CHAPTER 2

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2.1 Introduction:

"Light as small bodies emitted from shining substances" this view was no doubt influenced by the fact that light appears to propagate in straight line. A laser is a specialized light source that should be used only when its unique properties are required. Laser has many unique properties that make it a special light source, but these properties can be understood without knowledge of sophisticated mathematical complex idea. It is the objective of this study to explain the operation and calculations of different phenomenon in the discharge plasma. Laser has a narrower frequency distribution, high coherence and power than that available from more common types of light sources. Wavelength ranges from far infrared part of the spectrum to soft x-ray region. There are several types of units that are used to define laser wavelengths. These are ranges from micrometers or microns in the infrared to nanometers and angstroms in the visible, ultraviolet, vacuum ultraviolet, extreme ultraviolet etc.

The Bright, highly collimated, red (6328A) light beam from the helium neon laser discharge is familiar sight in the scientific laboratory, the industrial work place and even at the check out counter in most of the supermarkets. The He Ne lasers are manufactured in large quantities at low cost and with proper operation they can provide thousands of hours of useful service. Even though solid state diode lasers can now provide red laser light beams with intensities comparable to those obtained with He-Ne lasers, it is anticipated that the He-Ne laser will remain a common component in scientific and technical instrumentation in the foreseeable future.

2.2 Principle elements of a laser:

The elements essential to construct a laser source are:
1) The energy pump 2) Optical gain medium and 3) Optical resonator.

2.2.1 The Energy Pump:

At this juncture the role and importance of different elements may be discussed in details. A 1400-2000V high voltage D. C. power supply maintains glow discharge or plasma in a glass tube containing an optimal mixture typically 5:1 to 7:1 of helium and neon gas. The discharge current of the order of about 10 to 20 mA is sufficient to excite the gaseous mixture to get the laser output. Energetic electrons accelerating from the cathode to anode collide with He and Ne atoms and ions in the laser tube, producing a large number of He and Ne atoms and ions in excited states. He and Ne atoms in excited states can get deexcite and return to their ground states or lower energy states by emitting light spontaneously. This emission of light gives the bright pink red glow of the plasma that is seen 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 He-Ne laser this pumping process occurs through electron atoms collisions in a discharge. The pumping may be achieved in the He-Ne laser plasma by radio frequency discharge. The radio waves passing through the gaseous mixture accelerates the electrons and the accelerated electrons may excite and ionize the atoms and ions.

2.2.2 Optical gain medium:

To achieve laser action it is necessary to have large number of atoms in upper laser states than those in lower state and to get a population inversion. In the He-Ne discharge the excitation process can takes place in four ways: A) An energetic electron collisionally excites a He atom to the state labeled 2's. A He atom in the excited state is often written He* (2's), where the * indicates that the He atom is in excited state. B) The excited He* (2's) atom collides with an unexcited Ne atom and the atoms exchange internal energy and results in an unexcited He atom and excited Ne atom.
written as \( \text{Ne}^* (3s_2) \). This energy exchange process occurs when the excited states of the colliding particle are very close to each other. C) The \( (3s_2) \) level of Ne is a metastable atomic state. After relatively large period \( \text{Ne}^* (3s_2) \) atom deexcite to the \( 2p_4 \) level by emitting a photon of wavelength 6328A with certain probability. This emission may lead to lasing action if suitable optical configuration is utilized. D) The excited \( \text{Ne}^* \) \( 2p_4 \) atom rapidly deexcite to the ground state by emitting additional photon or by collisions with the plasma tube walls. There are more Ne atoms in the \( 3s_2 \) state than in the \( 2p_4 \) state and population inversion is achieved between these two levels and the discharge can act as optical gain or amplification medium.

2.2.3 Optical resonator or cavity:

Neon atom in the \( 3s_2 \) metastable state decay spontaneously to the \( 2p_4 \) level after a relatively long period of time under normal conditions. A He-Ne discharge is placed between two highly reflecting mirrors that form an optical cavity or resonator along the axis of the discharge tube (6). When the discharge is operated a discharge column is formed along the resonator axis. Few neon atoms make transitions from \( (3s_2) \) to \( (2p_4) \), emitting a photon at wavelength 6328A. If the photon travels in a direction parallel to axis of the cavity can be reflected hundreds of times between the two highly reflecting end mirrors of the cavity. These reflected photons can interact with other excited \( \text{Ne}^* \) \( (3s_2) \) atoms and cause them to emit variation at 6328A light by the process known as stimulated emission. The new photons produced in this emission have the same wavelength, direction, phase and electric field as that of stimulating photons.

