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High-pulse-repetition-rate UV lasers with the inductance – capacitance discharge stabilisation

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Abstract. **Compact high-pulse-repetition-rate XeF and KrF excimer lasers and an N_2 laser with plate electrodes and the inductance – capacitance discharge stabilisation are studied. The composition and pressure of the active medium of lasers are optimised for obtaining the maximum output energy and maximum pulse repetition rate at comparatively low (no more than 19 m s^{-1}) active-medium flow rates in the interelectrode gap. The pulse repetition rate achieved 4 – 5 kHz for the relative root-mean-square deviation of the laser pulse energy less than 2 %. It is found that the energy of the N_2-laser pulses changes periodically under the action of acoustic perturbations appearing at high pulse repetition rates. It is shown that the use of the inductance – capacitance stabilisation of the discharge provides the increase in the maximum pulse repetition rate by 0.5 – 1.5 kHz (depending on the active medium type). It is found that the stability of the output energy and maximum pulse repetition rate depend on the location of preionisation sparks with respect to the gas flow direction. Some ways for the development of the technology of plate electrodes and inductance – capacitance discharge stabilisation are proposed.**

Keywords: *electric-discharge XeF (KrF, N_2) laser, plate electrodes, inductance – capacitance stabilisation, pulse repetition rate, radiation energy stability, optical inhomogeneities.*

1. Introduction

At present, UV lasers with pulse repetition rates f up to a few kilohertz are being developed for various technological applications. Excimer ArF (KrF) lasers with $f \approx 4 - 5$ kHz and the gas flow rate $V \sim 60$ m s^{-1} are used in microlithography [1 – 4]. A large value of f in these works was achieved by reducing the discharge width and using the appropriate gas flow rate. The increase in the pulse repetition rate due to further increasing the gas flow rate involves considerable technical difficulties.

For example, the pulse repetition rate $f \approx 5.5$ kHz was achieved in the discharge volume of $550 \times 14 \times 2.8$ mm of a XeF laser at the active-medium flow rate $V \approx 55$ m s^{-1} [3]. The preionisation of the interelectrode gap was performed by a sliding discharge on the surface of a sapphire plate located upstream of the gas flow near a grounded electrode. The maximum value of f in the same chamber for a KrF laser was ~ 5 kHz [4].

The pulse repetition rate achieved in an electric-discharge nitrogen laser with the discharge width 1.6 mm and the gas-flow rate in the interelectrode gap $V \approx 55$ m s^{-1} was $f \approx 11$ kHz [5]. It was shown that the main reason preventing the increase in the pulse repetition rate was a competing breakdown in the region of a heated and ionised plasma trace remaining after the previous discharge. To eliminate the negative influence of this factor, additional gas channels were used to isolate a highly ionised plasma displaced downstream of the gas flow from electrodes. The maximum pulse repetition rate in a laser without additional channels was only 6.1 kHz.

The first studies of high-pulse-repetition-rate excimer lasers with a multisectional discharge gap fabricated based on plate electrodes and inductance – capacitance discharge stabilisation were performed in papers [6, 7]. This technology, which was proposed in [8], is based on the formation of extremely narrow and especially stable pump discharges of the laser active medium. The near-field laser beam width was ~ 1.3 mm. The maximum pulse repetition rate achieved 4 kHz for the moderate gas flow rate ($V \leqslant 19$ m s^{-1}).

The aim of this paper is to study further high-pulse-repetition-rate XeF and KrF lasers with F_2 donors and a high-pulse-repetition-rate nitrogen laser with additions of buffer gases He and Ne into the working mixture. Some ways for the development of the technology of plate electrodes and the inductance – capacitance discharge stabilisation are proposed.

2. Experimental results

UV lasers were fabricated based on the working chamber of a standard CL-5000 laser (TsFP, General Physics Institute, RAS, Troitsk, Moscow region) and a new electrode unit with a multisectional discharge gap described in [6, 7]. The height and total length of the discharge gap formed by twenty-five pairs of anode and cathode plates were 12 and 260 mm, respectively.

Preionisation was performed with the help of 25 spark discharges located from one side of the discharge gap downstream or upstream of the gas flow. The gas mixture was pumped with a diametric fan, which was rotated with

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the help of a magnetic clutch by a 80-W GEA-6A electric dc motor. The pulsed pump scheme of the laser is described in [6, 7].

The parameters of the XeF laser were studied in the active Xe – F_2 – Ne(He) mixture. The donor of fluorine atoms was F_2, unlike paper [6], where NF_3 was used for this purpose. For the NF_3-based active mixture [6], the output energy of a XeF laser using mixtures with buffer He and Ne gases was virtually the same, the maximum output energy being ~ 3 mJ. For mixtures based on F_2, the output energy of XeF and KrF lasers with the buffer Ne gas was higher by a factor of ~ 1.6 than that for the helium mixture. Therefore, the XeF laser was studied with the Ne buffer gas.

