Efficient Non-Chain Discharge HF and DF Lasers

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Abstract – Discharge and laser parameters in mixtures of SF_6 with H_2 and D_2 are studied using inductive and LC-generators. Excitation pulse parameters providing ultimate performance of discharge non-chain HF-and DF-lasers are determined. Processes affecting efficiency of the lasers are discussed. Ultimate intrinsic efficiency η_{int} of the HF and DF lasers up to 10 % and 7%, respectively, was realized in the SF_6–$H_2(D_2)$ mixtures. Electrical efficiency of the lasers up to η_0 = 5–6% with the output over 1 J was demonstrated for the first time.

1. Introduction

At present, discharge non-chain HF(DF)-lasers are widely used in various area. Therefore improvement of their output parameters, first of all, efficiency, is of great practical interest. To date, large number of papers devoted to study of discharge HF (DF)-lasers has been published and high output parameters has been obtained. But special investigations into improvement of the efficiency were not performed. As a rule, electrical efficiency (relative to stored energy) of the non-chain DF and HF lasers is not higher η_0 = 3–4% [1–5]. One of the reasons limiting the efficiency is development of discharge non-uniformities[6]. Additions into gas mixtures of the non-chain lasers or replacement of $H_2(D_2)$ with hydro- or deuterocarbons [7, 8] along with development of small-scale roughness on the electrode surface [9] increase discharge stability. In some cases increase of the preionisation intensity improves the laser efficiency [2, 10]. Therewith, specific output from the SF_6–C_2H_6 mixtures about 9 J/l and electrical efficiency of non-chain laser up to η_0 = 4.7% were obtained in the X-ray initiated discharge [11]. However, maximal efficiency of discharge HF-laser (η_0 = 6.3%) at the output level 0.14 J was achieved in a SF_6–H_2 mixture under 20 ns excitation from a pulse-forming network [12]. The efficiency dramatically decreased at longer discharge duration.

Earlier we have demonstrated that discharge stabilization allows to improve the laser intrinsic efficiency η_{int} (relative to deposited energy) and η_{int} = 10% in wide range of the pumping pulse parameters was obtained [13]. In the present report, pumping pulse parameters providing ultimate efficiency of discharge non-chain HF- and DF-lasers are found and processes affecting the laser efficiency are discussed. For the first time, non-chain discharge HF and DF-lasers with the output over 1 J and electrical efficiency up to 5–6% are developed.

2. Experimental Technique and Measurement Procedure

Discharge initiated HF(DF) laser was similar to the setup excited by the inductive or LC-generators and described in details in [13]. The discharge gap d = 3.8 cm between two polished special shaped stainless steel electrodes 70 cm in length, providing uniform electric field in the active volume, was preionised by 72 spark gaps evenly distributed along both sides of the anode. The LC-generator has primary capacitor C_0 = 13–260 nF and provides discharge pulse duration 100–400 ns. The inductive generator with C_0 = 70 nF produces ~ 100 ns input pulses. Parameters of the electric discharge and laser radiation were studied in gas mixtures of the SF_6:$H_2(D_2)$ = 8:1 or SF_6:C_5H_{12} = 20:1 composition at pressure p = 0.03–0.12 atm. The laser active volume was 150–400 cm^3 depending of the gas mixture composition and charging voltage of the primary capacitor U_0.

The laser cavity was formed by a plane aluminum mirror and Thallium Iodide or Thallium Bromide plane-parallel output plates. The laser output and radiation pulse waveform were measured by the IKT-1N calorimeter or the FL-250A-EX sensor with OPHIR energy meter 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 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. Optimal Excitation Parameters

The experiments performed showed that output parameters of the non-chain discharge chemical lasers mainly depend on the discharge uniformity and stability in the gas mixture under study. The following factors affecting the discharge parameters in gas mixture of SF_6 with H_2, D_2 and C_5H_{12} were found during our investigation.

Uniformity of electric field in the discharge gap. When profiled electrodes were replaced by electrodes with cylindrical shape the laser output was lower 0.2 J even in mixtures with pentane at maximal stored energy. Integral discharge photographs show a lot of brilliant spark channels in the laser gap and oscillating discharge current through the laser gap was measured. Character of current flow through the laser gap was found to be additional criteria of the discharge uniformity. In the case of volume discharge current in the gap interrupts and residual voltage can be measured across the laser electrodes. Development of spark channels resulted in zero residual voltage and oscillations of discharge current are observed.

