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Influence of the specific pump power on the output energy and efficiency of a 223-nm gas-discharge-pumped excimer KrCl laser

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***Abstract*. The influence of the specific pump power on the output energy and efficiency of a 223-nm gas-discharge-pumped KrCl excimer laser operating on the Ne – Kr – HCl and He – Kr – HCl mixtures is studied. The optimal specific pump powers are found at which the maximum values of the total efficiency and output energy of the KrCl laser are achieved. The optimal specific pump power for the Ne – Kr – HCl and He – Kr – HCl mixtures lies in the ranges from 5.0 to 5.5 MW cm^{-3} and from 5.8 to 6.5 MW cm^{-3}, respectively. The output energy of 700 mJ at the efficiency 1.0 % for the KrCl laser on the Ne – Kr – HCl mixture is obtained for the first time.**

Keywords: *KrCl excimer laser, specific pump power, output energy, efficiency.*

1. Introduction

Along with widely used ArF and KrF excimer lasers emitting at 193 and 248 nm, a 223-nm KrCl excimer laser can be successfully employed in a variety of technological, photochemical, biophysical, and medical applications. This is explained by the fact that a number of materials and biological tissues have the absorption maximum near 220 nm and, therefore, can be efficiently excited by laser radiation at 223 nm. To promote applications of gas-discharge-pumped KrCl excimer lasers, it is necessary to find optimal excitation conditions under which the maximum output energy is achieved at the maximum total efficiency. In this connection the study of the influence of pumping parameters on the efficiency of the KrCl laser is of current interest. In this paper, the total efficiency of the laser (hereafter, simply the efficiency) is defined as the ratio of the output energy of the laser to the energy stored in a storage capacitor of the excitation system.

It is known from numerous papers devoted to the study of excimer lasers that the most important parameter affecting the output power and efficiency of a laser is the specific pump power (intensity) of the active medium. However, the specific pump power is defined differently in different papers. In our paper, as in [1], the specific pump power is defined as $W = E_{st}/(V\tau)$, where E_{st} is the energy stored in a peaking capacitor; V is the active volume; and τ is the base duration of the first half-period of the current discharge. Because gas mixtures have different compositions and different processes proceeding in the plasma of lasers on different excimer molecules, the optimal specific pump powers providing the maximum efficiency and output energy of lasers will be also different. The optimal specific pump powers for the most popular 193-nm ArF, 248-nm KrF, and 308-nm XeCl excimer lasers are measured quite accurately [1 – 5]. Thus, for example, the optimal specific pump power for a gas-discharge-pumped XeCl excimer laser is the lowest and is equal to 1.0 MW cm^{-3} [1 – 3]. For KrF and ArF lasers on neon mixtures, the optimal specific pump power is higher (1.8 – 2.5 MW cm^{-3}) [1], while for the same lasers on helium mixtures this power is 3.0 – 4.0 and 4.5 – 5.0 MW cm^{-3}, respectively [4, 5].

The measurements of optimal pumping parameters for a gas-discharge-pumped KrCl laser performed in papers [6 – 12] gave inconsistent results.

The authors of papers [6, 7] recommended to use the specific pump power $W = 24$ MW cm^{-3} for obtaining the maximum values of the output energy and efficiency η. In this case, the output energy of the KrCl laser on the Ne – Kr – HCl mixture with an active volume of 70 cm^3 achieved 180 mJ at $\eta = 0.3$ %. In [7], the resonator Q factor was optimised to obtain 220 mJ of output energy at $\eta = 0.4$ %. The value of the optimal specific pump power equal to 24 MW cm^{-3} is doubtful because it is not clear from the paper how this value has been obtained and how the energy equal to 21 J has been achieved in the excitation system with a rechargeable capacitance and 17 J of energy stored in a peaking capacitor [6]. Therefore, the specific pump power equal to 24 MW cm^{-3} is obviously overstated.

