on the optical table for the cavity carefully. The cavity should be placed away from other beams and located so that there can be two steering mirrors before the cavity. (At this point, remove the vinyl end caps)

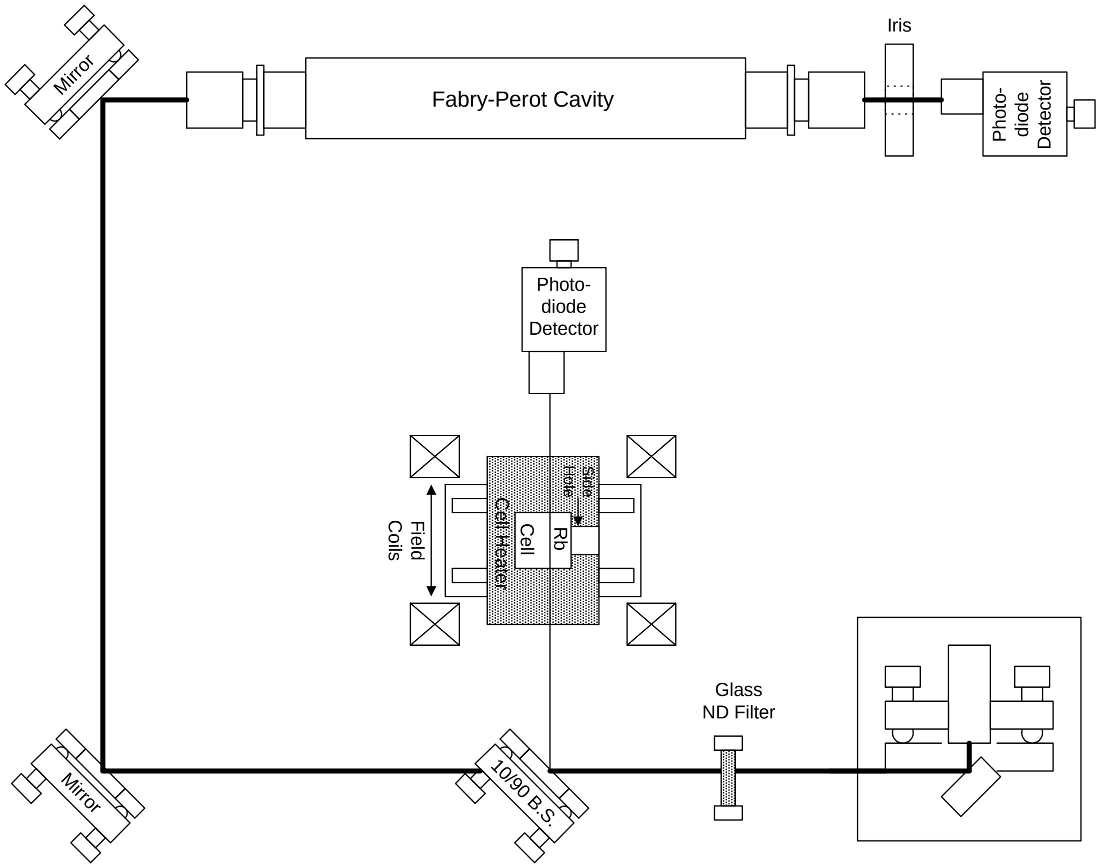
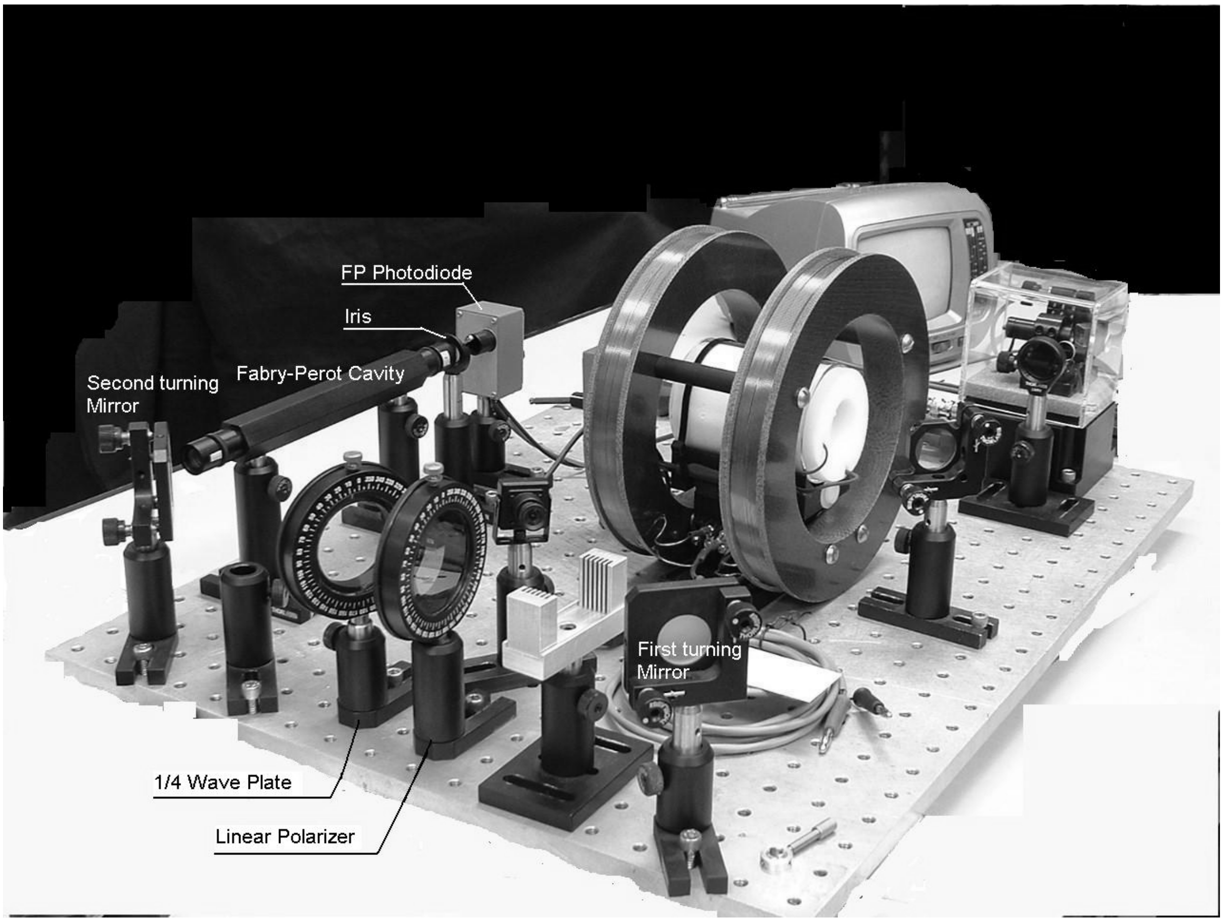


