# INCREASE OF THE EFFICIENCY OF EXCIMER ArF AND KrF LASERS WITH He AS A BUFFER GAS

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*Results of experimental investigations of the energetic and temporal pumping and lasing characteristics of pulsed gas-discharge excimer* ArF (193 nm) *and* KrF (248 nm) *lasers with* He *as a buffer gas are presented. The parameters of a modified high-voltage exciting circuit of LC-inverter type with automatic preionization have been optimized with the use of RU–65 spark-gap switch. Lasing efficiency of* 1.5% *has been obtained for the active medium* $He:Ar:F_2$ *in ratios* 79.7:20:0.3 *at a total pressure of* 2.2 atm *for an output energy of* 360 mJ. *The maximum output energy for the* ArF *laser was* 550 mJ *for efficiency of* 1.4%, 12-ns *pulse duration at half maximum, and an output energy density of* 4 J/l. *The efficiency of the* KrF *laser with the active medium* $He:Kr:F_2$ *in ratios* 89.8:10:0.2 *at a total pressure of* 2.5 atm *was* 2.4% *for an output energy of* 570 mJ. *The maximum output energy for the* KrF *laser was* 820 mJ *for efficiency of* 2.0%, 24-ns *pulse duration at half maximum, and an output energy density of* 5.9 J/l.

## INTRODUCTION

At present the most interesting and promising area of application of electric-discharge excimer ArF and KrF lasers is medicine (ophthalmology, cardiac surgery, stomatology, neuro-surgery, and dermatology) where the UV radiation is used for ablation of submicron layers of biological tissue without thermal injury.

The excimer lasers for medical applications should satisfy the following requirements on the lasing parameters: 1) the radiant energy should exceed 0.5 J to obtain an energy density of 5–6 $J/cm^2$ at the tissue surface, 2) the pulse duration should be as short as possible (commonly less than 30 ns), 3) the pulse repetition frequency should not exceed 20 Hz to minimize the thermal effect of radiation. The uniformity of energy distribution over the beam cross section, the lifetime of the active gaseous laser medium, and the simplicity and reliability of an electric exciting circuit play important roles as well.

For the first time, laser generation on transitions of BX excimer molecules of ArF (193 nm) and KrF (248 nm) mixtures was obtained in Refs. 1–3. In Ref. 1 the laser generation at these wavelengths was obtained in mixtures $He:(Ar)Kr:SF_6$ excited by a double transverse electrical discharge with preionization by a transverse discharge through a dielectric. The feasibility of KrF laser operation in the periodic pulse regime with a pulse repetition frequency of 100 Hz was first demonstrated in Ref. 4. Burnham and Djeu[5] demonstrated laser that preionization of the active medium by the UV spark radiation is more promising for obtaining high lasing efficiency and output energy and $F_2$ is better as a donor of fluorine.

A high-voltage exciting circuit of LC-inverter type without peaking capacitor (the Blumlein circuit) was used in Refs. 2 and 3. It has some advantages over the circuit with recharging capacitor.[6] Among the advantages are: 1) the feasibility of the increase of the discharge gap voltage that improves the uniformity of a space charge and increases the efficiency of energy pumping in the active medium at low charging voltages, 2) the decrease of loading on the high-voltage switch and the subsequent increase of its lifetime, because the high-voltage switch is not connected in series and hence only a portion of pumping energy is transferred through it.

A peaking capacitor is commonly inserted in the LC-inverter circuit to make the inductance of the discharging circuit low and to decrease the duration of edges of voltage and discharging current pulses. In so doing nonlinear magnetic chokes are additionally inserted in the high-voltage exciting circuit to compress the pulses and to disconnect the peaking capacitor and the discharge gap from the LC inverter when measuring the polarity of voltage on capacitors of the inverter.[7]

In Ref. 8 excimer lasers were described with He or Ne as a buffer gas that generated pulses with energies of 280 (ArF) and 500 mJ (KrF) and lasing efficiency of 0.6 and 1.1%, respectively. No significant difference between the output energies was observed for each buffer gas. The output energy density was 2.4 J/l.

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The lasers were pumped at charging voltages between 40 and 45 kV with the use of the circuit with recharging capacitor. The peak output energies were 2 J for the ArF laser, 5 J for the KrF laser[9,10] with Ne as a buffer gas, and 4.5 J for the KrF laser[10] with He as a buffer gas. The two-step Marx generator with charging voltages between 190 and 220 kV was used as an exciting circuit in these lasers. The efficiency of both lasers did not exceed 0.5%.

