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Laser

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Abstract

The goal of this experiment is to build and operate a Helium-Neon gas laser. The operating principles for the laser will be tested both qualitatively as well as quantitatively. These experimental results will be compared to theoretical predictions.

Contents

1 Introduction

Since the advent of Light Amplification by Stimulated Emission of Radiation (L.A.S.E.R.) in the mid 20th century, lasers have become useful for various modern technologies such as atomic clocks, gas spectroscopy, laser eye surgery, and many others. For these varying tasks many different types of lasers have been developed. One such laser, the HeNe gas laser, can often be found in ring gyroscopes and has a bright red line at 633 nm. Gas lasers work by having an excited gas inside of a cavity, which consists of two mirrors pointed at eachother. Photons will bounce back and forth inside of this cavity, where they will induce stimulated emission from the excited gas into the same wavelength, direction, and polarization as the trapped photons. If one of the mirrors is slightly transparent, a beam of photons can escape from the cavity, and a laser be produced.

2 Theory

2.1 Optical Gain

This theory section will mainly consider the case of two relevant energy levels for lasing. The lower and upper lasing energy level will be called 1, and 2 respectively. There are three possible interactions to be aware of. If an atom is in the lower energy level, and a photon with a wavelength corresponding to the energy difference between the two levels ($\frac{hc}{\lambda} = E_2 - E_1$) comes along, it can be **absorbed**, which excites the atom. An excited atom can randomly **spontaneously emit** a photon at any time, or, when stimulated by an incident photon, emit a photon in the same quantum state as the incident photon. The latter is called **stimulated emission**.

The rate at which photons are stimulated or absorbed is the same, so in order to have the gas amplify light sent through it, there needs to be more excited atoms than low energy atoms.This means there needs to be **population inversion**: $N_2 > N_1$.

This cannot be achieved by direct pumping from state 1 into state 2, and must instead be achieved by using an additional state.

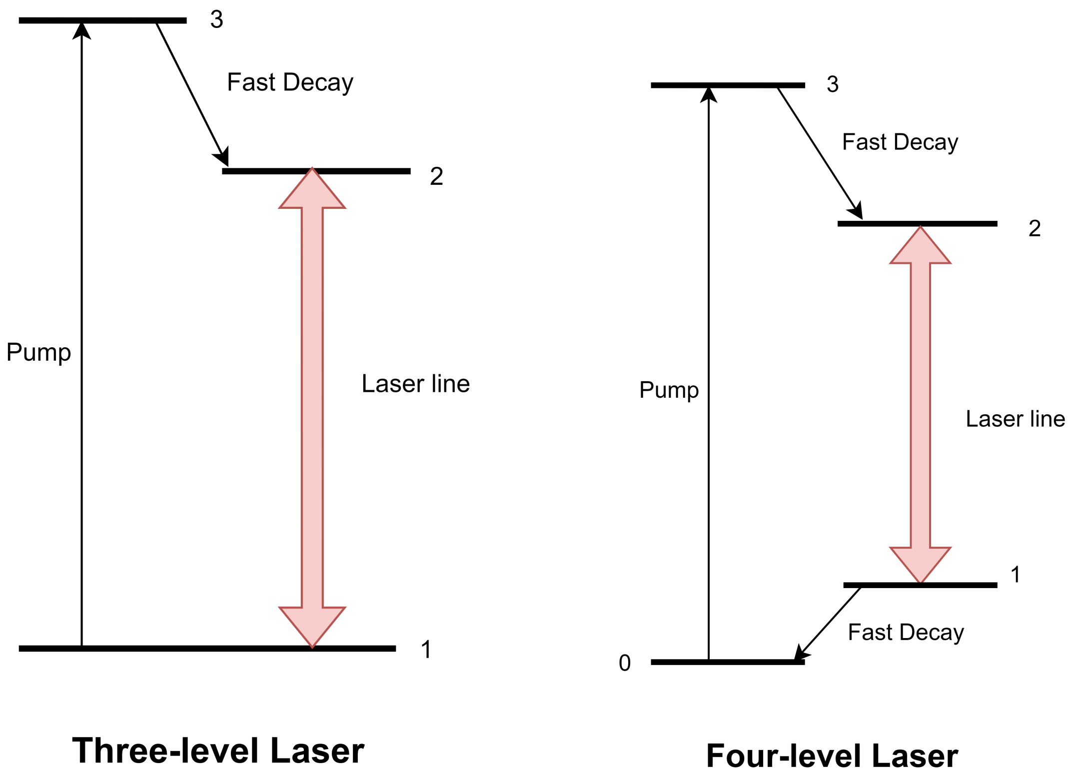

Figure 1: Diagrams showing the relevant energy levels for a three and four-level laser.

