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Peculiarities of active medium formation in a short-pulse electric-discharge XeCl laser

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***Abstract*. The effect of the conditions of discharge on the output radiation parameters and efficiency of an electric-discharge XeCl laser pumped by 20 ns pulses is studied experimentally. It is shown that the highest specific energy extraction ~ 3.9 J L^{-1} atm^{-1} from the active medium is realised in a discharge formed by pronounced macroinhomogeneities. The maximum laser efficiency of 2.7 % is attained for discharge current densities of 1.2 – 1.4 kA cm^{-2}.**

Keywords: *excimer laser, active medium, medium inhomogeneities, laser efficiency, specific energy extraction.*

1. Introduction

Electric discharge excimer lasers continue to be the most efficient sources of coherent radiation in the UV spectral region, and have been drawing the attention of scientists in their quest for new pump regimes and endeavours to improve the lasing parameters. The radiation pulse duration in such lasers is usually 15 – 200 ns. Since gas-discharge plasma serves as the active medium in this case, each pump pulse duration corresponds to quite definite plasma parameters that ensure the highest energy and lasing efficiency. In this context, it becomes quite important to study the conditions of plasma formation and the effect of its parameters on the output characteristics of the laser, as well as to find optimal pump regimes for a specific pulse duration.

In most experimental works devoted to investigations of the active medium of electric-discharge excimer lasers, development of inhomogeneities in the gas-discharge plasma is treated as the main reason behind a deterioration of the output characteristics of the laser. The dynamics of growth of inhomogeneities has been studied in several experimental [1 – 5] and theoretical [6, 7] works. The discharge inhomogeneities 'growing' from the cathode surface were registered in [1 – 4, 8, 9]. In one case [3, 8, 9], the inhomogeneities were connected with bright cathode spots, while in another case [4] they were observed in the absence of cathode spots (the discharge current density in this work was 100 – 250 A$\times$ cm^{-2}). Some authors [3, 8 – 10] attribute the emergence of inhomogeneities to nonuniform emission of electrons and the formation of cathode spots, while some other authors [11, 12] assume that inhomogeneities appear due to an inadequate overlapping of electron avalanches in the discharge gap.

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The theoretical model considered in [6] treats the evolution of inhomogeneities of various spatial scales as the reason behind the premature termination of the lasing pulse. Thus, microinhomogeneities in the form of $\sim 0.5 - 1$ mm-long channels cause a depletion of halogen in them and a subsequent initiation of spark. According to this model, discharge microinhomogeneities of the size 0.01 – 0.1 mm can strongly scatter laser radiation.

In an earlier publication [13] on the influence of macro- and microinhomogeneities on radiation parameters, we showed that discharge plasma with different types of inhomogeneities has different properties. For example, amplification is observed throughout the duration of the pump pulse ($\sim$ 100 ns) in discharge regions with macroinhomogeneities, while amplification is replaced by absorption in the regions where microinhomogeneities are manifested.

Investigations of discharge in the above-mentioned publications are confined to half-maximum current pulse durations of $\sim$ 100 ns and more. In the present work, we describe the experimental results of discharge studies for a XeCl laser pumped for a current pulse duration $\sim$ 20 ns, and study the effect of discharge inhomogeneities on the laser radiation parameters.

2. Experimental

Experiments were carried out on an electric discharge XeCl laser whose basic electric excitation circuits are shown in Fig. 1. The reservoir capacitor C_1 comprised of TDK capacitors (30 kV, 2.7 nF), while the discharge capacitor C_2 was formed by KVI-3 capacitors (16 kV, 0.47 nF). Thyratron TGI1-1000/25 was used as the switch. The UV preionisation of the discharge gap was carried out automatically during charging the discharge capacitor. Preionisation spark gaps were arranged at a distance of 30 mm from the discharge axis and were separated from one another by 20 mm. The size of the spark gaps varied from 0.5 to 2 mm. The working surface of the discharge electrodes was 650-mm long, and the gap between the electrodes was 22 mm. The electrode working surface was a spherical surface element whose radius varied in the course of the experiment. A 950-mm long plane – parallel cavity

