

## PHGN 480 Laser Physics

### Lab 4: HeNe resonator mode properties

Due Thursday, 2 Nov 2017

For this lab, you will explore the properties of the working HeNe laser.

#### **1. Observation of higher-order modes:**

Realign your HeNe laser, starting with the output coupler close to the end window of the tube. Leave room for an iris placed near the Brewster window. Optimize the power. Set up a CCD camera to observe the profiles of the output beams as the cavity alignment is changed. However you choose to set up your observation, be sure to leave room at the output end so that the output coupler can be brought out to a cavity length equal the radius of curvature of the mirror (assuming you have one flat and one curved mirror in your resonator). Two options for observing the laser mode: You can reflect the output beam off a surface to reduce the beam intensity, then direct the beam onto your CCD camera with a neutral density filter, but without the lens. Or you can put the beam onto a card, and use the CCD with its lens to make an image of the card on the camera. In either case, if the beam is small, you can use a negative lens to expand the beam.

- a. For the initial cavity length (OC near the tube window, but with enough gap to allow insertion of an iris), record a picture of the output beam when the laser power is optimized. Comment on the azimuthal symmetry of the beam profile, and whether the beam seems to be an ideal Gaussian.
- b. When the OC is misaligned, you should be able to see a higher-order or multimode (non-Gaussian) structure on the beam. Record some images of interesting mode shapes. A rectangular pattern of lobes indicates a Hermite-Gaussian mode, and typically indicates that there is something that is breaking the circular symmetry. A radial pattern (doughnut, ring shapes) correspond to Laguerre-Gaussian modes. You will see better modes later when you extend the cavity length, but see what you can find at this cavity length.
- c. Place an iris near the Brewster window. Gradually closing the iris, align its transverse position so that it is perfectly centered on the laser beam. Show that you can use the partially-closed iris to discriminate against the higher-order spatial modes and force laser operation only on the Gaussian (TEM<sub>00</sub>) mode.
- d. Since the OC is flat, there should be a beam waist at that position in the resonator. While operating the laser in the lowest order mode, use the camera to measure the  $1/e^2$  radius of the Gaussian beam. Make this measurement either directly at the laser output or on the beam reflected from the Brewster window, at a distance from that window that is equal to the distance from the window to the OC.
- e. As you had done previously when you measured the output power vs cavity length, gradually move the OC back towards the hemispherical point (cavity length just less than the radius of curvature). Repeat the inspection of the modes with the mirror centered and slightly detuned. Also repeat the measurement of the lowest order mode size.

## **2. Longitudinal mode measurements using the scanning Fabry-Perot:**

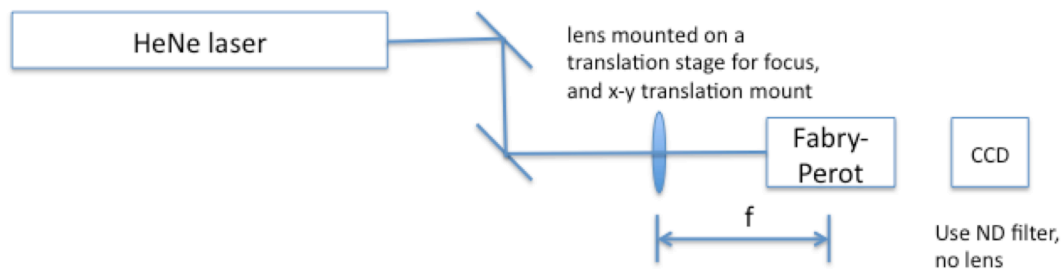
A brief review of the physics to help you understand the different magnitudes of the frequencies in the system:

The HeNe laser has a gain bandwidth of approximately 1.5GHz FWHM, set by the Doppler broadening of the gas in the tube. The resonator constrains what electromagnetic modes can be supported by the laser. For example, for the lowest-order spatial mode, the mode spacing is  $\Delta\nu = c/2L$ . So if your cavity length is  $L = 30\text{cm}$ , then the mode spacing will be 500MHz. Since this is less than the gain bandwidth, we expect to see more than one longitudinal mode. An additional factor is that higher-order modes of the resonator will be at frequencies that are in general different than the lowest-order. For a longitudinal mode to be lasing, the gain must be greater than the losses. These losses are controlled by the output coupling, the alignment, and the internal iris.

In working with the scanning Fabry-Perot interferometer, the first challenge is to align the beam into the resonator and to make sure that you understand what you see on the oscilloscope. For this reason, at first you want to use a laser running with only the lowest-order Gaussian transverse mode. Therefore, you can begin by using one of the commercial lasers, but ultimately you will need to use your home-built laser because it can operate with higher-order modes. If you use a commercial (sealed-tube) laser, be aware that they can be more sensitive to temperature variations: as the tube warms up, the cavity length can increase, which changes the longitudinal modes frequencies. The mode spacing is roughly constant, but changes enough so that the absolute frequencies will drift.

