Helium-Neon Laser

Experiment objectives: assemble and align a 3-mW HeNe laser from readily available optical components, record photographically the transverse mode structure of the laser output beam, and determine the linear polarization of the light produced by the HeNe laser.

Basic operation of the laser

The bright, highly collimated, red light beam ($\lambda = 6328\mathring{A}$) from a helium-neon (HeNe) laser is a familiar sight in the scientific laboratory, in the industrial workplace, and even at the checkout counter in most supermarkets. HeNe lasers are manufactured in large quantities at low cost and can provide thousands of hours of useful service. Even though solid-state diode lasers can now provide red laser beams with intensities comparable to those obtained from HeNe lasers, the HeNe laser will likely remain a common component in scientific and technical instrumentation for the foreseeable future.

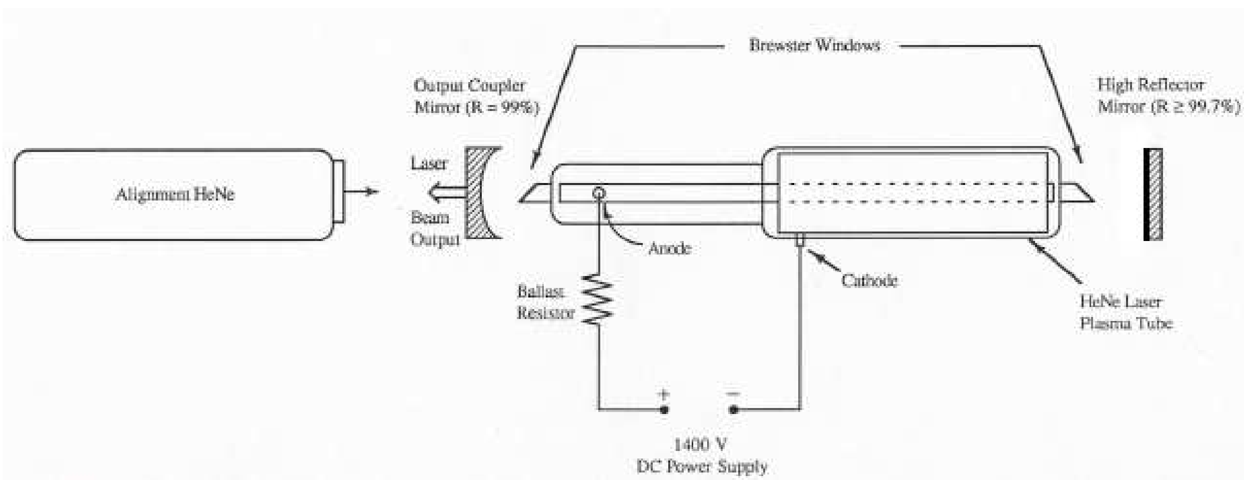

Figure 1: Diagram of optical and electrical components used in the HeNe laser experiment.

The principal goal of this experiment is for you to get hands-on experience with the various optical components of a working laser; however, to help you appreciate fully the role played by each of the components, a brief overview of the principles of HeNe laser operation is given here. The three principal elements of a laser are: (1) an energy pump, (2) an optical gain medium, and (3) an optical resonator. These three elements are described in detail below for the case of the HeNe laser used in this experiment.

1. **Energy pump**. A 1400-V DC power supply maintains a glow discharge or plasma in a glass tube containing an optimal mixture (typically 5:1 to 7:1) of helium and neon gas, as shown in Fig. 1. The discharge current is limited to about 5 mA by a 91-kΩ 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 excited states. He and Ne atoms in excited states can deexcite and return to their ground states by emitting light spontaneously. This light makes up the bright and diffuse pink-red glow of the plasma that is seen at even in the absence of laser action.

   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 the discharge. In other types of lasers, pumping is achieved by using light from a bright flashlamp or by using chemical reactions. Common to all lasers is a process for preparing large numbers of atoms, ions, or molecules in appropriate excited states so that a desired type of light emission can occur.

