

Helium-Neon Laser

1 Introduction

The Helium-Neon Laser, short HeNe-Laser, is one of the most common used laser for alignment, reference laser and optics demonstrations. Its most used wavelength is at 632.8nm (red). It also has lasing transition in IR, orange and green. This experiment will make you familiar with basic cavity alignment procedures, cavity characteristics, beam profile analysis and Gaussian optics.

2 Background

2.1 Helium-Neon Gain Medium

The Gain medium is a mixture of the two gases Helium and Neon. Mostly the mixture ranges from 5:1 to 20:1 ratios with relatively low pressure. A high voltage source (typical value of 1kV) is exciting the Helium atoms to long-lived, meta-stable states. Collisions of the excited Helium atoms with the ground state Neon atoms results in a transfer of the energy. The excited Neon atom can relax to ground state by spontaneous and stimulated emission of a photon. The strongest transitions are at 1.5 μm and 3.39 μm . In the visible, transitions at 543.5 nm (green, measured in vacuum), 594 nm (yellow) and 612 nm (orange) exists. The typical red laser uses the transition at 632.8 nm(measured in air).

2.2 Laser Cavity

A laser cavity is a resonant feedback system necessary for a laser. They can be setup in a ring or linear configuration. In this experiment, you will build a linear cavity composed of two curved mirrors. For resonance condition, there has to be integral numbers of half wavelength in between these two mirrors

$$L = q \frac{\lambda}{2n} \quad (1)$$

where L is the length of the cavity, λ the wavelength, n the refractive index and q an integer. Eqn (1) can be rewritten in terms of frequency ν

$$\nu = q \frac{c}{2nL}, \quad (2)$$

where c is the speed of light in vacuum. This means only discrete frequencies are resonant inside the cavity and contribute to the lasing. These frequencies are also called longitudinal modes. Eventually, the lasing modes are defined by the overlap of the gain medium spectrum and the cavity spectrum.

2.3 Hermite-Gaussian or transverse Modes

In the paraxial approximation, the solution to the wave equation are pure transverse electric and magnetic (TEM) waves. In this experiment, you will investigate some properties of TEM₀₀ (Gaussian) and TEM₀₁ modes. These modes are called transverse modes in a laser. In figure 1 the three different TEM-modes are shown. These TEM modes also affect the longitudinal modes, since the phase shift of higher Hermit-Gaussian modes is more complicated when propagating

from one side of the cavity to the other one. (Note: the phase shift description is just a different interpretation of the integers half wavelength that fit inside the resonator). So the frequencies of the $\text{TEM}_{m,p,q}$ can be written in the form:

$$\nu_{m,p,q} = \frac{c}{2nL} \left[q + \frac{1+m+p}{\pi} \cos^{-1}(g_1 g_2)^{1/2} \right] \quad (3)$$

with $g_{1,2} = 1 - \frac{L}{R_{1,2}}$ where $R_{1,2}$ are the radius of curvatures of the mirrors.

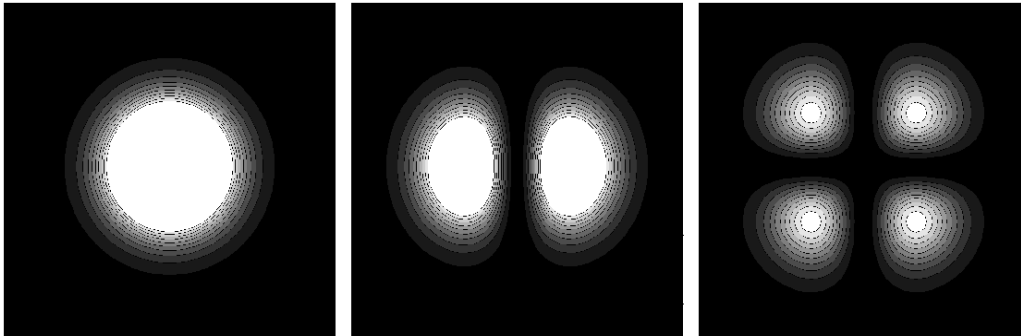


Figure 1: The intensity profile of a TEM_{00} (left), the TEM_{10} (middle) and the TEM_{11} (right) are shown.

3 Experiments

3.1 Basic cavity alignment

For the alignment, we will use another He-Ne laser to perform the alignment of this laser, which brings the question of the egg and the chicken: how were the first He-Ne lasers aligned? My old Boss at Philips Research Labs in Eindhoven had his technique. He looked down the tube, to center the image of the pupil of his eye. Then he placed the second mirror, lined it up, and ... jumped away when the laser oscillation started.

3.2 Alignment of a Long Laser Tube: The Virtual Pivot

HeNe and Argon lasers typically have very small bore diameters. It is therefore difficult to send an alignment laser beam through these tubes. In addition, the laser manufacturer makes your life most difficult by locating the external cavity mirrors so close to the tube, that there is no way to insert any sophisticated mirror mount between the end mirror mount and the tube.

The solution is an optical arrangement that enables you to rotate the beam around a pivot point located at the tube entrance. The optical setup should also allow for independent positioning of this “pivot point”. The principle of such a setup is described below in Fig. 2.

