Characteristics of a Laser Beam

Apparatus: Laser, photodetector on translation stage, amplifier, knife edge with mount.
Purpose:

1. To verify if the profile is Gaussian
2. To determine the spot size and beam divergence
3. To measure the power distribution within the beam

Methodology: The beam is scanned horizontally and intensity recorded using a photodetector and amplifier.

I Theory:

The light emitted form a conventional light source (like a sodium lamp) is said to be incoherent because the radiations emitted from different atoms do not, in general, bear any definite phase relationship with each other. On the other hand, the light emitted from a laser has a very high degree of coherence and is almost perfectly collimated. ‘Laser’ is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. The basic principle involved in lasing action is the phenomenon of stimulated emission, which was predicted by Einstein in 1917. Einstein argued that when an atom is in the excited state, it can make a transition to a lower energy state through the emission of electromagnetic radiation; however, in contrast to the absorption process, the emission can occur in two different ways:

1. **Spontaneous Emission**, in which an atom in the excited state emits radiation even in the absence of any incident radiation. It is thus not stimulated by any incident signal but occurs spontaneously.
2. **Stimulated Emission** in which an incident signal of appropriate frequency triggers an atom in an excited state to emit radiation.

Using the phenomenon of stimulated emission, C.H. Townes and A.H. Schawlow, in 1958, worked out the principle of the laser.

I.1 Stimulated Emission:

Consider a gas enclosed in a vessel containing free atoms having a number of energy levels, at least one of which is metastable. By shining white light into this gas many atoms can be excited, through resonance, from the ground state to excited states. As the atoms get de-excited (electrons drop back to the lower energy levels), many of them will become trapped in the metastable states. If the pumping light is intense enough we may obtain a population inversion, i.e. more electrons in the metastable state than in the ground state.

When an electron in one of these metastable states spontaneously jumps to the ground state, the atom emits a photon. As the photon passes by another nearby atom in the same metastable state, it stimulates that atom to radiate a photon of the same frequency, direction and polarization as the primary photon and in exactly the same phase. Both these photons, when passing close to other atoms in their metastable states, stimulate them to emit in the same direction with the same phase. However, transitions from the ground state to the excited state can also be stimulated, where the primary photons are absorbed. An excess of stimulated emission gives population inversion. Thus if the conditions in the gas are right, a chain reaction can be developed, resulting in high intensity coherent radiation.

In this process, the amplification achieved, or the gain, is proportional to the lifetime of the excited state, related to what is called the Einstein A coefficient.

I.2 Laser Design:

In order to increase the amplification further, the lasing material is placed in a resonant optical cavity. For this, a cavity is fitted with two end mirrors with high reflecting power. The light from stimulated emission gets reflected back and forth between these mirrors and stimulates further emission. Photons moving at an appreciable angle to the walls of the cavity will escape and be lost. Those photons emitted parallel to the axis will reflect back and forth from end to end. Their chance of stimulating emission will now depend on the high reflectance at the end mirrors and a high population density of metastable atoms within the cavity. If both these conditions are satisfied the build-up of photons surging back and forth through the cavity can be self-sustaining and the system will oscillate or lase, spontaneously.

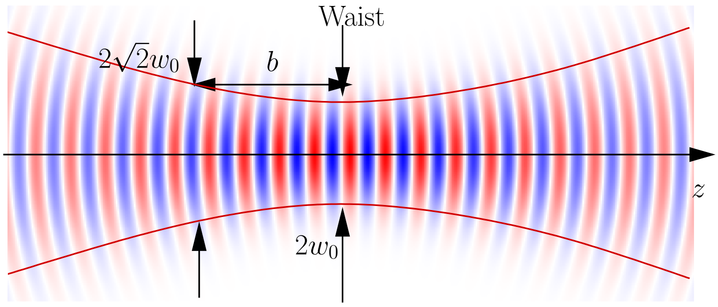
An aperture made at one of the ends can now let out a highly intense and collimated beam of coherent light. The form of the wavefront and other beam characteristics depend on the geometry of the cavity. One can solve the Maxwell equations in a cylindrical cavity with perfectly reflecting endcaps. Superposition of reflected beams will decide the wavelength of the beams that constructively interfere and build up inside. The form of the waves, given by the geometry of the cavity, is essentially Hermite polynomials modulated by a Gaussian.

