Commercial sealed-off copper-vapor lasers of crystal type with the enhanced efficiency and output power

N.A. Lyabin

State Scientific Production Enterprise "Istok," Fryazino, Moscow Region

Received January 27, 2000

The results of experimental studies on enhancing the efficiency and output power of commercial repetitively pulsed copper-vapor lasers are presented. Owing to designing, technological, and circuitry innovations, the laser efficiency at the generator operation was increased up to 1–1.2% as referred to power consumed from a rectifier and up to 1.4–1.6% if referred to the power deposited into the active element. The possibility of increasing the efficiency up to 1.8 and 2.9%, respectively, is demonstrated. In the amplifier operation mode the efficiency and power were 1.2–1.3 times higher as compared with that in the generator operation mode. In the generator operation mode the output power from a Crystal LT–30 Cu active element with the active (working) medium volume of 250 cm^3 achieved 37 W, while in the amplifier mode it was 44 W. For other active elements these parameters had the following values: for Crystal LT–40 Cu 350 cm^3 in volume – 44 and 60 W and for Crystal LT–50 Cu 900 cm^3 in volume – 55 and 70 W, respectively.

Introduction

Metal-vapor lasers are now widely used in scientific research, engineering, and medicine. Their most advantageous performance characteristics are high efficiency, output power, and radiation quality. A copper-vapor pulsed laser is the most effective and most widely used device of this class. This laser operates in the visible spectral region at the wavelength of 0.51 and 0.58 μm.

This paper presents the results of experimental studies on enhancing the efficiency and output power of the sealed-off self-heating repetitively pulsed copper-vapor laser at a relatively high pump power. There are many papers[1–12] in the literature that are devoted to the problem of increasing the efficiency and output power of lasers of this type. The maximum efficiency (1%) was experimentally achieved for the first time in Ref. 2.

Foreign papers report sufficiently reliable operation of high-power flow-through lasers with the efficiency about 1% and higher with the discharge channel of 6 to 12 cm in diameter.[6,7] The authors of these papers believe that enhancement of the output power by increasing the volume of the active medium is the most effective way from the practical point of view.

Experimental setup

A commercially available GL–201 sealed-off self-heating active element (AE) with the discharge channel of 2 cm in diameter, electrode separation of 93 cm, and the active medium volume of 250 cm^3 was used as a basic active element.[8–10] The modified version of the AE with the same geometry is called Crystal LT–30 Cu. The modernization consisted in improved design and production technology. Most parts, dimensions of the AE, and dimensions of the discharge channel remained unchanged. Such a modification resulted in a 1.5 times increase in the laser output power and the efficiency under the same excitation conditions.

The AE was heated and excited from a pulsed power supply based on a TGI1–2000/35 water-cooled hydrogen thyratron as a switch.[13] The first part of the experiments was conducted with a modulator of the traditional circuitry (Fig. 1*a*), in which the thyratron, energy storage capacitor, and AE form a single discharge circuit.[8,9] Therefore, in this case the characteristics of pump pulses depended directly on the thyratron parameters, and the total duration of current pulses varied from 200 to 350 ns depending on the capacitor capacity and the pulse repetition frequency. To achieve a higher efficiency and output power, the duration should be decreased down to the lifetime of the population inversion.[8]

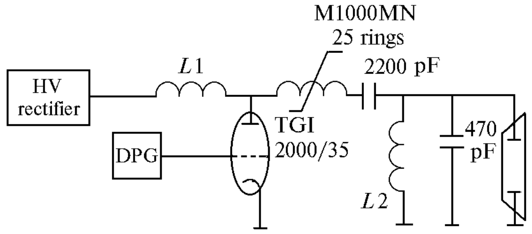
In the second part of the experiments, the more efficient excitation scheme was used, namely, the scheme with the capacitive voltage doubling and nonlinear saturable choke in the discharge circuit as a magnetic compression unit (Fig. 1*b*).[14]

We used a plano-spherical optical cavity with a totally reflecting mirror having the radius of curvature about 3 m (ρ = 99%).