A two lens combination can be used to obtain an ideal alignment beam: a diameter small enough to penetrate the capillary tube of the laser, yet not too small in order to have a reasonable divergence (say a waist of $850\mu\text{m}$ over 3 meters). In order to align the beam with the axis of the tube, it should be rotated around a point A located at the tube entrance (where it is of course not possible to position a mirror). The solution is to have the point A (the “virtual pivot point”) be the image of a real pivot point A_0 as sketched in Fig. 2.

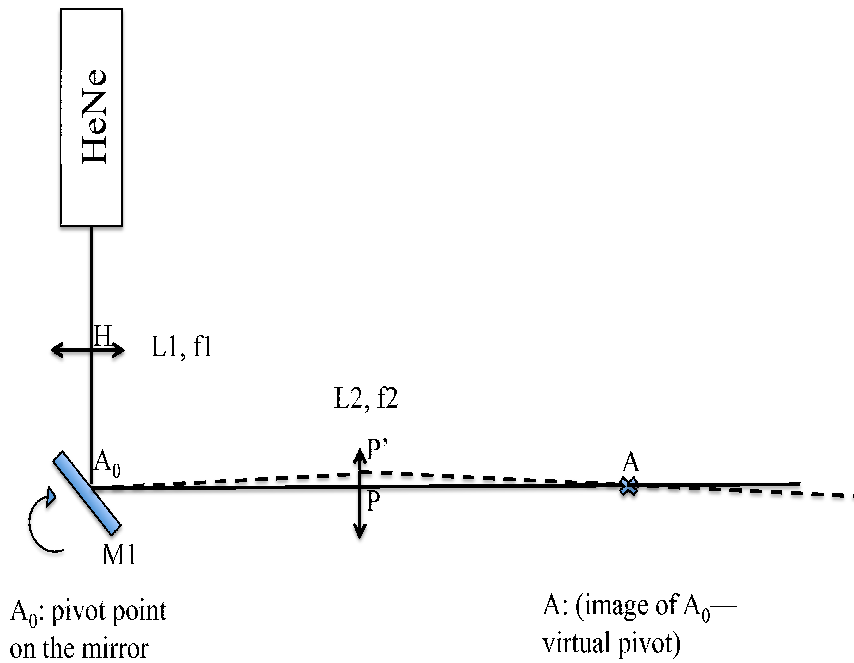


Figure 2: The virtual pivot. Note: The HeNe symbol here refers to a combination of a HeNe laser and optics that ensure minimal divergence, i.e. a well-collimated beam.

Since A is the image of A_0 in the geometrical optics approximation, one sees that:

$$\frac{1}{\overline{A_0P}} = \frac{1}{f_2} - \frac{1}{\overline{AP}} \quad (4)$$

Given f_2 and \overline{AP} (a convenient working distance from the tube), one can determine $\overline{A_0P}$. To position the lens L_1 , the telescope system of lenses L_1L_2 should be **confocal** (in order to transform one collimated beam into another collimated beam). One determines the distance $\overline{HA_0}$ from the relation $\overline{HA_0} + \overline{A_0P} = f_1 + f_2$.

Fine adjustment of the distance $\overline{A_0P}$ is required to correct for the fact that the geometrical optics approximation was used to position the lenses (in order to obtain the minimum divergence for the beam).

Verify the existence and position of a “virtual pivot point”.

Tips for alignment:

Make sure the HeNe alignment laser is horizontal all the way along the optics table, even after every optics (mirrors, lenses). You need to budget 10% of your time on this.

Make sure the HeNe alignment laser hit the pivot of mirror M1. It should be mounted on a mount with it’s pivot on the center of the mirror, but not outside. In this case you acquire an independent adjustment of beam direction.

Using a 50-50 beamsplitter, position the point A at the entrance face of the laser tube to be aligned (see Fig. 3). Lens L2 is mounted on a 3-dimension translation stage to provide an independent position adjustment of virtual pivot A. Now you have both beam direction adjustment (by M1) and position adjustment (by L2).

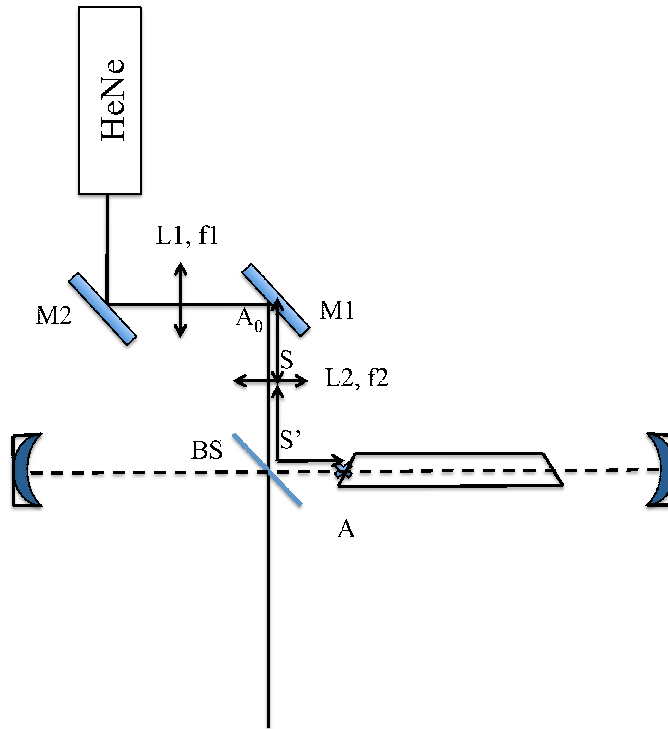


Figure 3: Laser alignment with the virtual pivot.

