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Kinetic analysis of the factors limiting the output power of the Ne–CuBr UV laser*

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The parametric optimization of the Ne–CuBr UV laser excited by longitudinal pulsed discharge is analysed by using a self-consistent kinetic model. Consistent characteristics of the optimization process are obtained by comparing with the experimental results. Simulation results show that neon ions come into being along with considerable depletion of the ground-state copper atoms. And the optimization of the discharge tube diameter is the tradeoff between the specific output photon density and the total active volume. Both the optimal neon gas pressure and the optimal reservoir temperature result from the balance between the neon ion density and the ground-state copper atom density to arrive at a maximum of their product.

Keywords: parametric optimization, Ne–CuBr UV laser, pulsed discharge
PACC: 4255, 4255H, 4260B, 5280P

1. Introduction

The Ne–CuBr UV laser excited by a high repetition rate longitudinal pulsed discharge can output five deep UV laser lines of 248.6, 252.9, 259.7, 260.0 and 270.3 nm,[1,2] which come from the transitions between the 5s states and the 4p states in a univalent copper ion.[3] For the configuration of the Ne–CuBr UV laser is very similar to the commercial Ne–CuBr atomic laser, it is possible to fabricate a commercial Ne–CuBr UV copper ion laser, which has really a very attractive prospect.

The previous work showed that the tube radius had a tremendous influence on the laser output power, and the higher output power could be obtained only with a small tube radius (several millimetres).[4] It was considered that the radiation trapping effect on the transition from the lower laser levels of 4p states to the metastable levels of 4s states beneath would reduce the depopulation rate of the lower laser level, for the spontaneous transitions from the 4p states to the 4s states are the main channel for depopulating the lower laser levels.[4,5] By the further technical improvements on prolonging the tube lifetime,[6,7] nowadays, the Ne–CuBr UV laser with practical parameters was realizable, of which the multiline average output power was increased up to 1.3 W and the laser tube lifetime was more than 500 h by periodical refreshment of the neon buffer gas.[4,7] Moreover, the Ne–CuBr UV laser has a very narrow line width (0.3 pm) and high beam quality near diffraction limit,[8] which can be applied to many areas including microbiology, microelectronics, genetic engineering, surface processing, writing fibre Bragg grating (FBG) and so on.

Compared with the stepwise successes in experiment, a few quantitative investigations on the kinetic processes of the Ne–CuBr UV copper ion laser were reported. In our previous work, a self-consistent kinetic model for the Ne–CuBr UV laser was built concentrating on the 248.6 nm laser line, in which typical evolutions of the main micro species were simulated, and the obtained results were consistent with measurements.[9] In the present paper, the kinetic processes of optimizing the discharge tube diameter, the neon gas pressure and the reservoir temperature are analysed by using the kinetic model, and the factors limiting the laser output power are also discussed.

2. Description of kinetic model

The kinetic model was described in the previous work in detail.[9] It was composed of a set of self-consistent first order differential equations including the excitation circuit equations and kinetic rate equa-

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tions. Besides the energy levels related to the 248.6 nm in a univalent copper ion, eleven atomic copper levels were considered to describe the micro kinetic processes. The univalent neon ion, the atomic ground and metastable levels of neon, and five levels of univalent bromine ion were also considered for the relevant charge transfer reaction and Penning ionization. The processes considered in the discharge plasma including the collisional excitation, ionization and deexcitation between electrons and the species, spontaneous and stimulated transitions, ionic recombinations, charge transfer reaction, Penning ionization, the radiation trapping effect, and the loss of species due to radial diffusion. The relevant cross sections and rate constants were obtained from Refs.[10–21]. The simulation results were determined by a set of boundary parameters including the geometrical dimension of the discharge tube, the parameters of the optical cavity, the neon buffer gas pressure, the reservoir and tube wall temperatures, and the parameters of the excitation circuit, of which the typical values were given in Ref.[9]. The equations were solved by using the ODE solver of the Matlab software, in which a set of self-consistent boundary values is obtained by ten circles calculation, and the differential equations were then solved by the backward differentiation method.

