Inversion Life Time of the Copper Vapor Laser Transitions

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Abstract : The most important parameter inversion lifetime of the laser transition gas studied and described. The inversion lifetime of $^2P_{3/2}$ → $^2D_{5/2}$ and $^2P_{1/2}$ → $^2D_{3/2}$ 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 amplification of the radiation in the laser medium takes place as long as population inversion is present in the medium. The inversion lifetime of the transition is obtained under two conditions as the exciting pulse width narrower than the laser pulse width and exciting pulse width narrower comparable the laser pulse width. The effect of initial inversion density on the inversion lifetime is also investigated.

***Key Words* - inversion lifetime, excitation, deexcitation, fluorescence lifetime, inversion density, laser transitions etc.**

I. INTRODUCTION

The knowledge of inversion lifetime is very much essential to increase the efficiency and laser output power. In cyclic lasers, the pumping pulse produces the inversion favorable for stimulated emission. The rate equations for the excitation and deexcitation of the laser states are written as

$$\frac{dN_u}{dt} = N_g N_e R_{gu} - \left[\frac{N_u}{T_u}\right] - S_{ul}(N_u - N_l) - N_u N_e X_u + O_u + \sum_n A_{nu} N_u \qquad 1$$

$$\frac{dN_l}{dt} = N_g N_e R_{gl} - \left[\frac{N_l}{T_l}\right] - S_{ul}(N_u - N_l) - N_u N_e X_l + \left[\frac{N_u}{T_l}\right] + O_l + \sum_n A_{nl} N_l \qquad 2$$

The excitation and deexcitation of the laser states takes place by electron impact excitation and few other processes like cascading processes, spontaneous and stimulated emission. The cyclic lasers the upper laser state must be excited with high excitation rate. A high voltage and high current discharge pulse with narrow pulse width through the copper-helium or copper-neon mixture produces high inversion density [1]. The spontaneous and stimulated emission together destroys population inversion produced by the pumping pulse. After a typical time the inversion becomes zero and then negative. The laser medium favors amplification as long as the population inversion is present. When the inversion becomes negative, the medium starts absorbing the radiations which reduces the laser beam intensity. The time in which the inversion becomes zero is called inversion life time. It is determined together by shape of the pumping pulse, the density of the electrons in the pumping pulse, the temperature of the electrons in the pumping pulse, the fluorescence life time of the laser states and the flux of the stimulating radiations.

Population and Depopulation Of The Laser States

The laser states are populated by the electron collisions. The excitation rate depends upon the electron density, copper density and EIERC. In copper atom the energy states lying above the laser level are excited with low excitation rate coefficient. The higher states are coupled to the other states which reduce the excitation rate of the laser states by the cascading process. The contribution of cascading processes to the excitation of the laser states is negligible. While calculating the inversion density, the electron collision deexcitation of the laser states may be considered as negligible. Thus in absence of the stimulated emission of the radiation, the rate governing the density of the upper laser states is given by

$$\frac{dN_u}{dt} = -\frac{N_u}{T_u} \qquad 3$$

Having solution

$$N_u(t) = N_u(0)\exp\left(^{-t}/_{T_u}\right) \qquad 4$$

Where $N_u(0)$ is the population of the upper laser state at t=0 and T_u is the fluorescence life time of the upper laser state.

The energy states of the copper atoms are radiatively coupled to the states having decay life time 40 nanoseconds. In fact the state decays only to populate the lower laser state. Thus the decay of the upper laser state and the population of the lower laser state take place according to equation 4. The lower laser state has the fluorescence of 700 nanoseconds, which is longer than the fluorescence lifetime of upper laser state. Assuming the decay of the lower laser state to be negligible during the decay of upper laser state, the population of the lower laser state at time t may be expressed as

$$N_l(t) = N_l(0) + N_u(0)\exp(-t/T_u) \qquad 5$$

Subtracting equation 5 from 4 and dividing the resulting equation by $N_u(0)+N_l(0)$, we get

$$n(t) = [1+n(t_l)\exp(-t/T_u)]-1 \qquad 6$$

where $n(t) = [N_u(t)-N_l(t)]/ [N_u(t)+N_l(t)]$ normalized inversion density at time t

$n(t_i) = [N_u(0)-N_l(0)]/ [N_u(0)+N_l(0)]$ normalized inversion density

The equation 6 gives the normalized density at any time t. At time t=0 the first term in the equation is equal to 1+n(t_i) and the normalized inversion density is equal to the initial inversion density n(t_i).

