SCANNING FABRY-PEROT INTERFEROMETER AND PHOTOMIXING

Brief Overview
Experiments #7 and #8 will use the same lab setup. They can be treated as a single experiment that requires two lab periods to complete. You will do these two experiments in two consecutive weeks. Readings and prelab questions are divided into two separate assignments.

In this set of experiments you will learn the use of scanning Fabry-Perot interferometer and build one yourselves to study Gaussian modes. You will study the modes of a single laser and the beating of two different lasers. You will study the properties of the laser modes using a high Finesse scanning Fabry-Perot cavity and through an interference effect called photomixing in a fast photo-detector. The combined analysis of scanning Fabry-Perot interferometry and photomixing will help you understand use of the scanning Fabry-Perot and some of the aspects of laser mode dynamics (see background information below).

Theoretical and Instrumentation Background: Photomixing and laser modes

If two waves, \( E_1 \) and \( E_2 \), with different optical frequencies, \( \nu_1 \) and \( \nu_2 \), are incident on a photodetector, a difference or "beat" frequency can appear at the output of the detector. (Detectors are often called "mixers" when used in this fashion.) If the two propagation vectors, \( k_1 \) and \( k_2 \), make a small angle \( \theta \) with respect to one another and the polarizations of the waves are parallel, then the total electric field \( E_1 + E_2 \) will produce an intensity variation

\[
I(y,t) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \left( 2\pi \left( \nu_1 - \nu_2 \right) t - 2\pi \theta \frac{y}{\lambda} \right)
\]  

(1)

We can get some measure of the time variation of Equation 1 with a photo-detector – a device that produces an electronic current which is proportional to an averaged intensity on the detector. In order to actually observe the time variation, we must have that \( \theta \) and the width of the detector in the y–direction must be small enough to keep the cosine term from averaging to zero spatially. The two beams need to be very well aligned to keep the spatial fringes larger than the photodetector (for comparison, in Experiment 3 we magnified the interference pattern to be larger than the photodetector). The time response of the photocurrent (limited by the physics of the detection mechanism) must be fast enough to measure the mode beating frequency \( \left( \nu_1 - \nu_2 \right) \).

In Experiment 4 both beams came from the same laser, but by moving the mirror at a constant velocity we were able to make \( \nu_1 \) and \( \nu_2 \) differ by a few kHz. In this experiment, \( \nu_1 \) and \( \nu_2 \) will be either two different modes of the same laser or modes of two different lasers, and \( \left( \nu_1 - \nu_2 \right) \) will be in the frequency range 0 – 1.5 GHz.

To observe the beating, we will need to use a device called an electronic spectrum analyzer (ESA). This device analyzes the frequency composition of a time-dependent electrical signal, like the current from a photo-detector. Heuristically, the input electrical signal is passed through a very narrow band-pass filter, which is scanned over a wider frequency range. The power of the transmitted signal is then recorded, so we can observe how the power of the electrical signal is distributed in frequency, basically a display of integrated electrical power vs. frequency. With APh24’s ESA, we will be able to observe the spectrum anywhere in the range from 0 to 1250 MHz. The intensity beating caused by frequency differences, so
called “mode beating”, will appear as sharp peaks separated by several hundred MHz, well within the ESA’s scanning range. Obviously (at least it should be), we will not be able to directly observe intensity variations in the optical frequency range varying as $\nu_1$, $\nu_2$, $\nu_1 + \nu_2$, etc.

