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Repetitively pulsed DF laser with a pulse repetition rate up to 1200 Hz and an average output power of $\sim$ 25 W

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Abstract. **The operation of an electric-discharge repetitively pulsed DF laser with an 8 – 10-mm discharge gap and a working mixture circulating along a closed gas-dynamic channel is experimentally studied. The main laser parameters and the experiments are described, and the experimental results are analysed. The reasons for the decrease in the output pulse amplitude and lasing suppression at high pulse repetition rates are discussed. The acoustic waves arising due to the repetitively pulsed initiation of the mixture were shown to be the principal factor reducing the average output power at high pulse repetition rates and leading to the output instability and even to lasing suppression. The methods for the suppression of the perturbations, resulting in an increase in the output power are described. An average output power of 25 – 30 W was achieved for a pulse repetition rate of up to 1200 Hz and a technical efficiency of $\sim$ 2 %.**

Keywords: *electric-discharge DF laser, repetitively pulsed laser, electrodes, gas-dynamic loop, mixture density inhomogeneity, acoustic perturbations.*

1. Introduction

At present, considerable attention is paid to the development of compact repetitively pulsed DF lasers, which are promising for applications in medicine, ecology, and other fields [1, 2]. It is important to optimise the design of these lasers for increasing the output power, the output stability, the technical efficiency, and improving other characteristics.

To achieve the limiting parameters of repetitively pulsed DF lasers, it is necessary to optimise the composition and pressure of the working mixture and to ensure the uniformity of its flow in the interelectrode gap of the discharge chamber (DC) along with the development of a compact DC, a pulsed voltage generator (PVG), and preionisation techniques which allow producing a stable volume discharge.

As the pulse repetition rate is increased, progressively more stringent requirements are imposed on the spatial uniformity of the energy input in the main discharge and on the density homogeneity of the mixture in the active volume of the laser. To maintain the interelectrode-gap mixture replacement ratio within recommended limits [3], it is necessary to reduce the width of the main DC electrodes, which impairs the discharge uniformity and can be only partly compensated for by the proper profiling of the electrodes and the chamber design. The mixture density fluctuations arising from both the energy input nonuniformity and the acoustic perturbations in the medium due to repetitively pulsed initiation may attain values at which their effect on the uniformity and stability of the volume discharge becomes significant [4 – 6].

This work continues the investigations reported in Refs [2 – 4, 7].

2. Experimental setup

The setup is intended for the study of DF laser operation in pulsed and repetitively pulsed modes. The functional diagram and design of the setup are similar to those given in Ref. [6], except that neither a heat exchanger nor the system for sulphur precipitation were required in the setup described below. The main element of the setup is the gas-dynamic channel representing a closed annular cavity between the outer and inner housings, where the axial ventilators are placed to produce the mixture flow, as well as the filter filled with a sorbent to clean the mixture from the products of chemical reactions and the dielectric flow guides. In the narrowest part of the channel, the gas flow passes through the interelectrode gap. The mixture velocity in the gap was between 12 and 36 m s^{-1}, depending on the type and number of ventilators employed, the design of the electrodes built into the DC, and the electrode spacing.

The filter design and location were selected so as to minimise its gas-dynamic resistance. As in Refs [2 – 4], activated Al_2O_3 with a granule dimension of 2 – 3 mm was used as the sorbent. The granules were poured between two metal meshes placed in front of the ventilators.

The DC was made in the form of a separate unit with a gas-dynamic channel that narrowed from both sides towards the interelectrode gap. The cross section in the narrowest place was $(8 - 10) \times 280$ mm. The main electrodes – the anode and the cathode, and the preionisation electrodes connected to the cathode via blocking capacitors and high-voltage buses were secured in the central part of the DC.

The main DC electrodes were made of an aluminium

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alloy and possessed the 18-mm wide Stappaerts profile [8] with a smooth surface (smooth electrodes) or with an incision in the form of knife edges on the profile surface (knife-edge electrodes). The features of the volume discharge production between such electrodes upon single initiation of the mixture are described in Ref. [7]. The preionisation electrodes were as in Ref. [7].

The devices for mounting and adjusting the mirrors of the optical resonator were placed at the ends of the laser unit coaxially with the longitudinal axis of the DC. We used plane CaF_2 mirrors with a dielectric coating on the external surfaces. The reflectivities in the spectral emission range of DF^* molecules were ~ 0.96 for the highly reflecting mirror and ~ 0.65 for the output mirror.

The PVG was assembled based on the single-stage Fitch generator circuit with voltage doubling. The PVG capacitance could be varied in a broad range by varying the number of capacitors, resulting in the variation in the stored energy E_{st}. A controlled gap or a thyratron was used as a switch.

