Technical Physics Letters, 2026, Vol. 52, No. 3

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Parametric study of a CuBr laser with subnanosecond excitation pulse rise time at a pulse repetition frequency of up to 100 kHz

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Received October 14, 2025
Revised November 17, 2025
Accepted November 17, 2025

The results of experimental studies on the lasing characteristics of a copper vapor laser on self-terminating transitions (active medium: $\mathrm{CuBr + Ne + H_2}$) pumped by pulses with subnanosecond rise times are presented. In a burst mode, a stable average output power per unit length of 65 W/m was achieved in a gas discharge tube with a diameter of 1.1 cm at a pulse repetition frequency of up to 100 kHz, with a lasing efficiency of 0.6 % relative to the energy stored in the operating capacitor.

Keywords: copper vapor laser, pulses, subnanosecond rise time.

DOI: 10.61011/TPL.2026.03.63063.20524

Owing to the rapid development of semiconductor and diode-pumped solide-state lasers, copper vapor lasers have been driven out of most applications. However, several promising domains of their application, which include high-speed projection systems with brightness amplifiers [1], still remain. Copper halide lasers are best suited for this purpose, since metastable states of copper relax in microseconds [2], providing the capacity to operate at pulse repetition frequencies of hundreds of kilohertz [3]. Compact lasers with a high average power are needed to expand these applications further. A significant improvement in the output characteristics of self-terminating lasers may be achieved by reducing the excitation pulse rise time to ~ 1 ns or less. This has been demonstrated for Cu(I), Ba(II), and Ca(II) lasers (see [4] and references therein). Such experiments for CuBr lasers have not been performed yet. The present study is aimed at filling this gap.

A $\mathrm{CuBr + Ne + H_2}$ vapor-gas mixture was used for experiments. The quartz gas discharge tube (GDT) had an interelectrode distance of 25 cm and an internal diameter of the BeO ceramic insert of 1.1 cm (the excited volume was $24\,\mathrm{cm^3}$). A container with a sample of CuBr purified by vacuum distillation was positioned in front of the grounded electrode of the discharge channel. The operating temperature was maintained using an external heater mounted outside the stainless steel return conductor. The medium was excited by a negative-polarity pulse burst (40–100 pulses) with repetition frequency f up to 100 kHz. Pulses were produced by pulsed charging of capacitor $C = 160$ nF from a transistor generator with its subsequent discharge through the GDT and an eptron (a switching device combining a plasma cathode and a slot discharge channel [5]). The diameter of the SiC ceramic cathode of the eptron was 28 mm, and the length of the active section was 20 mm. The slot discharge channel 50 mm in length with a cross-section of 15×0.3 mm had the shape of a meander. The working gas (helium) pressure in the eptron was $\sim 15{-}20$ Torr, and the time of switching to active load $R = 68\,\Omega$ was less than 0.5 ns at an eptron electrode voltage above 15 kV. Signals were recorded using a Tektronix MDO3104 oscilloscope with a bandwidth of 1 GHz and a sample rate of 5 GHz. The experiments were carried out under weak flow of the $\mathrm{CuBr + Ne + H_2}$ mixture at the optimal pressure of gas components of 30 and 1 Torr respectively.

When the GDT is heated, lasing arises at $\lambda = 510.6$ nm (green line) at CuBr container temperature $T \sim 400\,^\circ$C and consists of several pulses in the middle of a burst. An example is provided in Figs. 1, *a*–*c*, which illustrate the evolution of lasing parameters in the process of GDT heating at $f = 60$ kHz. For clarity, the signal from a coaxial vacuum phototube CVP-22 in the full burst mode was stretched artificially by increasing the load resistance to $5{-}20\,\mathrm{k\Omega}$. Experiments revealed that lasing at $T = 407\,^\circ$C starts with the 12th pulse, reaches its maximum by the 22nd pulse, and vanishes by the 36th pulse. The green lasing line with duration $\tau \approx 3.5$ ns at half maximum is still the only one present. Further GDT heating leads to expansion of

