

**OPTI 511L  
Fall 2018****Experiment 1: The HeNe Laser, Gaussian beams, and mode-matching**

(Part 2 of 2)

Overview of objectives (continued):

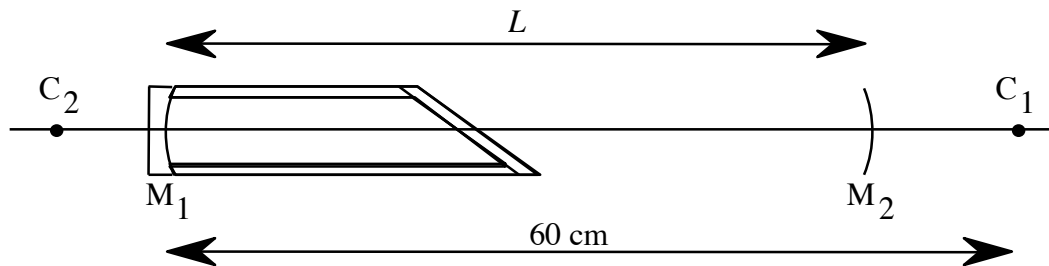
- (iii) Learn to align and operate an open-cavity Helium Neon laser and explore conditions for resonator stability and fundamental-transverse mode operation.
- (iv) Generate higher-order Hermite-Gaussian modes, and determine the optical frequency spectrum associated with the different transverse modes of a spherical mirror cavity.
- (v) Generate beams other than the Hermite-Gaussian modes by converting Hermite-Gaussian beams to Laguerre-Gaussian beams with a cylindrical telescope.  
(note: you will do this part of the lab in week 3)

**(iii) Open-cavity HeNe laser: resonator stability**

In the first part of this lab you used *passive* optical cavities to analyze laser light. Now, we will explore an *active* cavity (ie laser) and note the affect of cavity alignment and stability on laser operation. In order to further explore cavity stability, and to generate higher order Hermite-Gaussian modes, we use a HeNe discharge tube with a Brewster window attached to one end, and one mirror attached to the tube. In contrast to the usual sealed-mirror design, this provides access to part of the region inside the resonator, defined using an external mirror that is not attached to the tube. The HeNe laser is more difficult to align than many other lasers, due to its low gain and the narrow bore of the plasma tube, resulting in very little amplified spontaneous emission. In a HeNe laser the lower lasing level decays to a metastable level, which can only decay to the ground state through collision with the bore wall. Thus the gain in a HeNe discharge tube is inversely proportional to the bore diameter and cavity length. See e.g. refs 1 or 2 for further discussion of the pumping mechanism and atomic levels involved in the HeNe laser system. For this experiment we simplify the alignment task by using a tube with one sealed mirror that is already aligned.

**Be extremely careful with the high-voltage electrical connections for this laser, as you can be seriously hurt if you touch the electrodes when the laser is turned on.** Check that you can run the electrical discharge (plug in the power supply and the tube should glow). Then introduce an output coupler mirror  $M_2$ .

Fig. HeNe laser setup



Steps for part (iii)

In this section, you will choose one of the available mirrors for  $M_2$ , set it up and coarse-align it, and turn on the discharge. Center the spot of fluorescence emitted along the bore on a good (clean & unscratched) part of  $M_2$ , then use an iris to make sure the retro-reflection is sent back into the bore. The laser will be close to aligned. Scan the angle of  $M_2$  systematically around this position, until you see a flash of laser action. Using a photodiode, optimize for maximum output power. ***Be careful not to touch or get close to the electrical connections on the HeNe tube while you are aligning.***

Some possible reasons why laser oscillation might elude you:

- unstable or misaligned resonator
  - dirty/scratched mirrors or Brewster window
  - low gain due to gas contamination or problem with power supply
  - $M_2$  reflectivity too low
1.  $M_1$  has radius of curvature (ROC) of 60cm. ***Calculate and record in your lab notebook*** the range of mirror separations for which the resonator is stable, for all three available output couplers with 45cm, 60cm, and  $\infty$  (flat). If you do not know how to calculate this, discuss with your lab partners and TA. Pay special attention to the 45cm ROC mirror.
  2. Begin with the  $M_2 = 60$  cm ROC output coupler using an approximately 45 cm laser cavity. Align for lasing and maximize the output power.
  3. Does your setup oscillate in the fundamental transverse mode? If not, can you think of a way to force it to do so?

