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# A 223-nm KrCl excimer laser on a He – Kr – HCl mixture

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***Abstract*. The results of experimental studies of the parameters of a 223-nm electric-discharge KrCl excimer laser on a He – Kr – HCl mixture depending on the excitation conditions and the composition of the active gaseous medium are presented. To achieve the maximum values of the output energy and the efficiency of the KrCl laser on mixtures with buffer gaseous helium, an excitation system was used that included a circuit with an *LC* inverter with a high-voltage switch based on an RU-65 spark gap. An output energy of 320 mJ with an efficiency of 0.5 % relative to the energy stored in the capacitors is obtained in a KrCl laser with an active medium based on the buffer He gas at a charging voltage of 30 kV. Radiation pulses with a duration of $22 \pm 1$ ns and a pulse power of 15 MW are obtained.**

***Keywords***: *KrCl excimer laser, active medium.*

## 1. Introduction

It is known that the emission spectrum of gas-discharge excimer lasers consists of lines that fill the UV spectral range of 193 to 353 nm with comparatively large spacings. Lasing is observed on excimer molecules of halides of noble gases: ArF (193 nm), KrF (248 nm), XeCl (308 nm), and XeF (349 – 353 nm). Due to their high efficiency and specific features of application, ArF, KrF, and XeCl lasers are commonly used. Note that, despite the high efficiency and the long service life of a 308-nm XeCl laser, ArF (193 nm) and KrF (248 nm) lasers (i.e., with high quantum energies of 6.5 – 5 eV) are the most widespread sources. The quantum energy is the most important parameter for many applications in the fields of microelectronics, photolithography, and medicine (ophthalmology). This is associated with the strong absorption of laser radiation at these wavelengths by most of substances and with the photochemical interaction mechanism that does not lead to a thermal destruction and ensures the submicron accuracy of processing the surface of a material.

However, one more excimer laser on $KrCl^*$ molecules with $\lambda = 223$ nm, which lies between 193 and 248 nm and is also of practical interest, has been unfairly neglected. This wavelength exceeds 200 nm that corresponds to the boundary of the high transmittance of many quartz-type optical materials and to the beginning of the absorption that introduces noticeable radiation losses in optical systems and leads to difficulties related to the quality and radiation resistance of reflecting surfaces.

However, the 223-nm radiation is quite short-wavelength and the mechanism of its action on various materials is similar to the action of the 193-nm radiation. Therefore, in some fields of use, such as ophthalmology (microsurgery of the eye cornea), the 223-nm radiation can be successfully replaced by the 193-nm radiation, which is used for this purpose, being in agreement with the spectral properties of eye cornea [1]. For such applications, a KrCl laser must have the radiation energy and time parameters close to those of 193- and 248-nm lasers: an output energy higher than 500 mJ and a maximum efficiency of $\sim 1$ %. In addition, an important parameter is the cost of the laser operation, which mainly depends on the frequency of replacing the active gaseous medium and the cost of its components. As is known, the use of helium as a buffer gas appreciably reduces the cost of the laser operation. Therefore, the objective of this work was to develop a highly efficient gas-discharge KrCl excimer laser with an active medium based on helium as a buffer gas.

Lasing in an electric discharge on the $B \rightarrow X$ transitions of $KrCl^*$ molecules near 223 nm was reported for the first time in Refs [2, 3]. In Ref. [2], a He – Kr – $BCl_3$ mixture was used as the active gaseous medium, which was excited by a double transverse discharge. In Ref. [3], a He – Kr – $Cl_2$ mixture was excited by a high-power transverse discharge and an attempt was made to obtain lasing at 223 nm in a superluminescence mode. However, the efficiency of such lasers turned out to be very low. It was shown in Ref. [4] that the energy characteristics of a KrCl laser can be improved by increasing the active volume and the stored energy and also by using HCl molecules as chlorine donors. In this work, an output energy of 100 mJ was obtained in a He – Kr – $Cl_2$ mixture excited by a transverse discharge from a low-inductance high-voltage cable storage with UV preionisation of the active medium. In this case, the total pressure of the gaseous mixture was 3.8 atm and the charging voltage was $\sim 50$ kV.

The maximum output energy (740 mJ) in a He-containing active medium of a gas-discharge KrCl laser was achieved in Ref. [5]. An active volume of 0.5 L at a 5-atm pressure was excited using a Marx generator with a charging

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voltage of 70 kV. The lasing efficiency relative to the stored energy was only 0.09 %. The maximum efficiency of a KrCl laser with an active medium based on buffer He was obtained in Ref. [6]. Its value was 0.35 % at an output energy of 50 mJ. When the buffer He gas in this laser was replaced with Ne, the efficiency and output energy increased to 0.8 % and 150 mJ, respectively.

