Chapter 1

The HeNe Laser

1.1 Prelab

In this lab, you will be building an optical resonator (a laser), and you will find that the laser cavity is only stable for certain mirror separations. The stability condition is derived based on ray optics in your text book (Saleh and Teich, *Fundamentals of Photonics*). Alternatively, the stability condition can be derived using Gaussian optics and ABDC matrices. This is your task for this prelab (do not copy the treatment given in Wikipedia).

The key to the derivation is the assumption (like for the ray optics derivation) that the Gaussian beam parameter, q, must be periodic - that is q must be the same after a cavity round trip. Using the ABCD matrix and the transformation law for q, derive the stability condition for the resonator. Recall that q_1 transforms to q_2 after passing through an optical system with an ABCD matrix as

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D}. \tag{1.1}$$

Your result will be a quadratic equation in q. Using the physics of the problem, put limits on solution of q to find the regions of stability for the resonator. You should either (1) show that this condition is mathematically identical to the condition derived from ray optics or (2) describe qualitatively the implications of the condition you find by considering limiting cases and argue that it is equivalent to the one derived from ray optics.

1.2 Objective

In this lab you will construct a HeNe laser. By observing and investigating its fundamental properties and operating conditions, you will learn how a laser works and what determines its output characteristics.

1.3 Introduction to the Helium-Neon laser

The helium-neon (HeNe) laser was among the first lasers ever constructed, and has since proved to be among the most popular. Used throughout the scientific

laboratory and industrial workplace, these devices are easy to construct and relatively inexpensive. In general, a laser consists of three basics items: (1) an energy pump to provide energy/power to laser, (2) a gain medium to provide optical gain and (3) an optical resonator to provide positive optical feedback.

1.3.1 Energy Pump

A 1700 V high voltage, DC power supply maintains a glow discharge or plasma in a glass tube containing a mixture of helium and neon gas, as shown in Fig. 1.1. The discharge current is limited to about 5 mA by a 91 kW ballast resistor. Energetic electrons accelerating from the cathode to the anode collide with He and Ne atoms in the laser tube, producing a large number of neutral He and Ne atoms in electronically excited states. He and Ne atoms in excited states can de-excite and return to their ground states by spontaneously emitting light. This light makes up the bright pink-red glow of the plasma that is seen even in the absence of laser action.

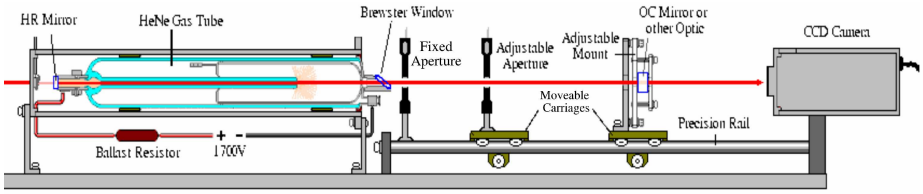


Figure 1.1: Open Frame HeNe Laser cavity. This is a schematic of the HeNe laser cavity that you will align in this lab.

The process of producing He and Ne in specific excited states is known as pumping and in the HeNe laser this pumping process occurs through electron-atom collisions in a discharge. In other types of lasers, pumping is achieved by light from a bright flashlamp or by chemical reactions. Common to all lasers is the need for some process to prepare an ensemble of atoms, ions or molecules in appropriate excited states so that a desired type of light emission can occur.

1.3.2 Gain Medium

As shown in Fig. 1.1, the laser you will build uses a glass tube filled with a helium-neon mixture (typically 5:1 or 7:1) at a low pressure (2-5 Torr) as the gain medium. To achieve laser action it is necessary to have a large number of atoms in excited states and to establish what is termed a population inversion. To understand the significance of a population inversion to HeNe laser action, it is useful to consider the processes leading to excitation of He and Ne atoms in the discharge. These processes can be identified using the simplified diagram of atomic He and Ne energy levels given in Fig. 1.2. A description of the rather complex HeNe excitation process can be given in terms of the following four steps.

(a) An energetic electron collisionally excites a He atom to the state labeled (in the Russell-Saunders notation) 2^1S_0. A He atom in this excited state is often written $He^*(2^1S_0)$, where the asterisk means that the He atom is in an excited state.

