Quantum Electronics **49** (8) 749–753 (2019)

https://doi.org/10.1070/QEL16987

Frequency and energy characteristics of a Cu–Ne laser at different durations of the leading edge of the excitation pulse

P.A. Bokhan, P.P. Gugin, Dm.E. Zakrevskii, M.A. Lavrukhin

Abstract. **The lasing characteristics of a copper vapour laser in a tube with forced heating, having a length of 50 cm and a diameter of 2 cm, excited by a train of pulses are investigated. Comparative studies of the frequency and energy characteristics of the laser are performed with a leading edge duration of the excitation pulse of ~25 ns (when the capacitance discharges through a thyratron and a magnetic compression line) and ~3 and 1 ns (using circuits with a high-speed switch – kivotron). It is shown that a decrease in the leading edge duration gives rise to an increase in the optimal pulse repetition rate up to ~30 kHz, the generation efficiency up to 3.2% and the generation power per unit length over 100 W m^{-1}. The results obtained confirm the concept of limiting the frequency and energy characteristics of a copper vapour laser due to the insufficient rate of energy input into the plasma at high prepulse electron concentrations.**

Keywords: *copper vapour laser, frequency and energy characteristics, duration of the excitation pulse leading edge.*

1. Introduction

Despite the competition from diode-pumped solid-state lasers in the visible range, a copper vapour laser, thanks to a number of its unsurpassed parameters, is used in the field of precision materials processing [1, 2], medicine [3], in physical experiments [4, 5], in high-speed registration of objects and processes with the help of amplifiers of brightness [6–10], etc. For high-speed amplifiers of brightness, high repetition rates of generated pulses f together with a high output power are required. These requirements are satisfied by $CuBr-Ne-H_2$ mixture lasers having a maximum output power at repetition rates of tens of kilohertz [11, 12]. However, for practical applications, long-life sealed devices are more promising, e.g., those using a mixture of $Cu-Ne-H_2$ or Cu–Ne at high (more than 100 Torr) pressure of neon. The optimal repetition rate for these lasers, corresponding to the maximum power and lasing efficiency, lies in the range f = 5–20 kHz [12–15], and for $CuBr-Ne-H_2$, the values of f = 20–50 kHz [12, 16] are typical. With increasing f, the energy parameters become worse. In Ref. [17], the lasing efficiency of a $CuBr-Ne-H_2$ laser was ~0.7% at an optimal repetition rate of f = 50 kHz, 0.42% at f increased to 100 kHz, and 0.13% at f = 200 kHz. In Ref. [18], in a copper vapour laser with modified kinetics, the lasing efficiency reached 2.8% at f = 18 kHz, and in Ref. [19] it was 1.4% at f = 25 kHz, 0.7% at 50 kHz and 0.3% at 100 kHz. At present, under the conditions of a lower energy input the repetition rate $f \approx 230$ kHz has been achieved in $Cu-Ne-H_2$ lasers [20] and $f \approx 700$ kHz in $CuBr-Ne-H_2$ lasers [11], but these lasers have a low output power and efficiency, which limits the field of their applications.

In Ref. [21], it was shown that the limitation of the frequency and energy lasing characteristics in a copper vapour laser arises due to an insufficient energy input rate, which leads to slow heating of electrons at their high prepulse concentration n_e^0. When the pulses become closer to each other and n_e^0 grows, a variety of processes occur that worsen the lasing conditions, such as reduction of the electron gas heating rate, skin effect, stepwise processes of resonant states depopulation, increasing the degree of vapour ionisation, etc. Finally, this leads to a redistribution of the upper and lower laser states pumping in favour of the latter, which limits the frequency and energy characteristics of lasing [22, 23].

One of the ways to increase the efficiency of lasing on self-terminating transitions is to shorten the leading edge of the pump pulse, up to the 'instantaneous' one, with a duration of $\sim 10^{-9}$ s [14, 21, 24]. In Ref. [25], it was shown that in this case the frequency and energy characteristics are also significantly improved. In particular, it is predicted to increase the average lasing power per unit length to ~200 W m^{-1} without decreasing the efficiency in gas-discharge tubes (GDTs) with a diameter of d = 2 cm [22]. At present, it is the shortening of the leading edge and control of the pump pulse duration that is expected to offer prospects for increasing the power and efficiency of self-terminating lasers [14, 15, 25–27].

