Ph 77 ADVANCED PHYSICS LABORATORY
– ATOMIC AND OPTICAL PHYSICS –

Expt. 71 – Fabry-Perot Cavities and FM Spectroscopy

I. BACKGROUND

Fabry-Perot cavities (also called Fabry-Perot etalons) are ubiquitous elements in optical physics, and they are used for such applications as sensitive wavelength discriminators, as stable frequency references, and for building up large field intensities with low input powers. Also, lasers are all made from optical cavities. For our diode lasers, the cavity is made from a semiconductor material a few millimeters in length, and the light propagates inside the semiconductor. Cavities are often made from two curved mirrors as shown in Figure 1.

In this lab you will investigate some cavity properties, and you will see how a cavity can be used as an "optical spectrum analyzer" to measure the spectral content of a laser. In this capacity, you will use the cavity to observe radio-frequency (RF) sidebands on the laser output.

A basic Fabry-Perot cavity consists of two reflectors separated by a fixed distance L, as is shown in Figure 1; curved reflectors are typically used because such a configuration can trap light in a stable mode. (Two flat mirrors can also make a cavity of sorts, but it is not stable; the light "walks off" perpendicular to the cavity axis.) An excellent detailed discussion of the properties of Fabry-Perot cavities is given by Yariv (1991), and you may want to look through Chapter 4 of this text to better understand the details of cavity physics. Another useful, although somewhat dated, reference is attached as an appendix at the end of this hand-out.

Much of the physics of optical cavities can be understood by considering the flat-mirror case, which reduces the problem to 1D. Physically, this case can be realized if the flat mirrors have effectively infinite extent and the input light can be approximated by a perfect plane wave. For two identical mirrors, each with reflectivity R and transmission T ($R+T=1$), the amplitude of the transmitted and reflected electric field amplitudes (which you will calculate as a prelab problem) are given by

$$\begin{aligned} E_t &= \frac{Te^{i\delta}}{1-Re^{2i\delta}}E_i \\ E_r &= \frac{(1-e^{i2\delta})\sqrt{R}}{1-R\,e^{i2\delta}}E_i \end{aligned}$$

where E_i is the amplitude of the incident light and $\delta = 2\pi L/\lambda$ is the phase shift of the light after propagating through the cavity (we assume the index of refraction is unity inside the cavity). The transmitted light intensity is then

$$\frac{I}{I_0} = \left|\frac{E_t}{E_i}\right|^2 = \left|\frac{Te^{i\delta}}{1-Re^{2i\delta}}\right|^2$$

The cavity transmission peaks when $e^{2i\delta}=1$, or equivalently at frequencies $\nu_m = mc/2L$, where m is an integer, c is the speed of light. At these frequencies the cavity length is an integer number of half-

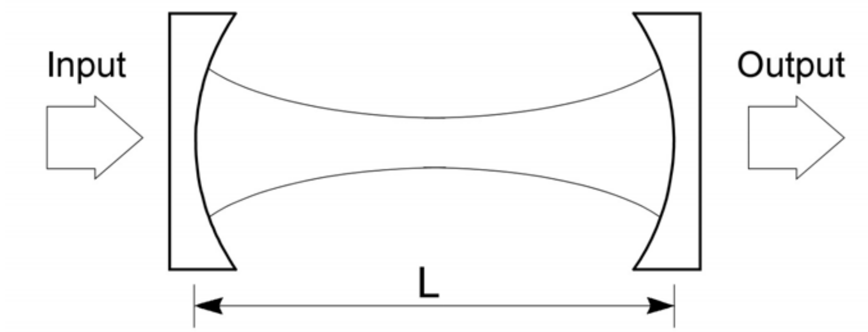

Figure 1. The basic Fabry-Perot cavity. The curved surfaces of the mirrors are coated for high reflectivity, while the flat surfaces are anti-reflection coated and have negligible reflectivity. The curved lines inside the cavity represent the shape of the resonance optical mode.

wavelengths of light. Note that the peak transmission is $I/I_0 = 1$, regardless of R.