To better understand this experiment, we need to review some basics about lasers and describe the phenomena of mode pulling. In the simple picture given so far, a laser is essentially a Fabry-Perot interferometer (FP) with an amplifying medium inside of it. The amplifying medium (He-Ne gas, ruby crystal, silicon dopant, etc…) can increase the amount of emitted power in a given frequency range. Neglecting the FP effect of the laser’s mirrors, the amplification or gain will follow a smooth peaked curve in frequency. This is illustrated by the bell curve (black) on the left graph of Figure 1. Above a certain gain level, the so-called oscillation threshold, sustained amplification or lasing can occur. However, only certain frequencies, the FP resonances, are allowed in the cavity. As you may recall from APh23 Lecture #5, these resonances are separated by the free spectral range the cavity $\Delta\nu = c/2L$. The resonances are illustrated by the vertical (red) lines in the left graph of Figure 1. Thus, the emitted frequencies will be the laser’s FP resonances which have gains that are above the oscillation threshold. These emitted frequencies are called laser modes. The extent that the gain curve is above threshold determines how much relative power is allocated in each mode. Stronger modes are closer to the peak of the gain curve. Weaker modes are closer to the threshold gain. As you may recall from APh23 Lect #5 and its demo, we can observe the laser modes and their relative strengths with a diagnostic scanning Fabry-Perot (SFP). To illustrate, in Figure 1 the gain curve shown by the graph on the left would produce a SFP spectrum similar to the graph on the right. In Figure 1, only four resonances happen to be above threshold and are (nearly) symmetrically placed about the gain curve maximum. In a real laser, the length of the laser will thermally drift. The resonances will shift relative to the gain curve, resulting in a fluctuating power distribution among the lasing modes.

Figure 1. Laser Gain Curve for a He-Ne laser and the Spectrum Seen with a Scanning FP

The actual lasing frequencies, in practice, are approximately, but not exactly equal to the Fabry-Perot resonances with vacuum in between the mirrors. It turns out that gain medium introduces a phase shift to the light in the cavity. As you may recall from basic mechanics or the model of dispersion discussed in APh23, when you are near a resonance, there is a corresponding phase shift. This phase shift alters the Fabry-Perot resonance condition inside the laser cavity. For a lasing medium, the frequency region below the peak of the gain curve is phase retarded, that is, the light’s phase is behind where it would be in vacuum. To compensate, a slightly higher frequency than the empty-cavity mode frequency is needed to be resonant in the laser cavity. Thus, the actual lasing frequency is slightly higher than the cavity mode frequency. We say the mode has been pulled higher. The frequency region above the peak of the gain curve is phase advanced, that is, the light’s phase is ahead where it would be in vacuum. To compensate, a slightly lower frequency than the empty-cavity mode frequency is needed to be resonant in the laser cavity. The actual lasing frequency is lower than the cavity mode frequency. We say the mode has been pulled lower. Right at the peak of the gain curve, there is no phase shift. If a cavity mode happens to fall right at the gain peak, the actual lasing frequency will not be shifted from the cavity mode resonance. In general, the further the modes are from the peak of the gain curve, the more shifted they will be. If the cavity modes are symmetric about the gain curve peak, then
the actual lasing frequencies will also be shifted symmetrically: modes to the left of the gain peak will shift up by the same amount that modes to the right of the peak are shifted down in frequency. If the cavity modes are asymmetric about the gain peak, then the mode shifts will also be asymmetric.

If you have any questions concerning the laser mode description above, you should discuss it with TA in the lab.

Prelab assignment:

First week (Exp#7):

1. **Review and reading**: Review Hecht 9.6.1. Also read Hecht 13.1.3 (this section is important to understand some of the experiment questions). Skim over section 12.2 of Siegman’s “Lasers”. Yariv’s Quantum Electronics book also has good descriptions of Fabry-Perot cavity resonator and its stability. Go through the introductory part of the photomixing above at the beginning of the handout. Do the following problems in your notebook.

2. **Scanning Fabry-Perot Interferometers**.

   (a) (40 pts) Summarize briefly the important formulas you've learned about Fabry–Perot (FP) interferometers. Define all quantities, such as free spectral range, finesse, transmission linewidth and spectral resolution, etc. In a scanning FP, the spacing between two mirrors is linearly ramped. How does this change the transmission frequencies of the FP? What would be scanning rate \( df_0/dL \) where \( f_0 \) is a FP resonant transmission frequency and \( L \) is the PF mirror spacing?

