KrF laser with a power of 100 W

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ABSTRACT

The development of effective discharge pulse-repetition KrF laser is informed. Research the possibility of forming in this laser long laser pulse with input pump energy for a few half periods of the discharge current are presented. In the repetitively pulsed regime (up to 100 Hz) laser provides laser pulses with energy of 1 J and duration of 60 ns at the base. The maximum total efficiency of the laser is 3%. The results of studies on the formation in this laser of narrowband radiation with a wide spectral band tuning are reported. The possibility of forming a radiation pulse with a linewidth 2 pm, energy 0.15 J and spectral tuning region 247.5-249.6 nm are demonstrated.

Keywords: KrF-laser, laser efficiency, volume discharge, specific pump power, high quality beam, oscillator, amplifier, amplified spontaneous emission (ASE).

1. INTRODUCTION

Discharge pulse-repetition KrF-lasers have widely practical applications in microelectronics, photolithography and medicine. For expanding of the application field of these lasers is necessary to increase the energy and quality of the output radiation improve the efficiency, reliability and service life of the laser, as well as reduce the overall weight and size and cost of the laser setup. It is known the efficiency of compact discharge KrF laser, which have automatic ultraviolet (UV) preionisation and generating pulses with energies up to 0.5 J, can be up to 4 %[1]. However, with increasing energy generation up to 1 J or more and use the same circuit design of the pump, the efficiency of these lasers is reduced to 2-2.6 %[2,3].

The main reason leading to a decrease in efficiency of the laser with great energy generation, due to increasing problems in the formation of a homogeneous volume discharge in the pump circuit with a large inductance. Therefore, it is necessary to make significant design changes for further increase the laser energy with maintaining its efficiency. In addition, a high gain and the short duration of pulse in excimer laser greatly complicate the formation of radiation with high quality. Therefore, the problem of increasing the efficiency of powerful KrF laser and quality of radiation is important.

In most cases the high-quality and high-energy radiation produced using a laser system consisting of two lasers: a small-aperture master oscillator (MO) and a wide-amplifier (Ampl). Though, there are several problems, one of which is the difficulty of synchronization of lasers. To remove this problem or significantly simplify the design and reduce its cost, a wide-laser module, in which the formation and amplification of the laser beam occurs in one of the active medium can be used[4-6]. However, at formation of a narrow bandwidth radiation in wide-aperture laser output beam takes only a small fraction of the energy stored in the active medium. In this case the spectral tuning range of the laser also becomes narrower. . These effects are due to the presence of the high level of selective and nonselective losses, the short duration of the generation and the occurrence of amplified spontaneous emission (ASE) in the optical system of the laser.

In literature some effective methods of formation of qualitative and powerful radiation in wide-aperture excimer lasers are considered. Various schemes of resonators for their realization are used : the wide-aperture dispersive resonator with spectral and spatial selection[4-6,8], the optical resonator consisting of the small-aperture spectral and dispersive resonator and the wide-aperture regenerative amplifier having the same optical axis[7,9], small-aperture dispersive resonator and one or two pass amplifier located in the same active medium[10,11]. From our point of view the last method is the most perspective. The purpose of this study was to develop an efficient KrF laser radiation energy of 1 J, to study the conditions of formation of pulses with long duration and investigation the possibility of obtaining a powerful narrow-band radiation pulse with a broad spectral tuning range.

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2. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

The studies were conducted on a compact the repetitively pulsed discharge excimer laser series EL, developed at HCEI SB RAS. The generator assembled according to the scheme of the LC-inverter with recharging at discharge capacity was used for the pump discharge in the laser.Electrical circuit of the pump generator is shown in Fig. 1. Storage C1 and C2 capacitances were 49 and 97 nF, respectively, consist of capacitors TDK UHV-6A, 2700 pF & 30 kV. Discharge C3 capacity was 30 nF and consisted of 17 capacitors Murata DHS, 2000 pF & 40 kV. The TPI1-10k/20 thyratron was used in lasers as switch. The inductance L1, L2, L3 electrical circuits were 20, 100 and 4 nH, respectively. The electrodes of the discharge gap (DG) had a length of 450 mm working surface and located at a distance of 25 mm from each other. Laser chamber windows were made of CaF_2 and were set at the Brewster angle to the optical axis. Preionization of the gap was performed UV - radiation that occurs when triggered spark gaps (SG) installed in the electrical circuit to the discharge capacity.