According to Borisov et al.,[11] the efficiency of generation of the ArF laser was 2.1% for an output energy of 270 mJ and the efficiency of the KrF laser was 3.9% for an output energy of 500 mJ. According to Ref. 12, the output energy of the ArF laser was 500 mJ for efficiency of 1% and the output energy of the KrF laser was 810 mJ for efficiency of 2.6%. These parameters of generation were achieved in mixtures with Ne as a buffer gas with the use of the high-voltage exciting circuit with recharging capacitor and automatic preionization (AP) by the UV spark radiation.

As follows from the above-discussed literature data on the gas-discharge ArF and KrF lasers, their lasing efficiency did not exceed 1.1% in mixtures with He as a buffer gas. Considering that these lasers are used in medicine where the expense of the gas mixture change is important, the problem of increasing the efficiency of these lasers with He as a buffer gas becomes urgent. Its successful solution will allow one not only to increase the lifetime of gaseous mixture, but also to increase the lifetime of elements of a discharging chamber (electrodes) and to improve the degree of uniformity of laser radiation distribution over the beam cross section.

Results of experimental investigations of the pumping and lasing energetic and temporal characteristics of the ArF and KrF lasers on mixtures with He as a buffer gas are presented in the paper. The design features of the discharge chamber and the shapes of electrodes are also studied.

The high-voltage exciting circuit of LC-inverter type with peaking capacitor and automatic UV preionization is optimized to obtain the minimum inductance of the exciting circuit and hence high pumping power and to provide the maximum efficiency of lasing and the maximum output energy for the minimum pulse duration and low charging voltages without saturating magnetic chokes.

## INSTRUMENTATION AND MEASURING TECHNIQUES

In the course of our experiments we measured energetic, amplitude, and temporal characteristics of voltage, current, and radiation pulses of nanosecond duration.

The IMO–3N calorimeter was used to measure the output energy. The FEK–22 coaxial photocell was used to record signal waveforms. The amplitude and temporal characteristics were measured with the S1–75 and S8–12 oscillographs and the I2–7 meter of nanosecond time intervals. Voltage pulses were investigated with the use of calibrated capacitive and resistive voltage dividers with an error ≤ 2%. A low-inductive ohmic shunt with a resistance of 0.02 Ω was used to measure electric current pulses. First we measured the voltage drop on the ohmic shunt and then recalculated it to the current. The amplitudes the electric current and voltage were measured with an error ≤ 5%.

## EXPERIMENTAL SETUP

Main electrodes of the discharging chamber were made of nickel and had the Chang shapes with 30-mm base widths. In the course of experiments we used the electrodes with different radii of working and side surfaces. The best results were obtained for the electrodes with working surface radii of 100 mm and side surface radii of 13 mm. The electrodes were spaced at 22 mm and the length of active part was 640 mm, so the active volume was 140 $cm^3$ for the discharge 10 mm wide. Two rows of spark gaps 2 mm wide were used for automatic UV preionization. The number of spark gaps on both sides of high-voltage electrode was 39. In the course of the experiment the distance from the electrode to the spark gap was varied from 5 to 20 mm. We analyzed the width and the degree of uniformity of the discharge, the energy distribution over the beam cross section, and the total efficiency of the laser. The optimal distance was found to be 10 mm. Laser windows were made of $MgF_2$; one window served as an output mirror of a laser resonator without dielectric coating. An external dielectric mirror with reflection coefficients of 95% at 193 nm and 99% at 248 nm served as the second mirror of the resonator 120 cm long.

The high-voltage exciting circuit of the laser comprised storage capacitors $2C_1$ and $2C_2$ and a peaking capacitor $2C_3$. The standard RU–65 spark-gap gas-filled switch was used as a high-voltage commutator. The capacitors $2C_1$ and $2C_2$ represented batteries of 66 and 132 KVI–3 capacitors, respectively, 680 pF each. The total capacitance of $2C_1$ was 45 nF and the total capacitance of $2C_2$ was 90 nF. Therefore, the total storage capacitance was 135 nF. After triggering of the switch and changing of the polarity of voltage on $2C_1$, the capacitors $2C_1$ and $2C_2$ were connected in series and the discharging capacitance was 30 nF. The capacitance of $2C_1$ and $2C_2$ was found by optimization of the output energy and efficiency of the laser. The capacitor $C_3$ comprised the KVI–3 capacitors 1000 pF each placed on both sides of the discharging chamber in the longitudinal direction to minimize the inductance of the discharging circuit.

The capacitance of $2C_3$ was varied from 20 to 45 nF to achieve the maximum efficiency of energy transfer from the storage capacitor to the peaking one. The optimal capacitance of $2C_3$ that provided the maximum output energy and efficiency of the laser was 34 nF. The capacitor $2C_3$ was charged from $2C_1$ and

$2C_2$ through 78 chokes having the inductance 1 μH each. These chokes were connected to the spark gaps of the UV preionization to provide synchronous triggering. The total inductance of the chokes connected in parallel was 12.8 nH. The storage inductance of $L_1$ was 2.5 μH.

