CHAPTER 10

SUMMARY AND CONCLUSIONS

10.1 Summary of the work:

Present work is divided and presented in ten chapters. Most of the work done is displayed in the form of graphs. Presentation of numerical calculations in the form of tables is avoided. Diagrams are included wherever necessary. Necessary formulae which are derived and the formulae which are used in present work but are taken from other papers are given in short and corresponding references are quoted. Each formula is identified by its own unique number.

The first chapter contains short description of copper vapor laser and its applications. A short review of the work done in the field of CVL is also given. In the beginning of the chapter various properties of CVL are described in short. The CVL is built using compound of copper and copper vapors is discussed. The comparative review is given. The different types of pumping systems are described and compared. The applications of CVL in various fields of science and technology are discussed. The chapter continues with the review of the work done in the field of theory and experiment. Entire work done in the field of CVL is not described but the important discoveries have been included. Lastly the plan of present work is given.

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

The rate equations are categorized in three ways 1) The rate equations governing the circuit parameters like current, voltage, resistance etc, 2) The rate equations governing the temperature and pressure of the gas inside the discharge tube and 3) The rate equations governing densities in the laser medium. The important processes of excitation and deexcitation of the laser states are described.

The third chapter is related to ionization and recombination rate coefficients and fractional abundances. The ionization rate coefficients of the helium and copper are obtained using four different formulae proposed by four different groups (1-4). The results are compared and the formula which gives the values closer to experimental results is used for further calculations. The chapter continues with the description of recombination processes. The rate coefficients of the radiative and dielectronic recombination processes are computed and compared. It is observed that the dielectronic recombination dominates the radiative recombination over a wide range of electron temperature (5-6).

From the knowledge of ionization and recombination rate coefficients the fractional abundances of different ionic species of copper, helium and neon are obtained. The fractional abundances are functions of electron temperature and they are controlled by electron density very weakly via dielectronic recombination processes.
The fourth chapter discusses the excitation rates of the laser states by different processes like charge transfer, penning transfer and electron impact excitation. Considering the possible values of the parameters influencing the penning transfer, charge transfer and cascading processes, 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 have compared the rate coefficients of the various processes and found that the electron impact excitation is the dominant processes of excitation. The effect of gas temperature on the penning transfer rate coefficient and charge transfer rate coefficient has been investigated.

The fifth chapter deals with spatial and temporal distribution of densities and different parameters like the electron temperature, gas temperature etc. The effect of discharge tube walls on the distribution of densities has been studied. Because of cooling due to tube walls the plasma resistivity and hence the current density changes radially. The variation in the current density is the origin of uneven heating of the laser plasma across the discharge tube. This gives rise to the radial profiles of electron temperature, electron density, ion density, laser state density and 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 \(7\). Furthermore the excitation in the copper vapor laser is transient, the discharge current 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 behavior of the discharge and laser parameters.

In the sixth chapter we have tried to explain the reasons behind the annular shape of the output laser beam (8). The annular shape has its 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 computations done by Kushner and Warner (8) may not be applied to the study of 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 have obtained the laser power delivered by the laser medium. The temporal behavior of the annular shape of the output beam also has been described.

In chapter seven we have studied some properties of copper ion laser discharge. We have extended our model calculations to the copper ion laser which delivers the laser beam in the ultra violet region of the spectrum. We have obtained the spatial profiles of density and spectral emission in the copper ion laser. We have also obtained the laser power delivered by laser medium as a function of electron temperature.

In the eighth chapter the method of obtaining inversion density as a function of electron temperature is described. The most important parameter inversion life time of laser transition has been studied and described. 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 electron temperature. It is also studied that the population inversion decays as time passes and ultimately it becomes zero. The amplification of radiation in the laser medium takes place 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 the 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 lifetime is also investigated.

The scope of the present work is given in chapter nine. It is seen that many branches in CVL are open for detailed study. If the deeper study is done copper vapor laser with high efficiency and with good quality laser beam can be built. Looking to present type of the theoretical computations many other theoretical calculations can be done. It is also shown that the behavior of the parameters like angle of divergence, inversion density, spatial profiles of the densities of electrons, CuI, CuII etc must be considered while designing the copper vapor laser.

The last chapter deals with the summary of the work and important conclusions. In the beginning 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.