   (b) (30 pts) A Fabry–Perot interferometer has a mirror spacing of 10 cm and a finesse of 200. What is the effective reflectivity of the mirrors? If the spacing between the mirrors were to increase linearly with time (scanning), what fraction of the time would monochromatic light pass through it (approximately)?

   (c) (30 pts) A Fabry-Perot (FP) spectral analyzer has a free spectral range (FSR) of 10 GHz. Sketch the spectrum (transmission in vertical axis vs. Fabry-Perot frequency scan in horizontal axis) you expect to observe over three FSR in the following cases: 1) a laser with a single frequency, 2) a laser emitting two frequencies separated by 200 MHz, with different intensities; and 3) a laser emitting two modes separated by 13 GHz. Discuss your observation of using scanning FP analyzer to determine a laser spectrum.

Second week (Exp#8):

3. **Alignment** (30 pts). How well aligned in angle must two He-Ne laser beams be to produce a beat signal on a photodiode 0.1 mm by 0.1 mm? If the both beams have a 1 mm diameter and pass through a 1 mm diameter hole, how close must the spots be at a 1-meter distance from the hole to satisfy this alignment?

4. **Laser Mode Beating**. For now, assume a laser’s emitted frequencies are only determined by the Fabry-Perot resonances, which, in turn, are determined by the length of the cavity \( L \). Assume the laser emits at a few frequencies \( f_m = mc/2L \), \( f_{m+1} = (m+1)c/2L \), … where “\( m \)” is the mode number (number of half wavelengths in the cavity).
(a) (20 pts) If the length of the cavity is perturbed by \( \delta L \), calculate the change in the emitted frequency \( \delta f_m \) of the \( m \)th mode. Numerically evaluate this expression for typical parameters: \( L = 30 \) cm, \( \lambda = 632.8 \) nm, and \( \delta L = 0.01 \) micrometers r.m.s. (a rough estimate of the optical table’s vibrations).

(b) (20 pts) Assume this laser in incident upon an ideal photodetector. Calculate the frequency width of the intra-mode beat that you expect to see. Numerically evaluate using the parameters of (a).

(c) (20 pts) Now suppose you mix the above laser with another HeNe laser of nearly the same length \( L \). Assume the length perturbations \( \delta L \) of each laser are statistically independent (i.e., their effects add in a root–sum–squared manner). Calculate the frequency width of the beat between the two lasers. How does this compare in relative magnitude to (2b)? In practice, this will be a lower bound of the beat frequency width. Numerically evaluate using the parameters of (a).

5. Observing Mode Pulling with Photomixing. Assume a laser is incident on an ideal photodetector. The detector is hooked up to an electrical spectrum analyzer, which can measure up to 1250 MHz. The laser has three modes, which oscillate at frequency \( \omega - \Delta, \omega, \) and \( \omega + \Delta \), where \( \omega \) is the optical frequency (~500THz) and \( \Delta \) is the free spectral range of the laser (~500MHz). These modes will interfere with each other in a way more complicated than described Equation 1. In general, there will be cross terms that oscillate at the sum frequency and difference frequency of all the various possible pair combinations of mode frequencies.

(a) (20 pts) Write down the unique frequencies that are created from all the pair-wise combinations of the original three modes. Sketch what the electrical spectrum analyzer would display.

(b) (20 pts) Suppose mode pulling causes an asymmetric spacing between the modes and the modes now oscillate at \( \omega - (\Delta - \delta), \omega, \) and \( \omega + \Delta + \delta \), where \( \delta \) is the amount of mode pull and \( \delta \sim 10^5 \) Hz \( \ll \Delta \). Write down the unique frequencies that are created from all the pair-wise combinations of these modes. Sketch what the electrical spectrum analyzer would display in the immediate neighborhood of frequency \( \Delta \).