2. **Optical gain medium**. To achieve laser action it is necessary to have more atoms in excited states than in ground states, and to establish what is called 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, using the simplified diagram of atomic He and Ne energy levels given in Fig. 2. The rather complex excitation process necessary for lasing occurs in four steps.
(a) An energetic electron collisionally excites a He atom to the state labeled 2_1S^0 in Fig. 2. A He atom in this excited state is often written He*(2_1S^0), where the asterisk is used to indicate that the He atom is in an excited state.

   (b) The excited He*(2_1S^0) atom collides with an unexcited Ne atom and the two atoms exchange internal energy, with an unexcited He atom and excited Ne atom, written Ne*($3s_2$), resulting. This energy exchange process occurs with high probability because of the accidental near equality of the 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 time – on atomic that is – that the Ne*($3s_2$) atom deexcites to the $2p_4$ level by emitting a photon of wavelength 6328 $\AA$. It is this emission of 6328 $\AA$ light by Ne atoms that, in the presence of a suitable optical suitable optical configuration, leads to lasing action.

   (d) The excited Ne*($2p_4$) atom rapidly deexcites to the Ne ground state by emitting additional photons or by collisions with the plasma tube deexcitation process occurs rapidly, there are more Ne atoms in the $3s_2$ state than there are in the $2p_4$ state at any given moment in the HeNe plasma, and a population inversion is said to be established between these two levels. When a population inversion is established between the $3s_2$ and $2p_4$ levels of the excited Ne atoms, the discharge can act as an optical gain medium (a light light amplifier) for light of wavelength 6328 $\AA$. This is because a photon incident on the gas will have a greater probability of being replicated in a $3s_2 \rightarrow 2p_4$ stimulated emission process (discussed below) than of being destroyed in the complementary $2p_4 \rightarrow 3s_2$ absorption process.

3. **Optical resonator**. As mentioned in 2(c) 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, a HeNe discharge is placed between two highly reflecting mirrors that form an *optical cavity* or *resonator* along the axis of the discharge. When 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 high-reflectance end mirrors of the cavity. These reflecting photons can interact with other excited Ne*($3s_2$) atoms and cause them to emit 6328 $\AA$ light in a process known as *stimulated* emission. The new photon produced in stimulated emission has the same wavelength and polarization as the stimulating photon, and it is emitted in the same direction. It is sometimes useful for purposes of analogy to think of the stimulated emission process as a "cloning" process for photons. 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 Ne* $3s_2 \rightarrow 2p_4$ 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 that one of the two resonator mirrors, usually called *the output coupler*, has 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 diameter, bandwidth,