*Chapter 10. Summary and conclusions*
10.2 Conclusions:

The comparison of the radiative recombination rate coefficients and dielectronic recombination rate coefficients for all ions show that the dielectronic recombination rate coefficient is about two orders of magnitude more than the radiative recombination rate coefficient. In the computations of the fractional abundances the dielectronic recombination must be considered. At higher temperatures the radiative recombination rate coefficient may be neglected in comparison with the dielectronic recombination rate coefficient.

The computations of the laser output power is based on the fractional abundance of the atomic copper species. In the computation of the 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 the copper atoms can be obtained. It is found that for electron temperature more than 2 eV entire copper gets converted into singly ionized or doubly ionized copper leaving behind very few copper atoms. This reduces 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 abundance in detail. It is also shown in the present work that the fractional abundance plays central role in the determination of output power. Thus while designing the copper vapor laser the concept of fractional abundance must be taken into account.

When plasma is heated by ohmic heating process the electrons are heated to higher temperatures than the ions as they are lighter than the ions. The collision
frequency of the electrons with other particles is also high due to above said reasons. Although the cross section for the collision process is always high. In fact we have already shown that the electron impact excitation is dominant process of excitation among all processes of excitation. Thus for any type of calculations only the electron impact excitation rates may be considered.

The computation of the fractional abundances as a function of electron temperature shows that a certain range of electron temperature is favorable for the excitation by electron impact. From the behavior of product of Cu* R_u as a function of electron temperature it is clear that the excitation rate of laser states is maximum at electron temperature 2 eV. It seems that the electron temperature between 0.7 to 4 eV is favorable for getting the maximum laser power with high efficiency. Thus above said electron temperature range must be maintained over maximum volume of laser medium to extract high laser power from the discharge tube.

The fractional abundances of the ionic species are solely determined by electron temperature. 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 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 their origin in the radial profiles of the electron temperature. The plasma electrons are heated by discharge current and cooled by the walls. This gives rise to non uniform heating of the discharge

Chapter 10. Summary and conclusions
plasma and hence the spatial distribution of plasma parameters. The plasma column must be studied only when the spatial variation is taken into account. The spatial profiles have their origin in the spatial profile of the electron temperature which is given by the expression

\[ T(R) = T_0 \left[ 1 - \left( \frac{R}{R_0} \right) \right]^2 \]

The radial profile of the electron temperature gives rise to the radial profiles of electron density and fractional abundances. As the electron temperature is maximum on the axis and goes on decreasing towards the tube walls, the EIE rate coefficient is also maximum on the axis and goes on decreasing towards the walls. The EIE rate given by Cu* R o n_e 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 fractional abundance, electron density and EIE rate coefficient. We have computed the radial distribution of the densities of the laser states. The computed radial profiles are in very good agreement with experimental results (9). Thus we can conclude that the assumptions made by us in the present work are good assumptions. The annular shape of the laser beam is explained on the basis of radial profiles of the densities of the excited states. The experimentally observed annular shape (6) of the laser output could be explained by present type of calculations. This makes our assumptions stronger.

The radial profiles of spectral emission are decided by the population density of upper laser state. It is implicit that the radial profiles of spectral emission is same as the radial profile of the upper state density. The spectral
emission corresponding to the spontaneous decay would have same radial profiles as the upper state density as 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.

The output 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 lower state population is high, the output laser beam shape is entirely different from the profile of the upper laser state. Whereas if the stimulating radiation density or the inversion density is less than the threshold value, laser beam does not come out from the 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 dependent parameters.

By studying the radial distribution of the population inversion density, oscillator amplifier a configuration having high power and high efficiency may be designed and built. The output power and efficiency of an oscillator amplifier configuration system is high if radial distribution of the inversion density in the oscillator and amplifier are identical.

Chapter 10. Summary and conclusions
References

1. M. J. Seaton

2. Wilson and White
   (Unpublished)

3. W. Lotz


5. C. Jordan


7. Y. Xianhua, T. Yongxiang, C. Baogen


9. Y. Izawa, T. Yamanaka, S. Nakai, T. Takeda, T. Shimotsu, Ch. Yamanaka,
    N. Nakashima et al.

Chapter 10. Summary and conclusions