Efficient gas lasers pumped by run-away electron preionized diffuse discharge

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ABSTRACT

It was shown that run-away electron preionized volume (diffuse) discharge (REP DD) can be used as an excitation source of active gas mixtures at elevated pressures and can produce laser emission.

We report experimental and calculated results of application of the REP DD for excitation of different active gas mixtures. It was shown that the REP DD allows to obtain efficient lasing stimulated radiation in the IR, visible and UV spectral ranges.

Kinetic model of the REP DD in mixtures of nitrogen with SF_6 is developed allowing to predict the radiation parameters of nitrogen laser at 337.1 nm.

Promising prospects of REP DD employment for exciting a series of gas lasers was demonstrated. Lasing was obtained on molecules N_2, HF, and DF with the efficiency close to the limiting value. It was established that the REP DD is most efficient for pumping lasers with the mixtures comprising electro-negative gases.

Keywords: run-away electron preionized diffuse discharge, efficient gas lasers

1. INTRODUCTION

In recent years, there is increasing interest to study of run-away electron preionized diffuse discharges (REP DD). This discharge can be formed in gases at pressure up to tens of atmospheres in discharge gaps formed by electrodes providing non-uniform electric field (between needles, blades and so on) when voltages pulses with a high amplitude and sub-ns rice-time are used. Therewith runaway electron beams and X-ray are observed during REP DD formation. The REP DD important feature is very high input electric power and possibility to form uniform plasma in active gas mixtures at very high pressure. This feature makes very promising the REP DD application for pumping different gas lasers because new operation modes of lasers can be obtained and laser emission on transitions, which cannot be obtained by conventional methods, can be achieved.

Early[1–4] it was shown that gas mixtures at elevated pressures pumped by a runaway-electron-preionized volume (diffuse) discharge (REP DD) exhibited lasing in the IR[1], visible[2] and UV[3, 4] spectral ranges. In those works, runaway electrons and laser radiation were generated in the same discharge gap. Runaway electrons formed in a separate gap were used for preionizing the main lasing gap, in which the generation on nitrogen[5] and carbon[6] dioxide molecules was realized. In addition, the voltage pulses used for obtaining runaway electrons in atmospheric air were also employed for pumping a laser on ZnSe crystals[7]. The runaway-electron beams formed in a separate gap by kilovolt voltage pulses were used to pump gas lasers in the IR range at low and moderate pressures[8–10].

Analysis of popular works shows that the pumping of lasers efficiently operating at elevated pressures of working mixture[11, 12] is more promising if the diffuse discharge is formed by a runaway electron beam. The duration of the current pulse of runaway electrons formed in gases at pressures of hundred Torr and higher is comparatively small (~100 ps) and the current density of the beam at atmospheric pressure usually does not exceed several amps per square cm[13,14]. Such values are explained by the mechanism of forming the runaway electron beam at elevated pressures[13]. In these conditions, most of runaway electrons are produced between the front of the ionization wave and the anode, and the

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current pulse duration of the beam is limited, in particular, by the wave-front of the ionization wave arriving at the anode.

In this report, experimental study and simulation of laser parameters in different gas mixtures pumped by the REP DD is performed and the most promising gas mixtures for realizing efficient lasing are determined.

2. EXPERIMENTAL SETUP AND MEASURING METHODS

Lasing in various gas mixtures was studied under pumping by the voltage pulses of nanosecond duration formed by a RADAN-220 generator. The circuitry of the RADAN generator includes a high voltage pulsed forming line (PFL) with capacitance *C*=50 pF and oil insulation, which is charged from a Tesla transformer (TT) and than is switched on a load with commercial two-electrode high-pressure nitrogen spark gap R-49 [15]. Wave resistance of the forming line is $\rho = 22$ Ohm. The half-height voltage duration on the matched load was ~2 ns and the front duration of a voltage pulse in the forming line was approximately 0.5 ns. With connected discharge chamber, the front duration of the voltage pulse increased to ~2 ns, the half-height pulse duration also increased. The duration of the current pulse depended on the pressure and type of gas and at low helium and neon pressures reached several hundred nanoseconds in the oscillating regime.