Preionisation. Illumination of the laser volume by UV radiation increases the laser output in the SF_6-$H_2(D_2)$ mixtures especially at high gas pressure. In this case disconnection of the preionisation results in twofold decrease of the laser output and strong deterioration of discharge stability was also evident.

The mixtures with pentane have lower sensitivity to the preionisation. Minor preionisation effect on the laser output is evident only at high pressure and (or) low charging voltage of the primary capacitor. A large number of small bright spots on the cathode surface, very uniform discharge luminescence without any sign of arcing are evident independently the presence of preionisation. Without preionisation discharge appears in several local points (cathode spots). Than new cathode spots form around the point of discharge appearance under the action of UV-illumination from initial spots and discharge expands on whole electrode surface. The time of discharge expansion decreases at high U_0 resulting in lower energy losses spent for discharge formation and the laser output in mixtures with hydro- or deuterocarbons similarly to [21] can be independent on the preionisation. In the case of H_2 (D_2)-based mixtures arcs can form high probability from the initial spots with and UV illumination is necessary to shorten the time of discharge formation in order to avoid discharge constriction and improves the laser output.

Pumping pulse duration. It was found that the laser output decreases by a factor of about two when the current pulse duration was expanded from 100 to 250 ns. Earlier similar behavior of non-chain laser parameters was observed for mixtures of SF_6 with deuterium [2] and hydrocarbons [5] for current pulse duration longer than 300 ns. In our experiments, the input pulse duration was about 100 ns (for the inductive or LC-generators with $C_0 = 13$–39 nF) and maximal laser output was achieved in hydrogen based mixtures. For excitation pulses longer than 200 ns (the LC-generators with $C_0 =$ $= 70$–260 nF) mixtures with pentane were found to be more efficient. Maximal HF-laser output up to $Q = 3$ J (8 J/l) was obtained in the SF_6–C_5H_{12} mixture and $C_0 = 260$ nF. In this case discharge duration was about 400 ns, and the laser efficiency was only $\eta_0 = 3.5\%$.

Mixture composition and specific input energy. Comparison of the laser output in different mixtures showed that if the discharge homogeneity is violated due to non-uniform electric field in the laser gap, increase of pumping pulse duration and (or) low preionisation intensity mixtures with pentane provides higher radiation energy. However, under optimal experimental conditions, maximal efficiency of non-chain chemical lasers was achieved in the SF_6–$H_2(D_2)$ mixtures. Fig. 1 depicts intrinsic efficiency η_{int} of HF-laser pumped by the LC-generator with $C_0 = 13$–70 nF versus specific input energy. Maximal $\eta_{int} = 9$–10% was obtained at the input energy level of 30–70 J/l and $C_0 = 13$–39 nF (which corresponded to the specific output of 3–7 J/l). For higher specific pumping similarly to [9, 11, 14] η_{int} sharply decreased. Low efficiency obtained with $E_{in} < 30$ J/l seems to be due to threshold losses at low pumping power. The following fact supports this suggestion. The inductive generator multiplies input power and intrinsic efficiency of the DF and HF lasers is maintained at the maximal level $\eta_{int} = 7$–10% even at $E_{in} \sim 10$ J/l.

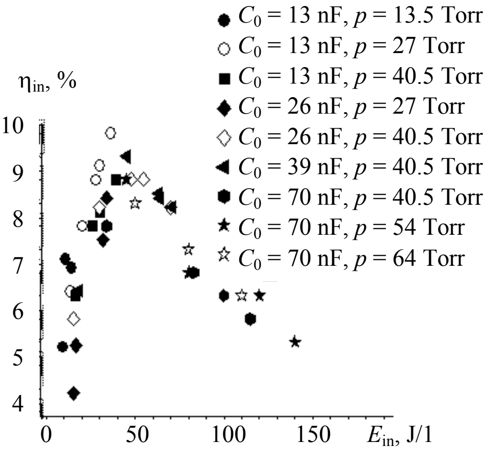

Fig. 1. Intrinsic efficiency of the HF-laser under pumping by the LC-generator as a function of specific input energy in the $SF_6 : H_2 = 8 : 1$

4. Output Parameters of Efficient HF and DF Lasers

Thus, the experiment performed allowed us to formulate necessary pumping conditions providing both very uniform discharge and maximal efficiency of the non-chain chemical lasers. There are uniform electric field in the discharge gap, intense preionisation, relatively short discharge current pulse (100 ns), specific input energy $E_{in} = 30$–70 J/l and the gas mixtures with $H_2(D_2)$. Basing on these results, efficient non-chain chemical lasers were developed.

