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Efficient e-beam and discharge initiated nonchain HF(DF) lasers

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Abstract

The spectral and amplitude-temporal parameters of HF (DF) lasers pumped by nonchain chemical reactions initiated by radially convergent or planar e-beams and self-sustained discharge were studied. Intrinsic efficiency of the HF lasers up to ~10% was obtained for both excitation methods. It was shown that the high efficiency of an e-beam-initiated HF laser may be attained as a result of the simultaneous formation of atomic and molecular fluorine and of the participation of F_2 in population inversion. A laser pulse has a complex profile caused by the successive generation of P-lines and the overlap during the radiation pulse of both the rotational lines of the same vibration band and of individual vibration bands. Experimental conditions providing high intrinsic efficiency of a discharge nonchain HF (DF) laser are determined. Intrinsic efficiency of HF and DF lasers up to $\eta_{in} \sim 10\%$ and 7%, respectively, is obtained using excitation by inductive and LC generators in the SF_6-H_2 (D_2) mixtures. High discharge uniformity obtained with the use of special shaped electrodes along with uniform UV preionization is a key parameter for improving the intrinsic efficiency of discharge HF (DF) lasers. It was found that in this excitation condition, output spectra of the HF laser significantly widen and cascade laser action on some rotational lines of the vibrational transitions of HF molecules $\nu(3–2) \rightarrow \nu(2–1) \rightarrow \nu(1–0)$ is observed. This can explain the high intrinsic efficiency obtained. Specific output of the discharge HF laser over 8 J/L (140 J/L×atm) and total laser efficiency $\eta_t \sim 4.5\%$ were achieved. For the discharge DF laser, specific output and total efficiency were as high as 6.5 J/L and 3.2%, respectively.

Keywords: E-beam and discharge pumping; High intrinsic efficiency; Nonchain HF(DF) laser

1. INTRODUCTION

At present, chemical HF (DF) lasers pumped by chain and nonchain chemical reactions are widely investigated. Electron beam and self-sustained discharge are the main methods for initiation of the chemical reaction (Gross & Bott, 1976; Basov, 1982). The use of an e-beam in the initiation of chain and nonchain chemical reactions in HF lasers makes it possible to excite large volumes of the active media and to obtain considerable energies and (or) radiation efficiencies (Velikanov *et al.*, 1996; Gastaud *et al.*, 1997; Tarasenko *et al.*, 1998). The highest radiation efficiencies and energies are attained in chain lasers pumped by chain reactions. However, in the practical applications of HF (DF) lasers, the latter must have high-energy characteristics in an individual-pulse regime. The lasers must also be safe and convenient in operation. From this point of view, e-beam-initiated nonchain HF lasers are more promising. Intrinsic efficiency for an e-beam-initiated nonchain HF laser can be as high as 9–11% (Bashkin *et al.*, 1977).

Parameters of lasers with nonchain chemical reactions excited by a self-sustained discharge are determined by discharge and pumping pulse parameters. In certain experimental conditions, high radiation parameters were obtained without preionization of the laser active volume (Zapolsky & Yushko, 1979; Apollonov *et al.*, 1996, 1998). Up to now, specific output of 7–8 J/L (50–75 J/L × atm) and total HF laser efficiency of 3–4% are reached (Apollonov *et al.*, 2000*a*; Tarasenko *et al.*, 2001). As for a discharge DF laser, its output parameters are about 0.8 of that of the HF laser (Apollonov *at al.*, 1996, 2000*a*, 2000*b*).

Under excitation by the X-ray-initiated electric discharge at initial E/p parameter value across the laser gap exceeding static breakdown, the laser-specific output of 9.6 J/L (~55 J/L × atm) and total efficiency of $\eta_t = 4.7\%$ were

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obtained in the mixtures with C_2H_6 while only 5.75 J/L was achieved in the H_2-based mixtures (Richeboeuf *et al.*, 1998, 1999; Lacour *et al.*, 2001). It was shown that this excitation mode allows improved intrinsic efficiency of the laser on SF_6-H_2 mixture; the efficiency up to $\eta_{in} = 8\%$ was obtained at low input energy 10–15 J/L (~0.1 kJ/L × atm), η_{in} decreased to 6.5% at 100 J/L. Intrinsic efficiency of a nonchain HF laser was improved using a pulse generator with inductive energy storage. With this, $\eta_{in} = 5.5\%$ was obtained at relatively high specific input power of 50 J/L (~0.85 kJ/L × atm; Baksht *et al.*, 1999).

The present article reports development of e-beam and discharge-initiated HF lasers with intrinsic efficiency $\eta_{in} = 10\%$. Discharge DF lasers with $\eta_{in} = 7\%$ and specific output of 6.5 J/L were developed as well. It was shown that high efficiency of e-beam-initiated HF lasers may be attained as a result of the simultaneous formation of atomic and molecular fluorine and of the participation of F_2 in population inversion. Discharge stability was found to be one of the main parameters determining output parameters of a nonchain HF (DF) laser with initiation by a self-sustained discharge.

2. EXPERIMENTAL TECHNIQUE AND MEASUREMENT PROCEDURE

Two e-beam devices and a discharge HF (DF) laser were used in our experiments. The first setup with the volume of 30 L (1 m in length and 20 cm in diameter) was pumped by a radially convergent e-beam from four cathodes (Abdullin *et al.*, 1997).

Device two was used previously to investigate broadband emission and was similar to that described in Sereda *et al.* (1993). The accelerator made it possible to generate an e-beam with a cross section of 42×1.5 cm^2, a current density of 2.5 A/cm^2, a current pulse duration at half amplitude of 50 ns, and an electron energy of 155 keV after crossing the separation foil.

The discharge-initiated HF (DF) laser was similar to the long pulse excimer laser excited by the inductive energy storage with semiconductor opening switch (Baksht *et al.*, 2002). The laser has active volume about 200 cm^3. The discharge gap $d = 3.8$ cm between two polished special shaped stainless steel electrodes, which significantly reduce electric field nonuniformity in the active volume, was uniformly preionized by 72 spark gaps evenly distributed along both sides of the anode. The laser was pumped by the LC generator with primary capacitor $C_0 = 70$ nF and pulse duration of about 200 ns or by the inductive generator which forms 100-ns pulses.