In these experiments the discharge gap *d* between the anode and cathode was 1.2 or 1,8 cm. The both electrodes were shaped as blades. The length of the discharge domain was 20 or 28 cm. The cavity comprised plane mirrors placed on end walls of the discharge chamber. The highly reflecting mirror was made of a plate with an aluminium coating. For the output mirror we used the plane-parallel plates made of quartz, CaF_2, KRS-5, KRS-6 or Ge. We also used plane mirrors with dielectric coatings and the reflection coefficients in the UV and visible ranges $R = 20 – 80$ %.

The chamber was evacuated by a diffusion pump and was filled with various gases. Its side wall had an additional window for shooting the discharge and detecting the pulses of spontaneous emission. The REP DD current was measured with resistive shunt made from low-inductance chip-resistors. The schematic diagram of the laser chamber is shown in Fig.1.

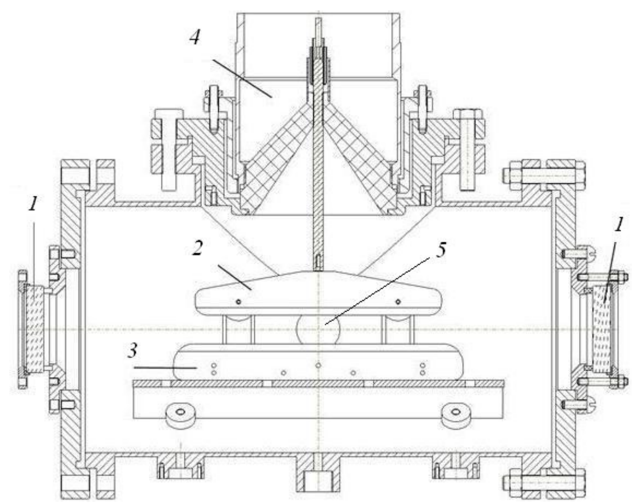

Figure 1. Schematic diagram of the laser pumped by REP DD. (1) mirrors of the laser resonator, (2, 3) blade electrodes, (4) the RADAN-220 pulse generator, (5) side window.

The amplitude – time characteristics of visible and UV radiation were detected with a FEK-22SPU photodiode, the IR radiation was detected with a FSG-23 photoresistor. The lasing domain was determined by luminescence on the screen placed on the output mirror. The discharge glow and screen luminescence were photographed by a Sony A100 digital camera. The spectra of radiation were recorded with a StellarNet EPP2000-C25 spectrometer with calibrated spectral sensitivity in the wavelength range $\lambda = 200 – 850$ nm at a resolution of 0.75 nm. Spectra in the range $\lambda = 2.8 – 4.2$ mm were recorded by using an MDR-12 monochromator equipped with a 300 lines mm^{-1} grating and FSG-23 photoresistor.

In performing the measurements, the photodetectors operated in a linear regime, which was provided by attenuating the laser radiation by a series of metal meshes. The energy of laser radiation was measured by an OPHIR calorimeter with a

PE-50BB measuring head. The electrical signals were recorded with a TDS-3054B oscilloscope (0.5 GHz, 5 samples per 1 ns).

Earlier it was established that addition of electro-negative gases substantially, by the order of magnitude[3], increases the radiation energy and power of the laser operating on the second positive system of nitrogen. The increase in the radiation energy in the mixtures comprising electro-negative gases is mainly explained by the increased gap breakdown voltage on the installations with the electrodes of a small radius of curvature.

The following mixtures with electro-negative gases were employed in the experiments: $N_2 – NF_3$ (SF_6), $H_2 – C_2H_6 – SF_6$, $H_2(D_2) – SF_6$, $He – NF_3$, $Ne – NF_3$ и $Ar – NF_3$, as well as $Ne(He) – Xe – NF_3$. The generation parameters of those mixtures were studied earlier under the excitation by a transversal volume discharge and electron beam[11, 12, 16–18].

