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Highly efficient pulse-periodic XeCl lasers

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Abstract. **The parameters of electric-discharge pulse-periodic XeCl lasers with a pulse duration of 25–40 ns, an energy of 0.2–0.7 J, and a pulse repetition rate up to 100 Hz have been investigated. It is shown that the total laser efficiency of 2.6 % and the maximum efficiency with respect to the stored energy of 3.8 % are obtained at a specific pump power of 2.8–3.3 MW cm^{-3} and a discharge circuit inductance of 3.5–4 nH.**

Keywords: *excimer laser, pump power, laser efficiency, uniform volume discharge, laser pulse duration and energy.*

1. Introduction

Currently, excimer lasers, which are the highest power and most efficient sources of coherent UV radiation, are used both in research and technology. To be widely used, these lasers should have a high efficiency and provide high energy and power densities. It is fairly difficult to satisfy all these requirements simultaneously, especially for pulsed-periodic commercial lasers, in which very simple two-circuit pumping is applied.

A XeCl excimer laser, which generates at a wavelength of 308 nm, is the second most efficient generator after the KrF laser. The typical values of the total efficiency and specific lasing energy extraction for pulse-periodic XeCl lasers are, respectively, 1 %–2 % and 2.5–4 J L^{-1}. These parameters are generally obtained at a specific pump power of ~1 MW cm^{-3} and pulse durations of 30–50 ns [1]. At the same time, the investigations performed on experimental breadboard XeCl lasers in [2–4] showed that even higher efficiency and specific lasing energy can be obtained. A XeCl laser with a record (45 MW cm^{-3}) specific pump power and discharge current density of 14 kA cm^{-2} was investigated in [5]. However, the efficiency of this laser turned out to be very low (only 0.8 %); the maximum specific lasing energy and the output beam intensity were, respectively, 2.4 J L^{-1} atm^{-1} and 4.8 MW cm^{-2}. Miyazaki et al. [6] used UV preionisation in the XeCl laser to obtain a record total efficiency (2.9 % at an output beam intensity of 6.5 MW cm^{-2}) but at a fairly low specific lasing energy (0.6 J L^{-1} atm^{-1}). A maximum efficiency was reached at a pump power density of 3.77 MW cm^{-3}. With an increase in the mixture pressure from 4 to 6 atm and a charging voltage from 18 to 36 kV the laser efficiency decreased to 1.8 %; however, the specific energy extraction and output radiation intensity increased to 1 J L^{-1} atm^{-1} and 15.7 MW cm^{-2}, respectively. Having ignited a discharge in the form of many diffuse channels, we have obtained a record specific lasing energy (about 3.9 J L^{-1} atm^{-1}) and a high laser beam intensity (14.9 MW cm^{-2}) [7]. The specific pump power in the channels and the discharge current density were estimated to be 10 MW cm^{-3} and 5 kA cm^{-2}, respectively. Unfortunately, the efficiency of the laser with this active medium was rather low: 1.2 %.

Note that in all aforementioned studies the laser efficiency decreased significantly when the specific lasing energy from the active medium reached a maximum value. In addition, the experimental results were obtained on breadboard lasers in the single regime, which was undeniably favourable for record parameters due to the minimised inductance in the discharge pump circuit. The design of commercial pulse-periodic lasers imposes additional requirements on the discharge pump circuit, as a result of which the discharge-circuit inductance increases.

In this context, the problem of increasing the efficiency of pulse-periodic lasers with a high radiation intensity is undoubtedly urgent. In this paper, we report the results of studying three types of pulse-periodic XeCl lasers, which were developed at the Institute of High-Current Electronics, Siberian Branch of the Russian Academy of Sciences (Tomsk), in order to find the optimal pump regime, providing simultaneously a high lasing efficiency and a high laser beam intensity.