To generate pump pulses with a nanosecond leading edge, a new type of a switch, kivotron, was used as a discharge device with a planar or coaxial geometry based on an 'open' discharge with generation of counterpropagating electron beams [28–30]. Recent studies have made it possible to determine the range of operation conditions and parameters, in which high switching characteristics of kivotrons, which are of interest for the excitation of lasers, are preserved. The utmost separately achieved parameters of kivotrons are as follows: switching time for an active inductive load up to 100 ps, f up to 100 kHz, operating voltages U = 2–100 kV, and switched current densities up to 1 kA cm^{-2} [30].

The purpose of this work is a comparative study of the frequency and energy characteristics of a Cu–Ne laser for dif-

P.A. Bokhan, P.P. Gugin, M.A. Lavrukhin A.V. Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13, 630090 Novosibirsk, Russia; e-mail: bokhan@isp.nsc.ru;
Dm.E. Zakrevskii A.V. Rzhanov Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13, 630090 Novosibirsk, Russia; Tomsk State University, prosp. Lenina 36, 634050 Tomsk, Russia

Received 1 March 2019; revision received 12 April 2019
Kvantovaya Elektronika **49** (8) 749–753 (2019)
Translated by V.L. Derbov

ferent durations of the leading edge of the excitation pulse under a wider range of conditions than those considered in Ref. [25].

2. Experimental setup and measurement technique

The studies were performed with a copper vapour laser, having an active element similar to that described in Ref. [25], except for the fact that a 50 cm long GDT with an internal diameter d = 2 cm was made of BeO ceramics. Cylindrical electrodes made of reactively sintered silicon carbide SiC with a specific resistance of $\rho \approx 0.5$ Ohm cm were mounted at the ends of the GDT. The external surface of the electrodes was metallised with a molybdenum film and connected to water-cooled cylindrical inlets installed at the ends of the silica casing. With a return conductor installed near the housing, the calculated inductance of the active element was ~150 nH. The tube was placed in a silica casing with a diameter of 60 mm, filled with a heat insulator made of special-grade ZrO_2 powder. The GDT had independent temperature control (up to 1600 °C) with the help of a built-in heater made of Mo wire, wound on the external surface. Temperature control was carried out using an infrared pyrometer of the KM3st series. The heaters were powered by half-cycles of the mains voltage through a step-down transformer, protected from the effects of high-voltage pulses by LC filters. In every fourth pause of heater pulses, a train of 10 high-voltage pump pulses was applied. The pulse-train method for studying laser properties has several advantages over the regular-pulse method in the self-heating regime, because in the latter case it is difficult to observe the optimal temperature conditions and pump parameters simultaneously. The method makes it possible to study the lasing characteristics in a wide range of excitation parameters and active medium temperatures.

Comparative studies were carried out for three types of pump pulses: (i) formed by the capacitance during its discharge through a TGI1-1000/25 thyratron and the magnetic compression line with the leading edge duration $\tau \approx 25$ ns after the terminal stage (at a level of 0.1–0.9); (ii) formed by a kivotron with $\tau \approx 3$ ns filled with a mixture of He and H_2 with a pressure of 2 and 1 Torr, respectively, and operable up to a repetition rate of $f \approx 30$ kHz with a switched voltage of up to U_0 = 19 kV; and (iii) formed by a kivotron with $\tau \approx 1$ ns, filled with a mixture of He and H_2 with a pressure of 4 and 0.5 Torr, respectively, and operable up to $f \approx 13$ kHz at U_0 = 17 kV. A planar kivotron with the generation of counterpropagating electron beams was used, consisting of two accelerating gaps of 3 mm each, separated by a common molybdenum anode grid with a geometric transparency of ~92%. The working diameter of SiC cathodes with ρ = 0.5 Ohm cm was 30 mm.

Figure 1 shows how the GDT is connected to the power supply when using a kivotron. In contrast to Ref. [25], the GDT was grounded at one end through current-measuring resistance and shunted by three parallel arrays of high-speed C4D05120E SiC diodes. This made it possible to reduce the voltage pulse on the GDT during the charging of the working capacity during 50–60 ns to a voltage $U \approx 300$–400 V, which does not affect the output characteristics of the laser. In the variant with magnetic compression, the traditional pumping circuit with peaking capacitance was used [14]. The pump and lasing parameters were recorded using a Tektronix TDS 2024B oscilloscope with a 200 MHz band, signals to which were fed from resistive voltage dividers, a current shunt, and a FK 32 vacuum photodiode. The switching characteristics of the kivotron were measured using a Tektronix DPO 70804 oscilloscope with a bandwidth of 8 GHz, and the laser output power was recorded with a S310C thermal sensor (Thorlabs). As a rule, the parameters of the pump and lasing pulses were set to the third pulse and then remained unchanged until the end of the train. The experimental data presented below is mainly obtained by measuring parameters in the tenth pulse.