In a **three-level laser** atoms are pumped to an additional pump state, from where the quickly decay to state 2. Assuming the pump rate is high enough, and spontaneous emission from state 2 is rare enough, it is possible to pump enough atoms to achieve population inversion. But as initially all of the atoms are in the ground state, which is state 1 in the three level laser, getting a strong enough pump for population inversion can be difficult.

The **four-level** laser improves on the three-level laser by using an intermediate level as the lower lasing level. Atoms in the lower laser level decay quickly to the ground state, making population inversion significantly easier to achieve. The HeNe laser is a four-level laser, lasing off of a neon transition pumped through collisions with the plasmafied helium.

The three and four-level laser models are a simplification of real lasers where there may be many more energy levels to consider, or where there may be multiple at omic species interacting with eachother to operate the laser. But to first order most lasers can be understood through these models.

2.2 Optical Cavity

Most lasers utilize a cavity to produce a continuous coherent beam. Such a cavity consists of two mirrors around the gain medium, trapping photons such that they can repeatedly stimulate more photons to be emitted:

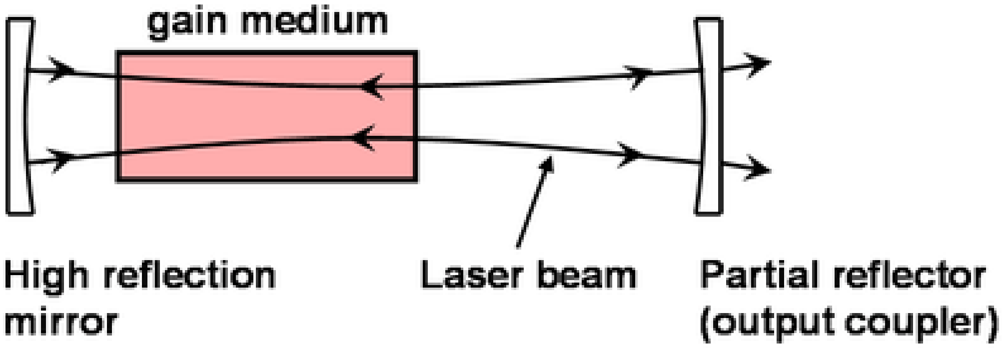

Figure 2: A diagram showing a typical concave-concave optical cavity around a gain medium (e.g. gas cell).

For the laser to operate, it must at minimum produce more light than it loses in each cavity pass. That is to say, if on average each photon stimulates the emission of one more photon on a pass though the cavity, then the laser can still operate if the transmission of the outcoupling mirror is less than 50%. This also goes for other losses, such as dirt on optical components, polarization optics in the cavity, losses due to bad reflections from the glass cell holding the gas in place etc.

For a stable cavity mode to exist, the mirrors need to be tuned properly. If both mirrors are divergent for example, light cannot get trapped as it will simply be scattered out of the cavity. Similarly if the mirrors are too strongly convergent, light will also escape the cavity. Curved spherical mirrors are typically described by their radius of curvature R. The smaller the radius the more curved the mirror. For a stable cavity to be formed the length of the cavity and radius of curvature of the mirrors must be within a certain range. This condition is known as the **cavity stability condition**:

$$0 \leq g_1 g_2 \leq 1, \tag{1}$$

where

$$g_i = 1 - \frac{L}{R_i}. \tag{2}$$

This condition needs to be met for a stable laser to form. Note that typically one mirror is high reflectivity, and the other mirror is lower reflectivity. This is the outcoupling mirror, and it is the direction in which the laser will emit light.