The PVG capacitors were charged to a certain voltage using a pulsed charging unit. A signal from the system for controlling the repetitively pulsed mode actuated the switch and the PVG discharged on the DC, the blocking capacitors being charged first. During charging of the capacitors, spark discharges occurred between the preionisation electrodes and the anode. The UV radiation of the sparks stimulated the main discharge between the anode and the cathode. The mixture components were ionised, the volume discharge was produced, and a laser pulse was generated with some delay.

The voltage pulses from PVD capacitors and the signals from a pyroelectric detector, which measured the amplitude and repetition rate of laser pulses, were simultaneously recorded with oscilloscopes. The total laser energy in the pulse train was measured with thermocouple calorimeters.

The mixture pressure was varied from 0.08 to 0.75 atm. The ratio between the active components of the mixture was invariable in all experiments ($SF_6 : D_2 = 6 : 1$). This ratio is believed to be optimal for DF lasers of this type [3]. The design of the laser unit allowed direct observations of the discharge between the main electrodes in the visible spectral range. The discharge was photographed with a camera through a transparent side window and in several cases through the output resonator window.

3. Experimental results

When the interpulse mixture replacement ratio providing the recovery of lasing properties and transparency of the mixture is achieved and when the preceding pulses have no effect on the subsequent ones, the amplitude and shape of laser radiation pulses in the repetitively pulsed mode and in the single-pulse mode should be virtually identical. This assumption was confirmed by our preliminary studies on the setup optimisation.

In the first experiments in the repetitively pulsed mode, we studied the possibility of using different electrode pairs considered earlier in Ref. [7]: both electrodes are smooth, a smooth anode and a knife-edge cathode, both electrodes are of the knife-edge type; the separation between the electrodes was 8 mm in all cases. For constant $U = 18$ kV and $E_{st} \sim 1.44$ J, we recorded the energy of laser pulses averaged over 0.1 s. The pulse repetition rate f was raised in steps from one experiment to another. The mixture flow velocity in the interelectrode gap was varied between 36 and 28 m s^{-1}, and the mixture replacement ratio decreased from pulse to pulse inversely with f. In a time of 0.1 s, the mixture did not manage to make a complete turn in the gas-dynamic channel, and therefore its composition, density, and temperature could be considered invariable.

Fig. 1a shows the dependence of the average energy E_0 of laser pulses on the frequency f for all combinations of the electrodes. As in Ref. [7], the combination with two knife-edge electrodes proved to be the best one. In this case, the quenching of lasing was observed for $f_c \sim 800$ Hz, whereas for other combinations, for ~ 650 and 250 Hz. The use of knife-edge electrodes is equivalent to raising U and improves the laser efficiency, the discharge stability also improving in this case.

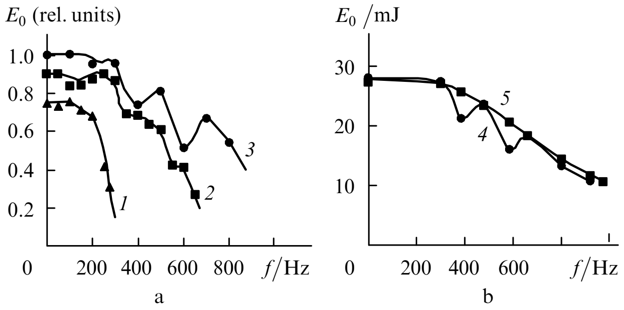

Figure 1. Dependences of the 0.1-s time-averaged laser pulse energy on the pulse repetition rate for $p_m = 0.16$ atm ($SF_6 - D_2$) in experiments with an RU78 gap, without meshes (a): (*1*) both electrodes are smooth, (*2*) a smooth anode and a knife-edge cathode, (*3*) both electrodes are knife-edged; and in experiments with a TP-10k/25 thyratron, a smooth anode and a knife-edge cathode (b): (*4*) without meshes, (*5*) with additional meshes.

The low f_c value in the case of two smooth electrodes can be attributed to large mixture flow perturbations in the interelectrode gap because of the 3-mm electrode protrusion beyond the dielectric flow guides. In this case, the flow velocity V in the interelectrode gap was ~ 36 m s^{-1}. In the case of two knife-edge electrodes, only the knife edges protrude beyond the dielectric flow guides, and the perturbations they introduce into the flow are significantly smaller than in the case of smooth electrodes. Moreover, there occurs a substantial peaking of the electric field (according to Ref. [9], by a factor of five and over) at the knife edges, which facilitates the discharge formation. Both factors contributed to the rise of average pulse energy and to the increase in f and f_c values compared to the combination of two smooth electrodes.

