

PULSE-PERIODIC XeCl LASER WITH A SYSTEM OF GASEOUS MIXTURE REGENERATION

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Results of investigations aimed at increase of the output energy, operating lifetime, and beam quality of a typical XeCl laser are reported in this paper. Double-peak dependence of output energy on the ratio of peaking and storage capacities has been discovered for the first time in experimental run. The reasons for the occurrence of these peaks have been explained. Data on mirror fouling and cyclic operation regime allow us to conclude that laser power is decreased due to occurrence of finely-dispersed particles in an active medium at the initial stage of laser operation (up to 10^6 switching on). Efficiency of a new system of gaseous mixture regeneration has been demonstrated. This system does not require cryogenic apparatus, maintains the HCl concentration constant, and removes finely dispersed particles and a number of harmful molecular admixtures.

Field of applications of pulse-periodic excimer lasers (PPEL) is intensively extended. First of all, this is connected with a possibility to focus an output beam in a spot of small diameter and with insignificant reflection of radiation from plasma formed by the leading edge of a light pulse. In the last few years appreciable efforts have been made to improve the energy parameters and to increase operating lifetime of these lasers.

When effect of the discharge circuit parameters on laser output energy was studied, the ratio of peaking and storage capacities was found to be optimal for two-circuit design with $C_p/C_s \ll 1$ (see Refs. 1–3) or $C_p/C_s \sim 1$ (see Refs. 4 and 5), where C_p and C_s denote the peaking and storage capacities, respectively. Longer operating lifetime can be achieved using systems of gaseous mixture purification and regeneration. Such systems are based on freezing out of admixtures and addition of HCl into gaseous mixture⁶ or on freezing out of particles of admixtures and removal of the remainder through their reaction with askarite followed by elimination of products of this reaction using molecular sieves⁷.

This technique of gaseous mixture purification and regeneration is complicated because cryogenic apparatus is used. It is a long multistage process, and a pause in laser operation is required. Moreover, one of the main components of excimer gaseous mixture (HCl) is removed together with harmful admixtures, whereas gaseous mixture is polluted by water vapor,⁷ which is to be removed using molecular sieves.

In this paper, performance of a typical pulse-periodic XeCl laser is studied to increase its output energy and operating lifetime.

In our experiments, we used an excimer laser with a system of regeneration developed by us that does not require cryogenic apparatus.

An active volume of the laser was formed by two stainless steel electrodes, and a discharge gap was 500 mm long.

Preionization of gaining region was provided by the UV radiation from two rows of auxiliary discharges (100 spark gaps) on both sides of a grounded electrode. Each auxiliary gap was powered by an individual capacitor C_{pr} .

Gas circulation through a discharge region was provided by a diametric fan with a magnetic coupling. Gaseous mixture was cooled using a radiator manufactured as a set of copper plates spaced 6 mm apart. A resonator was composed of a nontransmitting flat mirror with a multilayer dielectric coating (reflectance at 308 nm was $R = 99.6\%$) and a plane-parallel quartz plate of KU-1 type.

A discharge was excited by a high-voltage generator of two-circuit design with a TGI1-1000/25, commutation switch (see Fig. 1a). Storage battery capacity C_s and preionization capacity C_{pr} of a condenser battery intended for power supply of auxiliary discharges were 40 and 1.6 nF, respectively. Peaking capacity was varied from 0 to 40 nF. Charging voltage up to 25 kV was applied to storage capacitor through a smoothing resistor $R = 200 \Omega$.

Output energy and average power were measured by the IMO-2N power meter. In our experiments, we used He being 99.995 pure, Xe being 99.999 pure, HCl being 99.0 pure, and H₂ being 99.95 pure.

During lifetime tests, average output power was monitored using the EN 3001-2 recorder.

A system of laser gaseous mixture regeneration with gas vacuum apparatus is shown in Fig. 2.

