Efficient pulse-periodic excimer lasers

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Received March 27, 2008

Results of experimental and theoretical studies of discharge excimer lasers with 30–35 ns radiation pulse length are presented. The energy of the laser radiation pulses is 0.2–0.6 J and the pulse repetition rate is up to 100 Hz. It is shown that the total laser electric efficiency of 2.6% and the working gas mixture resource more than 10^6 pulses can be reached.

Introduction

At present, excimer lasers are most powerful and efficient UV-radiation sources, therefore, they are widely used in scientific investigations and technological processes, exhibiting the most promise in microelectronics, medicine, and other applied spheres. The typical specifications of commercial XeCl lasers are: an efficiency of 1–2% and specific output power of an active medium of 0.5–1 J/(l · atm). These parameters are usually realized at a specific pump power up to 1 MW/cm^3 and 20–30 ns pulse length.[1] The possibility for the XeCl laser to increase these parameters by more than two-fold was shown with the use of experimental prototypes.[2–4] However, in most cases the laser efficiency significantly decreased, when extracting maximal specific output power from the active medium. The causes of the decrease can be either the development of instabilities in the discharge or non-optimal conditions for formation and quenching of the working molecules XeCl* in plasma due to the proceeding plasma-chemical reactions. Therefore, the task of increasing the efficiency of commercial lasers with high specific output power is of scientific and practical importance.

A laser with a 45 MW/cm^3 pumping power and 14 kA/cm^2 discharge current density was described in Ref. 5. The power efficiency of the laser was equal to 0.8%, maximal specific output power was ~2.4 J/(l · atm), and output beam intensity was 4.8 MW/cm^2. Using UV-preionization, the conditions for discharge combustion at 3.77 MW/cm^3 pump power density, 2.9% efficiency, 0.6 J/(l · atm) specific output power in the active medium, and 6.5 MW/cm^2 output beam intensity were realized.[6] When changing the pressure in the mixture from 4 to 6 atm and the charge voltage U_0 from 18 to 38 kV, the laser efficiency decreased to 1.8%, specific output power reached ~ 1 J/(l · atm), and output beam intensity was 15.7 MW/cm^2. In Ref. 7, the possibility of discharge combustion was realized, which consisted of numerous diffused channels at an average pumping power of 10 MW/cm^3 and an average current density of 5 kA/cm^2. The efficiency of the laser with such an active medium was 1.2%, its specific output power equaled to ~ 3.9 J/(l · atm), and the output beam intensity was 14.9 MW/cm^2.

The experimental prototypes of the lasers worked in the single mode, which allowed the realization of minimal inductance in discharge pump circuit without taking into account the requirements to commercial pulse-periodic lasers.

In this work we describe theoretical and experimental possibilities for the increase of efficiency and specific output power of pulse-periodic XeCl lasers.

Instrumentation

The commercial electric-discharge laser of EL series designed in HCEI SB RAS (Tomsk) has been under study. These lasers can provide for radiation energy in the pulse of 0.5 J and a pulse repetition rate of 10–100 Hz.[8–10] The resource of laser mixture is ~10^7 pulses.

A typical two-circuit scheme was used for laser pumping (Fig. 1).

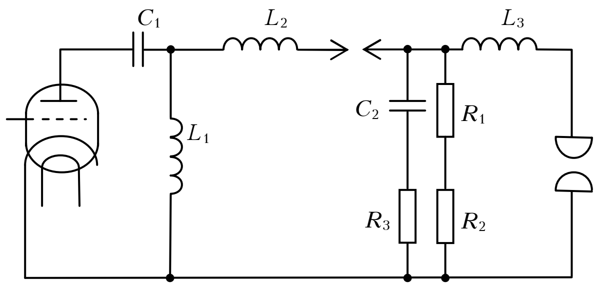

Fig. 1. Electric circuit of the laser: C_1 = 107 nF; C_2 = 72 nF; L_1 = 100 μH; L_2 = 150 nH; L_3 = 4 nH; R_3 is current shunt; R_1/R_2 is ohm divider.

