PHYSICS AND TECHNOLOGY OF COPPER-VAPOR LASERS WITH CONTROLLED PARAMETERS

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The paper discusses the problems of controlling the energetic temporal and optical characteristics of metal vapor lasers. Some ways for controlling these parameters by initiating an auxiliary repetitive pulsed discharge with a variable time delay with respect to the main excitation pulse are considered. Such a superposition of two repetitive pulse voltages in one and the same active medium enables one to realize an excitation with controlled ionization which in its turn makes it possible to optimize the efficiency and to control the laser pulse duration and energy.

1. Lasers being used for solving some spectroscopic problems concerned with analysis of gaseous, liquid, and solid media as well as for developing new technologies based on the spectral properties of materials (isotope separation, production of ultrapure materials, laser processing of materials, etc.) are imposed by the requirements to vary their energy, frequency, and spectral characteristics in as wide range as possible. From this point of view, among other laser sources the repetitive pulse metal vapor lasers (MVL) operating by the transitions from resonance to metastable levels of atoms and ions (Cu, Pb, Au, Sr, etc.) are of especial interest because of their unique combination of properties.[1] First of all, their ability to generate pulses of nanosecond duration with a pulse repetition rate of tens of kilohertz should be noted, which is most important when developing superflexible laser systems. However, it becomes possible to extend considerably the field of application of these systems and to increase their informative abilities, if the control of output laser characteristics is provided.

2. In this paper the parameters of the copper-vapor laser (as the most characteristic for the gjven family of lasers) are analyzed from the point of view of lasing control in a wide range with respect to pulse repetition rate f, duration of radiation pulses τ^1, pulsed output power W_p, average output power W, step-by-step wavelength tuning λ_i, and continuous wavelength tuning $\Delta\lambda$. On the one hand, the use of the self-heating mode of the MVL excitation substantiated in Ref. 2 has improved drastically the output laser parameters, but the MVL potentialities in further increasing the efficiency η, parameters W and f have not been exhausted. On the other hand, this technique fails to vary f in a wide range and has limited possibilities to control W and W_p. In this connection further development of the self-heating excitation technique as well as the search for new ways of excitation and physical and technical principles of controlling the MVL lasing seem to be of great importance.

3. A comprehensive study of the discharge dynamics, electrokinetic and optical characteristics of the plasma of the repetitive pulsed discharge (RPD) in the active media of the MVL has revealed that the main lasing controlling characteristics are as follows: the temperature T_e and concentration n_e of electrons, the concentration of active particles being in the ground state N_0, and the density of the forced radiation generated by the p_t transition.[3–5]

Under the typical conditions when a capacitor discharges onto the discharge gap for the first 10–20 ns after the onset of excitation, a high rate increase in T_e occurs, what provides generating an inverted medium through the operating transition. For T_e equal to 2–4 eV the ionization proceeds at a higher rate, n_e sharply increases, what in its turn results, on the one hand, in a decrease in electric field and T_e, i.e., in an increase in the excitation rate of metastable states, and, on the other hand, in quickened stepwise collapse of the resonance level. Prior to the excitation pulse (EP) the value of n_e is 10^{12}–10^{13} cm^{-3}, while toward the end of the pulse it is 10^{14}–10^{15} cm^{-3}. Usually, n_e reaches a maximum after the termination of the laser pulse. The time needed for T_e to relax up to a point near the gas temperature T_g is about 5–10 μs, what corresponds to the maximum of the recombination afterglow. The high value of T_g at the discharge axis is caused by low thermal conductivity in the tube of large diameter with the highly reduced input energy. The latter limits on E, W, and lasing frequency f for a longitudinal repetitive pulsed latter discharge. Investigations have shown that the two phases of the RPD are interdependent, the achievable values of W and f are dependent on n_e and T_e both during the EP and in the interpulse period (IPP). The high ionization degree of the active medium (30–80% of the metal vapor during the EP) caused by direct and stepwise processes necessitates a "prolonged relaxation period and sets limits for f and W. Moreover, the considerable excess of the energy delivered into the EP over an optimal value results in a significant decrease in efficiency and W.