2. Experimental

The lasers developed by us have pulse repetition rates from 1 to 100 Hz and pulse energies in the range of 0.2–0.7 J [8–13]. Figure 1 shows one of these lasers: EL-500-100. Here, the control of laser parameters and replacement of the active medium were computer-aided. To determine the optimal pump

Figure 1. Appearance of the EL-500-100 laser.

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regime, we carried out experiments with changing the parameters of the electric circuit; the profile, length, and interelectrode gap for the main and preionisation electrodes; the charging voltage; and the laser mixture composition and pressure. Our developments were based on the results of these studies.

The laser active medium is formed (volume discharge is ignited) using a two-loop electric circuit with automatic UV preionisation of the discharge gap (Fig. 2). In lasers of different types the storage capacitance C_1 and the discharge capacitance C_2 were varied from 48 to 107 nF and from 22 to 72 nF, respectively. In the EL-200-50 laser the capacitance C_1 was formed by KVI-3 capacitors, while the capacitance C_2 was formed by UHV-6A capacitors (2700 pF, 30 kV). In other lasers only TDK capacitors were used. The storage capacitance C_1 was charged from a compact dc power supply to U_0 = 20–25 kV. Charging the capacitance C_1 changes the commutator state and initiates pulsed charging of the discharge capacitance C_2. A TPI1-10K/20 thyratron was used as a commutator. The charged circuit inductance L_2 = 120–150 H promotes an efficient charge exchange from the first capacitance to the second capacitance for a rather long time (150–180 ns), thus ensuring a long thyratron lifetime. The charging of the capacitance C_2 is accompanied by automatic UV preionisation of the laser discharge gap from spark gaps. After the pulse charging of the capacitance C_2 to a voltage close to U_0, the laser gap breaks, and the laser is pumped. The laser chamber, discharge capacitors, and conductors between the capacitors and discharge electrodes are arranged so as to provide a minimum inductance L_3 in the discharge circuit (3.5–4 nH). A small inductance provides a fast increase in the discharge current, which is very important for igniting a uniform volume discharge throughout the entire discharge gap.

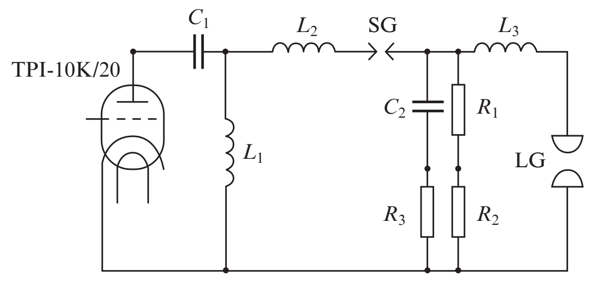

Figure 2. Laser excitation scheme:
(C_1) storage capacitance, (C_2) discharge capacitance, (L_1–L_3) circuit inductances, (R_3) current shunt, (R_1/R_2) ohmic voltage divider, (SG) preionisation spark gaps, and (LG) laser discharge gap.

The insulating chamber contains the main-discharge electrodes with a working surface 65 cm long. The interelectrode distance in lasers of different types changed from 22 to 28 mm. The effective discharge width was varied in the range of 5–10 mm, depending on the charging voltage and laser-mixture composition. At both sides of the main discharge gap there are spark gaps for UV preionisation. Mirrors of a plane-parallel cavity with reflectances of 0.99 and 0.07 are mounted on the chamber faces; the cavity length is about 100 cm.

The discharge chamber is hermetically connected with a cylindrical aluminium housing, which contains systems for circulating, cooling, and purifying the laser mixture. All metal elements located in the housing and its inner surface are coated by an electrochemically deposited protective Al_2O_3 layer. The gas flow in the chamber is formed by a diametrical fan, which is rotated by an electric motor through a magnetic clutch. The gas circulation rate changes, depending on the response frequency of the laser, to provide a linear increase in the laser power with increasing frequency. The developed system of circulation provides a gas flow velocity from 5 to 20 m s^{-1}. The gas mixture is cooled by heat sinks, through which tap water is passed. The mixture is purified by an electrostatic filter, which traps contaminant particles. The laser active medium is a Ne–Xe–HCl–H_2 gas mixture at an absolute pressure of 3.6–3.8 atm; it is formed directly in the laser chamber.