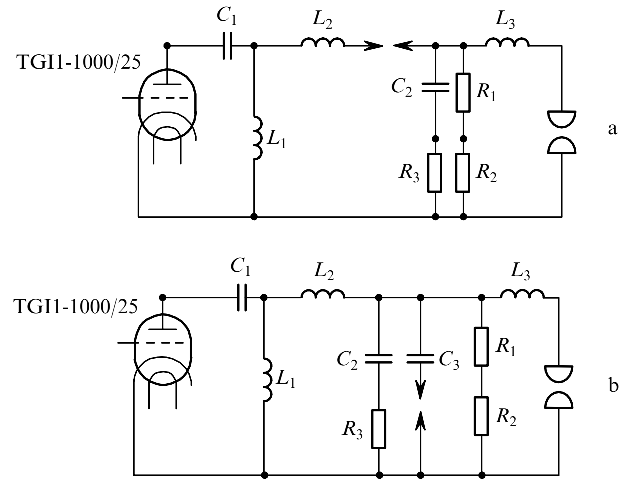

Figure 1. Basic electric circuits used in the experiment.

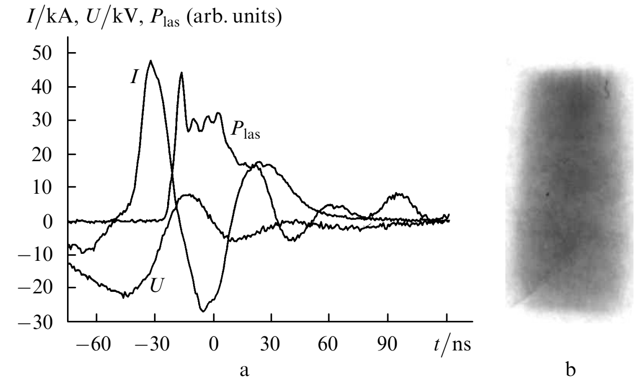

Figure 2. (a) Oscillograms of voltage (U), current (I) and output power (P_{las}) pulses and (b) the laser beam autograph for the Ne : Xe : HCl = 1000 : 15 : 1 gas mixture under a pressure $p = 3.5$ atm for $C_1 = 36.5$ nF, $C_2 = 22.4$ nF, $R_c = R_a = 60$ mm (where R_c is the cathode radius and R_a is the anode radius), charging voltage $U_0 = 23$ kV and laser radiation energy $E_{las} = 100$ mJ.

formed by a quartz plate and an external mirror with a reflectivity of 97 % was used in the experiments. The working medium was a Ne – Xe – HCl gas mixture under an overall pressure $p = 3 - 4$ atm.

The current – voltage characteristics of the discharge were recorded using a shunt that measured the current through one of the discharge capacitors, as well as a potentiometer-type voltage divider. The inductive component present during voltage recording was taken into account while calculating the discharge parameters. The output radiation energy was measured by the radiation energy and an IMO-2N power meter, the radiation pulse was recorded by a FEK-22SPU photodetector, and TDS 3014 and 3032 Tektronix oscilloscopes were used to record the current and voltage oscillograms as well as the radiation-pulse shape. The discharge glow photographs were taken through an attenuating filter in the visible spectral range using a VNC-703 CCD camera. The spatial form of laser radiation was recorded on photographic paper.

3. Experimental results

Initially, the experiments were aimed at determining the pump power at which the laser has the maximum efficiency. For this purpose, the laser was excited using the electric circuit shown in Fig. 1a. A Ne : Xe : HCl = 1000 : 15 : 1 gas mixture under an overall pressure $p = 4$ atm was used. The charging voltage $U_0 = 23$ kV remained unchanged in the course of measurements.

When electrodes with a 60-mm radius of the working surface were used, a homogenous volume discharge was formed in the electrode gap. The volume of the active medium was 1.2 cm × 2.2 cm × 65 cm, while the maximum discharge current density was 0.6 kA cm^{-2}. It can be seen from the oscillograms presented in Fig. 2a that the laser radiation pulse lasts till the end of pumping (~ 100 ns). Two periods of discharge current oscillations can be accommodated in this time interval. The autograph of the laser beam (radiation print on photographic paper) shown in Fig. 2b demonstrates a highly uniform intensity distribution in the beam. However, the laser efficiency in this mode (relative energy stored in the discharge capacitor) does not exceed 1.9 %.