3. Experimental results and discussion

As an example, Fig. 2a shows waveforms of voltage U on the GDT, current I through it, input instantaneous pump power, which is their product, $P = UI$, and the laser pulse, in the case of power supply from a generator with magnetic compression line. The optimal working capacitance $C = 15d^2/L \approx 1100$ pF (d and L expressed in cm) was used. The peaking capacitance was $C_p \approx 1000$ pF. The pressure of the neon buffer gas was p_{Ne} = 45 Torr, the tube temperature T = 1525 °C was close to an optimal one, and the repetition rate and the voltage were f = 3 kHz and U_0 = 16 kV. Figure 2b shows oscillograms for the case of feeding the GDT with the pulses generated by the

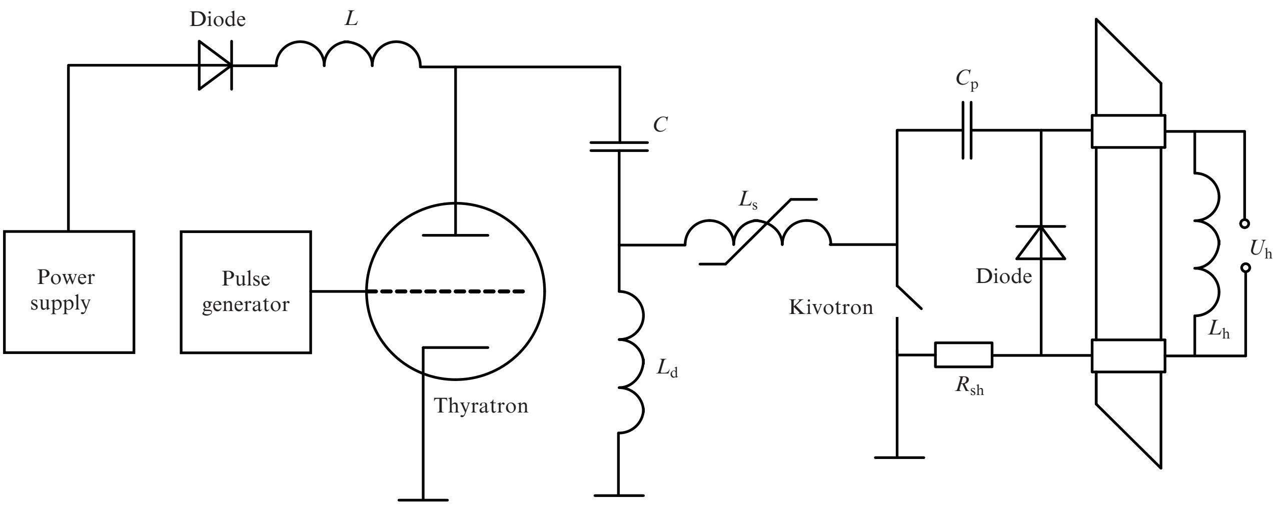

Figure 1. Wiring diagram of the active element connection.

kivotron with $\tau \approx 1$ ns, $C = 1100$ pF, $p_{\text{Ne}} = 45$ Torr, $T = 1570\,°\text{C}$, $f = 10$ kHz, $U_0 = 17$ kV. From the oscillograms of the current I and the input power P, it can be seen that they are significantly different. In particular, when powered by a kivotron on the leading edge of a current pulse, a surge having a duration of ~5 ns is registered, caused by the displacement current through the parasitic capacitance of the GDT and the inductance of the current shunt. The discharge current reaches a maximum with the delay time τ_d, which at $f = 10$ kHz amounts to ~10 ns. With increasing f, this delay decreases, and at $f > 20$ kHz the peaks of the displacement current and the discharge current merge. The value of τ_d also decreases with increasing the GDT temperature. As a result, a nearly square-shaped pump pulse P is formed on the GDT, in contrast to the bell-shaped pulse generated in the circuit with magnetic compression.