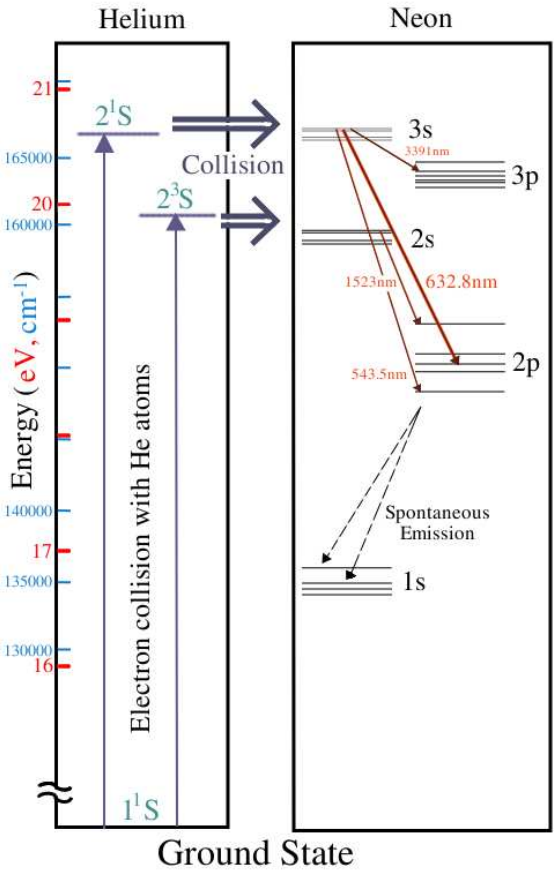


Figure 1.2: Simplified HeNe energy levels. This figure shows the energies level involved to produce population inversion for the HeNe laser.

(b) The excited $He^*(2^1S_0)$ atom collides with an unexcited Ne atom and the atoms exchange internal energy, thereby producing an unexcited He atom and excited Ne atom, written $Ne^*(3s_2)$. This energy exchange process occurs with high probability only because of the coincidental (and advantageous) near equality of the two excitation energies of the two levels in these atoms.

(c) The $3s_2$ level of Ne is an example of a metastable atomic state, meaning that it is only after a relatively long period of time - on atomic time scales - that the $Ne^*(3s_2)$ atom de-excites to the $2p_4$ level by emitting a photon of wavelength 632.8 nm. The wavelength of the emitted photon is determined by the energy difference between the two states (ΔE). Specifically, $\lambda = hc/\Delta E$ (where h is Planck's constant, c is the velocity of light). It is this emission of 632.8 nm light by Ne atoms that, in the presence of a suitable optical configuration (discussed below), leads to lasing action.

(d) The $Ne^*(2p_4)$ atom rapidly de-excites to its ground state by emitting additional photons or by collisions with the plasma tube walls. Because of

the extreme quickness of the deexcitation process, at any moment in the HeNe plasma, there are more Ne atoms in the $3s_2$ state than there are in the $2p_4$ state, and a population inversion is said to be established between these two levels. A web animation showing this entire 4 step process can found on the course web page.

When a population inversion is established between the $3s_2$ and $2p_4$ levels of the Ne atoms in the discharge, the discharge can act as an optical gain or amplification medium for light of wavelength 632.8 nm. This is because a photon incident on the gas discharge will have a greater probability of being joined by another photon in a $3s_2 \Rightarrow 2p_4$ stimulated emission process (discussed below) than of being absorbed in the complementary $2p_4 \Rightarrow 3s_2$ absorption process. This complementary process is suppressed by the rapid depletion (emptying) of the $2p_4$ state.