As the electrode radius is reduced to 30 mm, the width of the discharge decreases to 5 mm, while the current density increases to 1.4 kA cm^{-2}. The laser efficiency in this case increases to 2.7 %. Figure 3a shows typical current – voltage characteristics and the radiation pulse in this excitation regime. One can see from the laser beam autograph in Fig. 3b that the distribution of radiation intensity near the cathode is nonuniform. Fig. 4 shows the time-integrated photograph of the discharge glow in this regime. A pronounced glow layer at the cathode surface is connected through a dark space with the main discharge volume by diffuse current channels. No visible cathode spots are formed at the places where these channels are connected with the cathode layer [4, 14].

Upon a further decrease in the electrode radius to 15 mm, the width of the discharge decreases to 3 mm, which corresponds to an average current density of 2.3 – 2.5 kA cm^{-2}. In this case, large-scale inhomogeneities that completely cover the discharge gap are observed in the discharge. The pump efficiency of the laser in this regime does not exceed 1.7 %.

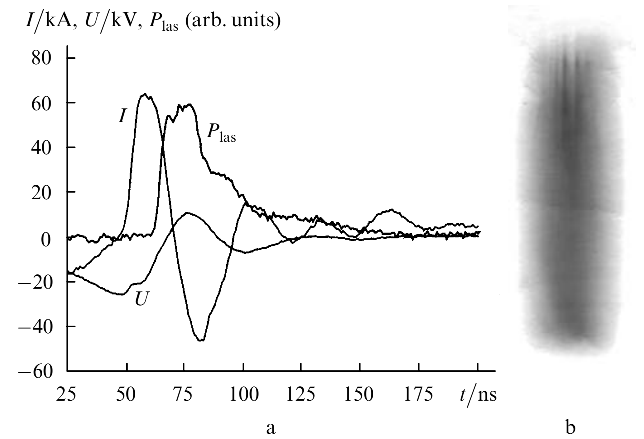

Figure 3. (a) Oscillograms of voltage (U), current (I) and output power (P_{las}) pulses and (b) the laser beam autograph for the Ne : Xe : HCl = 1000 : 15 : 1 gas mixture under a pressure $p = 4$ atm for $C_1 = 36.5$ nF, $C_2 = 22.4$ nF, $R_c = R_a = 30$ mm, $U_0 = 23$ kV and $E_{las} = 175$ mJ.

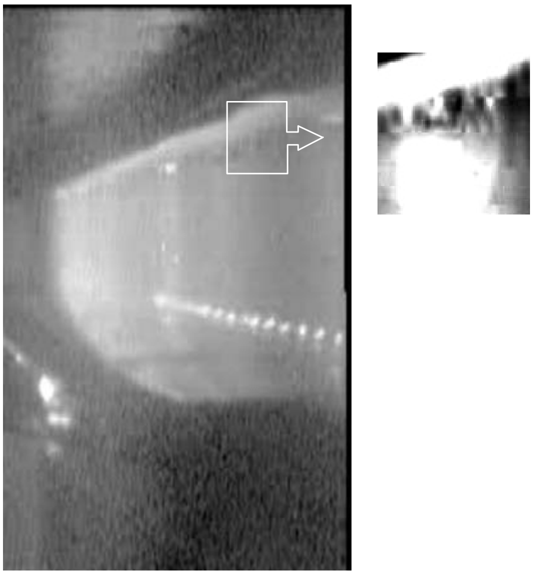

Figure 4. Time-integrated discharge glow for the Ne : Xe : HCl = 1000 : 15 : 1 gas mixture under a pressure $p = 4$ atm for $C_1 = 36.5$ nF, $C_2 = 22.4$ nF, $R_c = R_a = 30$ mm, and $U_0 = 23$ kV. A magnified fragment of the discharge region is shown on the right.