One of the basic parameter of a gas laser is its efficiency which in turn is determined by the self-breakdown voltage of the P-49 spark gap U_0. This voltage can be estimated for measurements of short-circuit current in the laser gap. Waveform of the current is shown in Fig. 2. Therewith the discharge circuit can be considered as a capacitor C=50 pF,

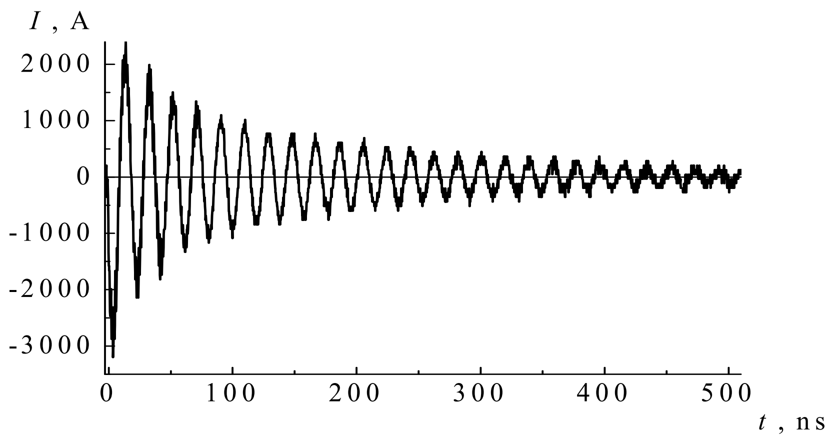

Figure 2. Waveform of the short-circuit current in the laser gap.

circuit resistance R and circuit inductance L connected in series and the discharge current is determined by the following well known equation[19]:

$$I = -\frac{dQ}{dt} = Q_0 \cdot \omega_0 \cdot \left(\frac{\omega_0}{\omega}\right) \cdot \exp\left(-\beta \cdot t\right) \cdot \cdot Sin\left(\omega \cdot t\right), \quad (1)$$

where $\omega_0 = \sqrt{\frac{1}{L \cdot C}}$, $\omega = \sqrt{\frac{1}{L \cdot C} - \frac{R^2}{4 \cdot L^2}}$, $\beta = \frac{R}{2 \cdot L}$. Therewith current integral on time is equal to

$$\int_0^\infty I \cdot dt = -\int_0^\infty \frac{dQ}{dt} \cdot dt = Q_0 \cdot \omega_0 \cdot \left(\frac{\omega_0}{\omega}\right) \int_0^\infty \exp\left(-\beta \cdot t\right) \cdot Sin\left(\omega \cdot t\right) \cdot dt = Q_0, \quad (2)$$

where initial charge on the capacitor plates is $Q_0=U_0C$. Since the running time in the PFL (2 ns) is one order less than the oscillation period of the discharge current (20 ns) the quasistationarity condition is performed and expressions (1) and (2) are valid. Than it is easy to calculate initial energy stored in the PFL as $E_0=CU_0^2/2$. From our measurements it was obtained that U_0=240±10 kV and stored in the PFL energy does not exceed E_0=1.56 J.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Nitrogen laser (λ = 337.1 nm)

For obtaining the generation on the UV transition of nitrogen molecule (λ = 337.1 nm) the value of the parameter E/p in the discharge gap should be at least 100 V cm^{-1} $Torr^{-1}$. Under pumping by a self-sustained discharge the voltage across the gap falls in several nanoseconds. Correspondingly, for increasing the efficiency of generation on nitrogen molecules the discharge current pulses should have the duration shorter than 10 ns. Thus, to obtain high efficiency under such conditions, one has to design supply circuits providing fast (≈10 ns) injection of high energy (≈0.1 J cm^{-3}) into the working medium in order to rapidly reach the lasing threshold. On the whole, the laser design should simultaneously satisfy many requirements to provide high efficiency. Primarily, one has to use short-time energy transfer from the energy storage to load (no longer than the inversion lifetime), precisely choose operating pressure and composition mixture (if additives of other gases are used), and apply appropriate thermal conditions. Besides, to develop a nitrogen laser with maximum efficiency, one has to perform a detailed numerical simulation of the processes occurring in the active medium and pump generator. Hence, it is necessary to develop a complete numerical model making it possible to choose the optimal parameters of the supply circuit and laser geometry based on the required lasing characteristics. One of the purposes of our study is to construct this theoretical model of the electric-discharge laser on nitrogen-electronegative gas mixtures, excited by run-away electron preionized discharge.

When simulating the plasma-chemical processes in the volume discharge plasma in $N_2-SF_6(NF_3)$ mixtures and the lasing on transitions in nitrogen, we calculated the following parameters, processes, and objects:

(i) EEDF fe(E/p, ε, t) in the self-sustained discharge, where E and p are, respectively, the field strength and gas pressure in the discharge gap; ε is the electron energy; and t is time;

(ii) the electron mobility μ_e, temperature T_e, and diffusivity D_e and the rate constants or reactions of electrons with plasma particles;

(iii) kinetic processes involving heavy particles, more than 100 kinetic processes are considered;

(iv) laser radiation;

(vi) pump generator circuit.