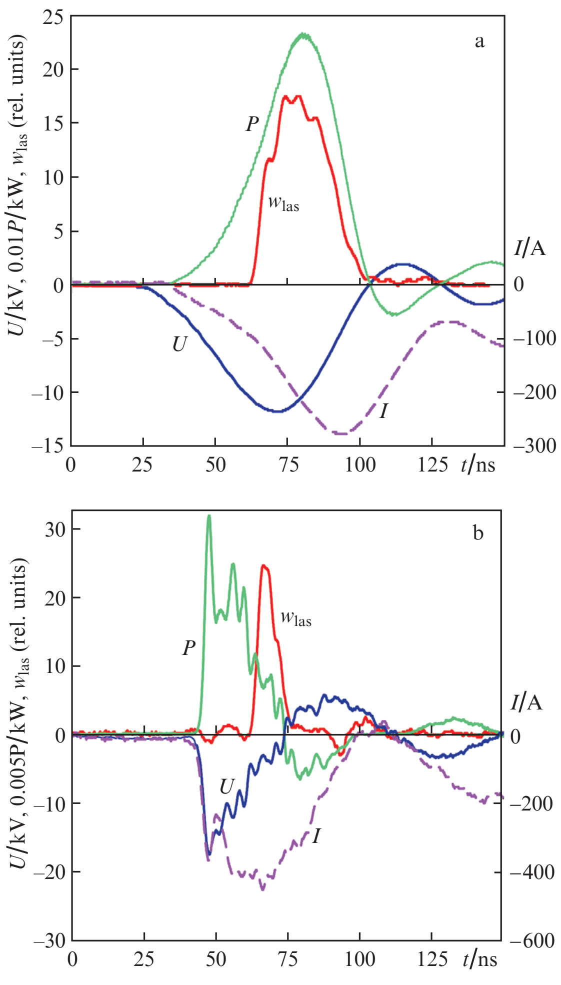

Figure 2. Oscillograms of pulses of voltage U, current I, pump power P, and lasing energy w_{las} for the tenth pulse in a train of pulses: (a) circuit with magnetic compression, $C = 1100$ pF, $T = 1525\,°\text{C}$, $f = 3$ kHz, $U_0 = 16$ kV and (b) circuit with a kivotron, $C = 1100$ pF, $T = 1570\,°\text{C}$, $f = 10$ kHz, $U_0 = 17$ kV.

Figure 3 shows the behaviour of the lasing energy (in the tenth pulse) w_{las} as a function of T in the gas-discharge tube in the circuit with magnetic compression for $f = 3$ kHz and in the circuit with kivotron for $f = 10$ kHz. The increase in the optimal operating temperature T_{opt} corresponding to the maximum of w_{las}, when using a kivotron, is associated with the achievement of a higher magnitude of the voltage amplitude at a given value of U_0, which allows maintaining the required temperature of electrons at higher pressure of copper vapour.

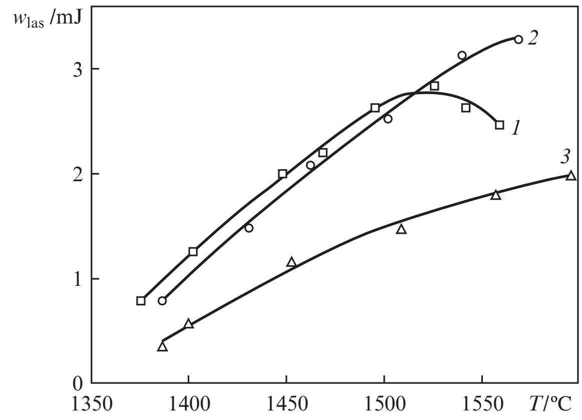

Figure 3. Effect of temperature T on the lasing energy w_{las} in the tenth pulse: (*1*) circuit with magnetic compression, $f = 3$ kHz, $\tau \approx 25$ ns, $U_0 = 16$ kV, $C = 1100$ pF, $p_{\text{Ne}} = 45$ Torr; (*2*) circuit with a kivotron, $f = 10$ kHz, $\tau \approx 1$ ns, $U_0 = 19$ kV, $C = 1100$ pF, $p_{\text{Ne}} = 45$ Torr; (*3*) circuit with a kivotron, $f = 20$ kHz, $\tau \approx 3$ ns, $U_0 = 20$ kV, $C = 440$ pF, $p_{\text{Ne}} = 150$ Torr.