To gain an appreciation of how sensitive the longitudinal mode frequencies are, calculate the cavity length change required to move the frequency of the  $n$ th longitudinal mode into the position of the  $(n+1)$  mode. Does this length change depend on the starting cavity length?

Alignment of the Fabry-Perot: see the instruction manual on the Thorlabs website for the device you are using. The manual for the driver is also online. The resonator in the Fabry-Perot is confocal, which is more forgiving on the quality of mode-matching required than other resonators. Good alignment is still critical, however. Use a setup similar to the schematic shown below.



Use mirrors to get the beam level and straight to the table holes, then position your interferometer and camera at the same beam height. The lens should be mounted on a

translation stage for focus adjustment and in the XY lens mount for fine adjustment of the beam pointing. The camera will be just behind the FP, and the correct focal plane will be near the line scribed on its barrel. The beam does not necessarily have to be collimated but you need to identify where the focal position is first. For a 1mm beam size, Thorlabs recommends using  $f=100\text{mm}$  and  $f=250\text{mm}$  for the 10GHz and 1.5GHz, respectively. First get the FP centered on the beam using its front iris, then look for the back reflection. Next, with the FP driver running in the sawtooth mode, look for any transmission. Before adjusting the lens, try to manually position the FP position and angle to get the two transmitted spots close to each other, then lock the post in place. Use the XY adjustment and the FP angle adjustments to get as clean and small a transmitted beam as possible. Finally, use the focus adjustment to fine-tune. You should have a single, nearly Gaussian transmitted beam if you have good mode matching. Try to avoid any asymmetry in the beam, as this will introduce odd-order FP modes.

- a. Using the sawtooth driving waveform for the Fabry-Perot and the lowest sweep speed, you should see a pattern of spikes that repeats itself. The period of this pattern in frequency space is called the free spectral range (this varies with the device, the Thorlabs devices are 1.5 or 10GHz). Measure the corresponding time on the scope to calibrate sweep time to MHz/division. Zoom in on one of the lines and measure the FWHM of a single peak. You may need to optimize the alignment to make sure the line is as narrow as the specification (Finesse is approximately 200, so it should be about 7.5MHz wide). At near-optimal alignment, the trace may get noisy because of feedback into the laser. Try using an iris near the laser output to reduce this effect.
- b. Measure the cavity length and calculate a prediction for the mode spacing in MHz ( $\Delta\nu = c / 2L$ ). Record the longitudinal mode spectrum for your laser, using the internal iris to ensure the laser is operating in a single transverse mode. Compare the measured mode spacing for your laser to your prediction.
- c. Open the internal iris to allow the laser to operate with multiple transverse modes. The higher transverse modes have a slightly longer round trip time and therefore different mode spacing. See if you can observe new frequency components or at least a broadening in the longitudinal mode spectrum. Record an image of this lineshape. To have a chance of seeing the higher order modes, the Fabry-Perot must be operating at its spec resolution.
- d. With more cavity loss, we can force the laser (inefficiently) to single mode operation. Look at the longitudinal modes as you gradually make the iris smaller. See if you can get single mode operation.
- e. With less cavity loss, more longitudinal modes should be above threshold. Switch from an output coupler (transmission  $\sim 1\%$ ) to a flat high reflector. An easy way to do this is to place the HR mirror on the output beam behind the OC while the laser is operating. Choose a relatively long cavity length to get small longitudinal mode spacing. Align the HR to get feedback into the laser, then remove the OC

and re-optimize. You will see lower output power (record the difference) because more of the laser power is retained in the cavity. Observe the number of longitudinal modes, and see if the envelope around those modes traces out the Doppler broadened width of the HeNe gain profile.

- f. Go back to TEM00 operation. Based on the envelope around the longitudinal modes, estimate the full width at half maximum for the gain of the lasing transition. The standard value given is 1.5GHz.

### **3. Single longitudinal mode operation with intracavity etalon:**

The gain bandwidth of the HeNe laser is large enough to support lasing on a few longitudinal modes. By adding a window to the cavity, it is possible to introduce loss to all but one of those modes and force oscillation on a single longitudinal mode. The window acts as a low-reflectivity passive Fabry-Perot cavity, with a frequency spacing that is larger than that of the laser cavity. We have windows of 3 different thicknesses. The thinner ones should be easier to insert while maintaining lasing, but the thicker ones will likely give better discrimination against the other modes.

- a. Supporting calculations:

- calculate the longitudinal mode spacing for your laser cavity and for the etalons available
- The angle of the etalon will need to be adjusted so that a transmission peak can be centered on one of the laser modes. With the passive Fabry-Perot you found that the transmission varied with angle. The round trip phase of the etalon will be  $\phi(L, \theta_2) = \frac{2\pi n}{\lambda} 2L \cos \theta_2$ , where  $\theta_2$  is the internal refracted angle.

Plot  $\phi(L, \theta) / 2\pi$  vs. *incident* angle near normal incidence to determine the range of angles you will need to sweep through to get a full wave of phase shift.