All calculation procedures (in the form of individual program blocks) are combined into a self-consistent model, described in details in[20]. Kinetic model of the REP DD allows us to determine optimal gas mixture for achieving maximal laser efficiency and to predict the radiation parameters of nitrogen laser at 337.1 nm in different gas mixtures of nitrogen with electro-negative additions. Calculated voltage, current of the REP DD and laser pulses in optimal mixture of N_2 with SF_6 are shown in Fig.3. Modification of this model allows us to estimate REP DD voltage, current and energy deposition for SF_6-H_2 mixtures.

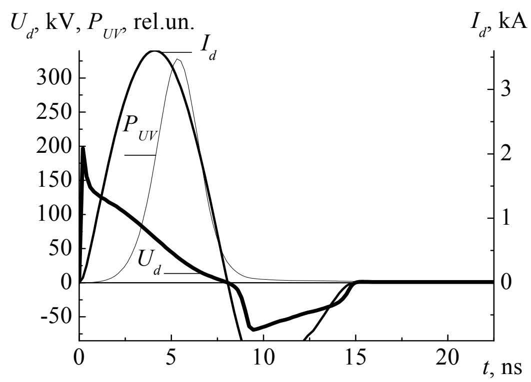

Figure 3. Calculated waveforms of the REP DD current, voltage across the laser gap and laser pulse at λ =337, 1 nm in the $N_2 : SF_6 = 300 : 45$ Torr mixture.

It is followed from the above, that the pulse generator used in the experiments is optimal for pumping a nitrogen laser and the employment of nitrogen mixtures with SF_6 provides matching the discharge resistance with generator impedance, which increases the pump power and energy of the UV radiation. In this case, the diffuse discharge without gap preionization was formed in nitrogen and its mixtures with SF_6 at pressures of up to several atmospheres.

Experimental results obtained are shown in Fig. 4. Under REP DD pumping, simultaneous lasing on the second (λ = 337.1 nm) and first (λ = 865–1048 nm) nitrogen systems was observed, which started 3 ns after the breakdown of the discharge gap. The generation domain width was 0.5 cm with the uniform distribution of laser radiation power over the discharge aperture, the peak radiation power reached 0.7 MW. The maximal energy of the UV radiation was 3.1 mJ at the electrical efficiency (with respect to the energy stored in the forming line of the RADAN-220 generator) $\eta_0 \approx 0.2$ %. Such efficiency is close to the limiting theoretical value for this type of the laser[21] and to maximal efficiencies obtained experimentally[21, 22].

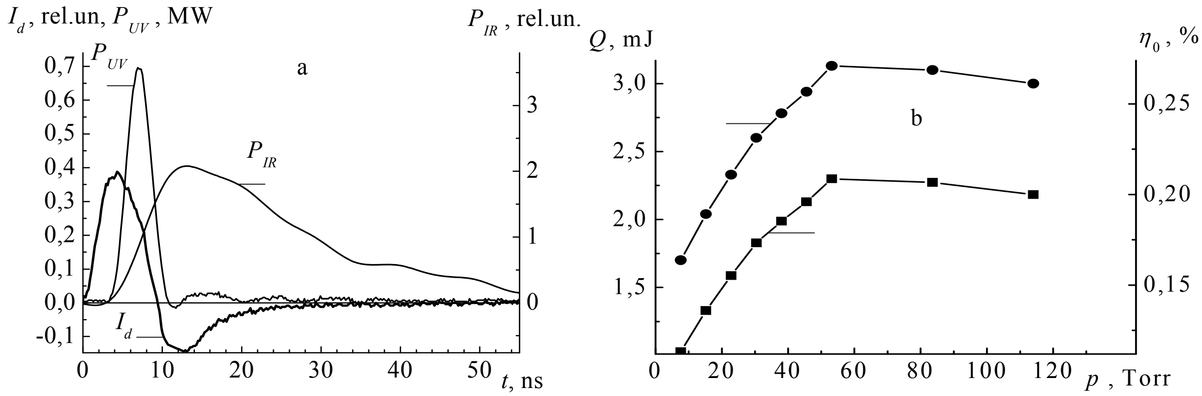

Figure 4. Oscillograms of REP DD current pulses and generation in the mixture N_2:SF_6=300:45 Torr on the first (P_{IR}) and second (P_{UV}) positive bands of nitrogen (a) and dependences of radiation energy Q at λ=337.1 nm and electrical efficiency of nitrogen laser η_0 on pressure of SF_6 at the nitrogen pressure 300 Torr (b).