However, the photographs of the volume discharge suggested that it was more homogeneous for the combination of a smooth anode and a knife-edge cathode than for two knife-edge electrodes. Since the sacrifice in laser energy was moderate, this combination was adopted as the basic one. The electrode gap was increased to 10 mm and the velocity in the interelectrode gap lowered to ~ 28 m s^{-1}, resulting in the reduction of flow perturbations. The dependence of the average energy E of laser pulses on the initiation frequency for these experimental conditions is shown in Fig. 1b (curve *4*).

We already mentioned above about the role of flow perturbations in the interelectrode gap caused by the electrode protrusion beyond the dielectric flow guides. There also exist other reasons for significant mixture density variations and the quenching of lasing at a low pulse repetition rate. The mixture density homogeneity is disturbed not only by periodic and virtually instantaneous energy release in pulsed discharges (these inhomogeneities are carried out of the active region by the mixture flow), but also by the production of shock waves in pulsed discharges. Having a small amplitude, these waves rapidly transform into acoustic ones. These acoustic waves are reflected from different surfaces of the gas-dynamic channel and interact with each other to give rise to local inhomogeneities of the mixture pressure and density in the interelectrode gap. This effect was previously noted in Ref. [3]. These effects are likely to be inherent in repetitively pulsed lasers of any design. The design determines the features of the effects considered and the ways of suppressing them.

Subsequent investigations showed that resonance phenomena and effects akin to the stroboscopic one can occur in a DF laser. Every next pulsed discharge may or may not coincide in time and space with the adverse result of the interaction of acoustic perturbations: there occurs no discharge where the mixture is significantly densified, whereas a streamer can develop where the density is lowered. The existence of numerous regions in the interelectrode gap where the discharge is not produced, or is inefficient, in fact reduces the active region, resulting in a decrease in the output energy.

The dependences shown in Fig. 1a possess a characteristic feature which confirms the aforesaid. We observed a wave-like frequency dependence of the average energy of output laser pulses when one of the electrodes was knife-edged. The local energy minima were repeated with a period of ~ 200 Hz.

The local minima of dependence (*4*) in Fig. 1b are also shifted by ~ 200 Hz relative to one another. It seems likely that these minima are mainly caused by acoustic perturbations that propagate upstream and return to the active region upon reflection from the plate securing the ventilators. The perturbations travelling in the opposite direction are evidently suppressed by the filter with a sorbent. The wave reflected by the ventilator-securing plate is estimated to arrive at the interelectrode gap in ~ 5.4 ms for the design of a repetitively pulsed chemical laser involved. Therefore, the mixture density in the interelectrode gap may be non-optimal at repetition rates that are multiples of $\Delta f = 1/(5.4 \times 10^{-3}\ \text{s}) \sim 190$ Hz, resulting in a reduction in the output energy. The period $\Delta f = 190$ Hz agrees well with a repetition period of the minima of ~ 200 Hz observed experimentally.

An attempt was made to suppress the above acoustic perturbations by placing in their path an assembly of two metal meshes with a total transmittance of $\sim 40\,\%$. The results of experiments with the additional meshes are given in Fig. 1b (curve *5*). A comparison of curves (*4*) and (*5*) in Fig. 1b suggests that we succeeded in eliminating the periodic variation of the output laser energy with frequency f by suppressing the waves that propagated upstream, which confirmed the above assumption. However, the lowering of the average pulse energy for frequencies greater than 250 – 300 Hz was still observed.

We present another evidence that it is the interaction of acoustic waves which affects the production of an inhomogeneous volume discharge, resulting in the decrease in the average energy of laser pulses. Fig. 2a shows the visible-light photographs of time-integrated (over 0.1 s) discharge glowing along the electrodes taken for different repetition rates. The three dark stripes in Fig. 2a are the shadows of reverse conductors. An analysis of these photographs suggests that the acoustic waves propagating across the gas flow along the laser axis affect the formation of the volume discharge. The glow brightness is enhanced in the lowered-density regions, and vice versa, the glowing is, as a rule, absent where the density is high. Estimates show that the distance between the centres of the dark (and bright) regions corresponds to the coincidence of the fronts (and rarefaction regions) of the acoustic waves travelling towards each other after reflection from the side surfaces – the places of mounting of the resonator mirrors. As the frequency increases, the dark and bright regions expand and shift, i.e., a clear stroboscopic effect is observed.