The light field in the cavity can be described using classical gaussian optics, which in turn can be derived from Maxwell's equations. The cavity mode of a well aligned cavity can be decomposed into a series of transverse modes, one of which are the gauss-hermite modes, these are known as the Transverse Electric Modes (TEMs):

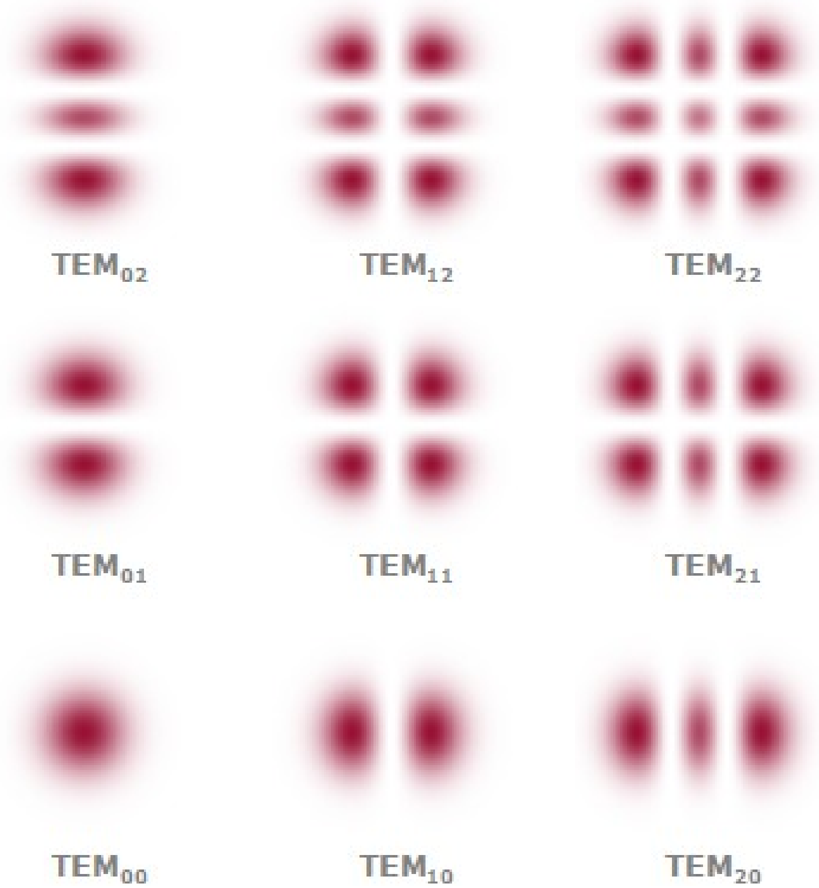

Figure 3: An image showing the the first few TEM orders.

Most cavity modelling and physics is done using the TEM_{00} mode as it is typically the most stable cavity mode. Which modes are low loss in any given cavity requires a more careful treatment using gaussian optics, which will not be covered here, but can easily be found in any decent book on the subject.

Longitudinally, a cavity mode will generally take on the shape of a gaussian beam, having a beam waist at a certain point, and diverging linearly in the far field:

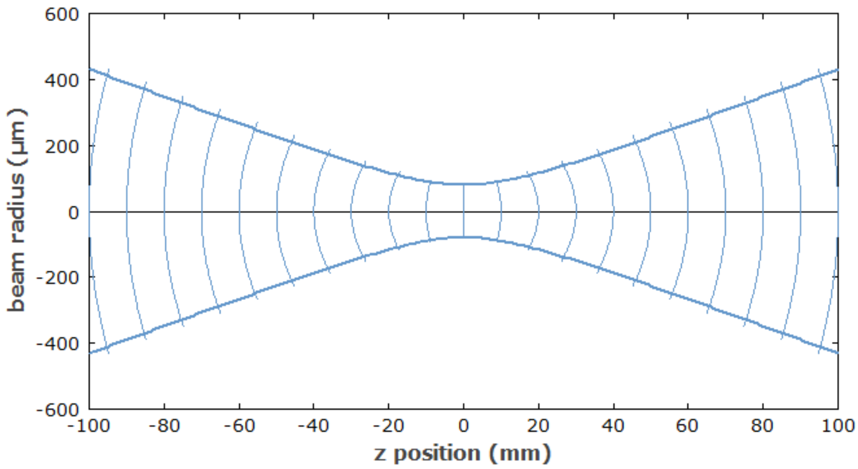

Figure 4: A diagram showing the shape of a typical gaussian beam, with a beam waist at z=0.

The position and size of the beam waist depend on the radius of curvature of the two cavity mirrors, and the cavity length. For a concave-flat configuration, the beam waist is expected at the flat mirror's surface. For a concave-concave configuration, the beam waist will be somewhere between the two mirrors.