The separation between adjacent peaks, called the *free-spectral range,* is given by

$$\begin{aligned}\Delta\nu_{FSR} &= \nu_{m+1} - \nu_m \\ &= \frac{c}{2L}.\end{aligned}$$

If the mirror reflectivity is high (for our cavity mirrors it is approximately 99.5 percent) then the transmission peaks will be narrow compared with $\Delta\nu_{FSR}$. The full-width-at-half-maximum, $\Delta\nu_{fwhm}$, (*i. e.* the separation between two frequencies where the transmission is half the peak value) is written as

$$\Delta\nu_{fwhm} = \Delta\nu_{FSR}/F,$$

where F is called the cavity "finesse." If $T \ll 1$ the finesse can be shown from the above to be approximately

$$\begin{aligned}F &\approx \frac{\pi\sqrt{R}}{1-R} \\ &\approx \frac{\pi}{T}\end{aligned}$$

The results so far describe an ideal cavity, in which there is no absorption or other loss of light inside the cavity. The peak transmission of such an ideal Fabry-Perot cavity is unity, as can be seen above. Introducing small losses in the cavity leads to the expression

$$E_t = \frac{T\alpha e^{i\delta}}{1 - R\alpha^2 e^{2i\delta}} E_i$$

where α is a loss parameter (the fractional intensity loss from a single pass through the cavity is equal to $\varepsilon = 1 - \alpha^2$). This gives a peak cavity transmission

$$\frac{I_{peak}}{I_0} \approx \frac{T^2(1-\varepsilon)}{(T+\varepsilon)^2} \approx \frac{T^2}{(T+\varepsilon)^2}$$

and a finesse

$$
\begin{aligned}
F &\approx \frac{\pi\alpha\sqrt{R}}{1-\alpha^2 R} \\
&\approx \frac{\pi}{T+\varepsilon}
\end{aligned}
$$

It is sometimes useful to think of the Fabry-Perot cavity as an interferometer, and it is also useful to think of it as an optical resonator. If the input laser frequency is not near ν_m, the beam effectively just reflects off the first mirror surface (which after all does have a high reflectivity). If the input is equal to ν_m, however, then light leaking out from inside the cavity destructively interferes with the reflected beam. Right after turning on the input beam, the power inside the cavity builds up until the light leaking out in the backward direction exactly cancels the reflected input beam, and the beam leaking out in the forward direction just equals the input beam (neglecting cavity losses). Thus at ν_m the total cavity transmission is unity, and the light bouncing back and forth in the cavity is $\sim 1/T$ times as intense as the input beam.

Problem 1. Derive the above expressions for E_r and E_t as a function of δ when $\varepsilon = 0$. [Hint: write down a series expression that describes the sums of all the transmitted and reflected beams. Use reflected and transmitted amplitudes r and t, where $r^2 = R$ and $t^2 = T$. Then sum the series. Use the fact that if the reflected amplitude is r for light entering the cavity, then it is $r' = -r$ for light reflecting from inside the cavity (why? in one case, light is going from in air into glass; in the other case, light is going from glass into air).] Also derive the peak cavity transmission I_{peak}/I_0, and finesse F, in the limit $T, \varepsilon \ll R$. Plot the transmitted and reflected intensities, I_{tran}/I_0 and $I_{reflect}/I_0$, of a cavity as a function of δ for $R = 0.9$, 0.95, 0.99 and $\varepsilon = 0$.

The Optical Spectrum Analyzer. If we can scan the cavity length, for example by attaching one mirror to a piezo-electric transducer (PZT) tube, as shown in Figure 2, then we can make an interesting gadget called an optical spectrum analyzer. Scanning the spacing L (which equivalently scans the phase δ you used in your calculations) then scans the cavity resonant frequencies ν_m . If the laser beam contains frequencies in a range around some ν_0, then by scanning the PZT one can record the laser spectrum, as is shown in Figure 2. Note that there is some ambiguity in the spectrum; a single laser frequency ν_0 produces peaks in the spectrum analyzer output at $\nu_0 + j\Delta\nu_{FSR}$, where j is any integer. If a laser contains two closely spaced modes, as in the example shown in Figure 2, then the output signal is obvious. But if the laser modes are separated by more than $\Delta\nu_{FSR}$, then the output may be difficult to interpret.

In the lab, you will scan the laser frequency while keeping the cavity length fixed, but the resulting measurements are basically the same as if you scanned the cavity length.

Laguerre-Gaussian Modes. The above analysis strictly holds only for the 1D plane-wave case, and real cavities must have mirrors of finite extent. In this case, it's best to thing of Fabry-Perot cavities as full 3D optical resonators, rather than simply a set of two mirrors. By curving the mirrors, the cavity supports a set of trapped normal modes of the electromagnetic field, known as *Laguerre-Gaussian modes.* As long as the cavity has cylindrical symmetry, the transverse mode patterns are described by a combination of a