In our experiments the pump-discharge current–voltage characteristics were recorded using a current shunt (which measured the current of one of the discharge capacitances) and an ohmic voltage divider. The temporal shape of the laser pulse was recorded by a FEK-22SPU photodiode. All electric pulses were recorded on Tektronix TDS 3014 and 3032 oscilloscopes. The radiation energy output was fixed by a Gentec-E power and energy meter. The laser intensity distribution over the beam cross section was measured using a diaphragm 1 mm in diameter and a photodiode. The beam uniformity was estimated from the pulse amplitude and shape.

3. Results and discussion

When developing these lasers, we performed preliminary experiments to determine the optimal pump conditions. It was found that, to provide efficient operation of a XeCl laser with a short pulse width at half maximum (25–40 ns), the specific pump power should be in the range of 2.5–3.5 MW cm^{-3}. In this context, all our investigations and subsequent developments were carried out in this power range for different pump pulse durations (widths at half maximum of 23, 30, 35, and 39 ns for the discharge current) [8–10]. To obtain a pump power density of 2.5–3.5 MW cm^{-3}, it is necessary to provide a discharge current density above 1 kA cm^{-2}. The ignition of a discharge with a high current density imposes more severe requirements on the level and uniformity of discharge gap preionisation, the electric field homogeneity in the gap, and the rate of volume discharge formation. The purpose of our study was to find the conditions satisfying these requirements.

Figure 3 shows typical oscillograms of lasing pulses and voltage and current pulses on the discharge capacitance C_2 for the three types of lasers developed. An oscillogram of specific pump power (with a maximum value of 3.3 MW cm^{-3} for an active medium 130 cm^3 in volume) is also presented for the EL-500-100 laser. All these data correspond to the optimal lasing conditions for each laser. The oscillograms demonstrate that the leading edge of the discharge current pulse is very short for all lasers: 15, 24, and 26 ns, respectively. The shortest discharge formation time (15 ns) in the EL-200-50 laser allowed us to form a uniform discharge in it (22 ns at half maximum), without visible plasma spots on the cathode [8]. This pump regime makes it possible to reduce significantly the erosion of the electrodes and increase the laser lifetime. An increase in the laser energy and the pump pulse duration (to 35 ns) leads to the formation of plasma spots on the cathode surface, which deteriorate the volume discharge homogeneity. The time delays of the lasing pulse with respect to the pump pulse beginning are, respectively, 15, 17, and 23 ns. The delay time is determined by the rate of the increase in the pump power and the formation time of XeCl molecules in the discharge plasma. Obviously, to obtain the highest lasing efficiency, the delay time must be minimally possible. In all cases under consideration