(c) (Reading) The actual photo-mixing process does not stop after the first round of pair-wise combinations. There can be additional mixing terms that are due to what is called “4-wave mixing” in the He-Ne laser itself. The gain material behaves non-linearly and can produce weak side-bands on each of the fundamental laser modes analyzed in part 2 above. When the free spectral range (FSR) of the laser modes is equal from mode-to-mode (after accounting for mode-pulling), as in the symmetrical situation where the modes are centered about the gain peak, then this 4-wave mixing process does not create any new frequencies (given an infinite frequency comb). When the mode spectrum is asymmetrical about the gain curve, and mode-pulling results in different mode-spacings across the frequency comb, then the 4-wave mixing process can create new laser frequencies in the sidebands of the original laser modes. In order to determine what sideband modes are created during the 4-wave mixing process, one can simply take the sum and/or difference of the frequency of ANY three of the laser modes, to create a fourth (new) laser mode frequency (hence the term 4-wave mixing). The strongest set of 4-wave mixing sideband peaks (call them \textbf{first-order 4-wave mixing peaks}) will be due to mixing of three of the original laser modes to create a fourth (new) frequency peak. The second set of strongest 4-wave mixing peaks (call these \textbf{second-order 4-wave mixing peaks}) will be due to mixing of only two of the original laser modes with one of the first-order 4-wave mixing peaks, to create a fourth (new) frequency peak in the laser spectrum. This non-linear process continues indefinitely, creating an infinite number of frequency components of decreasing amplitude with the order of the 4-wave mixing process.
**Experiment Procedure**

There are not many activities, but it can take some time to make the individual measurements.

Caution: The SFP detector and high voltage connections must not be interchanged. If you need to reconnect the SFP to SpectraPhysics driver 476, please ask a TA for help.

Exp#7 Scanning Fabry-Perot (First Week)

Read the instruction manual for the Tropel Model 240 scanning Fabry–Perot spectrum analyzer and the Spectra–Physics 476 SFP driver.

Examine Figure 2. Identify the optical component in the diagram and on the table (the experiment layout may be slight different from what’s shown in the figure, ask TA if you have questions). Both lasers should already be on. This has been done to ensure thermal stability. For now in Exp#7, laser 2 is used for Part B below.

![Figure 2](image)

**Figure 2.** Optical component layout for photomixing experiment. M1, M2, M4=mirrors, M3=flip mirror, SFP1=Spectra-Physics scanning Fabry-Perot, SFP2=Tropel scanning Fabry-Perot, I1=iris, ISO1=optical isolator, NRC 877 APD=high-speed avalanche photodiode, BS1=pellicle beamsplitter coated for 50:50 splitting at $\lambda$=632 nm.

**Important Note:** The setup for this experiment is *already completely aligned* and ready for use. Except for part A, do not misalign the set-up (in part A you will practice aligning the second scanning Fabry-Perot, SFP2). If you wish to go through the full alignment procedure, one of the TAs will be more than happy to misalign everything for you.
A. Scanning Fabry–Perot Interferometer (1.5 hrs, 100 pts)

1. Flip the “flippable” mirror mount, M3, into the “up” position so laser #1’s beam is reflected to M4 and SFP2 (see Fig. 3 below for beam path). Paste this figure in your notebook.

2. Read the instruction manual for the Tropel Model 240 and SP 476 Driver, if you haven't already. Make sure the oscilloscope sweep is set to “V-t” mode, with channel 1 your scanning ramp and channel 2 your photodetector signal. The SP476 Driver will provide the ramp signal. The ramp signal is \( V(t) = V_0 + C \cdot t \). Call in your TA for a brief review and explanation as how the setup is similar to “x-y” mode, and how to use the direct “x-y” mode on the scope (and why we do not use the mode”).

3. Remove the detector and lens from the Tropel Scanning Fabry–Perot (SFP2), and direct the small He–Ne laser through the SFP. Observe the spots on a white screen. (Why are there two spots?) Wouldn't you expect an infinite sequence of spots if you tilted a Fabry–Perot with 2 flat mirrors? Ask your TA for an explanation, and record it in your notebook.

Tilt and recenter the SFP (4 degrees of freedom required, so you may need to use the tip-tilt on the SFP mount and M3 and M4 adjustments) until the 2 spots merge. It is easier to do this if the SFP is being
scanned, otherwise, the spots flicker on and off slowly as the SFP mirror separation drifts thermally. When the two spots have been merged, turn–off the scan and observe this flickering.