Figure 1 **This is a schematic of the setup used for aligning Fabry Perot cavity. The linear polarizer and quarter-wave plate which were placed between the two steering mirrors are not shown.**



One of Many Possible Configurations for Using the Fabry-Perot Cavity

This photograph shows only one possible arrangement of components for using TeachSpin's Fabry-Perot Cavity. We have shown a very compact version so that we could photograph it easily. Depending upon the space you have available, and the kinds of experiments you wish to do, other configurations may be far more useful.

The photograph shows the location of the linear polarizer and ¼ wave plate which were not included in the schematic. These are not used in the initial set up and are added somewhat into the process of tuning the cavity. As you can see, ¼ wave plate is tilted around its vertical axis. This is one of the degrees of freedom you can use when adjusting this "poor man's optical isolator" to prevent the light reflected off the Fabry-Perot surfaces from returning to the laser. (See page 9 of this discussion.)

Now it is time to turn on the laser and get the beam near center of two steering mirrors. Use the mirrors to make the beam parallel with the top of the breadboard and at a height of about 4 inches. The iris provided will make this task easier.

Tune the laser to the Rb spectrum and use one photodiode to monitor the absorption. This is not necessary to run the FP, but the cleanness of the absorption spectra will be used a diagnostic to tell you when reflections for the FP are getting back into the laser and changing its wavelength. The upper trace in Figure 2 is a normal spectrum; below is one corrupted by feedback. (Well-stocked optics labs may have an optical isolator that can be used to eliminate the back reflections.) We will also describe later how the linear polarizer and quarter-wave plate may be set up as a "poor man's" optical isolator. Other techniques that can reduce the feedback are putting an attenuating filter in the beam path and keeping the optical path length between the laser and Fabry-Perot cavity as long as possible. (The distance helps because the beam reflecting from the FP is diverging due to the curvature of the mirrors.)

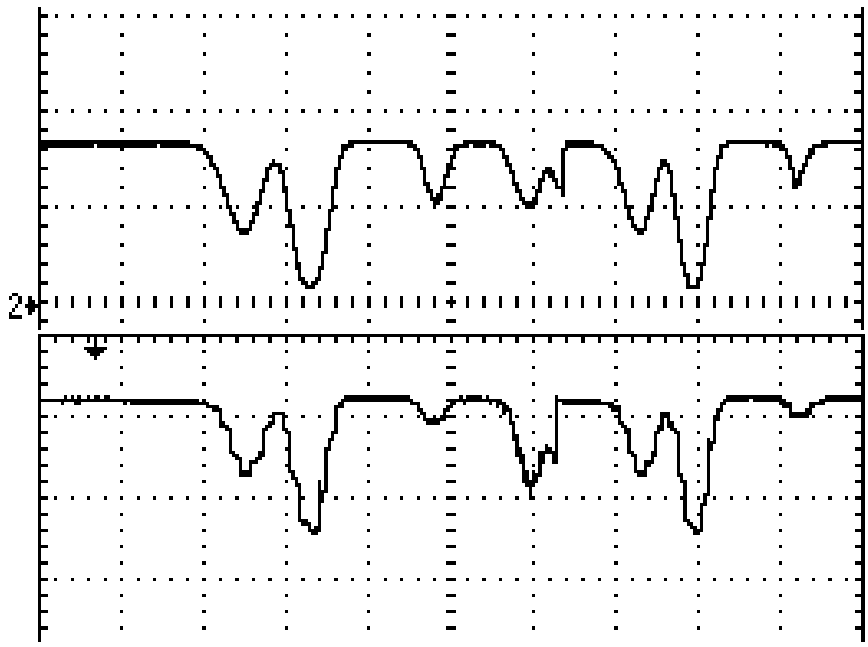


Figure 2 The upper trace shows a normal absorption signal. The trace below is the same signal in the presence of optical feedback from the Fabry-Perot cavity to the diode laser.