Analysing the literature shows that there are a few works devoted to studies of 223-nm gas-discharge KrCl lasers with a buffer-He-based active medium. Lasers with this active medium are characterized by a low radiation energy or efficiency and by high charging voltages. Therefore, this work was aimed at the development of a highly efficient gas-discharge KrCl laser with the maximum attainable output energy and an active medium based on buffer He using a simple and reliable excitation circuit based on an RU-65 standard high-voltage switch.

## 2. Experimental setup

The energy and amplitude – time characteristics of the voltage, current, and radiation pulses in the nanosecond range were measured experimentally. The radiation energy was measured with an IMO-3N calorimeter and a PE50-BB pyroelectric detector (Ophir Optronics Ltd.). The shape of laser pulses was recorded using a FEK-22 coaxial photocell. The amplitude – time characteristics were measured with a Tektronix TDS 220 oscilloscope. The voltage pulses were studied using calibrated capacitive and ohmic dividers to an accuracy of $\pm 2$ %. The parameters of current pulses were measured using a low-inductance 0.02-$\Omega$ ohmic shunt. The accuracy of measuring the voltage and current amplitudes was 5 % in all experiments.

The experimental setup was described in detail in Ref. [7]. The cross section of the laser electrode had a shape close to the Chang profile with a 30-mm-wide base. The interelectrode spacing was 2.2 cm, and the length of the active medium was 60 cm. Thus, at a discharge width of 0.8 cm, the active volume was 105 cm$^3$. The automatic UV preionisation was performed by two rows of spark gaps located with 2-mm spacings at the side of the main electrodes. The chamber was sealed with plane-parallel KU1-quartz plates, one of which served as the resonator exit mirror. The second reflector was a dielectric mirror with a 97 % reflectivity at 223 nm. The resonator was 120 cm long. The gaseous mixture was circulated at a velocity of $\sim 8$ m s$^{-1}$ through the discharge gap in the transverse direction using a radial fan. The total volume of the discharge chamber with the fan was $\sim 25$ L.

A high-voltage excitation system, which included an $LC$-inverter circuit and a system for lateral automatic preionisation with UV radiation was used in the experiments (Fig. 1). This circuit consisted of storage capacitors $C_1$ and $C_2$ and two peaking capacitors $C_3$. An RU-65 standard spark-gap switch operated as a high-voltage switch. $C_1$ and $C_2$ capacitor banks were composed of identical 2.7-nF capacitors (TDK UHV-6A) with capacitances of 48 and 102 nF, respectively. After the spark gap operated and the polarity of the voltage across $C_1$ changed, the capacitors $C_1$ and $C_2$ connected in series exchanged their charges through two capacitors $C_3$, and the impact capacitance of the latter became equal to 33 nF. The capacitors $C_3$ were composed of 1.3-nF capacitors with a 40-kV breakdown voltage (TDK UHV-8A), which were mounted directly on the discharge chamber on its two sides. The optimised capacitance of each $C_3$ was 15 nF.

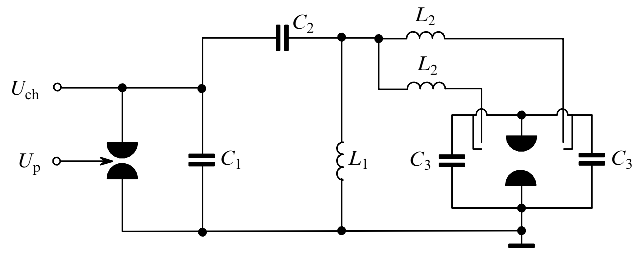


**Figure 1.** Electrical circuit of the laser: ($U_{ch}$) charging voltage; ($U_p$) ignition voltage; $C_1 = 48$ nF; $C_2 = 102$ nF; $C_3 = 15$ nF; $L_1 = 2.5$ μH; and $L_2 = 1$ μH $\times 39$.

The capacitors $C_3$ were charged from $C_1$ and $C_2$ through 78 chokes with a 1-μH inductance each, which were mounted to ensure the simultaneous operation of the spark gaps of UV preionisation. Therefore, the total inductance of all the chokes connected in parallel was $\sim 13$ nH. The charging inductance was $L_1 = 2.5$ μH. The improvement of the $LC$-inverter circuit included the use of an RU-65 standard switch in it, a decrease in the inductance of the discharge circuit, and the introduction of an inductance into the return-current conductor in order to achieve the maximum efficiency of energy transfer from the storage to the discharge circuit. The latter included the active medium.