The laser cavity was formed by a spherical copper mirror with a radius of curvature of 2.5 m or a plane mirror with Al coating and thallium iodide or thallium bromide plane-parallel output plates. The laser output and radiation waveform were measured by the IKT-1N calorimeter or energy meter OPHIR with the head FL-250A-EX and the FSG-22 photocell cooled by liquid nitrogen, respectively. The laser spectra were recorded by the MDR-12 monochromator equipped with the FSG-22 photocell. Discharge current and voltage across the laser gap were measured with a Rogovsky coil and voltage divider, respectively. Electric pulses were recorded by the TDS-220 or TDS-224 digital oscilloscopes. The Olympics 2000 digital camera takes integral luminescence of the laser discharge.

3. EFFICIENCY OF NONCHAIN HF LASER WITH E-BEAM INITIATION

3.1. HF-laser pumped by the planar e-beam

The HF laser output energy for gas mixture of a SF_6:H_2 = 7:1 composition in the range of pressure 0.1–1 atm is shown in Figure 1. The change the e-beam energy absorbed in the gas media (see Fig. 1, curve 1) was calculated by the formula: $W_{in} = j_b \cdot (dE/dx) \cdot V \cdot t_b$. Here j_b is the e-beam current density, dE/dx is the average energy lost by an electron per unit of length, V is the laser active volume, and t_b is the e-beam duration. Average electron energy was measured to be 130 keV; the energy losses calculated according to the method described in Komar *et al.* (1982) were 1.8×10^3, 3.5×10^3, 6.48×10^3, 15.6×10^3, and 19×10^3 eV/cm for the mixture pressure 0.096, 0.184, 0.344, 0.82, and 1 at., respectively. The radiation energy rise (see Fig. 1, curve 2) saturation with pressure is caused by the e-beam energy distribution (Bashkin *et al.*, 1977; Basov, 1982; and Orlovskii *et al.*, 1999). Maximal laser output is mainly determined by competition between formation of HF^* molecules in chemical reaction and their collisional decontamination. This tends to make the efficiency and laser output decrease (see Fig. 1, curve 3) with pressure. However, maximal laser efficiency was as high as $\eta_{in} = 5.5\%$.

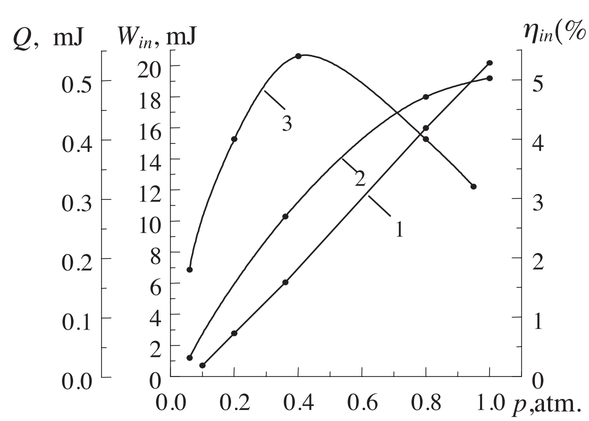

Fig. 1. Input energy W_{in} (1), radiation energy Q (2) and HF laser intrinsic efficiency η_{in} (3) as a function of the mixture pressure. Initiation was by the planar e-beam.

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3.2. HF-laser pumped by the radially convergent e-beam

The main results obtained under initiation of the SF_6-H_2 mixture and pure SF_6 by the radially convergent e-beam are shown in Figure 2. Curves 1 and 2 depict input energy calculated by the pressure jump in the mixture and pure SF_6. The difference between the curves is the energy from the chemical reaction. The chemical energy increases near linearly and is about 20% of the energy deposited by the e-beam.

It is evident from Figure 2b that maximal specific output on the laser chamber axis is observed at $p = 0.45$ atm. The peak specific output of ~ 5 J L^{-1} was recorded at a distance 1–3 cm from the foil while the total laser energy was as high as 115 J. Both input energy and the laser output from the area near the foil increase with the pressure. Maximal laser output up to ~ 200 J was obtained at $p \sim 1.1$ atm. However, uniformity of the energy distribution over the output beam area deteriorates with the mixture pressure.

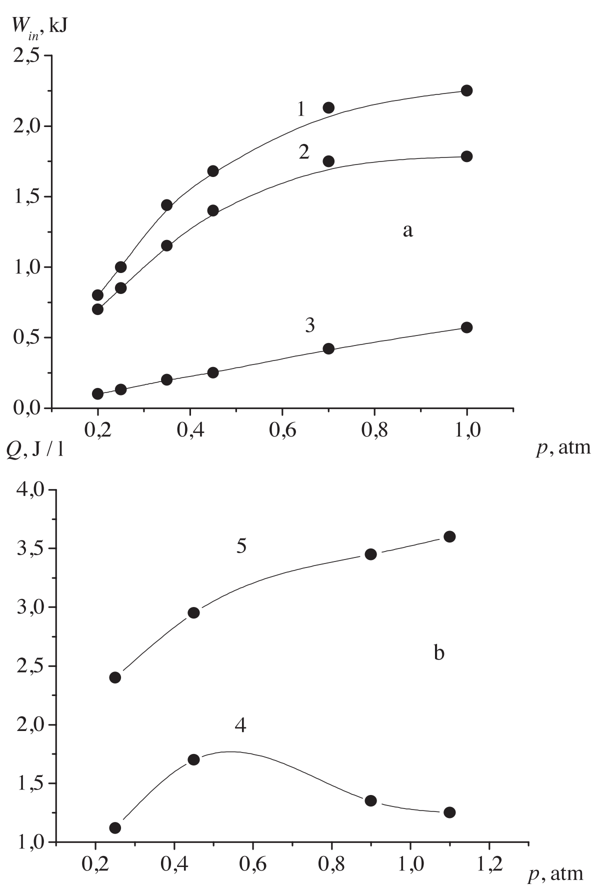

Fig. 2. Input energy W_{in} measured on the pressure jump (a) and specific HF laser output Q (b) as a function of the SF_6-H_2 mixture (1, 3, 4, 5) or pure SF_6 (2) pressure. Curve 1 is total energy deposited by the e-beam and the chemical reaction, curve 2 is the energy deposited by the e-beam, curve 3 is the energy deposition from the chemical reaction. Curves 4 and 5 are specific output on the axis of the laser chamber and at the distance of 8 cm from this axis, respectively.