At the neon pressure $p_{\mathrm{Ne}} = 2000$ Torr and the voltage applied to the motor above 23 V, the failure of fan operation occurred (the magnetic clutch ceased to transfer the rotational moment to the diametric fan). For the maximum voltage of 28 V applied to the motor, the failure of fan operation was observed already at $p_{\mathrm{Ne}} = 1300$ Torr. In this connection the frequency characteristics of excimer lasers were studied for 'light' ($p_{\mathrm{Ne}} = 1100$ Torr) and 'heavy' ($p_{\mathrm{Ne}} = 2000$ and 2400 Torr) mixtures. The gas flow rates for 'light' and 'heavy' mixtures were ~ 19 m s^{-1} and no more than 16 m s^{-1}, respectively.

When the buffer gas pressure was changed, the amplitude and duration of the rising front of a voltage pulse were optimised by switching additional inductances into the thyratron circuit.

For $f \sim 5$ kHz, the failure in the thyratron operation occurred. Note that the higher the charging voltage, the stronger thyratron overloaded, and therefore the failure in the thyratron operation with increasing f occurs at the charging voltages 20 – 22 kV earlier than at 16 – 18 kV. The range of the stable operation of the thyratron also depends on the value of the additional inductance used in the thyratron circuit. For this reason, to obtain limiting pulse repetition rates of lasers, experiments were mainly performed at the charging voltage across the storage capacitor equal to $U_0 = 18$ kV. The stability of the laser pulse energy at maximal pulse repetition rates is determined most likely both by the stability of the discharge and thyratron operation. The limitation of the maximum pulse repetition rate by the range where the thyratron operated stably was also pointed out in [4].

Figure 1 presents the average pulse energies E of the XeF laser and relative root-mean-square deviations σ of the output energy in a packet of 1000 laser pulses at high repetition rates and different pressures of the buffer Ne gas.

As the neon pressure is increased from 1100 up to 2000 Torr, the pulse energy of the XeF laser increases by a factor of ~ 1.6 at all pulse repetition rates studied; as the neon pressure is further increased from 2000 to 2400 Torr, the pulse energy increases by a factor of ~ 1.4 at pulse repetition rates up to 4 kHz. A further increase in the neon pressure is impossible due to the failure in the magnetic clutch operation, and because of this the maximum Ne pressure was 2400 Torr.

Figure 1 shows that for $p_{\mathrm{Ne}} = 1100$ and 2000 Torr, the output energy decreases weakly with increasing f. For $p_{\mathrm{Ne}} = 2400$ Torr, the output energy decreased faster for $f \geqslant 3.5$ kHz. For all pressures in the range $f = 0.5 - 4$ kHz, the value of σ did not exceed 2 %, while its value drastically increased in the range $f = 4 - 5$ kHz. The limiting pulse repetition rates at neon pressures 1100, 2000, and 2400 Torr were 5 kHz ($\sigma = 2.3$ %), 4.5 kHz ($\sigma = 1.7$ %), and 4.25 kHz ($\sigma = 2.2$ %), respectively. The lower limiting pulse repetition rates observed in 'heavy' gas mixtures are caused by a lower gas glow rate. The stability of the output energy at high neon pressures and pulse repetition rates up to 4 kHz remained high ($\sigma \sim 1$ %).

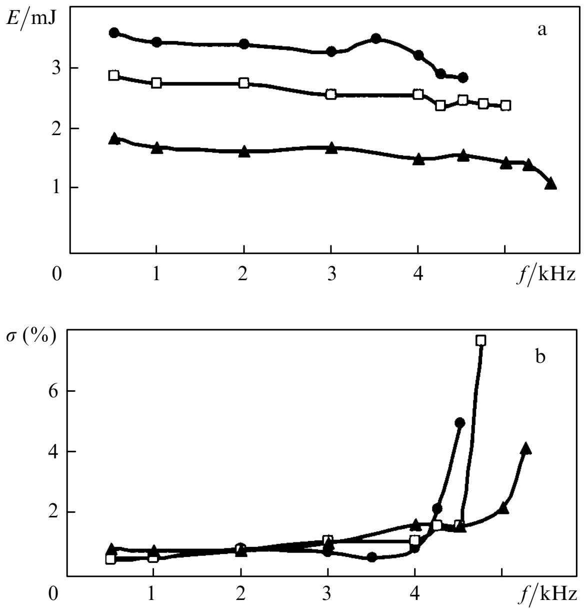

Figure 1. Dependences $E(f)$ (a) and $\sigma(f)$ (b) for the working mixtures F_2 : Xe : Ne = 10 : 10 : 1100 Torr (▲), F_2:Xe:Ne = 7:10:2000 Torr (□), and F_2 : Xe : Ne = 7 : 10 : 2400 Torr (●) of the XeF laser for $U_0 = 18$ kV.

The average output energy for $p_{\mathrm{Ne}} = 2400$ Torr, $f = 4$ kHz, and $U_0 = 18$ kV was ~ 3.2 mJ, while the average laser radiation power was ~ 12.7 W. The pulse energy at high repetition rates was 80 % – 85 % of the single pulse energy for the maximum efficiency of theXeF laser equal to 0.76 % ($p_{\mathrm{Ne}} = 2000$ Torr). As the energy input was increased by a factor of 1.5 (when U_0 was increased from 18 to 22 kV), the laser efficiency decreased down to 0.56 %. At increased energy inputs, when the thyratron operated without failure, the stability of the output radiation energy at the same pressures and pulse repetition rates remained the same.