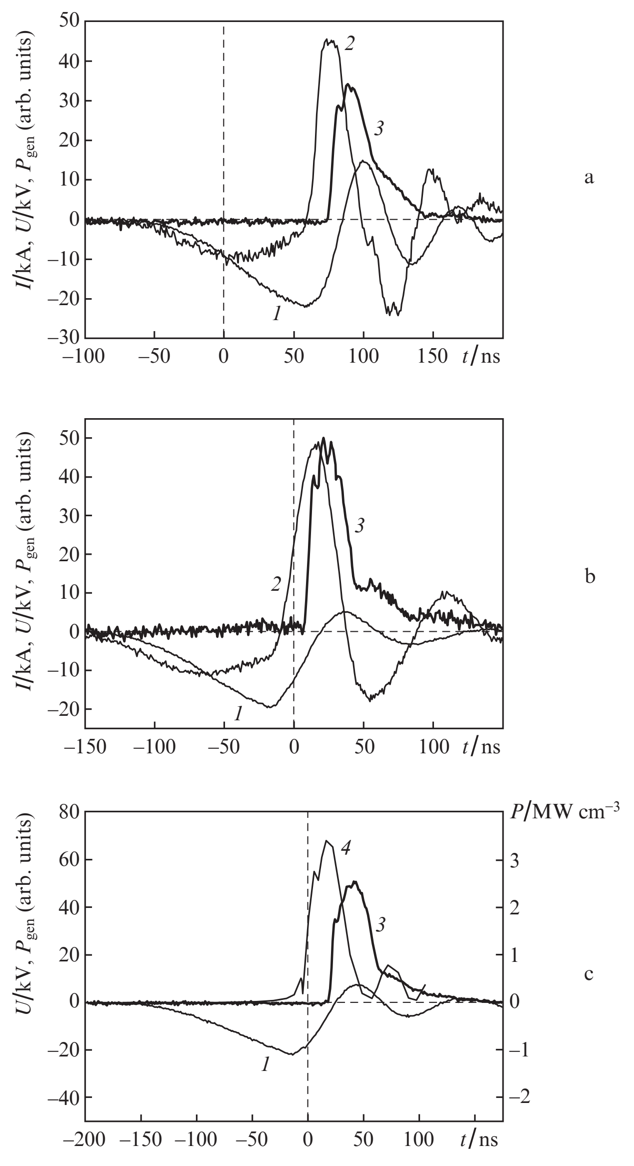

Figure 3. Oscillograms of (*1*) the voltage across the capacitance C_2, (*2*) the current through this capacitance, (*3*) the laser pulse, and (*4*) the specific pump power for the (a) EL-200-50, (b) EL-350-10, and (c) EL-500-100 lasers. The $Ne:Xe:HCl:H_2 = 1000:15:1:0.5$ gas mixture was used for the EL-200-50 laser and the $Ne:Xe:HCl:H_2 = 800:8:1:0.5$ mixture was a working medium for the EL-350-10 and EL-500-100 lasers.

lasing occurs during three half-periods of the discharge current. This indicates that the discharge retains the volume character not only in the first half-period of the discharge current.

Our main purpose was to increase the lasing efficiency. Figure 4 shows the experimental dependences of the total lasing efficiency η, which was determined as the ratio of the laser energy to the energy stored in the capacitance C_1, on the charging voltage U_0. It can be seen that maximum efficiency is 1.8% for the EL-200-50 laser and 2.6% for the two other lasers. However, the maximum efficiency was obtained at different U_0 values for the EL-350-10 and EL-500-100 lasers: 22 and 18 kV, respectively. With an increase in the charging voltage to 25 kV the efficiency reduced to 1.7%.

To find out why the EL-500-100 laser had a lower efficiency, we analysed the dependence of the efficiency of stored energy transfer (*2*) from the capacitance C_1 to C_2 and the

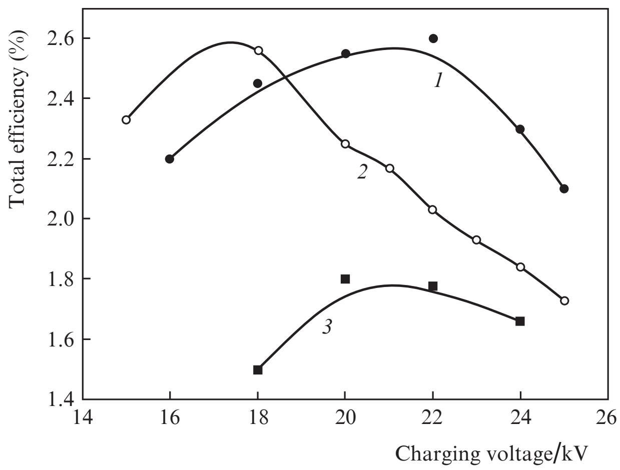

Figure 4. Dependences of the total efficiency η on the charging voltage U_0 for the (*1*) EL-350-10, (*2*) EL-500-100, and (*3*) EL-200-50 lasers with the optimal gas mixture at pressures $P = $ (*1*,*3*) 3.8 and (*2*) 4 atm.

internal lasing efficiency η_1 on the energy stored in the discharge plasma during the first period of the discharge current. The pump power and stored energy were calculated (using the OrCAD program) based on the experimental current–voltage characteristics of the discharge, with the discharge resistance as a variable fitted. The discharge volume was estimated by multiplying the length of the working electrode surface by the area corresponding to the laser beam intensity above the level of $1/e^2$.