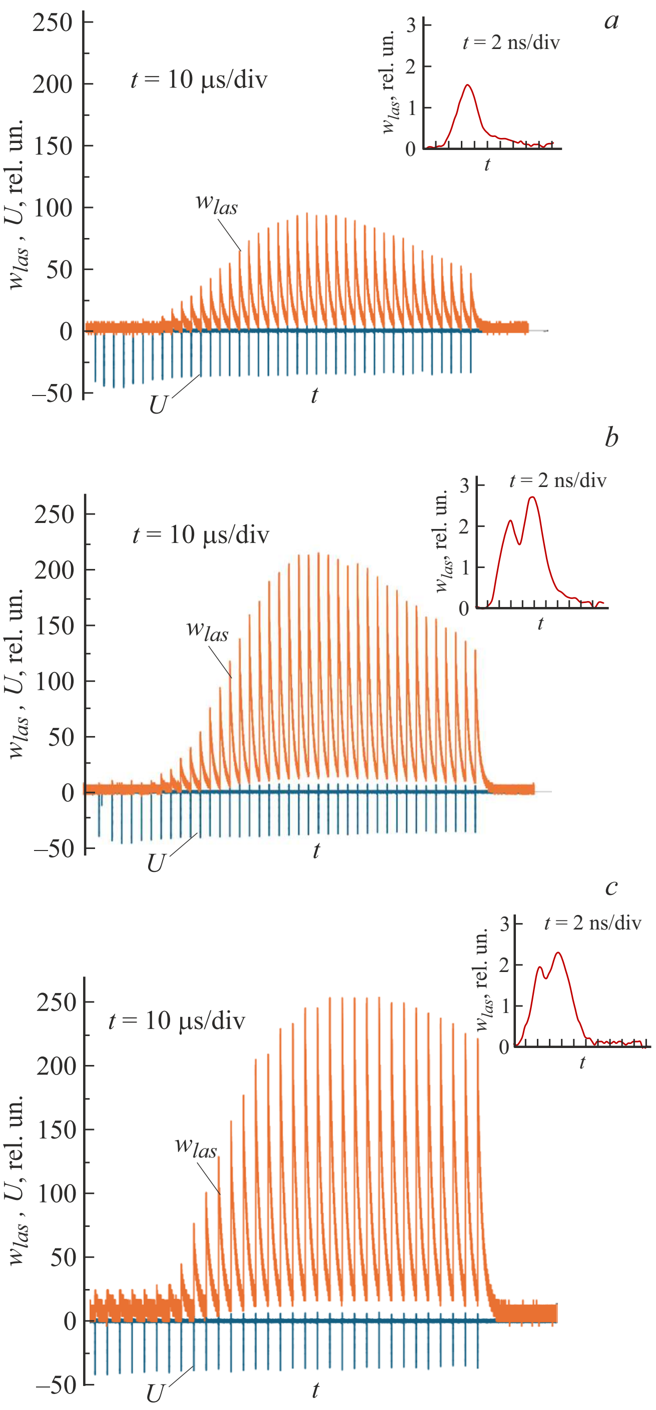

Figure 1. Evolution of lasing parameters in the process of GDT heating. $T = 427$ (a), 527 (b), and 571 °C (c). The lasing pulse shape is presented in the insets ($f = 60$ kHz).

the lasing domain within a pulse burst. Lasing pulses arise at earlier pump pulses and persist until the end of a burst. At $T = 427\,^\circ$C (Fig. 1, a), the lasing pulse fall time is extended due to the emergence of a yellow line with $\lambda = 578.2$ nm, and the pulse duration at half maximum is increased to$\tau \approx 3.8$ ns. The lasing power at maximum is three times higher than the power at $T = 407\,^\circ$C and is ~ 2 times lower at the end of a burst than in the middle of it. At $T = 467\,^\circ$C, the power of the line with $\lambda = 578.2$ nm becomes equal to that of the line with $\lambda = 510.6$ nm; as a result, the lasing pulse expands to $\tau \approx 7.45$ ns.