3.3. Efficiency of a nonchain HF laser with e-beam initiation

It was shown that efficiency of an e-beam-pumped HF nonchain chemical laser is influenced by the formation of not only atomic but also molecular fluorine (Tarasenko *et al.*, 1998). Both particles are formed as a result of the dissociation of SF_6 molecules when an electron beam is injected into the laser mixture. The vibrationally excited HF molecules may be formed in this case as a result of two main processes:

$$F + H_2 \rightarrow HF(v \le 3) + H + Q_1(31.8\ \text{kcal/mol}), \qquad (1)$$

$$F_2 + H \rightarrow HF(v \le 6) + F + Q_2(98\ \text{kcal/mol}), \qquad (2)$$

where Q_i $(i = 1, 2)$ is the energy evolved as a result of the chemical reaction. In this case, the population inversion can be represented as follows (Gross & Bott, 1976; Tarasenko *et al.*, 1998). Since the specific rate of reaction (1) is 5.5 times greater than the rate of reaction (2), and the latter takes place after the formation of a sufficient number of hydrogen atoms, the first stage consists of the inversion of population of the HF with $v \le 3$. This, in fact, leads to the lasing as a result of vibration transitions with $v \le 3$. Reaction (2) occurs in the second stage and inversion of the population of the HF molecules is attained, including the inversion as a result of higher vibration transitions $4 \le v \le 6$. Furthermore, the atomic fluorine formed in the second reaction can again participate in the population inversion as a result of transitions with $v \le 3$ (see reaction (1)). Thus, short chains leading to an increase of the HF laser efficiency may occur in the active mixture, whereas vibration transitions with $v = 4$–6 should be present in the lasing spectrum in this case. The radiation-pulse duration should then exceed the duration of an e-beam pulse.

The energy distribution over the spectrum for the SF_6:H_2 = 7:1 laser mixture is illustrated in Figure 3. For the three pressure investigated, lasing was observed as a result of transitions with $v > 3$. At higher pressures (0.82 and 0.344 atm), lasing was detected for all six P-branch transitions $(P_1, P_2, P_3, P_4, P_5, P_6)$, whereas the maximum energy corresponded to the P_2 transition. The emission spectra obtained agree very well with the emission spectrum of a chain HF laser based on an H_2-F_2 mixture (Azarov *et al.*, 1999). A decrease in pressure to 0.096 atm led to lasing as a result of the P_1, P_2, P_3, P_4, P_5 transition (there was also lasing as a result of transitions with $v \ge 3$) and a shift of the lasing maximum to the P_1 transition.

The temporal and spectral-temporal characteristics of the HF laser were investigated both for the total laser radiation and for individual lines in the pressure range 0.1–1 atm for the SF_6:H_2 = 7:1 laser mixture. A typical e-beam pulse and a laser radiation pulse obtained on the setup with pumping by a radially convergent e-beam are shown in Figure 4a. The lasing threshold was attained 40 ns after the injection of the e-beam, whereas the radiation pulse duration significantly

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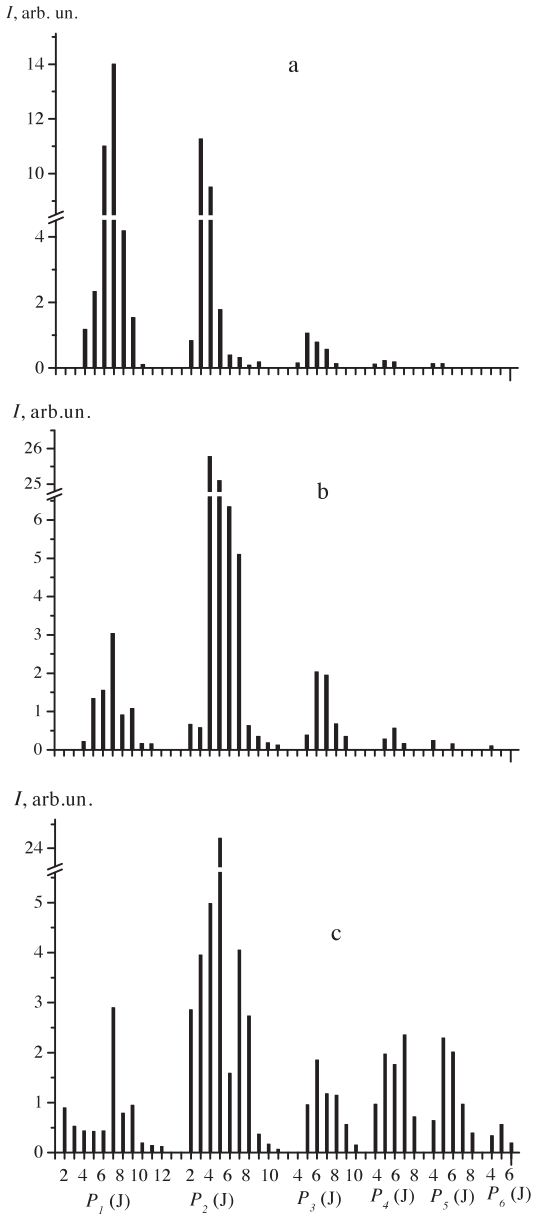

Fig. 3. Intensity distribution over the lasing spectrum at pressures in the SF_6:H_2 = 7:1 laser mixture of 0.096 atm (a), 0.344 atm (b), and 0.82 atm (c) obtained on device 2.