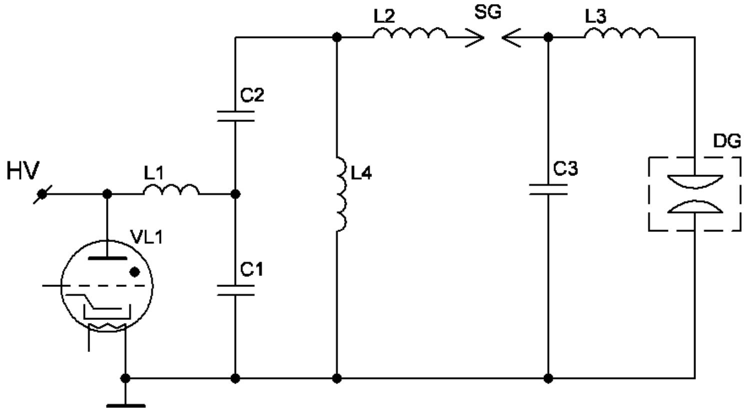

Fig. 1. Electrical schematic of the laser. C1 = 49 nF; C2 = 97 nF; C3 = 34 nF; L1 = 20 nH; L2 = 90 nH; L3 = 4 nH; L4 = 100 µH.

In experiments a gas mixture of $Ne/Kr/F_2$ at full pressure of 3.6 atm were used. Charging voltage of storage capacitor was varied in the range of 18-25 kV. Measurement of the temporal shape of the laser pulse was performed by the FEC 22SPU photodiode with an oscilloscope TDS-3032. Radiation energy was measured with a calorimeter Gentec-E. The pulse shape voltage was measured using a resistive divider located between the condenser C3 and the discharge gap. The pulse shape current was detected by low-inductance ohmic shunt installed on the capacitor C3. The spectral composition of the laser radiation was detected by spectrograph HR-4000 (Ocean Optics Inc.), the meter wavelength WS6 776 and monochromator MDR-23 with FEM (Hamamatsu). The width of the emission spectrum was determined by means of air Fabry-Perot interferometer IT28-30. The divergence of the radiation was measured using a positive lens, which focuses installed calibrated diaphragm.

3. EXPERIMENTAL RESULTS

The authors of the works presented above, come to conclusion или infer that the main reason for limiting the growth of energy and quality of radiation is insufficient lifetime of the active medium. It is shown that the reduction in the duration of generation is caused by the formation of the inhomogeneities in the discharge plasma[12]. The rate of instabilities in the discharge volume grows with increasing a specific pump power and duration of the pump pulse. In our previous studies[12, 13], we define the conditions allowing to realize effective operation of XeCl laser with the high specific power of the pump. The basis of the main requirements is the use of an electric pump circuit, which provides a very steep leading edge of the discharge current and the oscillation mode of energy input into the volume discharge. In this case, the laser pulse duration corresponds to the length of time consisting of several half-cycles of the discharge current. It is known that the volume discharge in a KrF laser is more difficult to implement than in the XeCl laser. Faster formation of instabilities in the plasma discharge KrF laser is caused not only required a high specific power of the pump, but also the fact that the unexcited molecules of fluorine, unlike HCl, more involved in the plasma-chemical reactions of dissociative electron attachment. In preliminary experiments, we studied the optimal conditions of the electrical circuits and design features of the discharge chamber KrF laser. It has been defined the required profile of the electric field in the electrode gap and provide intensive and homogeneous preionization in it. Also found were the conditions under which the generator pump provides high efficiency of energy transfer from the storage to the discharge capacity.