## 3. Experimental results and discussion

The dependence of the lasing energy on the concentrations of Kr and HCl in active medium based on the buffer He was studied experimentally. Figure 2a shows the dependences of the lasing energy $E$ on the HCl percentage in the

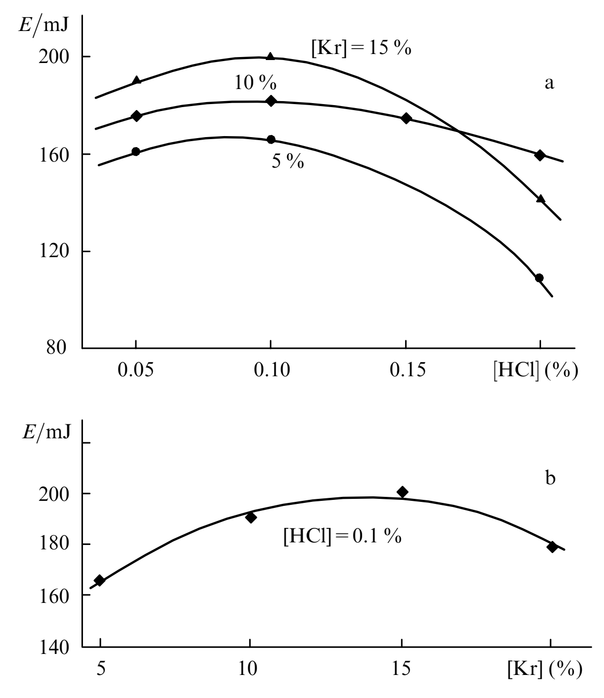


**Figure 2.** Laser output energy $E$ as a function (a) of the HCl content at various concentrations of Kr and (b) of the content of noble gas Kr at an HCl concentration of 0.1 % (for $U_{ch} = 24$ kV).

active medium for various Kr concentrations. These curves show that the maximum energy is reached at an HCl concentration of 0.1 %. Figure 2b shows the lasing energy $E$ as a function of the Kr percentage in the active medium. The maximum energy $E$ is reached at a 15 % Kr concentration. As a result, the optimal ratio of the gaseous-mixture components was obtained: He : Kr : HCl = 84.9 : 15 : 0.1. The total optimal pressure depended on the charging voltage and changed from 2.4 to 4.0 atm in the voltage range of 20–32 kV.

Figure 3 shows oscillograms of voltage pulses $U$ across the discharge gap, discharge-current pulses $J$, and laser-power pulses $P$ of the KrCl laser for a 30-kV charging voltage. We see that the delay between the fronts of the UV-preionisation and current pulses is 140 ns, at which the voltage across the peaking capacitor is 40 kV. Thus, the efficiency of the energy transfer from the storage circuit to the discharge circuit was $\sim$ 35 %. The current-pulse duration (at the base) was 40 ns; the delay time between the fronts of the discharge-current and radiation pulses was 35 ns. The radiation pulse had a bell-shaped profile and the FWHM of $22 \pm 1$ ns.

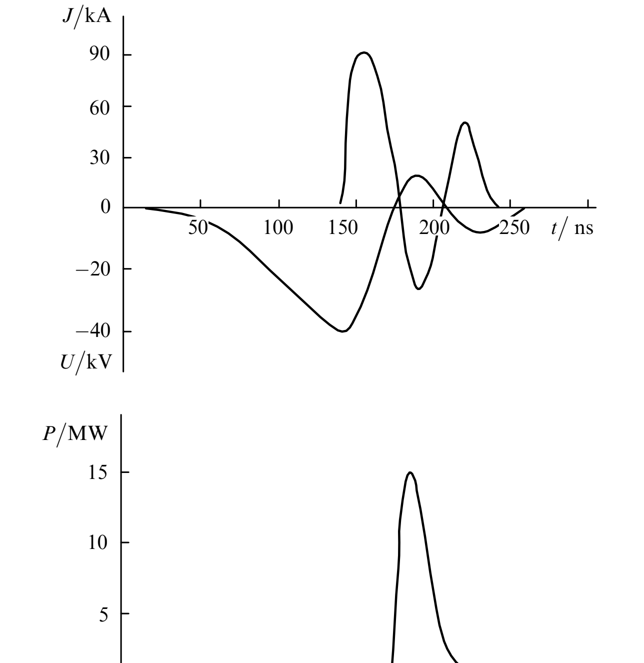


**Figure 3.** Oscillograms of voltage pulses $U$ across the discharge gap, discharge-current pulses $J$, and laser-power pulses $P$ for a mixture of the He : Kr : HCl = 84.9 : 15 : 0.1 composition; $p = 3.8$ atm and $U_{ch} = 30$ kV.

