Limitations on the copper vapor laser efficiency and ways to lift those

N.A. Yudin

Institute of Semiconductor Physics,
Siberian Branch of the Russian Academy of Sciences, Novosibirsk
"Kogerentnye Tekhnologii" Scientific and Production Association, Novosibirsk

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We analyze the physical causes that impose limitations on the pulse repetition frequency and power of copper vapor lasers (CVL). The CVL efficiency is shown to increase as the density of electrons existing in the active medium before the pump pulse decreases. The critical pre-pulse electron density therewith is equal to ~ 10^{14} cm^{-3}, at which the CVL efficiency is practically zero. At the same time there exists some critical pre-pulse density of copper atoms at lower laser levels (~ (3–5) · 10^{13} cm^{-3}), at which no lasing occurs. To realize the CVL power potentiality, we propose to pump the active medium in a repetitively pulsed mode by double pulses. The first pulse forms the field in the cavity, and the second one amplifies it. More than tenfold higher pump efficiency as compared with that in the standard pump mode is validated.

Introduction

The copper vapor laser (CVL) is one of the most efficient gas lasers operating in the visible spectral region. Though the CVL efficiency is estimated to be at the level of ~10% (Refs. 1 and 2), the real efficiency, which has been obtained already in the first work with a self-heating CVL,[3] remains at the level ~1%. That, relatively low practical level of the CVL efficiency is usually caused by insufficient relaxation of the copper atoms in metastable states[4] and slow recombination of plasma in the afterglow.[5,6] The most significant limitation is attributed, as a rule, to the pre-pulse density of electrons (n_{e0}), because it is impossible to rapidly heat electrons due to the presence of an inductance in the discharge circuit of the laser gas-discharge tube. This results in population of the lower laser levels by the leading edge of the pump pulse and in a redistribution of the rates of population of the upper and lower laser levels in favor of the latter ones during the pump pulse.[5,6]

In fact, the primary cause of the limitation on the CVL efficiency may be in the copper atom itself, and all the above causes can be considered as additional factors limiting the pulse repetition frequency and energy characteristics of the laser; these causes may manifest themselves depending on the way of excitation of the active medium.[7]

1. Formation of population inversion in a CVL active medium

Consider the operation of a laser discharge circuit (Fig. 1), in which the pump pulse is formed due to partial discharge of the charge-storage capacitor C through an ideal switch K. The time, during which the switch K is on, is determined by the energy deposited into the active medium during the pump pulse E_d. The energy capacity of the charge-storage capacitor is determined by the condition

$$CU_C^2/2 >> E_d, \qquad (1)$$

where U_C is the voltage applied to the charge-storage capacitor. Consider the ideal case that the inductance of the discharge circuit is $L_d = 0$ and the capacitance of the gas discharge tube (GDT) is $C_d = 0$, that is, the charge-storage capacitor discharges only into the active load. In this case, electrons are heated instantaneously up to the temperature (T_e) determined by the strength of the electric field in GDT, and T_e remains unchanged during the excitation pulse. Consequently, the effect of n_{e0} resulting in populating the lower levels of the lasing transition at the leading edge of the pump pulse is absent, and no redistribution in the rates of population of the upper and lower levels in favor of the latter ones during the pump pulse is observed.

Fig. 1. Circuitry of excitation of the CVL active medium: charging resistor R_g, shunt inductance L_{sh}, charge-storage capacitor C, ideal switch K, active and reactive components of the GDT impedance R, C_d, and L_d.