We now need to place the FP cavity in the beam such that the beam goes approximately down the center of the cavity. This is not a simple task because the highly reflecting mirrors mean that only a very small fraction of the light will pass through the cavity. (The mirrors are specified to be 99.5% reflective and we will make a power measurement to put an upper limit on this number.) You can use the iris as an alignment aid.

Place the FP in its approximate position. Place the iris at a location on the table so that it will be just after the FP. Now remove the FP and position the iris so that the beam goes through the center. Reduce the iris size and use the IR viewing card or a photodiode detector (PD) to help in correct positioning. Even if you don't use the PD to help center the iris it's a good idea to place it on the table now and center the PD on the beam. Keep the PD reasonably close to the iris and cavity. You will be making small changes in the position of the beam through the cavity; you don't want the beam to move off of the active area of the PD as you do this.

Now place the FP back in the beam path. Use the iris to center the downstream section of the FP on the beam and use the IR viewing card to position the upstream (input mirror) of the FP centered on the beam path.

Open up the iris so that the hole is at its largest opening and monitor the PD voltage on an oscilloscope as the diode is swept through the Rb absorption. Set the gain of the PD near its maximum value (1 to 10 Mohm). You should see an ugly signal on the 'scope. (See Figure 3 below -- note the evidence, in the Rb absorption signal, of feedback from the FP to the diode laser)

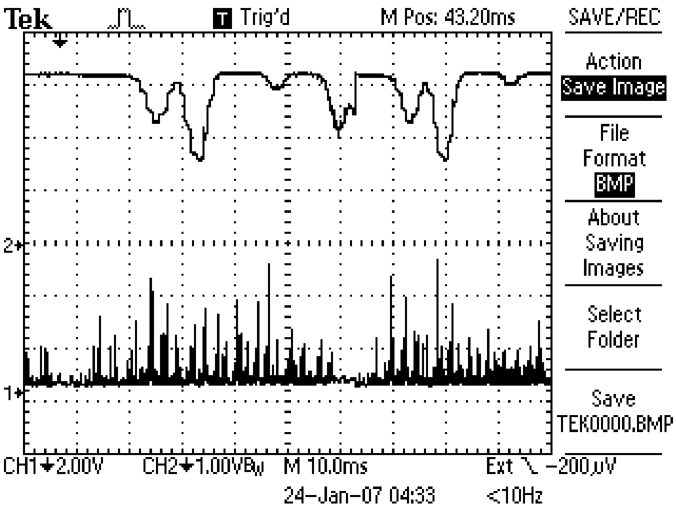


Figure 3 First view of F-P with no attenuation or isolator in beam path.
Upper Trace is Rb detector. Lower trace shows transmission through F-P cavity.
Gain in FP PD detector is 3.3M ohm. Gain Rb absorption detector is 10k ohm.

Now, place the glass neutral density filter in front of the laser. Adjust the photodiode and 'scope gains to display the signals again. The filter does a good job of reducing the back reflection because it attenuates the light both going from and returning to the laser. Figure 4 shows the 'scope trace with the feedback reduced. The PD gain of the FP PD has been increased to 10 MΩ and the room lights have been turned off. (If you cannot reduce the room lights you can also try putting a black cloth or paper "roof" over the gap between the end of the cavity and the snout of the photodiode detector to reduce the amount of stray light entering the PD.)

We can see from Figure 4 that the attenuator has reduced feedback to the laser. The rubidium absorption spectrum now shows that the laser is tuning smoothly and continuously in frequency.

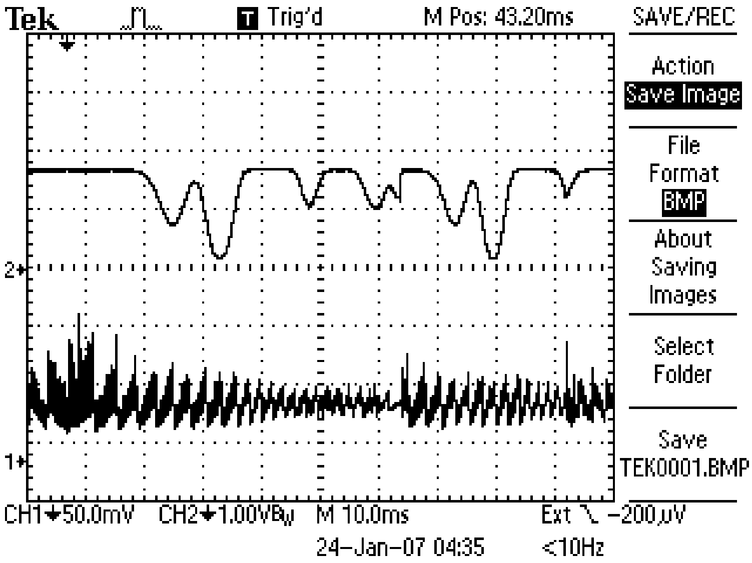


Figure 4 FP with a glass neutral density filter in beam path.
FP PD gain = 10 MΩ, Rb abs PD gain = 100 kΩ, Room lights off.

Tweak the two steering mirrors to maximize the transmission signal through the cavity. Your oscilloscope traces should begin to look like Figure 5. We can now see some structure in the FP transmission signal. Each peak represents the excitation, by the laser, of a different resonant mode of the FP cavity. The transmission maxima occur in repetitions of a cluster of modes. Successive 'clusters' are spaced by the cavity's free spectral range, and differ in the 'longitudinal mode number' of the cavity mode. Within each cluster is a collection of modes, which occur because you are exciting various *transverse* modes of the cavity.