3.2 Non-chain chemical HF(DF) lasers

An interesting feature of SF_6 mixtures with hydrocarbons is the possibility of forming the volume discharge without preionization[23]. However, the discharge in the SF_6 mixtures with H_2 or D_2 in conventional excitation regimes is unstable and hence the electrodes are required capable of providing the uniform electrical field in the discharge gap[24]; the maximal efficiency in non-chain HF(DF) lasers in the mixtures with $H_2(D_2)$ was obtained with short pump pulses (~20 ns)[25].

In our experiments, the duration of the discharge current pulse was about 10 ns, and estimated energy deposition into the laser active medium was ~0.7 J. At the volume of the laser active medium 15 cm^3 such energy deposition corresponds to the specific pump energy of 50 J/l, which is optimal for a non-chain electro-discharge HF laser[26]. The pump power under these conditions reached 20-30 MW/cm^3.

Fig. 5 shows the generation energy for HF(DF) lasers versus the reflection coefficient of the output mirror. The maximal

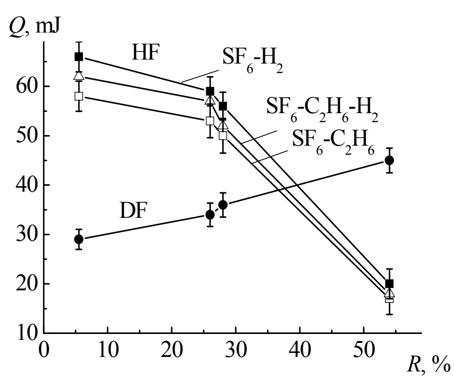

Figure 5. Output energy of laser on molecules HF and DF vs the reflection coefficient of the output mirror of cavity for the mixtures: SF_6:$H_2(D_2)$=8:1, SF_6:H_2:C_2H_6=44:3:1, and SF_6:C_2H_6=20:1 at the pressure of 275Torr

radiation energy of the HF laser (65 mJ) obtained, similarly to[26], in a mixture with hydrogen. It corresponds to the internal (relative to the energy deposited into the discharge plasma) generation efficiency, which is close to the limiting value 10%. The radiation energy of the DF laser raises linearly with increasing cavity Q-factor and at the reflection coefficient of the output mirror R=55% reached 45mJ. The obtained generation efficiency (η_{int}=6.5%) is also close to the limiting value for the DF laser (8%). One may expect a further increase in the radiation energy and efficiency at greater R. Similarly to[26], the integral, with respect to spectrum , radiation pulse of non-chain lasers with REP DD pumping had a single peak and intensive cascade transitions were observed in the generation spectrum.

Spectral parameters of non-chain REP DD pumped lasers are shown in Fig.6. The number of lasing lines attained 16 in mixtures of SF_6 with hydrogen. The radiation energy distribution over bands was $Q(P_1) : Q(P_2) : Q(P_3)$ = 1 : 0.62 : 0.1. The maximal energy was radiated at the P_1 band of the HF molecules. The number of DF lasing lines attained 26, and lines of the P_2 band had maximal intensity. A decrease in the number of lasing lines as compared to[26] can be related to a shorter active length of the discharge gap.