- The angular change will introduce a shift in the beam as it zig-zags between the interfaces. As you saw before, if that shift is large, there is no interference between the beams and therefore no etalon effect. Calculate the maximum shift for the  $2\pi$  phase change, and compare it to the laser cavity beam size near the output coupler. (If the OC is flat, this shift should not dramatically change the alignment of the end mirrors.)
- b. Check the alignment of your HeNe laser for lasing, and mark the output beam with external irises. Make sure there is sufficient room between the OC and the tube to insert a mirror mount to hold the window. Align the reference laser beam to those irises. Mount the window or slide and insert it into the cavity near the output coupler. Use the alignment laser to make sure that you are starting with the window at normal incidence to the cavity axis. Try to get the laser operating again by sweeping through the range of angles you calculated above. An alternative approach with the thinnest window would be to insert the window near the Brewster angle (near zero reflectivity), then to try to place the window at the same angle of incidence but reflecting out of plane. This will require some creative

mounting, but effectively allows tuning of the reflectivity as the incidence varies from P to S.

- c. See if you can angle tune the etalon across two neighboring longitudinal modes. Estimate the angle over which you adjust the etalon and compare to what you would predict from the mode spacing calculation.
- d. Assuming you are able to get the laser operating again, check for single mode operation with the scanning Fabry-Perot.

#### **6. Extended double curved mirror cavity:**

Instead of using a flat OC, the laser should also work with a curved OC. The alignment will be challenging.

- a. With the laser operating with the flat OC, set two irises to mark the output beam direction, making sure that they are not in the way of where the new OC will go (maximum room to allow will be  $R_2=43\text{cm}$ ). Align your reference laser to this direction, which locates the laser cavity axis.
- b. The laser resonator will have two zones of stability when there is a mismatch in the curved mirror radii. Check the stability calculation for the resonator and place the new OC in the middle of the outer zone. Align the back reflection off the OC to retroreflect and try to get the cavity to lase.
- c. Depending on the cavity length (and the mode size back at the HR), the laser may run multimode. You can put an iris at the beam waist position to force single mode operation. Measure the output power of your cavity.
- d. If you have time, try to move the OC to shorten the cavity length to find the inner edge of the stability region. Compare this with the stability calculation.

#### **7. Variable output coupling:**

The output power is a function of the amount of power coupled out of the cavity. For zero output coupling, there is zero output. For too much output coupling, the threshold for lasing is high, and there is low output. There is a maximum in the middle.

1. Using your alignment irises and reference laser, swap out the output coupler for a flat HR and get the laser to lase. There will be very low output, but you should be able to see the internal beam. Measure any output power through that mirror, off the Brewster window, and out the back HR.
2. Mount the thinnest window (the cover slip) on a rotation stage and insert it into the cavity at the Brewster angle. Adjust the angle for minimum reflection from the window. You may need to tweak the end mirror to optimize power. Note the angle on the rotation stage – this is the Brewster angle, giving you minimum output coupling. Measure the output power, if any.
3. At various window angles, measure the output power. Always make sure the power is peaked up. Make a plot of output power vs angle, then use the Fresnel equations for the reflectivity of the glass vs incident angle to make a plot of output power vs output coupling percentage. Determine the optimum degree of output coupling. Remember that there are two interfaces that reflect and that the internal beam passes through it twice. If the beam offset is small, the two

reflections may be superposed and the actual reflectivity will be affected by etalon effects. Using a thicker slide may avoid this issue.

#### 8. Spatial filtering

A beam that has scattered light or distortions can be cleaned up with what is called a spatial filter. The beam is focused through a pinhole, and if the focused spot size just fits through the pinhole, all of the beam imperfections will be scraped off.

1. Mount the pinhole in an XY mount, and center the pinhole on the unfocused HeNe beam. You should see light diffracted through the pinhole with a characteristic Airy disk pattern. See [https://en.wikipedia.org/wiki/Airy\\_disk](https://en.wikipedia.org/wiki/Airy_disk)
2. Put the beam on a CCD camera and record the pattern. If you measure the distance from the center to the first minimum, you can measure the size of the pinhole:  $\sin\theta \approx 1.22\lambda / d$ . Here  $d$  is the pinhole diameter, and  $\theta$  is the half angle to the first minimum. The diameter measured this way should be consistent with the marked pinhole diameter.
3. Estimate or measure the input beam  $1/e^2$  radius, and use this to calculate what focal length to use so that the pinhole diameter is about 2x the  $1/e^2$  focal spot diameter. Then align the beam through the pinhole: one approach is to start with the pinhole farther from the lens than the focal length so that you get some light through. Center the transmitted light, then gradually move the pinhole towards the focus.
4. With the spatial filter aligned, if you put some lens tissue into the beam, and the beam distortions you should be able to see that the beam past the pinhole is still clean.

#### Resources:

There is a huge amount of practical information on the website Sam's Laser FAQ:  
<http://www.repairfaq.org/sam/laserhen.htm#hentool1>