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Copper vapour laser with an efficient semiconductor pump generator having comparable pump pulse and output pulse durations

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Abstract. **We report the results of experimental studies of a copper vapour laser with a semiconductor pump generator capable of forming virtually optimal pump pulses with a current rise steepness of about 40 A ns^{-1} in a KULON LT-1.5CU active element. To maintain the operating temperature of the active element's channel, an additional heating pulsed oscillator is used. High efficiency of the pump generator is demonstrated.**

Keywords: *copper vapour laser, optimal pump pulses, pumping efficiency, semiconductor pump generator, matching, lasing.*

1. Introduction

Despite great progress in studying and designing copper vapour lasers (CVLs) [1] that are promising from the viewpoint of their potential parameters among pulsed lasers operating in the visible range, some of the key parameters and specifications of CVLs being developed are still far from their potentially attainable values. For example, the lasing efficiency is much less as compared with its attainable limit because of the problems associated with the development of nearly optimal pump sources and their matching to the laser tube [2].

For CVLs with an active element (AE) representing a sealed-off self-heating gas-discharge laser tube, the requirements for optimal pumping to ensure a high lasing efficiency are well known [3]: at the lowest possible rise time duration, the discharge current pulse duration should be close to that of the output laser pulse (10 – 50 ns), while the repetition rate of high-voltage pump pulses should be sufficient to heat up the discharge channel to the operating temperature. Thus, the lower metastable laser levels should effectively relax during an inter-pulse interval. However, with decreasing, by some means or other, pump pulse rise time and duration, a significant increase in the AE power consumption is observed, which is associated with an increase in scattering of high-frequency electromagnetic radiation on the AE and in the power supply circuit. As a consequence, attempts of development and application of pump generators with improved performance often encounter difficulties in achieving the operating temperature in the AE gas discharge channel [4]. As to the self-heating tubes, this problem can be solved by applying a relatively low-voltage pulsed discharge synchronised with the pump pulses for additional heating of the gas discharge channel. This approach represents a compromise that allows the laser power and efficiency to be increased at optimum pumping; however, the potentially attainable limiting values of these parameters are not achieved in this case.

Another important problem of designing a CVL is the development of semiconductor pump generators that would be more compact, cheaper and possess a greater service life than the tube and thyratron oscillators, which is particularly important for developing instrumental commercial CVL samples. However, the parameters that have been achieved in implementation of the proposed solutions do not exceed, but are rather inferior to the parameters of the best CVL samples with tube and thyratron oscillators [5 – 7].

This work is aimed at solving the above problems. We present the research results of the CVL operation with a semiconductor power supply, having comparable pump pulse and output pulse durations and additional heating of the AE gas discharge channel by a pulsed discharge. The experiments have been performed using a commercial KULON LT-1.5CU AE manufactured at the 'Istok' Research and Production Enterprise (neon buffer gas pressure of 600 Torr, discharge channel diameter of 0.7 cm, channel length of 17.5 cm, and specified radiation power of 1.5 W).

2. AE power supply circuit

The scheme of the AE power supply circuit is shown in Fig. 1. The circuit forms high-voltage (about 10 kV) pump pulses and heating pulses having an amplitude of several hundred volts, which are combined at the AE electrodes. In this case, the heating pulses are synchronised with the pump pulses in such a way that they can be applied to the AE with a predetermined delay or prior to the pump pulses.

The AE pump generator operates as follows. When switching on the transistor (*5*) by applying a rectangular voltage pulse with duration of $\pi(LC)^{1/2}$ to the gate electrode, the capacitance C is charged up to about doubled rectified mains voltage. Immediately after that thyristors (*3*) open, and the capacitance C rapidly discharges on the primary coil of the transformer (*4*). Herewith, two thyristor assemblies (*3*) are triggered sequentially, which ensures reliable operation at frequencies up to 13 kHz. To generate high-voltage pulses with a steep edge, a well-known phenomenon of sharp recovery of the diode conduction when passing the reverse current is used [8]. In the circuit, at a direct current in the secondary circuit of the block (*4*), the capacitance C_1 rapidly charges with simultaneous saturation of the core in the block (*4*). At a sudden breakage of the reverse current in the chain (*6*), a high-volt-