3. Results and discussion

As pointed out in 1976, the pumping scheme of this copper ion UV laser is the charge transfer reaction between the ground-state copper atom and the ground-state neon ion, by which the upper laser levels of $5s$ states of copper ion are selectively excited.[3] In the Ne–CuBr UV laser, neon ions are produced by longitudinal pulsed discharge, and the copper atoms are created through the dissociation of CuBr molecules. Figure 1 shows the temporal behaviours of densities of the ground state neon ion, copper atom and ion during the afterglow of discharge. It can be seen from the figure that about $10^{14}/\mathrm{cm}^3$ of the neon ion density is produced at the end of pulsed discharge, and then it drops off due to the recombination and the charge transfer reaction with copper atoms. But unfortunately because of the low ionization energy of copper atoms, more than one third of the copper atoms are depleted from the pulsed discharge, most of which are consumed by ionization.

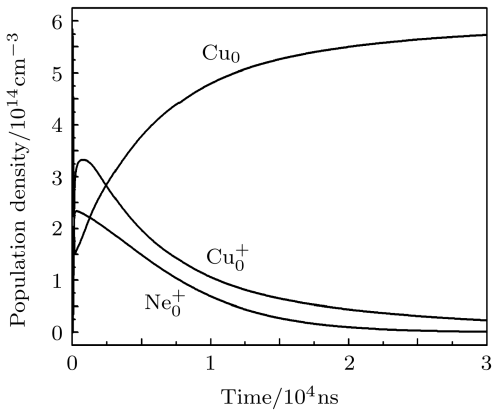


Fig.1. Time evolutions of densities of ground state neon ion, copper atom and ion.

With the self-consistent kinetic model described in Ref.[9], we have the volume number density of photons, N_p, in the cavity as a function of the tube diameter, so the laser pulse power and the laser pulse energy in the cavity can be calculated from the following relations:

$$P_p = h\nu V N_p \frac{c}{L_c} \ln\left(\frac{1}{R_1 R_2}\right), \tag{1}$$

$$E_p = \int_{t_0}^{t_1} P_p \mathrm{d}t, \tag{2}$$

where $h\nu$ represents the energy for a photon, V is the total active volume, c is the speed of light, L_c is the cavity length, R_1 and R_2 are the reflectivities of two cavity mirrors, separately. Thus, the formula of calculating the laser output power is expressed as

$$P_l = E_p f T, \tag{3}$$

in which f is the pulse repetition rate, and T is the transmission coefficient of the output mirror. The dependence of the laser output power on the discharge tube diameter was investigated with formulas (1)–(3), and the obtained results are shown in Fig.2. For comparison, the experimental result from Ref.[4] was also given there. In general, the tendency that the laser power increases with the reduction of tube diameter is the same both in theory and in experiment. The calculated optimal tube diameter is a bit smaller than the experimental result. It maybe originates from the assumption of the uniform radial distribution of the population density in the model, while the effective diameter of discharge plasma is usually smaller than the tube diameter, and also from the stability of discharge, which is difficult to maintain in the case where too small a tube diameter is used in experiment: an unstable discharge may make the laser power drop off more quickly than the calculated results.

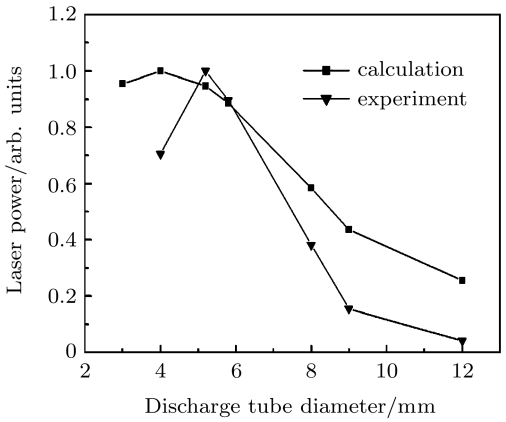


Fig.2. Dependence of laser output power on tube diameter.