The oscilloscope records of GDT voltage U, GDT current I, and lasing w_{las} pulses are shown in Fig. 2. The current pulse has two distinct stages. At the first stage (4–5 ns), sharp peaks with a duration of ~ 1.5 ns, which are induced by the process of charging and discharging of the intrinsic GDT capacitance, are observed. The duration of this stage increases with decreasing frequency f. Accordingly, an increase in f leads to shortening of the first stage, and it merges with the second one (GDT breakdown) at $f > 80$ kHz. Rate of current rise dI/dt at the second stage is $dI/dt \approx 40$ A/ns at $f = 60$ kHz and increases to ~ 55 A/ns at $f = 100$ kHz. At $T = 527\,^\circ$C, the yellow line is dominant, and the lasing pulse is extended slightly to $\tau \approx 7.65$ ns (Fig. 1, b). At $T = 571\,^\circ$C, lasing reaches its maximum with further strengthening of the yellow line relative to the green one, and the pulse energy at the end of a burst is $\sim 90\,\%$ of the maximum energy level (Fig. 1, c). At $T = 617\,^\circ$C, lasing is already ~ 1.6 times weaker than at $T = 571\,^\circ$C; however, having reached maximum, it maintains its parameters until the end of a burst (even when f increases to 100 kHz and the number of pulses in a burst increases to 100) with a slight reduction in duration to $\tau = 6.8$ ns. The evolution of lasing parameters with increasing temperature is presented in the generalized form in Fig. 3, a.

Figure 3, b presents dependences $P_{las}(U)$ of the average steady-state lasing power on the initial working capacitor voltage at $f = 75$ kHz and dependences $P_{las}(f)$ of the lasing power on the pulse repetition frequency at $U = 18$ kV (the temperature of the container with CuBr is $T = 617\,^\circ$C). The lasing efficiency under the same conditions is presented as a function of energy stored in the working capacitor in Fig. 3, c. It follows from these data that the energy and efficiency of lasing increase faster than pump energy w (calculated as $w = CU^2/2$) and faster than pulse repetition frequency f at $U = 18$ kV. At frequency $f = 100$ kHz, a value of $P_{las} = 16.1$ W, which is calculated as $P_{las} = w_{las} f$ (w_{las} is the lasing energy at the end of a burst), was obtained at an efficiency relative to the stored energy of $\sim 0.6\,\%$, specific radiated energy $w_{las} \approx 6.7\,\mu$J/cm^3, and a peak power of 10^3 W/cm^3. The evolution of the lasing pulse shape with frequency increasing to $f = 85$ kHz is presented in Fig. 4; it varies little through to $f = 100$ kHz, mostly due to further intensification of the green line relative to the yellow one. At the same time, the domain of existence of lasing within a burst expands; at $f = 100$ kHz, lasing starts with the 6–7th pulse and reaches a plateau by the ~ 30th pulse. With a resonator consisting of just one plane-parallel plate, $\sim 70\,\%$ of

