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Electric-discharge pulsed $F_2 + H_2(D_2)$ chain reaction HF/DF laser with a 4.2-L active volume

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Abstract**. The properties of a pulsed chemical HF/DF laser with the $10 \times 10.5 \times 40$-cm active volume and the 10-cm discharge gap are studied. Chain and nonchain chemical reactions were initiated by a barrier discharge in the active volume of the laser with the $SF_6 - H_2(D_2)$ and $SF_6 - F_2 - O_2 - H_2(D_2)$ mixtures, respectively. The discharge was stabilised by electrodes made of semiconductor ceramics. The maximum output energy of the 'nonchain'-mixture HF laser was $E_{max} = 15$ J, the specific energy $E/V = 3.6$ J L^{-1}, and the technical efficiency, calculated by the stored energy, was $\eta_t = 4.3\,\%$. For the 'chain'-mixture HF laser, these parameters were $E_{max} = 130$ J, $E/V = 31$ J L^{-1} and $\eta_t = 37\,\%$. The parameters of the 'nonchain'- and 'chain'-mixture DF lasers were lower by $\sim 35\,\%$ and $\sim 50\,\%$, respectively.**

Keywords: *chemical pulsed HF/DF laser, nonchain and chain reactions, barrier discharge, discharge gap, specific energy output.*

1. Introduction

The scaling of electric-discharge chemical HF/DF lasers is related to solving the problem of discharge stabilisation in large volumes of electronegative gases such as SF_6, NF_3, and F_2.

The stabilisation of a discharge in lasers with a large discharge gap (above 10 cm) and a large active volume was performed by using blade electrodes [1], by electron-beam preionisation of gases [2], and by using electrodes with surfaces processed by sandblasting to produce microscopic cusps [3]. The authors of paper [3] obtained the record characteristics of a pulsed chemical 'nonchain'-mixture HF laser: the output energy $E \approx 407$ J, the specific energy $E/V \leqslant 6.7$ J L^{-1}, and the technical efficiency $\eta_t \leqslant 4.3\,\%$. The authors of papers [3 – 5] investigated the mechanism of production of inhomogeneities in the discharge, determined conditions for the efficient use of preionisation by UV radiation and soft X-rays and concluded that there was no need to use preionisation in wide-aperture lasers with large discharge gaps.

The methods for discharge stabilisation mentioned above have their advantages and disadvantages from the point of view of the discharge homogeneity, the energy efficiency and the possibility of obtaining the repetitively pulsed lasing. In the repetitively pulsed regime, inhomogeneities can be accumulated and developed from pulse to pulse, which in the case of blade electrodes can lead to incomplete initiation of the active volume and deterioration of lasing characteristics [6]. The noticeable deterioration of lasing characteristics in passing to the repetitively pulsed regime was observed for a photopreionised nonchain laser [7].

Pulsed and repetitively pulsed HF/DF lasers initiated by a barrier electric discharge efficiently operate at pulse repetition rates up to 50 Hz [8] and a discharge gap width of 10 cm [9]. The use of semiconductor barriers to stabilise the discharge provided its homogeneity and, hence, good reproducibility of laser characteristics. The laser initiation system was simple and reliable. However, laser setups with a barrier discharge had so far comparatively small active volumes 50 cm^3 [8] and 440 cm^3 [9, 10]. The stable operation of a 'chain'-mixture laser was observed when the fluorine content in the mixture was up to 35%. In this case, the values $E/V \leqslant 20$ J L^{-1} and $\eta_t \leqslant 22\,\%$ were obtained. The discharge homogeneity was controlled by radiation spots on a photosensitive paper. For a laser setup with composite barrier electrodes and an order of magnitude greater active volume, such an estimate of the discharge homogeneity is not sufficient.

In our opinion, it is interesting to study the properties of nonchain and chain HF/DF lasers with large active-media volumes and compare them with results obtained in [9]. In this paper, we investigated the characteristics of a chemical HF/DF laser by scaling the active volume up to 4.2 L and the discharge gap up to 10 cm. The data reported in the paper are the results of the first stage of investigations aimed at the development of repetitively pulsed $F_2 + H_2$ chain reaction chemical lasers with a large discharge gap.

2. Experimental

A pulsed chemical HF/DF laser contains a discharge chamber, a discharge circuit with a pulsed voltage generator (PVG), a system for gas supply and neutralisation of toxic gases, resonator mirrors, and an optical system for measuring laser characteristics.