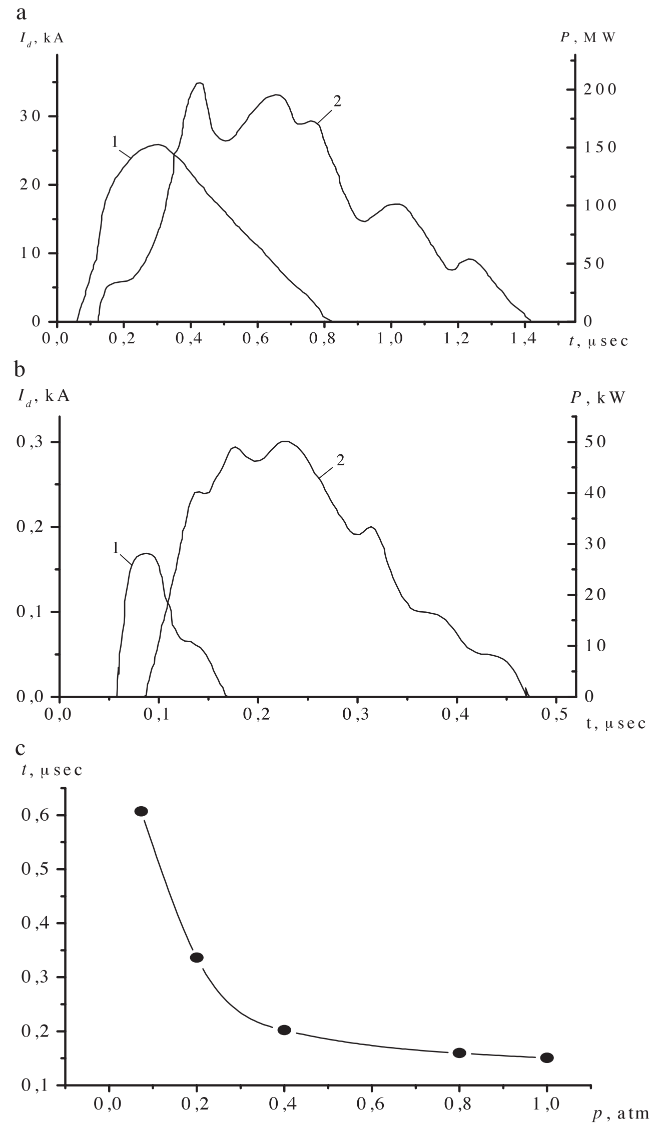

Fig. 4. E-beam current pulse (1) and lasing pulse (2) for the SF_6:H_2 = 7:1 mixture pumped by radially convergent (a) and planar (b) electron beams at pressures of 0.45 atm (a) and 0.344 atm (b) and dependence of the radiation pulse duration, obtained on device 2, on the pressure in the same mixture (c).

exceeded the pumping pulse duration and had a complex spike structure. This is apparently also associated with the fact that different vibration transitions, including the transitions with $v > 3$, as a result of which lasing has long delay times, participate in the lasing process.

Figure 4b shows e-beam current and lasing pulses obtained on the setup with pumping with a planar e-beam. These pulses have obviously similar structures. The pressure dependence of the half-amplitude duration of the radiation pulse is shown in Figure 4c. An increase in pressure increases the specific energy inputs into the active mixture and the rates of the chemical reactions, which, in fact, leads to a decrease of the radiation pulse duration, but at a pressure of 1 atm, the latter exceeded the pumping pulse duration. Thus, when the mixture pressure changes from 1 to 0.1 atm, the lasing pulse duration changed from 150 to 600 ns, whereas the laser emission delay time relative to the instant of the e-beam injection changed from 20 to 100 ns.

The order in which lasing appeared as a result of individual vibration transitions was as follows: $P_2 \rightarrow P_1 \rightarrow P_3 \rightarrow P_4 \rightarrow P_5 \rightarrow P_6$. The laser radiation was initially detected only on the most intense transition lines, whereas the P_4, P_5, P_6 transition lines were detected only in the second half of the radiation pulse. Figure 5 presents the time dependences of the lasing energy of individual lines detected as a result of the transitions of the P_2 band at a pressure of 0.344 atm. Evidently, lasing as a result of P_2 transitions with a high

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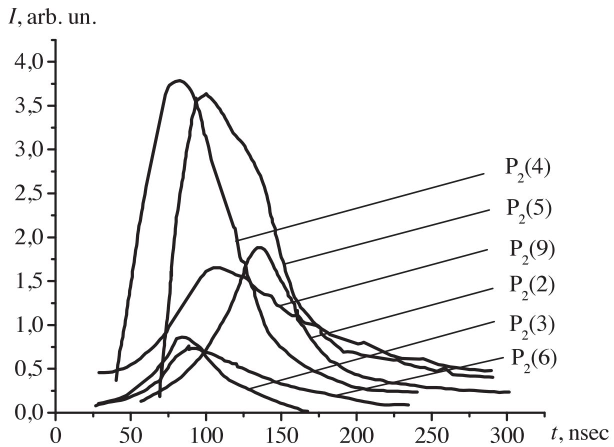

Fig. 5. Time variation of the individual P_2 transition lines at a pressure of 0.344 atm in the SF_6:H_2 = 7:1 mixture, setup 2.

rotational number J is observed simultaneously with lasing as a result of transitions with a low J, which indicates a significant departure from equilibrium in the distribution of the molecular energies over rotational levels.

According to Orlovskii *et al.* (1999) ultimate intrinsic efficiency of a nonchain HF-laser with participation of only atomic fluorine in population inversion cannot exceed ~9% and is determined by the relationship $\eta_{in} = 0.88 \cdot 10^{-2} \cdot h\nu$, where $h\nu = 10.2$ kcal/mol.

In the present work, we obtained an efficiency greater than 10% on the setup with a radially convergent e-beam. The presence in the lasing spectrum of the six P-branch transitions indicates that molecular fluorine participates in the population inversion formation. In this case, ultimate efficiency of an e-beam-initiated HF laser determined by the relationship $\eta_{in} = 10^{-2} \cdot (9 + 12.5m)$, (here m is the part of deposited energy spent for F_2 formation) can exceed 10% (Wilkins, 1972).

4. NONCHAIN HF(DF) LASER WITH INITIATION BY A SELF-SUSTAINED DISCHARGE

4.1. HF laser output and discharge stability

Different factors (discharge gap size, mixture composition and pressure, electrode shape and surface conditions, preionization intensity, pumping power, pulse duration, etc.) have an effect on the discharge stability in gas mixtures with SF_6 and the discharge uniformity determines the laser output parameters. The laser action was obtained in a wide range of gas mixture compositions and pumping pulse parameters. The gas mixture of a nonchain discharge HF laser contains more than 70% SF_6. However volume discharge in these mixtures is relatively easy to form. Development of small-scale roughness on electrode surfaces (especially on the cathode surface) improves conditions for volume discharge formation in gas mixtures with hydrocarbons. Preionization and a uniform electric field in the discharge gap of a nonchain laser with large activity is not necessary (Zapolsky & Yushko, 1979; Apollonov *et al.*, 1996, 1998, 2000*a*, 2000*b*).