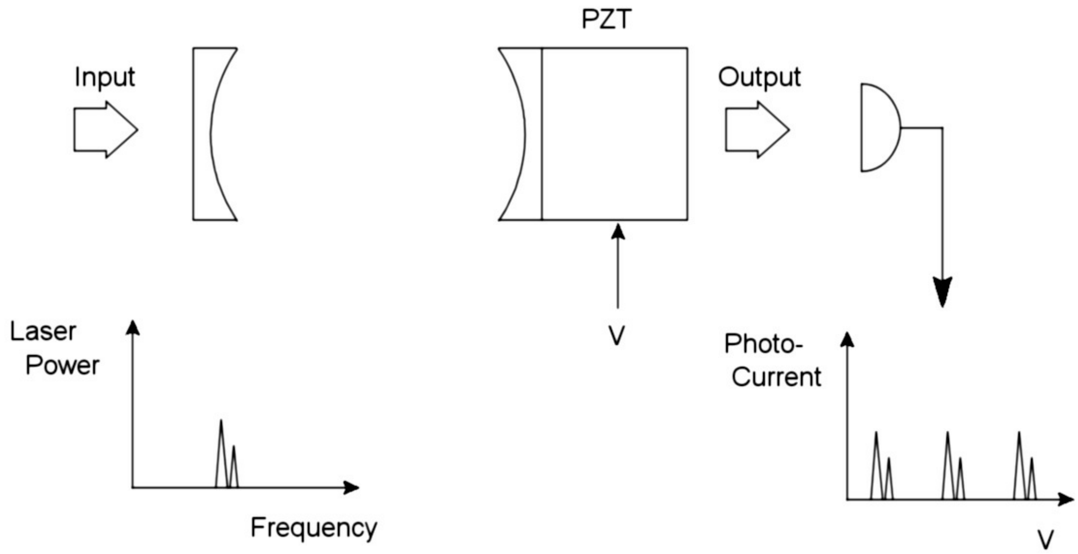

Figure 2. Using a Fabry-Perot cavity as an optical spectrum analyzer. Here the input laser power as a function of frequency $P(f)$ is shown with a multi-mode structure. By scanning the cavity length with a piezoelectric (PZT) tube, the laser's mode structure can be seen in the photodiode output as a function of PZT voltage $I(V)$. Note the signal repeats with the period of the cavity free-spectral range.

Gaussian beam profile with a Laguerre polynomial. The modes are labeled by $\text{TEM}_{p\ell}$, where p and ℓ are integers labeling the radial and angular mode orders. The intensity at a point r, ϕ (in polar coordinates) is given by

$$I_{p\ell}(r,\phi) = I_0 \rho^\ell \left[L_p^\ell(\rho)\right]^2 \cos^2(\ell\phi) e^{-\rho}$$

where $\rho = 2r^2/w^2$ and L_p^ℓ is the associate Laguerre polynomial of order p and index ℓ. The radial scale of the mode is given by w, and modes preserve their general shape during propagation. A sample of some Laguerre-Gaussian modes is shown in Figure 3.

This figure displays the transverse mode profiles; the longitudinal profile of the mode is that of a standing wave inside the cavity, which has some number n of nodes. The various modes with different n, p, and ℓ in general all have different resonant frequencies. The TEM_{00} mode has a simple Gaussian beam profile, and this is the mode one usually wants to excite inside the cavity. Lasers typically use this mode, and thus generate Gaussian output beams. As you will see in the lab, however, it is not always trivial to excite just the TEM_{00} mode inside a cavity.

Note that the mode shape shown in Figure 1 essentially shows w for a TEM_{00} mode as a function of position inside the cavity. The mode has a narrow *waist* at the center of the cavity, and diffraction causes the beam to expand away from the center. At the waist, the wavefronts of the electric field (or equivalently the nodes of the standing wave) are flat and perpendicular to the cavity axis. At the mirrors, the wavefronts are curved and coincide with the mirror surfaces, so the wave reflects back upon itself.