In order to study the effect of discharge inhomogeneities on the efficiency of laser operation, we carried out investigations with nonuniform electron emission from the cathode or with initial nonuniform preionisation. To increase the nonuniformity of electron emission, we used unpolished electrodes with a working surface of radius 30 mm. In this case, the discharge glow for the Ne : Xe : HCl = 1000 : 15 : 1 gas mixture was more nonuniform than that shown in Fig. 4. As the concentration of HCl in the mixture was increased to the ratio $[\mathrm{Ne}]/[\mathrm{HCl}] = 300 - 800$, the discharge consisted almost completely of a multitude of diffuse current channels. However, only the glow of the cathode layer was observed as before on the cathode surface without any individual cathode spots. Figure 5 shows the current, voltage and lasing pulse oscillograms, as well as the autograph of the laser beam in this mode. In this case, the output radiation energy was 150 mJ, which corresponds to a laser efficiency of 2 %.

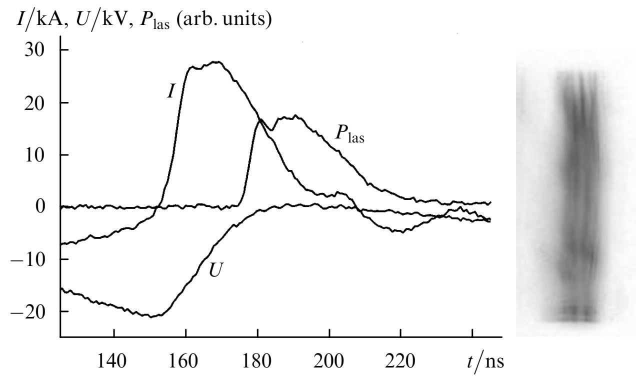

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Figure 5. (a) Oscillograms of voltage (U), current (I) and output power (P_{las}) pulses and (b) the laser beam autograph for the Ne : Xe : HCl = 833 : 16 : 1 gas mixture under a pressure $p = 4$ atm for $C_1 = 39.8$ nF, $C_2 = 35$ nF, $R_c = 20$ mm, $R_a = 40$ mm, $U_0 = 22$ kV and $E_{las} = 150$ mJ.

We also studied in our experiments the effect of the electrode material on the nature of discharge. In the specific pump power range 1.2 – 3.3 MW cm^{-3}, the nature of discharge and the output radiation parameters do not change much for electrodes made of different materials (aluminium, 12X18H9T steel, brass, brass with an electrochemically deposited nickel layer). However, if the properties of the cathode material were not uniform along its length, a stratification of the discharge was observed. No discharge glow was observed on the local zones with a lower adhesion on nickel-plated electrodes (Fig. 6). The existence and location of cathode spots were determined not by the boundary between zones with different adhesions, but by the local enhancement of the electric field (on an isolated microtip or the edge of an electrode). The cathode spots disappeared after polishing the electrode surface or upon a change in the profile of its endfaces. The existence of a microtip on the cathode and the cathode spot associated with it lower the laser energy by more than 40 %. However, the nature of the output radiation remained unchanged for an electric field nonuniformity $\Delta E/E$ of the order of 2 % caused by a variation of the separation between electrodes.

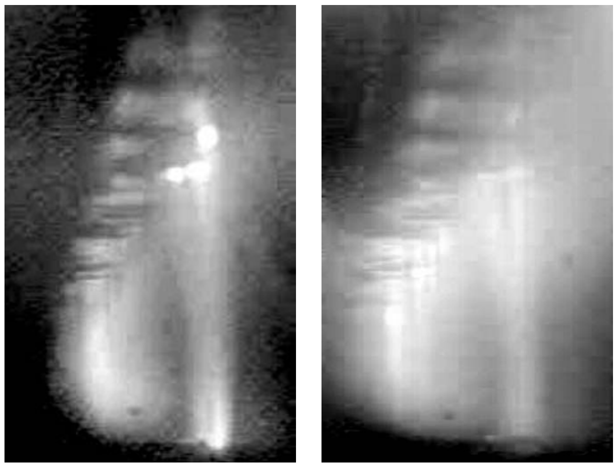

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Figure 6. Time-integrated discharge glow for (a) Ne : Xe : HCl = 500 : 10 : 1 and (b) 1190 : 10 : 1 gas mixtures under a pressure $p = 4$ atm for $C_1 = 36.5$ nF, $C_2 = 22.4$ nF, $R_c = R_a = 60$ mm, and $U_0 = 23$ kV.