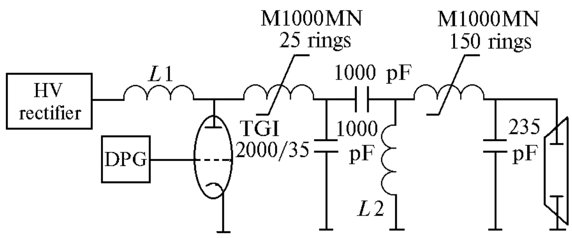
In the experiments we measured the total mean output power and the power at separate wavelengths, the temperature of the discharge channel, and power losses in the thyratron with a thyractor[13] and in the pulse compression unit. The oscillograms of the pump voltage, current, and radiation pulses were recorded. The output power was measured with the use of a TI–3 power converter and M136 millivoltmeter; the

0235-6880/00/03 234-07 $02.00

temperature of the discharge channel was measured by a "Promin" optical pyrometer. A compensated voltage divider was used to record voltage pulses, and a Rogowski loop and S1–75 oscilloscope were used to record current pulses. Radiation pulses were measured with a FEK–14K coaxial photodetector and S1–75 oscilloscope. The power losses were estimated by the calorimetric method from heating and consumption of the cooling water.



a



b

Fig. 1. Electric circuits of a pulsed power supply.

Results of studies of a Crystal LT-30 Cu active element

Traditional scheme of a power supply

Figure 2 shows the experimental characteristics of the laser as functions of the power from the rectifier in the stationary thermal regime for the AE of Crystal LT–30 Cu type at the pulse repetition frequency $f = 10$ kHz, buffer gas (neon) pressure $p_{Ne} = 150$ mm Hg, capacity of the energy storage capacitor $C_s = 2200$ pF, and the peaking capacitor $C_p = 470$ pF. It is seen that lasing appears at the discharge channel temperature about 1300°C ($P_{rect} = 1.6$ kW), that is, at the concentration of copper atoms about $0.7 \cdot 10^{14}$ cm^{-3} ($p_{Cu} \approx 0.01$ mm Hg) (Fig. 3).[15] The maximum output power of 20 W (curve *1*) is achieved at the channel temperature of 1550°C ($P_{rect} = 2.7$ kW), which corresponds to the concentration of copper atoms of $2 \cdot 10^{15}$ cm^{-3} ($p_{Cu} \approx 0.35$ mm Hg). At this point the power emitted at separate wavelengths is also maximum: 11 W (55%) at $\lambda = 0.51$ μm and 9 W (45%) at $\lambda = 0.58$ μm. As the temperature increases above 1550°C, the power at the green line (0.51 μm, curve *2*) falls off more rapidly than that at the yellow line (curve *3*). This is connected with the fact that the lower (metastable) atomic energy level of the yellow line transition is higher than that of the green line, and, correspondingly, it is less subject to thermal population.[4] Under these conditions the lasing is fully terminated at the channel temperature about 1650°C ($P_{rect} = 3.2$ kW) at the green line and at 1700°C ($P_{rect} = 3.4$ kW) at the yellow line.

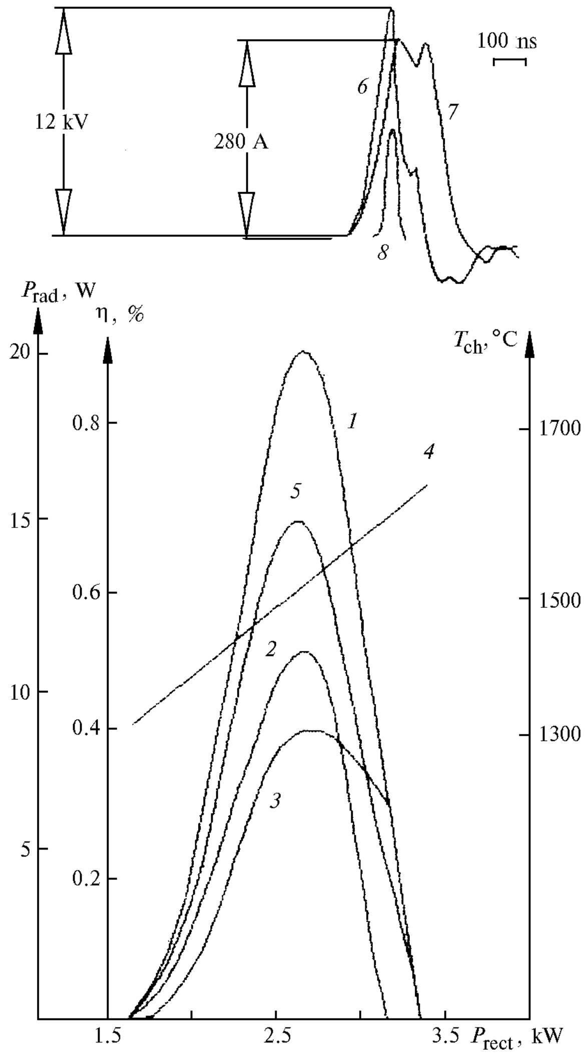


Fig. 2. Total mean output power (*1*), power at $\lambda = 0.51$ (*2*) and 0.58 μm (*3*), temperature of AE discharge channel (*4*), and efficiency (*5*) vs. power from the rectifier with the traditional scheme for a Crystal LT–30 Cu active element.

