CHAPTER 11

SUMMARY AND CONCLUSIONS

11.1 SUMMARY OF THE WORK:

The presentation of the work is divided into eleven chapters and two appendices depending upon the nature of the work to be described. Most of the work done is displayed in the form of the graphs. The presentation of the numerical calculations in the form of tables is avoided. Diagrams have been included in the work where very necessary. The necessary formulae from other papers and the formulae derived in the present work are given in short. Each formula is identified by its own unique number.

The first chapter includes a short description of CVL, the applications of CVL and the review of the work done in the field of the CVL. In the beginning of the chapter various properties of the CVL are described in short. The copper vapour lasers built using the compound of copper and copper vapours are discussed. The comparative review is given. The different types of pumping systems are elaborated and compared. Then the applications of copper vapour laser in various fields of science and technology have been discussed. The chapter continues with the review of the work done in the field of theory and experiment of the CVL. Although entire work is not described but the important discoveries have been included. Lastly the plan of the present work is
presented.

The second chapter is mainly divided into two parts: 1) the experimental parameters and 2) the pertinent rate equations governing population of the laser states. The experimental parameters like charging voltage, discharge current, gas pressure, electron temperature etc are described. The ranges in which the values of these parameters lie are discussed.

The rate equations are divided into three categories:

1) the rate equation governing the circuit parameters like current, voltage, reactivity etc., 2) the rate equations governing the temperature and pressure of the gas inside the discharge tube and 3) the rate equations governing various densities in the laser medium.

In the third chapter we present the results regarding the ionisation and recombination rate coefficients. The ionisation rate coefficients of the helium and copper are obtained using three different formulae proposed by three different groups (1-3). The results are compared with each other and the formula which gives the values closer to experimental results is used for further calculations. The second part of the chapter describes the recombination processes. The rate coefficients of the recombination by radiative and dielectronic recombination processes are computed and compared. It has been observed that the dielectronic recombination dominates the radiative recombination over
a wide range of the electron temperature (4-5).

From the knowledge of the ionisation and recombination rate coefficients we obtain fractional abundances of the ionic species of helium and copper and results are presented in chapter four. The fractional abundances are functions of electron temperature and they are controlled by the electron density very weakly via dieletronic recombination process.

The fifth chapter discusses the excitation rates of the laser states by various processes like charge transfer, Penning transfer and electron impact excitation. Considering the possible values of the parameters influencing the Penning transfer, cascading processes and charge transfer the rates of the processes are obtained at various values of the parameters. The electron impact excitation rate coefficients of the laser states are obtained for Maxwellian velocity distribution of the discharge electrons. We compare the rate coefficients of the various processes and show that the electron impact excitation rate coefficient is the most dominant one. The influence of the gas temperature on the Penning transfer rate coefficient and charge transfer rate coefficient has been investigated.

A method of obtaining the inversion density as a function of the electron temperature is described. The most important parameter "THE INVERSION LIFE TIME" of the laser transition has been studied and described in
the sixth chapter. The inversion life time of \( ^2P_{3/2} \rightarrow ^2D_{5/2} \) and \( ^2P_{1/2} \rightarrow ^2D_{3/2} \) transitions of the copper atom are obtained as a function of the electron temperature. It is also studied that the population inversion decays as time passes and ultimately it becomes zero. The laser medium amplifies the radiation as long as population inversion is present in the medium. The inversion life time of the transition is obtained under two sets of experimental conditions: 1) the exciting pulse width narrower than laser pulse width and 2) the excitation pulse width comparable with the laser pulse width. Furthermore, the effect of the initial inversion density on the inversion life time is also investigated.

Seventh chapter deals with the spatial and temporal distribution of the densities and different parameters like the electron temperature, gas temperature etc. The effect of the discharge tube walls on the distribution of densities has been studied. Because of the cooling due to tube walls the current density changes radially. The variation in the current density gives rise to uneven heating of the laser plasma across the discharge tube. This ultimately gives rise to the radial profiles of the electron temperature, electron density, ion temperature, ion density, laser state density, excitation rates etc. Consequently the inversion density would not be uniform across the discharge tube and hence the intensity of the laser beam across the discharge
tube is not uniform (6). Furthermore, as the excitation in the copper vapour laser is transient the discharge current, the fundamental parameter, would not be constant during the current pulse through the discharge tube. We explore various possibilities of the current pulse shapes and study the temporal behaviour of the discharge and laser parameters.