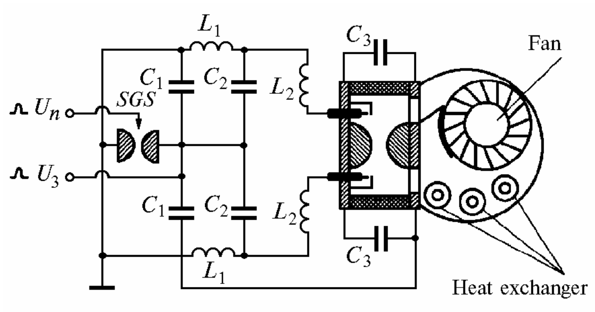


*FIG. 1. Circuit diagram and cross section of the laser: SGS denotes the* RU-65 *spark-gap switch,* $C_1$ = 22.5 nF; $C_2$ = 45 nF; $C_3$ = 17 nF; $L_1$ = 2.1 μH; $L_2$ *comprises 39 inductors* 1 μH *each.*

To achieve the high efficiency of energy transfer from $2C_1$ and $2C_2$ to $2C_3$ and the high efficiency of energy pumping into the gas mixture with He as a buffer gas without magnetic saturating choke, the high-voltage exciting circuit should have the minimum inductance. The total inductance of the circuit was a sum of the corresponding inductances of $C_1$, $C_2$, $C_3$, RU–65 spark-gap switch, input buses, and back current lines. The inductance of capacitors $C_1$, $C_2$, and $C_3$ was neglected, because each capacitor comprised many KVI–3 capacitors connected in parallel with self-induction of ~ 1 nH each. The inductance of the RU–65 spark-gap switch was ~ 10 nH and remained unchanged. It primarily affected the rate of polarity change on the capacitors $C_1$. Therefore, optimization of the circuit operation was connected with the selection of positions of the capacitors included in $C_1$ and $C_2$ near the discharge chamber and the back-current line design to maximize the efficiency of energy transfer from $2C_1$ and $2C_2$ to $2C_3$ and to shorten the time of energy pumping into the active medium.

As a result, we have developed the exciting circuit in the form of two parallel circuits comprising the spark-gap switches and the conductors $C_1$ and $C_2$ (see Fig. 1).

## RESULTS AND THEIR DISCUSSION

A composition of the active gas mixture with He as a buffer gas and its total pressure were optimized in the course of the experiments. Optimal ratios of mixture compounds established for the maximum lasing energy of the ArF laser on the mixture He:Ar:$F_2$ were 79.7:20:0.3. For the KrF laser on the mixture He:Kr:$F_2$ they were 89.8:10:0.2. The optimal total pressure depended on the charging voltage and increased from 2.2 to 2.8 atm as the charging voltage increased from 19 to 25 kV.

Figure 2 shows waveforms of pulses of the voltage on the discharge gap *U*, discharge current *J*, and laser generation $I_1$(ArF) and $I_2$(KrF). A delay between the start of the UV preionization pulse and the start of the discharge current pulse was found to be 175 ns. The current pulse was fairly short. Its length at half maximum was 25 ± 1 ns. As can be seen from the waveforms of the voltage *U* and current *J*, the discharge voltage pulse is nearly aperiodic, which provides high lasing efficiency of the ArF and KrF lasers on mixtures with He. The lasing pulse duration at half maximum was 12 ± 1 ns for the ArF laser and 24 ± 1 ns for the KrF laser.

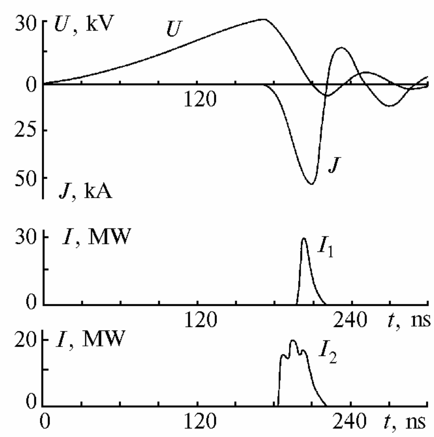


*FIG. 2. Waveforms of pulses of the voltage on the discharge gap U, discharge current J, and laser generation* $I_1$ (ArF) *and* $I_2$ (j rF) *for* $U_0$ = 19 kV.