The authors of papers [8 – 12] proposed the other values of W for obtaining the maximum output energy and maximum efficiency. It was reported in [8] that the output energy of a KrCl laser on the Ne – He – Kr – HCl mixture with an active volume of $90 \times 3.6 \times 1.5$ cm achieved 600 mJ for $W \sim 1.5$ MW cm^{-3} and $\eta = 0.3$ %. The specific pump power was defined in this paper as in [1]. In [9], 150 mJ of output energy with the efficiency of ~ 0.5 % was obtained in a laser on the Ne – Kr – HCl mixture with an active volume of $60 \times 3.6 \times 1.5$ cm pumped by ~ 1.5 MW cm^{-3}. However, the definition of the specific pump power was not given in

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this paper. The maximum output energy of the KrCl laser in experiments [9] was 350 mJ for $\eta = 0.3$ %. In [10], 150 mJ of output energy with the efficiency $\eta = 0.8$ % was obtained in a KrCl laser on the Ne–Kr–HCl mixture. However, excitation parameters were not presented in this paper. In [11], KrCl lasers of different designs were studied. In particular, 650 mJ of output energy with the efficiency $\eta = 0.65$ % was obtained in a laser on the Ne–Kr–HCl mixture with an active volume of $60 \times 3.6 \times 1.5$ cm when the specific pump power was 2.0 MW cm^{-3}. According to [11], the output energy of 150 mJ and efficiency of 0.8 % were obtained for the laser described in [10] for $W = 5.5$ MW cm^{-3}. The specific pump power was estimated by the expression $W = U_d J_d / V$, where U_d and J_d are the discharge voltage and current, respectively, and V is the active volume. This estimate of the specific pump power differs from the estimate used in this paper and in [1] in that the time of energy deposition into a discharge was neglected in [11]. Therefore, according to [1], taking this time into account, the specific power will be not 5.5 MW cm^{-3} but approximately 2.2–2.5 MW cm^{-3}.

The optimisation of parameters of the excitation system and discharge chamber of the KrCl laser resulted in the increase in the specific pump power up to 3.0 MW cm^{-3}, which provided 250 mJ of output energy of the laser on the Ne–Kr–HCl mixture of volume $50 \times 2.7 \times 0.7$ cm at the efficiency of 0.8 % [12].

Based on the results presented above, it is difficult to find the optimal pump parameters at which the maximum output energy and maximum efficiency are achieved. The aim of our paper was to build a high-power and highly efficient KrCl laser on mixtures with He and Ne buffer gases. The main problem was the determination of the optimal pump parameters for this laser and, first of all, the optimal range of the specific pump power.

The use of helium as a buffer gas in active mixtures of KrCl lasers described in [6, 7, 10, 11] considerably reduced the output energy. Similarly to ArF and KrF lasers [4, 5], we can assume that this is explained by relatively low specific pump powers (2.0–3.0 MW cm^{-3}) and helium mixtures also require higher pump powers than in the case of neon mixtures. It was shown in [13] that, as the specific pump power of the KrCl laser on the He–Kr–HCl mixture was increased from 2.2 to 6.3 MW cm^{-3}, the output energy increased from 120 to 300 mJ and the efficiency increased from 0.35 % to 0.5 %.

The pump parameters for the KrCl laser on helium mixtures found in [13] are not accurate because the specific pump power was estimated by assuming that the active volume was invariable, i.e. its increase due to the increase in the discharge width with increasing the charging voltage, which was observed experimentally, was neglected. This means that the value of the specific pump power obtained in [13] is correct only for the charging voltage equal to 28 kV. For lower charging voltages, the values of the specific pump power are understated, while for higher charging voltages they are overstated. We took into account this circumstance in our studies [4, 5, 14, 15].

The aim of our paper was to study experimentally the influence of the parameters of the active medium and specific pump power on the efficiency of the gas-discharge-pumped KrCL excimer laser and to determine conditions under which the maximum output energy and maximum efficiency of this laser can be achieved.

2. Experimental

The experimental setup and measurement methods used in this study are described in [13]. Recall only that the excitation system included an LC inverter with a RU-65 spark gap, automatic UV preionisation, and a low-inductive discharge circuit. To increase the specific pump power of the active medium, it was necessary to reduce the loss of energy stored in the LC inverter. This was achieved by including an additional inductance in the circuit between the LC inverter and a low-inductive discharge circuit. The influence of this inductance on the specific pump power of ArF and KrF excimer lasers is described in detail in our papers [4, 14, 15]. Such a modification of the excitation system allows us to vary the specific pump power in a broad range. Depending on the parameters of the active medium (the composition and pressure of a gas mixture and a discharge gap geometry), this power can achieve 6.0–7.0 MW cm^{-3}.