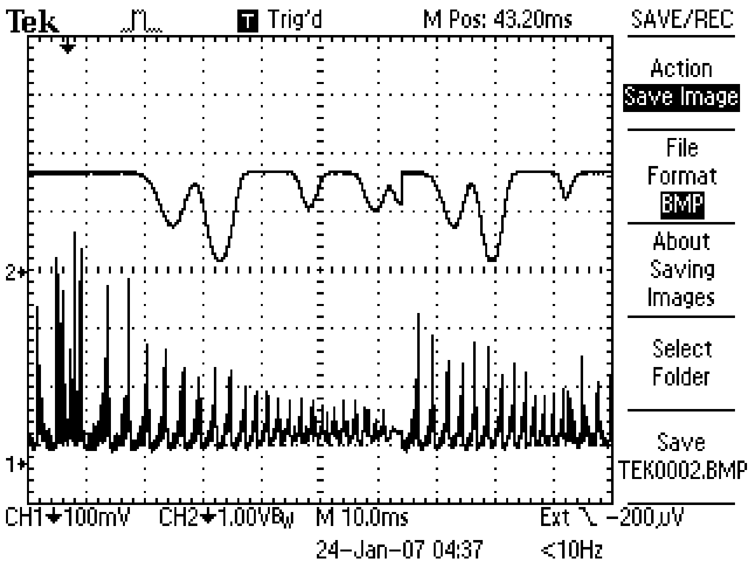


Figure 5 Same signal as Figure 4, but steering mirrors have been tweaked for maximum signal.

In Figure 5, we can see that these transverse modes are occurring at distinct frequencies. This is because the cavity length is not set to the confocal condition (where all the transverse modes become degenerate, and occur at the same frequency).

When tweaking the steering mirrors, you may notice that there is still some light feeding back into the laser. Now is a good time to use the linear polarizer and quarter wave plate to construct a “poor man's” optical isolator. See appendix A for one technique of adjusting these components.

Figure 6 shows a made trace after the linear polarizer and quarter wave plate were inserted and adjusted to reduce feedback into the laser. The horizontal scale has been expanded from Figure 5. The scan has been shifted so that the turning point of the piezo scan, which is shown by the arrow on the upper margin, is near the center of the trace. In this section of the scan, the grating first lengthens, then shortens, the wavelength of the laser. You might notice that the long tails of cluster of modes stretch towards the *long* wavelength side of the spectrum. This tells us that the cavity length is not at the confocal condition and needs to be lengthened. (A tail to the *short* wavelength part of the scan would indicate a cavity that needed to be shortened.)

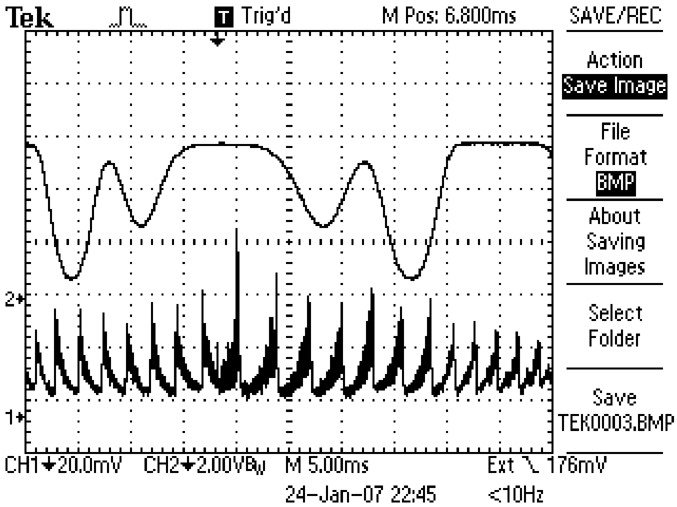


Figure 6 Oscilloscope trace with optical isolator in place. The turning point of piezo scan, shown by the arrow on the upper margin, is near the center of the ‘scope trace.

When you have determined whether the cavity is too long or too short, change the length by tuning one of the adjustable lens tubes on either end of the cavity. Watch the ‘scope display as you do this. Figure 7 shows the scan for our cavity with one adjuster rotated 5 turns. (You can put small pieces of masking tape on the lens tubes to keep track of how far you have turned them.)

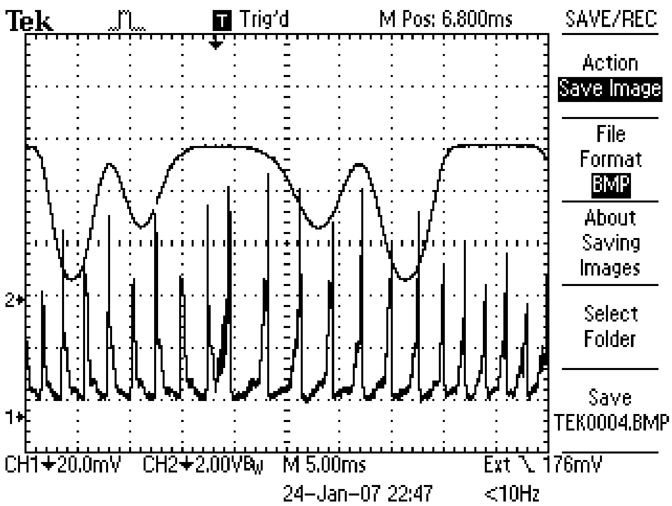


Figure 7 Cavity length increased by five turns of one lens tube.