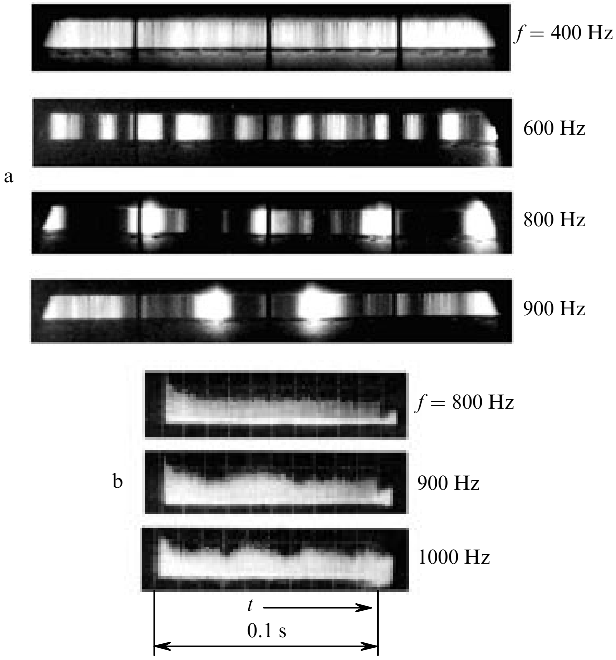

Figure 2. Glowing of the discharge in an $SF_6 - D_2$ mixture observed along the electrodes for different pulse repetition rates (a) and variation of the output laser energy in a pulse train in the absence of inclination of the side walls for $p_m = 0.16$ atm (b).

The effect of these waves can be reduced or completely eliminated by inclining the side chamber walls with respect to the axis of the active region (the resonator axis) and, in particular, by introducing optical windows tilted about the axis into the resonator. In our laser, the DC side walls were tilted at an angle of 30° to the axis and to one another, which improved the discharge homogeneity. The oscilloscope traces in Fig. 2b illustrate this. In this case, the side walls are not inclined and the additional meshes are absent. During the first 10 – 12 pulses their energy lowers to 0.6 – 0.7 of the initial one and subsequently oscillates about this value. The initial energy fall is supposedly related to the accumulation of the heated and partially ionised mixture between the knife edges. The subsequent energy oscillations clearly result from the interaction of acoustic waves in the mixture. Their suppression by all means could reduce the energy pulsation in the train of laser pulses.

The increase of the sound velocity V_s in the mixture due to its dilution with a light gas, in particular with helium, became a radical way of suppressing acoustic waves in the interelectrode gap. Increasing the sound velocity in the mixture contributes to a faster smoothing of its density inhomogeneities during the interpulse periods. In this case, the change of the electrical properties of the mixture gives promise that the homogeneity and stability of pulsed discharges should also improve.

Fig. 3a shows the visible-light discharge glowing for different initiation pulse repetition rates in experiments when He at a pressure of 0.45 atm was added to the mixture. A comparison of these photographs with those given in Fig. 2a suggests that the discharge homogeneity improved significantly after an addition of He to the mixture, including repetition rates of 1200 Hz and over. In these and all subsequent experiments, the side surfaces were inclined and additional meshes were fixed.

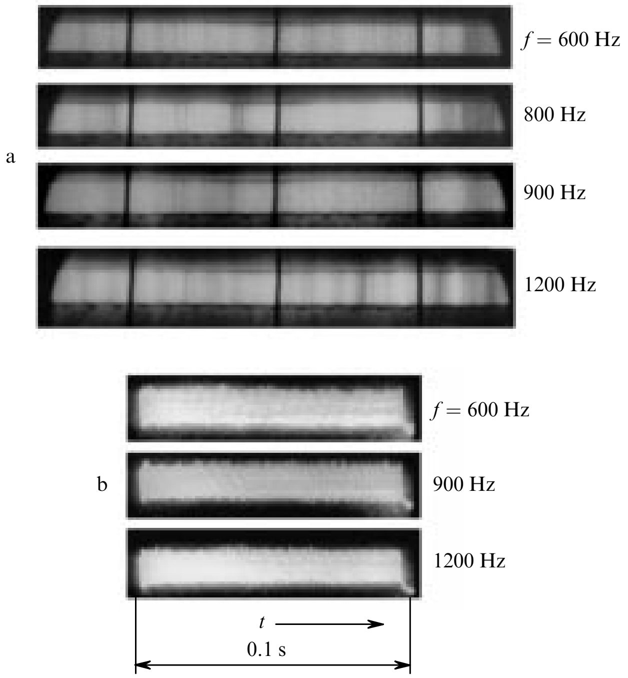

Figure 3. Glowing of the discharge in an $SF_6 - D_2$ mixture observed along the electrodes for $p_m = 0.14$ atm on addition of 0.45 atm of He (a) and variation of the output laser energy in a pulse train (b) for different pulse repetition rates, with the side walls inclined at 30° with respect to the resonator axis and additional meshes fixed.