The authors of [3] obtained the limiting pulse repetition rate ~ 5.5 kHz for $\sigma \approx 2.7$ % for a XeF laser at the same energy inputs per discharge gap length unit as in our paper. Note that the active-medium flow rate in [3] was ~ 55 m s^{-1}. In our paper, the limiting pulse repetition rate for the XeF laser at $V \leqslant 19$ m s^{-1} was ~ 5 kHz at the same energy stability as in [3], while for $V \leqslant 16$ m s^{-1} and $f \sim 4.5$ kHz, the stability was better by a factor of 1.5.

Similar studies were performed for the KrF laser. Figure 2 presents the average pulse energies E and relative root-mean-square deviations σ of the output energy for different neon pressures.

In the case of the KrF laser, the output energy decreased at all pressures more rapidly with increasing pulse repetition rate than in the case of the XeF laser. As the repetition rate was increased up to ~ 3.5 kHz, the pulse energy decreased down to 65 % – 80 % of the single pulse energy, depending on the neon pressure. This is most likely explained by a lower stability of the discharge to the perturbations of the

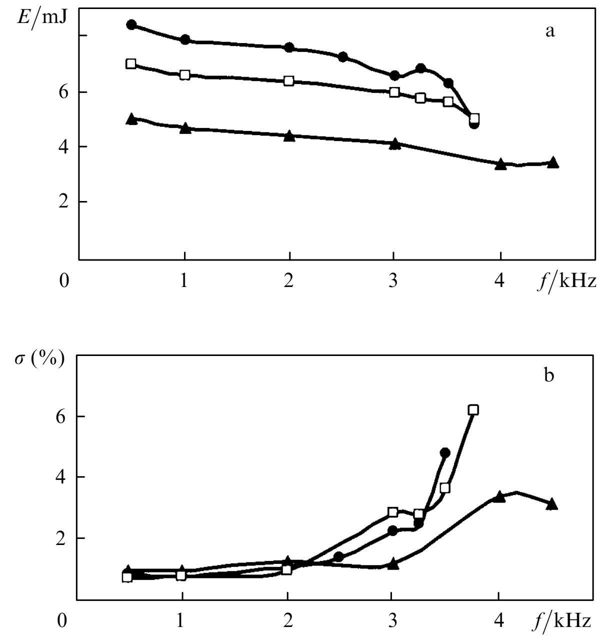

Figure 2. Dependences $E(f)$ (a) and $\sigma(f)$ (b) for the working mixtures F_2 : Kr : Ne = 4.5 : 60 : 1100 Torr (▲), F_2 : Kr : Ne = 4.5 : 60 : 2000 Torr (□), and F_2 : Kr : Ne = 4.5 : 60 : 2400 Torr (●) of the KrF laser for U_0 = 20 kV.

active-medium density in the KrF laser due to high krypton pressures.

As the neon pressure was increased from 1100 up to 2000 Torr, the pulse energy increased approximately by a factor of 1.4 in the entire interval of pulse repetition rates. As the pressure was further increased up to 2400 Torr, the pulse energy increased by a factor of 1.1 – 1.2. As in the XeF laser, for $p_{\mathrm{Ne}} = 2400$ Torr, the output energy drastically decreases and σ increases for $f \geqslant 3.25$ kHz because the gas flow rate is not high enough. For $p_{\mathrm{Ne}} = 2000$ and 2400 Torr in the range $f = 0.5 - 2.5$ kHz, we have $\sigma \leqslant 2\,\%$, and for $p_{\mathrm{Ne}} = 1100$ Torr and $f \leqslant 3$ kHz, we have $\sigma \leqslant 1.5\,\%$. As for the XeF laser, the maximal limiting frequency $f = 4.5$ kHz ($\sigma = 3.2\,\%$) was obtained in the 'light' mixture.

The average output energy for $p_{\mathrm{Ne}} = 2400$ Torr, $f =$ 3.25 kHz and $U_0 = 20$ kV was ~ 6.6 mJ, and the average power was ~ 21.6 W. The maximum efficiency of the KrF laser of $\sim 1.8\,\%$ was achieved at the same pressure ($U_0 =$ 18 kV).

In [9], the influence of the concentration of halogen-containing molecules on the discharge homogeneity was pointed out, which should affect the laser operation stability. In this connection we studied the parameters of XeF and KrF lasers at different fluorine pressures in the active mixture (Fig. 3). One can see that, as the fluorine pressure p_{F_2} is decreased, the limiting pulse repetition rate increases and $\sigma(f)$ decreases. However, the output energy decreases with decreasing the fluorine pressure. Thus, as p_{F_2} in the XeF laser was decreased from 10 to 5 Torr, the output energy decreased by 15 %. The decrease of p_{F_2} in the KrF laser from 6 down to 3 Torr reduces the output energy by 30 %. The optimal fluorine pressure with respect to the pulse repetition rate and output power was 7 Torr for the XeF laser and 4.5 Torr for the KrF laser. Note that the working concentration of F_2 in the active medium in our study is two-three times higher than that in [3]. This is probably explained by a considerably higher (by factor of ~ 3) specific pump power used in our paper. Thus, the discharge stability with respect to the density perturbations in the active media of XeF and KrF lasers increases with decreasing the concentration of F_2 molecules. As a result, the limiting pulse repetition rate increases and the laser operation stability improves; however, the output pulse energy decreases.

