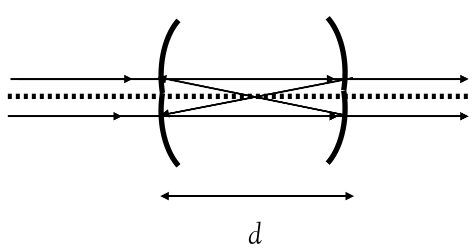
Lab 7

The Confocal Fabry-Perot Interferometer and the Longitudinal Modes in a HeNe Laser

Before lab: *Read over Bennett 5.10. You do not have to work through the math (we'll do that in class) but look over the diagrams and try to pick up some of the "lingo." Application note 5.4 at the end gives a brief introduction to the HeNe laser. Then start on Bennett Chapter 7. Again, don't worry about equations. You are principally interested in the HeNe laser so you can skip over the discussion of molecules, solids and semiconductors if you like. Once you have read 7.4.1.1 on the HeNe you can skip to 7.5 and stop when you finish that. We'll come back to some later sections next week when you will be putting together a HeNe.*

A Fabry-Perot interferometer (FPI) consists of two partially reflecting mirrors facing each other. Today we will be dealing with two different Fabry-Perot interferometers. One is a laser cavity and the other is a confocal interferometer that we will use to analyze the light from the laser.

First, consider the laser cavity itself. This consists of a flat high reflector at the "back" end and a curved "output coupler" on the front which lets 1% or so of the light escape out of the laser every pass. The laser cavity is carefully aligned so that the light is going down the axis ("lowest transverse mode"). In such a device, as in a mechanical string with two fixed ends, we find resonances when any integer number, n, of half wavelengths of light fit exactly into the length, d, of the laser cavity (that is: $d = n\lambda / 2$). Or to put it another way: the path length difference accumulated on one round trip across the cavity and back is $2d$ and when $2d = n\lambda$ all of the waves are in phase. Note that because the optical wavelength is so small that in a laser the size we are using $n \approx 10^6$! Resonance means that lots of light energy is built up inside in the cavity, which means that a comparatively large intensity of light leaks out. It is convenient to restate the resonance condition in terms of the frequencies of light for which there is maximum output. These frequencies are evenly spaced and depend inversely on the cavity length: $f_n = n\left(c/2d\right)$. The difference in frequency between consecutive cavity modes is defined as $f_{FSR} = c/2d$, the "free spectral range" (FSR).



Now consider the external confocal FPI mounted on the four post "cage" on your optical breadboard. It has a pair of spherical concave mirrors with very high reflectivity (>97%) at the HeNe laser wavelength. The mirrors have radius of curvature *R=38.6 mm.* For such a mirror, the focal point is at *R/2*. If we arrange these two mirrors in a "confocal" geometry (i.e. sharing a common focal point) they are spaced by twice the focal length, i.e. by distance *d*=*R*.

As suggested by the figure, the resonant wavelengths for this structure occur when the light is has gone through an integral number of wavelengths in *two* round trips of the cavity, i.e. by: $d = n\lambda / 4$. Hence the resonant frequencies are $f_n = n(c/4d)$, and the free spectral range is $f_{FSR} = c/4d$. A resonance inside the cavity means that a lot of light it transmitted by the cavity. Note that because the mirror reflectivities in both the laser cavity and the external cavity mirrors are high, both cavities are high-Q resonators, that is the width of the resonance peaks is only a small fraction of the resonance frequency.

The figure below shows in more detail the modes (standing wave patterns) in a optical resonator. You might find it clears up some questions raised by the geometric optics picture sketched above. Looking at the diagram for the "near planer" regime, the closely spaced modes labeled 0,1,2,3,4,5 differ in their transverse behavior. In the case of the laser, the cavity is carefully aligned so that we only excite the modes labeled "0" (i.e. those right along the axis). (In a later lab we will see that it is possible to excite the other modes if you open up the laser and fiddle with the mirror alignment). The free spectral range (labeled "$\Delta\omega_{ax}$" in the figure) , that is the change in frequency to go from *q-1* to *q*, is $\frac{c}{2L}$. In the case of the confocal cavity, if we excite some mixture of modes (and that is usually what happens unless one is very careful about controlling the way the light couples into the cavity) the apparent spacing is half as big, $\frac{c}{4L}$, as suggested by the geometric optics picture given above.

