Influence of the pumping method on the output energy of a wide-aperture electric-discharge XeCl laser

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The influence of the pumping method on output parameters of a wide-aperture electric-discharge XeCl laser is studied. An output of 9.5 J was obtained under excitation by a capacitive-storage stripline pump generator with a preliminary discharge. The XeCl laser parameters were calculated for different pumping modes. It was shown that the use of an inductive energy storage with a semiconductor opening switch and a primary storage in the form of a capacitor increases the breakdown voltage of the laser gap and the discharge current rise rate. The calculated laser output energy and the laser efficiency at low charging voltages of the primary storage can be as high as 9 J and 3.6%, respectively.

Introduction

Nowadays electric-discharge excimer lasers are finding increasing application in various production processes of microlithography, clearing of metal surfaces, annealing of semiconductors, production of nano-sized particles, sensing of the Earth's atmosphere, and study of laser ablation of different materials.[1] These applications require high-efficiency UV and VUV lasers with a high output power, in particular, electric-discharge XeCl lasers with a relatively high pulse energy (~10 J). The construction of electric-discharge XeCl lasers with an output energy of ~10 J and higher, particularly, with the high efficiency (~4%) was reported in Refs. 2–6. All these lasers employ different schemes of a pump generator.

In Ref. 7, the pumping by a double discharge with formation of a prepulse, using the inductive energy storage and the opening switch based on SOS diodes, was proposed. The inductive energy storage generates a prepulse and ensures a high breakdown voltage and fast increase of the volume discharge current. Then, the most part of the pump energy is deposited into the laser active medium from the primary storage (capacitor or stripline). It was shown in Refs. 8 and 9 that the joint action of these factors significantly improves the laser discharge homogeneity and the discharge glow stability.

Based on this method of discharge formation, long-pulse XeCl and XeF lasers with an active volume up to 1 l (discharge gap cross section up to 2×4 cm) and an output energy up to 1.5 J at an efficiency up to 4% with respect to the deposited energy were developed.[8–11] However, pump generators with the inductive energy storage and semiconductor opening switch were not used earlier to pump wide-aperture excimer lasers.

In this paper, we study theoretically and experimentally how the pumping mode influences the output of a wide-aperture XeCl laser, in particular, a pump generator with the inductive energy storage and a semiconductor opening switch. The laser output parameters in cases of pumping from the pump generator with the inductive energy storage, from the stripline, and from the double-loop *LC* circuit with a reservoir capacitor and a peaking capacitor are compared. In addition, in some experiments with pumping from a capacitive storage, a predischarge was initiated in the laser gap.

Instrumentation

In the experiments, we used a wide-aperture laser pumped by a transversal discharge with a design similar to that of the XeCl laser described in Ref. 6. The X-ray source was used for preionization of the active volume. A cylindrical laser chamber had a length of 150 cm. The excited volume with a length of 100 cm and an aperture up to 6.5×10 cm^2 was formed by two shaped electrodes. A vacuum diode of the soft X-ray source was fixed at the chamber bottom.[12] X-rays penetrated into the chamber through a thin-walled cathode. The duration of the X-ray pulse was 500 ns. The peak of the energy distribution of X-ray quanta fell in the range 25–30 keV. The exposure dose of the X-ray radiation in the active volume filled with the Ne–Xe–HCl mixture at a pressure up to 4 atm was ~1 R. The anode was connected through an insulator to the pump generator. The design of the insulator and a return current lead ensured the inductivity of the discharge circuit of the input and laser gap $L_1 = 20$ nH.

For pumping, a universal pump generator was used, which allowed the pumping from both the

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capacitive energy storage and the pump generator with the inductive energy storage. The circuit of the laser with the pump generator is shown in Fig. 1.