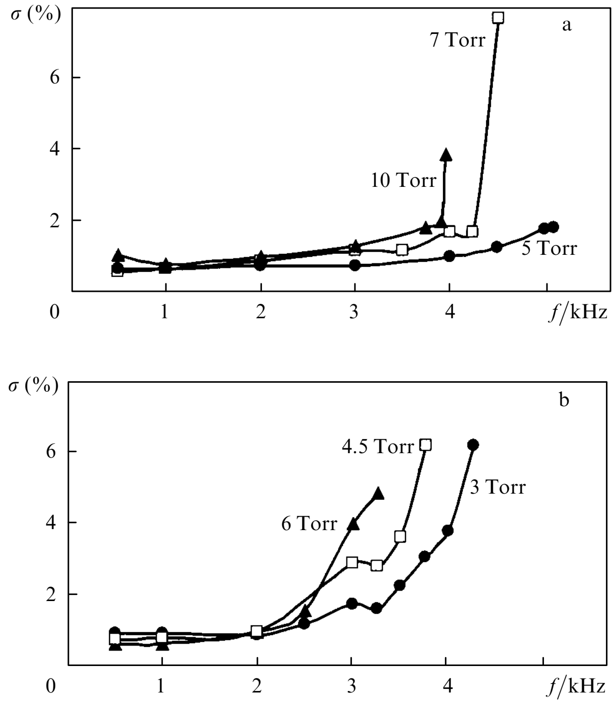

Figure 3. Dependences $\sigma(f)$ for the XeF (a) and KrF (b) lasers at different fluorine pressures in active mixtures F_2 : Xe : Ne = F_2 : 10 : 2000 Torr (a), and F_2 : Kr : Ne = F_2 : 60 : 2000 Torr (b); U_0 = 18 kV (a) and 20 kV (b).

The active medium of the nitrogen laser can be considerably varied both in its composition and pressure, thereby varying the sound speed in the active medium in a broad range. The active medium does not contain chemically active components and has a high gain. This allows one to study quite easily the influence of different factors, for example, the role of acoustic perturbations in the active medium of a high-pulse-repetition-rate laser on its frequency characteristics. Nitrogen lasers are still being used in scientific studies, and therefore the development of high-pulse-repetition-rate nitrogen lasers with the use of a commercial laser chamber can be of interest in itself.

The output energies for the N_2, N_2 – Ne, and N_2 – He active media of the nitrogen laser at low buffer gas pressures differ within 10 % – 15 %. Figure 4 presents the dependences of the average pulse energy and the relative root-mean-square deviation of the output energy from pulse to pulse on the pulse repetition rate for different compositions of the active medium.

The laser pulse energy decreases with increasing pulse repetition rate for all active mixtures [curves (*1* – *3*)]. This is probably explained by the development of acoustic perturbations in the active medium. Because the sound speed in the N_2 – He active medium is considerably higher, acoustic

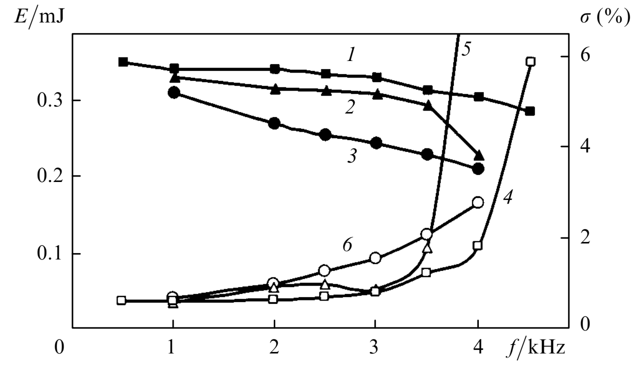

Figure 4. Dependences $E(f)$ (*1, 2, 3*) and $\sigma(f)$ (*4, 5, 6*) for the active media of the nitrogen laser of compositions N_2 : He = 36 : 350 Torr (*1, 4*), 100 Torr N_2 (*2, 5*) and N_2 : Ne = 25 : 200 Torr (*3, 6*); U_0 = 20 kV.

perturbations decay in this medium faster, while the output energy decreases slower than in the N_2 – Ne mixture and in pure N_2. This is also confirmed by the better stability of the output radiation in the N_2 – He mixture [curve (*4*)].

The maximum output pulse energy of 0.35 mJ (efficiency 0.063 %) was obtained in the N_2 : He = 36 : 350 Torr mixture and the average output laser power was ~ 1.2 W for $f = 4$ kHz. As the He pressure in this mixture was increased up to 600 Torr, the output power decreased, while the limiting pulse repetition rate increased up to 5.5 kHz when the charging voltage of a storage capacitor was decreased down to 18 kV. For $U_0 = 22$ kV, the high stability ($\sigma \leqslant 1.3$ %) of laser pulses was achieved for $f \leqslant 4.5$ kHz.

The best stability of the pulse energy ($\sigma \approx 0.3$ %) in the N_2 : He = 25 : 350 Torr mixture was achieved for $f \sim$ 0.5 – 1 kHz. This demonstrates an extremely high stability of the discharge in the active mixture of the nitrogen laser at moderate pulse repetition rates.

