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Prototype of a high-power, high-energy industrial XeCl laser

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Abstract. **We discuss the results of fabrication and experimental study of a high-power excimer XeCl laser for industrial applications. Compactness of the laser is achieved by the employment of a laser chamber based on a ceramic tube made of Al_2O_3. High laser output energy (1.5–2.5 J pulse^{-1}) is obtained using a wide-aperture (up to 55 × 30 mm) volume discharge with pre-ionisation by a creeping discharge. The pre-ionisation is realised through a semi-transparent electrode by the UV radiation of a creeping discharge in the form of uniform plasma sheet on a surface of a plane sapphire plate. The operating lifetime of the gas mixture amounts to ~57 × 10^6 pulses at a stabilised average laser power of 450 W. The results obtained demonstrate real prospects for developing a new class of excimer XeCl lasers with an average power of ~1 kW.**

Keywords: *excimer XeCl laser, wide-aperture laser, creeping discharge.*

1. Introduction

Technology of high-power excimer lasers requires a self-sustained volume discharge at a high pressure of the mixture of inert gases (Ne, He, Xe, Kr, Ar) with halogen (F_2, HCl). A discharge of this type is unstable and the laser output characteristics are determined by a number of factors with complicated interrelations. The main factors are the conditions of preliminary ionisation of the gas volume, the regime of energy supply into the discharge, the geometry of the active volume and the conditions of gas volume circulation. The pre-ionisation conditions include, first of all, the level of electron concentration prior to the onset of the main discharge and the uniformity of the electron distribution over the discharge volume.

In 1990s, efforts of many research groups were focused on the development of kW-power excimer lasers mainly on XeCl molecules in the frameworks of national and international programmes, some of these groups succeeded in fabricating lasers with a power of 1 kW and more [1–4]. However, most of these projects have not been realised commercially because of the high operating cost, which was mainly determined by the lifetime of the laser gas mixture containing chemically active elements.

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A longer lifetime of the gas mixture comprising halogens requires the employment of metal-ceramic design of a laser chamber. The most popular variant of a metal-ceramic excimer laser has been realised more than 30 years ago by D. Basting from Lambda Physik [5]. Presently, it is the main variant for the majority of commercial excimer lasers shipped to the world market. In these excimer lasers, the UV pre-ionisation is made by discharges, usually corona discharges, along both sides of elongated metal electrodes. Such lateral UV pre-ionisation limits the transverse cross section of the discharge, the volume of active medium, and, consequently, the output energy. In most powerful (up to 540 W) commercial Lambda SX 540 C excimer lasers [6], the aperture of the discharge is 37 × 13 mm (37 mm is the discharge height and 13 mm is the width). At the optimal large length of the discharge (~1 m) the output energy is at most 1 J. An increase in the aperture of the discharge with lateral pre-ionisation results in a nonuniform distribution of initial electrons in the gap between electrodes and, hence, in a nonuniform discharge burning and inefficient light generation. For obtaining the pulse energy of ~2 J needed for providing high-volume manufacturing of liquid crystal displays, producers of commercial lasers developed a new VYPER laser system [6, 7], in which two synchronised XeCl lasers are used simultaneously, each of them having the output energy of ~1 J. From our point of view, such an approach substantially complicates the laser system and makes it expensive.

One more drawback of the gas circulation loop of the laser chamber [5] is that the gas flow sharply changes its direction in the discharge zone, which also limits the possibility of increasing the transverse cross section of the discharge.

In order to overcome the limitations caused by lateral UV pre-ionisation, we have suggested and developed a new efficient and simple type of UV pre-ionisation based on a creeping discharge on a dielectric surface [8–10]. The electrode system of the laser described in [8, 9] was placed in a ceramic-metal chamber which comprised an aluminium tube of diameter 0.5 m and a ceramic flange made of 1 × 0.3 × 0.1 m Al_2O_3 with gasketing on the tube. The aperture of the volume discharge obtained in this laser was 55 × 30 mm and the output energy was 2.5 J at the discharge length of 700 mm. At the pulse repetition rate of 200 Hz, the excimer XeCl laser provided an average power of 500 W. Single filling of the gas mixture provided such a power for several days of continuous laser operation. Despite good output characteristics, the drawbacks of the laser were stringent requirements to the strength of the ceramic flange made of Al_2O_3, which undergoes the force of 15000 kg in the case of filling the laser chamber by the working gas mixture at a pressure of 5 bar.