Energy and efficiency. Fig. 2 depicts output energy and efficiency of HF(DF)-lasers obtained with different pumping generators. With the inductive generator, maximal output of the HF-laser was as high as $Q = 1.4$ J (specific energy 5.5 J/l) while intrinsic efficiency reached $\eta_{in} \sim 9$–10% and depended only slightly on the charging voltage U_0. For the DF-laser, output up to $Q = 1.2$ J was obtained and η_{int} was 6–7% in whole range of the charging voltage. Total efficiency of the lasers was $\eta_0 = 3$–3.5%. The reason for relatively low η_0 is energy losses in the inductive generator. From one hand, stored energy is dissipated in the SOS-diodes during the current interruption phase. From the other hand, some part of the energy remains in the generator circuit due to high discharge resistance in the SF_6 based mixtures. Thereby the primary capacitor recharges the driving capacitor. However, optimization of the generator circuit can decrease the energy losses and improve the non-chain laser total efficiency.

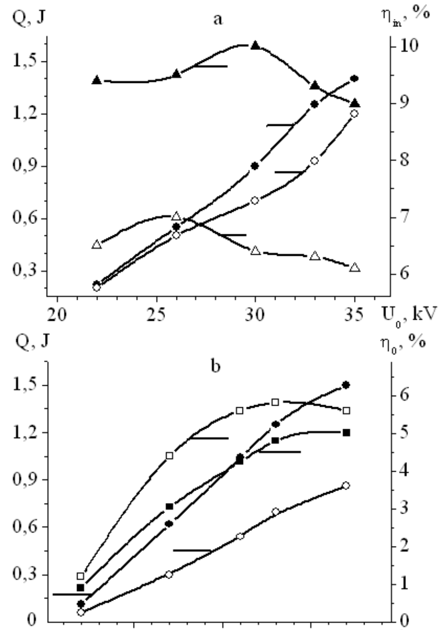

Fig. 2. Output energy and intrinsic (*a*) and electrical (*b*) efficiency of HF (solid symbols) and DF (empty symbols) lasers obtained with the inductive generator in the SF_6–$H_2(D_2)$ mixture at $p = 48$ Torr (*a*) and LC-generator with $C_0 = 39$ nF in the SF_6–H_2 mixture at $p = 40{,}5$ torr and with $C_0 = 26$ nF in the SF_6–D_2 mixture at $p = 24$ Torr (*b*) versus charging voltage of C_0

With the LC-generator, maximal electric efficiency of the laser was reached when $C_0 = 13$–39 nF. HF laser energy close to 1.5 J was obtained with $C_0 = 39$ nF which corresponds to the specific output of about 6 J/l, intrinsic efficiency was as high as $\eta_{int} = 7$–9%. DF laser energy was about 1 J. Maximal total efficiency of the HF laser reached 6% while that of the DF-laser is as high as 5%. This is maximal on the present date electrical efficiency of non-chain discharge lasers with the output of about 1 J.

Radiation spectra. Inversion population in non-chain chemical lasers is formed in the following chemical reactions:

$$F + H_2 \rightarrow HF^* \ (\nu \leq 3) + H + 139 \text{ kJ/mol}; \quad (1)$$

$$F + D_2 \rightarrow DF^* \ (\nu \leq 4) + D + 133 \text{ kJ/mol}, \quad (2)$$

where ν is vibrational level of HF or DF molecule, populating in corresponding reaction. Fluorine atoms are produced in discharge volume in processes of SF_6 decomposition. Chemical energy is distributed among accessible HF and DF vibrational states and is channeled preferentially into the $\nu = 2$ and $\nu = 3$ levels [22]. Output spectra of the lasers usually includes 10–15 lines, maximal laser energy is emitted on the vibrational bands with $\nu = 2$ [1, 7, 10, 14].