As time advances the first term decrease and after a time a time t_n called the inversion life time the first term becomes +1 i.e. the inversion density becomes zero. At a time later than the inversion lifetime t_n, the first term becomes more than 1 and the inversion becomes negative. After time t_n the laser medium starts absorbing the radiation reducing the intensity of the output laser beam. The electrical energy deposited into the laser beam at time t which is more than the inversion lifetime t_n, is wasted. The inversion lifetime t_n may be calculated by substituting n(t)=0 in equation 6. The equation thus obtained is rewritten after re arrangement as

$$t_n = T_u \ln[1+n(t_i)] \quad 7$$

The equation 7 shows that inversion lifetime is a function of fluorescence lifetime and the normalized initial inversion density. Thus we may state that the increase in the initial inversion density increases the inversion lifetime. The normalized inversion density varies from 0 to 1. It shows that when the exciting pulse is very narrow and n(t_i) is about 1, the inversion lifetime is maximum and it is $T_u$ln2.

In case of transversely excited lasers the exciting pulse is narrow and the excitation of the states during the formation of the laser pulse may be very less. When the excitation of the laser medium is longitudinal, the exciting pulse is relatively longer and the rate equation for the upper laser states may not be written as in equation 5. The excitation due to electron impact during the laser pulse formation must be taken into account. Thus the rate of change of population of upper laser state may be written as

$$\frac{dN_u(t)}{dt} = \left[\frac{-N_u(t)}{T_u}\right] + R_{gu}N_gN_e \quad 8$$

If the term $R_{gu}N_gN_e$ is slowly varying as compared to the first term, then equation 8 may has the solution

$$N_u(t) = N_u(0)exp\left(\frac{-t}{T_u}\right) + C_1 \quad 9$$

Where C_1 is the constant and it depends upon the pumping characteristics.

Furthermore, the wider pump pulse increases the value of $N_i(0)$ by a constant factor. The new value of the population of the lower state may also be denoted by $N_l(0)$. Using the value of $N_u(t)$ given by equation 9, the expression for the inversion lifetime may be obtained and it is expressed as

$$T_{nl} = [T_c \ln (nT_i) +1]/K \quad 10$$

$$\text{Where } K= 1-[C_1/(N_u(0) + N_l(0))]$$

When the pumping pulse is narrow, the value of the constant C_1 goes to zero and the constant K tends to unity. Under this approximation equation 10 reduces to equation 7. The discharge pulse width depends upon several parameters like charging voltage, gas pressure and temperature in the discharge tube, pulse repetition rate, shape and size of the electrodes, distance between the electrodes etc. Thus the discharge pulse parameters like pulse shape and height and heating of the plasma electrons during the discharge pulse may be studied as a function of above parameters. A flat plate double Blumelein pulse forming circuit is used in the transversely excited laser [2-6].The pumping pulse is very narrow and the discharge electrons cool down to a value where excitation rate coefficient (ERC) is very small. In Nitrogen laser discharge the pumping pulse electrons cool down to 1.5 eV from 14 eV within a fractions of nanoseconds. The pumping pulse for the CVL excited by the transverse discharge should have the same properties. The ERC at 1.5 eV electron temperature is 5 times less than that at its value at 14 eV. It may be assumed that the discharge pulse is very narrow and the inversion lifetime is computed using equation 7

In the longitudinal electrical field pumping, the separation between the laser electrodes is more than in the transverse electric field configuration system. The increase in the separation between the electrodes increases pulse length of the discharge current by decreasing the pulse height. Consequently the electron density is also reduced resulting in less output power and electrical efficiency. The electrical efficiency of the transverse electric field configuration system is in general more as the energy of the discharge pulse is condensed in the narrow current pulses.

The expressions 7 and 8 are the expressions for the inversion lifetime where there is only spontaneous decay of the laser levels. This is not always the situation as there is a stimulated emission also. After the onset of the stimulated emission the rate of decay of the population inversion increases resulting in the shortening of the inversion lifetime. The expression for the inversion lifetime gives maximum possible value at the time for which the inversion can persist in the laser medium. The formation of the laser pulse starts after the firing of the discharge pulse by spontaneous emission of the radiation from the laser state. The pulse grows in amplitude as long as there is inversion density in the medium. When the major part of the inversion density is exhausted by spontaneous and stimulated emission, the pulse height goes on decreasing. The process of amplification of radiation terminates at time $t = t_{nl}$. At later time $t > t_{nl}$ the population inversion becomes negative and the medium starts absorbing the radiations hence zero intensity laser piulse width Δt_p at the most is equal to the inversion lifetime t_{nl}. The condition may be mathematically written as $\Delta t_p < t_{nl}$.

Population Inversion Density Of The Transition

The inversion density plays a vital role in the determination of the output laser power and pulse width of laser beam. The inversion density produced by the discharge pulse before initiation of building of the oscillations is called as Initial Inversion Density. Later on the inversion density is destroyed by the spontaneous and stimulated emission. The figure 1 shows the decay of the inversion density. When the stimulated emission is switched on the inversion density in the discharge is destroyed faster than that is destroyed by the spontaneous emission. The destruction rate of the inversion density by the stimulated emission is determined by the photon flux at the laser wavelength and the Einstein's coefficient.