The oscillograms *6*, *7*, and *8* shows the voltage, current, and radiation pulses in the AE optimal thermal regime, namely, the regime providing for maximum output power. The duration of current pulses (at the base) was ≈ 300 ns, what is roughly seven times longer than the emission pulse (curve *8*), i.e., the inversion lifetime. For this reason, highly effective operation of laser cannot be expected with the use of the traditional excitation scheme. The maximum efficiency by power consumed from a rectifier in this experiment was only 0.75%.

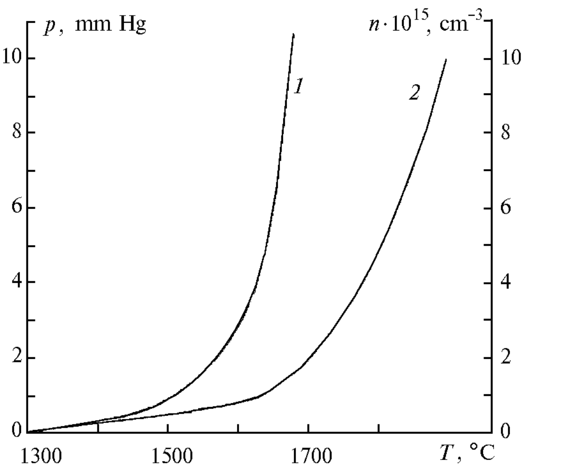


Fig. 3. Temperature dependence of the partial pressure (*1*) and concentration of copper atoms (*2*).

To extend the range of excitation conditions, the studies were conducted at the capacity of the energy storage capacitor C_s = 1650 and 3300 pF and the buffer gas (neon) pressure from 60 to 250 mm Hg. The results of these studies are given in Table 1.

Table 1

p, mm Hg	60	100	150	250
C = 1650 pF, P_{rect} = 3 kW				
T_{ch}, °C	1590	1585	1580	1560
P_{rad}, W	25.0	24.6	23.3	22.8
efficiency, %	0.83	0.82	0.78	0.76
C = 3300 pF, P_{rect} = 2.45 kW				
T_{ch}, °C	1600	1555	1545	1520
P_{rad}, W	18.3	18.0	17.0	15.0
efficiency, %	0.75	0.73	0.69	0.61

The following conclusions can be drawn based on analysis of data presented in Table 1. As the capacity of the energy storage capacitor decreases, the working temperature of the discharge channel, output power, and efficiency increase. As this takes place, the pump pulses become longer and their amplitude increases. For example, if at C = 3300 pF and p_{Ne} = 60 mm Hg the current pulse duration is about 350 ns, the output power is 18.3 W, and the efficiency is 0.75%, then at C = 1650 pF they are, respectively, 250 ns, 25 W, and 0.83%.

At the increasing pressure, the characteristics of the pump pulses worsen and the energy characteristics of the output radiation fall off. The power at the green line falls off faster than that at the yellow line. This is explained by the higher energy of its upper (resonance) level. However, the better are the excitation conditions, the less is the decay of the power and efficiency. If at C_s = 1650 pF the power and efficiency decreased less than 1.1 times, as the pressure increased from 60 to 250 mm Hg, then at C_s = 3300 pF they decreased more than 1.2 times. Therefore, the effective operation of the laser at high pressure is possible with short pump pulses, and this fact is important from the viewpoint of increasing the AE service life. The higher is the buffer gas pressure, the lower is the consumption of the active matter per unit time and slower the optical windows are dusted.