19.3 GAUSSIAN TRANSVERSE MODE FREQUENCIES 763

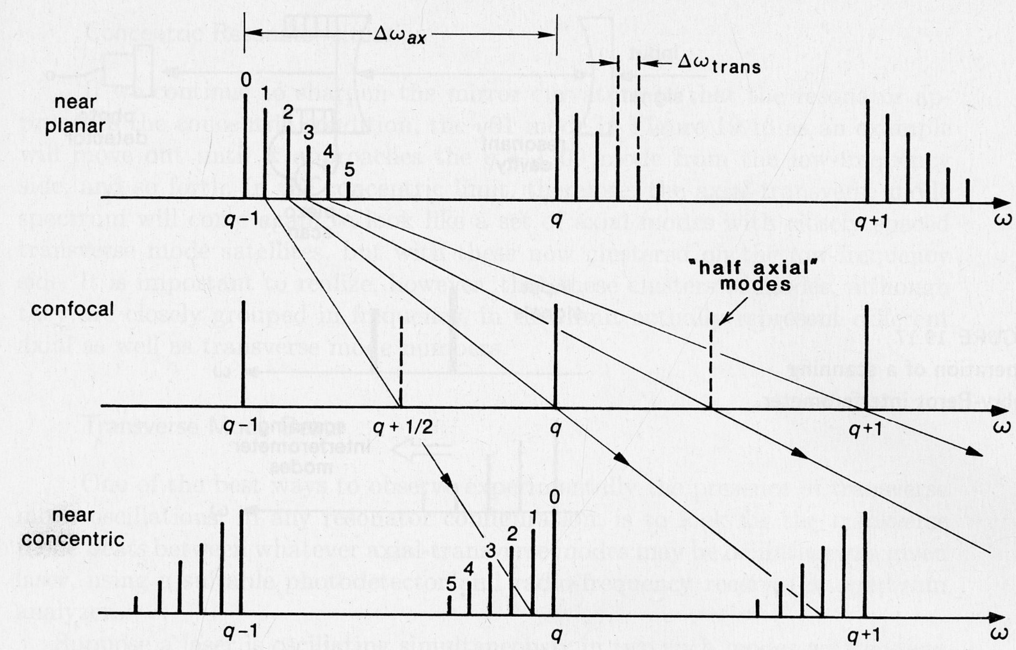


FIGURE 19.16
Transverse mode frequencies in various stable gaussian resonators.

from Siegman, *Lasers*

Part I. Spectral analysis of a HeNe laser using the confocal FP cavity

1. *Identify the parts.* Look at the setup and identify the following items: 2 HeNe Lasers (one portable, small 1 mW laser; one pre-mounted, longer, 10 mW laser), two mirrors to turn and steer the beam into the confocal cavity, the cage containing the concave cavity mirrors, the wires connected to one mirror (for fine tuning the cavity length via piezoelectric elements), a photodiode to detect transmitted intensity and a filter to let through only light near 633 nm. The three piezos which push on the mirror are driven by a voltage from an amplified function generator.

   You will be using many nice features of the digital oscilloscope today. Remind yourself about some of the various options like 'DISPLAY' (to turn on or off the 'persistence' of the trace), 'CURSOR' (to measure distances in x or y direction), 'RUN/STOP' (to freeze the trace).

2. *Set the scanning voltage.* The function generator should be set to make a triangle wave, and the power supply for the amplifier set to about 40-50 V. This voltage, applied to the piezos in the mount, causes the length of the Fabry Perot cavity to be being scanned back and forth. The function generator should be connected to the scope (say CH 1), as well as to the piezo control box. Adjust the function generator to produce a 5 Hz triangle wave. You should adjust the horiz axis to see one up (or down) ramp on the screen.

3. *Coarse positioning of the FP mirrors.* Now let's set up the FP cavity. *Note: These cavity mirrors cost of order $1000 a pair, and one fingerprint or scratch will do severe damage to them. Only touch the mounts, keep fingers away from the optical surfaces, please!* Above, I listed the radius of the concave mirrors. Adjust the micrometer on the second cavity mirror to the middle of its range, and carefully slide the entire back mirror mount along the rails towards the front mirror until the cavity length is measured (via a ruler) to be correct for the 'confocal' condition. [FYI: the inside distance from mirror mount to mirror mount is about 5 or 6 mm less than the distance from mirror center to mirror center.] Get as close as you can with this 'coarse' alignment (to within 1 or 2 mm).

4. *Beam alignment.* Set up two turning mirrors to direct the laser light into the cavity. Keep the beam level and centered on each mirror. Look at the beam spot entering the confocal cavity to make sure it is centered. Now look for evidence of several spots on the back mirror. The idea is to get these several spots to merge into one, while keeping the spot on the input side centered. You will need to adjustment both turning mirrors together to achieve both translation and rotation of the beam. Be patient, make a small movement with one, then optimize with the other. Also look for the very divergent large spot reflected from the front face of the cavity, and center this back on the laser output hole (The orientation of the spherical mirrors is relatively non-critical (unlike plane mirrors which need to be very accurately parallel to function as a Fabry-Perot.)