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The kinetics of population density of the energy levels yielding the lasing transition in Cu atoms and the electron density during the pump pulse are considered based on the model accounting for the population of these levels from the ground state of CuI and ionization of Cu due to the processes of direct and stepwise ionization from the upper levels of the lasing transition:

$$\frac{\mathrm{d}N_\mathrm{m}}{\mathrm{d}t} = N_{\mathrm{m}0} + (N_\mathrm{Cu} - N_\mathrm{iCu})n_\mathrm{e}k_{0\mathrm{m}}, \qquad (2)$$

$$\frac{\mathrm{d}N_\mathrm{r}}{\mathrm{d}t} = (N_\mathrm{Cu} - N_\mathrm{iCu})n_\mathrm{e}k_{0\mathrm{r}} - N_\mathrm{r}n_\mathrm{e}k_\mathrm{ri}, \qquad (3)$$

$$\frac{\mathrm{d}N_\mathrm{iCu}}{\mathrm{d}t} = n_{\mathrm{e}0} + (N_\mathrm{Cu} - N_\mathrm{iCu})n_\mathrm{e}k_{0\mathrm{i}} + 2N_\mathrm{r}n_\mathrm{e}k_\mathrm{ri}, \qquad (4)$$

where N_Cu, N_m, N_r, N_iCu are the population densities of the ground, metastable, and resonance levels of Cu atoms and Cu ions, respectively; $n_\mathrm{e} = N_\mathrm{iCu}$ is the electron density; $k_{0\mathrm{m}}$, $k_{0\mathrm{r}}$, $k_{0\mathrm{i}}$, k_ri are the rate constants of excitation of the metastable and resonance levels, direct ionization from the ground state, and stepwise ionization from the resonance level, respectively. The corresponding rate constants of excitation and ionization have been borrowed from Ref. 8; k_ri is the generalized constant accounting for de-excitation of the resonance level not only into the state of ionization, but also into the higher-lying levels if assuming instantaneous ionization from these levels. Figures 2–4 show the time behavior of N_m, N_r, and N_iCu for different values of T_e and $n_{\mathrm{e}0}$; $N_{\mathrm{m}0} = 1.5 \cdot 10^{13}$ cm^{-3} is the pre-pulse density of the metastable level and $N_\mathrm{Cu} = 2.0 \cdot 10^{15}$ cm^{-3}.

Fig. 2. Time behavior of the density N_m, N_r, and n_e in the pump pulse for $T_\mathrm{e} = 2$ eV; N_m (*1*), N_r (*2*), and n_e (*3*) for $N_{\mathrm{m}0}$; $n_{\mathrm{e}0} = 1 \cdot 10^{13}$ cm^{-3}. N_m (*1.1*), N_r (*2.1*), n_e (*3.1*) for $N_{\mathrm{m}0}$; $n_{\mathrm{e}0} = 4 \cdot 10^{13}$ cm^{-3}; N_m (*1**), and N_m (*1.1**) for $N_{\mathrm{m\,cr}}$; $n_{\mathrm{e}0} = 1 \cdot 10^{13}$ cm^{-3} and $N_{\mathrm{m\,cr}}$; $n_{\mathrm{e}0} = 4 \cdot 10^{13}$ cm^{-3}, respectively.

From the dependences presented, it can be seen that as $n_{\mathrm{e}0}$ and T_e increase, the time for achieving the threshold conditions for lasing and the population inversion lifetime shorten, the energy deposited into the GDT increases, but the population inversion increases only with the increase of T_e.

As $n_{\mathrm{e}0}$ increases, not only the population inversion itself, but also its lifetime decrease. This is reflected in the fact that at a complete ionization of Cu atoms it is impossible to obtain lasing. Actually, there exists some critical pre-pulse electron density ($n_{\mathrm{e\,cr}} \sim 10^{14}$ cm^{-3}),[9,10] at which the lasing efficiency is close to zero (Fig. 4). Similarly, there occurs some critical pre-pulse population density of the lower levels ($N_{\mathrm{m\,cr}} \sim 3$–$5 \cdot 10^{13}$ cm^{-3} depending on T_e) of the lasing transition, at which population inversion does not appear under any excitation conditions, if T_e is below some threshold value (see Figs. 2–4).