II. RESULTS AND DISCUSSION

We have computed normalized population inversion density of the laser transition as a function of time for different initial inversion densities of the transition ${}^2P_{3/2} \rightarrow {}^2D_{5/2}$. The time is taken as initial time when the discharge pulse is fired. The behavior of the inversion density has been studied for the initial inversion density from 0.1 to 1. The results are displayed in figure 2. All the curves show decay of the population inversion density. The inversion lifetime of the transition ${}^2P_{3/2} \rightarrow {}^2D_{5/2}$ of the copper atom is computed using equation 10 and the results are displayed in the figure 3. The curves are obtained for the values of K varying from

0.1 to 1. The inversion lifetime of the transition increases as initial inversion density increases. The inversion lifetime can be as long as 120 nanoseconds if the pumping pulse is longer enough. However as the pumping pulse width increases the electrical efficiency of the laser system decreases because the lower laser state gets more and more populated reducing the population density. In case of 3371 A^0 ultraviolet nitrogen laser the inversion lifetime is measured by Steinvall and Anvary [7]. The experimental values show good agreement with the theoretical values.

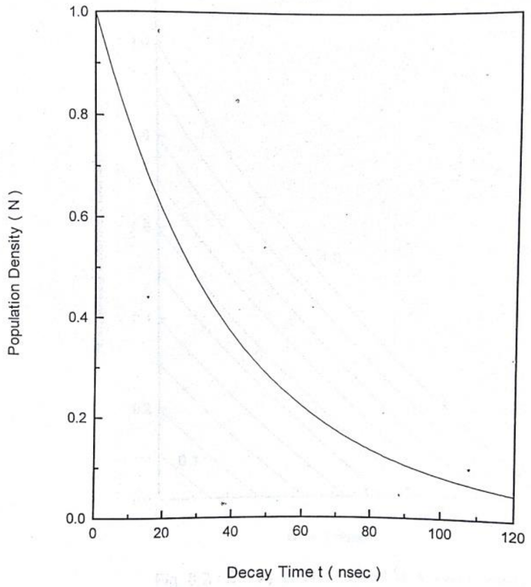
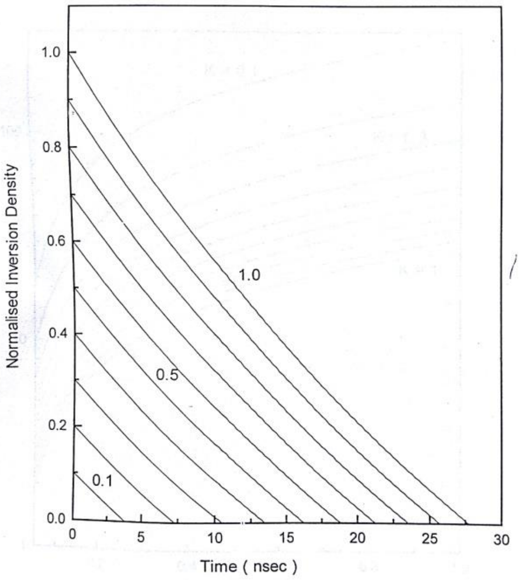
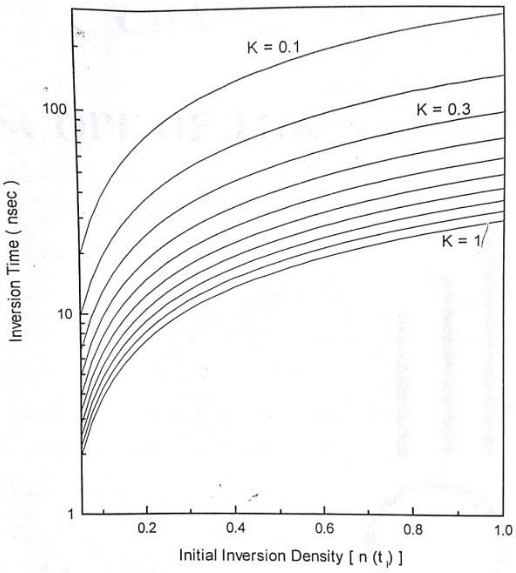


Fig.1:Decay of Population of $^2P_{3/2}$ Energy State of Copper atom



Decay of Normalisted inversion density for $^2D_{3/2} \rightarrow {}^2D_{5/2}$ Transition of copper atom



Inversion time (tnl)of the $^2P_{3/2} \rightarrow {}^2D_{5/2}$ Transition of copper atom as function of the initial inversion density

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