5. *Place the photodiode.* Line up the photodiode with the transmitted light from the cavity. If you place the 633 nm interference filter right in front of the photodiode, you can work with the

room lights on. Make sure that the little amplifier box attached to the photodiode is turned on, and that its output is hooked up to the scope.

6. *Fine tune the FP cavity length.* Hopefully you can see some small peaks in the photodiode signal. Slide the photodiode around to optimize this. The exact confocal geometry can now be found experimentally by observing the Fabry-Perot peaks. When the geometry is not quite confocal you will see, (a) very small peaks and (b) a confusing jumble of peaks due to all the transverse modes. Even with a complicated set of peaks, you should see a repetition of the pattern about half way across the scope trace. Use the micrometer on the rear mirror mount to fine tune the cavity length. (It is possible that you will need to do more coarse tuning by gently moving the rear mirror mount along the rails). As you get closer to the right length the peaks should grow in size, become sharper, and the pattern should begin to simplify noticeably (it won't ever become just a single peak). Note that the repetition period of the pattern remains the same. You can also adjust the screws on the front FPI mirror. If necessary, you can fine-tune the input alignment also to optimize the signal. The goal is to get max peak height, maximum sharpness (i.e. minimum peak width), and symmetric-looking peaks. This takes some patience.

   When you are done, you should see two complete sets of several FP transmission peaks. The max photodiode voltage of these peaks when the optical system is tuned up nicely is around 1 volt - if yours are way smaller the FP is probably not lined up correctly.

7. *Calibrate the x axis on the scope.* Now with the interferometer tuned up we can use it to study the laser. We are going to use the letter n to represent the integer number which characterizes a particular mode of the laser cavity, and we will use m to represent the mode number associated with the scanning confocal FP cavity. The x-axis (which is really time) is effectively mirror position (i.e. change in length d) and hence effectively frequency (modulo the FSR of the FP cavity!). The overall repetition time on the scope trace of the complete pattern of peaks must correspond to consecutive modes of the confocal cavity (say m and $m \pm 1$). Measure the time difference between the FP modes on the scope (you might want to increase the persistence time and use the Run/Stop button to freeze the action). You can calculate the f_{FSR} of the Fabry-Perot from the known radius of curvature of the mirrors.

   With this information you can find the frequency difference between any two light frequencies coming into the interferometer (assuming that the frequency difference is less than one free spectral range!).

   By the way, what is the physical distance that the mirror is moving during a scan?

8. *Measure the laser frequency splittings.* Now that you have calibrated your frequency axis focus on one set of peaks (i.e. the m^{th} mode of the FP cavity). It should be clear that the laser is not exactly monochromatic. The overall range of frequencies which can be produced by the HeNe depends on the atomic emission properties of the neon gas. One can easily work out that at the gas temperature, the Full width @ $1/e$ height of this Doppler-broadened profile is around 1 GHz. We call this the 'gain curve' of the laser. For this particular laser the cavity length is such that there are typically two or three cavity modes (values of n) which have frequencies that lie

within the 1 GHz range set by the atoms. As the laser tube expands or contracts those modes will drift in frequency relative to the fixed gain curve set by the atoms. You should be able to observe that behavior.

What is the experimental FSR for the laser cavity modes? (*You want to be making time measurements on the scope and then convert those to frequency differences using the calibration factor you found in the previous section*). Convert your FSR value to an effective length of the laser cavity and compare to the physical length, which is almost the length of the laser housing. (Turn the laser off while you do this calculation, we want it to cool down a bit before the net part).

9. *Drifting modes.* After the laser has cooled off for a couple of minutes, turn it back on and observe the drifting of the modes. As the laser tube warms up and expands, you should see the modes walking across the screen. Does the positive *x*-direction on the scope indicate higher or lower laser frequency? Given that the length change of the glass tube is probably about $\Delta d / d \approx 10^{-5} / {}^{0}\mathrm{C}$, how much is the temperature of the tube changing in 1 second?

10. *Gain curve.* To get a sense of the laser gain curve set the "Persistence" on the scope to "Infinite." You will now see the laser modes continue to walk, but the scope will not refresh. Let things proceed until the gain curve of the laser is evident. Note that it's roughly Gaussian shape. Using the cursors, measure the full-width of this curve at about *1/e* (i.e. about 1/3) of the maximum height and convert to a frequency width. In this kind of a gas laser the width is predominately determined by the Doppler shift of the moving atoms.