We used in experiments a discharge chamber, in which the distance between the main electrodes was 2.2 cm and the active part length was 60 cm. Our study has shown that the width of the discharge region determines the active volume of the laser and depends on the charging voltage U_{ch} and the gas mixture composition, in particular, on the buffer gas type. The width of the discharge region was measured by the method described in [15]. It was found that, as the charging voltage in the KrCl excimer laser was increased from 20 to 32 kV, the width of the discharge region in the mixture of Kr–HCl with buffer He increased from 0.4 to 0.8 cm. Thus, for the constant interelectrode gap and active length, the active volume changed from 60 cm^3 for $U_{ch} = 20$ kV up to 120 cm^3 for $U_{ch} = 32$ kV in the neon mixture and from 50 to 100 cm^3 in the helium mixture for the same charging voltages. These results were later used to estimate the specific pump power.

Automatic UV preionisation was performed by using two rows of spark gaps located on the side of one of the main electrodes [4]. The discharge chamber was sealed with MgF_2 plane–parallel plates, which were simultaneously the elements of the optical resonator. The resonator also contained an external plane dielectric mirror with the reflectivity equal to 97 % at 223 nm. The optical length of the cavity was 120 cm.

3. Results and discussion

We studied experimentally the energy and temporal parameters of the gas-discharge-pumped KrCl laser as functions of the pump parameters and gas-mixture composition. The results of such investigations for the helium mixture are partially described in [13]. In this paper, we took into account a change in the active volume at different pump levels, which allowed us to measure the specific pump power more accurately and to determine the optimal range in which the maximum efficiency is achieved.

The composition of the active gas mixture in experiments was optimised by the maximum output energy. The optimal composition of the Ne : Kr : HCl gas mixture obtained in experiments was 89.9 : 10 : 0.1. This composition was used in further investigations.

Figure 1 presents the oscillograms of voltage pulses U on a peaking capacitor, the discharge current J, and the radiation pulse I for the KrCl laser on the Ne–Kr–HCl

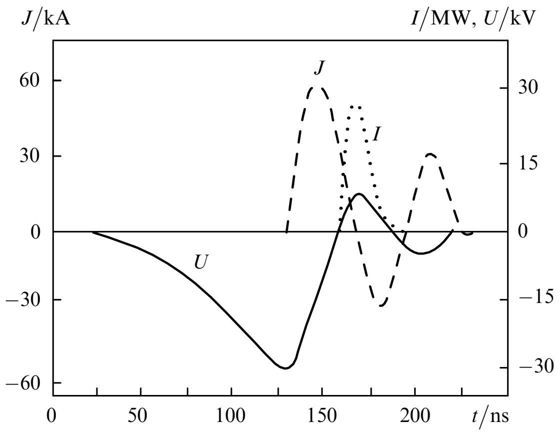

Figure 1. Oscillograms of voltage pulses U on the peaking capacitor, the discharge current J, and laser radiation I for the KrCl laser on the Ne : Kr : HCl = 89.9 : 10 : 0.1 mixture for $p = 4.2$ atm and $U_{ch} = 22$ kV.

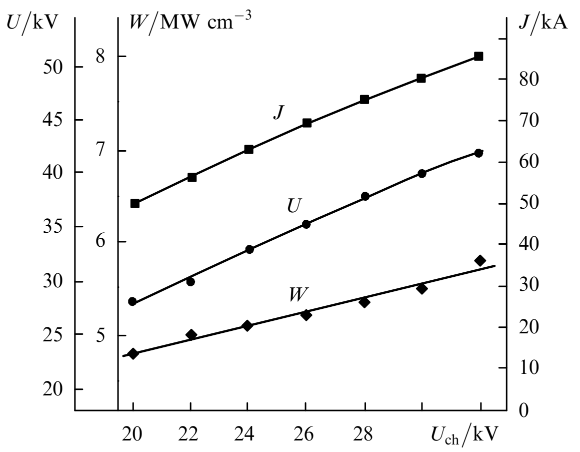

Figure 2. Dependences of the voltage U on the peaking capacitor, the discharge current J, and the specific pump power W on the charging voltage U_{ch} for the Ne : Kr : HCl = 89.9 : 10 : 0.1 mixture.