Figure 3 shows the energy of laser generation *E* and the total lasing efficiency η of the ArF laser as functions of the charging voltage $U_0$. The obtained results demonstrate that the maximum total efficiency of the ArF laser equal to 1.5% is reached for a low charging voltage of 19 kV and an energy of laser generation of 360 mJ. As the charging voltage increased up to 25 kV, the lasing efficiency decreased slowly down to 1.4%, which allowed the record energy of laser generation equal to 550 mJ to be obtained. From this it follows that the radiant power of the ArF laser is 46 MW per pulse and the radiant energy density is 4.0 J/l.

The effect of the buffer gas composition on the lasing efficiency of ArF and KrF lasers was also studied. Our experiments on measuring the output energy and the efficiency of the laser for different ratio between He and Ne showed that addition of 50% of Ne to He did not change the amplitudes of pumping pulses illustrated by Fig. 2.

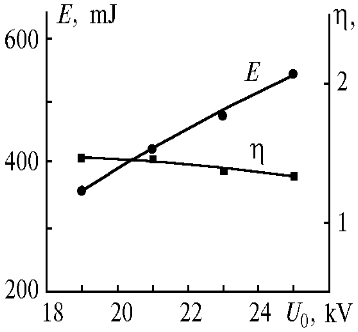


*FIG. 3. Energy of* ArF-*laser generation E and lasing efficiency* η *as functions of the charging voltage* $U_0$ *in the mixture* He:Ar:$F_2$ *in ratios* 79.7:20:0.3.

The energy of ArF-laser generation remained unchanged under these conditions, whereas the energy of KrF-laser generation increased from 570 to 700 mJ (see Fig. 4) at a charging voltage of 19 kV. Its efficiency also increased from 2.4 to 2.9%. We achieved the maximum energy of generation equal to 920 mJ with the maximum charging voltage equal to 25 kV and the lasing efficiency equal to 2.2%. The further increase of the ratio of He in the mixture in excess of 50% and the use of pure Ne as a buffer gas led to the decrease of the output energy and efficiency of ArF and KrF lasers by 20%.

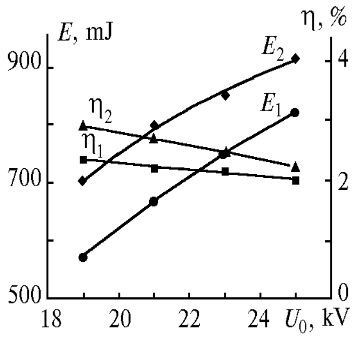


*FIG. 4. Energy of* KrF-*laser generation and lasing efficiency as functions of the charging voltage* $U_0$ *in mixture* He:Kr:$F_2$ *in ratios* 89.8:10:0.2 ($e_1$, $\eta_1$) *and* He:Ne:Kr:$F_2$ *in ratios* 49.9:49.9:10:0.2 ($e_2$, $\eta_2$).

Our investigations allowed us to design the exciting circuits for ArF and KrF lasers with high pumping power. The average ($W_{\rm av}$) and peak ($W_{\rm p}$) pumping powers were calculated. The peak power $W_{\rm p}$ was determined by integration over the waveforms of the discharge current $J$ and voltage $U_R$ equal to the difference between the total voltage $U$ and its inductive component $U_L$, that is, $U_R = U - U_L = U - L(\mathrm{d}J/\mathrm{d}t)$, where $L$ is the inductance of the discharge circuit equal to 2.7 nH. The average pumping power was calculated by the formula $W_{\rm av} = E/V\tau$, where $E$ is the energy stored in $2C_3$, $V$ is the active volume, and $\tau$ is the discharge current pulse duration. It was found that for the KrF laser the average and peak pumping powers were equal to 1.8 and 2.2 MW/cm$^3$, respectively, for the minimum charging voltage equal to 19 kV. For the ArF lasers, they were 1.9 and 2.4 MW/cm$^3$, respectively. As the charging voltage increased, the average and peak pumping powers also increased and for a voltage of 25 kV they reached 3.0 and 5.6 MW/cm$^3$ for the ArF laser and 2.5 and 3.8 MW/cm$^3$ for the KrF laser. The corresponding efficiency was 3.1% for the ArF laser and 3.6% for the KrF laser.

## CONCLUSION

As a result of our investigations, we have developed high-efficient ArF and KrF lasers with He as a buffer gas. High average and peak pumping powers have been achieved being equal to 3.0 and 5.6 MW/cm$^3$ for the ArF laser and 2.5 and 3.8 MW/cm$^3$ for the KrF laser. For the first time we obtained efficiency of 1.5% (360 mJ) for the ArF laser and 24% (570 mJ) for the KrF laser. Their maximum energy of generation was 550 and 820 mJ with efficiency equal to 1.3 and 2%, respectively. Their radiant energy density was 4 (ArF) and 5.9 J/l (KrF).

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