Preionization of discharge gap was activated by UV-radiation, which appeared during sparking in gaps of the electric circuit, intended for recharging capacitors C_1 and C_2. The C_1 capacitor varied from 66 to 107.2 nF for EL-350-10 and EL-500-100 lasers, respectively. The charging was realized from the direct current source up to U_0 = 22–24 kV. The

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TPIZ-10k/25 thyratron was used as the switch. Optimal value of the first circuit inductance $L_2 = 150$ nH provided for an efficient recharging of the capacitors for a relatively long time (~150–180 ns), which provided for minimal losses at the switch. The capacitor C_2 = 51.7 and 72 nF in the second circuit for EL-350-10 and EL-500-100 lasers discharged through the plasma, providing for the active medium pump. Parameters of capacitors C_1 and C_2 (TDK UHV-6A) were 2700 pF and 30 kV. The construction of the laser chamber and C_2 capacitors provided for low inductance $L_3 = 3.5$–4 nH and, correspondingly, short pumping pulse length and high discharge current (up to 65 kA).

Active volumes for EL-350-10 and EL-500-100 lasers were 100 and 130 cm^3, respectively. The gas mixture Ne:Xe:HCl = 800:8:1 at 3.6–3.8 atm total pressure was used. The cavity length was 100 cm and the reflection coefficients of the mirrors were 0.95 and 0.07.

The laser beam shape was measured by PEC 22SPU photodiode with the help of TDS-3032 oscillograph. Radiation energy was recorded by the Gentec-E calorimeter.

Results and discussion

The choice of these two lasers was stipulated by close parameters of pump modes. In both cases the maximal discharge current density was 1.3–1.4 kA/cm^2 and the specific pumping power was 2.5–3.5 MW/cm^3. When changing external circuit characteristics, the particular pumping mode was set by the change of profile, length, and height of the electrodes.

The typical oscillograms of current and voltage pulses on C_2 capacitor, as well as laser radiation pulse and specific pump power of EL-500-100 laser are given in Fig. 2, where estimated dependence of specific pump power pulse is presented as well.

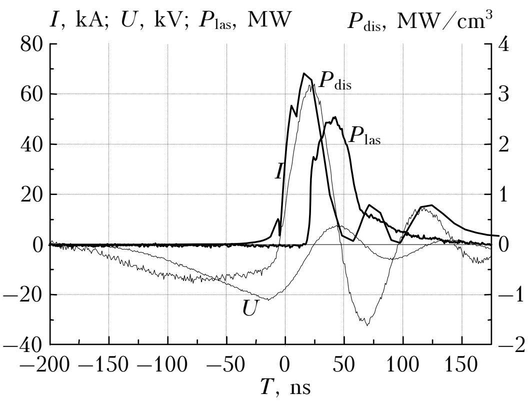

Fig. 2. Temporal behavior of voltage U and current I on C_2 capacitor, as well as laser pulse P_{las} and specific pumping power P_{dis}.

Data are presented for the Ne:Xe:HCl = 860:8:1 mixture at P = 3.8 atm and charge voltage of 24 kV. Since the active medium volume was 130 cm^3, the maximal specific pump power was 3.3 MW/cm^3. The laser efficiency, determined from the ratio of generation and pump powers, was 3.5%.

The experimental U_0 dependences of laser total efficiency are illustrated in Fig. 3.

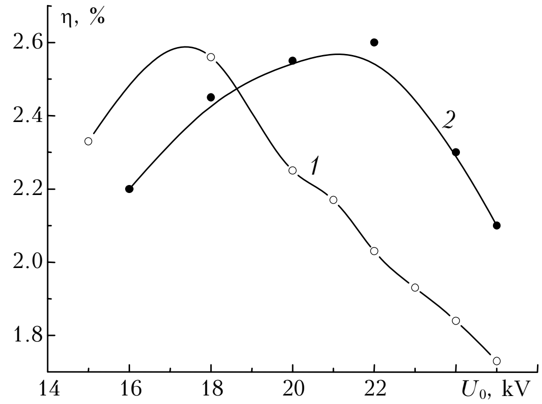

Fig. 3. The dependences of laser total efficiency on charge voltage: for EL-500-100 laser (*1*); for EL-350-10 laser (*2*).