Of interest is the periodic change in the energy of pulses detected in the N_2 : He = 25 : 600 Torr mixture (Fig. 5). This is probably explained by a stable periodic nature of acoustic perturbations produced in the active medium of the nitrogen laser. Note that this periodicity was observed only at certain pulse repetition rates and for the mixture composition mentioned above, which indicates the resonance nature of perturbations. In other cases, energy randomly changed from pulse to pulse. This suggests that rather strong acoustic perturbations are produced in the active medium of lasers under study, which, however, do not exhibit a stable periodic behaviour.

Then we studied the role of the inductance – capacitance stabilisation on the operation of high-pulse-repetition-rate lasers. Investigations were performed for nitrogen, XeF, and KrF lasers. To exclude the capacitance decoupling and to reduce maximally the inductance decoupling, the supports of cathode electrode plates were connected with a common conductor. Similarly, the inductance decoupling of anode electrode plates was almost completely excluded. Note that an electrode consisting of electrode plates connected by a common conductor is not equivalent to a massive electrode. Nevertheless, the effect of inductive stabilisation is preserved for the durations of energy supply into the discharge studied, but its efficiency is considerably reduced.

Figure 6 presents the dependences of the energy of the first 1000 pulses from the nitrogen laser on the pulse number for variants with the inductance – capacitance stabilisation and without it.

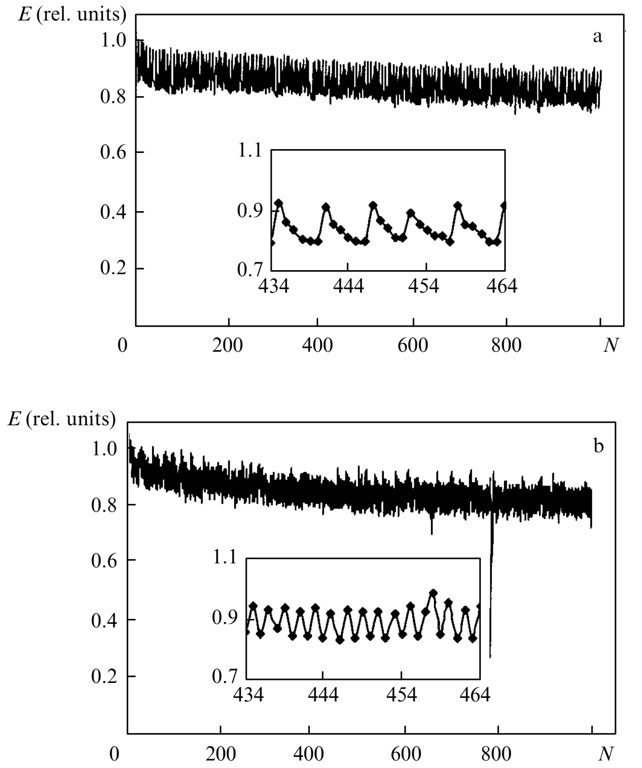

Figure 5. Dependences of the radiation pulse energy E on the pulse number N for $f = 4$ kHz, $\sigma \leqslant 5.2$ % (a) and $f = 5$ kHz, $\sigma \leqslant 6.7$ % (b). The mixture composition is N_2 : He = 25 : 600 Torr.

Figure 7 presents the frequency dependences of the relative root-mean-square deviations σ of the output energy from pulse to pulse in the nitrogen laser with the inductance – capacitance stabilisation and without it. One can see that the inductance – capacitance stabilisation of the discharge does not improve the stability of pulses for $f = 0.5 - 2.5$ kHz, but provides a considerable increase in the pulse repetition rate by more than 1.5 kHz. The same behaviour of σ was observed in the nitrogen laser with the inductance – capacitance stabilisation and without it in mixtures based on N_2 and N_2 – Ne.

Similar experiments were performed for XeF and KrF lasers (Fig. 8). The inductance – capacitance stabilisation of the discharge in the XeF laser does not improve the pulse stability in the pulse repetition range from 0.5 to 2 kHz. For $f \geqslant 2$ kHz, the value of σ in the laser without stabilisation considerably increases; the higher the energy input, the more rapidly σ increases (Fig. 8a). The value of σ in the XeF laser with the discharge stabilisation weakly increases up to $f = 4$ kHz and then drastically increases. Thus, the inductance – capacitance stabilisation provided the increase in the limiting pulse repetition rate in the XeF laser by ~ 1.5 kHz. Note that the stability of the XeF laser with the inductance – capacitance discharge stabilisation for U_0 = 18 and 20 kV is almost the same in the entire range of pulse repetition rates studied.