Suppose the axis of the cavity is along z, the propagation direction. If $\rho^2 = x^2 + y^2$ then the basic Gaussian solution for the electric field in the cavity has the form

$$E(\rho, z) = U_0 e^{-\rho^2/w^2(z)} \tag{1}$$

$$\text{where } U_0 = i\frac{E_0 w(0)}{b w(z)} e^{i(kz-\omega t)} e^{i\alpha} e^{ik\rho^2/2R(z)} \tag{2}$$

Here, $w^2(z) = 2\frac{z^2+b^2}{kb}$, and $w(z)$, the beam diameter at z is known as the Spot Size. $b = \pi w(0)^2/\lambda$ is a parameter dependent on the cavity geometry and $R = (z^2 + b^2)/z$ is the radius of the wavefront.



A Gaussian beam of this sort of least diameter $w(0)$ at the waist. Though highly collimated, there is some divergence that can be understood as due to diffraction. The intensity reduces as $w(z)^{-1}$ as beam spreads. Angular spread from the waist is $\Theta \approx \lambda/w(0)$. Spherical wavefront is due to the fitting of the waves inside a cavity with spherical end mirrors, so the beam is returned along itself and gets amplified.

The intensity of the beam as a function of ρ and z is therefore also Gaussian and given by

$$I(\rho, z) = |E|^2 = I_0 \frac{w(0)}{w(z)} \exp\left(-\frac{2\rho^2}{w^2(z)}\right). \tag{3}$$

The divergence θ of the beam is calculated from the beam spot sizes $w(z_1)$ and $w(z_2)$ at two locations on the beams as

$$\tan\theta = \frac{w(z_1) - w(z_2)}{z_1 - z_2}. \tag{4}$$

For a laser, the divergence is very small, and $\tan\theta \approx \theta$.

To study the power distribution in the beam, one can block the beam partially by placing a knife edge in its path. If the knife edge is a distance a into the beam from the center, then the total power transmitted past the edge is

$$P(a) = \int_{-\infty}^{\infty} dy \int_{a}^{\infty} dx I(x,y) = \frac{P(0)}{2} \mathrm{erfc}\left(\frac{\mathrm{a}\sqrt{2}}{\mathrm{w}_0}\right). \tag{5}$$

I.3 Helium-Neon Gas Laser:

The He-Ne laser was first fabricated by Al Jaran, Bennett and Harriott in 1961 at Bell Telephone Laboratories in USA. This consists of a mixture of helium and neon gases in a ratio of about 10:1, placed inside a long narrow discharge tube. (See Fig.5). The pressure inside the tube is $1mm$ of Hg. The gas system is enclosed between a pair of plane mirrors. One of the mirrors is of very high reflectivity while the other is partially transparent so that energy may be coupled out of the system.

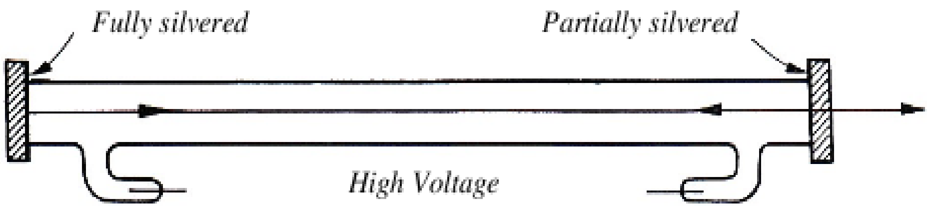


Figure 1: He-Ne gas laser

All the lower energy levels of He and Ne are shown in an energy level diagram in Fig. 6. The normal state of helium is $1S_0$ level arising from two valence electrons in $1s$ orbits. The excitation of either one of these electrons to the $2s$ orbit finds the atom in a $1S_0$ or a $3S_1$ state, both metastable, since transitions to the normal state are forbidden by selection rules.