The discharge chamber consists of a dielectric housing with built-in barrier-electrode panels and fluorite windows for coupling radiation out of the active volume. Each barrier

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electrode is formed by a number of ceramic plates covered inside with a current-conducting layer and fastened together on a common metal electrode. The barrier electrodes have the active area of size 10.5 × 40 cm. The internal surface of the discharge chamber had a deposited covering protecting from the action of aggressive gases.

The voltage generator is built based on the two-stage Marx generator circuit. Four 87-nF capacitors connected in parallel are charged by a charging device up to the maximum voltage 45 kV. The capacitors were connected in series by supplying an ignition pulse to gas-filled gaps and switching a 180-kV voltage pulse to the discharge volume of the discharge chamber.

The maximum energy stored in PVG capacitors was ~ 350 J. In a number of experiments, two additional capacitors were included into the PVG, resulting in the increase in the energy storage by 30 %. Discharge current and voltage pulses were recorded with a TDS-3012 digital oscilloscope, and the energy supply to the discharge was measured by the method described in [9]. The maximum energy supply to the discharge for the two variants of the PVG was ~ 230 and ~ 330 J, respectively. The radiation energy was measured with IMO-2 and TPI-2M.1 calorimeters placed at a distance of ~ 4 m from the output window of the discharge chamber.

The laser resonator consisted of a highly reflecting plane aluminium mirror and a semi-transparent plane mirror with the reflectance ~ 0.3 in the wavelength range under study. The laser pulse shape was detected with an Au–Ge photodetector and recorded with a digital oscilloscope.

During experiments we varied the pressure and composition of the gas mixture in the discharge chamber and the energy supply to the discharge (by changing the capacity of PVG capacitors and charging voltage).

3. Experimental results and discussion

3.1 'Nonchain'-mixture laser

The characteristics of nonchain pulsed chemical HF/DF laser were studied in the $SF_6:H_2 = 9:1$ and $SF_6:D_2 = 7:1$ mixtures. The mixture pressure in the discharge chamber was varied from 3.5 to 13 kPa and the energy supply to the discharge was varied by changing the PVG charging voltage (30, 40 and 45 kV).

The maximum of the pressure dependence of the laser energy corresponds to the minimal losses of the PVG energy for the energy transfer coefficient to the discharge equal to 0.65–0.67. The maximum output energy of the HF laser ($E = 15$ J) was obtained at pressures $p = 8.5 - 9.5$ kPa and the energy supply to the discharge $W = 53$ J L^{-1}. The maximum output energy of the DF laser ($E = 9.5$ J) was achieved under the same conditions. For $p > 11.5$ kPa, the contraction of the discharge was observed, which was accompanied by a noticeable decrease in the output energy. The oscillograms of the discharge current pulse and emission of the nonchain HF/DF laser are shown in Figs 1 and 2. One can see that the laser pulse half-width is close to that of the current pulse or slightly exceeds it.

When the energy supply to the discharge was changed from 25 to 53 J L^{-1}, the output laser energy increased linearly at invariable values of the technical efficiency (the ratio of the radiation energy to the electric energy stored in capacitors) 4.1 % and 2.8 % for HF and DF molecules, respectively. The connection of additional capacitors to the PVG circuit resulted in the increase in the output energy by ~ 25 %. The discharge current pulse duration increased from 220 to 250 ns and the limiting pressure, at which the discharge contraction appeared, decreased down to 9–10 kPa.

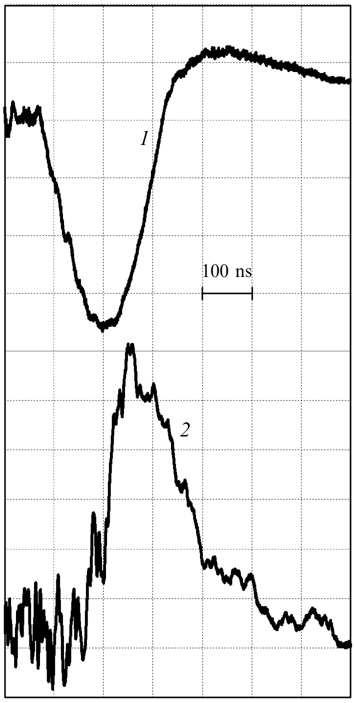

Figure 1. Oscillograms of discharge current (*1*) and output (*2*) pulses of the nonchain pulsed chemical HF laser.