Fig. 2 shows typical timing waveforms laser current and voltage in the discharge capacity C3 in one mode of operation of the laser. We used the gas mixture $Ne/Kr/F_2$ = 3500/120/4.5 mbar, at a total pressure P = 3.6 bar and the external plane-parallel resonator length of 110 cm. The duration of the laser pulse was 30 ns (FWHM) and at the total pulse duration is more than 60 ns. Energy generation was 0.7 J at a charging voltage of 18 kV. Generation began in the first half-period of the discharge current at the maximum pump and ends at the end of the second half period. From the shape of the discharge current pulse can be seen that the leading edge of the pulse duration of 8-10 ns and the rate of increase of the discharge current in this case is 4.5×10^{12} A/s. Implementation of the steep leading edge of the current pulse and intense homogeneous preionization ensure the formation of the volume discharge and burning during several half-cycles. In addition, a rapid increase of the pump power has reduced delay time threshold generation that led to additional increase in the pulse duration of the output radiation.

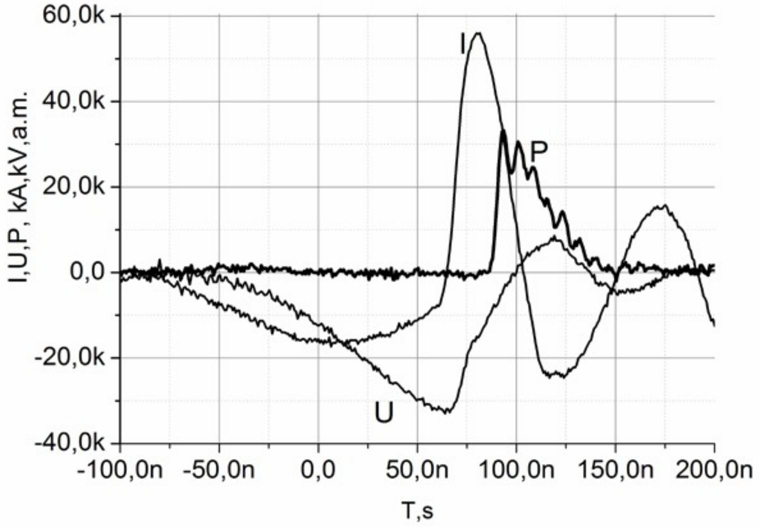

Fig. 2. Oscilloscope traces of the laser beam (P), the discharge current (I) and the voltage (U) at the discharge capacity of C3 for a mixture of $Ne/Kr/F_2$ = 3500/120/4.5 mbar, P = 3.6 bar, for U_0=18 kV.

The dependence of the energy generation and total efficiency of the laser from the charging voltage for a mixture of $Ne/Kr/F_2$ = 3400/120/7.5 mbar at a total pressure P = 3.6 bar are shown in Figure 3. It can be seen that for the charging voltage of 18-20 kV the maximum efficiency of the laser makes up 3 %. With further increase of the charging voltage laser efficiency drops to 2.2 %. This effect is due to the development of inhomogeneities in the volume discharge and reduction in the share of energy transmitted from the storage in the discharge capacity. Changing the charging voltage of 18 to 25 kV virtually no effect on the width of the discharge current, this was 9.5 ± 0.5 mm. In this case, the volume of the active medium 109 ± 6 cm3, the maximum specific output energy reaches a value of 9.5 ± 0.4 mJ/cm^3.

For the formation of high-quality beam in the laser module, we used the optical system consisting of a master oscillator (MO) and two-pass amplifier. As an active medium for MO and amplifier was used different spatial parts in one volume discharge. The volume of the active medium was 115 cm^3 for discharge width of 10 mm.

Figure 4 shows the optical scheme of the KrF laser. The MO was used a dispersion resonator with a diffraction grating 2400 mm^{-1}, set in autocollimation reflection mode in the second diffraction order. Before a diffraction grating a prism telescope with twelvefold increase was placed. The laser beam is carried out through the coupling mirror with R = 8%. To reduce the divergence of the output radiation without increasing selective losses in resonator MO either side of the active medium placed two slotted aperture dimensions 2×5 mm^2. The length of the dispersion resonator was 1200 mm. The measured beam divergence in one plane is 0.2 mrad and 0.7 mrad in the other, respectively used aperture size. The output beam of the MO was 3 mJ at a wavelength of 248 nm.