Use of the capacitive voltage doubling and magnetic compression unit

As the voltage is doubled, the duration of excitation pulses is almost halved. Figure 4 shows the energy characteristics of the laser in the stationary thermal regimes as functions of the power consumed from the rectifier and the oscillograms of the pump pulses in the regime of maximum output power (optimal thermal regime) at the pulse repetition frequency f = 10 kHz, the charge capacity of the energy storage capacitor C_s = 1000 + 1000 = 2000 (pF), the capacity of the peaking capacitor C_p = 235 pF, and the neon partial pressure p_{Ne} = 150 mm Hg. The duration of the voltage pulse (curve *6*) was about 100 ns and the amplitude was 21 kV. For the current pulse (curve *7*) these parameters were 160 ns and 380 A, respectively. As in the traditional scheme, lasing (curve *1*) appears at the discharge channel temperature about 1300°C (curve *4*) (P_{rect} = 2.2 kW). The maximum values of the output power (≈ 37 W) and the efficiency (≈ 1%) (curve *5*) are achieved at the temperature higher by 80°C, i.e., at T_{ch} = 1630°C (P_{rect} = 3.6 kW). At this temperature the pressure and concentration of copper atoms are 0.85 mm Hg and $5 \cdot 10^{15}$ cm^{-3}, respectively.[14] Thus, compressing doubly the pump pulses at the generator operation resulted in a 1.8 times increase of the output power (at p_{Ne} = 150 mm Hg and C_s = 2200 pF), while the efficiency referred to power consumption from the rectifier increased by 1.4 times. At this point the power at separate wavelengths (curves *2* and *3*) takes not only maximum, but almost the same values. The termination of lasing occurs at T_{ch} = 1750°C at the green line (curve *2*) and at T_{ch} = 1800°C at the yellow line.

To assess the feasibility of further enhancement of the efficiency, the dependence of instantaneous values of the mean output power on the consumed power was measured at the constant temperature of the discharge channel (Fig. 5, curve *1*). The main idea of this experiment was in a sharp change of the rectifier power from the optimal working point (P_{rect} = 3.6 kW; T_s = 1630°C; P_{rad} = 37 W; see Fig. 3) by regulating the voltage and measuring the output power. The power was measured with a TI–5 power meter having the time constant of no more than 6 s. The transition to a new regime took only several seconds, what did not lead to a sharp change in the thermal regime of the AE, which possessed high thermal capacity. Moreover, after transition the changed value of the output power remained at the same level for a long time. This, in turn, indicated that the initial temperature of the discharge channel and, correspondingly, the concentration of the active matter kept unchanged. For example, at P_{rect} = 2.8 and 4.4 kW this time was about

3 min, and at P_{rect} = 1 kW it was roughly 0.5 min. This was enough to record the main parameters of the excitation and lasing.

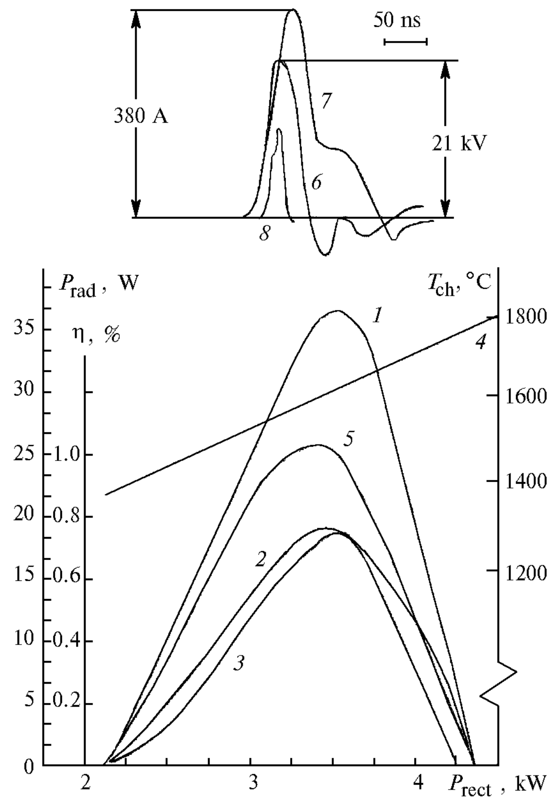


Fig. 4. Total mean output power (*1*), power at separate wavelengths: 0.51 (*2*) and 0.58 μm (*3*), temperature of the discharge channel (*4*), efficiency (*5*) vs. power from rectifier with voltage doubling scheme for Crystal LT–30 Cu. Oscillograms of voltage (*6*), discharge current (*7*), and radiation pulses (*8*) of AE.

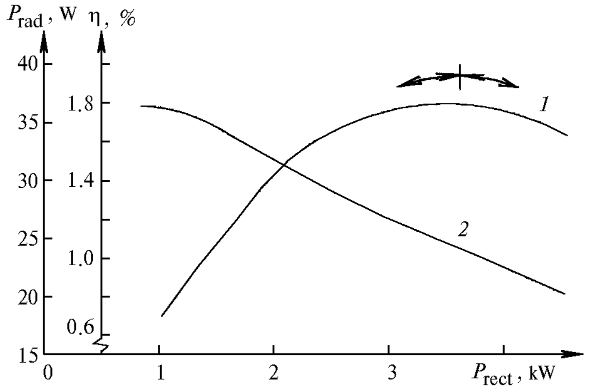


Fig. 5. Instantaneous values of the output power (*1*) and efficiency (*2*) vs. power consumed from rectifier with the voltage doubling scheme at T_{ch} = 1630°C for Crystal LT-30 Cu gas-discharge tube.