For a more careful treatment of laser and cavity physics see:

Modern Classical Optics by G. Brooker.

Laser Physics by S. Hooker, and C. Webb.

Lasers by A.E. Siegman.

3 Experimental Setup

3.1 Laser Safety

The guiding laser is a class 2 laser, it is generally safe, so long as you dont stare at its output.

When operating, the HeNe laser is a **class 3b** laser, which can damage your eyes even through brief exposure.

DO NOT STICK YOUR HEAD IN THE BEAM PATH

DO NOT STICK ANYTHING REFLECTIVE IN THE BEAM PATH

3.2 Experimental Devices

This experiment consists of various devices which will be described in this section.

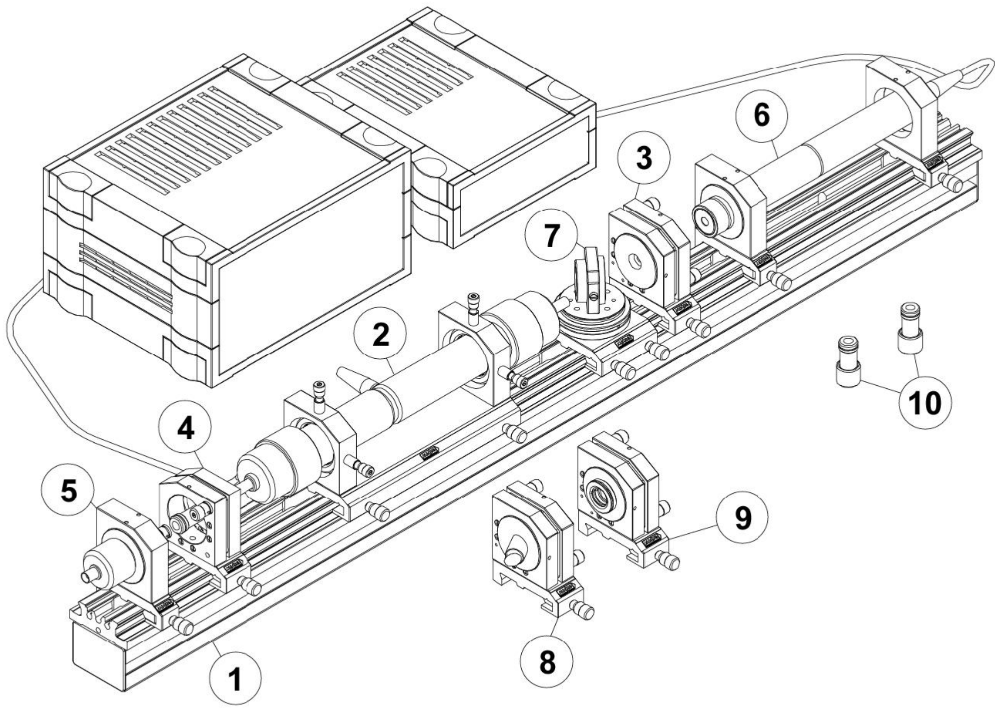

Figure 5: A diagram of the main components used in the experiment.

1. Optical rail

The optical rail makes sure all the optical components are at least roughly aligned.

2. HeNe laser tube.

   The laser tube has brewster angle windows to ensure no reflections additional to those of the cavity can occur, and adjustment screws so that it can be more finely aligned to the beam path.

3. Cavity mirror adjuster.

4. Cavity mirror adjuster.

   These adjusters hold the cavity mirrors and allow for fine angle adjustments so that they can be aligned to the beam path.

5. Photodetector.

   Broken and replaced with a thorlabs photodetector. The mount can still be used as a target for the alignment laser.

6. Alignment laser + power supply.

   A small laser to be used for aligning the subsequent optics to the beam path.

7. Birefringent tuner.

   Not used.

8. Littrow prism tuner.

   Not used.

9. Single mode etalon.

   Not used.

10. Set of mounted cavity mirrors.

    Cavity mirrors of various reflectivities and radii of curvature. You will need the following:

    a An outcoupling mirror with R=70 cm, and lower reflectivity

    b A High-reflectivity mirror with R=70 cm.

    c A High-reflectivity flat mirror with R=∞.

    These mirrors should be capped when not in use.