1.3.3 Optical Resonator

As mentioned in 1.3.2 above, Ne atoms in the $3s_2$ metastable state decay spontaneously to the $2p_4$ level after a relatively long period of time under normal circumstances; however, a novel circumstance arises if, as shown in Fig. 1.1, a HeNe gas discharge tube is placed between two highly reflecting mirrors that form an optical cavity or resonator along the axis of the discharge. When such a resonator structure is in place, photons from the $Ne^*3s_2 \Rightarrow 2p_4$ transition that are emitted along the axis of the cavity can be reflected hundreds of times between the two highly reflecting end mirrors of the cavity. These reflecting photons can interact with other excited $Ne^*(3s_2)$ atoms and cause them to emit 632.8 nm light in a process known as stimulated emission. The new photon produced in stimulated emission has the same wavelength, polarization, and phase. And the photon is emitted in the same direction, as the stimulating photon. It is sometimes useful for purposes of analogy to think of the stimulated emission process as a "cloning" process for photons, as depicted in 1.3. The stimulated emission process should be contrasted with spontaneous emission processes that, because they are not caused by any preceding event, produce photons that are emitted isotropically, with random polarization, and over a broader range of wavelengths.

As stimulated emission processes occur along the axis of the resonator a situation develops in which essentially all $3s_2 \Rightarrow 2p_4$ Ne* decays contribute deexcitation photons to the photon stream reflecting between the two mirrors. This photon multiplication (light amplification) process produces a very large number of photons of the same wavelength and polarization that travel back and forth between the two cavity mirrors. To extract a light beam from the resonator, it is only necessary to have one of the two resonator mirrors, usually called the output coupler, have a reflectivity of only 99% so that 1% of the photons incident on it travel out of the resonator to produce an external laser beam. The other mirror, called the high reflector, should be as reflective as possible. The small diameter, narrow bandwidth, and strong polarization of the HeNe laser beam are determined by the properties of the resonator mirrors and other optical components that lie along the axis of the optical resonator

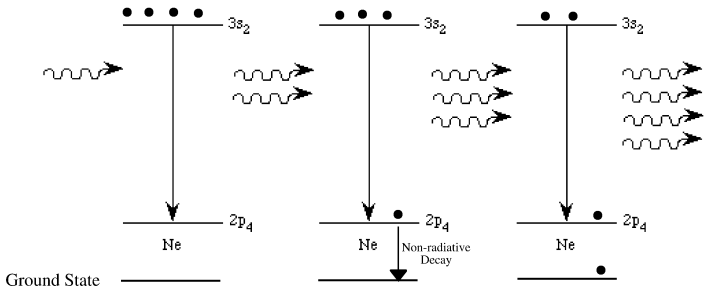


Figure 1.3: Stimulated emission. When a population inversion between the $3s_2$ and $2p_4$ is present, an incident photon will stimulate an electron (circles) to fall from the higher to the lower energy level and realize a "cloned" photon. In this diagram one can also note the importance of having a long-lived upper state ($3s_2$) and a short-lived lower state ($2p_4$); otherwise it is difficult to maintain a population inversion

1.3.4 Resonator Theory

Spherical-Mirror Resonators

An optical resonator composed of two planar mirrors ($R_1 = R_2 = \infty$) is stable for any mirror separation so long as they have been perfectly aligned. The difficulty with this arrangement is that in practice planar mirrors are extremely sensitive to misalignment; they must be perfectly parallel to each other and perfectly normal to the incident light rays. This sensitivity can be reduced by replacing the planar mirrors with spherical ones. The trade off, however, is that spherical-mirror resonators are only stable for specific geometric configurations. These mirrors can be either concave ($R < 0$) or convex ($R > 0$).

Limiting yourself to ray optics, and specifically to the methods of paraxial matrix-optics, it is possible to determine that the region of stability for any spherical-mirror resonator is given by;

$$0 \leq \big(1 + \frac{d}{R_1}\big)\big(1 + \frac{d}{R_2}\big) \leq 1 \tag{1.2}$$

where d is the optical cavity length, and R_1 and R_2 are the radii of curvature for the two mirrors. Typically, the two middle terms are written in terms of the ***g* parameters**

$$g_1 = 1 + \tfrac{d}{R_1} \quad \text{and} \quad g_2 = 1 + \tfrac{d}{R_2}$$

It is left as an exercise to demonstrate that this result is valid. You should record this derivation in your lab book. A good starting point for this analysis in located in your text book (Saleh and Teich, *Fundamentals of Photonics*).