Below we present the results of fabricating a high-power wide-aperture excimer XeCl laser that has no mentioned drawbacks.

2. Laser design

Figure 1 shows the transverse cross section of the laser chamber that we have suggested in [11]. The point is to fabricate a laser chamber from a ceramic (Al_2O_3) tube. According to a contract with Lambda Physik which is now a branch of Coherent Inc., we have realised this idea. The main difficulty in producing the laser chamber was to join the ceramic tube of diameter 450 mm with the mounting and end flanges. The problem was solved in the following way: the ceramic tube was placed in a rigid and tight framework in the form of a metal tube of a large diameter with ring flanges for holding the end flanges of the laser chamber. The elements of the case made of steel have been welded with the subsequent high-precision mechanical treatment of the connection flanges, which provided their alignment. The ceramic tube was installed inside the metal framework on fluoroplastic supports. This construction excludes direct contact of metal with ceramics, simplifies integration of the laser chamber and improves reliability. Also, the framework serves as a shield against electromagnetic noise. The high-voltage semi-transparent electrode and the pre-ionisation system are mounted directly on the ceramic tube. The rest elements of the laser chamber (the grounded electrode, heat exchangers, fan, spoilers and guide vanes) reside only on the end flanges not touching the surface of the ceramic tube. The grounded electrode is connected to a power supply through the current conductor that is transparent for the gas flow.

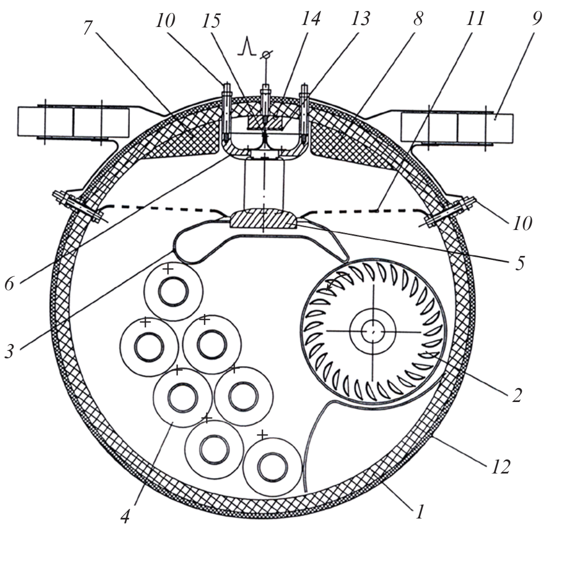

Figure 1. Design of an excimer XeCl laser:
(*1*) laser chamber based on an Al_2O_3 ceramic tube; (*2*) diametrical fan; (*3*) air deflectors; (*4*) tubes of heat exchanger; (*5*) grounded electrode; (*6*) high-voltage electrode; (*7*, *8*) ceramic flow guides with cylindrical surfaces; (*9*) pulse capacitors; (*10*) current leads; (*11*) gas-transparent leads; (*12*) steel cylindrical case; (*13–15*) UV pre-ioniser [(*13*) plane sapphire plate; (*14*) initiating electrode; (*15*) edge igniter electrode].

3. Laser characteristics

The results of the experiments on modelling the gas-dynamic contour of the laser chamber based on a ceramic tube are presented in Fig. 2, in the form of gas velocities near the high-voltage electrode, in a centre between the electrodes and near the grounded electrode. Velocities of the gas flow were measured using a Pitot tube. The rate of rotation of the stainless steel fan of diameter 150 mm was 3000 min^{-1}. One can see from Fig. 2 that the gas flow velocity near the grounded electrode was 23–25 m s^{-1}, whereas near the high-voltage electrode it was 30–32 m s^{-1}.