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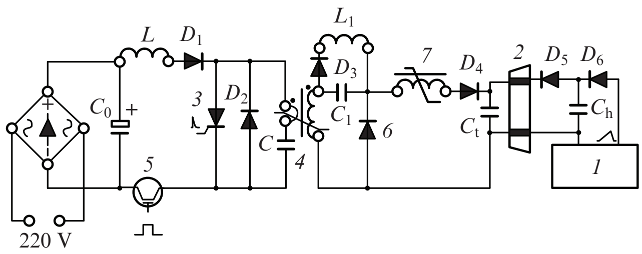

Figure 1. Schematic of the AE power supply circuit: (*1*) heating pulse generator; (*2*) KULON LT-1.5CU active element; (*3*) two assemblies of 12 KU221A(B,V) thyristors connected in parallel; (*4*) assembly of four pulse transformers (the ratio of turns is 1/3, the cores of eight ferrite M1000NM rings with dimensions of 20 × 10 × 8 mm, the primary windings are connected in parallel, the secondary ones – in series); (*5*) IRG4PH50UD transistor; (*6*) chain of 11 KD203G (D) diodes; (*7*) saturable choke (eight turns of two ferrite M2000NM rings with dimensions of 18 × 8 × 5 mm); (C_1) KVI-3 capacitance (3.3 nF × 10 kV); (C) 4 K78-2 capacitance (0.1 × 1000); (C_h) capacitance (0.1 × 1000); (L) inductance (80 μH); (L_1) inductance (20 μH); (D_1) three FR607 diodes connected in parallel; (D_2, D_4) FR607 diodes; (D_3, D_5) chain of 12 FR607 diodes; (D_6) HER308 diode.

age pulse with a steep edge is formed, and the energy stored in the secondary coil inductance of the block (*4*) is supplied to the AE. The saturable choke (*7*) serves to delay the voltage pulse supply to the AE. Its parameters, along with the capacitances C_t and C_1 to a large extent determine the characteristics of the generated pump pulse. The D_3–L_1 chain serves to employ the energy of the reverse current oscillation in the primary circuit of the block (*4*) for heating the AE.

Typical oscillograms of current pulses in the chain (*6*) and heated AE, recorded by means of a current transformer – Rogowski coil, are presented in Fig. 2.

It is seen that with decreasing C_t, matching between the pump generator and the AE is worsened, but the amplitude and the current rise steepness increase, which leads to an increase in the pump pulse efficiency of the AE and, consequently, in the lasing pulse energy.

The pulsed heating generator (*1*), in synchronisation with the pump pulses, works out microsecond pulses charging the capacitance C_h, which is discharged on the resistance of the decaying plasma of the AE discharge channel, thus heating it. The adjustable power of the generator (*1*) (up to 400 W) is sufficient to heat the AE channel to the maximum permissible temperature of 1600 °C. In the absence of additional heating, the channel is heated up by the pump pulses merely to 1100 °C, while the lasing starts when the temperature of ~1300 °C is reached. The power that the AE power supply consumed from the mains does not exceed 1200 W.

3. Experimental results and discussion

In the experiments, we used a 50-cm-long semi-confocal resonator with a highly reflecting spherical mirror and a plane-parallel glass plate as an output resonator mirror. Laser pulses were recorded by a fast photodiode. The AE gas discharge channel temperature was monitored by a pyrometer. The presence of the heating pulsed generator (*1*) allowed us to operate at different pump pulse parameters, with no worries about reaching the AE operating temperature.

From the engineering viewpoint, it was easier to apply the heating pulses prior to pump pulses, since in this case the impact of the high-voltage and high-frequency pump pulses on the heating circuit operation is less. However, in the course of the experiments, it was quite surprisingly found that such an operation regime has a negative effect on the lasing parameters. It turned out that the supply of the heating pulses a few microseconds ahead of the pump pulses causes a strong reduction both in the lasing power and in the power ratio of the green (510.6 nm) and yellow (578.2 nm) radiation components, up to complete disappearance of the green component in some cases. This is due to the fact that, in the presence of even a small electric field, electrons in the discharge gap quickly gain the energy, which at $T \sim 1600$ °C many times exceeds the equilibrium energy ~0.24 eV of Ne atoms. The process of multiplying the average energy of electrons is characterised by the Townsend energy coefficient η. In the experimental conditions, $\eta \sim 25$ at the heating pulse's voltage amplitude of ~600 V and the ratio of the field intensity to the gas pressure of ~0.06 V cm^{-1} Torr^{-1} [9]. Therefore, the electron energy is definitely sufficient for exciting (populating) the lower metastable laser levels with the energies of ~1.39 and 1.64 eV. The lowest of these levels representing the lower transition level responsible for the green line of lasing is especially strongly populated, which explains its strong suppression. Further experiments were carried out in the regime of supplying the heating pulses with a delay of a few microseconds relative to the pump pulses.