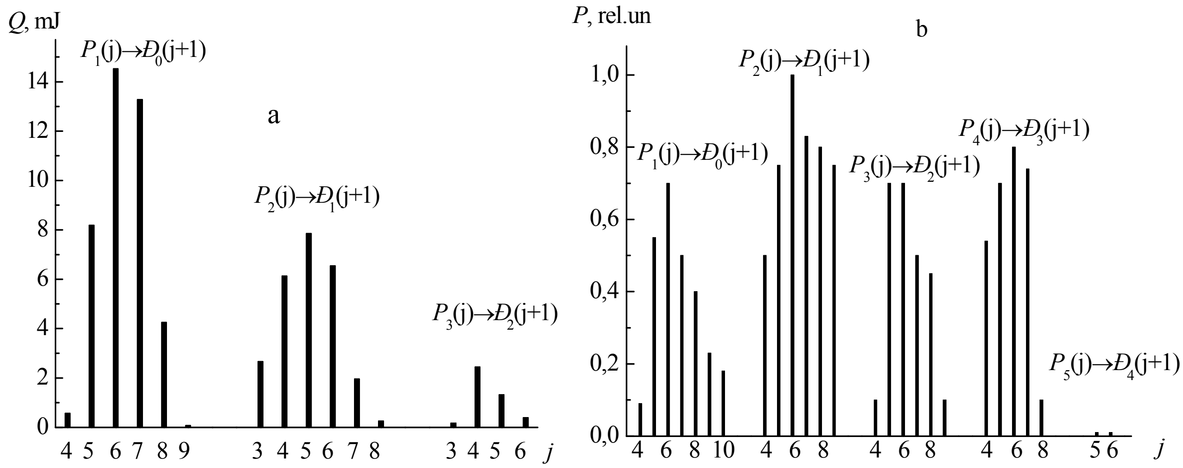

Figure 6. Energy (a) and intensity (b) lasing line distributions of a non-chain (a) HF and (b) DF laser pumped by REP DD, $SF_6 : H_2(D_2)$ = 240 : 30 Torr mixture is used. CaF_2 (a) and Ge (b) plates are used as exit mirrors of the laser cavity.

The maximal radiation energy of HF and DF lasers was observed in the bands P_1 and P_2, respectively (see Fig. 6). This fact proves the high uniformity of energy deposition into the active medium under REP DD pumping. It is knowledge that cascade transitions do not occur in a non-uniform discharge and the radiation pulse exhibits the well pronounced spike-mode character[26,27]. Cascade transitions increase the efficiency of energy extraction from the active medium of non-chain chemical lasers, because a single excited molecule HF (v=3) or DF (v=4), where v is the vibrational quantum number, may emit up to three photons. In addition, due to the powerful pump pulse, lasing in separate lines started within 15-20 ns after the discharge gap breakdown with a jitter of 5ns, which reduced the energy losses to attaining the generation threshold. These factors provide the high efficiency of the non-chain laser upon REP DD pumping. Note that the distribution of radiation power over the aperture of lasing spot was also comparatively uniform.

The high REP DD power at maximal Q-factor of the cavity resulted in appearance of weak lines in the generation spectrum of HF and DF molecules in the P_4 and P_5 bands with v=4 and 5, respectively (see Fig.7). Lasing in these lines started within ~75 ns after the onset of the discharge current, their intensity was weaker by 2–3 orders of magnitude than that other lines. The excited molecules HF (DF) with the vibrational quantum number $v > 3$ ($v > 4$) are formed in a “hot” reaction H(D) + F_2, whereas the generation in the $P_4 – P_6$ bands of HF molecules is usually observed under the powerful uniform electron beam pumping[28]. If the mixtures are excited by a conventional transversal self-sustained discharge, the generation threshold in the transitions of HF (DF) molecules with $v > 3 – 4$ is not attained.

3.3 Other gas lasers

Generation in the mixture Ne – NF_3 was earlier obtained at the wavelength of 585.3 nm (the transition 3p – 3s of Ne atom) under pumping by a transversal discharge; the uniformity of the latter was provided by the preionization from additional spark gaps[16]. Employment of the REP DD in the present work gave the chance to increase the optimal pressure of working mixture and the pressure of electro-negative gas NF_3. The generation pulses were observed with one or two peaks depending on the pressure of the mixture. The maximal power of radiation was 180 W. The double-peak generation was observed from the entire inter-electrode gap at the pressure of mixture less than 100 Torr without bright spark channels in the gap. The power of the second generation peak was lower and it had a delay of ~10 ns relative to the