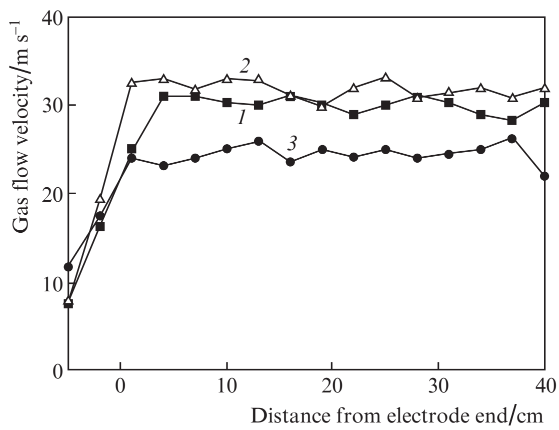

Figure 2. Gas flow velocity near the high-voltage electrode (*1*), at the centre between electrodes (*2*) and near the grounded electrode (*3*) in a laser chamber without air deflectors.

In the process of working with a prototype we have developed and tested pump systems for the XeCl laser to obtain the output energy of 1.5 and 2.5 J with UV pre-ionisation on the basis of a completed creeping discharge on the dielectric surface. The creeping discharge (CD) is heading over the dielectric (a sapphire plate) in two directions from a blade electrode (Fig. 3). The UV radiation passes through electrode slits and pre-ionises the gas between the electrodes.

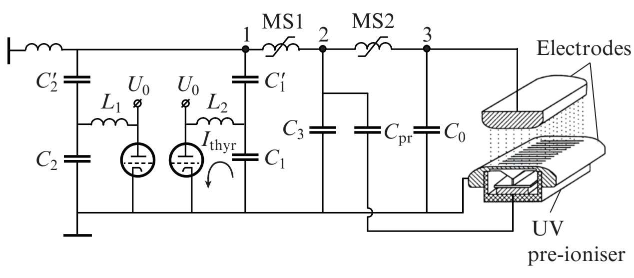

Figure 3. Scheme of the excitation circuit.

The design of the *LC*-inverter with two stages of pulse compression (Fig. 3) is similar to that described in our work [8, 9]. The *LC*-inverter is switched by two ITT 8614 thyratrons. Each of them is connected to the circuit of the *LC*-inverter through a saturated magnetic inductor (MI) intended for reducing start losses and equalising currents though the thyratrons (not shown in Fig. 3). The cross section of the magnetic coil and the number of turns of the MI needed for stable operation of thyratrons at a relatively low inductance in the saturated state have been determined. The magnetic switch (MS1) in the form of a multiple-turn saturated inductor provides an efficient transfer of the electric energy of the *LC*-inverter to an intermediate capacitor C_3 with the capacity of 140 nF and automatic pre-ionisation due to charging a small capacitor C_{pr} through the discharge gaps of the CD formation system. A single-turn magnetic switch MS2 of the second stage placed in the centre of the laser chamber is designed for transferring energy to the second-stage capacitor C_3 with the capacitance of 100 nF in a time interval of at most 180 ns.

Experimental oscillograms of the voltage pulse at the output of the *LC*-inverter (point 1 in Fig. 3), across the intermediate-stage capacitor C_3 (point 2) and across the last-stage capacitor C_0 are shown in Fig. 4 and refer to the laser prototype with the discharge aperture of 45 × 26 mm (45 mm is the separation between electrodes) for obtaining the pulse output energy of 1.5 J.

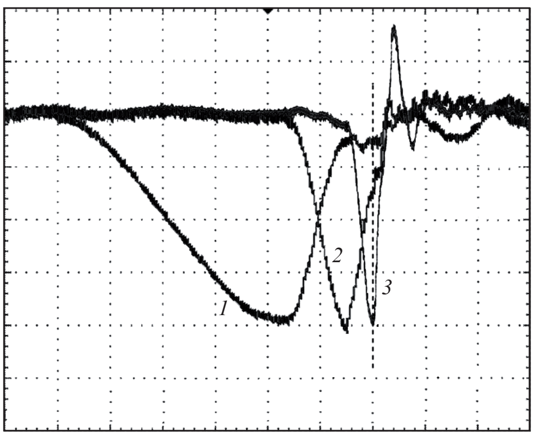

Figure 4. Experimental oscillograms (*1*), (*2*) and (*3*) of voltages in nodes 1, 2 and 3 of the electric circuit in Fig. 3, respectively. The scale is 10 kV div^{-1} for ordinate axis and 400 ns div^{-1} for the abscissa axis.