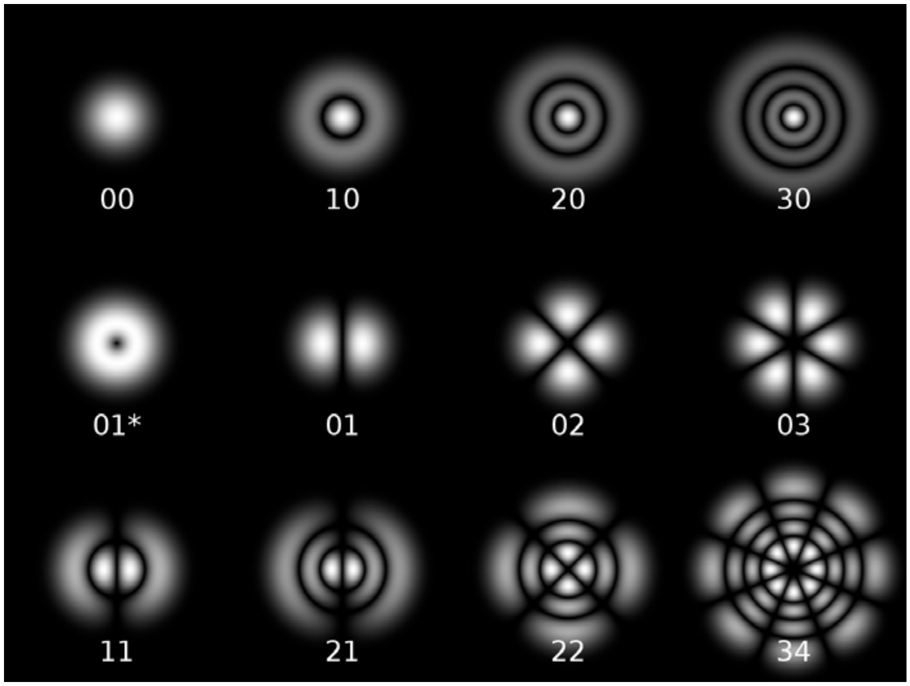

Figure 3. Several Laguerre-Gaussian modes, which are the electromagnetic normal modes inside a Fabry-Perot cavity. The TEM_{01}^{*} mode, called a doughnut mode, is a superposition of two (degenerate) TEM_{01} modes rotated 90° with respect to one another.

Confocal Resonators. An interesting (and useful) degeneracy occurs if we choose the cavity length to be equal to the radius of curvature of the Fabry-Perot mirrors, $L = R_{mirror}$. In this case, the mode frequencies of the various transverse modes all become degenerate with a separation of $c/4L = \Delta\nu_{FSR}/2$ (see Yariv, Section 4.6, for a derivation of this). For this special case, called a "confocal" cavity, the spectrum will look just like that shown in Figure 2, except the mode spacing will be $\Delta\nu_{confocal} = c/4L$. The width of the transmission peaks $\Delta\nu_{fwhm}$ stays roughly the same in principle, but in practice $\Delta\nu_{fwhm}$ depends on how well the cavity is aligned, and how precisely we have $L = R_{mirror}$.

Another nice feature of the confocal cavity is that the cavity transmission is insensitive to laser alignment. Figure 4 shows that each resonant mode in the confocal cavity can be thought of as a "bow-tie" mode, which traverses the cavity twice before retracing its path – hence $\Delta\nu_{confocal} = c/4L$. This is a crude picture, but it can be helpful in understanding the confocal cavity. It shows you in a rough way how the output spectrum might be insensitive to alignment, since the bow-tie modes are excited no matter where the beam enters the cavity. You will work with a confocal and non-confocal cavity in the lab, and hopefully this will all make good sense once you see it all in action.

FM Spectroscopy. In the radio-frequency domain, there exists a substantial technology built up around amplitude-modulation and frequency-modulation of an electromagnetic carrier wave (which gives us, for example, AM and FM radio broadcasting). If one boosts the typical carrier wave frequency from 100 MHz

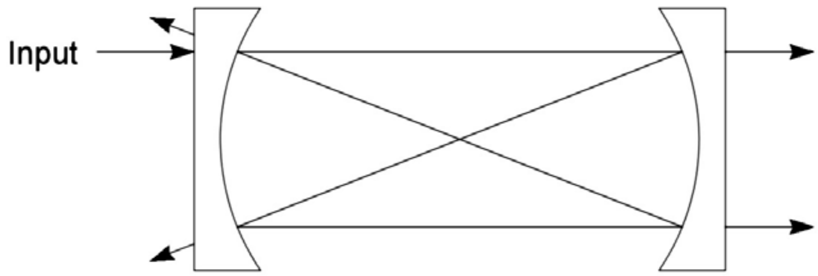

Figure 4. Ray paths for a confocal Fabry-Perot cavity (the off-axis scale is exaggerated).

(FM radio) to 500 THz (optical), the same ideas apply to AM and FM modulation of lasers. The resulting optical technology has many applications, the most dominant one being fiber-optic communications.

Modulating the injection current to the diode laser is a very simple way to modulate the laser output, both in frequency and amplitude. (Using non-linear crystal modulators is another way to modulate a laser beam.) The basic idea is that one drives the laser with an injection current which consists of a large DC part and a small high-frequency AC part on top. The AC part produces both AM and FM modulation of the laser, but we will ignore the smaller AM part for now.