The presence of the inductance – capacitance stabilisation in the KrF laser somewhat improved the operation stability but almost did not change the limiting pulse repetition rate. The continuous increase of σ in the KrF laser changed to its drastic increase for $f = 3.5$ kHz in the

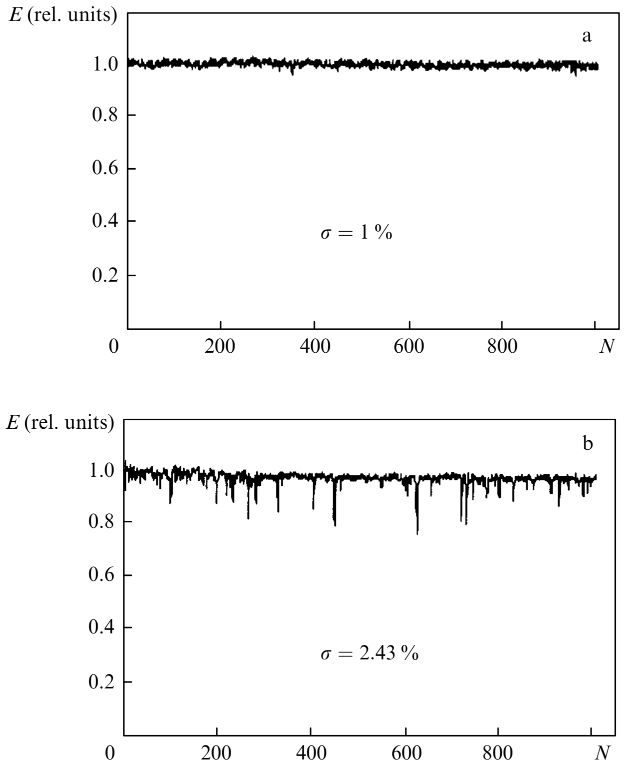

Figure 6. Dependences of the radiation pulse energy E on the pulse number for the nitrogen laser with the inductance – capacitance discharge stabilisation (a) and without it (b) for $f = 3$ kHz and $U_0 = 18$ kV. The mixture composition is $N_2 : He = 25 : 350$ Torr.

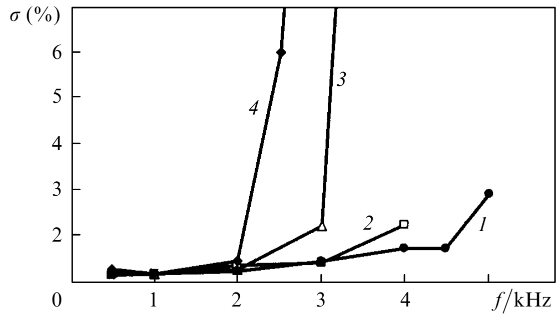

Figure 7. Dependences $\sigma(f)$ for the nitrogen laser with the inductance – capacitance discharge stabilisation (*1, 2*) and without it (*3, 4*) for $U_0 = 18$ kV (*1, 3*) and 20 kV (*2, 4*). The mixture composition is $N_2 : He = 25 : 350$ Torr.

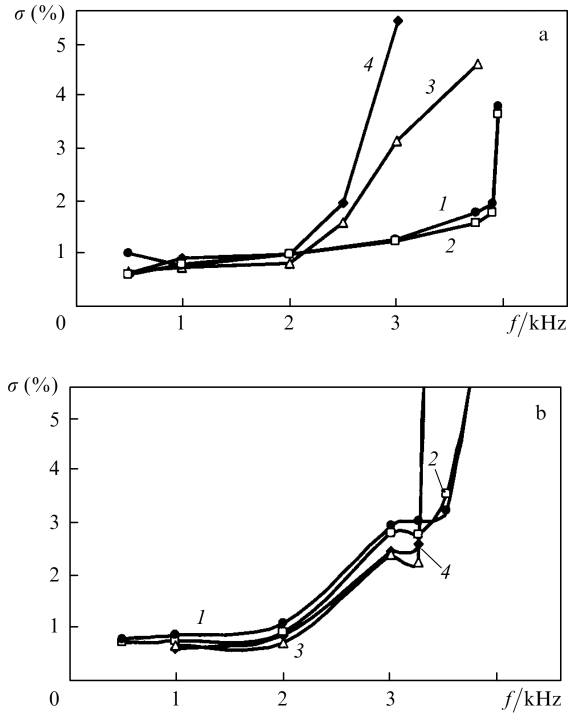

Figure 8. Dependences $\sigma(f)$ in XeF and KrF lasers with the inductance – capacitance discharge stabilisation (*1, 2*) and without it (*3, 4*) for $U_0 = 18$ kV (*1, 3*) and 20 kV (*2, 4*). $F_2 : Xe : Ne = 10 : 10 : 2000$ Torr (a) and $F_2 : Kr : Ne = 4.5 : 60 : 2000$ Torr (b) are mixture compositions.

case of discharge stabilisation and for $f = 3.25$ kHz without stabilisation (Fig. 8b). As for the XeF laser, the stability of the KrF laser for $U_0 = 18$ and 20 kV was almost the same over the entire range of pulse repetition rates. In both lasers with the 'light' mixture, the influence of the inductance – capacitance stabilisation was manifested stronger. Thus, the decrease in the buffer gas pressure down to 1100 Torr provided the increase in the limiting pulse repetition rate by ~ 2 kHz for the XeF laser and by ~ 1 kHz for the KrF laser.

Figures 7 and 8 show that the discharge stabilisation in different laser mixtures exhibits special features. To provide the independent operation of each pair of the anode – cathode electrode plates and, therefore, the maximum stabilisation, it is necessary to exclude the electric connection between adjacent electrode plates. This connection is caused by sparks produced in the interelectrode gap due to the appearance of the potential difference caused by the different location geometry of the plates and different discharge conditions between each pair of anode – cathode electrode plates. In particular, different conditions appear because of the differences in perturbations of the gas density in the discharge gaps of adjacent pairs of anode – cathode plates, which are produced at high pulse repetition rates. Thus, to avoid the initiation of sparks between adjacent electrode plates, the distance between them should be large enough.