4. Carefully replace the detector and observe the pattern on the oscilloscope. This is the frequency spectrum of the laser. With the dispersion control on the SP476 fully counterclockwise, you should see the same pattern repeated 4 or 5 times; these are free spectral ranges of the SFP. The two or three peaks within each repetition are the modes of the laser's own mirror cavity, essentially another Fabry–Perot, but larger mirror spacing. If the peaks are unstable in amplitude, tilt the SFP slightly; you may be aligned so well with the laser that the SFP and laser form a “super F–P” with 4 mirrors. You can see how well–aligned you are by looking at the reflection from the F–P back onto the front face of the laser. (Don't misalign more than you need to make the peaks stable in amplitude.) Now replace lens; this should increase the amplitude of the peaks and narrow them. The lens converts the collimated laser beam into a converging beam that better matches the SFP cavity modes.

5. (40 pts) Sketch what you observe and describe what happens with time, both amplitudes and positions of the laser lines. The mode spacing (free spectral range = FSR=c/4L for the confocal FP cavity) of the Tropel SFP (SFP2) is 1500 MHz. Using the dispersion controls adjust the pattern so that 1500 MHz equals 5 divisions on the x-axis of the scope. With this calibration, determine the frequency spacing between adjacent laser modes. Compare the length of the laser cavity you calculate from this mode spacing with the physical length of the laser package. Are they in agreement?

6. (30 pts) Increase the dispersion using the calibrated multiplier switch on the SP476. Use the centering control to track a single line. Observe the apparent width of a single laser mode at its half amplitude points (FWHM), in MHz. From this, calculate the finesse of the SFP. Does it agree with Tropel's claimed value of 200? Can you make the width narrower by slight angular and focusing adjustments of the SFP?

7. (30 pts) Observe the drift of the spectral lines and use the drift rate to estimate the dimensional drift rates due to the laser cavity or SFP cavity. What drift do you think this is?

B. Build your own Fabry-Perot (1.5 hrs, 100 pts).

In this part, you will build your own Fabry-Perot interferometer with a pair of spherical laser mirrors. This interferometer will not have the automatic scanning function like the Tropel SFP, but it will allow you to practice some interferometer alignment procedures and observe some spatial mode structures of the Fabry-Perot interferometer. The basic setup is shown in Figure 4 below.
a) Ask TA to explain the experiment layout. The actual light path arrangement may be difference than that shown in Fig. 4.

b) Remove FPM1 and the glass place out of the laser beam path. Note FPM1 is a flat mirror while FPM2 is a spherical mirror with the radius of curvature equal to 25 cm.

c) Adjust M1 and M2 to make the laser beam more or less horizontal and at the height of the FPMs.

d) Place FPM2 to the right (in the figure) to ensure you have enough room (> 12”) between M2 and FPM2. Adjust FPM2 height and position so that the laser beam hit around the center of the mirror. PFM2 mirror is mounted on a PZT mirror mount.

e) Adjust FPM2 mirror mount to have the laser beam retro-reflected. The base of the mirror mount should have been locked down.

f) Place the CCD camera behind the FPM2 to view the transmitted light or FP mode structure. The CCD camera does not have a lens in front. Note that farther away the camera is from the FPM2, the large the image, due to diverging beams from the FP, which helps to see the mode structures. There is an attenuator in front of the CCD camera. Do not remove the attenuator (there no reason for this experiment) unless you consulted with a TA.

g) (15 pts) Place FPM1 \leq 25 \text{ cm} away from the FPM2. This will ensure that you will have a stable cavity resonator. Make the mirror position and tilt adjustments similar to that of FPM2. At this point, you should see the scattered light off the mirror surfaces inside the cavity, and therefore, the indication of light bouncing between the two mirrors. You may have to turn off the room lights to see better (especially when the mirrors are either very clean or very dirty.)