4. Basing on the results of spectroscopic investigations we proposed to decrease n_e during the lasing period using a large-discharge capacitance or decreasing the energy delivered into the active medium during the EP by "shortening" the pulse. In combination with diffusion cooling this made it possible to elevate the upper limit of f at which an inverted medium can be produced by the RPD (up to 235 kHz for Cu vapors and 150 kHz for Au vapors), to optimize the repetition rates in tubes with diameters of 4–6 mm up to 50–60 kHz, and achieve $W = 50$–60 W in tubes having active volumes 0.5–0.8 liter (see Refs. 3, 6, and 7). Calculations have shown

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that reducing the ionization degree in the EP increases the physical efficiency of a copper-vapor laser up to 10% (the ratio of the output power to the energy deposited into the discharge till the end of the laser pulse).[8]

5. Let us consider lasers with controllable f, W, and E. Analysis of the processes occurring in the MVL has shown the possibility of highly prompt control of E and W in tuning the laser by varying n_e and T_e at any phase of the discharge. Controlling effect therewith is exerted by the discharge voltage $U(t)$ and current $I(t)$. The physical foundation of the developed controlling techniques is a separate optimization of the processes of heating and excitation of the active medium. For the self-heating lasers, this is accomplished using two repetitive pulsed discharges. Varying the pulse shape and the input energy one can control the laser pulse through variations in n_e and T_e and in the level populations in the ground N_0 state and excited N^* state. These principles form the basis of new ways for stabilization of E and W in prompt change in f (see Ref. 9). One of the ways for stabilizing E is to generate simultaneously the EP and the auxiliary pulse (AP) with duration τ_a (see Fig. 1). The risetime and amplitude of the auxiliary pulse are less than the corresponding EP parameters, while the energy deposited into the discharge during the AP exceeds the EP energy by a factor of K. The values of τ_a and K should satisfy the following relations:

$$\tau_a = (f_{max} - f) / f f_{max}; \quad K = (f_{max} - f) / f, \qquad (1)$$

where f_{max} is the upper limit of the laser excitation frequencies. Such a way of laser excitation in f turning requires that only one parameter, i.e., the AP energy, to be varied by changing τ_a. The laser pulse control can be accomplished, for example, by varying the amplitude of $U(t)$ if any. For the frequency range from 1 to 6.5 kHz, the stabilization accuracy for E was 1.5% when varying f with a rate of 1–2 kHz/min (Fig. 2).

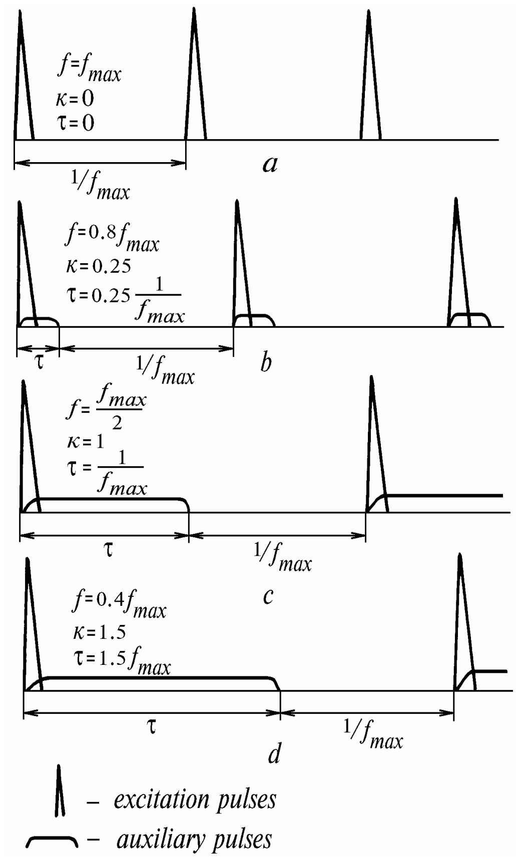

FIG. 1. Diagrams of the method of laser excitation with stabilization of output energy on varying f.