Fig. 3. Time behavior of the density N_m, N_r, and n_e in the excitation pulse for $T_\mathrm{e} = 4$ eV; N_m (*1*), N_r (*2*), and n_e (*3*) for $N_{\mathrm{m}0}$, $n_{\mathrm{e}0} = 1 \cdot 10^{13}$ cm^{-3}; N_m (*1.1*), N_r (*2.1*), n_e (*3.1*) for $N_{\mathrm{m}0}$, $n_{\mathrm{e}0} = 4 \cdot 10^{13}$ cm^{-3}; N_m (*1**), and N_m (*1.1**) for $N_{\mathrm{m\,cr}}$, $n_{\mathrm{e}0} = 1 \cdot 10^{13}$ cm^{-3}; $N_{\mathrm{m\,cr}}$, $n_{\mathrm{e}0} = 4 \cdot 10^{13}$ cm^{-3}, respectively.

Fig. 4. Time behavior of N_m (*1*), N_r (*2*), and n_e (*3*) in the excitation pulse for $T_\mathrm{e} = 2$ eV and $N_{\mathrm{m}0}$, $n_{\mathrm{e}0} = 1 \cdot 10^{14}$ cm^{-3}; N_m (*1**) for $N_{\mathrm{m\,cr}}$, $n_{\mathrm{e}0} = 1 \cdot 10^{14}$ cm^{-3}.

Realization of the CVL energy potential is limited by the processes naturally inherent in the laser active medium. The situation can be changed only if pumping of the active medium at a low pre-pulse electron density. One of the known ways to lift this restriction is to increase the rate of plasma recombination in the gap between pulses.[11–13]

Another way is to decrease the degree of ionization of the active medium during the excitation pulse. The intrinsic light field in the laser cavity is known to induce the optogalvanic effect on the CVL, that is, this field induces transitions from the resonance level to the metastable one, thus making the processes of stepwise ionization inefficient.[14]

The intrinsic light field with the minimum degree of ionization of the active medium takes place in the CVL cavity at the electron temperatures 1.7 eV $< T_e <$ 2 eV. The duration of the lasing pulse in such a case is maximum (see Fig. 2 and Ref. 15). In this case, if an extra high-voltage pulse with the duration comparable with that of the lasing pulse is applied during the lasing, then lasing must intensify without a considerable change in the plasma conductivity. This will provide for the conditions of efficient pumping of the active medium and improve the practical efficiency of the CVLs.

All the above-said and, first of all, the possibility of intensifying the lasing by the second pump pulse, that is, realization of the system "master oscillator–amplifier" in the same active element, requires experimental confirmation.

2. Intensification of lasing by the second pump pulse

To check experimentally the hypothesis formulated above, we used a CVL with an UL-102 gas discharge tube (gas discharge channel made of Al_2O_3 ceramic tube with the inner diameter of 2 cm and the length of 40 cm, with neon as a buffer gas). The electric circuitry of the experimental setup (Fig. 5) operated as follows.

The high-voltage rectifiers *1* and *2* charged, respectively, the charge-storage capacitors *C1* and *C2* through the charging choke-coils *L1* and *L2*, diodes *D1* and *D2*, and the inductance *L* connected in parallel with GDT *6*. The low-current and high-current pump pulses were generated due to discharge of the charge-storage capacitors through GDT by the switches *K1* and *K2*. A TGI1-270/12 thyratron was used as the switch *K1* for formation of the low-current stage of the discharge. The high-current stage was formed by the TGI2-500/20 thyratron as the switch *K2*. The thyratrons were triggered by pulses from the generator *4* through the controllable delay lines *3* and *5*, which allowed continuous tuning of the delay between the pump pulses at GDT.

At the initial stage of the experiment, the delay between the pump pulses was chosen so that the pulse formed by the switch *K2* immediately followed the low-current pulse. The parameters of the pump pulses were chosen based on the condition of self-heating operation of an UL-102 GDT.