The total laser efficiency was defined as the ratio of laser radiation energy to the energy stored in the C_1 capacitor. The behavior of experimentally measured and calculated output energy curves coincides to a satisfactory accuracy. Maximal efficiency for both lasers reached 2.6%. This efficiency for EL-500-100 lased was realized at $U_0 = 18$ kV. At a further increase of the charge voltage the laser efficiency decreased to 1.7% at 25 kV. This dependence for EL-350-10 laser is shown by curve *2*. To study the cause of the dependence, we have investigated the transfer efficiency of the initially stored energy to the discharge energy and the discharge energy transfer to the laser radiation energy.

Figure 4 illustrates the dependences of the laser internal efficiency (relative to the energy in the active medium) and the transfer efficiency of the energy stored in C_1 capacitor, to gas discharge plasma from the charge voltage.

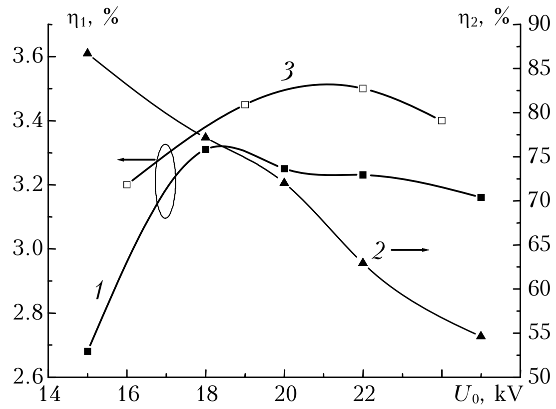

Fig. 4. The behavior of laser efficiency: (*1*), (*3*) for EL-500-100 and EL-350-10, respectively, and the efficiency of energy transfer from C_1 capacitor to gas discharge plasma (*2*) depending on the charge voltage for EL-500-100 laser.

The dependences *1* and *3* were calculated with the help of selection of the variable value of the discharge resistance from fitting the volt-ampere characteristics (VAC) of the model to experimental results. It is seen that the main cause of total laser efficiency decrease is attenuation of the efficiency of energy transfer from C_1 to C_2. In the range of charge voltage variation from 24 to 18 kV the value of specific pumping power changed insignificantly (from 3.3 to 3 MW/cm^3) at the sacrifice of discharge width narrowing. The value of specific power was ~2 MW/cm^3 during further decrease of the charge voltage to 15 kV. The generation threshold at the pumping power range higher than 3 MW/cm^3 was reached in 22–25 ns after the discharge current initiation. For EL-500-100 laser, the radiation pulse length at the intensity half-width was 36 ns, output radiation intensity reached 7.5 MW/cm^2 and the maximal generation power was 14.5 MW. For the EL-350-10 laser the radiation intensity reached 10 MW/cm^2 at a pulse length of 30 ns.

Experimental and calculated dependences of internal laser operation efficiency on the specific pumping power are illustrated in Fig. 5.

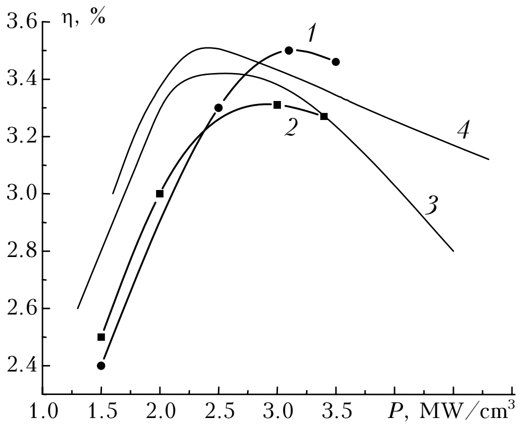

Fig. 5. Experimental (*1*, *2*) and calculated (*3*, *4*) dependences of laser operation internal efficiency on specific pump power and halogen concentration in the mixture.