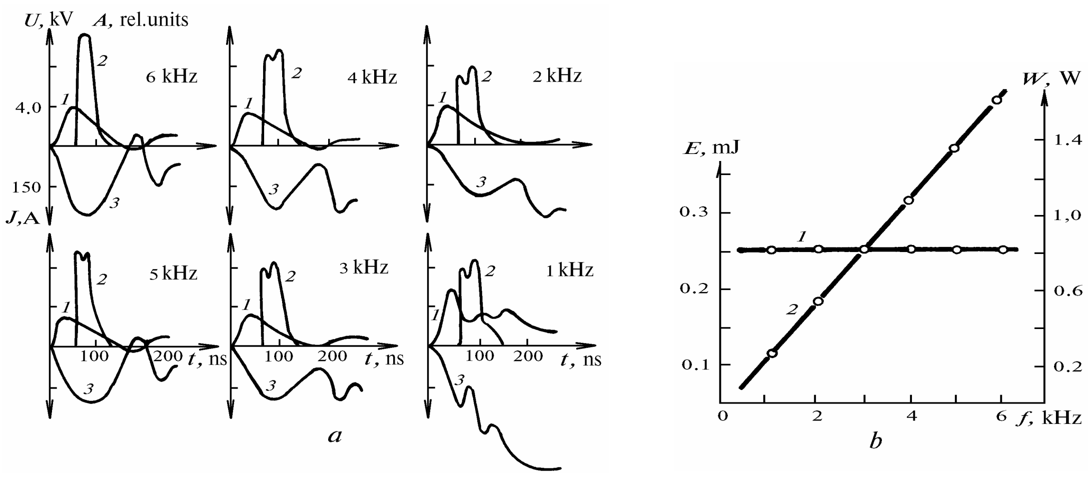

FIG. 2. Waveforms of voltage (1), laser radiation (2), current (3) (a) as weU as the pulse energy (1) and average power (2) (b) as functions of pulse repetition rate for a laser operating in the stabilization mode..

6. Now we describe lasers with a controllable output pulse duration. Depending on the excitation conditions (buffer gas pressure P_b and wall temperature T_w) τ^1 varies in a complicated way.[10] However, in most cases the P_b and T_w variations are sluggish processes. Therefore, we proposed the method for promptly controlling τ^1 by initiating in the discharge gap of an auxiliary "controlling" RPD with the same f as the main one but with a variable control time delay τ_{cd}. In this case the controlling parameters for τ^1 are the "microcharacteristics" n_e, T_e, N_0, and the concentration of metastable levels N_m, while the controlling effect is due to τ_{cd} or $U(t)$. The auxiliary pulse heats electrons, decreased the plasma recombination rate, and increases the

concentrations n_e and N_m thereby changing the initial conditions for the subsequent excitation pulse. Maintenance of a thermal balance in the active element is realized by complying with the condition $(E_e + E_c) f = \text{const.}$[9] This method is also applicable as the way to control the chromaticity when two or several spectral lines (for instance, $\lambda_1 = 0.51$ μm and $\lambda_2 = 038$ μm for the copper–vapor laser) generate simultaneously. A realization of this excitation technique is described in Ref. 10. The results of a fast change in τ^1 from 1.50 to 30 ns and in chromaticity are illustrated in Fig. 3.