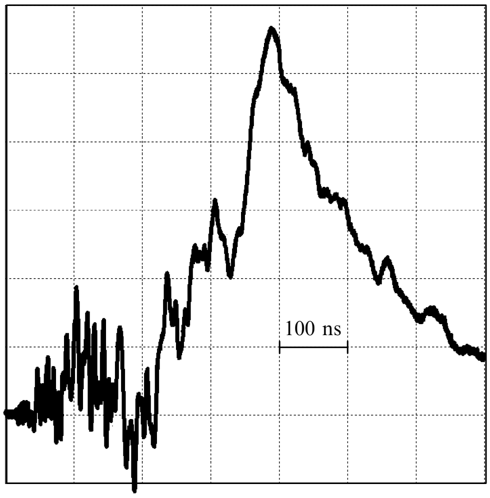

Figure 2. Oscillogram of the output pulse of the nonchain pulsed chemical DF laser.

The proportional increase in the output energy of the nonchain laser with increasing energy supply to the barrier discharge was observed earlier for a small sample [9]. The linear dependence of the output energy on the energy supply to the barrier discharge, visual observations and photographs of the discharge in the visible light, and the recording of laser radiation spots on a photosensitive paper indirectly confirm the discharge homogeneity. The discharge homogeneity was also estimated with the help of symmetric masks of aperture ~ 1.5 cm mounted on chamber windows at five points where the inhomogeneity of the discharge current density was assumed the highest (at four corners and at the geometric centre). The radiation energies measured in these local regions were the same within the measurement error [±(7 % – 8 %)]. It is obvious that the discharge homogeneity was not impaired with increasing the active volume by an order of magnitude, whereas the specific energy increased by ~ 25 %. Thus, the output energy of the nonchain laser can be efficiently increased by increasing the energy supply to the discharge, provided the barrier discharge contraction is absent.

3.2 'Chain'-mixture laser

The dependences of characteristics of the chain pulsed chemical HF/DF laser on the pressure and content of active components of the $SF_6 - F_2 - O_2 - H_2(D_2)$ mixtures were studied for their optimal ratio $F_2 : H_2(D_2) = (2.5 - 3.5) : 1$ for the invariable concentration ratio of oxygen and fluorine equal to 7 % and the PVG energy storage 350 J.

Figure 3 shows that the output energy of the laser increases linearly with increasing pressure up to ~ 12.5 kPa, and at higher pressures a stable contraction of the discharge appears which strongly reduces the output energy. Of interest are the energy characteristics of the laser operating on a mixture with a relatively small amount of active components and a low flame propagation velocity, which can be used in the repetitively pulsed regime by employing a gas flow through the resonator whose velocity exceeds the mixture burning rate (the so-called 'frequency' mixture) [8, 10].

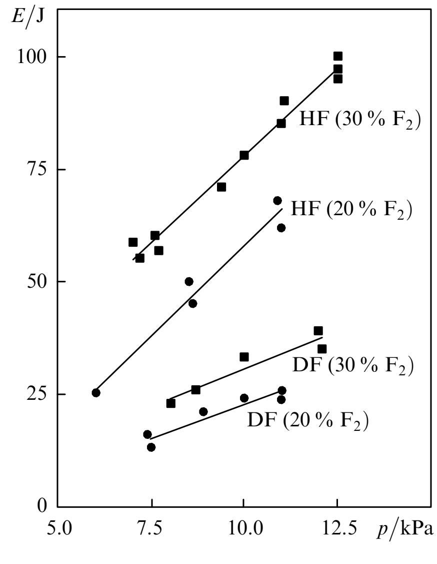

Figure 3. Dependences of the output energy of the chain pulsed chemical HF/DF laser on the pressure of the $F_2 : H_2(D_2) \approx (2.5 - 3.5) : 1$ mixture.

Figure 4 presents the dependences of the output energy of the laser on the hydrogen content in the mixture. One can see that the laser pulse energy increases with increasing the hydrogen content in the mixture up to 8 % – 12 % (the fluorine content in the mixture is 10 % – 30 %). As the hydrogen content is further increased, the laser pulse energy changes insignificantly. The dependence of this type can be explained by the increase in the rate of the 'cold' reaction with increasing hydrogen content, followed by the stabilisation of the radiation energy at high initial concentrations, which is caused by a relatively weak burning out of hydrogen until quenching of lasing under our conditions.