2.3 Current and Voltage:

The voltage required to run a discharge in case of helium neon laser at a particular current depends upon the pressure of the helium and the length of the discharge tube. Generally the discharge is operated at the
helium pressure between 1 Torr and 20 Torr and the discharge current between few tens and few hundreds of mA. The pressure range corresponds to the helium density range of $1.7 \times 10^{16}$ cm$^{-3}$ to $34 \times 10^{16}$ cm$^{-3}$ (1). The density of helium triplet metastable states play central role in the determination of the electron temperature in the cavity. The electron temperature in the discharge would also determine by the density of the neon ions. The density of the discharge electrons and densities of many of the laser states of neon ion. Brown and Dunn (2) have observed the effect of the discharge current and the pressure on the metastable density. They observed that the helium metastable density increases in the beginning as the pressure is increased and reach a peak value at around 2 Torr. As the pressure increases further the density decreases to almost half the peak value. Density of metastable state increases in the initial stages as the current is increased and gets saturated at about 20mA. The further current increase has no change on the metastable densities. Hence it is very clear from the work of Browne and Dunn that the maximum obtainable metastable density in pure helium discharge is about $10^{13}$ cm$^{-3}$. A. Z. McKenize (3) obtained the radial profiles of the metastable density in the pure helium discharge. The radial profile is flatter in shape than the zero order Bessel function. The maximum obtained density is $4 \times 10^{12}$ cm$^{-3}$ for 5 Torr helium pressure and 300mA discharge current in the pure helium discharge. The addition of cadmium reduces the density of the metastable state.

2.4 Pressure and Densities:

The electron density affects directly the ionization and recombination rates and determines the ion densities in the plasma. It also determines the population and depopulation rates of the laser states. The Duffenduck reaction rate and Penning reaction rates are related to the electron density through the ionization rate and electron impact excitation.
rate of the metastable state of helium atoms. The computation of the total power delivered by laser discharge needs the radial distribution of the electron density. The discharge tube consists of mixture of atoms and ions of buffer gas and active material (Ne, Cd, Zn, Se etc) and electrons. It is observed that the cadmium shows lasing action when used along with helium or neon as a buffer gas whereas neon could show the lasing action only with the helium as a buffer gas.

The overall processes in the discharge are completely determined by the discharge parameters like densities of helium, densities of neon atoms, densities of neon ions, electron density, electron temperature and gas temperature in the discharge tube. The total density of helium in the tube is determined by the pressure and may be computed by using the equation

$$N_{\text{He}} = 1.786 \times 10^{16} P_o$$

where $P_o$ is the helium pressure in Torr.

The discharge is operated at the helium pressure 1-20 Torr that corresponds to the density of helium atoms ranging from $10^{16}$ to $10^{17}$ cm$^{-3}$. Density of neon atoms, the electron temperature in the discharge tube mainly determines densities of ions and electrons in the discharge tube. Higher is the electron temperature in the discharge tube higher will be the ionization resulting in different properties of neon atoms and neon ions. The rate of change of relative densities of atoms and ions with the electron temperatures are elaborated in the articles related to the fractional abundance.

Efficiency of the laser system depends upon the density of singly ionized neon when compared to other species of the neon. As the electron atom collision is responsible for the process of ionization and therefore density of electrons determines the density of neon ions and further excitation of neon ions or atoms also to upper laser level. Therefore electron density plays an important role in the laser plasma processes.
2.5 Electron temperature and gas temperature:

When electric current is passed through the mixture of He-Ne laser tube the electrons at different positions in the discharge get heated to different extent. The discharge electrons gain energy from the accelerating potential applied to the discharge tube and they loose their energies in the process of collisions with the walls and other particles. Near the discharge tube walls electrons become very slow as they loose energy in the collisions with the walls. The electron temperature goes on decreasing as a point of observation moves from the axis to the walls. The ions and atoms are heated to different extent than the electrons because there is a large difference in their masses. As the electrons are lighter they are heated to high temperatures. Thus electron temperature in the discharge tube is few orders of magnitude more than the gas temperature. In most of the gaseous discharges the gas particles follow Maxwellian velocity distribution. In the positive column discharge the temperature of the electrons may be considered to be single temperature but in several discharges the electron velocity distribution may be considered very near to the addition of Maxwellian distributions at low or more electron temperatures. The energy of the plasma electron is determined by the electric field acceleration and collision. The electrons get cooled when they collide with the wall of discharge tube or with the ions. The collisions with the walls may be treated as the main source of cooling of the electrons. Because the electrons on the axis are far away from the walls and therefore do not loose their energy. Whereas the electrons near the walls impart lot of energy to the walls. The electron temperature at the walls may be assumed to be very near to zero and on the axis of the tube the temperature is maximum. Further, the rate of heating of the plasma electrons and ions depends upon the current density and resistivity of the plasma. The electron temperature and the electron density determine the resistivity of the plasma. As the
electron temperature is maximum at the axis and minimum at the walls we can assume that the resistivity should be minimum at the axis and maximum at the walls. The resistivity of the plasma (4) can be calculated by using the equation

\[ \eta = \frac{52 \times 10^3 \ Z \ ln \ (\Lambda)}{(T_e)^{3/2}} \ \text{ohm-cm} \quad (2.2) \]

where \( T_e \) is electron temperature measured in eV. The resistivity of the plasma becomes infinity near the walls giving rise to very low current densities. The points on the axis are maintained at high electron temperature giving rise to low resistivity and high current density. This phenomenon is further in favour of increasing the electron temperature at the tube axis and decreasing it near the tube walls.