For pure frequency modulation, we can write the electric field of the laser beam at some fixed location as:

$$\vec{E}(t) = \vec{E}_0 \exp(-i\omega_0 t - i\phi(t))$$

where $\phi(t)$ is the modulated phase of the laser output. We always assume that $\phi(t)$ is slowly varying compared to the unmodulated phase change $\omega_0 t$, since ω_0 is at optical frequencies, and our modulation will be at radio frequencies. If we're putting in a single sinusoidal phase modulation we have

$$\phi(t) = \beta \sin(\Omega t)$$

where Ω is the modulation frequency, and β, called the modulation index, gives the peak phase excursion induced by the modulation. If we note that the instantaneous optical frequency is given by the instantaneous rate-of-change of the total phase, we have

$$\begin{aligned} \omega_{\text{instant}} &= \omega_0 + d\phi/dt \\ &= \omega_0 + \beta\Omega\cos(\Omega t) \\ &= \omega_0 + \Delta\omega\cos(\Omega t) \end{aligned}$$

where $\Delta\omega$ is the maximum frequency excursion. Note that $\beta = \Delta\omega/\Omega$ is the dimensionless ratio of the maximum frequency excursion to frequency modulation rate.

It is useful to expand the above expression for the electric field into a carrier wave and a series of sidebands

$$\begin{aligned}
\vec{E}(t) &= \vec{E}_0 \exp[-i\omega_0 t - i\beta\sin(\Omega t)] \\
&= \vec{E}_0 \sum_{n=-\infty}^{n=\infty} J_n(\beta)\exp[-i(\omega_0 + n\Omega)t] \\
&= \vec{E}_0 \left\{ J_0(\beta)\exp(-i\omega_0 t) + \sum_{n=1}^{n=\infty} J_n(\beta)\left[\exp[-i(\omega_0 + n\Omega)t] + (-1)^n \exp[-i(\omega_0 - n\Omega)t]\right] \right\}
\end{aligned}$$

This transformation shows that our original optical sine-wave has now developed a comb-like structure in frequency space. The J_0 term at the original frequency ω_0 is the optical "carrier" frequency (in analogy with radio terminology), while the other terms at frequencies $\omega_0 \pm n\Omega$ form sidebands around the carrier. The sideband amplitudes are given by $J_n(\beta)$, which rapidly becomes small for $n > \beta$. Note that the total power in the beam is given by

$$\bar{E} \cdot \bar{E}^* = E_0^2 \left[J_0^2(\beta) + 2\sum_{n=1}^{n=\infty} J_n(\beta)^2 \right] = E_0^2$$

which is independent of β, as it must be for pure frequency modulation. Often one wishes to add two small sidebands around the carrier, for which one wants $\beta << 1$, and the sideband power is then given by $\sim J_1(\beta)^2 \approx \beta^2/4$. Evaluating the above sum, and convolving with a Lorentzian laser+cavity spectrum gives an output power

$$I(\omega) = J_0^2(\beta)L(\omega;\omega_0) + \sum_{n=1}^{n=\infty} J_n(\beta)^2 [L(\omega;\omega_0 + n\Omega) + L(\omega;\omega_0 - n\Omega)]$$

where $L(\omega;\omega_0)$ is a normalized Lorentzian function centered at ω_0.

Problem 2. Evaluate and plot the above optical spectrum, as you might expect to see it using your Fabry-Perot optical spectrum analyzer (remember that a photodiode measures optical *power*, not electric field amplitude). Plot versus frequency $\nu = \omega/2\pi$, which is what a frequency meter reads. Assume a Lorentzian laser+cavity linewidth of $\Delta\nu = 10$ MHz. Plot three curve with: 1) $\Omega/2\pi = 120$ MHz, $\beta = 0.5$; 2) $\Omega/2\pi = 30$ MHz, $\beta = 1.5$; and 3) $\Omega/2\pi = 1$ MHz, $\beta = 20$. Note for the last plot you will have to evaluate the sum up to fairly high n, at least to $n > \beta$. For $\beta \gg 1$, note that the spectrum looks much like what you would expect for slowly scanning the laser frequency from $\omega_0 - \beta\Omega$ to $\omega_0 + \beta\Omega$.

II. LABORATORY EXERCISES.

Your first task in this lab is to look at the light transmitted through a simple cavity using the set-up shown in Figure 5. Use the ramp generator in the laser controller to scan the laser frequency (ask your TA how), and monitor the photodiode output on the oscilloscope.

In order to get any light through the cavity, you need to align the incoming laser beam so that: 1) the beam hits the center of the first mirror, and 2) the beam is pointed down the cavity axis. The mirrors M1 and M2 provide the necessary adjustments to align the incident beam, and note that the different degrees of freedom are nicely decoupled – M1 mostly changes the laser position at the cavity, and M2 mostly changes the angle of the entering beam.