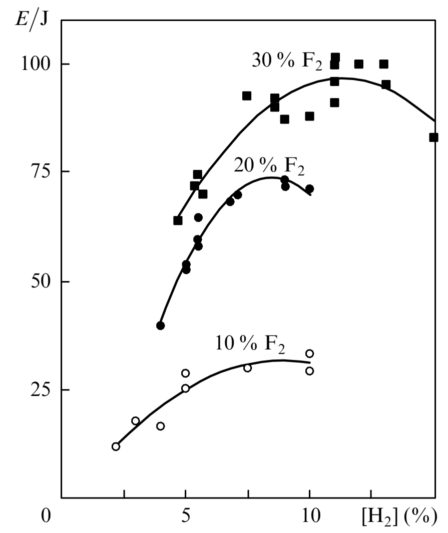

Figure 4. Dependences of the output energy of the chain pulsed chemical HF laser on the H_2 concentration in a mixture for $p = 11 - 12.5$ kPa (■) 10 – 11 kPa (●), and 10 kPa (○).

For 'frequency' mixtures containing 20 % – 30 % of fluorine and 5 % – 7 % of hydrogen, in which the flame propagation velocity does not exceed 2 – 3 m s^{-1} [8], we obtained the specific energy output 15 – 20 J L^{-1} and technical efficiency 17 % – 22 % in the pulsed regime.

The output energy of the HF laser depends linearly on the fluorine concentration (Fig. 5). The replacement of an aluminium mirror of the resonator by a copper mirror resulted in the increase in the output energy by 15 % – 20 % due to a higher quality of the copper mirror surface. A similar dependence obtained for the chain pulsed chemical DF laser showed that the output energy was lower by 50 % than that of the HF laser. The maximum output energy of the HF laser was 130 J. The parameters determining the

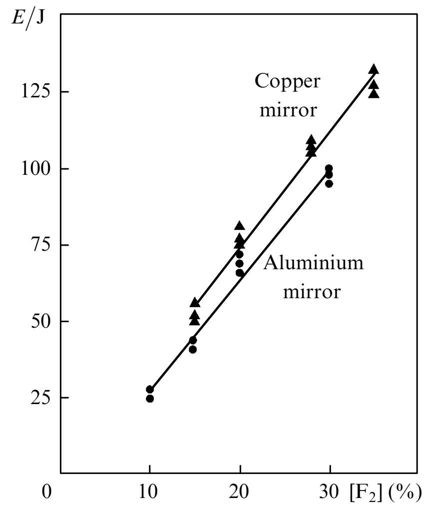

Figure 5. Dependences of the output energy of the chain pulsed chemical HF laser on the F_2 concentration in the $F_2 : H_2 \approx (2.5 - 3.5) : 1$ mixture.

conversion efficiency of the stored energy of the chemical reaction to radiation, namely, $E/V = 31$ J L^{-1} and $\eta_t =$ 37 %, were greater by a factor of $\sim$ 1.5 than those obtained in a small setup under similar conditions [9]. Figures 6 and 7 show the oscillograms of radiation pulses from pulsed chemical HF and DF lasers, obtained under the same conditions. One can see that the HF-laser pulse (150-ns FWHM) is noticeably shorter than the DF-laser pulse, which can be explained by the fact that the rate of reaction of fluorine with hydrogen is noticeably greater than the rate of reaction of fluorine with deuterium.

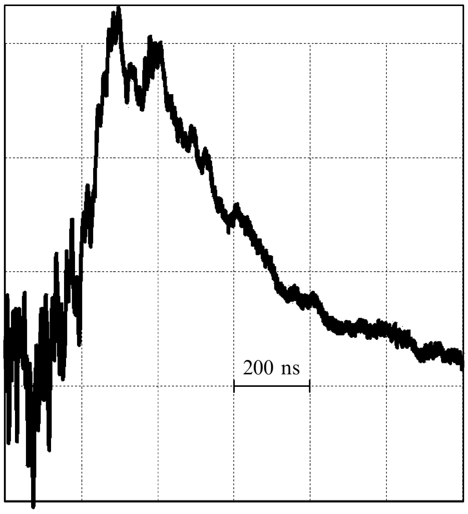

Figure 6. Oscillogram of the output pulse of the chain pulsed chemical HF laser.