In the active media of the nitrogen and XeF lasers, which are relatively stable with respect to perturbations of the gas density, the effects of stabilisation and increase in the limiting pulse repetition rate are well pronounced. The working mixture of the KrF laser is less stable to perturbations of the active-medium density. Because of this, at high pulse repetition rates, a large potential difference appears between adjacent plates, initiating sparks between them. As a result, the limiting pulse repetition rate of the KrF laser with the discharge stabilisation almost does not increase. It seems that an increase in a distance between adjacent electrode plates can improve the stability of laser pulses and increase the limiting pulse repetition rate in the KrF laser. In our opinion, good stability of laser pulses obtained at high repetition rates at the relatively low gas flow rate is caused by two reasons. First, we used thin electrode plates, which provide the high electric field strength near their working edge, which improves the discharge stability. In addition, an extremely narrow discharge produced between such plates allows one to obtain a relatively high gas interchange coefficient in the discharge gap at low gas flow rates. Second, the high stability of laser pulses is the incomplete exclusion of the inductive stabilisation of the discharge.

It was pointed out in [4] that at high pulse repetition rates ($f \approx 4$ kHz), high-current channels appear in the discharge products after the previous pulse, which are 'connected' to preionisation sparks located downstream. The appearance of competing breakdowns determines in fact the limiting pulse repetition rate. In this connection the parameters of XeF and KrF lasers were studied when preionisation sparks were located both upstream and downstream of the gas flow. The results of these studied are presented in Fig. 9.

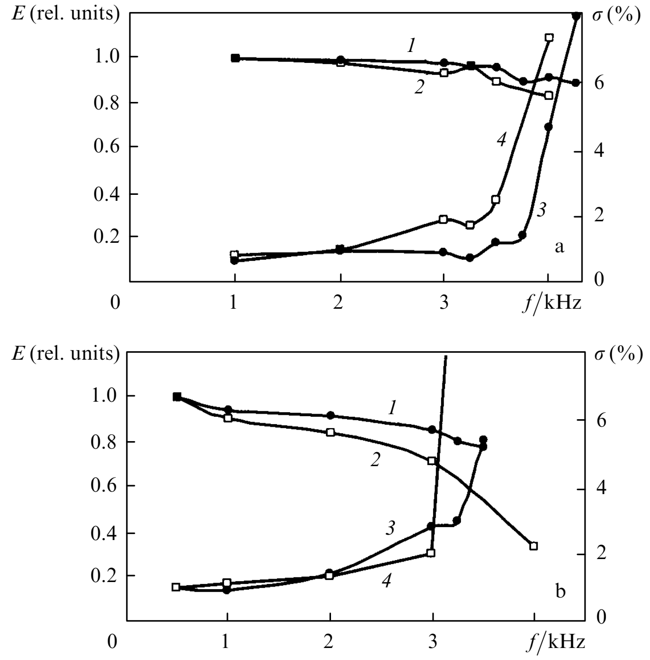

Figure 9. Dependences $E(f)$ (*1*, *2*) and $\sigma(f)$ (*3*, *4*) for preionisation sparks located upstream (*1*, *3*) and downstream (*2*, *4*) of the gas flow with respect to the discharge gap for $U_0 = 18$ kV. $F_2 : Xe : Ne = 10 : 10 : 2000$ Torr (a) and $F_2 : Kr : Ne = 4.5 : 60 : 2000$ Torr (b) are mixture compositions.

One can see from the figure that the location of preionisation sparks upstream of the gas flow provided the increase in the limiting pulse repetition rate by ~ 500 Hz for both lasers. The output energy of the XeF laser for $f = 4$ kHz decreased by 9 % with respect to the single pulse energy (spark located upstream) and by 17 % (sparks located downstream), for the KrF laser at $f = 3$ kHz this decrease was by 15 % and 30 %, respectively. The faster decrease in the output energy of the KrF laser with increasing the pulse repetition rate is probably explained by a lower stability of the discharge with respect to perturbations of the active-medium density.

Note that the deviation $\sigma \leqslant 2\,\%$ was achieved in our study by using spark preionisation, whereas similar deviation in [3, 4] was obtained by using a sliding discharge for preionisation. It was shown in [4] that the use of a sliding discharge reduces σ by several times compared to spark preionisation.

The high specific pump power (~ 9 MW cm^{-3}) and a small discharge width (~ 1 mm) initiate optical inhomogeneities of the type of a negative cylindrical lens in the discharge plasma, which are related to the high electron concentration, more exactly to its gradients [7]. This is manifested in the characteristic far-field splitting of a laser beam. The maximum gradient grad(Δn) of the change in the refractive index, determined by the electron concentration, was ~ 10^{-5} cm^{-1} for the KrF laser wavelength. The appearance of such a lens reduces the laser efficiency and considerably complicates the generation of laser radiation with a low angular divergence. To reduce the negative influence of this gradient, the electrode unit was proposed [7, 8] in which plates are oriented at a small angle with respect to the optical axis of the laser. To preserve the frequency characteristics of the laser, the plated should be arranged in zig-zag fashion, as in paper [10].