11. A Polarizer

    this is not shown, but there is also a linear polarizer which should be used for parts of the experiments. This is in effect a filter, which blocks light not of the correct polarization.

3.3 Optics Alignment

In order to get lasing the optical elements have to be carefully aligned, which has to be done through the following procedure:

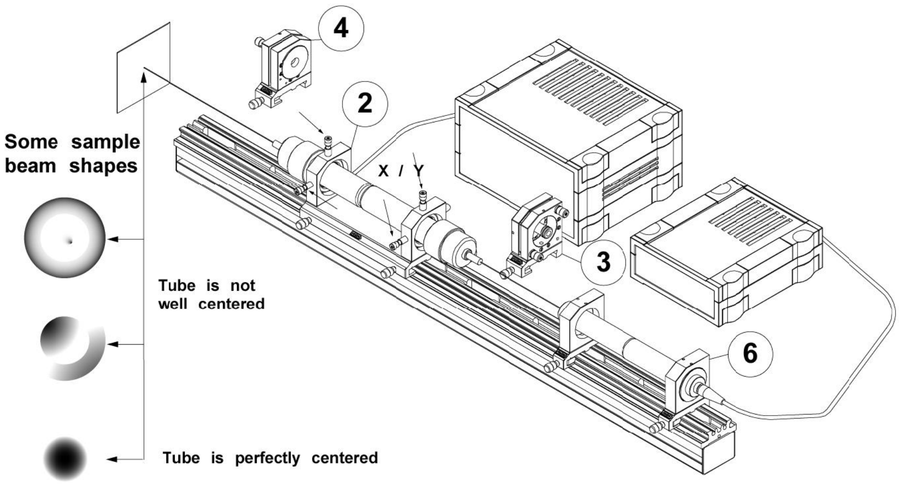

Figure 6: Step 4 in the alignment process

1. Remove all elements from the optical rail except the alignment laser, and a target. Align the guidance laser such that it hits the target precicely in the center.
2. Place the mirror holder (with mirror) with the reflective side towards the alignment laser. Adjust the fine adjustment screws to overlap the alignment laser with its reflection.
3. Place the other mirror holder with mirror in the beam path of the reflected beam, and adjust until the beam and its various reflections overlap and hit the target.
4. Remove the mirrors and place the laser tube on the optical rail. Look in the far field to see the shape of the alignment beam. Adjust the screws on the laser tube until the beam passes through the center of the tube. See Figure 4 for clarification.
5. Place the cavity mirrors in the spots where they were before and place a photodetector at the end of the optical rail. Turn on the tube current. There should now be lasing. Adjust the cavity mirrors to maximize the laser power as measured by the photodetector. This maximization step has to be performed every time the tube or cavity mirrors are moved.
6. Start the measurements

This procedure has to be repeated for both cavity configurations.

4 Measurements to take

There are two configurations which should be tested. A concave-concave configurations (using mirrors 10.a and 10.b), and A concave-flat configuration (using mirrors 10.a and 10.c).

Note that every time the laser tube or cavity mirrors are moved, step 5 from the alignment list has to be repeated.

4.1 Concave-Concave configuration

1. With the laser tube in the center, measure the laser intensity as a function of the tube discharge current.
2. Laser intensity as a function of the position of the laser tube inside the cavity.
3. Laser intensity as a function of the angle of the polarizer. For this part the polarizer has to be inserted into the cavity.
4. Laser intensity as a function of the cavity lenght (keep the tube in the center, but move both mirrors by equal amounts).

4.2 Concave-Flat configuration

1. With the laser tube close to the flat mirror, measure the laser intensity as a function of the tube discharge current.
2. Laser intensity as a function of the position of the laser tube inside the cavity.
3. Laser beam width inside the cavity at various points (keep the tube close to the cavity, but use non-reflective calipers to measure the beam diameter at different points between the tube and the concave mirror.
4. Laser intensity as a function of the cavity lenght (keep the tube at the flat mirror, and move the concave mirror).

5 The Report

In the report you should have descriptions of each measurement. Hypotheses of what you expect to see from each measurement with explanations based on the theory. Descriptions of how you've taken these measurements. Error estimates with reasoning. Graphs of the measurements taken with errorbars, and fitted with a model. Comparison of the measured data to the established hypotheses, alongside a discussion of potential sources of error.