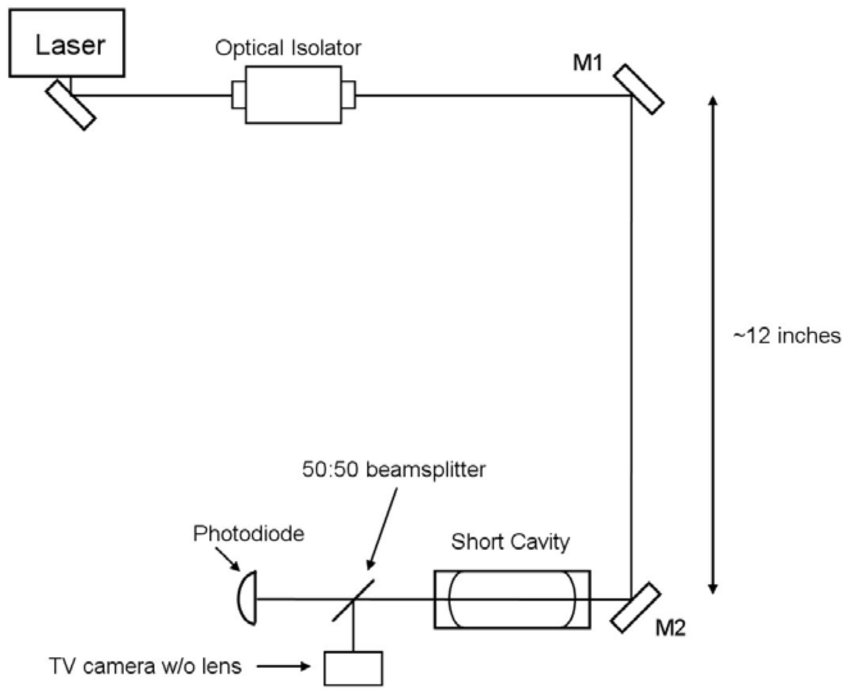

Figure 5. Optics set-up to view the light transmitted through the short cavity.

First adjust M1 so the beam is centered on the cavity, and then adjust M2 so the backreflected beam coincides with the incident beam. Use a white card with a hole in it to see the position of the backreflected beam. Iterate as necessary.

When this looks good, place a white card behind the cavity to view the transmitted beam. It will be faint, but you should be able to see a pair of bright spots, or perhaps a bright ring, on the card. To bring the transmitted beam to a single spot, you will probably need to "walk" the input beam, which is a way to systematically sample the 4-dimensional alignment space defined by the four adjustments of M1 and M2. Your TA can show you how. Once you have the transmitted beam down to a single, sharp spot, place the photodiode to intercept the beam, and place the TV camera to view the shape of the beam.

With the sweep on, you should see a forest of peaks on the transmitted signal. Each peak corresponds to a single cavity mode you are exciting with the laser. Each $\mathrm{TEM}_{np\ell}$ mode has a slightly different frequency, so each gives a separate peak. In addition, the spectrum repeats with a period of $\Delta\nu_{FSR}$. If you tweak the alignment of the incoming beam slightly, you will see the peaks all change height. This is because you excite different modes with different alignments.

With the sweep off, you can examine the shapes of the different modes using the TV camera. Move the piezo DC offset adjust to select different modes. Compare with Figure 3 above. **Print out an oscilloscope trace showing a typical scan, and tape it into your notebook.**

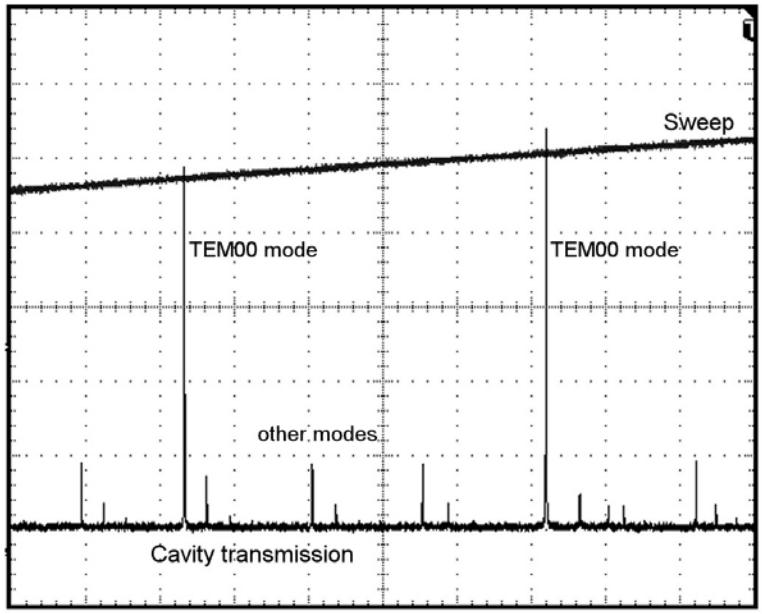

Figure 6. The cavity transmission with fairly good mode matching. Note the dominant TEM_{00} modes separated by $\Delta\nu_{FSR}$. The peaks heights are very sensitive to alignment and even to vibration.