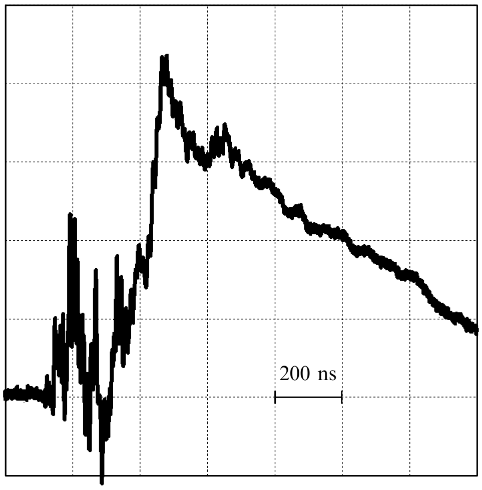

Figure 7. Oscillogram of the output pulse of the chain pulsed chemical DF laser.

The influence of the energy supply to the discharge on the output energy of the chain laser was studied either by varying the charging voltage of the PVG from 30 to 45 kV or by connecting two additional capacitors to the PVG circuit. In all experiments, a fluorine-hydrogen (deuterium) mixture of the composition $F_2:O_2:SF_6:H_2(D_2) =$ 28:2:62:8 at a pressure of $\sim$ 7.6 kPa was used, in which the discharge-gap breakdown was provided over the entire range of voltages applied to the discharge-chamber electrodes. The results of this study are presented in Fig. 8, which shows that the dependence of the output energy of the HF laser on the energy supply tends to saturate at specific energy supplies above 50–60 J L^{-1}, whereas the output energy of the DF laser increases linearly with increasing the energy supply to the discharge. The specific storage of the chemical energy of the mixture in the electric-discharge pulsed chemical HF/DF laser is almost an order of magnitude smaller than that in a flashlamp- or electron-beam-pumped pulsed chemical laser operating at the atmospheric pressure [11, 12]. For a comparable specific energy output for these lasers, this suggests that the electric-discharge pulsed chemical HF laser has a relatively high chemical efficiency. The technical efficiency of the chain HF/DF laser can be increased by increasing the resonator Q factor and decreasing simultaneously the energy supply to the discharge. It seems that the expected increase in the efficiency should be greater for the DF laser.

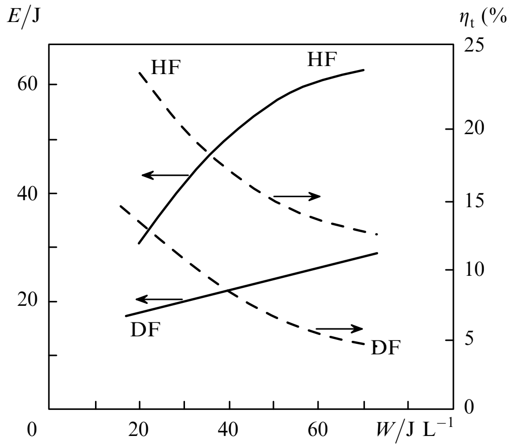

Figure 8. Dependences of the output energy E and technical efficiency η_t of chain pulsed chemical HF/DF lasers on the specific energy supply W to the discharge for the $F_2:O_2:SF_6:H_2(D_2) = 28:2:62:8$ mixture for $p = 7.6$ kPa.

The characteristics of the pulsed chemical HF/DF laser can be improved by increasing the active-medium pressure, which is suggested by a strong pressure dependence of the output laser energy (Fig. 3). In this case, it is important to increase the limiting pressure at which the discharge contraction appears, which strongly reduces the output laser energy. The limiting pressure can be efficiently increased by using a 'short-pulse' discharge circuit. Indeed, the decrease in the discharge pulse duration down to 50–70 ns resulted in the increase in the limiting pressure of the appearance of the barrier-discharge contraction in SF_6 up to 20–25 kPa [13]. At the same time, as the current pulse duration was increased under our conditions from 220 to 400 ns by increasing the circuit inductance, the limiting pressure of the discharge-contraction appearance in SF_6 decreased from 10 to 6 kPa.