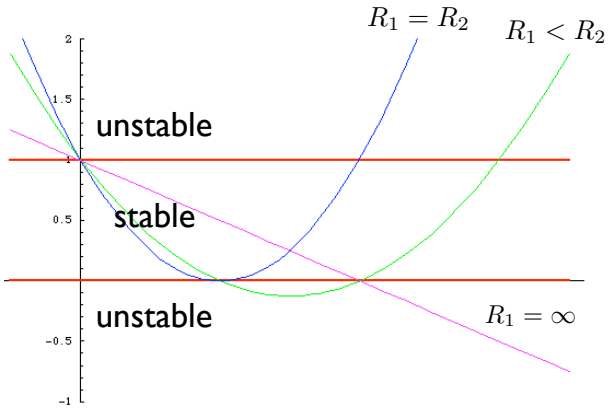


Figure 1.4: Plot of the middle term in expression (1.2) as a function of the mirror separation, d, for various mirror combiations (i.e. values of R_1 and R_2). The cavity is stable at all locations, d, for which the value of the term is between 0 and 1 (denoted by red lines).

Frequency Dependence of the Cavity Length

An important, but yet unmentioned, consequence of photon amplification is that in order for it to happen the photons must always be in phase (**why?**). This means that the light wave found in the laser cavity must be a standing wave, *i.e.* there can only exist a half integral number of wavelengths between the mirrors. Recalling that the wavelength λ is related to the frequency f by the relation $f = c/\lambda$ prove that the allowable laser frequencies are given by;

$$f_m = m\frac{c}{2L} \tag{1.3}$$

where L is the length of the laser cavity, and m is the number of half-wavelengths that fit between the mirrors.

From this you would expect lasing to occur only for very specific mirror distances. While in theory this is true, in practice lasing action can be obtained more or less continuously throughout the regions of stability (mirror separation) for a particular set of mirrors. **Explain why this is the case.**

1.4 Important Safety Rules

Do not be apprehensive of this lab. If you are careful the danger involved in this lab is extremely minimal. However, if you fail to heed the following warnings bad things will happen.

1.4.1 Do Not Touch the High Voltage Electrodes

There is a plastic casing surrounding the laser tube, there is no reason for you to remove this casing or to place your hands within the confines of it. People have died by mishandling laser power supplies. You won't, but there is no reason to test this theory.

1.4.2 Do Not Stare Into The Beam

This is not a high power laser beam; if for some reason the beam does impact near the area of your eyes your 'blink reflex' should be enough to protect you. This does not mean you should place your head/eye in the path of the beam to see where it is going. A small index card (provided) is a much better means of observing the path of the beam. It is also important to watch for stray reflections off of mirrors or other reflective surfaces. This means that any **watches, rings, or bracelets should be removed** before beginning this experiment. Laser goggles are provided should you feel uncomfortable.

1.4.3 Do Not Touch Any Optical Surface

It does not take many impurities on the optical surfaces to prevent lasing action from occurring. Scratches, fingerprints, and even dust on the cavity elements can prevent a laser from working. If you suspect that lasing is not occurring due to one of these causes, do not attempt to clean the optics yourself. Ask a TA and they will do it for you.

1.4.4 Do Not Remove the External Mirror Mount from the carriage

The height of the external mirror mount has been precisely adjusted so that the HeNe laser can lase with only the alignment of the two adjustment screws. If this height changes, the laser will not work. If you need to remove this external mirror mount, simply loosen the carriage and remove the entire assembly. In order to replace the mirror, carefully loosen the set screw and remove the 1" disc to which the mirror is glued. Carefully place the disk into the appropriately labeled box for storage. If you do remove the external mirror mount or inadvertently change its height, let a TA know that it needs to be replaced and adjusted.

1.4.5 Do not spend more than 15 minutes trying and failing to get the HeNe laser to lase

If you spend more than 15 or 20 minutes trying to get the HeNe to lase, there may be something more fundamentally wrong with the laser than alignment - like an optic is dirty or the external mirror mount height has been changed. You should not continue in vain but rather find a TA to help you diagnose and fix the problem.