Two possible ways the tube diameter affects the laser power were discussed in detail in Ref.[5]. On the one hand, the reduction of tube diameter impairs the radiation trapping effect on the transition between the lower laser level and the metastable level beneath, by which the depopulation rate of the lower laser level is expedited. On the other hand, the neon ion density increases with the reduction of tube diameter under the constant discharge current. The simulation results show that the reduction of tube diameter does increase the neon ion density markedly at a similar current amplitude, though the copper atom density decreases to some extent at the same time. The composite result is that the population density of the upper laser level $5s^3D_1$ increases remarkably, which leads to a corresponding increase of the population densities of the lower laser level $4p^3F_2^0$ and the metastable level $4s^3D_1$ as can be seen in Fig.3. According to the previous analysis, the population inversion would not occur when the population density of the metastable level reaches about $10^{13}/cm^3$ under a certain condition,[5]

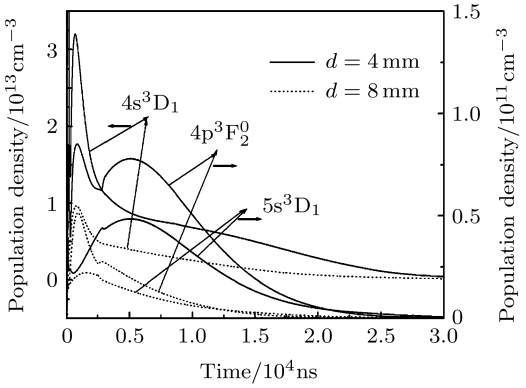


Fig.3. Temporal behaviours of populations of the upper $5s^3D_1$ and lower laser $4p^3F_2^0$ levels and the metastable level $4s^3D_1$ with different tube diameters.

but the calculation results in Fig.4 show that the photon density monotonically increases with the reduction of the discharge tube diameter. It indicates that the reduction of the tube diameter enhances the depopulation rate of the lower laser level. But the reduction of the tube diameter reduces the active volume directly. So the optimization of tube diameter results from the tradeoff between the specific output photon density and the total active volume.

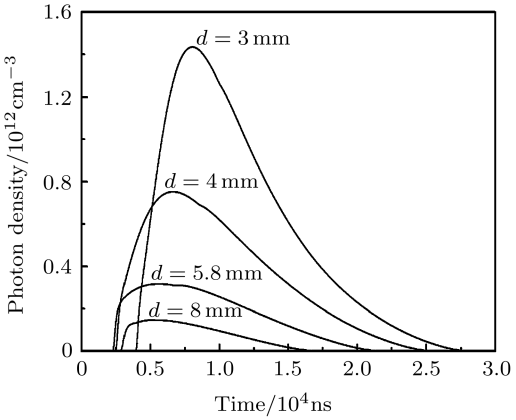


Fig.4. Temporal behaviours of the photon density at different tube diameters.

Figure 5 plots the evolutions of densities of the neon ion and the copper atom at different neon gas pressures ranging from 1.3 to 3.9 kPa. Obviously the increase of neon gas pressure causes the neon ion density to increase under the normal discharge condition, but the ground state copper atom density drops off at the same time as can be seen in Fig.5. Maybe it is because of larger excitation cross section of copper atoms at lower electron temperatures and higher neon gas pressures. So the optimization of neon gas pressure actually results from the balance between the

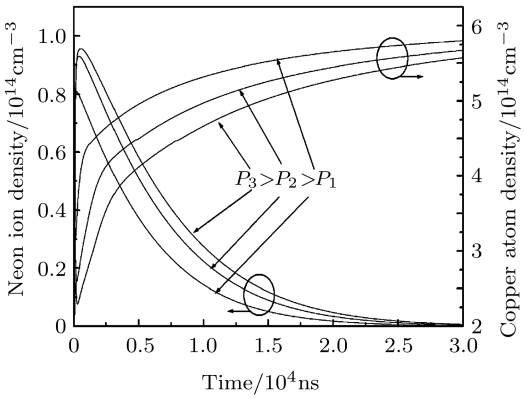


Fig.5. Evolutions of the neon ion and copper atom densities at different neon pressures.

neon ion density and the ground state copper atom density to arrive at a maximum of their product. During the discharge, the copper atom is produced through the dissociation of CuBr molecule, of which the vapour density is determined by the reservoir temperature.