Mode Matching. Now you should try to excite just the TEM_{00} mode of the cavity, which means you have to *mode match* the incoming beam to the cavity mode. If you think about the mode inside the cavity (see Figure 1), you can see that the beams leaking out of the cavity diverge in both directions. You can see this if you use a white card with a hole in it placed far from the cavity. The reflected beam from the cavity will make a large spot on the card, much larger than the incoming beam. Thus the input beam is not well matched to the cavity modes.

To match the TEM_{00} mode, the incoming beam should be converging. You can achieve this by placing a 500mm focal length lens about 11 inches in front of the cavity. Before aligning the cavity, note that the size of the reflected beam is now about equal to the incoming laser size, so the mode match is better than before.

Align the cavity with the lens in place and view the transmitted signal. You should see fewer large modes. Turn the sweep down to identify the different modes on the TV. Find the TEM_{00} mode, and tweak the mirror alignment to maximize this mode while minimizing the others. With some effort, you can produce a transmitted signal that looks something like that shown in Figure 6, with dominant TEM_{00} peaks separated by $\Delta\nu_{FSR}$. You cannot do much better than this, even in theory, for two reasons: 1) the mode-matching lens is actually not quite right to match to the cavity, so you are bound to excite some other modes; and 2) the incoming laser beam is itself not a perfect TEM_{00} mode (expand the beam with a lens and you can see that it doesn't have a perfect Gaussian shape), which means it contains other modes at some level. **Print out a trace showing your best TEM_{00} modes.**

The Confocal Cavity. The next task is to set up the confocal Fabry-Perot cavity as shown in Figure 7 and to look at some of its properties. Unlike the previous cavity, the confocal cavity is insensitive to the precise alignment and mode matching of the input beam, because the different transverse modes are degenerate in frequency (see the discussion in Section I above). Nevertheless, you still have to align things reasonably well, using the same procedures described above.

Observe the Mode Structure of the Cavity. Align the input beam and adjust the cavity length until the transmitted signal shows a series of sharp peaks (much different than with the non-confocal cavity!). Tweak the cavity length so the peaks are narrow and symmetrical, which should maximize the transmitted peak intensity. Once that looks good, change the cavity length by a large amount (say 10 turns of the mounting tube) and observed the transmitted spectrum. As the cavity length is changed away from the confocal length, the transverse modes are no longer degenerate. At first, you see the peaks broaden and become asymmetrical. Then, as you change the length more, you can see individual mode peaks show up. Change the input beam alignment to see the different modes change in amplitude. **Print out a few spectra with different cavity lengths.**

Measure the Transmitted and Reflected Intensities. Adjust the cavity length to its confocal value, and align the input beam to maximize the height of the transmitted peaks. Tweak the length and alignment with some care to produce sharp, symmetrical peaks with the highest possible amplitude. When that looks good, insert a "pick-off" mirror somewhere in the beam and send it to the second photodiode. Use the mirror to maximize the photodiode signal on the oscilloscope (so the beam is centered on the photodetector), and measure the output voltage (and note the photodiode gain). It works well to use the "measure" feature on the oscilloscope to measure the average output voltage. With care, you could convert this voltage to milliwatts of laser power, but you will be taking power ratios, so you don't need this conversion.

Without changing the cavity alignment, set up the second lens and photodiode as shown in Figure 7. Again make sure the beam is centered on the photodetector and measure the output signal. The value should be about 25% of what you measured previously (because the beam intensity was diminished twice by the 50:50 beamsplitter). If you don't get within a few percent of that value, something is wrong (probably the alignment).

Next send the first photodiode signal directly into the oscilloscope along with the second. Note that the dips in reflected light correspond to the peaks in transmitted light, as you would expect. Measure the peak widths and make sure they are greater than 20 μsec, so that the photodiode is fast enough to record the full peak. If not, use a slower scan. **Measure the height of the transmitted peaks and compare with the input beam intensity, to produce a peak transmitted fraction**. Keep in mind the photodiode gains, which may be different, and how many times the various beams went through the beamsplitter. You should be able to produce a transmitted fraction between 5% and 10%. If your measurement is above 10%, you probably made an error somewhere (or your cavity alignment is amazingly good). If