3.3 Beam Profile Measurements

1. Place a CCD camera with an appropriate choice of filters (neutral density and interference filters) near the exit of the output coupler (OC) with a weaker transmission. Be conscious of where the CCD array is located when positioning the camera with respect to the beam. Turn on the appropriate software and look at your beam. CCD's have a certain saturation level beyond which there is only a fixed amount of signal registered. By using the right filters you will be able to achieve a good signal that spans most if not all of the range of the camera without inducing saturation.
2. Make adjustments to the tip/tilt of the OC's to maximize the signal coming from the CCD and to make the profile appear as round as possible.
3. Insert a "mounted" hair inside the cavity pretty close to one of the output coupler's. With a little care and re-aligns of the laser you should be able to achieve the TEM(10) mode.
4. Remove the hair from cavity and play with the tip/tilt of the OC's. At some point it should be possible to observe a linear combination of the 00 and 10 modes. It will appear as an elongated elliptical like beam. Return the orientation of the OC's to the place where the beam is in the 00 mode.
5. Given R_1 , R_2 , and by measuring L calculate the location and size of the minimum beam waist as well as the rayleigh range. Using the CCD camera measure the beam size at several locations far beyond the rayleigh range (7-15 times, You may need some folding mirrors to get that kind of distance). From the propagation theory of Gaussian beam,

you then can calculate both the size the position of the beam waist. Compare two results. (Please remember that the beam waist often denoted w_0 is the radial distance from the peak to the place where the intensity reaches $1/e^2$.)

3.3.1 Questions:

1. Describe the basics on how a CCD array works.
2. Describe the basics on how an interference filter works.

3.4 Transverse and Longitudinal Modes

One of the common wavelengths emitted by the Helium-Neon Laser is 632.8 nm. Like all emission lines there is a finite bandwidth associated with this wavelength. The 1.5 GHz bandwidth of the Helium-Neon Laser is largely due to doppler broadening.

Another key feature of the Helium Neon laser is that it is a resonant cavity wherein you can have perhaps a 1,000,000 half-wavelengths (λ_1) fit inside it. If 1,000,001 half-wavelengths fit inside the same cavity this would obviously correspond to a slightly shorter wavelength (λ_2). Likewise due to the spatial structure of higher Hermite-Gaussian modes than just the 00 it is possible to obtain other wavelengths inside of the resonant cavity.

If various numbers of these wavelengths are permitted within the emission line of the laser you can often observe a beating between them. A beating of two (or more) wavelengths is really a periodic fluctuation in intensity due to the interference between two (or more) modes in time.

If you have enough wavelengths simultaneously beating against each other that are all locked in phase with respect to one another it is possible to achieve destructive interference in the vast majority of the cavity except in one place where a pulse is running. This locking of phases is appropriately called mode-locking, a deep and complex subject that is beyond the scope of this particular experiment.

The periodic beating of two wavelengths that are not separated by more than a few than 10^{-3} Å is observable by a fast photodiode detector. This is the goal of this experiment.

Use a spectrum analyzer to observe the beating frequency between longitudinal modes.

Make adjustments to the cavity OC's such that you once again observe the linear combination of the 00 and 10 modes. Look to see if there is difference in the output of the spectrum analyzer. By zooming in on and translating the frequency span note the locations of the new peaks that have arisen with respect to those that occur when only the 00 mode is present.

3.4.1 Questions:

1. What are the limiting factors on the output power of the Helium-Neon laser?
2. Let's say that you have a He-Ne laser where q half-wavelengths of 632.8 nm fit inside the cavity. Furthermore let's assume you also have the next mode ($q+1$) also riding along. Each of these has an electric field that goes with it that goes as $E = \sin(kx - \omega t)$. Plot $I_{total}(t) = E^2(t)$ at a fix position x to see the effect of beating.
3. In Michelson Interferometer experiment, the intensity recorded by the photodiode is given by $I = \frac{I_0}{2} [1 + \cos(\frac{\omega}{c} 2\Delta d)]$, in which Δd is the length variation of one arm. What will the intensity look like if the laser you are using has two adjacent longitudinal modes with equal intensity? How can you get the cavity length information from the intensity profile?

4. Create a table of the frequencies observed by the spectrum analyzer in this experiment. Compare what you measured with calculations (given the radius of curvature of two laser mirrors, measure the cavity length, then you can calculate the beat frequency).

3.5 Speed of Light measurement

Given the Eqns (1) and (2), develop a way to measure the speed of light by recording the beatnote of the longitudinal modes. Hint: There is no need to measure the total cavity length.