It is shown that at the specific pump power lower 2 MW/cm^3 the internal laser efficiency decreases. The dependences *1* and *2* were received experimentally for EL-500-100 and EL-350-10 lasers, respectively. The dependences *3* and *4* were received for the EL-500-100 laser by numerical calculations at different halogen contents in the mixture. The mixtures Ne:Xe:HCl = 860:8:1 and Ne:Xe:HCl = 560:8:1 were used in the first and second cases, respectively. As it follows from the calculated dependences, the internal laser efficiency increases with the increase of halogen content in the mixture, however, the range of operation pump power narrows. The comparison of resulting output radiation parameters with the internal laser efficiency shows that for the EL-500-100 laser the radiation pulse energy is 570 mJ, the efficiency η is 3.3% at a specific output power E_{rad}/V of 1.22 J/(l · atm); for the EL-350-10 laser the radiation pulse energy is 350 mJ, η is 3.5% at E_{rad}/V = 1 J/(l · atm).

The conducted analysis of the experimental and calculated data allows an assumption that the active medium has a higher potential for a more complete use of HCl molecules and for the increase of the saturation coefficient. Therefore, we can expect that further increase of specific pump power to the magnitude higher than 3.4 MW/cm^2 at the same pulse length will allow us to increase radiation energy for maintenance of laser high internal efficiency. However, there appear some difficulties for preserving the volume discharge uniformity, because at such pump levels either macro- or micro-nonuniformities inevitably appear in the discharge.[7] In the case of a high-power pump the type of the nonuniformity is mainly determined by the halogen concentration in the mixture. In our case, at Ne : HCl = 1000 : 1 there appear micrononuniformities; at Ne : HCl = 700 : 1 – macrononuniformities (Fig. 6).

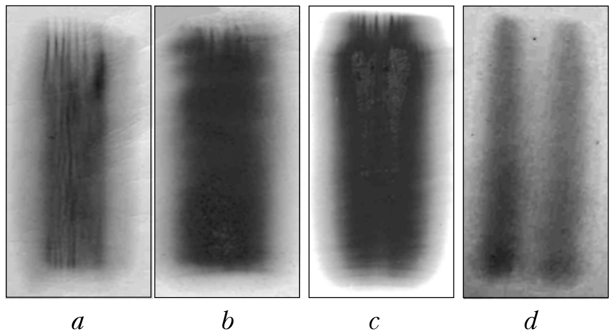

Fig. 6. Laser beam patterns: Ne:Xe:HCl = 600:8:1 (*a*); 860:8:1 (*b*); 1000:8:1 at *P* = 3.8 atm (*c*); Ne:Xe:HCl = = 1800:10:1 at *P* = 3.6 atm (*d*).

In the optimal mixture at Ne:HCl = 800:1 a lot of incomplete diffuse channels appeared in the discharge near cathode, which overlapped at some distance from it. At a given pump power the distance increased as the halogen concentration in the mixture increased.

Conclusion

The electric discharge pulse-periodic XeCl lasers of EL series have been studied theoretically and experimentally in order to increase the specific generation energy and laser efficiency. The output energy of laser radiation pulse between 350 and 570 mJ at a 30–35 ns pulse length was obtained. The lasers worked at 10 and 100 Hz pulse repetition rate. Total laser efficiency reached 2.6%, the specific output energy from the active medium was equal to 1.4 J/(l · atm), and output beam intensity was up to 10 MW/cm^2. It was shown that at about 35 ns pumping pulse length the increase of specific pump power from 2 to (3.2 ± 2) MW/cm^3 led to increase of the laser internal efficiency from 2.8 to 3.5%. A satisfactory agreement between experimental and calculated laser parameters has been reached.

Acknowledgements

The authors are grateful to Yu.I. Bychkov and A.G. Yastremsky for the numerical calculations of the laser internal efficiency and output parameters.

This work was financially supported by Russian Foundation for Basic Research (Project Nos. 07–08–00197 and 08–08–99075).

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