Once the laser reached full operation, the pump parameters were optimized. The output voltage of the high-voltage rectifier *1* was taken as low as possible to provide for lasing in the low-current pump pulse, while the voltage from the rectifier *2* was chosen following the condition of ensuring the self-heating operation of the CVL. The further investigations were carried out at the chosen pump parameters and the pump pulse repetition frequency (PRF) of 12.5 kHz. The low-current pump pulse was formed by the discharge of the 2200 pF charge-storage capacitor *C1* at a 2.3 kV output voltage of the high-voltage rectifier *1* and the consumed current ~ 190 mA.

Fig. 5. Circuitry of the experimental setup.

The high-current pump pulse was formed by the discharge of a 1340 pF charge-storage capacitor *C2* at a 5.1 kV output voltage of the high-voltage rectifier *2* and the consumed current ~ 210 mA. The lasing pulse in the low-current pump pulse appeared ~ 70 ns after the beginning of the pump pulse. The full width at half maximum (FWHM) of the lasing pulse was ~ 45 ns, and the pulse duration at the baseline was ~ 110 ns at the mean output power ~ 13 mW. In this case, lasing in the high-current pump pulse was not observed.

The change in the relative position of the pump pulses resulted in appearance of the lasing pulse typical of CVL in the high-current pump pulse. The lasing pulse in such a case appeared ~ 40 ns after the beginning of the pump pulse. The FWHM of the lasing pulse was ~ 20 ns at the mean output power ~ 3.2 W. The further investigations were carried out for the case that the high-current pulse followed the low-pulse one. As the delay between the pump pulses shortened, the part of the lasing pulse coinciding with the voltage front of the high-current pump pulse was amplified, as shown in Fig. 6.

The arrow shows the direction of change in the delay between the pump pulses. The pulses of current and voltage shown in Fig. 6 were measured with a coaxial current shunt and a noninductive ohmic divider, while the lasing pulses were measured with an FK-32 coaxial photocell and recorded on an S1-75 oscilloscope. The lasing pulse (Fig. 6) corresponding to the high-current discharge is shown qualitatively, in arbitrary units, because the amplitudes of the lasing pulses differ more than 100x. Figure 7 depicts the mean output power of CVL, and Fig. 8 depicts FWHM of the amplified lasing pulse as the high-current pump pulse moves about the lasing pulse from its trailing edge to the center (shown by the arrow in Figs. 7 and 8) in the low-current pulse. The initial time (t = 0 at the abscissa) corresponds to the beginning of the lasing pulse in the low-current pump pulse.

Fig. 6. Oscillograms of current (*1*) and GDT voltage (*2*) pulses, as well as lasing pulse (*3*) formed in the low-current pump pulse; amplification (*4*) of the lasing pulse (*3*) by the high-current pump pulse.

The coefficient of conversion of the laser radiation into the radiation with diffraction divergence in this mode of CVL operation must achieve ~80%, since, according to Ref. 16, the time for formation of the beam with diffraction divergence is ~42 ns for an unstable cavity with the gain $M = 30$. It is essential that the observed amplification of lasing by the high-current pump pulse manifests itself in the radial-temporal profile of the lasing pulse formed by the low-current pump pulse. Thus, at the trailing edge of the lasing pulse, a ring-shaped amplification near the walls of the GDT gas discharge channel at the lasing wavelength of 578.2 nm was observed. As the high-current pump pulse moved about the lasing pulse from its trailing edge to the center, the radial profile of lasing became gradually smoother at $\lambda = 578.2$ nm for ~20–25 ns, then ring-shaped lasing at $\lambda = 510.6$ nm was amplified as well, and then the radial profile of this lasing became smoother too.

Fig. 7. Variation of the mean lasing power at variation of the time position of the high-current pump pulse about the lasing pulse in the low-current pump pulse.

Fig. 8. Variation of FDHM of the amplified lasing pulse at variation of the time position of the high-current pump pulse about the lasing pulse in the low-current pump pulse.