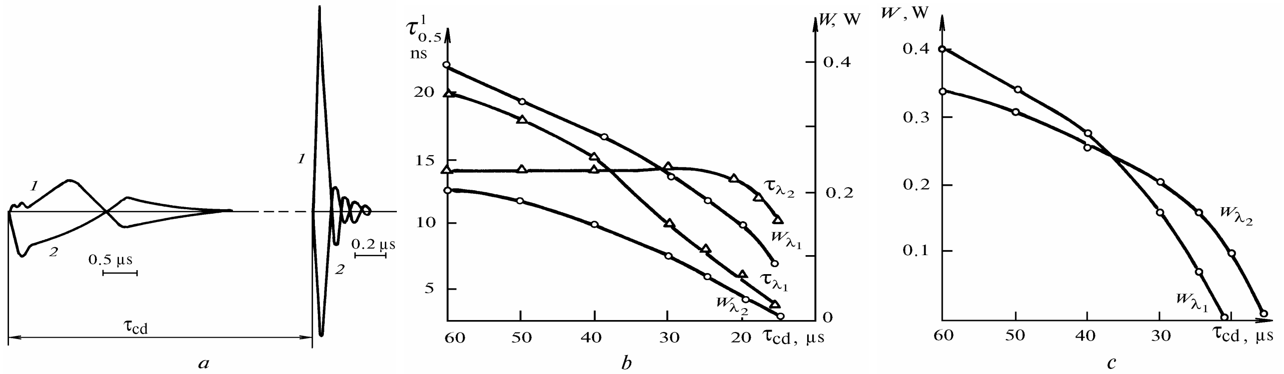

FIG. 3. Typical waveforms of current (1) and voltage (2) of the control pulses (on the left) and excitation pulses (on the right) (a). Dependence of the duration and average output power (b, c) for the green (1) and yellow (2) spectral lutes on the time delay τ_{cd}.

7. Let us consider the MVL with a combined heating of the active medium. An advantage of the lasers in which the output radiation parameters are controlled by producing auxiliary current pulses is simplicity in design of self-heating laser tubes. However, the AP has a detrimental effect on the active medium that results in decreasing the maximum achievable f, W, and efficiency. The best results in controlling the lasing can be obtained by means of heating the active medium up to operating temperatures with the help of built-in resistive heaters placed inside or outside of the high-temperature channel.[1] In the laser with a built-in resistive coil heater (Fig. 4) a specified power is supplied from the heating and excitation sources through the controlling unit. On achieving the operating temperature, the timing unit actuates the excitation source at the zero point of the sinusoidal voltage produced by a driver with a repetition rate determined by the driver. The control unit therewith decreases the amplitude of the heating source voltage down to a value at which a quasi–steady–state thermal mode is provided for the operating space. In this case the following conditions should be satisfied:

$$I_0\, U_0 = P - \Delta E\, f; \qquad \omega = \kappa \pi f;\ U_0 < U_a, \quad (2)$$

where U_0 and I_0 are the peak values of the heater sinusoidal voltage potential and current, U_a is the voltage of the arc discharge operating in the laser active medium, P is the power needed for heating the laser up to the operating temperature, ΔE is the portion of the excitation pulse energy dissipating into heat. This principle of operation ensures, on the one hand, an optimization of the laser excitation pulses with respect to a maximum W or η, and, on the other hand, a decrease in the power dissipated by the switches, what lengthens the laser lifetime. The main distinguishing feature of such a laser is its ability to operate in a waiting mode, when its availability for service is only maintained by the power of the heater. Moreover, there is a possibility to smoothly adjust f from zero to f_{max}. A prompt controlling effect on E and W is exerted by the amplitude of the excitation pulse voltage.

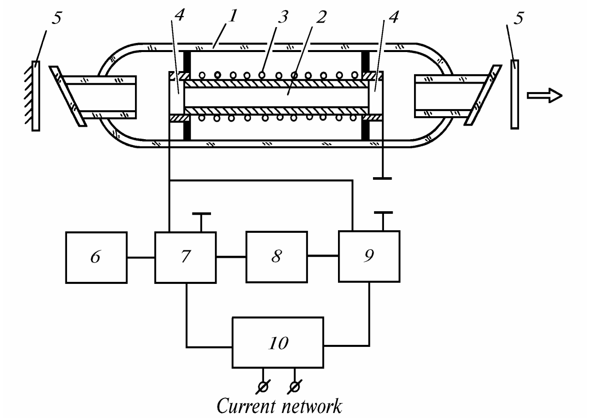

FIG. 4. Schematic diagram of a stabilized laser with a built-in resistance heater: 1) hermetically sealed case, 2) gas–discharge channel, 3) heater, 4) electrodes, 5) resonator mirrors, 6) pulse driver, 7) heating source, 8) timing unit, 9) excitation source, and 10) control unit.