Slowly increase the separation between the mirrors; you will note the scattered light inside the cavity will suddenly disappear beyond a given separation. Record this separation \( L_0 \). This is because the FP cavity is not unconditionally stable. The disappearance of the scattered light indicates the cavity cannot support stable modes (or light bouncing back and forth many times inside the cavity).

h) (15 pts) Now, set the separation of two mirrors just within \( L_0 \). You should lock down FPM1 at this point as well. Carefully adjust the two FP mirrors and observe the changes of the laser beam scattered off the FP mirrors. Record what you see and sketches in your notebook. Mirrors M1 and M2 can also be adjusted for optimizing the alignment.

i) Note that the FP you build is not very stable either because of not very sturdy mounts. You will see the bright transmitted modes come in and out of resonance in the camera, but will not be able to stay on one for very long. One could make this cavity scanning by attaching a signal generator to the piezoelectric driver for the mirror and scan automatically.

j) (30 pts) Observe and record various mode patterns you see. Discuss what you see vs. what you might expect. A number of lower order Gaussian modes are shown in Figure 5. Manually adjust the three piezo actuators independently to fine-tune alignment, and try adjusting the master control as well to adjust cavity length. You should be able to see various patterns.

Now change the separation of mirrors to about 2 cm. Repeat above. Sketch patterns you see. Discuss any differences you notice between two cases.
k) (40 pts) Go back to a larger mirror separation to allow enough room to place a tilt glass plate in the cavity. Insert the glass plate provided inside the Fabry-Perot cavity. The glass plate will introduce losses of the laser power circulating inside the cavity because of Fresnel reflection (what’s the typical loss?). Can you still observe the transmitted light? Why? How would you reduce the reflection loss and make the Fabry-Perot cavity work again (You may recall HeNe laser discharge tube windows discussed in APh23).

![Figure 5](http://www.statemaster.com/encyclopedia/Transverse-mode)
Exp#8 Photomixing (second week)

C. Photomixing One Laser: Mode Beating (1.5 hrs, 100 pts)

1. Make sure Spectra-Physics ramp generator is off. Disconnect SFP2 (“HV out” and “PD in”) from the Spectra-Physics Voltage Ramp Generator, and connect up SFP1. If you are unsure of how to connect things, ask TA for help. Flip ‘down’ M3 so that laser #1’s beam is entering the Spectra-Physics scanning Fabry-Perot (SFP1). The beam layout should now be as in Fig. 6. Cut out and paste Fig. 4 into your lab notebook. The Newport Corporation Model 877 silicon avalanche photo–detector is sufficiently fast (<200 psec.) that it will respond to the beat frequencies between the modes of a small laser such as the ones in this lab. Make sure the laser light is hitting the detector. Turn on the detector. Adjust the bias current to ~100 microamps.

2. Ask a TA to show you how to use the Hewlett-Packard Electrical Spectrum Analyzer (ESA). Record notes on this set-up in your lab book.

3. (20 pts) Start the ESA on its broadest scan range, 1250 MHz. This is done by clicking the red knob on the end of the “scan width per division knob” all the way to the right. Set the bandwidth to 3 kHz and “scan time per division” to 5ms. The display should be set to “10 db/div”. Which beat frequencies do you see on the ESA’s display? Use the digital camera to take pictures of the broad spectrum you see. Consult a TA to help you take and print out camera images of the ESA’s spectrum. Paste a print out of
the broad spectrum into your lab book and annotate the x-axis and y-axis, indicating the beat note center frequencies.

4. Adjust the center frequency knob to move the “v” notch (or “pip”) on the ESA display to be centered on the lower beat frequency. We are going to make a higher resolution scan of this beat frequency.

5. Set the display to "linear" rather than "10 dB/div." Now switch the ESA to higher resolution. Click the red knob from 1250 MHz to “per division”. Set the scan width to a coarse value, say 10 MHz, in order to find the peak. Center the peak by adjusting the center frequency knob. Gradually adjust the scan width down to 100 kHz/division. As you make the resolution finer, you will have to center the peak by adjusting the fine control of the center frequency knob.