The average output power and standard deviation of the laser output energy σ have been studied as functions of the laser gas mixture composition. The optimal composition of the HCl : Xe : Ne gas mixture was 3 : 12 : 4500 at a total pressure of 4515 mbar in the laser chamber.

Investigations of dependences of the average output power and standard deviation σ on the gas mixture temperature showed that the optimal temperature is 24 – 26 °C. At the average laser power of 500 W, the standard deviation of the output energy σ in a series of 6000 pulses was 0.75 % – 0.8 % and the maximal and minimal deviations of the energy from the average value in the series were ~6 %. This confirms high stability of output characteristics of the laser.

Under the optimal conditions mentioned above the FWHM duration of the generated laser pulse at a wavelength of 308 nm was 45 ns.

In long-term tests, the stabilised average power of 450 W was maintained by varying the charge voltage of the excitation circuit and by injecting halogen to the laser gas mixture. Additional studies were performed to determine the optimal algorithm of halogen injection. The results obtained are presented in Fig. 5. In this experiment halogen injection was made once for (2 – 3) × 10^6 pulses. The lifetime of the gas mixture in this case corresponded to 57 × 10^6 pulses.

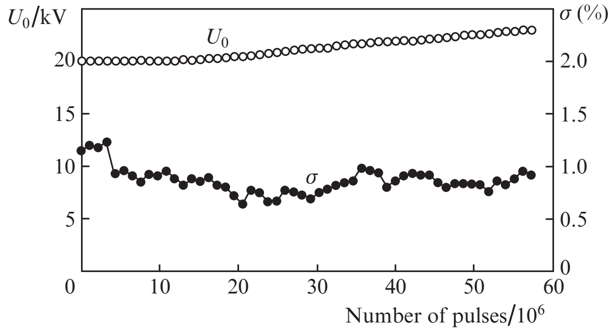

Figure 5. Charge voltage and standard deviation of the output energy σ in the regime of the stabilised output power of 450 W (1.5 J × 300 Hz) for a series of 57 × 10^6 pulses under a single gas filling with halogen injection performed by the optimal algorithm.

As was found in many experiments [1, 8 – 10], the optimal specific energy deposition to the gas mixture of wide-aperture XeCl lasers is ~100 J L^{-1}. Hence, a simple increase in the capacitance C_0 did not result in a proportional increase in the laser output energy. For increasing the energy from 1.5 J to 2.5 J it was needed to proportionally increase the energy storage of the pump system and the discharge volume. For obtaining the energy of 2.5 J the separation between electrodes was extended from 45 to 55 mm, in this case the width of the volume discharge was ~30 mm. The advantage of the developed electrode system with per-ionisation by radiation of the CD through a semi-transparent electrode is the possibility to produce a uniform volume discharge in a wide range of distances between electrodes without changing the electrode profiles [8, 9].

4. Conclusions

A simple and reliable laser chamber has been fabricated on the basis of a ceramic tube and successfully tested at the pressure of above 5 bar. For the prototype of the designed XeCl laser, we have studied the main factors affecting the stability of the output energy at the average stabilised output power ~450 W (1.5 J ×300 Hz). The conditions have been found at which the standard deviation of the output energy is no greater than 1 %.

The optimal conditions for laser operation in the long-term regime are experimentally determined, such as composition of the gas mixture, the gas temperature, the range of charge voltages of the excitation circuit, the algorithms for halogen injection, etc.

Long-term tests of the developed laser have demonstrated the possibility to provide the average stabilised power of 450 W during a cycle of 57 × 10^6 pulses for a single filling of the gas mixture.

With the same basic design, however, at increased separation between electrodes from 45 to 55 mm under an optimal increase in system energy storage, the output energy of the developed laser prototype has been found to be 2.5 J.

Estimates show that by increasing the pulse repetition rate and velocity of the cooling liquid one can obtain the average laser prototype power of ~1 kW.

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