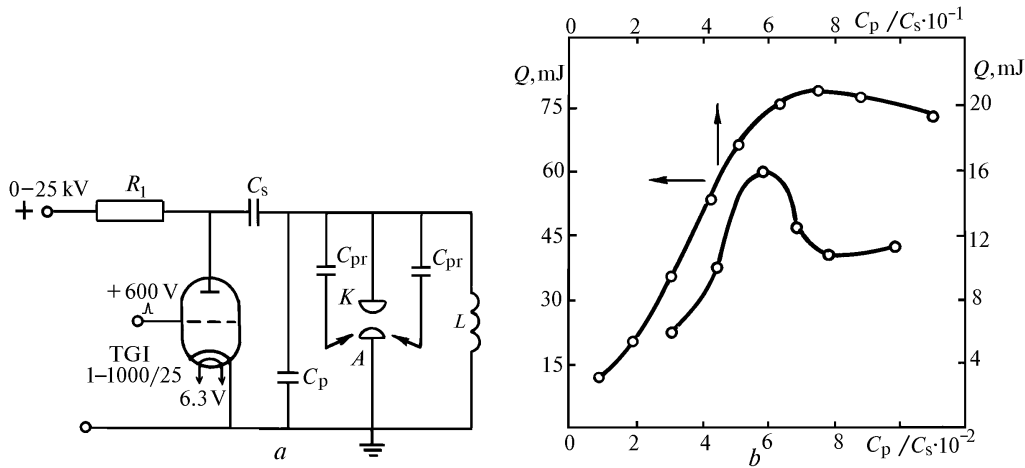


FIG. 1. Circuit diagram of discharge excitation. Here $R = 200 \Omega$, $C_s = 40 \text{ nF}$, $C_p = 0-40 \text{ nF}$, $C_{pr} = 1.6 \text{ nF}$, and $L = 45 \mu\text{H}$ (a). Laser output as a function of ratio C_p/C_s with $C_s = 40 \text{ nF}$, $U_{ch} = 22 \text{ kV}$, and $\text{He}:\text{Xe}:\text{HCl}:\text{H}_2 = 1000:100:1:0.5$ (b).

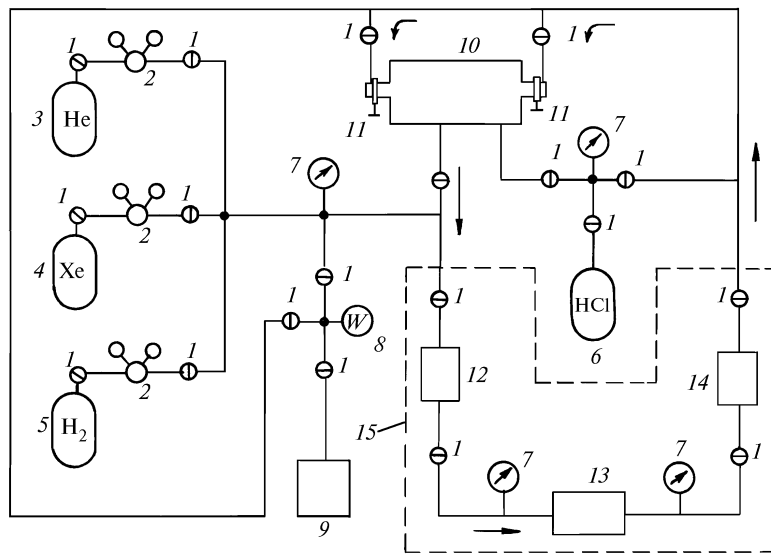


FIG. 2. System of gas admission and regeneration comprising gas-vacuum valves (1), high-pressure reducers (2), helium containing vessel (3), xenon containing vessel (4), hydrogen containing vessel (5), hydrogen chloride containing vessel (6), compound pressure and vacuum gages (7), MLT-2 thermocouple lamp (8), forevacuum pump (9), laser chamber (10), sluice valves (11), dust filter (12), oil-free microcompressor (13), regeneration cartridge (14), and regeneration system (15).

Exhausted gaseous mixture from the laser chamber 10 passed through the regeneration system 15 including the dust filter 12 for removal of large solid particles, the microcompressor 13 for forced gas circulation, and the regeneration cartridge 14. The purified gaseous mixture again entered the laser chamber.