During the experiments, the parameters of the choke (*7*) and capacitances C_1 and C_t were optimised. Obtaining the maximum average power of laser radiation was considered in the first place as a criterion, rather than matching the pump generator with the AE. Optimal capacitance is the resonance capacitance $C_1 \sim C/n^2$, where n is the transformation coefficient of the block (*4*). A decrease in the capacitance C_t improves the pump pulse characteristics and increases the laser pulse energy; however, at the same time, the matching between the pump generator and the AE is worsened and its contribution to heating of the AE channel is reduced. Accordingly, to maintain the channel temperature, it is neces-

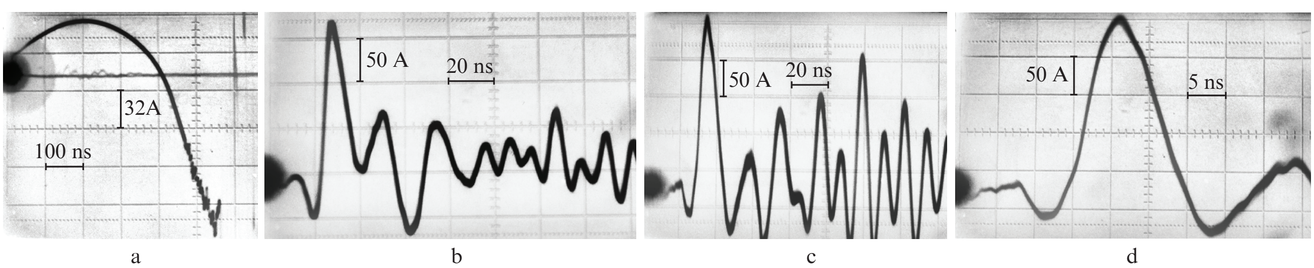

Figure 2. Oscillograms of current pulses in the chain of diodes (*6*) (a) and the AE at C_t = 120 (b) and 70 pF (c, d).

sary to increase the heating generator power. As a result, a weak growth of the average laser radiation power in the case $C_t < 120$ pF was observed, and therefore $C_t \sim 70$ pF was used as a working capacitance. For the choke (*7*), the optimum value of the product of the number of turns N and the core cross-section area S constitutes $\sim$4 cm^2. It should be noted that an increase in NS is accompanied by an increase in thermal load on the diodes (*6*), because the voltage amplitude on the diodes increases at the time instant they restore their conductivity. The result of this is that the pump generator provides almost optimal AE current pulses: rise time $\sim$6 ns, pulse duration at the bottom $\sim$15 ns, steepness of the current rise $\sim$40 A ns^{-1} at the current amplitude up to $\sim$250 A. For comparison, one may bring the parameters of a magnetic-thyristor generator with two sections of magnetic pulse compression, which provides the nameplate power and operation regime of the KULON LT-1.5CU AE from [5]: current pulse duration of 150 ns, amplitude of 150 A, steepness of the current rise $\sim$3.5 A ns^{-1}, pulse repetition rate of 15 kHz, power consumption of the mains up to 1.2 kW.

These experiments, as many other works (see, for example, [10]), have demonstrated a significant impact of the pre-pulse electron density in the discharge gap on the AE pump efficiency. For example, immediately after a small decrease in the pump pulse repetition rate, before the channel temperature drops, a slight increase in the average power of laser radiation is observed. Afterwards, after the power falls, when the temperature decrease is compensated for by the heating gain, the power is restored to its original level. In view of this, the experiments were performed at a single pump pulse repetition rate of $\sim$12.5 kHz. When the heating is switched off, an increase in the radiation power by 20% is observed and, apart from that, the matching between the pump generator and the AE significantly improves. All this is explained by the fact that increasing the repetition rate of the pump pulses or switching off the heating leads to a decrease in the pre-pulse electron density and, consequently, to an increase in the AE voltage amplitude due to a later breakdown of the discharge gap, which in turn causes a more strong avalanche breakdown and results in the growth of the amplitude and current rise steepness. As a result, the pump pulse efficiency and, consequently, the laser pulse energy, increase.