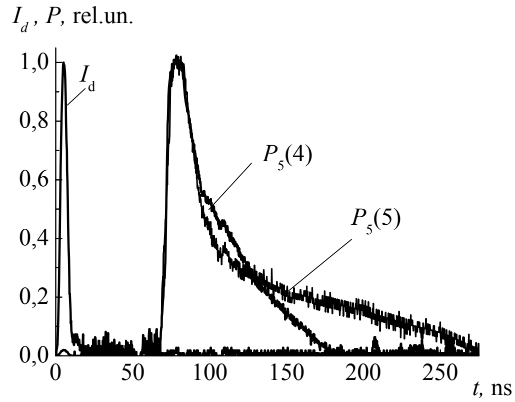

Figure 7. Oscillograms of discharge current pulses and lasing at $P_5(4)$ and $P_5(5)$ lines of a REP DD pumped DF laser in SF_6 : D_2 = 240 : 30 Torr mixture, a Ge plate is used as an exit mirror of the resonator.

first peak and was detected from a discharge domain near the anode. Appearance of the second peak may be explained by an increased pump power at the instant of second half-period of the discharge current. The half-height duration of the first (main) generation peak was ~3.5 ns at the optimal pressure. Disappearance of the second generation peak at an elevated pressure may be explained by contraction of the discharge. After the first generation peak, the intensity of the discharge emission detected through a lateral window of the discharge chamber increased and bright spark channels were observed in the gap.

Laser on Ar – NF_3 mixtures. Generation in Ar – NF_3 mixtures at the wavelength λ =750.3 nm (the transition 4p – 4s of Ar atom) was obtained earlier[16] under pumping by a transversal discharge with the spark preionization as in the mixture Ne – NF_3. The REP DD has increased the optimal pressure of the mixture and the pressure of NF_3. Generation of two radiation peaks was also observed in this mixture. The half-height duration of the first peak of a lower power was ~5 ns at optimal pressures.

Laser on He – NF_3 mixtures. In the mixture He – NF_3 the generation threshold on the transition 3s – 2p of He atom (λ = 706.5 nm) was not attained, probably due to the shorter (by four times) active length of the laser (~20 cm) as compared to that in[16] where pumping was made by a transversal discharge.

However, under REP DD pumping the generation was obtained in the range λ = 620 – 760 nm on the lines of atomic fluorine, which were earlier observed in the mixtures of helium with various fluorine donors excited by the self-sustained volume discharge[17]. Up to seven generation lines were observed at an elevated helium pressure. The generation power also increased with pressure. Most intensive were the atomic fluorine lines at λ = 712.8 and 731.1 nm. In all the lines the half-height duration of the generation pulse depended on the pressure and for the mixture He : NF_3 = 99 : 8 Torr it was ~10 ns.

XeF laser. The highest generation power under REP DD pumping of the mixtures of inert gases with NF_3 was obtained in the conditions of our experiment on transitions of XeF* molecule. At the mixture pressure of 4 atm and lower, the radiation power in the mixture with buffer helium gas was higher than in the mixture with the neon buffer gas and reached 30 kW. No measurements were performed at higher pressures because of the pressure limitation for the mixture in the installation. The half-height duration of generation pulse decreased from 8.5 to 5.5 ns if the mixture pressure increased from 1.2 to 2.6 atm. The generation spectrum depended on the contents of the working mixture. In the He – Xe – NF_3 mixture, the laser radiation was mainly observed at λ = 351 nm, whereas in the Ne – Xe – NF_3 mixture it was observed at λ = 351 nm and λ = 355 nm. The power of radiation at λ = 353 nm was twice greater. Not high values of generation parameters of various lasers on the mixtures with NF_3 are explained by the low resistance of the discharge because attempts to increase the concentration of this additive resulted in a fast loss of uniformity of the REP DD due to its stratification. The mechanism of this phenomenon was thoroughly considered in our work[29].

4. CONCLUSIONS

Thus, the investigations conducted show the promising prospects of REP DD employment for exciting series of gas lasers. Generation was obtained on molecules N_2, HF, and DF with the efficiency close to the limiting value. It was established that the REP DD is most efficient for pumping lasers with the mixtures comprising electro-negative gas SF_6. The addition of SF_6 increases the breakdown voltage in the gaps with electrodes having the shape of blades and makes the pump power higher. Under REP DD pumping the generation at transitions of helium, neon, argon, and molecules XeF* was obtained in the mixtures of inert gases with NF_3 also in visible and UV spectral ranges. However, in those mixtures the generation efficiency was comparatively low, seemingly, due to the loss of discharge uniformity at increased contents of NF_3 in the mixture.

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