Neon, with $Z = 10$, has 10 electrons in the normal state and is represented by the configuration $1s^2 2s^2 2p^6$. When one of the six $2p$ electrons is excited to the $3s, 3p, 4s, 4p, 4d, 4f, 5s$, etc., orbit, triplet and singlet energy levels arise. A subshell like $2p^5$, lacking only one electron from a closed subshell, behaves as though it were a subshell containing one $2p^5$ electron. The number and designations of the levels produced are therefore the same as for two electrons, all triplets and singlets. As free electrons collide with helium atoms during the electric discharge, one of the two bound electrons may be excited to $2s$ orbits, i.e., to the $^3S_1$ or $^1S_0$ states. Since downward transitions are forbidden by radiation selection rules, these are metastable states and the number of excited atoms increases. We therefore have optical pumping, out of the ground state $^1S_0$ and into the metastable states $^3S_1$ and $^1S_0$. When a metastable helium atom collides with a neon atom in its ground state, there is a high probability that the excitation energy will be transferred to the neon atom, raising it to one of the $^1P_1$ or $^3P_0, ^3P_1$, or $^3P_2$ levels of $2p^5 5s$. The small excess energy is converted into kinetic energy of the colliding atoms. In this process each helium atom returns to the ground state as each colliding neon atom is excited to the upper level of corresponding energy. The probability of a neon atom being raised to the $2p^5 3s$ or $2p^5 3p$ levels by collision is extremely small because of the large energy mismatch. The collision transfer therefore selectively increases the population of the upper levels of neon. Since selection rules permit transitions from these levels downward to the 10 levels of $2p^5 3p$ and these in turn to the 4 levels of $2p^5 3s$, stimulated emission can speed up the process of lasing.