However, discharge in H_2-based mixtures is more sensitive to the preionization conditions and distribution of electric field strength in the laser gap. In our experiments, deterioration of the electric field uniformity in the laser gap results in a dramatic decrease of the laser output and arc formation was evident 50–200 ns later than the gap breakdown.

The effect of the preionization on the discharge and the HF laser parameters under excitation by the LC generator is shown in Figures 6–8. Disconnection of preionization results in a two- to threefold increase of the breakdown voltage. However, strong deterioration of discharge stability is evident in hydrogen-based mixtures. At low pressure, chaotically distributed anode and cathode flares with different lengths penetrate into the discharge volume and short down the gap; discharge current slightly increases while the laser output decreases by a factor of 1.5. However at low pressure nearly constant discharge voltage U_d close to the critical voltage $U_{cr} = (E_{cr}/p)dp$, where $E_{cr}/p \sim 90$ kV/cm × atm (Lacour *et al.*, 2001) is the critical electric field strength, is observed across the laser gap. The number of these arc channels in the laser gap increases with the mixture pressure. A sharp increase of discharge current accompanied by a U_d fall 50–100 ns after the gap breakdown and further decrease of the laser output were observed. The use of preionization removes anode flares and arcs from the laser volume and improves the laser output. However, the discharge is not quite uniform and a large number of short cathode flares is evident.

In the case of gas mixtures with pentane, preionization has a much lower effect on the discharge quality (see Fig. 8). In both cases, a large number of small bright spots on the cathode surface, very uniform discharge luminescence without any sign of arcing, and minor differences of the laser

Fig. 6. Discharge view (negative) observed in the SF_6:H_2 = 24:3 Torr mixture without (a) and with (b) preionization under pumping by the LC generator at $U_0 = 30$ kV.

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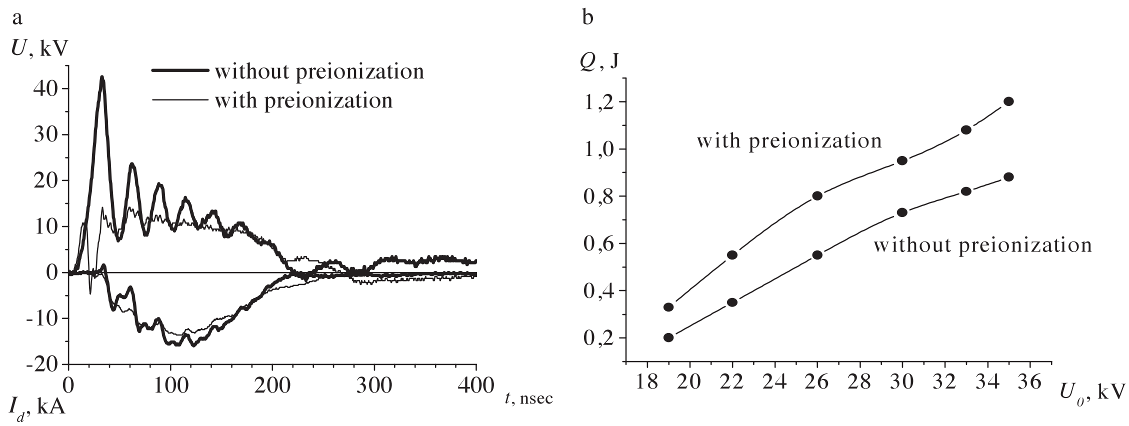

Fig. 7. Waveforms of the voltage across the gap and discharge current at $U_0 = 30$ kV (a) and laser output versus U_0 (b) obtained with and without preionization under pumping by the LC generator at $U_0 = 30$ kV. The SF_6:H_2 = 24:3 Torr gas mixture was used.

output only at low U_0 are evident. In the absence of preionization, discharge appears in several local points and than expands on the full electrode surface (Apollonov *et al.*, 2000*b*). The time of discharge expansion decreases at high U_0, resulting in lower energy losses spent for discharge formation. Therefore the laser output became independent on the preionization at $U_0 > 30$ kV.

An additional indication of the discharge uniformity in our experiments was the partial discharge of the storage capacitor C_0, and residual voltage U_{res} is measured across the gap after the discharge current termination. U_{res} increases directly to the mixture pressure and inversely to the charging voltage. Maximal U_{res} approaching U_{cr} were observed in mixtures with H_2 (see Fig. 9a). If U_0 is slightly lower than the critical voltage, breakdown of the laser gap did not occur. Development of discharge nonuniformities results in zero U_{res}. At low pressure and high U_0, stored energy can be totally deposited into the volume discharge (see Fig. 6) and $U_{res} = 0$, as well.

The use of the inductive generator and preionization similarly to Baksht *et al.* (1999, 2002) increases breakdown voltage by a factor of 1.5–2, shortens rise time of the discharge current, and in some experimental conditions increases the discharge current amplitude. The inductive generator allows the formation of a very uniform discharge even at low U_0 and elevated mixture pressure. This situation is shown in Figure 10. The LC generator cannot provide the gap breakdown in a similar mixture at $U_0 < 26$ kV. Breakdown voltage up to 50–60 kV and 50–100 ns excitation pulse with current amplitude up to 30 kA was obtained with the inductive generator. It is important that a considerable part of the stored energy is deposited into the laser active media at high E/p across the laser gap during the voltage drop after the gap breakdown. It is seen from a comparison of Figure 6 and Figure 10 that the inductive generator improves discharge homogeneity. Similarly to pentane-based mixtures, highly uniform discharge fluorescence without cathode flares was observed in mixtures with H_2. Note that