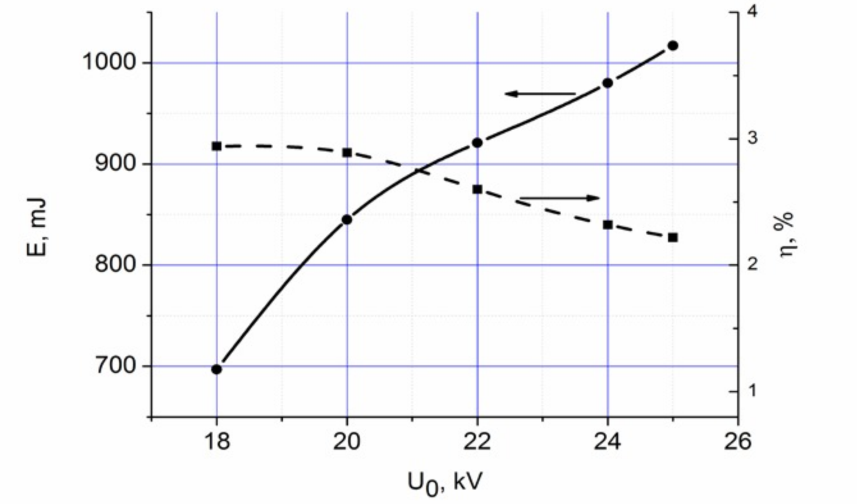

Fig.3. Dependences of the output energy and efficiency of the laser ratio the charging voltage U_0, for a mixture of Ne/Kr/F_2 = 3400/120/7.5 mbar at a total pressure P = 3.6 bar.

Further, the beam passes through the air Fabry-Perot interferometer with a base of 30 mm, lens telescope with a magnification M = 2 and got into another area of the laser active medium. The radiation energy was 30 mJ after the first pass through the amplifier, with duration of pulse of 18 ns (FWHM). Then, followed by another pass of radiation through a second matching telescope with M = 2 and the amplifier. As a result, the output beam energy was 200 mJ at a charging voltage of 24 kV. The size of the output beam was 7×18 mm^2.

Spectral tuning range of the output radiation was 247.7-249.3 nm. The energy of the beam decline smoothly and at the borders of tunable region was 80 % of the maximum value. The share of the ASE in the output beam does not exceed 10 % of the total energy of the beam. With further expansion of the spectral range of adjustment on the edges of the gain 247.5-247.7 nm and 249.3-249.6 nm, radiation energy is sharply reduced to 30 % of the initial value. The share of the ASE in the output beam increases rapidly and for the extreme points of the range is reached half of the total radiation energy.

It should be noted that the greatest influence on the formation of a narrow-band beam is available powerful radiations of ASE in the active medium. This type of radiation consists of three main parts.

The first is a single-pass ASE with a large angular divergence. In this case, set the diaphragm in the lens focal waist telescopes allowed to escape the noise emission. The second component includes highly directional radiation ASE appearing in MO. In this dispersive resonator there was sufficiently high level of optical losses leading to growth of a threshold of generation and, respectively, to increase in delay of emergence of generation.

In this case, when forming the quality beam at the trailing edge of the first half cycle of the current pulse needed to maintain the homogeneity of the active medium in the second half cycle of the pump current. These conditions are determined by the volume discharge without the presence of instabilities in the plasma, as described above. However, the formation of the laser pulse in the second half cycle of the pump current greatly reduces the gain of the active medium. In these conditions increases the degree of influence of ASE appearing in the active medium before the pulse generation. Improving the quality factor of the resonator is not allowed to increase the spectral tuning range of wavelengths in the output radiation. In the case of tuning of the radiation on the edge of the spectral profile of the gain sharply increased the share of the ASE in the output radiation.

To solve this problem, it has been enhanced specific power of the pump which is inserted into the active medium, from 2.5 to 3.5 MW/cm^3. The increase of specific pump in some cases leads to instability of the discharge, which took the form of the collapse of the width of the discharge end of the pump pulse, or to the development of small-scale instabilities in the plasma. In experimental studies we have determined the optimal conditions of the discharge, during which the plasma is homogeneous in the second half period of the current pulse. This resulted to a reduction in length of time for exceeding the lasing threshold and allowed to retain the required duration of the generation pulse. In this case, the output radiation had a narrow spectral linewidth in the broad spectral range of tunable wavelengths. The output beam of MO had a magnitude of spectral contrast to 100 for tunable spectral range.