In chapter eight we tried to explain the reasons behind the annular shaped output of the laser beam (7). In fact the annular shape has origin in the radial distribution of the electron temperature and the electron density as the electron impact excitation is the dominant process of excitation. The possibility of the effect of the skin depth on the radial distribution has been touched and it is shown that the computation done by Kushner and Warner (8) may not be applied to study the radial distribution of the parameters. Our computations show that the annular shape is because of the radial distribution of the electron temperature and electron density. Finally we obtained the laser power delivered by the laser medium. The temporal behaviour of the annular shape of the output beam also have been described.

The power condensation at point when the laser beam is focused is determined by the angle of the divergence of the laser beam. The beam having low divergence are focused to small spot giving rise to high photon
density. Unlike CW lasers the angle of divergence of the pulsed lasers is determined by the initial inversion density of the laser transition. We solve the rate equations for the laser state densities with the new boundary conditions i.e. no mirror at either ends of the laser cavity and obtain the laser output power. From these computations we obtained the angle of divergence of the laser beam. The details regarding the angle of divergence has been described in the chapter nine. The angle of divergence of the laser beam in case of oscillator amplifier configuration is also discussed.

The overall scope of present type of work is given in the chapter ten. It is shown that many branches in the copper vapour laser are open for the detailed study. If study goes deeper and deeper more and more sophisticated copper vapor laser having high efficiency and good quality laser beam would come ahead. Looking to present type of theoretical computations many other theoretical calculations would be done. It is also shown that the behaviour of the parameters like angle of divergence, inversion density, spatial profiles of the densities of electrons CuI, CuII etc must be taken into account while designing the copper vapour laser. The last chapter of the context deals with the summary of the work and important conclusions drawn in the work. In the beginning the chapter wise summary of the work is given. The chapter is ended with the description of the important conclusions drawn about different mechanisms
in the CVL discharge.

The constants required for the calculations of ionisation, recombination rate coefficients are given in Appendix A. Many constants are given in the tabular form. The list of symbols used in the work is given in the Appendix B.

11.2 CONCLUSIONS:

The comparison of the radiative recombination rate coefficients and dielectric recombination rate coefficients for all ions show that the dielectric recombination rate coefficient is about two of orders of magnitude more than the radiative recombination rate coefficient. In the computation of the fractional abundances the dielectric recombination rate coefficient must be consider. Rather, at higher temperatures the radiative recombination rate coefficient may be neglected in comparison with the dielectronic recombination rate coefficient.

The computation of the laser output power is based on the fractional abundance of the atomic copper species. In the computation of laser output power the total density proportional to partial pressure should not be considered. From the measurement of the partial pressure of the copper and fractional abundance of CuI, the density of copper atoms can be obtained. Figure 4.3 shows that at the electron temperatures more than 2 eV entire copper gets converted into the singly ionised or
doubly ionised copper leaving behind very few copper atoms. Thus reducing the net effective density of the atomic species by two to three orders of magnitude. Hence, it is very much essential to study the fractional abundances in detail. In the present work it has been shown that the fractional abundance plays central role in the determination of the laser output power. The design calculations of the copper vapour laser should include the concept of the fractional abundance.

In a plasma heated by ohmic heating phenomenon the electrons are heated to higher temperatures than the ions as they are the lighter particles. The collision frequency of the electrons with other particles is also high because of the same reason. Thus, although the cross section for the electron collision processes is small the rate coefficient of the electron collision processes is always high. In fact we have already shown that the electron impact excitation of the laser states is the dominant process of excitation among all the processes of excitation. Thus for any type of calculations only the electron impact excitation rates may be considered as the dominant process of excitation of the laser states.