To eliminate the uncertainty connected with selection of C_p/C_s ratio, the laser energy was measured

as C_p varied over a wide range. Other electrical parameters were fixed, the charging voltage was 22 kV. Data shown in Fig. 1 b indicate that there are two radically different peaks of output energy at $C_p/C_s = 0.06$ and 0.7. In our opinion, they may be caused by the following factors. When $C_p \sim C_s$, the discharge duration is shortest. Indeed, as C_p is increased up to C_s , the discharge duration shortens due

to energy accumulation in peaking circuit having the lowest inductance when the energy is added to gas, since the peaking capacitors are closer to a discharge glow-gap, because of their distribution along the electrodes and the absence of switch in this circuit. Thus, the condition of the shortest discharge duration is simultaneously the closest one to the condition of switchless energy addition to gas. As a rule, optimal C_p is slightly lower than C_s since discharge is initiated during voltage rise time and charging of C_p in the process of discharge glow.

Further increase in C_p leads to longer discharge duration. It is evident that optimal ratio C_p/C_s will slightly change for different excitation circuits, but condition of the shortest discharge duration must be preserved. In this case, the highest degree of discharge homogeneity is achieved, since temporal factor is especially important from the viewpoint of formation of microstructure and contraction of discharge when stepwise ionization significantly affects the current flow.

Occurrence of the second peak when $C_p \ll C_s$ can be explained using the approach developed in Refs. 8 and 9. According to this approach, discharge in XeCl mixtures exhibits an S-shaped current-voltage characteristic (CVC). Indeed, lower branch of this characteristic corresponding to positive differential conductivity, indicates that stable low-current homogeneous discharge formation is possible. In this case, a local increase in electron concentration n_e in plasma results in higher efficiency of electron attachment to vibrationally excited $\text{HCl}(v)$ molecules, whose rate of production increases in this region. Our estimations performed for the first peak of discharge current demonstrate that at $C_p/C_s = 0.06$, $n_e \approx 10^{13} \text{ cm}^{-3}$ is the highest possible value of electron concentration of lower branch of the discharge characteristic. Bending of current-voltage characteristic is at this point. Further increase in C_p leads to higher electron concentration and unstable discharge corresponding to the branch of current-voltage characteristic with negative differential conductivity.

Further behavior of output energy with increase in C_p and ratio C_p/C_s is caused by two competitive processes: lower degree of discharge stability due to stronger influence of stepwise ionization and improved degree of discharge homogeneity due to shortening of discharge duration.

In pulse-periodic operation mode of XeCl laser gradual decrease of output power is observed. This is caused first of all by occurrence of admixtures, fouling of optical parts, and HCl depletion. Output power as a function of operation time (curve 1 in Fig. 3, the first day of tests) was obtained at low pulse repetition rate without switching on the system of gas circulation through the discharge gap. It is seen that after 2 hours of continuous operation output power decreased by a factor of 2.5 at a specific energy supply of 115 mJ/cm^3 . Addition of hydrogen chloride to the

gaseous mixture did not result in appreciable increase of output power. Temperature of gaseous mixture remained constant and could not influence the output power. The main contribution to the decrease of the laser output power was made by mirror fouling. After mirrors were cleaned, the output power increased almost up to its initial level.

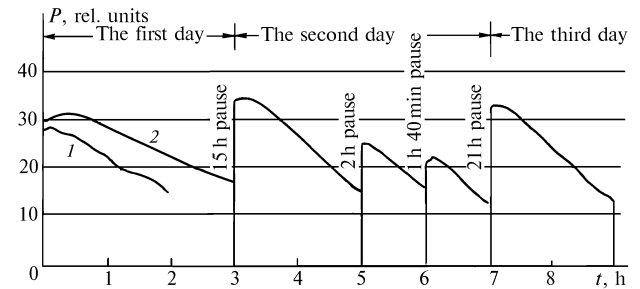


FIG. 3. Output power P as a function of operation time t for $p = 2.8 \text{ atm}$, $W = 100 \text{ J/l}$, $\text{He:Xe:HCl:H}_2 = 1000:100:1:0.5$, and pulse repetition rate $\nu = 30 \text{ Hz}$.

Output power versus time of operation at a pulse repetition rate higher than in the previous case is shown in Fig. 3 (the first day, curve 2). This curve was obtained after switching on the system of gas circulation. It is seen that after more than 3 hours of operation or $3.2 \cdot 10^6$ pulses, the output energy was halved. Hence, a 15-fold increase in lifetime is observed as compared to the first case without gas circulation. Transverse gas flow removes finely dispersed particles and hinders their gradient and light-induced drift toward mirror surfaces.¹⁰

It is well known¹¹ that such admixtures as CO_2 , NO_2 , and NO are produced in insignificant amounts in the XeCl laser after $\sim 10^6$ pulses. Concentration of Cl_2 molecules is insufficient to cause significant absorption at $\lambda = 308 \text{ nm}$ (see Refs. 12 and 13). Hence, it is reasonable to assume that initial decrease of output power is due to occurrence of finely dispersed particles in the active medium, for example, as a result of electrode sputtering and plasmochemical reactions running in discharge plasma. Data shown in Fig. 3 confirm this assumption.