The pump generator consisted of the main and auxiliary circuits. The main circuit included the capacitive storage C_0 consisting of three capacitors with a total capacitance of 45 nF or three FL-200 lines with a capacitance of 95 nF each with an impedance of 0.35 Ω. The inductance of the discharge circuit L_0 at $C_0 = 45$ nF was 100 nH. The storage C_0 was charged by pulses from the capacitor $C_{Pr} = 0.4$ μF for time of ~1–2 μs and then switched to the laser gap by a two-electrode multichannel spark-gap RG with the sharply inhomogeneous electric field near a blade anode. The discharge voltage for the capacitor C_{Pr} was $U_{Pr} = 34$–42 kV.

The auxiliary circuit included a capacitor $C_D = 8.3$ nF, a spark switch SW_D, and an inductance coil $L_D = 2.4$ μH. The capacitor C_D was connected to the gas-discharge chamber by six 1-m KVI-120 cables distributed uniformly along the potential electrode of the laser. This circuit ensured the direct current through diodes. When the laser operated without diodes, this circuit served for initiation of a low-current predischarge in the laser gap. The parameters of the circuits and the gas mixture were selected so that, first, electrons in the laser gap reached a concentration of 10^{12}–$5 \cdot 10^{13}$ cm^{-3}, which followed by a breakdown of the multichannel spark-gap. This favored the formation of the volume discharge.

When the auxiliary circuit was turned off, the pressure in the multichannel spark-gap was selected so that the breakdown of the spark-gap occurred at the maximal storage voltage U_0, which at $C_0 = 295$ nF (three striplines) and 45 nF (three capacitors) usually was equal to ~$1.2U_{Pr}$. In this case, the predischarge was not initiated.

In the case of pumping from the pump generator with the inductive storage, 12 or 14 SOS-120–4 diodes connected in parallel with the peaking capacitor C_1 and having a total capacitance of 4.5–6.6 nF were additionally used in the laser.

The discharge and lasing characteristics were studied in Ne–Xe–HCl mixtures at a pressure up to 3000 Torr. The cavity mirrors with a dielectric coating (reflection coefficients of 100 and 30% at λ = 308 nm) were used.

The laser output energy was measured by an OPHIR calorimeter with an FL-250A sensor head. The laser radiation from the whole discharge aperture was collected onto the measuring head by a telescope consisting of two quartz lenses. The pulse shape was measured in the far zone by an FEK-22 SPU vacuum photodiode, which received a part of the laser radiation reflected from the telescope external lens. For the photodiode to operate in the linear mode, the radiation at its input was attenuated by a series of metal meshes.

In the experiments, we measured the currents I_0 and I_1 in the circuits of the reservoir and peaking capacitors, the currents through the SOS diodes I_{SOS} and the laser gap I_d using shunts R_{sh}, and the voltages U_0 and U_1 across the capacitors C_0 and C_1 and SOS diodes using resistive voltage dividers R_1–R_2 and R_3–R_4. Electric signals were recorded by TDS-220 and TDS-3014 digital oscilloscopes.