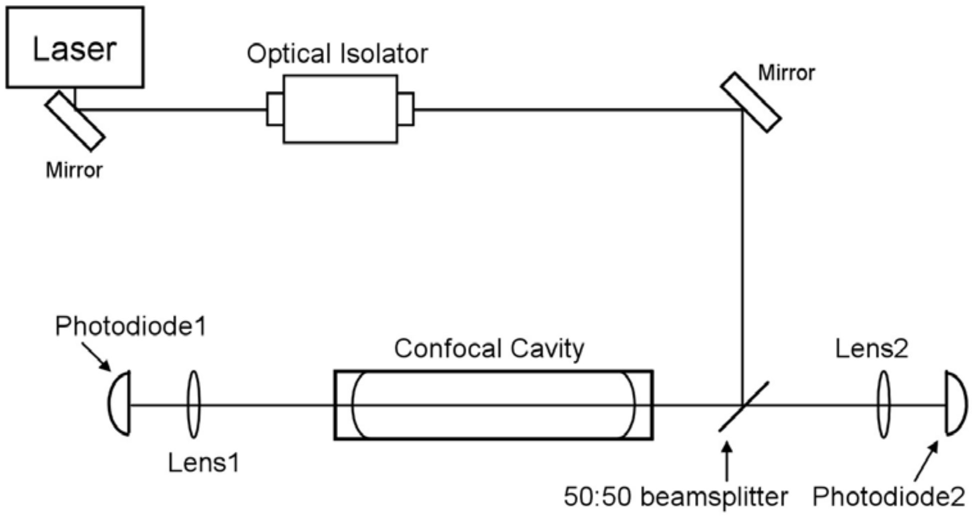

Figure 7. Optics set-up for the confocal cavity.

your measurement gives you something below 5%, again check for simple errors. If that's not it, tweak the cavity length and alignment until the peak transmitted fraction is above 5%. When everything looks good, **print out the spectrum showing sharp peaks.**

Measure the Cavity Finesse. Capture a single sweep on the oscilloscope and use the built-in cursors to measure the effective finesse of the cavity. Measure the spacing between the peaks (the free spectral range) and then change the time-base on the 'scope and measure the full-width at half-maximum of the peaks. The effective finesse is then $F = \Delta\nu_{FSR}/\Delta\nu_{FWHM}$. You should get $F > 100$ or even $F > 200$ if the cavity is well aligned.

Why is the transmitted peak intensity only 5%, when in principle it could be 100%? Part of the reason is losses inside the cavity, as described in the discussion in Section I, but that's only a small part. Calculate about how great the losses would have to be to produce a 5% transmitted intensity, assuming a mirror transmission of 1%. The actual mirror losses are probably less than 0.1% per bounce (unless the mirrors are very dirty, which they shouldn't be).

The main reason for the low transmitted intensity is that the mode degeneracy is not perfect. If you change the cavity length or input beam alignment only slightly, you can see the peak height drop quickly. Since the input beam is not mode-matched to the cavity, the transmitted intensity of any given mode is fairly low. And if the modes are not perfectly degenerate, they don't overlap well, resulting in a low peak intensity. With a non-confocal cavity and a well mode-matched beam, it is possible to achieve a peak transmitted intensity close to 100%. However, for simply looking at the frequency structure of a laser (i.e., with an optical spectrum analyzer), the confocal cavity is quite convenient to use, even with its lower transmitted intensity.

FM Spectroscopy. Next you should observe the FM spectra you calculated in the prelab exercises, using the confocal Fabry-Perot cavity as an optical spectrum analyzer. With the transmitted signal showing nice sharp peaks, reduce the sweep to zoom in on a single peak. Then take the RF function generator, turn it on, and feed it into the RF Input BNC of the diode laser. (NOTE: Do not disconnect the cable from its connection at the laser. The laser is sensitive to static discharge, which can easily burn out the diode. Also turn the RF generator on *first*, and then feed the output into the laser. This helps avoid voltage spikes that may occur when you turn the generator on.)

As you vary the oscillator frequency $\Omega/2\pi$ and the amplitude (which changes $\Delta\omega$ and thus β), you should observe the range of behavior you calculated. **Record several traces that correspond as closely as you can achieve to your three calculated plots.** You should get pretty good agreement (if not, check with the TA). One significant difference between calculated and measured spectra is that the measured spectra may be asymmetric. This is due to residual *amplitude* modulation of the laser, which we did not include in our pure FM calculation.

Measure the Free-Spectral Range. Finally, put two high-frequency sidebands on your laser, **print out a spectrum**, and use the known sideband frequency to measure the free-spectral-range of the Fabry-Perot cavity. Compare with what you expect for a cavity length of 20 cm (equal to the radius of curvature of the mirrors).

III. REFERENCES

Yariv, A. 1991, *Optical Electronics*, Saunders College Publishing, 4th ed.