Experiments were carried out during three days with pauses of different durations. Gaseous mixture composition was selected in such a way that slight change in HCl concentration does not result in appreciable decrease of laser output power¹⁴. It is seen that a 1.5–2 fold increase in the output power is observed after each pause depending on its duration (that is on the time between switching off and subsequent switching on the laser); moreover, the amount of power increase is proportional to the pause duration. Finely dispersed particles are apparently settled on inner surfaces of laser chamber in the absence of gas discharge, and in this way gaseous mixture is purified.

However, this method of laser output power recovery is inappropriate under conditions of continuous laser operation, since pauses should be rather long and molecular admixtures that have been produced cannot be removed in this way.

We suggest a technique of gaseous mixture regeneration and a system that does not require cryogenic apparatus, maintains the output power at a constant level, and allows us to increase the operating lifetime of XeCl laser by several factors of ten.

Our system of gas regeneration provides removal of finely dispersed particles and admixtures of H_2O , CO_2 , NO_2 , and Cl_2 with simultaneous control of hydrogen chloride concentration without its addition from outside.

To this end, gaseous mixture is circulated continuously or periodically through a regeneration chamber with a volume of 200 ml without switching off the laser. There are two chemical reactants in the regeneration chamber separated by gas permeable barrier. Thirty grams of these reactants are enough to provide several tens of regeneration cycles. Every molecule of admixture or hydrogen chloride that enters this chamber produces two molecules of hydrogen chloride.

This enables us to work without any addition of HCl from outside. Gas purification and regeneration is performed at room temperature.

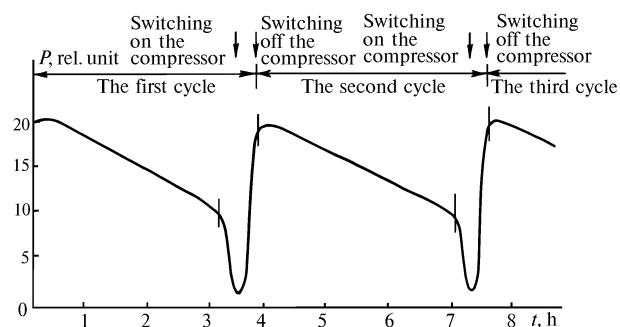


FIG. 4. Output power P as a function of operation time t with short-time switching on the regeneration system for $W = 100$ J/l, $\nu = 30$ Hz, $p = 2.8$ atm, and $He:Xe:HCl:H_2 = 1000:100:1:0.5$.

Figure 4 illustrates the output power of the XeCl laser versus its operation time as an example of cyclic regeneration. The output power was halved after 3.5 hours of operation at a pulse repetition rate of 30 Hz. At that moment, microcompressor was switched on without switching off the gas circulation, and a part of gaseous mixture began to pass through the regeneration chamber and to come back to a laser head. As a result, output power increased up to its initial value in 20–30 minutes. After microcompressor was switched off, the output power decreased by 50% during 3.5 hours, and then this

cycle was recurred. Thus, regeneration system developed by us provides fast and efficient purification and regeneration of gaseous mixture with the use of small amount of cheap reactants and without gaseous mixture exchange.

In conclusion, we summarize the following main results:

1. Occurrence of two peaks on the curve of output energy versus ratio C_p/C_s was observed for the first time in one experimental run. The reason for the occurrence of these peaks have been explained.

2. Data on mirror fouling and cyclic operating mode allow us to conclude that at the initial stage of operation (up to 10^6 switching on) the decrease of the output energy is primarily caused by the occurrence of finely dispersed particles in the active medium.

3. Efficiency of a new gas regeneration system has been demonstrated. This system does not require cryogenic apparatus, maintains the constant level of HCl concentration, and allows us to remove finely dispersed particles and a number of harmful molecular admixtures from the gaseous mixture.

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