For T_{opt} Fig. 4 shows the dependences of the average lasing power P_{las} and lasing efficiency η_{las} on f, determined rela-

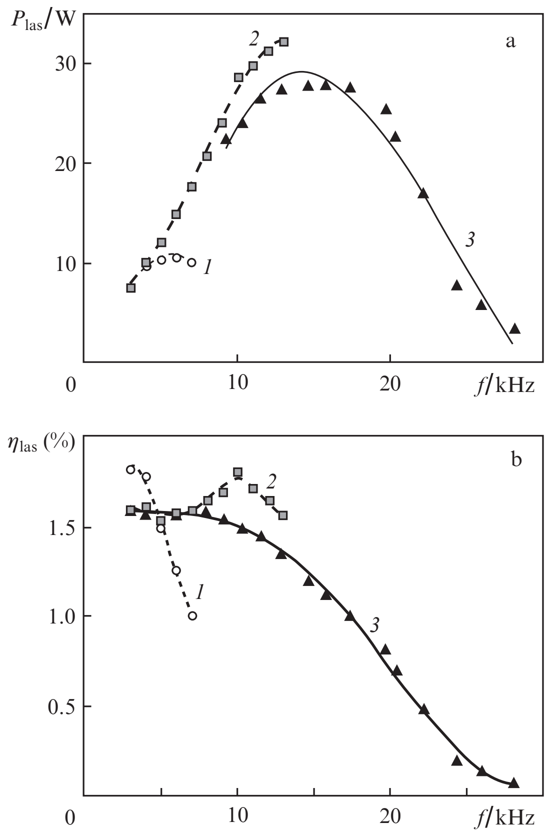

Figure 4. Dependences of (a) the average power P_{las} and (b) the lasing efficiency η_{las} on the repetition rate f: (*1*) circuit with magnetic compression, $\tau \approx 25$ ns, $p_{\text{Ne}} = 45$ Torr, $U_0 = 16$ kV, $C = 1100$ pF; (*2*) circuit with a kivotron, $\tau \approx 1$ ns, $p_{\text{Ne}} = 45$ Torr, $U_0 = 17$ kV, $C = 1100$ pF and (*3*) $\tau \approx 3$ ns, $p_{\text{Ne}} = 45$ Tor, $U_0 = 17$ kV, $C = 1100$ pF.

tive to the energy stored in the capacitance C, for the circuit with magnetic compression at $U_0 = 16$ kV and for the circuit with a kivotron with $\tau = 1$ ns at $U_0 = 17$ kV. The choice of the operating voltage at the kivotron, $U_0 = 17$ kV, was determined by the fact that at $f = 3$ kHz, the generation energy for both variants was the same. This condition leads to the fact that η_{las} in the circuit with a kivotron at low frequencies is lower than in the circuit with magnetic compression. At $f \approx 5$ kHz, the values of η_{las} become comparable, and at $f > 6$ kHz, the kivotron circuit turns out to be much more efficient. As a result, the maximum output power for a kivotron with $\tau = 1$ ns is nearly 3 times higher than for a circuit with magnetic compression. It is noteworthy that η_{las} in the circuit with a kivotron increases up to $f \approx 10$ kHz, and then a slow decrease occurs. It is due to the fact that, at $f > 10$ kHz, the kivotron itself is triggered earlier than the voltage at C_p reaches its maximum value, which leads to a decrease in the amplitude of the voltage applied to the GDT.

To increase the switching delay time and, therefore, to work at higher repetition rates, the kivotron operated at a reduced pressure of the $He-H_2$ mixture, which increased the switching duration τ to 3 ns. The lasing characteristics P_{las} and η_{las} as functions of f with $U_0 = 17$ kV are shown in Fig. 4 by curves *3*. It follows from them that, although the optimal repetition rate is $\sim$3 times higher ($f \approx 16-17$ kHz) than the frequency for the circuit with magnetic compression, P_{las} and η_{las} are smaller than these characteristics for the variant using a kivotron with $\tau = 1$ ns. The comparison of the voltage oscillograms shows that with increasing f a redistribution of the voltage drop between the GDT and the kivotron occurs not in favour of the GDT.