Before the next traces were made, the other end mirror was turned out four turns, making the cavity even longer. Note the change in scale of the y axis for the FP signal. It has changed from 20 to 200 mV per division. Evidently, as the cluster of modes coalesce, the intensity in the peaks increases dramatically. Here, the highest peak has gone from about 85 to 360 mV.

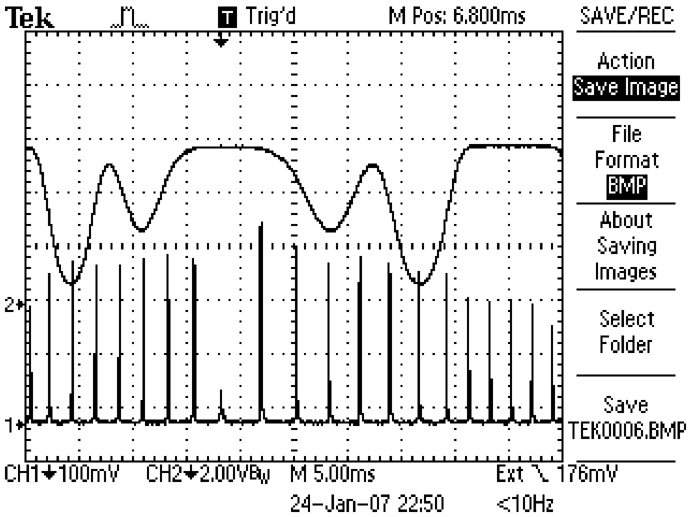


Figure 8 Cavity length increased by four turns at the other end of the cavity

Now you ought to check that you are not sweeping too fast through the Fabry-Perot transmission peaks. At a Gain of 10 MΩ, the PD has a 3dB bandwidth of about 5 kHz. We might estimate a resolvable pulse width to be about one half the period or about 100 us. In practice, we observe the FP transmission peaks on the scope and watch the peak heights while changing the sweep speed. As the sweep speed is reduced the peak height will increase. Keep reducing the sweep speed until no further increase in peak height is observed.

Figure 9 shows a scan through two transmission peaks. The tails have moved to the other side of the peaks, indicating that the cavity is now too long. You can convince yourself of this by increasing the cavity length further.

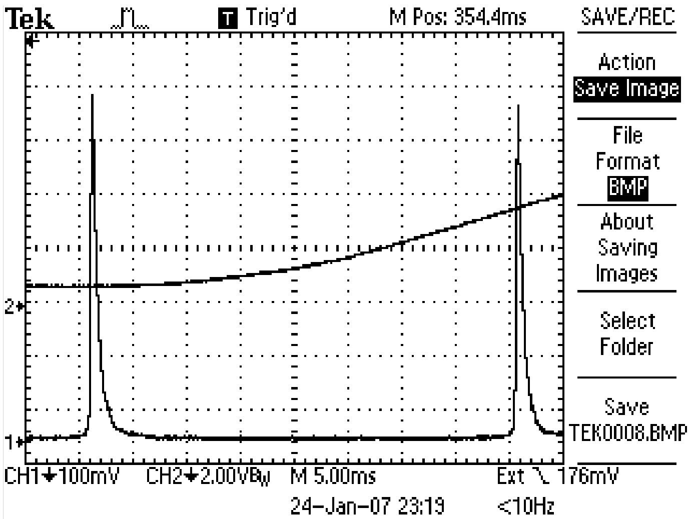


Figure 9 Scan for a slow sweep through two transmission peaks. Note that the "tails" are now to the short wavelength side indicating that the cavity is too long.

For the next screen captures, the cavity length was reduced by 1/4 turn. This gives the near optimal cavity length. See Figure 10 and 11.

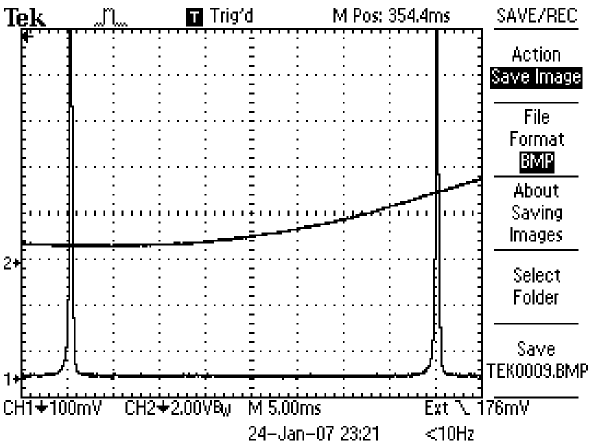


Figure 10 Near optimal cavity length

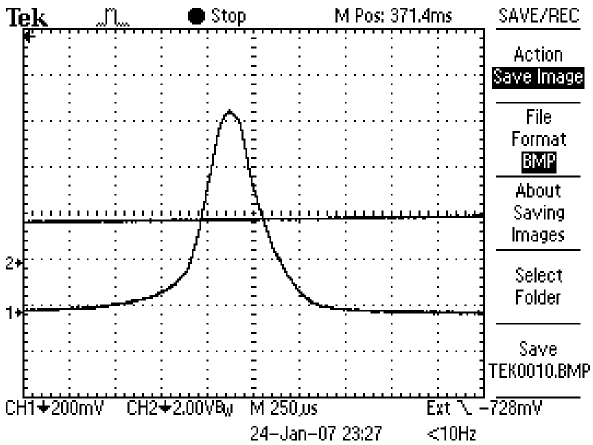


Figure 11 Expanded view of single peak from Figure 10.