From Fig. 5 it is seen that as the rectifier power changes from the optimal value (P_{rect} = 3.6 W) toward lower values, the output power (curve *1*) decreases, whereas the efficiency increases achieving its maximum value of 1.8% at P_{rect} = 1 kW. At the rectifier power higher than the optimal values the efficiency decreases. This is connected, first, with the decreasing output power because of the "overheat" of the active medium and, second, with the nonlinear growth of power losses in the thyratron switch.

Thus, it follows from the results of this experiment that the efficiency can be increased at the power less than optimal one, but under the condition of high temperature of the discharge channel, i.e., at high concentration of copper vapor. To provide the high temperature of the discharge channel at a relatively low power, either better thermal insulation of the AE or additional indirect heating is needed. These conclusions were confirmed by the experiment with the AE having an improved thermal insulation, whose efficiency in the optimal thermal regime (P_{rect} = 2 kW) was 1.2–1.3%.

To assess the laser efficiency more completely, it was estimated by the power deposited into the AE. Toward this end, the power losses in the thyratron-based circuit with a thyractor (Fig. 6, curves *1* and *2*), capacitive voltage doubling, and the magnetic compression (curve *3*) were measured calorimetrically.

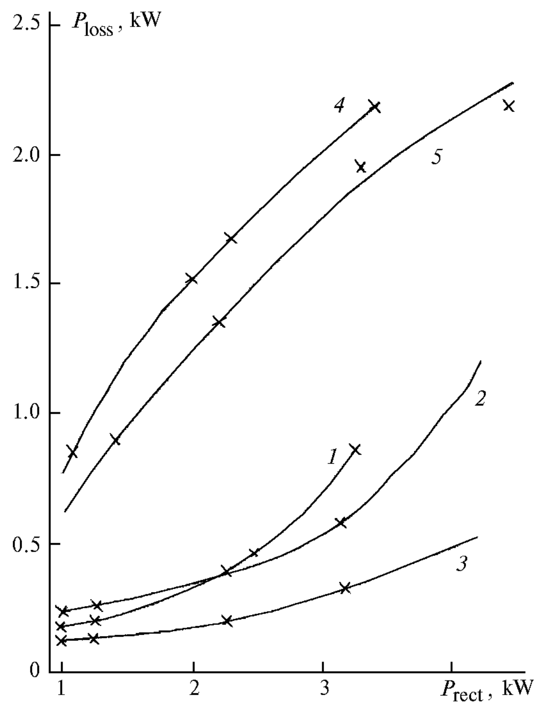


Fig. 6. Dependence of power loss in a thyratron with thyractor (*1*, *2*), magnetic compression unit (*3*), and AE (*4*, *5*) on power consumed from rectifier in the case of the traditional excitation scheme (*1*, *4*) and voltage doubling scheme (*2*, *3*, *5*) for Crystal LT–30 Cu gas-discharge tube.

The thyractor, which is a nonlinear choke, is intended for decreasing the start-up losses in the thyratron.[12] It is connected directly to the thyratron anode. According to the measurements by Fogelson,[13] the power losses in the rest elements of the charge-discharge circuit are about 10%. The power deposited into the AE (curves *4* and *5*) was calculated as the difference between the power from the rectifier and the total lost power. The circumstance that the curve *4* is above the curve *5* (by 0.15–0.2 kW) is explained by higher total loss in the case of the voltage doubling scheme. It is important that at $P_{rect} > 2.2$ kW the power loss in the thyratron with the voltage doubling scheme is lower (curve *2*), and therefore in this case the thyratron is operated in a light duty regime at high switched power, that is, its reliability increases.

Figure 7 shows the AE efficiency curves. As is seen, the maximum efficiency achievable with the traditional excitation scheme in the optimal stationary thermal regime (T_{ch} = 1550°C) was ≈ 1.1% (curve *1*) (P_{rect} = 1.84 kW), in the transient regimes it was ≈ 1.2% (curve *3*) (P_{rect} = 1.4 kW), and with the voltage doubling scheme it was ≈ 1.84% (curve *2*) (P_{rect} = 2.0 kW) and 2.9% (curve *4*) (P_{rect} = 0.7 kW), respectively.