Figure 4 shows the dependences of the voltage across the discharge gap $U$, the discharge current $J$, and the specific pump power $W$ on the charging voltage $U_{ch}$. As $U_{ch}$ increases from 20 to 32 kV, the voltage $U$ increases at approximately the same rate from 27 to 41 kV. The discharge current $J$ rapidly rises from 55 to 90 kA with an increase in the pump current. Similarly to [7], the specific pump power was evaluated as a function of the charging voltage. These estimates have shown that, as the charging voltage changed from 20 to 32 kV, the specific pump power increased from 2.2 to 6.3 MW cm$^{-3}$.

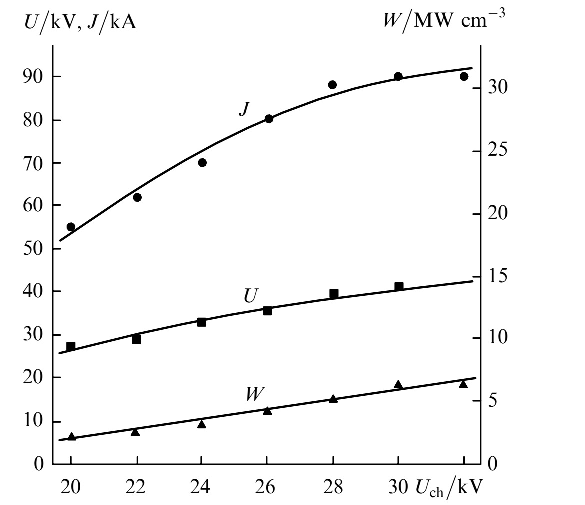


**Figure 4.** Voltage pulses $U$ across the discharge gap, discharge-current pulses $J$, and the specific pump power $W$ versus the charging voltage $U_{ch}$ for a mixture of the He : Kr : HCl = 84.9 : 15 : 0.1 composition.

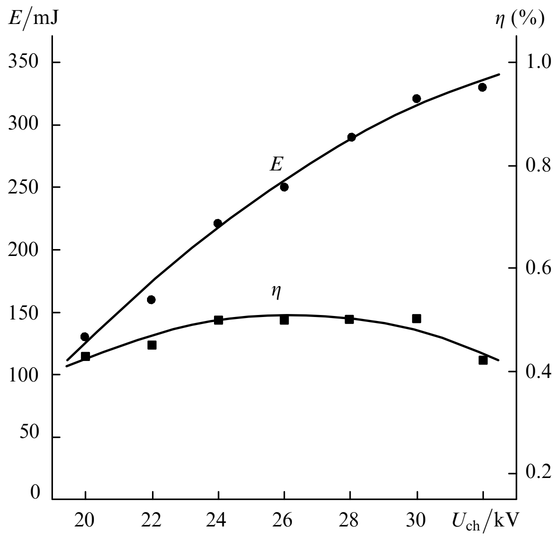


**Figure 5.** Laser output energy $E$ and the total efficiency $\eta$ of the KrCl laser as functions of the charging voltage $U_{ch}$ for a mixture of the He : Kr : HCl = 84.9 : 15 : 0.1 composition.

The high pump power and the short duration of the energy deposition allowed us to obtain a highly efficient KrCl laser with an active medium based on the buffer He gas. Figure 5 presents the radiation energy $E$ and the total efficiency $\eta$ of the KrCl laser as functions of the charging voltage $U_{ch}$. As the charging voltage increases, the radiation energy increases almost linearly. In this case, the total laser efficiency as a function of the stored energy changes slightly over the entire range of the charging voltage. The experiments performed have allowed us to obtain for the first time a lasing energy of 320 mJ with a 0.5 % efficiency for an active medium based on the buffer He gas. The efficiency relative to the deposited energy was $\sim$ 1.3 %, and the power was 15 MW for a half-height pulse duration of $22 \pm 1$ ns.

## 4. Conclusions

In this work, an efficient system for exciting excimer KrCl lasers has been developed. It includes an $LC$-inverter circuit based on an RU-65 spark gap and ensures the laser operation with a specific pump power of up to 6 MW $cm^{-3}$. A lasing energy of 320 mJ with an efficiency of 0.5% relative to the energy stored in the capacitors was attained for the first time in a gaseous medium of the He : Kr : HCl = 84.9 : 15 : 0.1 composition at a total pressure of 3.8 atm and a charging voltage of 30 kV. The laser-pulse FWHM and power were $22 \pm 1$ ns and 15 MW, respectively.

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