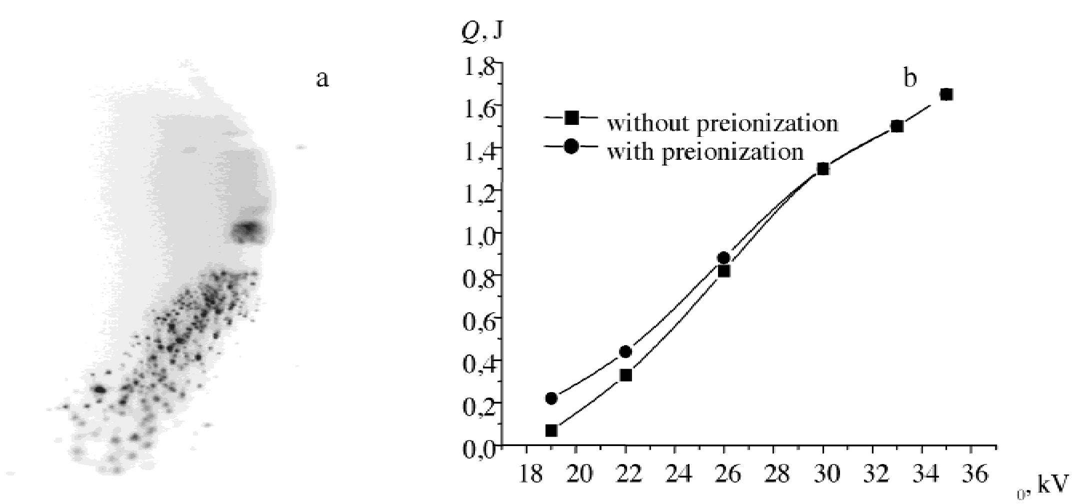

Fig. 8. Discharge view (negative) without preionization at $U_0 = 30$ kV (a) and effect of preionization on the laser output (b), observed in the SF_6:C_5H_{12} = 36:2 Torr mixture pumped by the LC generator.

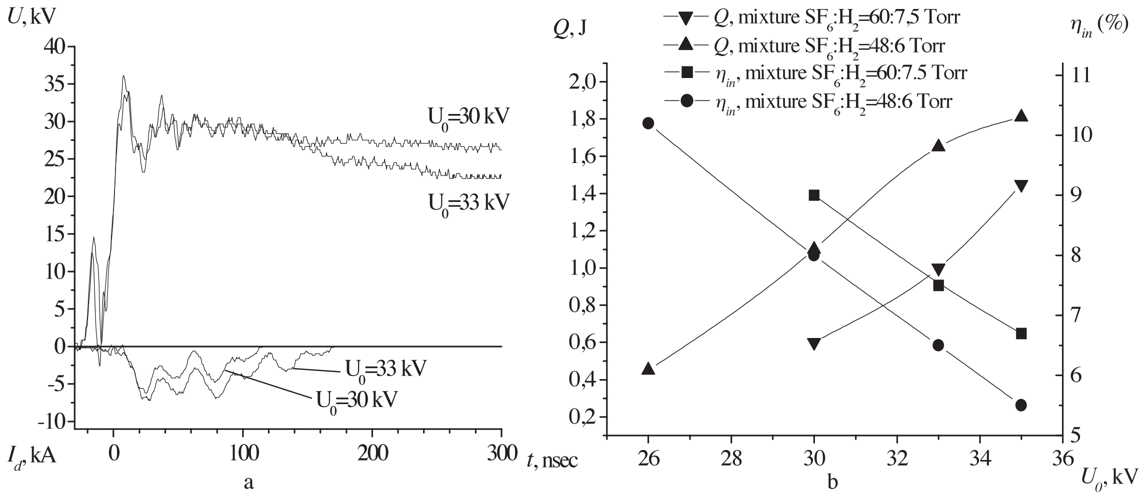

Fig. 9. Voltage across the laser gap and discharge current in the SF_6:H_2 = 60:7,5 Torr mixture (a), output energy and intrinsic efficiency of the discharge HF laser versus charging voltage (b); the LC generator was used.

about half of the energy stored in C_0 is lost in the semiconductor opening switch during current interruption and remains in the generator circuit. However, the inductive generator provides the laser output in the H_2-based mixtures close to that obtained with the LC generator, which means that intrinsic efficiency of the HF laser is improved.

4.2. HF laser efficiency and excitation pulse parameters

The experiments done show that output energy and laser efficiency are determined by the discharge parameters. Application of UV preionization improves the laser parameters due to the increase of the discharge uniformity. With an LC generator like that of Apollonov *et al.* (1998); Richeboeuf *et al.* (1999); Lacour *et al.* (2001); and Tarasenko *et al.* (2001) mixtures with hydrocarbons were more efficient as compared to those with H_2 due to better discharge uniformity. It was found that addition of a small amount of pentane into the H_2-based mixture allows for improvement of laser output and total efficiency. Maximal laser efficiency was about 4.5%, and specific output was as high as 8 J/L. However, if uniform discharge is formed using the inductive generator, better laser efficiency and higher output energy