Figure 10 presents the calculated distributions of the change in the refractive index and its gradient grad$|(\Delta n)|$ over the active-volume cross section for electrode planes oriented along the optical axis of the laser and at an angle of 8° to it. In the latter case, the change in the refractive index at the electron component can be reduced by a factor of ~ 3.2, and the gradient of the change in the refractive index can decrease by a factor of ~ 6.5. As a result, the near- and far-field laser radiation intensity distributions are improved. In addition, radiation loads on resonator mirrors are decreased, especially at high pulse repetition rates. The influence of the gradient of the change in the refractive index, which is determined by the electron concentration, can be reduced by optimising the specific pump power and its duration, and the pressure and composition of the active medium of the laser. For example, the electron concentration in the discharge during the laser pulse can be considerably decreased by matching pump pulses with the minimal second half-wave of the current pulse.

A further development in the laser technology based on plate electrodes aimed at increasing the output pulse energy

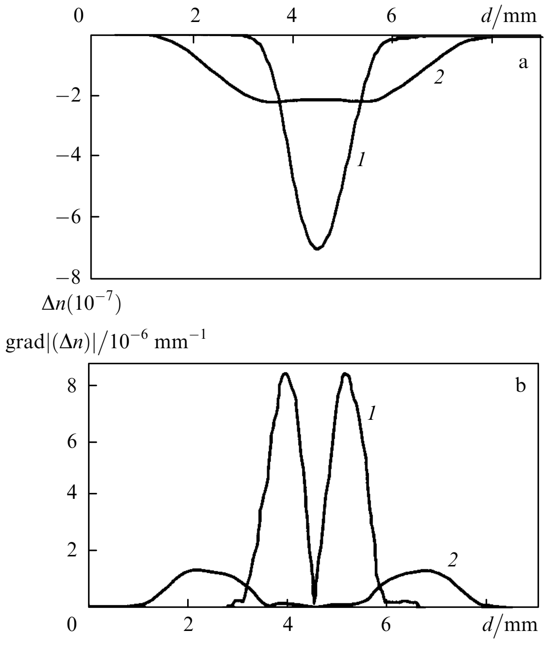

Figure 10. Distributions of the change in the refractive index (a) and its gradient (b) in the discharge plasma of the KrF laser produced on a negative electron lens [(*1*) experiment; (*2*) calculation]. Planes of electrode plated are located along (*1*) the optical axis of the laser and at an angle of 8° to it (*2*).

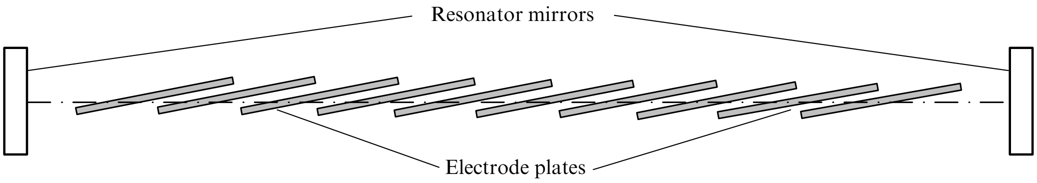

Figure 11. Scheme of the location of electrode plates in a laser with the increased pulse energy.

involves an increase in the number of electrode plates arranged at an appropriate angle to the optical axis of the laser (Fig. 11). Such a design allows one to retain a small width of the laser beam at the high output energy, reduce the acoustic perturbations of the laser medium, obtaining thereby high pulse repetition rates. The similar arrangement geometry of electrode planes was first used in the development of a chemical laser [11].

3. Conclusions

We have studied compact high-pulse-repetition-rate XeF and KrF excimer lasers and the nitrogen laser with pulse repetition rates up to 4–5 kHz. The stability of laser pulses at these repetition rates was 2 %–3 %. The pulse repetition rates achieved in the study have been obtained at record low active-medium flow rates (no more than 19 m s^{-1}). As the pulse repetition rate was increased, the pulse energy of all lasers decreased and the root-mean-square deviation σ continuously increased and then drastically increased at limiting repetition rates.

The influence of the inductance–capacitance stabilisation of the discharge on the stability of the laser pulse energy in UV lasers has been studied for the first time. It has been shown that the inductance–capacitance stabilisation of the discharge improves the laser stability and increases the limiting pulse repetition rate up to 0.5–1.5 kHz.

The influence of the location of preionisation sparks (upstream and downstream of the gas flow) on the frequency characteristics of lasers has been also investigated. It has been shown that the location of the sparks upstream of the gasp flow provides the increase in the pulse energy at high repetition rates and the increase in the pulse repetition rate by $\sim$ 500 Hz.

It has been pointed out that the orientation of electrodes at a small angle to the optical axis of the laser allows one to decrease by several times the gradient of the refractive index related to the electron concentration in the discharge plasma of the laser, which improves laser radiation parameters.

One of the aims of the proposed laser technology is the increase in the laser pulse energy. This can be achieved by increasing the number of electrode plates oriented at an appropriate angle to the optical axis of the laser.

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