Figure 3 depicts radiation spectra of HF-laser pumped by the LC-generator with $C_0 = 13$ nF. The number of separate lines was as high as 21. Delay time between onset of the lines is about 20 ns, than simultaneous lasing is observed on all lines. Waveform of the laser pulse is shown in Fig. 4. The radiation pulse begins ~ 100 ns later the gap breakdown, its intensity exponentially decreased with the characteristic time $t_{int} \sim 500$ ns for integral pulse and $t_{P_1} \sim 200$ ns for radiation on the ν_1 band. Distribution of energy over the vibrational bands $Q(\nu_1):Q(\nu_2):Q(\nu_3) = 7:3:1$ drastically differs from those presented in the available papers [1, 7, 10, 14]. Therewith about 60% of total laser output was emitted on $P_1(7)$ and $P_1(8)$ lines. The energy distribution obtained is due two intense cascade lasing. Therewith up to 85% of the laser output is emitted in the cascades ending on the most intensive lines of P_1 band. The number of HF laser lines increases with E_{in} and can be as high as 30 with $C_0 = 70$ nF [13]. The laser spectra are very similar to those obtained with the e-beam initiation providing uniform energy deposition into the laser active media [15, 16].

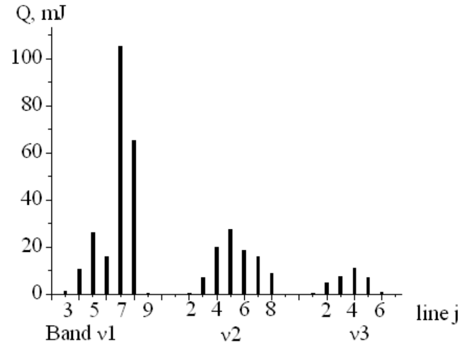

Fig. 3. Radiation spectra of the HF-laser with $\eta_0 = 6\%$. The LC-generator with $C_0 = 13$ nF and $SF_6 : H_2 = 24 : 3$ Torr mixture are used, $U_0 = 30$ kV

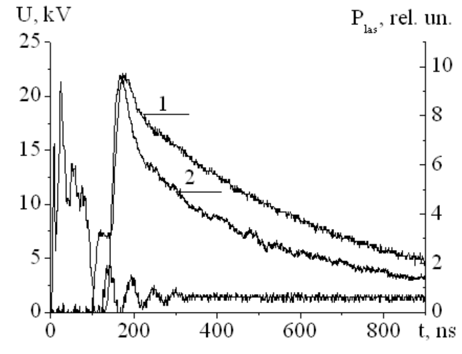

Fig. 4. Waveforms of voltage across the HF laser gap, integral laser pulse (*1*) and radiation on the ν_1 band (*2*). The LC-generator with $C_0 = 13$ nF and $SF_6 : H_2 = 24 : 3$ Torr mixture are used, $E_{in} \sim 40$ J/l

In the case of DF laser emission on 4 vibrational bands were observed in the output spectra. Therewith the number of lines was about 40 (see Fig. 5). The radiation pulse waveform was similar to that of the HF-laser while its duration was about 500 ns longer. The laser output was distributed over the bands of excited DF* molecules as follows: $P_1:P_2:P_3:P_4 = 0.92:1:0.6:0.18$. Otherwise, about the same energy was emitted on the P_1 and P_2 bands and lasing cascades were observed, as well. The intense cascades in the output spectra of the efficient non-chain lasers increase extraction efficiency from the active media because one excited HF*(DF*) molecule can produce up to 3–4 laser photons and improve the laser parameters.

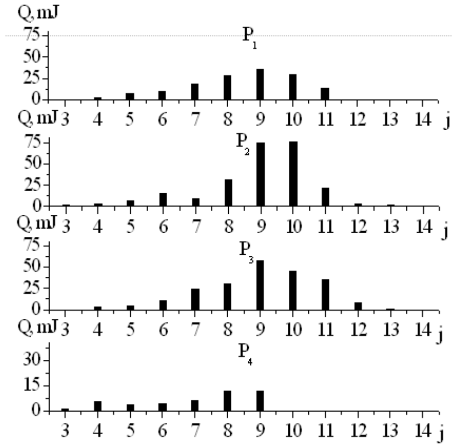

Fig. 5. Output spectra of the DF laser. Pumping by the inductive generator. Mixture $SF_6 : D_2 = 48 : 6$ Torr, $U_0 = 30$ kV