Considering the total dissociation, the laser pulses at different reservoir temperatures ranging from 500 to 560 °C were calculated in increments of 20 °C, and the results are shown in Fig.6. The characteristics of the laser pulses obtained by simulation accord with that of the laser pulses in experiment.[4] The delay of laser

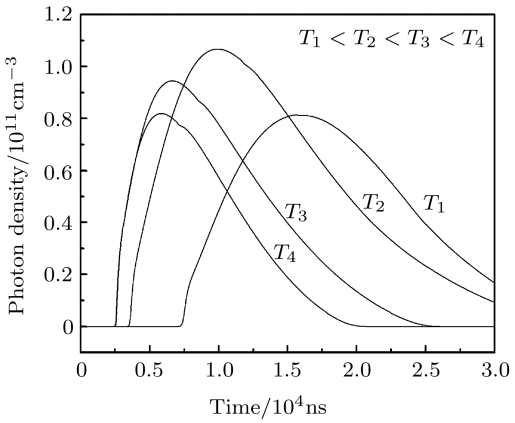


Fig.6. Time evolutions of photon density at different reservoir temperatures.

pulses with respect to the discharge current pulse decreases with the increase of reservoir temperature. When the reservoir temperature exceeds the optimal value, the laser pulse duration is shortened and the delay does not decrease any more. As the ground state copper atom density is a dominant factor, higher copper atom density provides a higher pumping rate of the upper laser level, which results in earlier laser oscillation. The minimal delay of laser pulse is caused by the relaxation of the lower laser levels populated by electron excitation in the discharge, which is affected little by the copper atom density. It is obvious that the entire evolution curve of the ground state copper atom density rises with the reservoir temperature. But the simulation results plotted in Fig.7 show that the neon ion density drops off at the same time due to the increase of energy consumption of the excitation of copper atoms and the decrease of the electron temperature. Thus again, the optimization of reservoir temperature is governed by the optimal combination of the neon ion density and the ground state copper atom density.

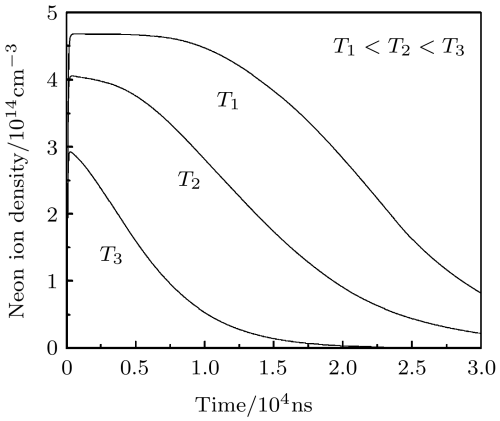


Fig.7. Evolutions of the neon ion density at different reservoir temperatures.

4. Conclusion

Kinetic simulation of the parametric optimization for the Ne–CuBr UV laser is carried out and analysed. It is shown that the production of neon ions and the depletion of ground state copper atoms is a contradiction in optimizing the Ne–CuBr UV laser output power. The output photon density increases with the reduction of the tube diameter for the impairment of radiation trapping effect and increasing neon ion density. The optimal discharge tube diameter results from the tradeoff between specific output photon density and the total active volume. The neon ion density increases with the neon gas pressure increasing, but higher neon gas pressure leads to the decrease of the ground state copper atom density, and the optimal neon gas pressure is obtained by balancing the neon ion density against the ground state copper atom density. A higher reservoir temperature brings about a higher ground state copper atom density, but it leads to the decrease of the neon ion density. Similarly, the optimal reservoir temperature is obtained by appropriately choosing the neon ion density and the ground state copper atom density.

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