Figure 11 shows an expanded view of one of the peaks in Figure 10. Traversing one free spectral range (FSR) occupies about 40 ms of time. The full width at half maximum of the peak shown in Figure 10 is about 300 us, giving a finesse slightly greater than 100. If you try and reproduce this data, you will find that vibrations in the air and room will distort the line shape.

Now you are seeing 'markers' equally spaced on the optical frequency scale, and they can serve to calibrate the frequency scale as soon as you can assign a numerical value to the free spectral range. If you could measure L well enough, you could compute this FSR from the equation $\Delta f = c/(4nL)$, but there is a better method. It involves modulating your diode laser, to put 'sidebands' on its heretofore monochromatic signal.

The TeachSpin diode laser is equipped with a special electrical input, in the form of an SMA connector right on the diode-laser head, at which a modulating current can be injected. We have used an RF signal generator which delivers a maximum RF power of 0.7 Volts peak to peak (into 50 ohms) or about 0 dBm. (1 mW of power into 50 ohms) It may be possible to damage the diode if more RF power than this is applied.

The laser current may be modulated at frequencies from 100 kHz to over 150 MHz through the SMA connector on the laser head. [Lower frequency modulation, (DC to 500 kHz), is possible via the current-modulation input on the front panel of the electronics box.] We have also provided a SMA to BNC adapter. Though we have not experienced any problems, you should always use extreme caution when modulating the laser via the direct SMA input. We always worry about turn-on transients damaging the diode. *Before applying AC power to the RF signal generator we make sure that the output amplitude has been set to its smallest value. Then, after AC power is applied, the output amplitude can be increased.*

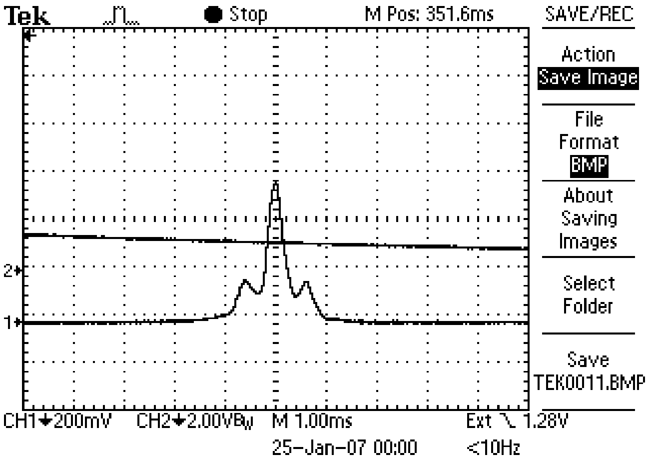


Figure 12a Low Amplitude Current Modulation

Modulation of diode-laser current at low amplitude, and 5 MHz frequency, has put sidebands on the laser's optical frequency. These are separated from the 'carrier frequency' by ±5 MHz, and are revealed by their ability to excite the FP cavity

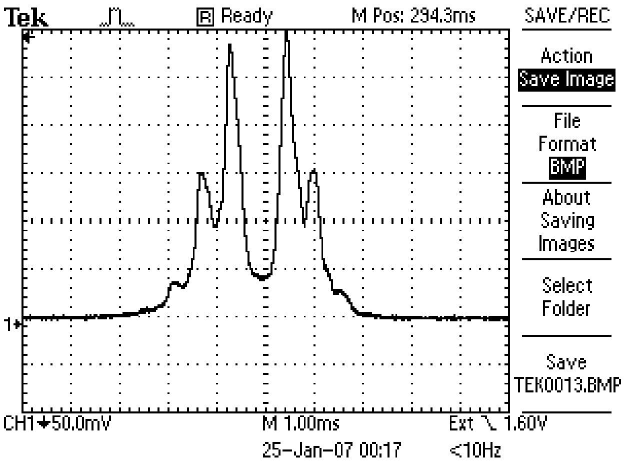


Figure 12b Increased Amplitude

Modulation with larger amplitude. Note that sidebands of order ±1 are now dominant, and sidebands of orders ±2 and ±3 are also visible. For this 'magic' choice of modulation amplitude, the original 'carrier frequency' now has a vanishing amplitude.

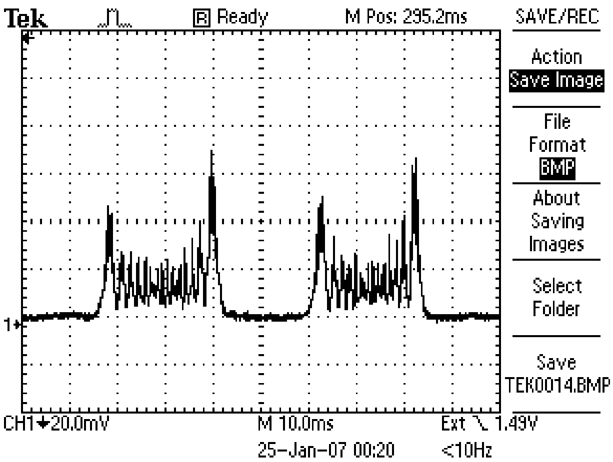


Figure 12c Maximum Amplitude

Maximum Amplitude trace shown using expanded time scale.