5. Discussion

Let us briefly discuss obtained results. In the experimental condition of Figs. 3–4 at $E_{\text{in}} \sim 40$ J/l main part of the output of efficient HF-laser is emitted on the P_1 band due to the cascade transitions. Therefore only emission on this band is considered. The lasing begins after pumping pulse and decreases with characteristic time $t_{P_1} = 200$ ns. According to [18] the energy for formation of fluorine atom in the discharge plasma is $E_F = 4$ eV, and for data E_{in} $n_{\text{F}} = 6\times10^{16}$ cm^{-3} fluorine atoms is generated. The rate of formation of vibrationally excited HF* molecules

$$\frac{dn_{\text{HF}}}{dt} = k_1 n_{\text{F}} n_{\text{H}_2}, \qquad (3)$$

where $k_1 = 3\times10^{-11}$ cm^{-3} c^{-1} is the rate constant [19], n_{F} and n_{H_2} are concentrations of fluorine atoms and hydrogen, respectively, is high and before the laser pulse onset main part of reactant components participated in reaction (3). Therewith losses of HF* molecules due to spontaneous emission are relatively low [8]. During the laser pulse concentration of the excited molecules is changed with time as:

$$\frac{dn_{\text{HF}}}{dt} = -\frac{n_{\text{HF}}}{\tau} - k_T n_T n_{\text{HF}}, \qquad (4)$$

here k_T и n_T are quenching constant and concentration of quenching particles, respectively. Quenching processes have strong contribution in reaction (4) if

$$n_T \geq \frac{1}{\tau k_T}. \qquad (5)$$

In the laser mixture under study hydrogen atoms and molecules, fluorine atoms and HF(0) molecules in the ground state can participate in the quenching processes. Estimation made on the base of rate constants listed in [20] showed that in the condition of our experiments HF(0) is main quenching component, but its contribution is insufficient as compared to the radiative decay of HF* molecules at $E_{\text{in}} \sim 50$ J/l. The estimation made allows us to conclude that one reason of η_{int} decrease when $E_{\text{in}} \geq 50$–70 J/l is hydrogen burning. Thus, at $E_{\text{in}} \sim 40$ J/l and initial concentration of H_2 is $n_0 \sim 10^{17}$ cm^{-3} and $n_{\text{H}_2} = n_{\text{F}} \approx 6\times10^{16}$ cm^{-3} of hydrogen molecules participated in reaction (3) forming HF* and, in the end, HF(0) molecules. Estimated n_{H_2} is in good agreement with the measurements of HF(0) formation in a volume discharge [7]. Hydrogen is fully used when $E_{\text{in}} > 60$ J/l and the laser efficiency begins to decrease, which is observed in the experiments.

Another reason of η_{int} fall is buildup of ground-state HF(0) molecules in the discharge region which results in strong radiation absorption in the active medium and increases the rate of the quenching processes. Absorption of radiation at laser wavelengths by HF(0) molecules with $n = 10^{17}$ cm^{-3} (the density number of HF(0) is formed in the active media at $E_{\text{in}} \sim 60$ J/l) on a path of 1 cm can be as high as 15%. The absorption is retrieved from the HITRAN and GEISA spectral databanks available at http://spectra.iao.ru/en.

Let estimate ultimate efficiency η_{int}(max) of the non-chain lasers. The HF laser photon energy is in average $E_{h\nu} \sim 0.42$ eV. Then, taking into account the cascade processes, one can conclude that one fluorine atom can in average produce ~ 2 laser photons. Extraction coefficient for discharge HF laser was measured to be about 50% [7]. Therefore it is easy to see that $\eta_{\text{int}}(\text{max}) = E_{h\nu}/E_{\text{F}} \sim 10\%$ and corresponds to the efficiency value obtained in our experiments.

6. Conclusion

Effect of different experimental parameters on the non-chain discharge HF(DF) laser performance was studied. It was found that uniform field in the laser gap and intense preionisation allows to produce uniform volume discharge. Discharge uniformity along with excitation pulses with duration of about 100 ns, input electric energy of 30–60 J/l and the use of $H_2(D_2)$ based gas mixture sufficiently improve the laser efficiency. Ultimate intrinsic efficiency of the HF and DF lasers $\eta_{\text{int}} = 7$–10% was realized with the inductive and LC-generators. Non-chain lasers with total efficiency $\eta_0 = 5$–6% and output energy $Q \geq 1$ J were developed.

Processes affecting the laser efficiency are discussed. To our opinion, high discharge uniformity contributed to development of intense cascade laser action on HF(DF) molecules which greatly improves both the energy extraction from the active media and efficiency of the discharge HF(DF)-lasers. The reason of the efficiency fall at high input energy is suggested to be hydrogen burning and buildup of ground-state HF molecules absorbing laser radiation.

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