mixture for the charging voltage $U_{ch} = 22$ kV and the total pressure $p = 4.2$ atm. One can see that the delay between the onsets of the UV preionisation and discharge current pulses is 125 ns, the peaking capacitor being charged up to 30 kV. The discharge current pulse duration over the base, or the time of energy input to the discharge, is 40 ns. The delay between the onsets of discharge current and laser pulses is 35 ns, and the laser pulse duration (FWHM) is 15 ± 1 ns.

Figure 2 shows the dependences of the voltage U across the peaking capacitor, the discharge current J, and the specific pump power W on the charging voltage U_{ch} for the Ne – Kr – HCl mixture. One can see that, as the charging voltage is increased from 20 to 32 kV, the voltage U across the peaking capacitor increases from 28 to 41 kV, while the discharge current J rapidly increases from 60 to 85 kA. It was found that for each value of U_{ch} the optimal value of p existed, which increased from 4.0 to 5.0 atm with increasing the charging current. The voltage across the peaking capacitor for the He : Kr : HCl = 84.9 : 15 : 0.1 mixture increases from 27 to 41 kV, the discharge current increases from 55 to 90 kA, and the pressure mixture increases from 2.4 to 4.0 atm [13].

By using the obtained results, we estimated the specific pump power for neon and helium mixtures, similarly to [1] taking into account the change in the active volume due to the change in the discharge region width. It was found for the Ne : Kr : HCl = 89.9 : 10 : 0.1 mixture that, as U_{ch} was increased from 20 to 32 kV, the active volume increased from 60 to 120 cm^3. Then, for the duration (over the base) of the first half-period $\tau = 40$ ns, the specific pump power W increases from 4.8 to 5.8 MW cm^{-3} (Fig. 2).

Taking into account the dependence of the active volume on the charging voltage, we refined the values of W for the He : Kr : HCl = 84.9 : 15 : 0.1 mixture presented in [13]. We found that, as U_{ch} was increased from 20 to 32 kV with increasing the active volume of the laser from 50 to 100 cm^3 and for $\tau = 40$ ns, the value of W changed from 5.4 to 6.8 MW cm^{-3}.

The use of such values of specific pump powers leads to the increase in the output energy and efficiency of the KrCl laser independent of the buffer gas type. Figure 3 presents the dependences of the output energy E and efficiency η of the KrCl laser on the Ne – Kr – HCl and He – Kr – HCl mixtures on the charging voltage U_{ch}. One can see from Fig. 3a that, as the charging voltage is increased from 20 to 32 kV, the output energy of the KrCl laser on the neon mixture increases from 270 up to 750 mJ, while the efficiency changes only slightly from 0.9 % to 1.0 %. Note that 700 mJ