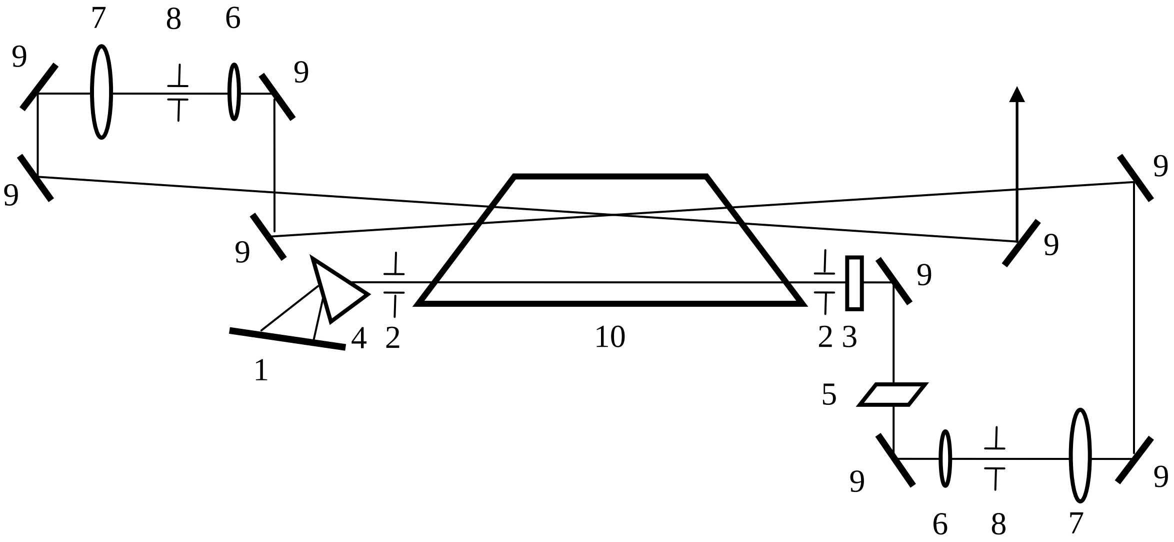

Fig. 4. Optical scheme of single-module KrF laser. 1- diffraction grating 2400 lines /mm, 2- diaphragm 2x5 mm^2, 3-output mirror with R = 8%, 4-prism teleckop M = 15, 5- air etalon (h= 30 µm), 6- positive lens F = 150 mm, 7 - positive lens F = 240 mm, 8-aperture with a diameter of 0.3 mm, 9-mirror R = 99%, 10- KrF active medium.

The third part of the ASE component in the output beam includes a double-pass flow of spontaneous emission. This noise radiation had good divergency and high intensity, which allowed him enter to the active medium of the MO and lead to the destruction forming beam. This effect significantly reduces not only the region of the spectral tuning, but also the energy of the radiation of the MO. For blocking this broadband emission, we used air Fabry-Perot interferometer with a base of 30 mkm, placed in front of the output mirror of the MO. As a result, the output of the laser was obtained by the beam having the following parameters:

- spectral linewidth of 2 pm;
- spectral tuning range of 247.5–249.6 nm;
- energy radiation of 120 mJ at a wavelength (247.8 nm);
- pulse duration of 20 ns (FWHM) and 40 ns (FWTM);
- polarization of 95 %;
- beam divergence of 0.2 mrad. (80% of energy);
- pulse repetition rate of 1-100 Hz.

It should be noted that the formation of a homogeneous active medium with a large gain and use of the original optical circuit has increased the tuning range of spectral wavelengths such lasers 1 nm to 2 nm[14].

4. CONCLUSION

Thus, as a result of present studies the repetitively pulsed KrF laser with beam energy of 1 J and the overall efficiency of 2.3 % was designed. Researches on the formation of a laser pulse with a long duration were conducted. The duration of the laser pulse was 30 ns (FWHM) and 62 ns (FWTM), which corresponds to the duration of the two half-periods of the pump current. The possibility of formation high quality beam with a pulse energy of 0.12 J with a spectral tuning in 247.5-249.6 nm was shown.

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