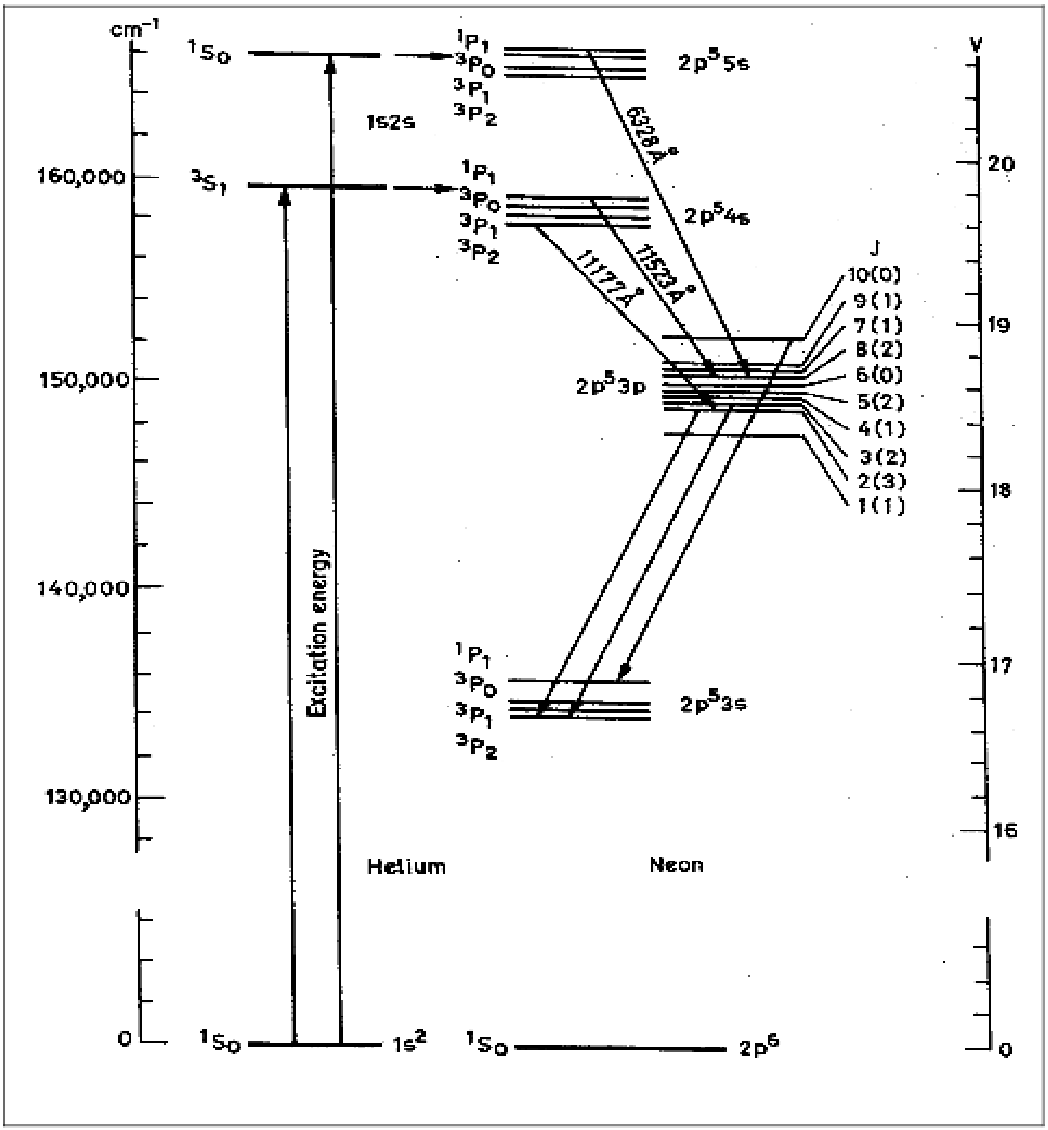


Figure 2: Transitions in the He and Ne atoms

Lasing requires only that the $4s$ and $5s$ levels of neon be more densely populated than the $3p$ levels. Since the $3p$ levels of neon are more sparsely populated, lasing can be initiated without pumping a majority of the atoms out of the ground state. Light waves emitted within the laser at wavelengths such as 6328, 11,177 and 11,523 Å will occasionally be emitted parallel to the tube axis. Bouncing back and forth between the end mirrors, these waves will simulate emission of the same frequency from other excited neon atoms, and the initial wave with the stimulated wave will travel parallel to the axis. Most of the amplified radiation emerging from the ends of the He-Ne gas laser are in the near-infrared region of the spectrum, between 10,000 Åand 35,000 Å, the most intense amplified wavelength in the visible spectrum being the red line at 6328 Å.

II Set-up and Procedure

The He-Ne laser and detectors are set up on the optical bench.

1. The beam is aligned horizontally, parallel to the bed of the bench.

2. The amplifier is connected to an ammeter
3. The photocurrent I is noted as a function of the detector position x across the beam.
4. The profile is measured at two different detector positions.
5. The photocurrent is expected to vary as Gaussian function of the position $x - x_0$ of the detector from the center x_0 of the beam. A plot to verify this must be drawn.
6. The spot sizes w_1 and w_2 at two locations of the detector can be determined from the graph and the divergence calculated.

For measuring the power distribution, the beam is partially blocked by a knife edge and the intensity profile is measured. Suppose the edge is a distance a into the beam from the center.

1. The intensity of the beam shows typical edge diffraction pattern. To be able to distinctly measure the maxima and minima, you can expand the beam using two lenses.
2. Record and plot the the beam profile for different values of a.
3. Calculate the total power P transmitted past the knife edge by finding the area under the I vs x curve.
4. Plot P vs a and show you get an error function graph.

Precautions:

1. *Never look into the laser beam directly or even reflected from an optical surface.*
2. *Beam must be parallel to the bed of the bench and all optical elements aligned to the central axis.*
3. *While making position measurements, the translation stage must be moved in the same direction throughout a set of readings.*
4. *Avoid prolonged exposure of the detector to the laser beam.*