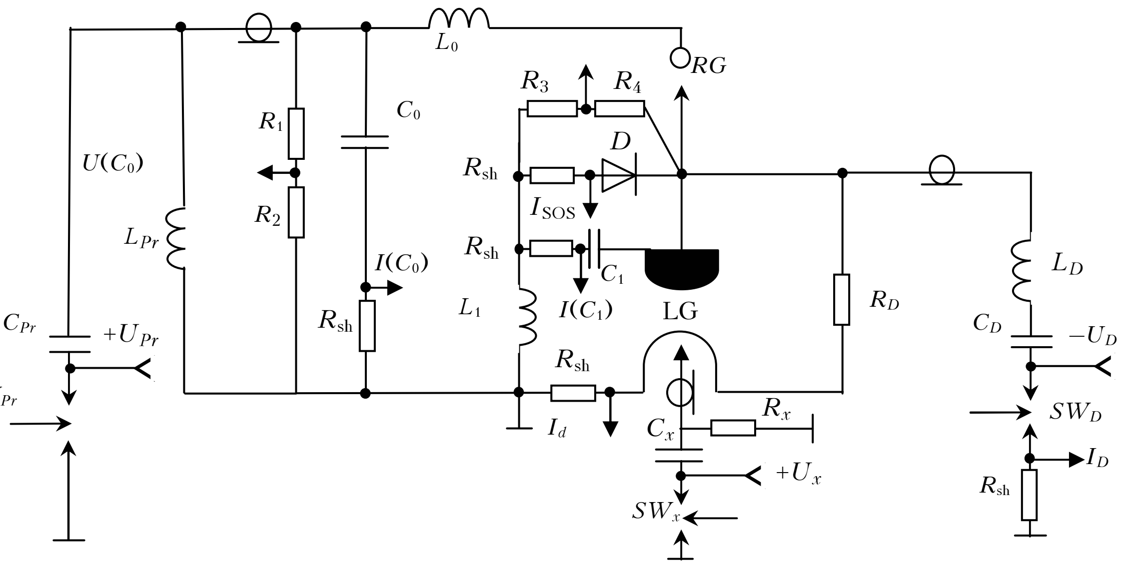

Fig. 1. Circuit of the wide-aperture XeCl laser: laser gap LG; SOS-diodes D; rail sparker RG; spark-gaps SW; capacitors C; inductance coils L; voltage dividers $R_1 - R_2$, $R_3 - R_4$; current shunts R_{sh}; charging voltages U, $U(C_0)$, $U(C_1)$; signals from voltage dividers and current shunts I.

Results and discussion

The highest output energy was obtained in the gas mixture Ne : Xe : HCl = 2100 : 10 : 1 at a pressure up to 4 atm and at the pumping from a stripline pump generator (C_0 = 295 nF) with initiation of a predischarge. Under these conditions, the reduced voltage across the volume discharge plasma was 0.5–0.6 kV/(cm·atm) and the discharge current density was 200–250 A/cm^2. At an output beam aperture of 4.7×7 cm, the output energy was equal to ~9.5 J, and the laser efficiency for the energy stored in C_{Pr} was 2.5%. The characteristic oscillograms of the voltage across the laser gap, discharge current, and lasing are shown in Fig. 2.

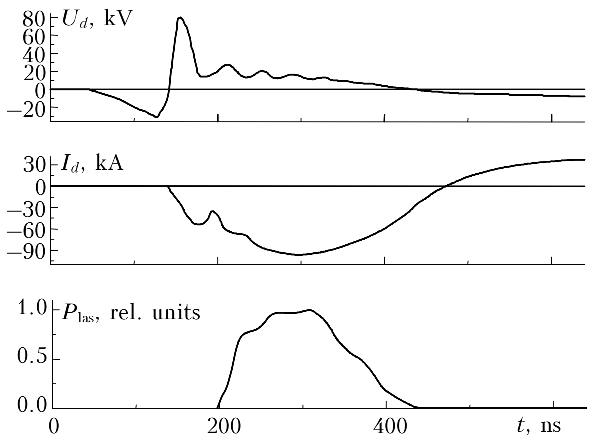

Fig. 2. Characteristic oscillograms of the voltage across the laser gap, discharge current, and lasing in the mixture Ne : Xe : HCl = 2100 : 10 : 1 at a pressure of 4 atm. The charging voltage of the capacitor C_{Pr} is equal to 50 kV.

The calculation based on the oscillograms of the discharge current and the voltage across the elements of the discharge circuit has shown that by the end of the first current half-period the capacitors store about 35 J. About 55 J is spent on the active resistance of the multichannel spark-gap and dielectric losses in lines. At an amplitude value of the volume-discharge current of about 90 kA, the power efficiency calculated as a ratio of the laser radiation specific power to the specific pump power is ~ 4.3%. The specific pump power achieves 0.5 MW/cm^3, and the laser efficiency with respect to the energy stored in the lines does not exceed 3%. As the voltage U_0 decreases from 50 to 45 kV, the pulse energy density at the output from the cavity decreases down to 5.5 J, while the laser efficiency with respect to the energy stored in striplines decreases down to ~1.9%.