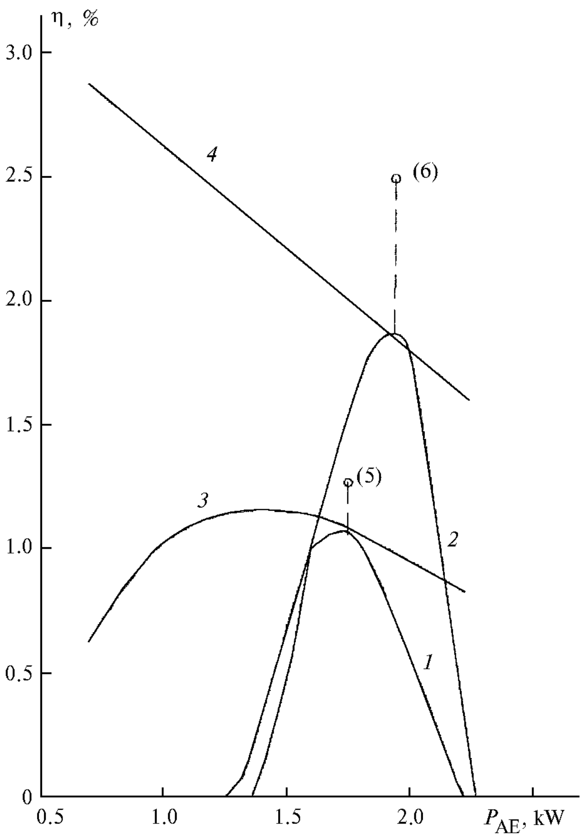


Fig. 7. Dependence of the efficiency in a stable thermal (*1*, *2*) and transient (instantaneous) (*3*, *4*) regimes on power deposited into the AE with the traditional excitation scheme (*1*, *3*) and voltage doubling scheme (*2*, *4*) for Crystal LT–30 Cu gas-discharge tube.

When the AE under study was used as a radiation amplifier in the system “master oscillator – spatial filter – amplifier” (Ref. 10), the output power increased from 20 to 23 W as compared with that in the generator operation with the traditional excitation scheme, while the efficiency increased from 1.08 to 1.24% (point 5, Fig. 7). As compared to the voltage doubling scheme, the power increased from 37 to 46.5 W and the efficiency increased from 1.84 to 2.31% (point 6, Fig. 7). Thus, the double compression of pump pulses, which caused the 2.5 times increase in the concentration of copper atoms (due to an increase in the working temperature from 1550°C to 1630°C) led to the doubling of the output power (46.5/23 ≈ 2) and the AE efficiency (2.33/1.22 ≈ 2). For further enhancement of the laser output power, we studied active elements with large volume of the active (working) medium V_{ac} = 350 and 900 cm^3. The active element Crystal LT–30 Cu served the basis for creation of these devices.

Results of studies of the Crystal LT–40 Cu and Crystal LT–50 Cu active elements

A Crystal LT–40 Cu AE with V_{ac} = 350 cm^3 in its design differs from the Crystal LT–30 Cu only by longer (by 30 cm) discharge channel (2 cm in diameter), what corresponds to the electrode separation of 123 cm. A Crystal LT–50 Cu AE with V_{ac} = 900 cm^3 has the same dimensions as Crystal LT–40 Cu while having a 1.6 times wider discharge channel (32 mm in diameter). The AE was excited from the power supply, whose modulator was built following the voltage doubling circuitry (see Fig. 1*b*). The optical cavity was of a plano-spherical type with the totally reflecting mirror having 3.5 m radius of curvature. The mean output power (generator operation) achieved 40–44 W with the Crystal LT–40 Cu AE and 50–55 W with the Crystal LT–50 Cu AE at the efficiency referred to the rectifier power about 1%, for the amplifier operation it was 55–60 and 65–70 W, respectively. For making comparative analysis the main parameters of the devices under study are given in Table 2.

For these AEs Figure 8 shows the dependence of the total mean output power on the neon partial pressure. As the pressure changed from 50 to 760 mm Hg, the output power for Crystal LT–30 Cu AE (curve *1*) decreased from 33 to 21.5 W (≈ 38%), for Crystal LT–40 Cu (curve *2*) it fell from 44 down to 25 W (≈ 43%), and for Crystal LT–50 Cu (curve *3*) it changed from 56 to 29 W (≈ 48%). This decrease is caused, first of all, by a decrease in the output power at the green line. From a comparison of the curves it follows that as the discharge channel becomes longer and wider, i.e., the volume of active medium increases, the relative decrease of the power becomes sharper. Therefore, AEs with a large volume usually have lower working pressure. If in the AE of Crystal LT–30 Cu type the value of the working pressure is 250 mm Hg, then for Crystal LT–50 Cu it is 100–150 mm Hg. However, on the other hand, the obtained results indicate that the copper-vapor laser can operate at the pressure close to the atmospheric one and deliver the power at the level of tens of watts. The high pressure of the buffer gas is one of the main ways to increase the service life of a sealed-off AE.