To increase the impedance of the GDT, the neon pressure in the active medium of the laser was increased to $p_{Ne} = 150$ Torr. Increasing the working pressure leads to the necessity of increasing U_0. To save the energy input, C was reduced to 440 pF. Figure 3 shows the effect of T on the lasing energy at $U_0 = 20$ kV and $f = 20$ kHz (*3*). An increase in U_0 leads to an increase in T_{opt} above 1600 °C, and in the experiment it was not reached. Figure 5 shows the dependences of P_{las} and η_{las} on f at $\tau = 3$ ns. Studies have been carried out for $f \geqslant 15$ kHz, since at lower frequencies the quasi-stationary regime does not have time to be established during a train of 10 pulses. One can see a significant increase in the optimal f in comparison with the repetition rate for $p_{Ne} = 45$ Torr. Due to the better matching of the pump generator with the GDT, higher efficiency was obtained. However, the value of the optimal energy input, corresponding to the maximum of w_{las}, despite the large differences in the pump pulse parameters, remains almost the same. This follows from Fig. 6, which shows the dependences of the lasing efficiency η_{las} on the stored energy W. Apparently, this fact is due to the development of stepwise processes of depopulation of the upper working levels, since according to calculations by the models of Refs [31, 32], the concentration of electrons reaches $(2-3)\times 10^{14}$ cm^{-3} by the end of the laser pulse.

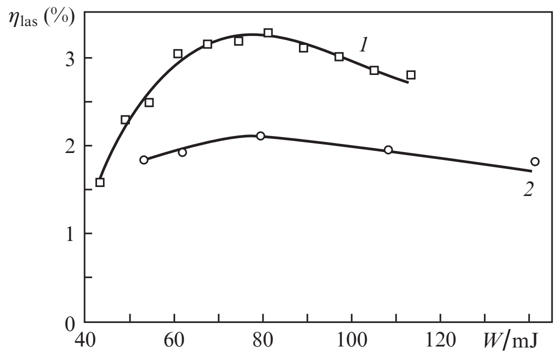

Figure 6. Dependences of the lasing efficiency η_{las} on the stored energy W: (*1*) circuit with a kivotron, $p_{Ne} = 150$ Torr, $f = 20$ kHz, $C = 440$ pF, $\tau \approx 3$ ns; (*2*) circuit with magnetic compression, $p_{Ne} = 45$ Torr, $f = 3$ kHz , $C = 1100$ pF, $\tau = 25$ ns.

A significant difference in the lasing characteristics is observed when using different ways to pump the laser. At $p_{Ne} = 45$ Torr and excitation by pulses in a circuit with magnetic compression line, w_{las} and η_{las} decrease at $f = 3$ kHz, and in a circuit with $\tau = 1$ ns, these parameters increased with the repetition rate until $f = 10$ kHz with a further gradual decrease. In the scheme with $\tau = 3$ ns, at an increased neon pressure $p_{Ne} = 150$ Torr, during a train of pulses, the average lasing power $P_{las} \approx 40-50$ W at $\eta_{las} \approx 2.6\%$ and $\sim$54 W at $\eta_{las} \approx 2.3\%$ was achieved. From the above results, it follows that P_{las} increases by 3 times when using the kivotron for the GDT with $p_{Ne} \approx 45$ Torr and 5 times for $p_{Ne} \approx 150$ Torr, compared to P_{las} for a power circuit with a magnetic compression circuit at a pressure $p_{Ne} \approx$ Tor. The lasing power per unit length at $p_{Ne} \approx 150$ Torr reaches $\sim$100 W m^{-1}, which is twice as good as the power for the active Kristall LT-40Cu element with the addition of hydrogen and a GDT length of 120 cm [13].

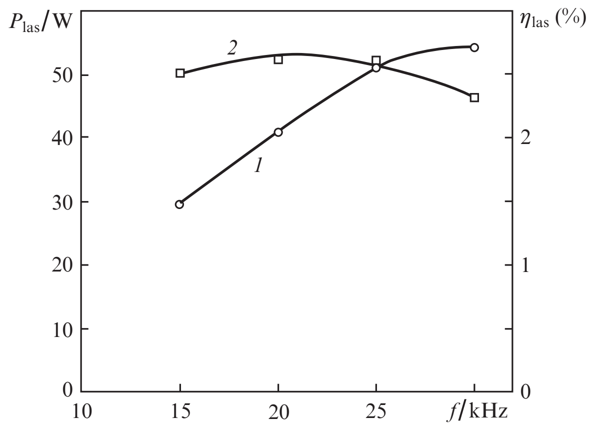

Figure 5. Dependences of (*1*) the average power P_{las} and (*2*) the lasing efficiency η_{las} on the repetition rate f; the scheme with a kivotron, $\tau \approx 3$ ns, $p_{Ne} = 150$ Torr, $U_0 = 19$ kV, $C = 440$ pF.