To reduce the discharge current pulse duration, we replaced PVG capacitors by lower-capacity (6.9 nF) capacitors with the energy storage of 132 J at $U_{ch} = 45$ kV. The current pulse duration with the use of a new circuit was reduced down to 140 ns, which allowed us to increase pressure at which the discharge contraction appears up to 15–16 kPa. We performed a series of experiments under new conditions and obtained the dependences of the radiation energy of chain pulsed chemical HF/DF lasers on the pressure of the $F_2:O_2:SF_6:H_2(D_2) = 30:2:60:8$ mixture (Fig. 9). By mounting a semi-transparent mirror with the reflectance $r = 0.5$ (at $\lambda = 4$ μm) in the DF laser resonator, we raised the resonator Q factor. Under these conditions, the output energy of the HF and DF lasers also increased linearly with pressure. The best parameters of the chain pulsed chemical HF laser were $E/V = 20$ J L^{-1} and $\eta_t = 52$ %, and for the DF laser – $E/V = 12.0$ J L^{-1} and $\eta_t = 30$ %. The increase in the output energy with increasing the resonator Q factor is greater for the pulsed chemical DF laser, which is manifested in the increase in the ratio E_{DF}/E_{HF} from 0.5 to 0.57. A further increase in the Q factor of the DF laser (achieved by mounting mirrors with $r = 0.75$) did not lead to a noticeable increase in the output energy. An increase in the mixture pressure for increasing the output energy of HF/DF lasers is reasonable in the absence of the discharge contraction.

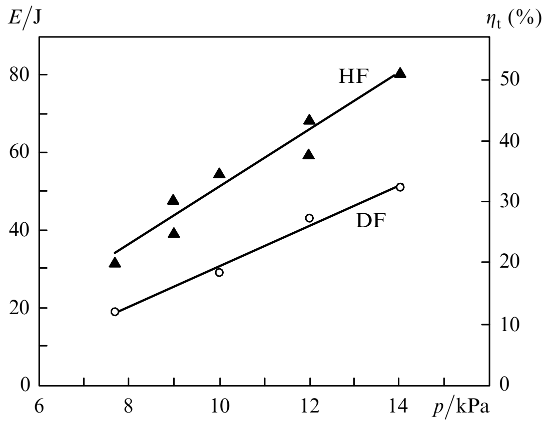

Figure 9. Dependences of the output energy E and technical efficiency η_t of chain pulsed chemical HF/DF lasers on pressure for the $F_2:O_2:SF_6:H_2(D_2) = 30:2:60:8$ mixture for the 140-ns discharge current pulse.

4. Conclusions

We have studied the characteristics of the wide-aperture pulsed chemical HF/DF laser with the 10-cm discharge gap and the 4.2-L active volume. The initiation of nonchain and chain reactions by a discharge based on barrier electrodes made of semiconductor ferroelectric ceramics provided the efficient and reliable operation of this laser upon increasing the active volume from 0.44 L [9] to 4.2 L and the active-medium length by a factor of four. In this case, the specific characteristics of the 'nonchain'-mixture and 'chain'-mixture lasers increased under similar conditions by ~ 25 % and ~ 50 %, respectively, which approximately corresponds to the results of model calculations of processes proceeding in the active medium of the pulsed chemical HF laser [10]. For the 'nonchain'-mixture HF laser, we obtained the maximum output energy $E_{max} = 15$ J, the specific maximum output energy $E/V = 3.6$ J L^{-1}, and the technical efficiency $\eta_t = 4.3$ %. These parameters for the 'chain'-mixture laser were $E = 130$ J, $E/V = 31$ J L^{-1}, and $\eta_t = 37$ %. For the 'nonchain'-mixture DF laser, we obtained $E/V = 2.3$ J L^{-1} and $\eta_t = 2.7$ %, while the maximum output energy of the 'chain'-mixture DF laser decreased by 50 % compared to that of the HF laser. The increase in the energy supply to the discharge from 53 to 72 J L^{-1} did not result in a noticeable increase in the output energy of the chain HF laser, whereas the output energy of the DF laser increased by 20 %–25 %.

We have raised the technical efficiency of the laser by reducing the energy supply to the discharge, shortening the current pulse duration, increasing the working mixture pressure, and increasing the resonator Q factor (the DF laser). After a series of experiments, the maximum value of η_t was 52 % for the HF laser and ~ 30 % for the DF laser.

These results can be used for predicting and optimisation of characteristics of high-power pulsed and repetitively pulsed chemical HF/DF lasers.

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