Table 2

Parameters of AE	d, cm	l, cm	V_{ac}, cm^3	P_{Ne}, mm Hg	f, kHz	P_{rect}, kW	P_{rad}, W Generator	P_{rad}, W Amplifier	$P_{max}/V_{ac\ ampl}$, W/cm^3
GL–201	2	93	250	250	10	3.2 – 3	23 – 25	25 – 28	0.11
Crystal LT–30 Cu	2	93	250	150 – 250	10	3.2 – 3.6	32 – 37	40 – 44	0.18
Crystal LT–40 Cu	2	123	350	180	10	4.0 – 4.4	40 – 44	55 – 60	0.18
Crystal LT–50 Cu	3.2	123	900	100 – 150	10	5.0 – 5.5	50 – 55	65 – 70	0.08

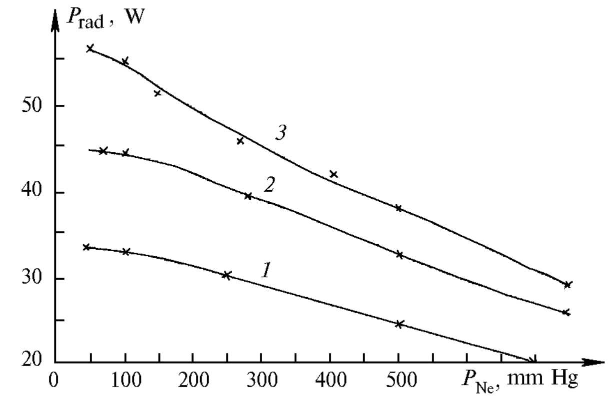


Fig. 8. Dependence of the total mean output power of Crystal LT–30 Cu AE (*1*), Crystal LT–40 Cu (*2*), and Crystal LT–50 Cu (*3*) on neon pressure at power consumed from the rectifier P_{rect} = 3.2, 4.0, and 5.5 kW and pulse repetition frequency f = 10 kHz.

The frequency characteristics of the AE (Fig. 9) were measured at the circuit parameters being the same as in Fig. 2*b*. As the pulse repetition frequency increased from 10.5 to 20.5 kHz, the output power achieved with a Crystal LT–40 Cu AE (curve *1*) decreased insignificantly, by about 14% (from 44 to 38 W), at the unchanged efficiency at the level of 1%, in Crystal LT–50 Cu it decreased by 13% (from 55 to 48 W) also with the unchanged efficiency about 1%. As the frequency decreased, a sharp decrease in the output power was observed due to the increasing losses in the thyratron (because of the increasing anode voltage) and the corresponding decrease of the discharge channel temperature. As the frequency decreased from 10.5 to 6 kHz, the power obtained with a Crystal LT–40 Cu AE fell down by 24% (to 33.5 W), for Crystal LT–50 Cu it also decreased by 24% (to 42 W), and the efficiency decreased from 1 to 0.75%.

When the capacity of the energy storage capacitor C_s = 1000 + 1000 = 2000 (pF) and the peaking capacitor C_p = 235 pF was changed to C_s = 1500 + + 1500 = 3000 (pF) and C_p = 300 pF at the frequency of 8 kHz, the output power and the efficiency were almost the same (points *4* and *5*) as at 10.5 kHz. As the experience shows, to obtain the maximum power, each frequency point should be optimized not only by the electrical parameters of the circuit elements (capacity and inductance) but also by the neon pressure.

The AE of the Crystal LT–50 Cu type served a basis for constructing a mockup with a 30-cm-longer discharge channel (the electrode separation of 150 cm, V_{ac} = 1200 cm^3). The mockup was partially studied. The output power was about 57 W in the generator operation mode and about 80 W in the amplifier operation.