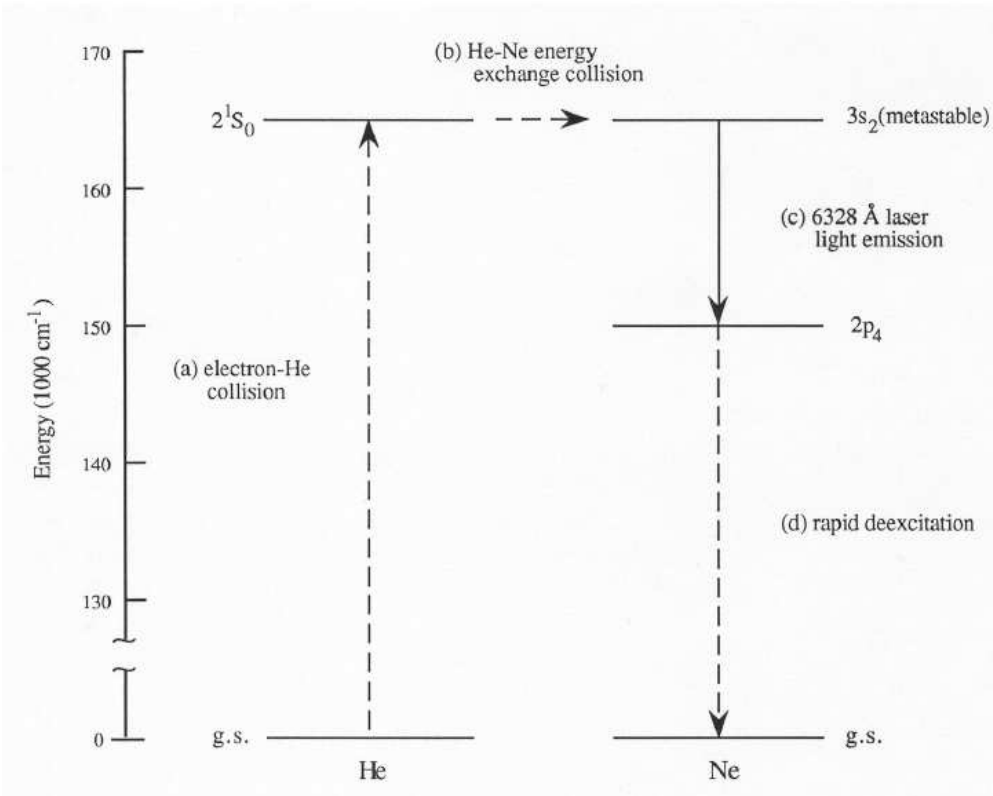

Figure 2: Simplified atomic energy level diagram showing excited states of atomic He and Ne that are relevant to the operation of the HeNe laser at 6328 $\AA$.

and 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.

Experimental Procedure

Equipment needed: Commercial HeNe laser, HeNe discharge tube connected to the power supply, two highly reflective mirrors, digital camera, polarizer, photodetector, digital multimeter.

Safety

A few words of caution are important before you begin setting up your HeNe laser.
First, **never** look directly into a laser beam, as severe eye damage could result. During alignment, you should observe the laser beam by placing a small, white index card at the appropriate point in the optical path. Resist the temptation to lower your head to the level of the laser beam in order to see where it is going.
Second, **high voltage** ($\approx$ 1200 V) is present at the HeNe discharge tube and you should avoid any possibility of contact with the bare electrodes of the HeNe plasma tube.
Finally, the optical cavity mirrors and the Brewster windows of the laser tube have **very delicate optical surfaces** that can be easily scratched or damaged with a single fingerprint. If these surfaces need cleaning, ask the instructor to demonstrate the proper method for cleaning them.

Alignment of the laser

To assemble the HeNe laser and investigate its properties, proceed with the following steps.

- The discharge lamp has very small and angled windows, so first practice to align the beam of the commercial HeNe laser through the discharge tube. To do that turn on the commercial laser, place a white screen or a sheet of paper at some distance and mark the position of the laser spot. Now without turning the power, carefully place the discharge tube such that the laser beam passes through both angled windows without distortion, and hit the screen almost in the same point as without the tube. Repeat this step a few times until you are able to insert the tube inside the cavity without loosing the alignment. Then carefully slide the tube out of the beam and clamp it down.
- Set up a hemispherical resonator configuration using a flat, high reflectivity (R = 99.7%) mirror, and a spherical mirror with a radius of curvature of r = 0.500 m and reflectivity R = 99%. The focal length f of the spherical mirror is given by f = r/2 = 0.250 m. In the diagram of Fig. 1, the flat, highly-reflective mirror will be serving as the right end of the cavity, and the spherical, less-reflective mirror will be serving as the left end of the cavity and is known as the output coupler. The high reflectivity of each mirror is due to a multilayer dielectric coating that is located on only one side of each mirror. Be sure to have the reflecting surfaces of both mirrors facing the interior of the optical cavity. Set the distance between the two mirrors to approximately d = 47 cm.
- To align the optical resonator of your HeNe laser it is easiest to use a beam of a working, commercial HeNe laser as a guide. Direct this alignment laser beam to the center of the high reflector mirror, with the output coupler and the HeNe discharge tube removed. With the room lights turned off, adjust the high reflector mirror so that its reflected beam returns directly into the output aperture of the alignment laser. Now insert and center the output coupler mirror, and also adjust it such that the reflected beam (from the back of the mirror) returns to the alignment laser. Now insert a small white card near the front of the output couplers very close to the laser beam but without blocking it, and locate the reflected beam from the high reflector mirror - it should be fairly close to the input beam. Using fine adjustment screws in the high reflector mirror overlap these two beams as good as you can. In case of success you most likely will see some light passing through a high reflection mirror - fine-tune the position of the mirror some more to make this light as bright as possible.
- Now reinsert the HeNe plasma tube between the two mirrors of the optical cavity and adjust the plasma tube position so that the alignment beam passes through the center of the Brewster windows of the plasma tube. Be careful not to touch the Brewster windows or mirror surfaces during this process. With the HeNe plasma tube in place, it should be possible to see a spot at the center of the high reflector mirror that brightens and dims slowly.
- Turn on the high voltage power supply to the HeNe plasma tube and (with luck) you will observe the HeNe lasing. If lasing does not occur, make small adjustments to the plasma tube and the two mirrors. If lasing still does not occur, turn off the high voltage supply, remove the HeNe plasma tube, and readjust the resonator mirrors for optimal interference rings. If after several attempts you do not achieve proper lasing action, ask the instructor for help in cleaning the Brewster windows and resonator mirrors.
- Once lasing is achieved, record your alignment procedure in your laboratory notebook. Turn off the alignment laser - you do not need it anymore.