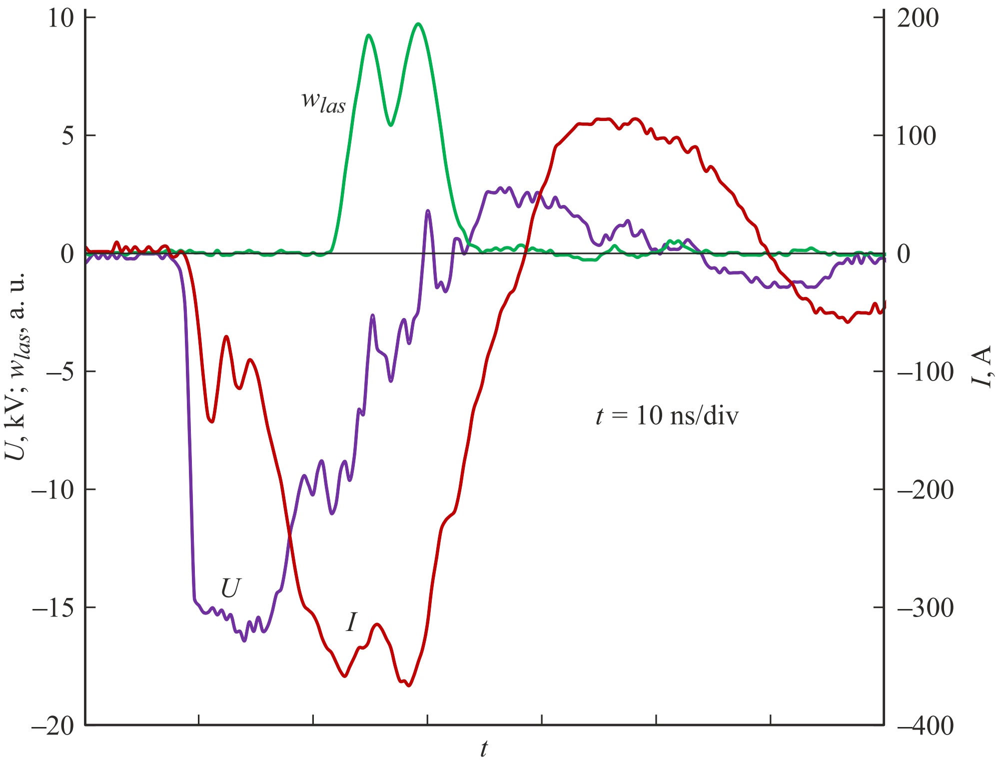

Figure 2. Oscilloscope records of voltage U, current I, and lasing w_{las} pulses ($T = 467\,^{\circ}$C, $f = 60$ kHz).

power corresponding to the use of a resonator consisting of a reflecting mirror and a plane-parallel plate are emitted, which is favorable for application in projection systems.

The behavior of lasing characteristics is interpreted as follows. The lack of lasing at the start of a burst is attributed the low degree of dissociation of CuBr vapor, and the lack of lasing at the end of a burst at low temperatures is explained by the almost complete ionization of copper vapor in post-pulse plasma and the expulsion of the working mixture into buffer GDT zones due to strong heating in the discharge zone (the temperature increases by $\Delta T \sim 70\,^{\circ}$C per pulse). Specifically, according to the oscilloscope record in Fig. 2 and relation $n_e = j/ev_e$ (j is the current density and v_e is the drift velocity in neon [6]), the electron density at the end of an excitation pulse under the conditions corresponding to those in Fig. 1, a is $n_e \sim 1.5 \cdot 10^{14}\,\mathrm{cm}^{-3}$ at a vapor concentration of CuBr $\sim 2 \cdot 10^{14}\,\mathrm{cm}^{-3}$. Since the drift velocity is reduced under the influence of CuBr vapor, the actual value of n_e may be even higher. As heating proceeds, lasing continues through to the end of a burst, but it reaches a steady-state value already at an operating temperature above the optimum for lasing in the first third of a burst, which is attributable to expulsion of the mixture due to heating and attainment of the optimum concentration of CuBr vapor for lasing. This is why the green line is intensified relative to the yellow one (Fig. 4) with an increase in pulse repetition frequency.

Thus, it was demonstrated that the use of pulses with a subnanosecond rise time for pumping a CuBr laser provides an opportunity to raise its operating frequency to at least 100 kHz and increase the number of pulses in a burst to 100 without reducing the lasing energy in a GDT with a diameter of 1.1 cm. With a discharge zone length of 25 cm, an average lasing power in a train of ~ 16.1 W and a power per unit length of ~ 65 W/m were achieved, which is comparable to the best results for large-diameter GDTs. The short duration of a lasing pulse, which is attributable to a high specific pump power, makes it possible to reach a 70% lasing power level in the superradiance mode (when the resonator is formed by a single plane-parallel quartz plate), boding well for application in projection systems with brightness amplifiers.