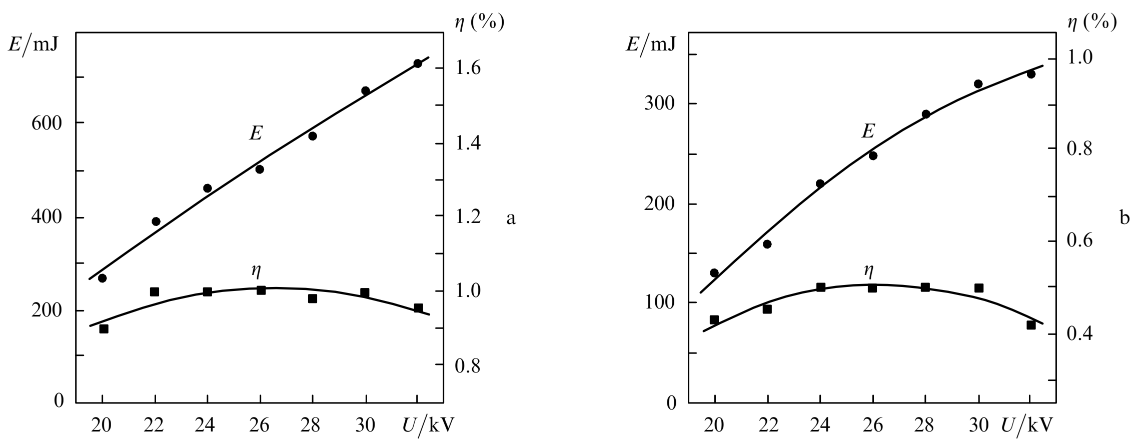

Figure 3. Dependences of the output energy E and efficiency η on the charging voltage U_{ch} for the KrCl laser on the Ne : Kr : HCl = 89.9 : 10 : 0.1 (a) and He : Kr : HCl = 84.9 : 15 : 0.1 (b) mixtures.

of output energy at the efficiency 1.0 % was obtained for the first time. These results were achieved by using the specific pump power 5.5 MW cm^{-3}. The radiation pulse duration (FWHM) measured in experiments was 15 ± 1 ns, which corresponded to the pulse power of 47 MW. The dependences of the output energy and efficiency of the KrCl laser on the helium mixture on the charging voltage were obtained in [13] (Fig. 3b). It follows from the results presented in this figure that the output energy and efficiency of the laser on the helium mixture are lower than those for the neon mixture. As the charging voltage was increased from 20 to 32 kV, the output energy of the laser increased from 130 to 330 mJ, while the efficiency changed only slightly ($\sim$0.5 %). The latter can be explained by an insignificant increase in the specific pump power with increasing the energy being stored. This is caused by the increase in the active volume of the laser due to the increase in the discharge width.

Our study has shown that the efficient operation of the KrCl laser can be provided if the specific pump power W exceeds 5.0 MW cm^{-3}.

Thus, we have determined the optimal pump parameters for the KrCl laser on the Ne – Kr – HCl and He – Kr – HCl mixtures at which the maximum efficiency is achieved. Figure 4 presents the efficiencies of the KCl excimer laser on the Ne – Kr – HCl and He – Kr – HCl mixtures on the specific pump power W. One can see that the optimal specific power range for the Ne – Kr – HCl and He – Kr – HCl mixtures is 5.0 – 5.5 MW cm^{-3} and 5.8 – 6.5 MW cm^{-3}, respectively.

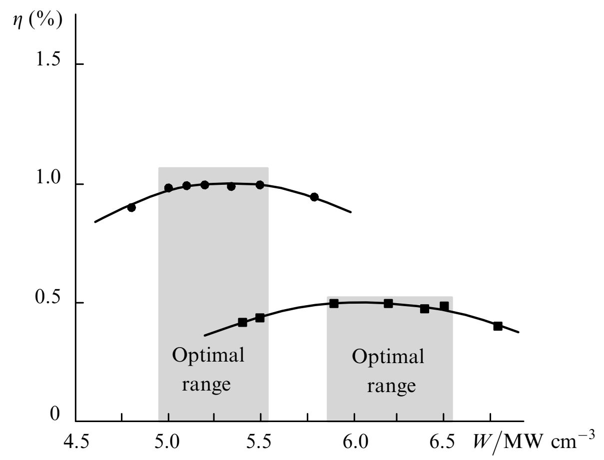

Figure 4. Dependences of the efficiency η on the specific pump power W for the KrCl laser on the Ne : Kr : HCl (●) and He : Kr : HCl (■) mixtures.

4. Conclusions

We have studied the dependences of the output energy and efficiency of the 223-nm gas-discharge-pumped excimer laser on the specific pump power. The optimal pump powers, at which the maximum efficiency and output energy are achieved, have been found for the KrCl laser operating on the Ne – Kr – HCl and He – Kr – HCl mixtures. The optimal specific pump power for the KrCl operating on mixtures with buffer neon gas is 5.0 – 5.5 MW cm^{-3}. If neon is replaced by helium, this value increases up to 5.8 – 6.5 MW cm^{-3}. The output energy of 700 mJ at the efficiency of 1.0 % has been obtained for the first time in the gas-discharge-pumped KrCl laser on the mixture Ne : Kr : HCl = 89.8 : 10 : 0.2 for $W = 5.5$ MW cm^{-3}.

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