1.5 Measuring the Wavelength

Using the supplied mirror, direct the (pink) fluorescence from the Brewster window into the monochromator (see the appendix for instructions on usage). Slowly tune the monochromator from 580 nm to 640 nm, noting the location and amplitude of the spectral lines. **How does this result compare to what you expect? What do you expect? Once you have successfully aligned the laser, as explained in the proceeding sections, repeat the**

monochromator measurement with the output from the laser. How (and why) is this different from the measurement of the fluorescence?

1.6 Aligning the Beam

The components of the lab have been left in place such that the alignment of the beam should not be overly tedious. The most important element is to remember not to adjust the height of the mirror or remove the mirror post from the post holder for any reason. Any changing of the mirrors should be done with the mirror mount left in place, this makes changing the mirrors a more delicate task but is far outweighed by the subsequent difficulties one would have in aligning the mirror if it were done otherwise.

There is a small screw in the mirror mount used to hold the mirror in place. In order to remove a mirror, loosen this screw while making sure to keep the mirror in place with your fingers. Do not touch the mirror surface, only the black disk that the mirror is attached to. Gently remove the mirror and place it in the mirror holder. To put a mirror in, just do the opposite as described above. Initial alignment should be done with a mirror with a radius of curvature in the range $40 < R < 65$ cm.

Referring to Fig. 1.1, now that the mirror is in place, translate the rail carriage so that the mirror is about 10 cm from the Brewster window. Make sure that the carriage is clamped tightly to the rail, as any stray motion may cause difficulties in the alignment process. There is a fixed aperture immediately in front of the Brewster window, you will use this as a guide to ensure that the incident light rays to the mirror are being reflected back along the same path. When the aperture is fully closed you should see the reflected light somewhere on the aperture surface. If it is not there check with an index card to see where the reflection is going. Using the x and y mirror mount controls only, slowly make adjustments such that the reflection returns back through the opening of the aperture. Lasing may not occur immediately, if this is the case slowly fine tune the position of the reflected beam in the opening. It will be obvious to you when lasing is taking place as there will be a bright red glow from the external mirror as well as an output beam from the OC mirror. Once you have the laser working, adjust the mirror until you have a beam of maximum intensity (brightest beam).

If you are having difficulty getting the mirror aligned, it may be necessary to place a second aperture close to the external mirror. If the post holder containing the second aperture is not already attached to a rail carriage, do so. Place the carriage within the laser cavity, just in front of the external mirror (see figure 1.1). Close the first aperture and make sure that the bright spot is located at the center of the second aperture. If this is not the case, you may need to adjust the height of the second aperture. Try to be as exact as possible, if it is not aligned properly then it will prevent you from obtaining lasing rather than helping you. Once it is aligned, proceed in the same manner as above, except that now you are attempting to make the reflection pass through the openings of both apertures. When starting it might be useful to only have one aperture closed at a time, as this will make the reflection more pronounced and easier to align.

1.7 Spatial modes of a spherical mirror Laser

A laser resonator is capable of supporting more than one spatial mode. Each of these modes has associated with it a specific optical frequency, and are therefore only stable for certain configurations of mirror curvatures and separation.

It is important to note that simply because a mode is capable of lasing at a given mirror configuration does not necessarily mean that it will. Modes undergo a gain competition within the gain medium whereby the one with the highest gain wins out and holds the others below threshold. In an ideal laser this results in a single dominant mode, however in ordinary lasers several modes may lase at the same time. In the case of a gas laser, the atoms in the tube are moving at different velocities along the cavity axis. This velocity distribution results in a similar distribution in the resonant frequencies of the atoms. If modes are produced with frequencies far enough apart one mode may obtain gain independent of the other, since these modes aren't competing with each other they are capable of coexisting.

It is typical in gas lasers such as the HeNe for the gain to be concentrated near the axis of the tube. As a consequence any modes that have a maxima on this axis tend to dominate. However, if a small object (such as a thin wire) is placed such that it impedes the gain at the axis center, then only those modes with a node (zero) occurring at the location of the object will lase. Thus by translating the object laterally across the profile of the beam it is possible to obtain spatial mode control.

1.7.1 Mode Control

Note: the mirror marked "HR" seems to work best for this "mode control" experiment involving the wire.