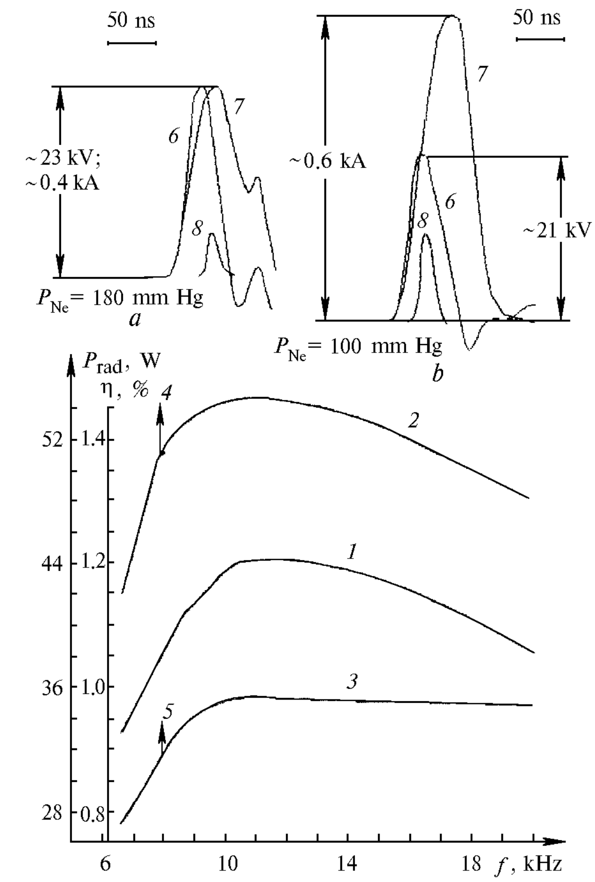


Fig. 9. Dependence of the total mean output power for Crystal LT–40 AE (*1*) and Crystal LT–50 Cu AE (*2*) and efficiency (*3*) on the pulse repetition frequency. Oscillograms of voltage (*6*), discharge current (*7*), and radiation pulses (*8*) for Crystal LT–40 Cu AE (*a*) and Crystal LT–50 Cu AE (*b*) at a pulse repetition frequency f = 10.5 kHz.

The AE of the Crystal LT–30 Cu type has been used for designing commercial sealed-off gold-vapor Crystal LT–4 Au (λ = 0.628 μm) AE with the output power up to 6 W at the neon pressure of 200–250 mm Hg, and the pulse repetition frequency of 10–20 kHz. The maximum power of 8.5 W was obtained upon optimization of the conditions of AE excitation at the neon pressure of 50 mm Hg

The guaranteed minimum service life is no less than 500 h for the Crystal LT–50 Cu AEs and Crystal LT–4 Au and no less than 1000 h for Crystal LT–30 Cu and Crystal LT–40 Cu AEs. The ways for further increase of the AE service life are now mainly determined, and experimental tests are being conducted.

References

1. A.A. Isaev and M.A. Kazaryan, Kvant. Elektron. **4**, 451 (1977).
2. A.A. Isaev, M.A. Kazaryan, and G.G. Petrash, Pis'ma Zh. Exp. Teor. Fiz., No. 16, 40 (1972).
3. A.A. Isaev and G.Yu. Lemerman, Kvant. Elektron. **4**, 1413 (1977).
4. V.M. Batenin, I.I. Klimovskii, and L.A. Selezneva, Teplofizika Vysokikh Temperatur, No. 18, 707 (1980).
5. P.A. Vokhmin and I.I. Klimovskii, Teplofizika Vysokikh Temperatur, No. 16, 1080 (1980).
6. M.I. Kusher and B.E. Warner, J. Appl. Phys. **54** (6), June 1983.
7. C.E. Webb, in: *Proc. of the International Conference on Lasers 87*.
8. V.V. Zubov, N.A. Lyabin, V.I. Mishin, M.L. Muchnik, G.D. Parshin, E.Ya. Chernyak, and A.D. Chursin, Kvant. Elektron. **10**, 1908 (1983).
9. V.P. Belyaev, V.V. Zubov, A.A. Isaev N.A. Lyabin, Yu.F. Sobolev, and A.D. Chursin, Kvant. Elektron. **12**, 74 (1985).
10. V.V. Zubov, N.A. Lyabin, and A.D. Chursin, Kvant. Elektron. **13**, 2431 (1986).
11. V.V. Zubov, N.A. Lyabin, and A.D. Chursin, Kvant. Elektron. **17**, No. 1, 28–31 (1990).
12. V.V. Zubov, A.D. Chursin, M.A. Lesnoy, and S.A. Ugolnicov, Proc. SPIE **2110**, 78–89 (1993).
13. T.B. Fogelson, L.N. Breusova, and L.N. Vagin, *Pulsed Hydrogen Thyratrons* (Sov. Radio, Moscow, 1971).
14. V.P. Ageev, V.V. Atezhev, V.S. Bukreev, et al., Zh. Tekh. Fiz. **56**, 1387 (1986).
15. V.F. Kovalenko, *Thermophysical Processes and Electrovacuum Devices* (Sov. Radio, Moscow, 1975).