4. Now you will vary the cavity length and maximize the power at each position. You don't need to try too many different lengths - about 3 or 4 would be a good number to determine the coarse behavior of power vs. length. Make sure you take measurements close to the positions where the cavity is marginally stable (e.g. the confocal position and near the longest allowed cavity length).

**For each cavity length, record:**

- i) the *maximum* output power you can achieve, and record (sketch) the corresponding lasing transverse mode profile. Is this a pure  $TEM_{mn}$  mode?
- ii) the maximum power you can obtain *in a  $TEM_{00}$  mode* (if any is possible). For this, you may wish to use a pinhole inside the laser cavity to force the laser into the lowest order mode.

To provide some insight as to the power dependence on cavity length, consider the mode volume of the lasing cavity mode. How does the beam diameter at the mirror surfaces change as a function of different cavity lengths?

If time permits, try the same procedure with the 45 cm ROC and/or flat output coupler as well.

**(iv) Hermite-Gaussian Modes.**

After the open-cavity laser is oscillating, proceed to explore the higher order resonator modes that can be excited. Using the 45 cm ROC output coupler placed so that the cavity length is about 40 cm is a particularly good configuration for this part of the experiment. Note the diameter of this mirror is small, so making sure the cavity mode is aligned on the center of the mirror is important.

In general you will excite more than a single transverse mode, as you may have noticed in the previous section, and will observe a *superposition* of many Hermite-Gaussian intensity patterns. When the laser is operating with multiple transverse modes, it is possible to introduce a spatially dependent loss such that you force it to oscillate on specific transverse modes. See how many different *pure* Hermite-Gaussian modes you can isolate, using a combination of cavity alignment and vignetting with a cotton fiber, mounted for rotation and x-y translation (ask your TA for help). Record and sketch your results, clearly indicating the different transverse mode structures of output beams you are able to generate.

When you are able to reliably excite single modes, especially  $TEM_{00}$  and  $TEM_{01}$ , add a second mounted fiber, perpendicular to the first. Try to achieve lasing in high-order modes. Modes at least as high order as  $TEM_{33}$  have been observed with this setup.

## Spectrum Analysis with the scanning Fabry-Perot Interferometer (FPI)

We will now analyze the spectrum of the open cavity HeNe and see how the spectrum changes for different lasing modes. Align the commercial scanning FPI with 1.5 GHz FSR for optical spectrum analysis. The laser will likely have much less power than the commercial laser you used previously, so careful alignment and use of a focusing lens is important.

The FPI requires more optical power than does our dark-adapted eye. You may therefore want to use the intense beam transmitted through the output coupler for spectrum analysis, and use the weak beam transmitted through the backside high reflector to keep track of the transverse mode.

1. With the laser oscillating in the  $TEM_{00}$  mode, examine the frequency spectrum of the laser. How many longitudinal modes are lasing, and what is the frequency separation between the modes? Measure the polarization of the lasing modes. Does this make sense?
2. Adjust the open cavity HeNe so it is oscillating on multiple transverse modes and observe the spectrum. Next, use the intracavity fiber to select different higher order Hermite-Gaussian modes, and observe and record the laser spectrum. Based on your cavity length and mirrors, calculate the expected frequency shift between the higher order transverse modes.  
Note: What is the resolution of your scanning FPI? Is this sufficient to resolve the transverse mode spacing?
3. You may want to try this with different cavity lengths (very short versus very long for example) and compare the observed spectrum of the HeNe if time permits.

(v) **Beams other than the Hermite-Gaussian modes. (week 3)**

In this last part of the experiment, the goal is to generate other types of beam-like solutions to the wave equation, i.e. the so-called Laguerre-Gaussian beams. You will use the open cavity HeNe laser from the last section.