Study of the mode structure of the laser output

Place a white screen at the output of your laser at some distance and inspect the shape of your beam. Although it is possible that your beam is one circular spot, most likely you will notice some structure as if the laser output consists of several beams. If you now slightly adjust the alignment of either mirror you will see that the mode structure changes as well.

As you remember, the main purpose of the laser cavity is to make the light bounce back and forth repeating its path to enhance the lasing action of the gain medium. However, depending on the precise alignment of the mirrors it may take the light more than two bounces to close the loop: it is often possible for the beam to follow a rather complicated trajectory inside the resonator, resulting in complex transverse mode structure at the output.

- Take photographs of the transverse mode structure of the HeNe laser output beam. By making small adjustments to the mirrors and the position of the HeNe plasma tube it should be possible to obtain transverse mode patterns. Mount your photographs in your laboratory notebook.
- Adjust the mirrors such that the output mode has several maxima and minima in one direction. To double-check that this mode is due to complicated trajectory of a light inside the resonator, very carefully insert an edge of a white index card into the cavity, and move it slowly until the laser generation stops. Now mover the card back and force around this point while watching the generation appear and disappear, and pay close attention to the mode structure of the laser output. You may notice that the complicated transverse mode pattern collapses to simpler mode when the card blocks part of the original mode volume, forcing the generation in a different mode. Describe your observation in the lab journal.

Measure the polarization of the laser light

When a linearly polarized light beam of intensity I_0 passes through a linear polarizer that has its axis rotated by angle θ from the incident light beam polarization, the transmitted intensity I is given by Malus's law:

$$I = I_0 cos^2\theta. \tag{1}$$

In our experiment the laser generates linearly polarized light field. This is insured by the Brewster windows of the HeNe plasma tube: the angle of the windows is such that one light polarization propagates almost without reflection. This polarization direction is in the same plane as the incident beam and the surface normal (i.e. the plane of incidence). The light of the orthogonal polarization experiences reflection at every window, that makes the optical losses too high for such light.

- Visually inspect the discharge tube, note its orientation in the lab book. Make a rough prediction of the expected polarization of the generated beam.
- Determine the linear polarization of the HeNe laser output beam using the rotatable polarizer and photodiode detector. Make detector readings at several values of angle θ (every 20° or so) while rotating the polarizer in one full circle, and record them in a neat table in your laboratory notebook. Graph your data to demonstrate, fit with the expected $cos^2\theta$ dependence, and from this graph determine the orientation of the laser polarization. Compare it with your predictions based on the Brewster windows orientation, and discuss the results in your lab report.

Acknowledgements

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