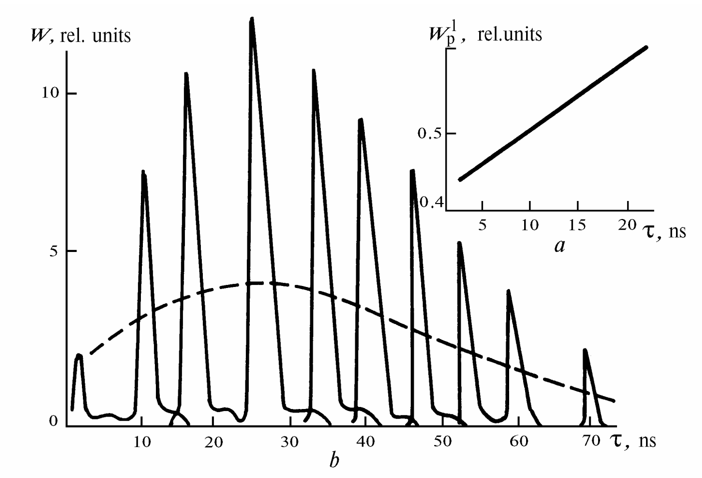

FIG. 5. Dependence of W of the OA system on τ^1 (a). Pulsed power W_p^1 of the OA system oscillator i *excitation pulses of the oscillator and amplifier (b). Dashed curve indicates superemission.*

8. The general feature of the operation of oscillator–amplifier (OA) systems is that the main radiation parameters of the driving oscillator are "copied", to a certain degree, in the wave form and duration τ^1 at the amplifier stages. Therefore, the above-described techniques of promptly controlling the laser output parameters can be used in the OA systems as well, and their capabilities are extended because in this case *E*, *W*, and W_p can vary within wider limits. In particular, by varying the time delay between the excitation pulses of the oscillator and amplifier τ_{OA} one can vary *E* and *W* by the linear law. Some results of this experiment are shown in Fig. 5.

One more way of controlling the output parameters in the OA system is varying τ^1 of the laser oscillator what makes it possible to control the radiation energy through "cutting out" inverted populations with different lifetimes in the active medium of the amplifier. In this case the control will be realized due to variation in the power of the stimulated radiation ρ_i, with the controlling effect exerted by the laser pulse duration τ^1.

9. The lasing control techniques discussed in Secs. 5 and 6 are particular cases of a more general mode with controlled ionization, which can be realized either by initiating several RPD's in the same discharge gap or by incorporating an additional controlling element into the circuit where a capacitor discharges spontaneously.

Double-channel superposition RPDs in vapors of metals and their compounds seems to offer one of the multipurpose excitation methods which makes it possible to carry out direct experimental investigations of the physical peculiarities of the MVL. Moreover, this method can be used to control n_e and T_e (during both the EP and interpulse periods) through "modeling" excitation pulses with complex shape and provides more complete laser optimization in efficiency, *f*, W_p, beam divergence, etc.

Figure 6 shows pulsed current-voltage characteristics of discharges in a Cu–Ne mixture for fixed parameters C_e and U_e of the excitation circuit and C_a and U_a of the auxiliary discharge circuit. To discuss the capabilities of such a discharge with a controlled shape of the excitation pulse, we put forward the following considerations.

In the first case, when producing the AP with $T_e < T_e^{thr}$ (T_e^{thr} is a threshold electron temperature above which oscillations occur) the adjustment of τ_{cd} makes it possible to affect the prepulse electrokinetic parameters and the populations of metastable levels and to control the output radiation intensity and chromaticity (see Fig. 3).