Furthermore, in the determination of the total power delivered by the discharge tube and the spectral quality of the laser output, the knowledge of the spatial and axial distribution of the discharge parameters is very important. The radial profiles of the fundamental quantities like temperatures and densities in the He-Ne discharge have not been measured so far. But the radial gain has been measured by Spoor and Latimer (5)

The radial profiles in the discharge tube have their origin in nonuniform heating of the plasma due to nonuniform current density. The rate of heating of the plasma electrons and ions depends upon the current density and resistivity of the plasma. The heating of the plasma on the axis is limited by the radiation loss of the plasma. Since there is no experimental data on the measurement of the electron temperature across the discharge tube one has to assume the suitable radial profiles which would fulfill the boundary conditions. In plasma discharges electron temperature and electron density profiles are assumed to be given by

\[ T(R) = T_o \ \{ 1 - (R/R_o)^2 \} \quad \text{and} \quad (2.3) \]

\[ N(R) = N_o \ \{ 1 - (R/R_o)^2 \} \quad (2.4) \]
Assuming this type of profile of the electron temperature and electron density the spatial distribution of ionic species HeI, HeII, HeIII, NeI, NeII, NeIII and NeIV may be computed for various electron temperatures at the axis.

2.6 ENERGY-LEVEL DIAGRAM:

In a helium neon laser, a low-pressure mixture of helium and neon (<15%) is contained in a narrow bore glass tube. A longitudinal, DC electrical discharge is maintained in the narrow tube. The collisions between the helium atoms in ground state and free electrons in the plasma excite the helium atoms and cause a significant number of them to be trapped in the lowest energy metastable states. These are the 2\(^1\)S and the 2\(^3\)S states, where one of the two helium electrons has been raised from the lowest energy 1S atomic orbital to the higher 2S orbital. Neon atom is relatively heavier atom and it is more complex atom, with 10 electrons rotating about the nucleus. The electrons are arranged in 1s\(^2\)2s\(^2\)2p\(^6\) configuration in the 1\(^1\)S\(_0\) ground state. Neon has many excited states, and the ones concerned with laser action are shown in the energy level diagram below. The multiple natures of the electronically excited states arise from the number of different ways in which the angular momenta of the electrons can be combined.

Two sets of excited states of neon (2s and 3s) occur at excitation energies similar to those of the 2\(^3\)s and 2\(^1\)s states of helium, which are favorably populated in the laser discharge. Within the plasma, atoms are rapidly colliding with other atoms, electrons, and with the walls of the tube. Collisions between excited state helium atoms and ground state neon atoms cause some of the neon atoms to be excited to the 2s and 3s states. Collisional energy transfer is a resonant process in which the total energy is conserved. The small energy mismatch is compensated by changes in the kinetic energy of the atoms.
Most of the neon laser wavelengths utilize transitions starting from 2s and 3s states and terminating into the 2p and 3p series of levels. For example, the 632.8nm red output is produced by the $3s_2 \rightarrow 2p_4$ transition. The 2p energy levels lie 150000 cm$^{-1}$ above the ground state and therefore are negligibly populated, even in the hot plasma. Consequently, a population inversion between 3s and 2p, and between 2s and 2p, in the ensemble of neon atoms in the plasma discharge is easily maintained by electron impact excitation and collisional pumping with excited helium atoms. Both the $3s \rightarrow 2p$ and $2s \rightarrow 2p$ transitions are optically allowed and hence can give rise to laser action. The 2p states are populated by the laser transitions but are rapidly depopulated by spontaneous emission to lower levels (7). With the exception of the 3.391-micron line, helium neon lasers are all low gain devices and require cavity mirrors of high reflectance in order to achieve lasing action. Typically, one end of the cavity is defined by a total reflector (reflectance $>99.9\%$), and the other end is defined by a mirror which permits $\sim 1\%$ of the intra cavity light to escape, forming the useful output of the laser. It therefore follows that the intra cavity beam is up to 200 times more intense than the output beam. The $3s_2 \rightarrow 2p_{10}$ transition in neon at 543.5 nm is a very low gain transition (8). To make a green He-Ne laser the corresponding transition is made to lase in a compact plasma tube by optimizing the tube design, gas mixture, processing techniques, and cavity mirror specifications. Since prisms are not desirable in commercial helium neon lasers (for economy and stability), cavity mirrors have to meet stringent wavelength dependent specifications in order to cause amplification at 543.5 nm, while suppressing the 632.8nm line and the very high gain 3.39-micron line.
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Figure 2.1 Pertinent Energy level Diagram of He-Ne laser