11. *Try the shorter laser.* Turn off the 10 mW laser, and turn on the shorter, 1 mW laser. You should be able to position it on the table in front of the 10 mW laser. Adjust its angle 'by hand' until you see the laser spots on the cavity mirrors in about the right place, then use the controls of the turning mirrors to complete the alignment. Fine tune to obtain maximum signal again looking at the scope. (*You do not need to adjust the interferometer itself, only the way the light goes in*).

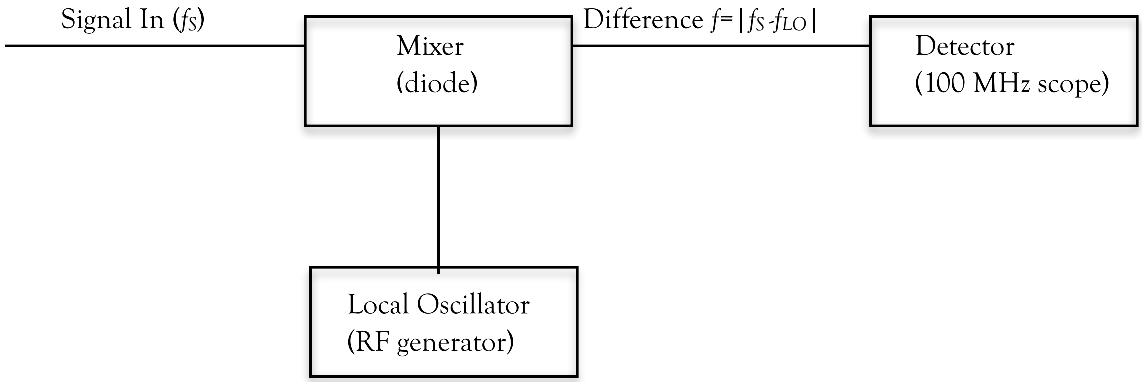
    What are the similarities and differences in what you see with this new laser. What is the new laser's FSR? Is this what you would expect based on its physical size(explain)? Compare the laser mode drifting behavior to what you saw before.

    You will probably see that the gain curve here looks somewhat different from the other laser. I believe that the peak of the Doppler-broadened Gaussian curve is not visible because of something called gain saturation. The number of atoms in the excited state is a balance between the rate at which they are pumped up by the discharge and dumped down by the light. If the light intensity gets high enough it can reduce the effective gain. Apparently in this shorter laser the conditions are such that this is more noticeable than in the other laser.

12. *Measure the finesse.* Finally, using either laser, measure the sharpness or "finesse" of the peaks produced by the confocal cavity. First re-optimize the peaks (height and sharpness) which may have drifted. The finesse is defined as the ratio of FSR/FWHM of the resonant peaks. You may wish to blow up the x-axis scale, and use the Run/Stop feature and cursors to measure this ratio. Ideally, the finesse only depends only on the reflectivity of the mirrors, and is given by $F = \frac{\pi\sqrt{R}}{1-R}$. Compare the measured finesse to that predicted for mirrors with reflectivity *R≈95%*.

Part II. Time domain measurements. *[There is one shared setup in the outside room].*

As you saw above, the light from one of the 10 mW HeNe lasers actually contains two or three discrete frequencies. Imagine that there are two equal amplitude modes at frequencies f_1 and $f_1 + f_{FSR}$. Show that there will be a term in the intensity of the laser which oscillates at f_{FSR}. This should be detectable with a photodiode.



In order to look for such a signal it is convenient to supply an auxiliary "local oscillator" at a frequency very near the signal frequency and use a non-linear mixer to produce a intermediate signal at the difference frequency ($|f_{LO}$-$f_s|$). This lower "intermediate frequency" signal can be detected by a relatively slow device (in our case an ordinary oscilloscope).

1. *Set up the circuit.* Find the fast photodiode (which is followed by an amplifier). The optical alignment is trivial: simply shine the 10 mW laser straight into the photodiode. Before switching anything on, hook up the rest of the circuit. The local oscillator is a (fancy) 0- 900 MHz signal generator. When the circuit is connected, turn everything on (note the switch on the photodiode box – there is a battery inside there). The mixer wants a local oscillator signal of about 0 dbM (=1 mW). Set the scope to the most sensitive voltage scale. Adjust the frequency of the signal generator to be near what you measured for the mode splitting (if you are within 10's of MHz of the right frequency you should see signal on the scope.

2. *Measure the frequency.* Once you have a signal, tune the frequency of the oscillator and verify that the difference frequency you observe on the scope behaves as expected. You should be able to measure the mode splitting quite accurately (and observe that it moves around a little in time).

3. *Compare.* How does this measurement compare to your earlier measurements with the Fabry-Perot?