In the second case, the "complex" shape of the EP (in contrast to the "simple" one that is realized in the case of *a* capacitor spontaneously discharging through the active medium) makes it possible either to accomplish a prompt control of the laser pulse duration or to obtain the maximum efficiency, increased *f*, etc.

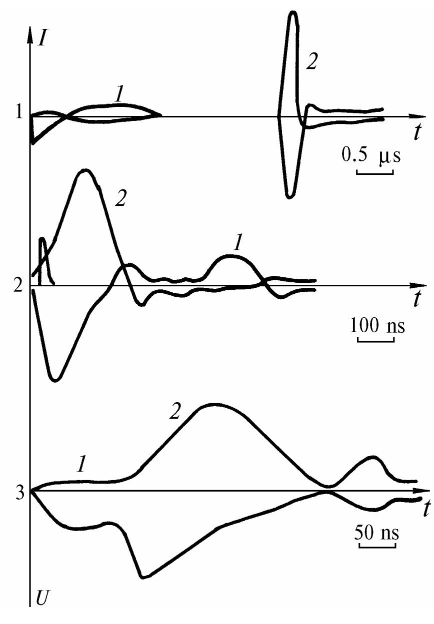

FIG. 6. Wave forms of the AP (1) and the EP (2) for different time delay: (a) the AP controls the output power and chromaticity through variations of n_e and N_m, (b) the AP is used as an additional heater, and (c) superposition of the AP and the EP results in a "complex" shape of the pumping current pulse with long risetime.

Figure 7 shows the result of the experiment where τ^1 was equal to 200 ns and variation in the excitation pulse duration allows a variation in τ^1 within a range of 3–200 ns. Note that τ^1 = 100–200 ns allows one to combine the functions of oscillator and amplifier in one and the same active space. This in turn results in the possibility of increasing the portion of the laser pulse energy confined within a diffracted divergent beam up to 90%.

10. Progress of the MVL technology has led to the creation of experimental and commercial devices capable of lasing at discrete wavelengths within the range 300–500 nm. The combination of controlled short-pulse radiation with high f generated by the MVL and continuous tuning within a wide λ range in dye lasers or color–center lasers is highly promising for many spectroscopic technologies and research methods.

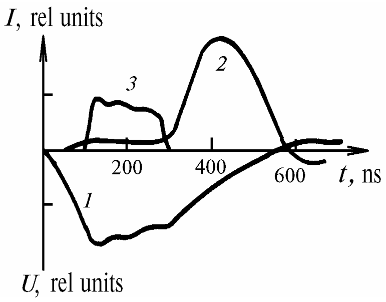

FIG. 7. Waveforms of voltage (1), current (2), and laser radiation (3) for the mode of controlled ionization.

Most of the papers devoted to this problem were aimed at broadening the tuning spectral range $\Delta\lambda$, with an increased efficiency of frequency conversion. Optimization of multicomponent dye mixtures leads to increasing the lasing efficiency within a range of 600–700 nm when a Cu laser is used for pumping. Use of Pb and Au lasers as a source of pumping extends the range of continuous tuning up to 835 nm. Conversion of the radiation of the color center MVL allows an extension of the turning range up to 1 μm,[1,12] and efficient frequency conversion in the region 2–3 μm. Continuous overlap of the $\Delta\lambda$ range up to 260 nm towards the UV region is accomplished through the conversion of the radiation of a dye laser pumped by the MVL into the second harmonic.

Thus, a combined conversion of the radiation of the MVL in dye lasers, lasers based on crystals with color centers and nonlinear crystals[13] makes it possible to cover the $\Delta\lambda$ range from 0.26 to 3 μm with continuous tuning. Note that in this case, though the MVL output pulse energy decreases in compliance with the efficiency of frequency conversion, nevertheless, the rest of the MVL parameters such as output pulse duration and repetition rate and the controllability of the output parameters are retained.

11. The principles and techniques of controlling laser radiation parameters discussed in this paper have been either embodied in actual devices or examined in experiment. Thus, it can be stated that a new line in the field of the MVL study has appeared, namely, the metal vapor lasers with controllable output parameters.

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