The computations of the fractional abundances as a function of the electron temperature show that a certain region of the electron temperature is favourable for the excitation by the electron impact. The figure 11.1 shows the behavior of the product $\text{Cu}^* R_u$ as a function of the
electron temperature. It is very clear from the figure that at the electron temperature of 2 eV the excitation rate of the laser state is maximum. It seems that the electron temperature between 0.7 eV and 4 eV is favourable for getting the laser power with high efficiency. Thus for extracting high laser power from the discharge tube the electron temperature in the above said region must be maintained over maximum volume of the laser medium.

The fractional abundances of the ionic species are solely determined by the electron temperature. And the fractional abundance would be different for different temperatures. Thus the radial profiles of the fractional abundance have their origin in the radial profiles of the electron temperature. The electron impact excitation rate coefficient is determined by the electron temperature. Thus the radial distribution of the densities of the excited states also have origin in the radial profile of the electron temperature.

The plasma electrons are cooled by the walls and heated by the discharge current. This gives rise to non uniform heating of the discharge plasma and hence the "Spatial Distribution" of the plasma parameters. The plasma column must be studied only when the spatial variation is taken into account. The spatial profile have their origin in the spatial profile of the electron temperature which is given by the expression
\[ T(R) = T(0) \left[ 1 - \left( \frac{R}{R_0} \right)^2 \right] \]

The radial profile of the electron temperature gives rise to the radial profiles of the electron density and fractional abundances. As the electron temperature is maximum on the axis and go on reducing towards the tube walls, the EIE rate coefficient is maximum on the axis and go on decreasing towards the walls fig. 5.1. The EIE rate given by \( \text{Cu}^* n_e \text{Ru} \) also varies from point to point across the discharge tube giving rise to the radial profiles of the densities of the laser states. From the knowledge of the fractional abundance, electron density and the EIE rate coefficient, we have computed the radial distribution of the densities of the laser states. The computed radial profiles show very good agreement with the experimental results (9). Thus we can conclude that the assumptions made by us in the present calculations are good assumptions. On the basis of radial profiles of the densities of the excited states the annular shape of the laser beam is explained. The experimentally observed annular shape (6) of the laser output could be explained by the present type of calculations. This makes the assumptions made by us more stronger.

The radial profiles of the spectral emission would be decided by the population density of the upper state of the transition. It is implied that the radial profile of the spectral emission is same as the radial profile of the upper state density. Thus spectral emission
corresponding to the spontaneous decay would have same radial profiles as the upper state density because the emission is proportional to the density of the upper state. However, if the lower state of the transition is metastable state the radial profile would change owing to the radiation trapping phenomenon by the highly populated lower state.

When one thinks about the output beam shape, it immediately occur to a mind that the beam shape must be same as the profile of the excited state. This is true to some extent when the stimulating field intensity is high enough and lower state is not highly populated. However, when the stimulating field strength is low and the lower state population is high. The ouput laser beam shape is entirely different from the profile of the upper laser state. Where as if, the stimulating radiation density or the inversion density is less than the threshold value, laser beam doesnot come out from that portion of the laser medium. Thus it may be concluded that the annular shape of the laser beam is because of the temperature profile and temperature dependant parameters.

The oscillator amplifier configuration having higher power and higher efficiency than those presently available system may be designed and built by studying the radial distribution of the population inversion density. If the radial distribution of the inversion
density in the amplifier and oscillator are identical. The output power of the system would be high and efficiency also would be high.
REFERENCES:

1) M J Seaton,

2) Wilson and White,
    (Unpublished).

3) W Lotz,

4) E D Post, V R Jensen, B C Tarter, H W Grasberger, and
    A W Lokke,

5) C Jordan,

6) K Hayashi, Y Iseki, S Suzuki, I Watanabe, E Noda, and
    O Morimiya,

7) Y Xianhua, T Yongxiang, C Baogen, and T Chenlifei,

8) M J Kushner, and B E Warner,

9) Y Izawa, T Shimotsu, Ch Yamanaka, N Nakashima, E
    Fujiwara, T Yamanaka, S Nakai, T Takeda, Y Ojima,
    and C Yamanaka,
Figure 11.1 The product Cu\(^*\)Ru as a function of electron temperature.