The electric circuit shown in Fig. 1b was used in the experiments aimed at studying the effect of the degree and nonuniformity of preionisation on the output energy of laser radiation. The level of preionisation was lowered due to a decrease in the capacitance charged through the spark gaps. Moreover, the gaps themselves were separated by steps of 30 mm and were located at a distance of 55 mm from the discharge axis. The working radius of the cathode and anode in this case was 30 mm. For the Ne : He : HCl = 1000 : 20 : 1 gas mixture and $p = 4$ atm, the laser radiation energy was 60 mJ. The oscillograms recorded in the experiments clearly show a marked increase in the discharge resistance. As the pressure of the mixture was reduced to 3.5 atm and the halogen concentration was lowered to Ne : HCl = 1150 : 1, the discharge resistance decreased and the radiation energy increased to 80 mJ, but the laser efficiency did not exceed 1 %. However, the discharge glow was homogeneous and comparable with that shown in

Fig. 4. It can be assumed that the microinhomogeneities present in such a discharge start absorbing laser radiation at a certain instant [13].

In addition to the above-mentioned inhomogeneities, we must also mention the one for which the laser intensity distribution over the discharge gap displays a dip at the centre. This type of nonuniformity is observed for the pump regime with a maximum laser efficiency upon a decrease in the halogen concentration in the mixture below the optimal value. In this case, the lasing delay time increases relative to the onset of the discharge current. For the Ne : He : HCl = 1300 : 20 : 1 gas mixture and $p = 3.6$ atm, the laser efficiency decreases to 2.4 %. Upon a further decrease in the halogen concentration in the mixture, the efficiency continues to fall, and the dip in the intensity distribution in the central part of the beam becomes even more pronounced (Fig. 7). Upon a decrease in the halogen concentration, the homogeneity of the discharge glow improves, and the region of maximum glow corresponds to the dip in the intensity distribution of the laser beam.

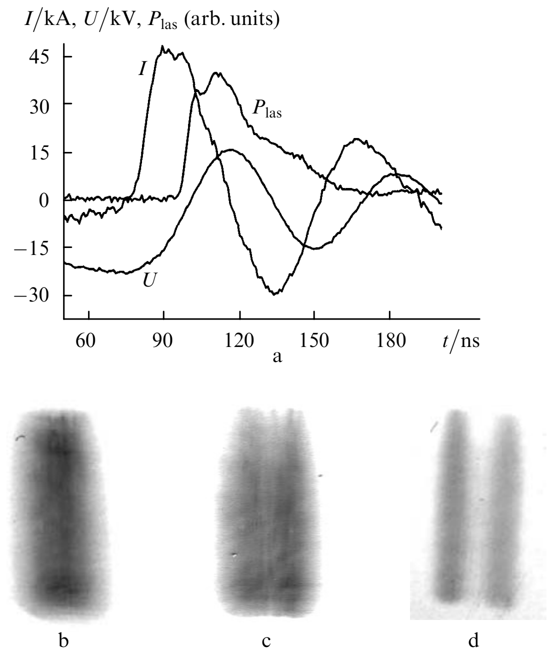

Figure 7. (a) Oscillograms of voltage (U), current (I) and output power (P_{las}) pulses and (b–d) laser beam autographs for the Ne : Xe : HCl = 1000 : 15 : 1 (b), 1285 : 30 : 1 (c) and 2000 : 30 : 1 (d) gas mixtures with pressure $p = 3.6$ atm for $C_1 = 39.8$ nF, $C_2 = 32$ nF, $R_c = R_a = 30$ mm, $U_0 = 22$ kV and $E_{las} = 210$ (b), 185 (c) and 80 mJ (d).