If you have not already done so, place the polarizer in the output beam line so that you can control the intensity of the beam hitting the camera. The image that you see on the camera will probably not resemble a perfect gaussian TEM_{00} mode. As you adjust the x and y components of the external mirror you should notice that the pattern on the camera (or as seen on the far wall changes). **Using the CCD camera or your artistic abilities, capture some of these patterns and print them out for your lab book and explain their occurrence.**

Re-adjust the mirror to the position of maximum intensity. Slowly open and close one of the apertures (making sure that the other is fully open), again making note of the appearance of the beam. **What happens and why?**

As stated above, mode control may be obtained by placing a thin wire in the open air section cavity of the laser (see Fig. 1.1). Since the mode control is easier in a cavity deep in the regime of stability, make sure that the external mirror is about 20 cm (or less) from the Brewster window. Place a rail carriage containing the shortest post holder on the rail roughly midway between the first aperture and the mirror. Insert the translation stage with the 25μm wire in the post holder and adjust it such that the laser beam is impeded by the wire.

By translating the wire across the profile of the beam you should be able to isolate individual spatial modes at different positions of the wire. Capture some of these modes with the CCD camera, print them and put them in your lab book. The theoretically expected spatial modes are families of Hermite-Gaussians (see

Saleh and Teich,*Fundamentals of Photonics* for the function form). Plot your observed modes with the theoretical expected spatial mode functions.

The wire is mounted on a translation stage with 20μm tics on the micrometer knob, this will allow you to quantitatively prove that each mode is maximized when the wire is at one of its nodes. To do this you need to measure the precise distances (with the micrometer) between isolated distinct modes, the length of the cavity, as well as the distance between the wire and the external mirror. These numbers plugged into the standard expression for the Hermite-Gaussian modes should produce the required result [1]. This is a lengthy analysis that is best done outside of the lab.

1.8 Determining Mirror Curvatures

By adjusting the length of the optical cavity, and carefully observing where lasing occurs, you should be able to determine the curvature of the internal mirror. Do this using a concave curved mirror (something in the range $40 < (-R) < 60$ cm) *a*nd the planar mirror. Note, you should start with the planar mirror since in this case there is only one unknown and you will have a linear term (as a function of d) in the stability inequality, expression (1.2). Using the value obtained for the radius of curvature of the internal mirror, you should theoretically predict the regions of stability for all the available mirrors in the lab. The available mirrors are as follows;

- Planar Mirror
- -1000 mm to -2000 mm Concave Mirror
- -250 mm to -300 mm Concave Mirror
- -40 mm to -45 mm Concave Mirror
- $+1000$ mm to $+2000$ mm Convex Mirror

Warning: most of the mirrors available in this lab to you are actually concave ($R < 0$), but be aware that their radius of curvature may be mis-labeled as a positive number. In fact, the " $+1000$ mm to $+2000$ mm" mirror is the only mirror with a positive curvature ($R > 0$ - i.e. a convex mirror) available in this lab.

Which of them could be used to produce lasing action? Is there one mirror that cannot be used to realize lasing?

1.9 Power Distribution

For this measurement, you will use the power meter. The detector head has a 25 μm pinhole mounted over the face and you will need to position it outside of the cavity so that the beam hits the pinhole. Start by removing the wire holder from the post holder and use the post holder to mount the power meter immediately to the right of the output coupler (OC) mirror. Make sure that the

[1] You will find it useful to look at the sections on Hermite-Gaussian beams and optical resonators in Saleh and Teich's *Fundamentals of Photonics*

output beam is aligned with the pinhole and that you have a measurable signal on the meter. Insure that the output beam is a TEM_{00} mode (this may require adjustment of the aperture in front of the Brewster window and/or small adjustments of the OC alignment). Translate the pinhole across the beam (beginning at the outer edge of the beam) taking distance and power measurements at precise intervals. Plot a graph of power vs. distance. **What kind of function is produced?**

1.10 Polarization

Place the Melles-Griot polarizer in the exit beam. Adjust the polarization angle and note the effect on the beam. **Why does this happen? Does this result make sense with respect to the Brewster window orientation?**

1.11 Wavelength measurement of the Laser Output

This is to remind you to repeat the monochromator measurement with the output from the laser. **How (and why) is this different from the measurement of the fluorescence?**