When the pump generator with the capacitors (C_0 = 45 nF) is used, the output energy in the mixture Ne : Xe : HCl = (750÷2500) : 10 : 1 decreases significantly. The main reason is the decrease in the specific power deposited in the gas. In addition, the study of variation of the multichannel spark-gap active resistance and active losses in lines depending on the current strength of the volume discharge in the Ne–Xe–HCl mixture has shown that at a specific pump power lower than 300 kW/cm^3 the energy losses in the generator are mostly determined by the multichannel spark-gap.

The previous optimization of the inductive-storage pump generator performance for the wide-aperture discharge gap was carried out at C_0 = 45 nF and the laser chamber filled with nitrogen or the mixture of nitrogen with sulfur hexafluoride or NF_3. The volume discharge was formed in the gap at the increased pressure and the optimal (for the nitrogen laser) values of the parameter E_0/p (E_0 is the maximal strength of the electric field at the gap before its breakdown). The inductive storage yielded the marked increase in the lasing efficiency and energy at the transition $C^3\Pi_u \rightarrow B^3\Pi_g$ of the nitrogen molecule. The maximal output energy higher than 100 mJ at λ = 337.1 nm was obtained with an interelectrode gap of 7 cm. The efficiency of the nitrogen laser in that case achieved 0.1%.

The further experiments were conducted with the mixture Ne : Xe : HCl = 1000 : 10 : 1. The use of the inductive energy storage with the semiconductor opening switch and of the primary storage in the form of the capacitor with C_0 = 45 nF has allowed the breakdown voltage of the laser gap and the rate of increase of the discharge current to be increased. The application of the generator with the inductive storage provided the formation of the homogeneous volume discharge in the mixture with high content of xenon and HCl and decreased the switching losses in the multichannel spark-gap. However, the decrease of the specific power deposited in the gas at C_0 = 45 nF did not allow the efficient laser performance to be obtained.

An attempt to increase the capacitance of the primary storage up to C_0 = 295 nF in this laser led to the breakdown and failure of the SOS diodes as the reverse voltage was applied to the gap. The cause is in too long length of voltage pulses of the reverse polarity at SOS diodes at the current break stage. This cause can be eliminated only by changing the design of the laser chamber and placing SOS diodes at a minimal distance from the discharge gap.

Advantages of the generator with the inductive energy storage were demonstrated using the laser of an active volume of 100×4×2 cm. At C_0 = 550 nF and a charging voltage of 20 kV, the output energy of the long-pulse XeCl laser with the inductive energy storage was 1.6 J. Characteristic oscillograms of the voltage across the laser gap, discharge current, and generation of the laser with the inductive energy storage are shown in Fig. 3. As the inductive energy storage was turned off, the output energy halved.

The performances of the wide-aperture XeCl laser pumped by the inductive storage were also studied through mathematical simulation. The model used is described in detail in Ref. 12. The model was tested by comparing the calculated and measured parameters of the XeCl laser with an active volume of $2 \times 4 \times 70$ cm pumped by the inductive storage.[12]

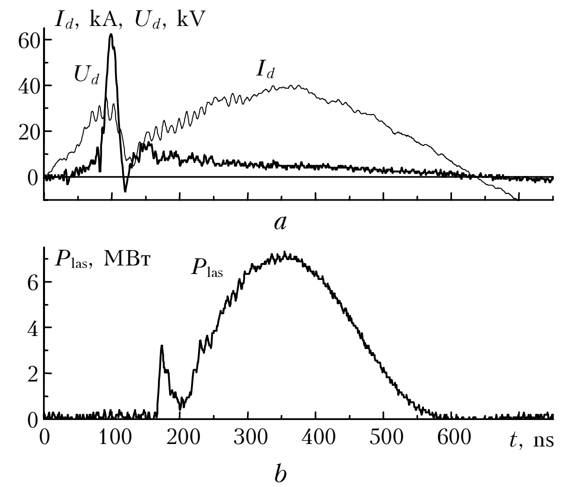

Fig. 3. Characteristic oscillograms of voltage across the laser gap, discharge current of the primary storage $C_0 = 550$ nF (*a*) and lasing (*b*) of the XeCl laser with the inductive storage, an active volume of $100 \times 4 \times 2$ cm; mixture Ne:Xe:HCl = 3 atm:10:1 Torr; U_0 = 20 kV.