Fig. 3b shows the oscilloscope traces of laser pulses for different initiation pulse repetition rates for the mixture with addition of He at 0.45 atm. A comparison of the oscilloscope traces depicted in Figs 2b and 3b suggests that the energy pulsation in the laser pulse train decreased considerably on dilution of the mixture with He. In this case, no energy fall was observed during the first laser pulses, which took place for mixtures without He.

Fig. 4 shows the dependences of the average laser pulse energy on the pulse repetition rate for mixtures with a different content of helium and without it for invariable $U = 18$ kV and $E_{st} \sim 1.44$ J. Naturally, the partial pressures of the active components had to be lowered to improve the impedance matching for the PVG and the discharge plasma at high concentrations of helium in the mixture. It follows from Fig. 4 that the maximum output energy E at frequencies of the order of 1000 Hz was obtained for a helium pressure of ~ 0.45 atm in the mixture. The reduced SF_6 density and the large content of the buffer gas for dependences (*4*) and (*5*) in Fig. 4 resulted in a lowering of E at low pulse repetition rates; at high repetition rates, the average energy rises to become for $f = 1000$ Hz as high as ~ 0.9 of the energy for a single initiation of the mixture without He. The output laser power and the technical efficiency were $Ef \sim 26 \times 10^{-3}$ J 1000 s^{-1} ~ 26 W and $100E/E_{st} \sim 100 \times 26 \times 10^{-3}$ J/1.44 J $\sim 1.8\,\%$, respectively.

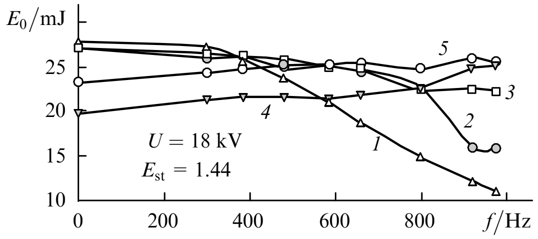

Figure 4. Dependences of the average laser energy E on the pulse repetition rate and the content of He in the working mixture for $p_m = 0.16$ atm ($SF_6 - D_2$), $V_s \sim 146$ m s^{-1} (*1*); $p_m = 0.16$ atm of ($SF_6 - D_2$) + 0.15 atm of He, $V_s \sim 207$ m s^{-1} (*2*); $p_m = 0.14$ atm of ($SF_6 - D_2$) + 0.3 atm of He, $V_s \sim 267$ m s^{-1} (*3*); $p_m = 0.14$ atm of ($SF_6 - D_2$) + 0.6 atm of He, $V_s \sim 395$ m s^{-1} (*5*).

The experiments were continued at repetition rates of 1100, 1200 Hz and over, though for lower U and E_{st} owing to the power limitations of the pulsed charging unit in use. The technical efficiency for dependences (*4*) and (*5*) equal to approximately 1.8 %–2 % is also retained for these repetition rates. The fact that the output laser energy was virtually constant as f was increased to ~ 1000 Hz at a high content of He indicates that the mixture initiation conditions found in the course of investigations were optimal.

4. Conclusions

We have built a DF laser with an output power of 25–30 W, a pulse repetition rate of up to 1200 Hz, and an efficiency of ~ 2 %. The main factor responsible for the reduction of the average energy of laser pulses and the quenching of lasing well before the attainment of the limiting pulse repetition rate for lasers of this type is acoustic perturbations in the active volume, which are induced by the repetitively pulsed initiation of the mixture. The interaction of acoustic waves in the medium produces mixture density inhomogeneities in the interelectrode gap and, as a consequence, leads to the impairment of the discharge homogeneity, local mixture overheat, the occurrence of streamers, and the reduction of the energy of laser pulses.

The following technical solutions can maximise the output laser parameters:

(i) the use of the electrode system with profiled knife-edge electrodes, which peak the electric field and do not introduce significant perturbations into the flow of the working mixture;

(ii) the suppression of acoustic perturbations in the active volume by tilting the side walls of the gas-dynamic circuit in the resonator region and placing two additional metal meshes in the path of the stream from the ventilators to the discharge chamber to eliminate the reflection of a part of the acoustic waves from the construction elements;

(iii) more than a three-fold dilution of the $SF_6 - D_2$ working mixture with helium to significantly increase the sound velocity. In this case, the mixture density variations incompletely eliminated by the above design modifications manage to fall, during the interpulse period, to the values which exert only a weak effect on the discharge quality and the lasing characteristics of the mixture.

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