4. Conclusions

Experimental studies have demonstrated the positive effect of reducing the duration of the voltage pulse leading edge on the energy characteristics of the Cu–Ne laser. With decreasing τ to 1–3 ns, the optimal pulse repetition rate range increases to $f \approx 30$ kHz, the lasing efficiency reaches 3.2%, and the lasing power per unit length at $p_{Ne} \approx 150$ Torr exceeds $\sim$100 W m^{-1}. In this case, the magnitude of the energy input corresponding to the maximum w_{las}, despite the differences in the parameters of the pump pulses, remains almost the same. The obtained results confirm the validity of the previously developed concept of the mechanisms for limiting the frequency and energy characteristics of a copper vapour laser [21, 22, 24, 25].

Therefore, we can expect a further significant improvement in its output characteristics with the improvement of the pump generator.

Acknowledgements. The study was supported by the Russian Foundation for Basic Research (Grant No. 17 – 08 – 00121).

References

1. Grigoryants A.G., Kazaryan M.A., Lyabin N.A. *Lazernaya pretsizionnaya obrabotka materialov* (Laser Precision Micromachining of Materials) (Moscow: Fizmatlit, 2016).
2. Soldatov A.N., Mirza S.Yu., Polunin Yu.P., Reimer I.V., Shumeiko A.S., Yudin N.A. *Steklo i Keramika*, (11), 3 (2014).
3. Peng Q., Juzeniene A., Chen J., Svaasand L.O., Warloe T., Giercksky K.-E., Moan J. *Rep. Prog. Phys.*, **71**, 056701 (2008).
4. Kireev S.V., Shnyrev S.L., Simanovsky I.G., Suganeev S.V. *Laser Phys. Lett.*, **11**, 095701 (2014).
5. D'yachkov A.B., Gorkunov A.A., Labozin A.V., Mironov S.M., Panchenko V.Ya., Firsov V.A., Tsvetkov G.O. *Quantum Electron.*, **48**, 75 (2018) [*Kvantovaya Elektron.*, **48**, 75 (2018)].
6. Abramov D.V., Arakelyan S.M., Klimovsky I.I., Kucherik A.O., Prokoshev V.G. *J. Opt. Technol.*, **74** (8), 569 (2007) [*Opt. Zh.*, **74** (8), 73 (2007)].
7. Buzhinsky R.O., Zemskov K.I., Isaev A.A., Vlasov A.V., Ralchenko V.G. *Instrum. Exp. Tech.*, **53** (2), 301 (2010) [*Prib. Tekh. Eksp.*, (2), 156 (2010)].
8. Osipov V.V., Evtushenko G.S., Lisenkov V.V., Platonov V.V., Podkin A.V., Tikhonov E.V., Trigub M.V., Fedorov K.V. *Quantum Electron.*, **46**, 821 (2016) [*Kvantovaya Elektron.*, **46**, 821 (2016)].
9. Trigub M.V., Platonov V.V., Evtushenko G.S., Osipov V.V., Evtushenko T.G. *Vacuum*, **143**, 486 (2017).
10. *Methods and Instruments for Visual and Optical Diagnostics of Objects and Fast Processes*. Ed. by G.S. Evtushenko (Nova Science Publishers, Inc., 2018).
11. Nekhoroshev V.O., Fedorov V.F., Evtushenko G.S., Torgaev S.N. *Quantum Electron.*, **42**, 877 (2012) [*Kvantovaya Elektron.*, **42**, 877 (2012)].
12. Evtushenko G.S., Shiyanov D.V., Gubarev F.A. *Lazery na parakh metallov s vysokimi chastotami sledovaniya impul'sov* (High-Pulse-Repetition-Rate Metal Vapour Lasers) (Tomsk: Izd-vo Tomsk Polytechnic University, 2010).