7. You should see "fine structure" on the beat frequency, which may be slowly fluctuating. The lasers are currently quasi thermally-stable. You can “manually” destabilize one of them to accelerate the fine structure changes. Carefully, gently place your hand near the back end of the laser 1 for a full minute or two. Do this with out moving the laser, otherwise, you will be staying late and realigning optics! It should feel quite warm. While holding the laser, you will thermally change the laser’s cavity length, which causes the laser modes to shift in frequency. You should see the beat pattern changing more quickly now.

8. (40 pts) Take a digital camera image of the fundamental beat note on the HP-ESA when the span of the fine structure is widest. Sketch (or take a digital camera image of) the SFP spectrum under these same conditions. Label the frequency scale of your HP-ESA print outs and measure the widths of the single components of the fine structure. How do these values compare with Prelab question 2b? Explain what causes fine structure in terms of mode pulling. Recall the background theory discussion and prelab problem 3. Try for 15 minutes or so to develop your own explanation and then check with a TA. Use sketches, the digital camera print outs, as well as words in your explanation. This part is worth 40 points - write a detailed explanation.

9. (40 pts) Do you observe that the fine structure occasionally disappears? Print out a trace of what the beat looks likes when the fine structure disappears. How wide is the “fine-structure”-less beat? How does this compare to the results from step 8? Sketch what the SFP spectrum looks like when the fine structure disappears. What causes the disappearances? How is this tied to mode pulling? This part is worth 40 points - write a detailed explanation.

D. Photomixing Two Lasers: Optical Heterodyning (1.5 hrs, 100 pts)

1. (20 pts) Set the ESA back to the 1250 MHz scale, 3kHz bandwidth, and 5 ms “scan time per division”. Cut and paste Fig. 2 into your lab book. Unblock laser 2. Block laser 1. The beat frequencies from laser 2 should be similar, but not identical, to those of laser 1. What is a plausible cause for any observed frequency differences? Support your argument with a simple numerical estimate.

2. (30 pts) Unblock laser 1. Look for the beat frequencies between the two lasers. They will be weaker frequency peaks which may be moving on the ESA. As a check, they should disappear when either laser 1 or 2 is blocked. Take a digital camera picture of the HP-ESA spectrum, print it out, and paste it into your lab book. Indicate the inter-laser beat frequencies on your print out. In terms of the relative integrated power (i.e. the estimated area under the curve), how much weaker or stronger are these beats as compared to the beats produced by laser 1 and 2? Are you results consistent with Equation 1? Explain.
3. (20 pts) Pick one of the inter-laser beat frequency peaks to zoom in on. Adjust the scale of the ESA to 2 MHz/div. By timing the peak’s movements, estimate the relative frequency drift rate between the lasers. In practice, this is how professionals measure the low frequency stability of ultra-stable lasers.

4. (30 pts) Now try measuring the width of the moving peak. This is tricky, because the peak is very quick! If feasible, reduce the filter bandwidth from 3 kHz to 1kHz and increase the “scan time per division” to 10ms to get higher precision. Track the peak with the fine center frequency control to keep the peak on the ESA display. While tracking the peak, gradually adjust ESA scale to 500kHz/div. You should be able to track the peak on the ESA’s display long enough to get a width measurement. You are looking for the minimum frequency width of a sharp peak. Watch for a while until you see a “fair” representative trace. Take a digital camera image of the “fair” trace and have it printed out. Paste it into your lab book and label the frequency scale. If you are lucky or really good (some people say these are the same thing), you can adjust ESA scale to 200 kHz/div and try to capture a trace with this setting. How does your narrowest peak width compare to the width of the single laser beat frequencies? With the values calculated in Prelab question 2c? Record these and any other interesting observations in your notebook. If you are not pressed for time, you might ask your TA or the instructor for some perspective about your observations and the experiment in general.

4. Clean up the lab. Do not turn off the lasers! They need to run continuously to reach thermal stability.