Figure 5 shows the dependences of these efficiencies on the charging voltage. Here, the behaviour of the efficiency η_1 for the laser EL-350-10 is also shown for comparison. These data indicate that the reduction of the total laser efficiency is mainly caused by the decrease in the energy transfer efficiency from the capacitance C_1 to C_2. To make this process more efficient, the discharge gap was increased from 25 to 28 mm. At a wider gap and a charging voltage of 24 kV in an $Ne:Xe:HCl = 900:15:1$ mixture at a pressure of 3.7 atm, the energy transfer efficiency η_2 increased from 55% to 72%, and the total laser efficiency changed from 1.85% to 2.24%. In our experiments the EL-350-10 laser demonstrated the highest efficiency.

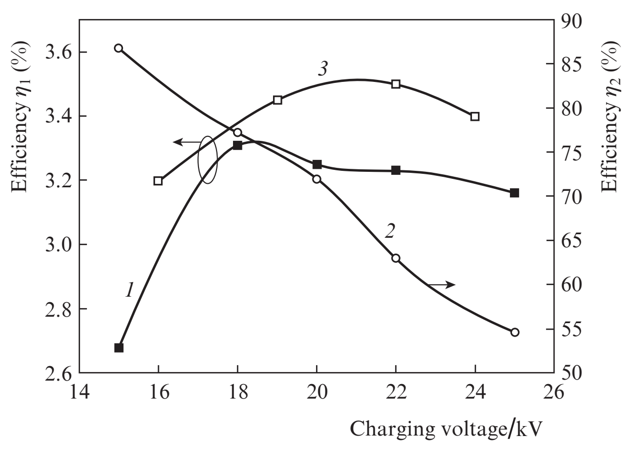

Figure 5. Dependences of the internal lasing efficiency η_1 of the (*1*) EL-500-100 and (*3*) EL-350-10 lasers and (*2*) the energy transfer efficiency η_2 from the capacitance C_1 to C_2 for the EL-500-100 laser on the charging voltage.

Table 1. Electric and optical parameters of the XeCl lasers of EL series.

Laser model	C_1/nF	C_2/nF	d/mm	Total efficiency (%)	$\tau_{1/2}$/ns	I/MW cm^{-2}	f/Hz	E_{max}/mJ
EL-200-50	48	32	22	1.8	27	9,5	50	210
EL-350-10	66	52	22	2.6	30	10	10	415
EL-500-100	107	72	25	2.15	35	8	100	615
			28	2.24	38	7		700

Note: d is the interelectrode spacing, $\tau_{1/2}$ is the lasing pulse width at half maximum, I is the output radiation intensity, f is the lasing pulse repetition rate, and E_{max} is the maximum lasing energy.

The calculation of the specific pump power for the EL-500-100 laser in the range of charging voltages from 24 to 18 kV showed that its change due to the discharge gap narrowing was insignificant (from 3.3 to 3 MW cm^{-3}). With a further decrease in U_0 to 15 kV, the specific power reduced to ~2 MW cm^{-3}. Figure 6 presents the dependences of the internal lasing efficiency for the EL-500-100 and EL-350-10 lasers on the specific pump power. It can be seen that the laser efficiency drops at specific pump powers below 2 MW cm^{-3}. The optimal pump power is in the range of 2.8–3.3 MW cm^{-3}. In our opinion, the main cause of the lower lasing efficiency of the EL-500-100 laser in comparison with EL-350-10 is the deterioration of the burning discharge homogeneity as a result of the longer pump pulse duration. A calculation of the specific pump power for the EL-200-50 laser showed that it does not exceed ~3 MW cm^{-3}, which is insufficient for a higher efficiency with a 23-ns pulse (Fig. 4).