Generating Laguerre-Gaussians beams:

A method to generate Laguerre-Gaussian beams is suggested by the fact that these beam-modes are readily decomposed in a basis of Hermite-Gaussian modes. We have for example the two 1<sup>st</sup> order Laguerre-Gaussian modes

$$E_{0,\pm 1}^L \propto \frac{Aw_0}{w(z)} \frac{\sqrt{2}r}{w(z)} e^{\mp i\varphi} = \frac{Aw_0}{w(z)} \left[ \frac{\sqrt{2}x}{w(z)} \mp i \frac{\sqrt{2}y}{w(z)} \right]$$

Noting that the two 1st order Hermite-Gaussians are

$$E_{10}^H \propto \frac{Aw_0}{w(z)} \frac{2\sqrt{2}x}{w(z)}, \quad E_{01}^H \propto \frac{Aw_0}{w(z)} \frac{2\sqrt{2}y}{w(z)},$$

we see that

$$E_{0,\pm 1}^L \propto \frac{1}{2} [E_{10}^H \mp iE_{01}^H]$$

To generate the Laguerre-Gaussians  $E_{0\pm 1}^L$  we can therefore start by generating the Hermite-Gaussians  $E_{10}^H$  and  $E_{01}^H$ , and then introduce a relative phase-change of  $\pi/2$  between them. Ref. [4] discusses mode-decomposition in more detail, and shows how the required phase shift can be produced with a cylindrical telescope.

To explain how a cylindrical telescope can be used as a mode-converter, we note that a Hermite-Gaussian beam  $E_{nm}^H$  that propagates from  $z_1$  to  $z_2$  picks up an extra phase term (the Gouy phase) given by

$$\phi_G = -(n+m+1) \tan^{-1} [(z_2 - z_1)/z_0].$$

The physical origin of this phase-shift is the changing radius-of-curvature of the wavefronts.

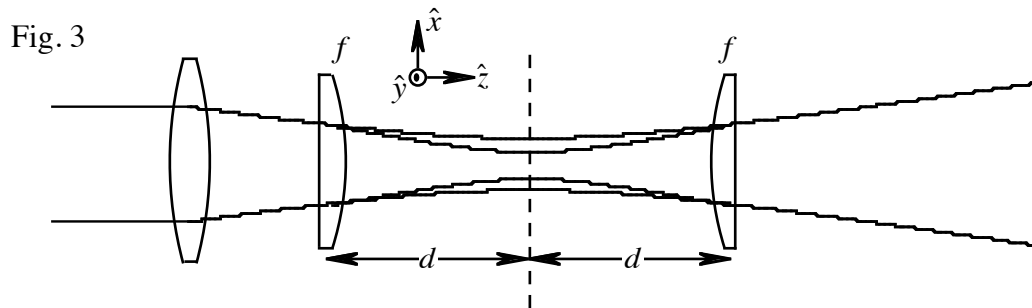
Fig. 3 shows a telescope consisting of two cylindrical lenses with focal length  $f$ , placed symmetrically at a distance  $d$  from the waist of a Gaussian beam having Rayleigh range  $z_0$ . If we choose  $f$ ,  $d$  and  $z_0$  appropriately, then we can achieve a situation where the modes  $E_{10}^H$  and  $E_{01}^H$  are unaffected after passage through the telescope, except that  $E_{10}^H$  has picked up a larger

Gouy phase-shift than  $E_{01}^H$  due to the difference in wavefront curvature inside the cylindrical telescope. Specifically, if we pick

$\hat{z}$

$$d = f/\sqrt{2} \quad \text{and} \quad z_0 = f + d = (1 + 1/\sqrt{2})f$$

then  $E_{10}^H$  picks up a Gouy phase shift of  $\pi/2$  relative to  $E_{01}^H$ .



1. Use the HeNe laser to generate the Hermite-Gaussian  $E_{10}^H + E_{01}^H$  (this is a Hermite-Gaussian rotated by  $45^\circ$  with respect to the  $x, y$  axis). We have at our disposal a pair of cylindrical lenses with  $f = 38$  mm. Calculate the  $z_0$  you need in order to make the mode converter work. Based on the position and curvature of the mirrors forming your HeNe laser cavity, determine the focal length and position of a lens that will convert your output into a beam with the proper  $z_0$ . Set up your cylindrical telescope for mode conversion.
2. How many, and which Laguerre-Gaussian modes can you generate? Use two crossed hairs to generate high-order Hermite-Gaussian modes, and record the effect of the mode converter on these modes.