Figure 4 shows the calculated time dependence of the pump power and the output laser power, as well as the voltage across the discharge gap and the discharge current for the gas mixture with a high content of xenon and hydrogen chloride.

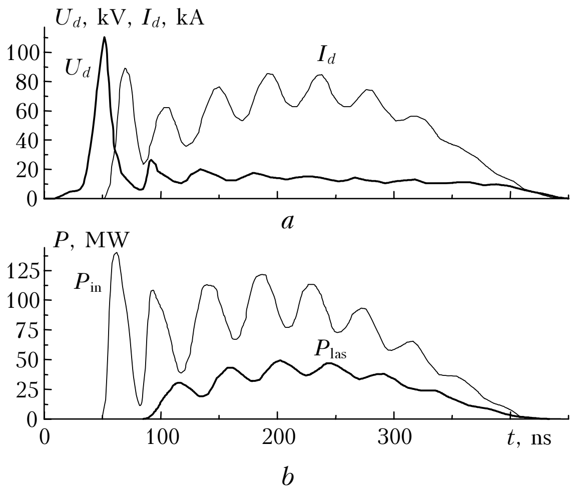

Fig. 4. Calculated time dependence of the pump power and the output laser power (*b*), voltage across the discharge gap and discharge current (*a*) for the mixture Ne : Xe : HCl = 2500 : 20 : 2.5; $p = 3.5$ atm at pumping from the generator with the inductive storage.

The break current in the diodes was 37 kA, and about 20 J were lost at the stage of break. The comparison of Figs. 2 and 4 shows that the use of the inductive storage significantly increases the breakdown voltage of the laser gap and the rate of increase of the discharge current (up to 90 kA for 20 ns). These factors provide for the formation of the homogeneous volume discharge and increase its stability. The short high-power (up to 1.4 GW and ~0.5 MW/cm^3) pump peak ensures the fast achievement of the lasing threshold and, correspondingly, decreases the loss of the pump energy. The energy deposited into the laser active medium was 25 J during the first pump peak. The laser pulse began already ~40 ns after the laser gap breakdown. Then the lasing continued during the entire first half-period of oscillation of the discharge current.

The calculations show that in these pumping modes more than 80% of HCl molecules of their initial content can be spent in plasmochemical reactions during a pulse of the discharge current. Therefore, for further increase of the laser energy, it is necessary to increase the initial concentration of hydrogen chloride in the mixture. The generator with the inductive energy storage is most efficient for pumping such mixtures. In the case of pumping from the capacitive storage, the lasing begins 20–50 ns later even at higher charging voltages (see Figs. 2 and 4). The calculated output energy in the mixture with the high content of HCl was 9.1 J at a laser efficiency of 3.6% with respect to the deposited energy. As the HCl concentration decreased, the output energy decreased down to 6.4 J.

Conclusions

It has been found that the use of the inductive energy storage with the semiconductor opening switch and the primary storage in the form of a capacitor increases the breakdown voltage of the laser gap and the rate of increase of the discharge current. These features of the generator with the inductive storage, on the one hand, lead to formation of the homogeneous discharge and increase its stability and, on the other hand, decrease the switching losses in the multichannel spark-gap. Owing to these factors, the application of the inductive storage allows the output energy and the efficiency of the XeCl laser to be increased at low charging voltages and a high content of hydrogen chloride in a mixture.

The kinetic processes of the wide-aperture XeCl laser have been analyzed theoretically in various pumping modes. It follows from the calculations that in the studied pumping modes a significant part of HCl molecules is spent in plasmochemical reactions during the pulse of the discharge current. The calculated output energy in the mixture Ne : Xe : HCl = 2500 : 20 : 2.5 pumped by the generator with the inductive energy storage was 9 J at an efficiency of 3.6%.

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