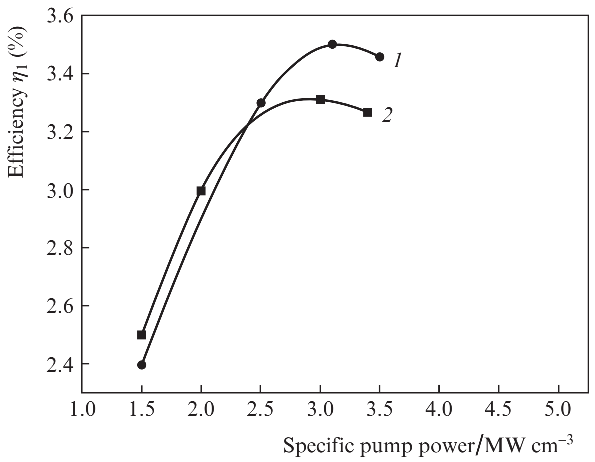

Figure 6. Dependences of the internal lasing efficiency η_1 on the specific pump power P for the (*1*) EL-350-10 and (*2*) EL-500-100 lasers.

An important laser parameter is the uniformity of the intensity distribution over the laser beam cross section. Our measurement showed that the pulse shape hardly changed throughout the entire cross section. The pulse amplitude did not change from electrode to electrode (except for the near-cathode region in the EL-500-100 laser) and had a flat central part with sharp edges in the perpendicular direction. All these facts indicate a high spatial uniformity of the laser beam.

As was noted above, in the standard regime of laser operation the pressure in the gas mixture is in the range of 3.6–3.8 atm. An analysis of the dependence of the output lasing energy on the laser mixture pressure showed that an increase in the mixture pressure from 3.6 to 4 atm increases the pulse energy to 615 and 415 mJ for the EL-500-100 and EL-350-10-415 lasers, respectively.

Table 1 contains the main electric and optical parameters of the lasers developed. Some other important experimentally obtained laser parameters were as follows: a specific lasing energy of 4.5–5 J L^{-1}, an internal efficiency of 3.3%–3.6%, and an efficiency defined as the ratio of the maximum lasing and pump powers of 3.5%–4%.

4. Conclusions

The parameters of the electric-discharge pulse-periodic XeCl lasers of the EL series were experimentally investigated. These lasers are characterised by pulse energies from 200 to 700 mJ at a pulse duration of 28–35 ns and a pulse repetition rate up to 100 Hz. The analysis performed showed the following.

(i) The optimal specific pump power, which corresponds to the maximum laser efficiency at a pump pulse duration of 20–40 ns, is in range of 2.8–3.3 MW cm^{-3}.

(ii) A highly uniform volume discharge was implemented in all lasers under study, which made it possible to support lasing during the entire pump pulse (three half-periods of the discharge current). The width at half maximum of the main lasing pulse always corresponds to the width of the first half-period of the current but with a time delay of 15–20 ns.

(iii) An output radiation intensity of ~10 MW cm^{-2} was obtained, which is record high for pulse-periodic XeCl lasers.

(iv) The total laser efficiency reached 2.6%, and the maximum efficiencies with respect to the stored energy and power were, respectively, 3.8% and 4%.

(v) At short (~20 ns) pump pulses the volume discharge burns without visible spots on the cathode, which is favourable for reducing the electrode erosion and increasing the laser service life. An increase in the pump pulse duration to 35 ns (with conservation of the specific pump power at a level of 3 MW cm^{-3}) results in higher brightness and larger sizes of visible spots on the cathode, which reduce the laser lifetime.

(vi) The configuration of the gas-dynamic channel used by us and the existing circulation system made it possible to increase the laser pulse repetition frequency to 200 Hz.

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