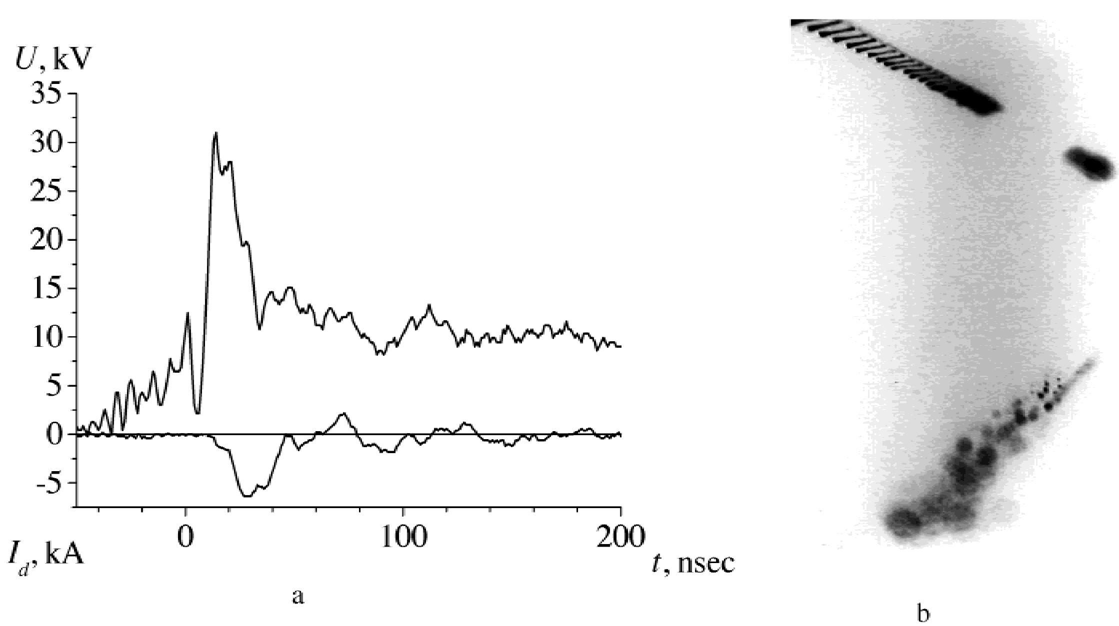

Fig. 10. Waveforms of voltage across the laser gap and discharge current (a) and discharge view (negative) (b) obtained in the SF_6:H_2 = 48:6 Torr mixture pumped by the inductive generator with preionization at U_0 = 22 kV.

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can be achieved in the H_2-based mixtures. Thus the inductive generator allows us to obtain very high intrinsic efficiency of the HF laser around $\eta_{in} \sim 10\%$ in the range of input energy from 10 to ~100 J/L (see Fig. 11). In our experiments, specific output up to 7 J/L and total laser efficiency over 3% were easily realized with the inductive generator.

Excitation mode with $\eta_{in} \sim 10\%$ can be realized with the LC generator at $U_0 \approx U_{cr}$ in H_2-based mixtures. This situation is illustrated by Figure 9b. Laser energy of 0.6 J (3 J/L) with $\eta_{in} = 9\%$ was obtained at low specific input energy (<10 J/L). Intrinsic efficiency as high as $\eta_{in} = 10\%$ and $Q =$ 0,4 J were achieved at lower gas pressure. In this excitation mode, the residual voltage U_{res} close to U_0 remains across the laser gap after termination of the discharge current. Therefore total laser efficiency is $\eta_t \sim 1\%$. However, η_t can be improved using a pulse forming line connected with laser gap in the impedance matched mode. An increase of U_0 affects η_{in}, but total laser efficiency η_t increases with U_0. In the pentane-based mixture, η_{in} was 7% lower probably due to lower production of fluorine atoms (Richeboeuf *et al.*, 1998). Note that $\eta_{in} = 8\%$ was obtained under excitation of HF laser by the X-ray initiated discharge in gas mixtures with H_2 and C_2H_6 at low input power and minimal possible U_0 (Richeboeuf *et al.*, 1998, 1999; Lacour *et al.*, 2001).

It was found that many more lines are observed in output spectra of the HF laser operating in the high efficiency mode as compared to those presented in other works (Brink & Hasson, 1980; Tarasenko *et al.*, 1998). The number of lines in each P_3, P_2, and P_1 vibrational transition increases to 8–11, and the total number of laser lines can be as high as 30. Besides, about the same laser power is obtained on rotational lines of P_3, P_2, and P_1 vibrational transitions, and cascade laser action on some rotational lines were observed. Thus the longest laser pulse duration is observed on the P_1 transition. In our experimental conditions, we did not observe strong lines from the upper P_4, P_5, and P_6 vibrational levels which were evident under e-beam excitation. Notice that maximal mixture pressure for the discharge HF laser was only 50–60 Torr, while the intensity of the P_4, P_5, and P_6 transition lines in the e-beam-initiated laser dramatically decreases at low mixture pressure (see Fig. 3).

In our opinion, three effects can contribute to the improvement of intrinsic efficiency of the discharge HF laser. First is discharge uniformity. The second effect is provided by the inductive generator. Breakdown electric field strength up to $E_0/p = 200$ kV/cm $\times$ atm and considerable energy deposition at high E/p value across the laser gap is typical for the inductive generator. This can increase the rate of F atom production in the mixture (Richeboeuf *et al.*, 1998). The third effect is cascade laser action. This means that one fluorine atom can produce up to three laser photons.

4.3. DF laser efficiency and excitation pulse parameters

The DF discharge laser output performance was very similar to that of the HF laser because the exothermicity of the pumping chemical reaction (1) and

$$F + D_2 \rightarrow DF(v \leq 4) + D + Q_3 \ (30.6 \text{ kcal/mol}), \qquad (3)$$

corresponding rate constants for reactions (2) and (3) and the collisional deactivation of HF and DF molecules are very similar (Gross & Bott, 1976). However, due to lower laser photon energy, output of a discharge DF laser is about 0.8 of that of HF laser (Apollonov *at al.*, 1996, Apollonov *et al.*, 2000*a*, 2000*b*).

The main results obtained in our experiments with the DF laser are shown in Figure 12. With the LC generator, maximal lasing energy was about 1.4 J which corresponds to the specific output of 6.5 J/L and total laser efficiency of 3.2%. Intrinsic laser efficiency at low energy deposition was as