Two successive traces of the Fabry-Perot transmission over the spectrum of the laser when it is frequency modulated by a 5 MHz wave form of maximum amplitude.

Figure 12 Modulation of diode-laser current at low, medium, and maximum amplitude and 5-Mhz frequency

Thus far, you have seen the results of exciting the 'bow-tie modes' of the cavity which are spaced at Δf = c/4L. Figure 13 shows the scan for a well tuned cavity.

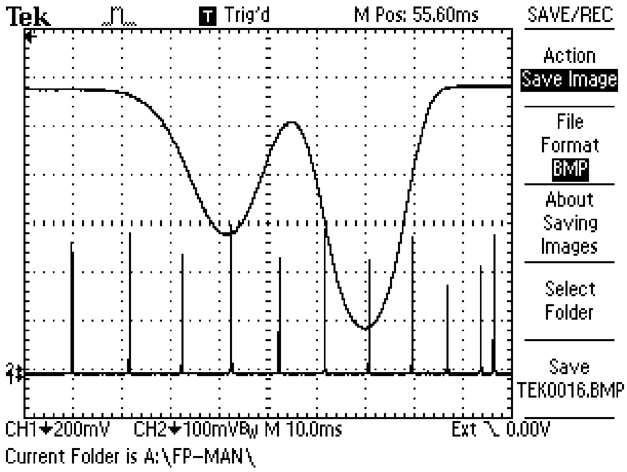


Figure 13 Normal input signal, FSR = c/4L

If your isolation between laser and cavity is good enough so that feedback is minimal, you can try exciting the on-axis modes. A ray-diagram for an on-axis beam would show a round-trip distance of 2L. In that case, the modes should occur at frequency spacing c/2L which is twice as big as what we have been seeing.

By tweaking your steering mirrors, you may be able to find this on-axis condition. As the beam becomes closer to on-axis, you will see a *drop* in the intensity of every other mode of the c/4L spacing. At the same time, as we can see from Figure 14, the magnitude of the alternate peaks increases. If you were able to be exactly on-axis, you would be exciting even, but not odd, transverse modes, and you would get complete suppression of every other peak in the mode spectrum.

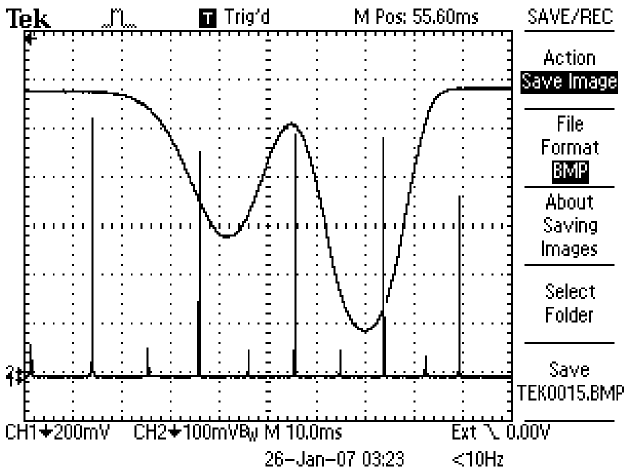


Figure 14 On-axis input, FSR = c/2L

In addition to doubling the free spectral range, exciting these on-axis modes also maximizes feedback to your laser. (Can you explain why?) This places the highest demands on isolation of the laser from the cavity.

Appendix A –` The "Poor Man's Optical Isolator"

The "poor man's optical isolator" is a means by which specular reflections may be reduced. It consists of a linear polarizer followed by a 1/4 wave plate. If the axis of the polarizer is placed at 45 degrees with respect to the axes of the 1/4 wave plate, the light beam will emerge from the 1/4 wave plate circularly polarized. The isolator works because when light is specularly reflected from a surface, there is a change in the momentum vector, but not the angular momentum! Thus a light beam that is right hand circularly polarized (RHCP) when approaching a mirror is left hand circularly polarized (LHCP) after a 180-degree reflection from the mirror. (See Figure 1 below.)

When the reflected light passes through the 1/4 wave plate in the reverse direction, the beam again becomes polarized. Because of the change in "handedness," the plane of polarization of the returning light is at a 90° angle to the Linear Polarizer and so its passage is blocked. We have optically "isolated" the source of the incoming light. In the case of a laser, this is extremely important because light re-entering a laser cavity significantly disturbs its performance.