Funding

This study was supported financially by the Russian Science Foundation, grant No. No 24-19-00037 (https://rscf.ru/project/24-19-00037/).

Conflict of interest

The authors declare that they have no conflict of interest.

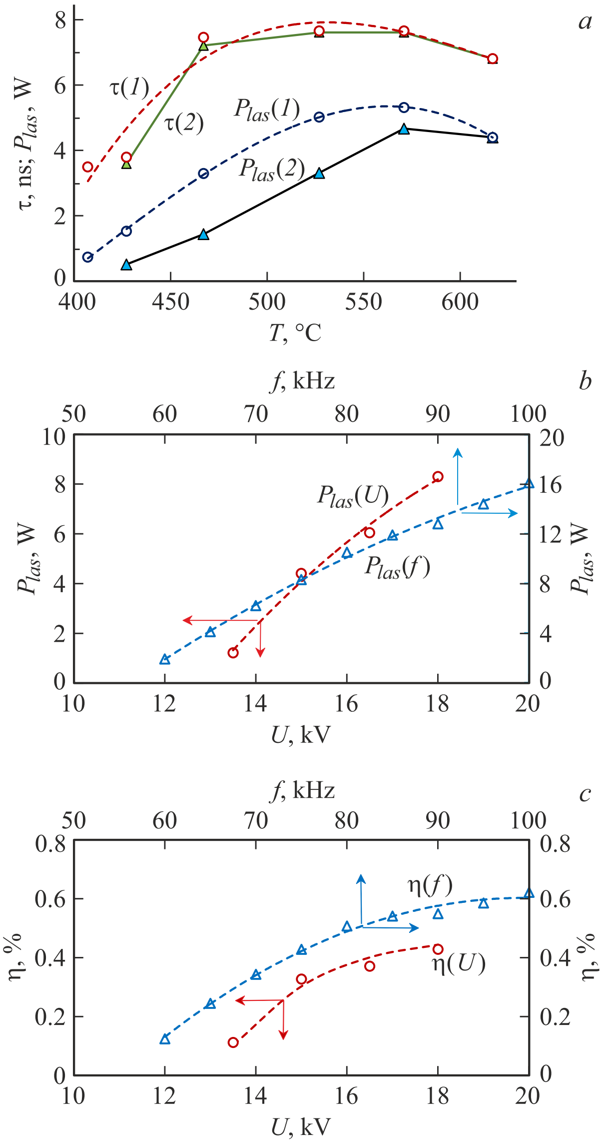

Figure 3. *a* — Dependences $P_{las}(T)$ and $\tau(T)$ in the middle (*1*) and at the end (*2*) of a burst; *b* — dependences $P_{las}(U)$ and $P_{las}(f)$: $f = 75$ kHz, $U = 18$ kV, and $T = 617\,^\circ$C; *c* — dependences $\eta(U)$ and $\eta(f)$: $f = 75$ kHz, $U = 18$ kV, $T = 617\,^\circ$C.

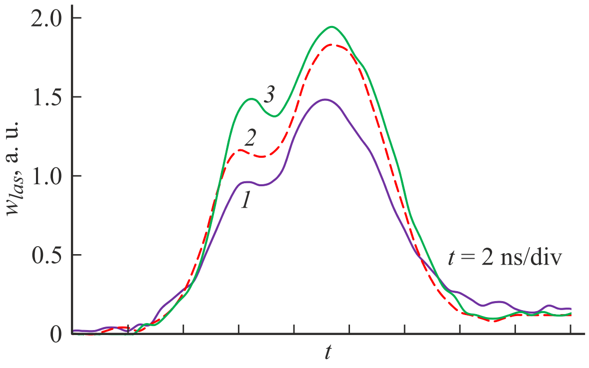

Figure 4. Evolution of the lasing pulse shape at $f = 75$ (*1*), 80 (*2*), and 85 kHz (*3*). $U = 18$ kV.

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Translated by D.Safin