Typical oscillograms of the current and lasing pulses at the average lasing power being close to its maximum are shown in Fig. 3. Temporal characteristics of the current and lasing pulses virtually coincide, and their duration at the half-height is about 9 ns. With increasing temperature of the AE gas discharge channel, the laser radiation power grows, and its decline is not observed even at a certain excess of 1600 °C. This indicates that the metastable levels, which are heavily populated by the impact of the heating generator pulses, become almost entirely depopulated to the next pump pulse. The power ratio for green and yellow radiation lines decreases with increasing AE temperature, reaching $\sim$1/1 at 1550 °C, $\sim$3/4 at 1600 °C, and $\sim$3/5 at 1650 °C. The maximum average radiation power obtained at T = 1600 °C is about 1.3 W. When the heating was switched off, before the AE channel temperature decreased, it was equal to $\sim$1.55 W. The measurements were performed with a laser tube that had been used long enough before that. Thus, due to thermal deformation of the AE channel, its output cross section was overlapped up to $\sim$65% of the nominal value.

Given this fact, we can assert that a high-quality tube could ensure the output power of $\sim$2 W, while, in the case of switched off heating, the power would constitute $\sim$2.4 W. A photograph of the channel from the side of the resonator output mirror is shown in Fig. 4.

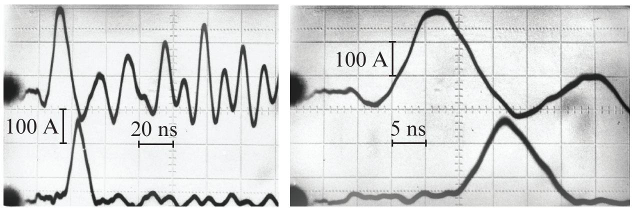

Figure 3. Oscillagrams of current pulses (upper curve) and lasing pulses (lower curve).

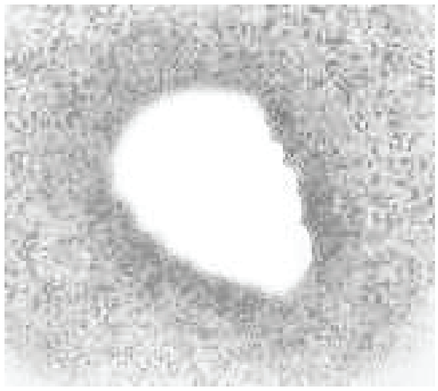

Figure 4. Photograph of the AE channel.

The contributions of pump and heating generators to the heating of the AE channel are approximately equal and constitute about 300 W at a channel temperature of $\sim$1600 °C. This implies that if the channel heating is only ensured by the pump generator, the output power can be doubled and reach the level of 4–5 W! This can be done by implementing a two-channel version of the thyristor assemblies (*3*) and by increasing the pump pulse energy. In this case, the pump pulse repetition rate would rise to $\sim$20 kHz, and the power consumed by the mains would constitute $\sim$1.5 kW.

4. Conclusions

The predicted and obtained power levels of laser radiation with the KULON LT-1.5CU AE are clearly and significantly higher as compared with the specified power, which indicates high efficiency of the pump generator. The design principles of the presented pump generator allow scaling of its output parameters, such as voltage and current amplitudes as well as pump pulse energy, while maintaining nearly optimal temporal pulse characteristics. This makes it possible to use this scheme (after relevant adjustment) for the power supply in more powerful laser tubes with a prospect of increasing the radiation power that is reached in their use. Thus, the semiconductor circuit of the power supply is compact and employs inexpensive serial components.

Of great interest is also the possibility of using the pump generator for excitation of the copper halide lasers requiring, as compared with CVLs, a significantly lower specific power to generate working concentrations of copper vapours. Therefore, if the pump generator proposed in this work is used for operation of the lasers with the tubes of small enough diameters, the power of ~300 W is quite sufficient for their heating [11].

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