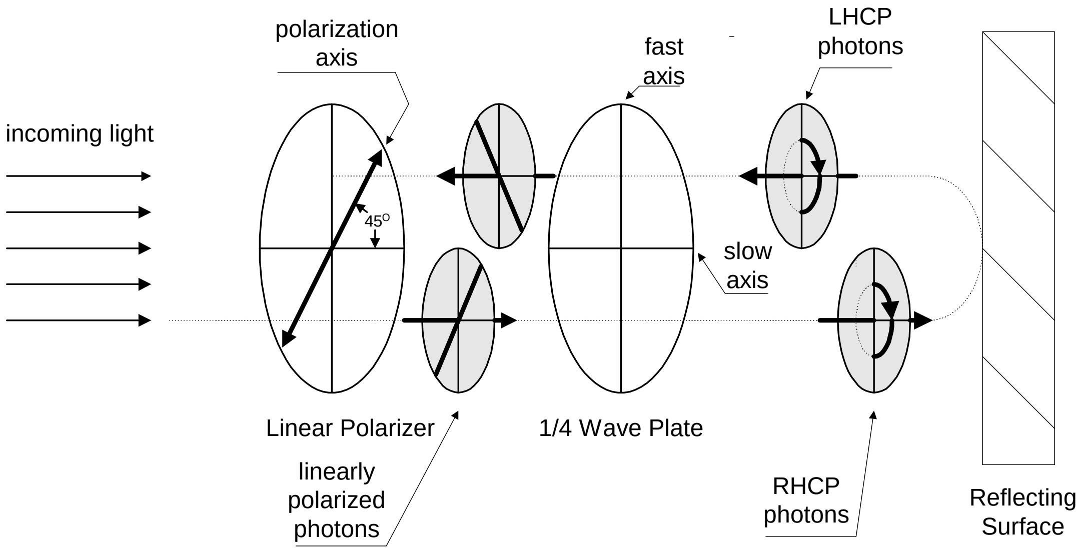


Figure 1: Schematic showing the change in the direction of circular polarization at reflection and the resulting change in linear polarization which prevents the light from passing back through the Linear Polarizer.

The 1/4 wave plates that come with your diode laser are not specified to be exactly a quarter wavelength for 780 nm light. Fortunately, it is possible to tune the optical thickness (retardation) of the wave plate by tilting the wave plate about either its fast or its slow axis. Rotation about the slow axis causes an increase in the retardation, and about the fast axis causes a decrease. In practice, one does not know which axis is the fast or slow, or whether the retardation needs to be increased or decreased. Happily, the optimal setting of the wave plate can be found empirically.

Set up the isolator near the source of the unwanted reflection. Position the 1/4 wave plate so that its 0 mark is at the top, making one of its axes vertical. Orient the linear polarizer so that its polarization axis is at 45 degrees with respect to the vertical. (It is best to NOT have any mirrors between the isolator and reflection optics because the mirror will cause a change in the polarization state of circularly polarized light.) You may observe that I did not follow this advice in the set-up shown in the photograph on page 5 of the manual. The reason for this was that I wanted to keep the second steering mirror close to the input of the F-P cavity for ease of alignment.*

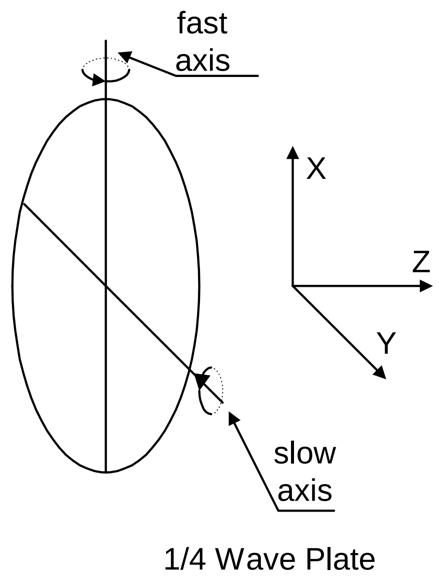


Figure 2: Diagram of 1/4 wave plate showing reference axes.

Alignment of the isolator involves two separate rotations: first, rotation of the wave plate in its own plane in the 360-degree mount that is provided, and secondly, rotation of the wave plate about the vertical axis using the optical mount that holds the wave plate to the table. The diagnostic you will use for alignment will be to minimize the intensity of the unwanted reflection. Punch a hole in one of the viewing cards and place it upstream of the isolator. Position the viewing card so that the incoming light goes through the hole. Use the CCD camera to observe the reflection. Warning: there will be several reflections! You should be able to see additional reflections for the linear polarizer and wave plate. By tilting the elements in their optical mounts you can identify which reflection belongs to which element. It is the reflection from the Fabry-Perot mirror that we wish to reduce. The other elements can be angled such that their reflections do not travel back into the laser.

Now that you have identified the reflection you wish to reduce, rotate the wave plate in its own plane to minimize this reflection. (You will be rotating around the Z-axis in the figure above.) By this process you will have adjusted the relative angles of the wave plate and polarizer to be 45 degrees. Now, try twisting the whole wave plate about the vertical axis using the optical mount that holds the optic to the table. (You will be rotating around the X-axis in the figure above.) If you find a point were the reflection becomes a minimum then you are done. You may however observe that the reflected spot only gets brighter as the wave plate is rotated. You have the “wrong” axis in the vertical direction. Rotate the wave plate in its own plane by 90 degrees, bringing the other velocity axis into the vertical position. Once again, try to minimize the reflected beam’s intensity by adjusting both the X and Z rotations. This time you should find a nice minimum. The alignment of your “poor man’s optical isolator” is now optimized. The isolation is far from perfect, but it is good enough to perform all the measurements that have been outlined in the Fabry-Perot manual.

* It may also be the case that, by empirically adjusting the isolator, I was able to compensate for the polarization change caused by the mirror.

Fabry-Perot Cavities and FM Spectroscopy

Student Laboratory Manual (Pg. 1-12)

California Institute of Technology

Dr. Eric Black and Professor Kenneth Libbrecht

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