4. Discussion of results

It can be concluded from the experimental studies that a high discharge current density ($\sim 1.2 - 1.4$ kA cm^{-2}) is required for an efficient operation of the laser with a pump pulse duration of ~ 20 ns. A large number of incomplete diffuse plasma channels overlapping at a certain distance from the cathode are observed in the discharge in the vicinity of the cathode. The distance at which this occurs for a certain pump power increases with halogen concentration in the mixture beyond the optimal value. In the limit, the diffuse channels may completely cover the discharge gap. In this case, the volume discharge is converted into a discharge consisting almost entirely of macroinhomogeneities. Assuming that the channels are equidistant along the gap as well as across it, approximate calculations lead to a value 3.9 J L^{-1} atm^{-1} for the specific output energy for such an active medium. The laser efficiency remains quite high (2 %) in this case. However, for a more homogeneous discharge and for the highest efficiency, the specific output energy did not exceed 1.2 J L^{-1} atm^{-1}, which is a typical value for electric-discharge XeCl lasers.

According to the experimental data, it can also be assumed that the discharge under consideration may contain inhomogeneities of two types (micro- and macroinhomogeneities). We believe that these inhomogeneities are due to the following reasons. In the initial stage of the discharge current growth, a finite number of electron avalanches always exist in the vicinity of the cathode due to limitations associated with secondary emission. Subsequently, the nonuniformity of electron concentration near the cathode region may spread to the entire region in the form of macro- or microinhomogeneities, depending on the power supplied to the discharge and the concentration of HCl in the mixture.

We believe that for a small concentration of the halogen carrier and a high pump power, the discharge current in the entire gap between the electrodes begins to flow through a large number of microfilaments over a short time. Such an assumption stems from the results of our earlier publication [13], where microinhomogeneities were detected directly upon an increase in the radiation intensity. Depending on the duration of pumping, such a medium may amplify or absorb laser radiation. The latter circumstance explains the dip in the intensity distribution observed at the centre of the beam in one of the series of our experiments. No such dip was observed upon a decrease in the pump power density (for an electrode radius of 60 mm).

Upon an increase in the concentration of HCl, the time during which it is burnt out in microinhomogeneities near the cathode increases. At the same time, the competition between microchannels and the possibility of their transformation into macrochannels increase. In our opinion this is accompanied by a change in the mechanism of electron emission from the cathode on account of an increase in the plasma conductivity. Thus, while secondary photo- and ion-electron emission may be sufficient for maintaining a large number of microchannels, a decrease in their number and an increase in the current density in them may lead to a transition to cold electron emission as a result of redistribution of the field in the electrode gap. In turn, an increase in the electron emission from the cathode leads to a rapid increase in the transverse size of the inhomogeneity. A steep leading front of the current passing through the discharge facilitates the emergence of a large number of equivalent centres of cold electron emission. This is confirmed by an examination of the cathode surface after the termination of its operation: a large number of local traces of erosion without microcraters are observed on the surface of the cathode. However, the presence of individual microtips on the electrode leads to a sharp enhancement of the electric field in these regions and to the emergence of favourable conditions for explosive emission, which is manifested outwardly in the form of bright cathode spots and diffuse channels associated with them.

5. Conclusions

The main results of this research can be summed up as follows.

(i) The maximum laser efficiency (2.7 %) of an electric-discharge XeCl laser with a pulse duration of 20 ns is attained for discharge current densities of 1.4 kA cm^{-2}.

(ii) Discharge with a clearly manifested glowing layer on the metal cathode surface without any perceptible cathode spots is observed for pump current densities of 0.6 – 1.4 kA cm^{-2}.

(iii) Inhomogeneities are always formed in a discharge for current densities exceeding 1.2 kA cm^{-2}. The type of inhomogeneity is mainly determined by the halogen concentration in the mixture. The discharge mainly consisted of macroinhomogeneities for a ratio $[Ne]/[HCl] = 800$, while for ratios $[Ne]/[HCl] = 1500$ and more, it consists of microinhomogeneities. The rate of formation of inhomogeneities increases with Xe concentration in the mixture.

(iv) The highest specific energy extraction from the active medium equal to ~ 3.9 J L^{-1} atm^{-1} for a high laser efficiency (~ 2 %) is realised in a discharge consisting of completed microinhomogeneities.

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