13. Grigor'yants A.G., Kazaryan M.A., Lyabin N.A. *Lazery na parakh medi* (Copper Vapour Lasers) (Moscow: Fizmatlit, 2005).
14. Batenin V.M., Boichenko A.M., Buchanov V.V., Kazaryan M.A., Klimovskii I.I., Molodykh E.I. *Lazery na samoogranichennykh perekhodakh atomov metallov – 2* (Lasers on Self-Terminating Transitions of Metal Atoms – 2) (Moscow: Fizmatlit, 2009) Vol. 1.
15. Batenin V.M., Bokhan P.A., Buchanov V.V., Evtushenko G.S., Kazaryan M.A., Karpukhin V.T., Klimovskii I.I., Malikov M.M. *Lazery na samoogranichennykh perekhodakh atomov metallov – 2* (Lasers on Self-Terminating Transitions of Metal Atoms – 2) (Moscow: Fizmatlit, 2011) Vol. 2.
16. Little C.E. *Metal Vapour Lasers: Physics, Engineering and Applications* (Wiley-VCH, 1999).
17. Shiyanov D.V., Evtushenko G.S., Sukhanov V.B., Fedorov V.F. *Quantum Electron.*, **32**, 680 (2002) [*Kvantovaya Elektron.*, **32**, 680 (2002)].
18. Le Guadec E., Coutance P., Bertrand G., Peltier C. *IEEE J. Quantum Electron.*, **35**, 1616 (1999).
19. Marshall G.D., Coutts D.W. *IEEE J. Sel. Top. Quantum Electron.*, **6**, 623 (2000).
20. Soldatov A.N., Fedorov V.F. *Sov. Phys. J.*, **26** (9), 844 (1983) [*Izv. Vyssh. Uchebn. Zaved., Ser. Fiz.*, **26** (9), 80 (1983)].
21. Bokhan P.A., Gerasimov V.A., Solomonov V.I., Scheglov V.B. *Sov. J. Quantum Electron.*, **8**, 1220 (1978) [*Kvantovaya Elektron.*, **5**, 2162 (1978)].
22. Bokhan P.A., Zakrevskii D.E. *Quantum Electron.*, **32**, 602 (2002) [*Kvantovaya Elektron.*, **32**, 602 (2002)].
23. Bokhan P.A., Zakrevskii D.E., Lavrukhin M.A., Lyabin N.A., Chursin A.D. *Quantum Electron.*, **46**, 100 (2016) [*Kvantovaya Elektron.*, **46**, 100 (2016)].
24. Batenin V.M., Klimovskii I.I., Selezneva L.A. *Teplofiz. Vysok. Temp.*, **18**, 707 (1980).
25. Bokhan P.A., Gugin P.P., Zakrevskii D.E., Kazaryan M.A., Lavrukhin M.A., Lyabin N.A. *Quantum Electron.*, **43**, 715 (2013) [*Kvantovaya Elektron.*, **43**, 715 (2013)].
26. Soldatov A.N., Fedorov V.F., Yudin N.A. *Quantum Electron.*, **24**, 677 (1994) [*Kvantovaya Elektron.*, **21**, 733 (1994)].
27. Yurkin A.A. *Quantum Electron.*, **46**, 301 (2016) [*Kvantovaya Elektron.*, **46**, 301 (2016)].
28. Bokhan P.A., Gugin P.P., Zakrevskii D.E., Lavrukhin M.A. *Tech. Phys.*, **60** (10), 1464 (2015) [*Zh. Tekh. Fiz.*, **85** (10), 50 (2015)].
29. Bokhan P.A., Gugin P.P., Zakrevskii D.E., Lavrukhin M.A. *Tech. Phys.*, **60** (10), 1472 (2015) [*Zh. Tekh. Fiz.*, **85** (10), 58 (2015)].
30. Bokhan P.A., Gugin P.P., Lavrukhin M.A., Schweigert I.V., Alexandrov A.L., Zakrevsky Dm.E. *J. Phys. D: Appl. Phys.*, **51**, 404002 (2018).
31. Borovich B.L., Yurchenko N.I. *Sov. J. Quantum Electron.*, **14**, 1391 (1984) [*Kvantovaya Elektron.*, **11**, 2081 (1984)].
32. Carman R.J., Brown D.J.W., Piper I.A. *IEEE J. Quantum Electron.*, **30**, 1876 (1994).