3. Optimization of pump parameters in the repetitively pulsed mode of pumping by double pulses

In the considered operation mode, the active medium was pumped in two stages. The first pulse induced the intrinsic field in the cavity, and the second one amplified it. Criteria of the optimal pump parameters for this method of excitation of the active medium are the following: formation of the first pump pulse with minimum energy consumption for generation of the intrinsic field in the cavity; formation of the second pump pulse with the duration comparable with that of the lasing pulse. The energy consumed for generation of the intrinsic field in the cavity is minimum, if the condition $1.7\text{ eV} < T_e < 2\text{ eV}$ is fulfilled during all the time for formation of the population inversion. This is attributed to the fact that the rate of population of the lower laser levels exceeds that of the upper levels at $T_e < 1.7$ eV, and with the increase of T_e the energy consumed for generation of the intrinsic field in the cavity increases. The value of T_e can be maintained within the needed range during formation of the intrinsic field in the cavity only if the condition $R > 2\sqrt{LC}$ is fulfilled for circuits with partial discharge of the charge-storage capacitor or if the pulse-forming line is used in circuits with the full discharge of the charge-storage capacitor.[17]

Based on these criteria, let us estimate the optimal parameters of the pump pulses for the above conditions of pumping of CVL with UL-102 GDTs. Simulation of the pumping conditions has shown that the pump pulse with the optimal parameters (Fig. 9) is formed in the circuit (Fig. 10) at the voltage of 3.8 kV applied to the pulse-forming line and ~ 10 kV applied to the charge-storage capacitor *C5*.

The self-heating mode is realized at the pulse repetition frequency ~100 kHz, when ~30–35% of energy is consumed for formation of the intrinsic field in the cavity and 65–70% of energy comes for amplification of lasing by the second pulse, of which energy only ~ 20% is stored in the GDT inductance. In this case, the energy consumption for formation of the lasing pulse decreases by 8 to 10 times as compared with that in the ordinary repetitively pulsed mode.

Fig. 9. Current pulses in the discharge circuit of the laser and GDT voltage pulses.

Fig. 10. Circuit for pumping the CVL active medium by periodic doubled pulses, where L_{sh} = 100 μH; ($L1 - L4$) = = 1 μH; ($C1 - C5$) = 200 pF; trigger pulse generator *1*; delay line *2*; pulse-forming line ($L1$–$L4$; $C1$–$C4$); switches K.

Conclusions

The analysis performed confirms the dependence of the CVL energy characteristics on the pre-pulse parameters of plasma. There exist a critical pre-pulse electron density ($n_{e\,cr} \sim 10^{14}$ cm^{-3}), at which the lasing efficiency is nearly zero, and a critical pre-pulse population density of the lower levels ($N_{m\,cr} \sim 3$–$5 \cdot 10^{13}$ cm^{-3}) of the lasing transition, at which the population inversion is not created in the active medium under no excitation conditions, if T_e is lower than the threshold value. This dependence of the CVL efficiency on the pre-pulse electron density is attributed to the high rate of de-excitation of the upper lasing levels into the state of ionization, which results in the significant increase of the energy consumed for formation of the population inversion in the active medium with the increase of n_{e0}. Besides, the electron temperature directly depends on the processes in the discharge circuit of the laser, and this also affects the CVL efficiency.

The pre-pulse population density of the lower levels of the lasing transition is governed by the process of its relaxation between the pulses. The rate of this process directly depends on the parasitic energy deposited into the active medium, and, consequently, removing parasitic energy deposition, we can lift the corresponding restriction. At the same time, to improve the CVL efficiency, it is necessary to reduce n_{e0} by increasing the rate of recombination in the gap between pulses and decreasing the rate of ionization in the pump pulse. Toward this end, it is proposed to pump the active medium by double pulses. In this case, the first pulse forms the intrinsic field in the cavity, and the second one amplifies it.

Simulation of the conditions of pumping the CVL active medium has shown that the energy consumed for formation of the population inversion can be reduced almost tenfold in this mode as compared to the ordinary repetitively pulsed mode. This results in a increase of the practical efficiency and the mean output power of copper vapor lasers. Certainly, in view of the great practical significance of the results obtained in this paper, further theoretical and experimental investigation of the proposed method of pumping is needed.

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