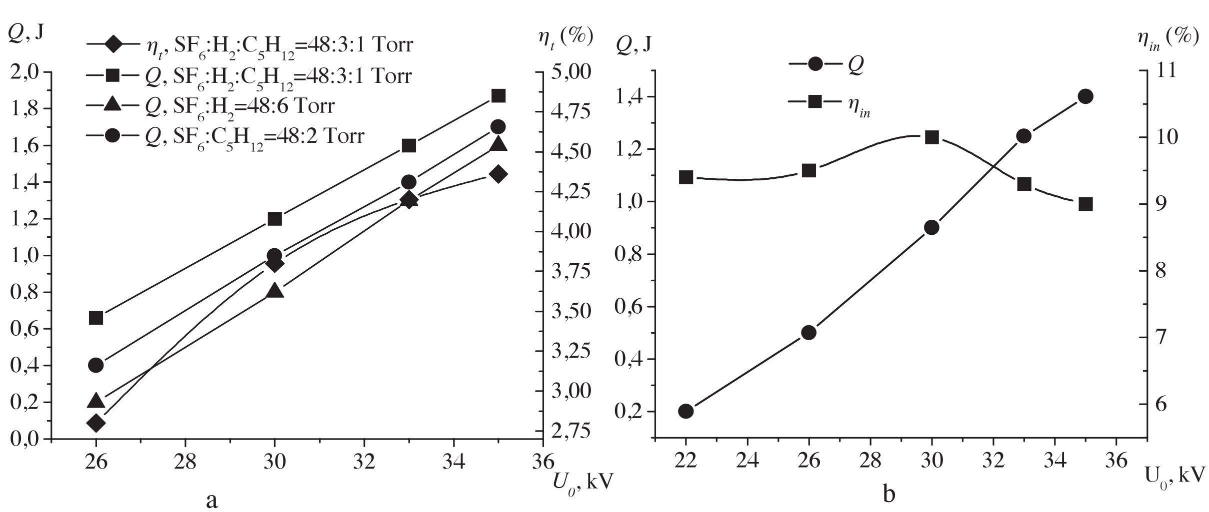

Fig. 11. Output energy and total efficiency of the HF laser obtained with the LC generator in different gas mixtures (a) and with the inductive generator in the SF_6:H_2 = 48:6 Torr mixture (b) versus charging voltage of the primary capacitor C_0.

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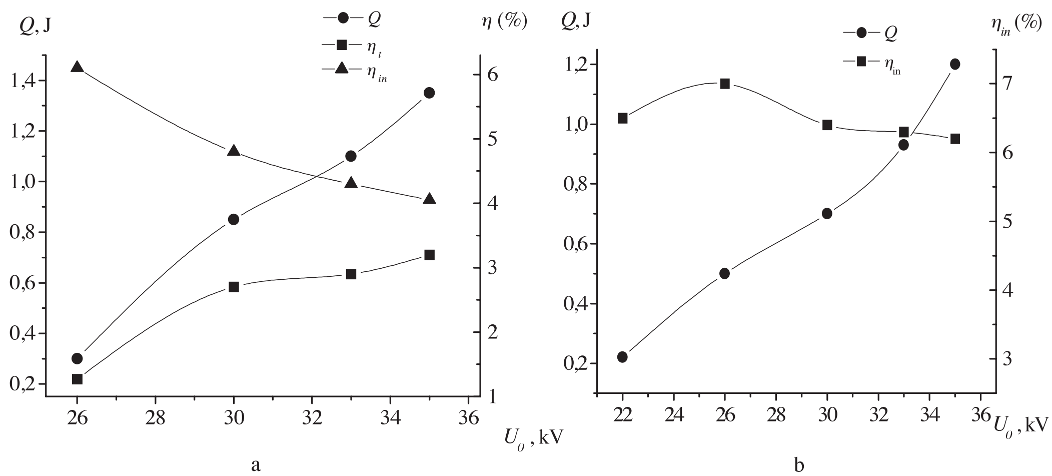

Fig. 12. Output energy and efficiency of the discharge DF laser obtained with the LC generator (a) and the inductive generator (b) in the SF_6:D_2 = 48:6 Torr mixture versus charging voltage of the primary capacitor C_0.

high as 6%. Similarly to the HF laser, the inductive generator significantly improves η_{in} of the discharge DF laser. The intrinsic efficiency of 6–7% was achieved in the specific input energy range from 10 J/L to ~100 J/L. The laser output with the inductive generator was as high as 1.2 J.

5. CONCLUSION

Nonchain HF(DF) lasers with e-beam and discharge initiation were studied. For the HF laser, intrinsic efficiency of η_{in} = 10% is obtained for both excitation methods; a discharge DF laser with η_{in} = 7% was developed on the basis of the inductive generator.

It was shown that efficiency of the e-beam pumped nonchain HF laser is determined by the participation of both molecular and atomic fluorine in the inversion population formation. Thus the lasing pulse has a complicated spectral-temporal structure due to sequential lasing on six *P*-branch transitions ($P_2 \rightarrow P_1 \rightarrow P_3 \rightarrow P_4 \rightarrow P_5 \rightarrow P_6$). Maximum laser energy and intrinsic efficiency up to 200 J and 11%, respectively, were achieved.

Discharge parameters were shown to have a strong effect on the HF (DF) laser output. Application of the inductive generator, electrodes of uniform field, and intense preionization allows formation of uniform volume discharge and improves intrinsic laser efficiency. Excitation modes with maximal intrinsic efficiency η_{in} = 10% were realized. The following excitation pulse parameters providing high intrinsic efficiency of HF laser with discharge initiation were found in our experiments.

1. In the case of a LC generator, η_{in} = 10% can be obtained only at low specific input energy (~10 J/L) and U_{res} approaching U_0. The laser output of several hundreds of millijoules and total laser efficiency of about 1% is typical for this excitation mode. Also, η_{in} is higher in gas mixtures with hydrogen. Nevertheless application of a pumping generator made on the basis of a pulse forming line connected with a laser gap in the impedance matched mode can significantly improve total laser efficiency. This excitation mode is promising for development of HF laser with high pulse repetition rate.
2. The use of an inductive generator allows us to obtain η_{in} = 10% in a wide range of input electric power (corresponding to 10–100 J/L). The inductive generator provides breakdown electric field strength up to E_0/p = 200 kV/cm × atm and a significant part of energy stored in the inductor is deposited into the laser active volume at high E/p value across the laser gap during a short current pulse. The laser energy up to 1.4 J, specific output of 7 J/L, and total laser efficiency over 3% were easily achieved.

Discharge uniformity, increase of the rate of fluorine atom formation in the laser active volume, and cascade laser action can explain high intrinsic efficiency of the discharge HF laser pumped by the inductive generator. Maximal output up to 1.9 J and total HF laser efficiency η_t = 4.5% were obtained in the SF_6-H_2-C_5H_{12} mixture with the LC generator.

Output parameters of the discharge DF laser were found to be 0.8 of that of the HF laser. Maximal output of 1.4 J (6.5 J/L) and total laser efficiency of 3.2% were achieved with the LC generator. With the inductive generator, intrinsic efficiency of the discharge DF laser was as high as 6–7% in a wide range of input electric energies.

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