CHAPTER 7

STUDY OF PROPERTIES OF CuII LASER DISCHARGE

7.1 Introduction:

The mixture of copper ions (Cu⁺) and inert gas (Neon or Helium) when excited by an electric discharge produces laser action at wavelengths 237 nm, 242, 248, 259, 270, 272 and 273 nm on the transitions 5S 3D₁ → 4P 3P⁰, 5S 3D₁ → 4P 3P⁰, 5S 3D₁ → 3F⁰, 5S 3D₁ → 4P 3D⁰, 5S 3D₁ → 4P 3D⁰, 5S 3D₁ → 4P 3P⁰ and 5S 3D₁ → 4P 3P⁰ of copper ion.

The mixture of copper vapors and inert gas is excited by continuous low voltage electric discharge and some times the mixture is also excited by half wave rectified ac line current producing pulses with a repetition rate of 50 Hz and duty cycles of 5-12 (In hollow cathode discharge) (1). The experimental set up is called as copper ion laser. The output of the laser is in continuous (CW) mode as the fluorescence lifetime of upper laser state is longer than that of lower laser state. The operating temperature of the laser discharge is near 1500 °C in order to produce copper atoms in gaseous form.

Investigation of copper ion laser properties has received wide attention owing to the fact that it has wide applications in different fields as the wavelengths fall in ultraviolet region and it is a CW laser. The Cu⁺ laser has its application in very large scale integration (VLSI), semiconductor

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processing (2). It can be used to improve the resolution of conventional visible light projection lithography by a considerable amount from the present limit of 3 µm to 0.2 µm (3), dye laser pumping, holography, laser printing, material processing, medical applications, photolithography etc. The power level of copper ion laser is typically from few to few tens of milliwatts.

The theoretical model developed by us can explain several experimental results in almost all gaseous lasers for e.g. He-Cd⁺, He-Se⁺, He-Zn⁺, Argon ion laser, copper vapor laser discharges etc. The idea of fractional abundance of the ions of helium, neon and CuII has not yet been introduced by any of the workers in the field.

The ionization rate coefficient of CuII, neon and helium is obtained as a function of electron temperature. The recombination rate coefficient is sum of the two rates i.e. radiative recombination rate coefficient and dielectronic recombination rate coefficient. From the knowledge of ionization and recombination rate coefficients the fractional abundances of helium, neon and CuII are obtained.

In order to obtain spatial variation of laser power, the radial profiles of spectral emissions, the radial profiles of density and total output power, the electron temperature profile has been assumed to be like zero order Bessel's function in this laser system also. For this temperature profile the radial profiles of densities of CuII have been obtained. Moreover

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the radial profiles of the spectral emission at laser wavelengths have also been computed. The investigation of spatial profile itself show that the output laser beam should have the annular shape. We have also computed the total power delivered by the discharge tube. The results are discussed in subsequent sections.

7.2 Radial profiles of spectral emission:

When the discharge is in steady state, the rate of emission of radiation at certain wavelength is equal to the rate of excitation of the upper state of the transition emitting the radiation at that wavelength. Thus the intensity of the spectral emission at a wavelength $\lambda$ would be proportional to the factor $N_{\text{CuII}} R_u N_e$.

The radial profiles of spectral emission of the laser discharge are the basis for calculations of the laser power output. The radial profiles are evaluated by using values of fractional abundance of CuII and corresponding temperature in the discharge tube. Darvin developed a theory and suggested that the EIE rate coefficient varies as temperature is changed in a different way for different transitions. For the $5S \, ^3D_1 \rightarrow 4P \, ^3P^0$, $5S \, ^3D_1 \rightarrow 4P \, ^3P_0$, $5S \, ^3D_1 \rightarrow \, ^3F^0$, $5S \, ^3D_1 \rightarrow 4P \, ^3D^0$, $5S \, ^3D_1 \rightarrow 4P \, ^3D_0$, $5S \, ^3D_1 \rightarrow 4P \, ^3P^0$ and $5S \, ^3D_1 \rightarrow 4P \, ^3p^0$ transitions the EIE rate would be given by

$$R = K T^{1/2} \quad \text{----- 7.25}$$

where $K$ is some constant
The values of EIE rate coefficient are then multiplied by the corresponding values of fractional abundance of CuII \((N_{\text{CuII}} R_{\text{CuII}} N_e)\) to obtain the values of spectral emission. The radius of the discharge tube is considered to be 2.5 cm. The electron density is assumed to be constant throughout the discharge tube. For the assumed variation of radial profile of electron temperature, the radial profiles of spectral emission of the discharge has been computed for electron temperature 1, 3, 5 and 7 eV. The results are displayed in figs 7.1, 7.2, 7.3 and 7.4 respectively. These profiles show similar behavior as the radial profiles of densities of singly ionized copper CuII. This is because the dominance of the term \(N_{\text{CuII}}\) in the product \(N_{\text{CuII}} R_e N_e\) (which gives the spectral emission).

For 1 eV electron temperature on the axis fig 7.1 the profiles show that the intensity is maximum on the axis about 0.8. The intensity goes on decreasing towards the edge of the output beam. For 3 eV electron temperature on the axis the profiles show a dip on the axis (fig 7.2). Intensity is slightly low along the axis. As we move towards the edge of the output beam, the laser intensity increases, reaches the maximum value and then gradually decreases and reaches the minimum value. The laser beam shows a slight annular shape. The intensity of the laser beam is concentrated on a circle of radius about 1.6 cm from the axis. For 5 eV electron temperature on the axis fig 7.3, the dip on the axis has further deepened. The radius of the circle on which the intensity of laser
beam is concentrated increased to about 2 cm. For 7 eV electron temperature on the axis the annular shape of the laser beam is more prominent. The circumference of the circle on which the intensity of the laser beam is concentrated has shifted more towards the walls of the discharge tube. The radius of the circle is now about 2.2 cm.

Initially for low electron temperature on the axis of the discharge tube like 1 eV, total density of CuII ions is also less moreover they are distributed near the axis of discharge tube. Their density decreases as we move towards the walls of the discharge tube. Hence the intensity profile shows Gaussian shape for low electron temperature on the axis. As temperature on the axis of discharge tube increases the CuII ions starts getting converted into CuIII and CuIV. The density of CuII ions along the axis of discharge tube decreases. The density starts getting shifting towards walls of discharge tube. Hence the intensity of laser beam shows a dip on the axis and the dip goes on deepening further as the electron temperature increases. The intensity of the laser beam is concentrated on the circumference of a circle. The diameter of this circle increases with increase in electron temperature. This is displayed in figures 7.2, 7.3 and 7.4 respectively. These profiles are in very good agreement with experimental profiles of Izawa et al for copper vapor laser (4).
7.3 Computation of total power output:

In the discharge configuration which are used to excite the copper ion laser might have similar features as the CuI discharge tube. The parameters that influence the laser power output do not have uniform values along and across the discharge tube. This is implicit from the radial profiles of electron temperature, electron density, density of CuII ions. Thus the power delivered by different volume elements of discharge tube is different. The power delivered by a cylindrical shell of inner radius \( R \) and thickness \( dR \) whose volume is \( dV \) is given by

\[
dP = N_{\text{CuII}} N_e R_a 2\pi R \ dR \ hv
\]

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The total power delivered by the discharge tube is obtained by above equation within the limits \( R = 0 \) to \( R = R_o \)

\[
P = \int_{0}^{R_o} N_{\text{CuII}} N_e R_a 2\pi R \ dR \ hv
\]

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We obtain the total power delivered by the discharge tube at two wavelengths 2600 A and 2703 A as a function of electron temperature. We compute the total power considering electron density \( N_e \) to be constant and \( N_e \) to be varying like zero order Bessel’s function of first kind. The corresponding results are shown in figures 7.5 and 7.6.

For 2600 °A transition (fig 7.5) initially as the axial temperature is increased the power output increases with fast rate. This is because of the
increase in the fractional abundance of CuII ions, the electron density \(N_e\) and electron impact excitation rate coefficient The trend of increase in output continue up to the axial temperature of about 3.2 eV. Above 3.4 eV the rate of increase of power becomes slower and the output power reaches a maximum value at 5.2 eV. The saturation of the output power may be attributed to the saturation in EIE rate coefficient. It is clear from the fig that the further increase in electron temperature shows the decline of the output power. However, rate of decrease is much slower than the rate of increase. The nature of both the curves with constant \(N_e\) and varying \(N_e\) like zero’th order Bessel’s function of the first kind are found to be same except that the curve with constant \(N_e\) lies slightly above the curve with varying \(N_e\). The decrease of the output power at higher temperature is because of the ionization of CuII ions to form CuIII ions.

The behavior of output power as a function of electron temperature at 2703 \(^0\)A wavelength is similar to the behavior at 2600 \(^0\)A wavelength. These results are in very close agreement with the experimental results (5, 6).

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References

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Fig. 7.1: Power distribution across the output laser beam in Cu$^+$ laser at an event when temp = 1 eV on the axis.
Fig. 7.2: Power distribution across the output laser beam in Cu⁺ laser at an event when temp = 3 eV on the axis
Fig. 7.3 Power distribution across the output laser beam in Cu\(^+\) laser at an event when temp = 5 eV on the axis
Fig. 7.4: Power distribution across the output laser beam in Cu⁺ laser at an event when temp = 7 eV on the axis
Fig. 7.5: Output power as function of the electron temperature on the axis of the discharge tube with i) constant $N_e$ and ii) $N_e$ varying, as Bessel's function of zeroth order, across the discharge tube for 2600 °A transition of copper ion laser ($Cu^+$).
Fig. 7.6: Output power as function of the electron temperature on the axis of the discharge tube with i) constant $N_e$ and ii) $N_e$ varying, as Bessels function of zeroth order, across the discharge tube for 2703 Å transition of copper ion laser ($Cu^+$).