Power, temporal, and spectral characteristics of non-chain HF laser pumped by planar *e*-beam and *e*-beam initiated discharge

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We present here the experimentally obtained power, temporal, and spectral characteristics of non-chain HF lasers pumped by a planar *e*-beam and semi-self-maintained discharge. It was shown that the radiation energy increases by 2.8 times when using an *e*-beam-initiated low-pressure pulsed discharge to excite HF molecules. It was found that a laser pulse has a complex spectral and temporal composition caused by a successive generation of *P*-lines $P_2 \to P_1 \to P_3 \to P_4 \to P_5 \to P_6$ and overlap of rotational spectral lines of the same vibrational band.

The interest in HF lasers pumped by chain[1,2] and non-chain[3–6] chemical reactions initiated by *e*-beams and discharges, in particular, *e*-beam-initiated discharge, has markedly increased in recent years. *E*-beams are applied because of high penetrating power of electrons. They make possible homogeneous initiation of large volumes of an active medium of a chemical HF laser at a sufficiently high pressure and provide for a significant pump power. Besides, possibilities of various applications of non-chain HF lasers emitting in the infrared region impose some restrictions on their characteristics, including the spectral region of lasing. However, optimal operating conditions of non-chain HF and DF lasers are to be studied now.

In this paper we present the results of studies of power, spectral, and temporal characteristics of the HF laser pumped by a non-chain chemical reaction initiated by a planar *e*-beam and *e*-beam initiated discharge. The latter pump method was earlier used in Ref. 7.

1. Experiment

Experiments were conducted with the setup similar to that described in Ref. 8. An accelerator formed an *e*-beam with the following parameters: current density of 2.5 A/cm^2, *e*-beam cross section of 42·1.5 cm, duration of 50 ns at halfmaximum of the current amplitude, and electron energy of 155 keV after passage through foil (maximum at the curve of the electron energy as a function of the electron number). The chemical reaction was initiated either by an *e*-beam or in the process of semi-self-maintained discharge from a capacitor bank with capacity of $3.9 \cdot 10^{-9}$ F. The discharge was initiated by an *e*-beam. The anode–cathode separation was 2.3 cm. The laser cavity was formed by a spherical copper mirror 2.5 m in radius and a plane-parallel KRS–5 plate with 33% reflectance in the 3 μm region. IMO–2N and IKT–1N calorimeters were used to determine the radiation energy. The temporal characteristics of a radiation pulse were recorded with a cooled FSG–22–3A2 photodetector spectrally sensitive in the region of 1.5–11 μm. The spectral characteristics of radiation were measured with an MDR–12 monochromator, in which the reflective diffraction grating of 300 lines/mm (inverse linear dispersion of 9.6 nm/mm) was used as a dispersion element. Current pulses of the *e*-beam and the current through the discharge gap were recorded with calibrated current shunts.

2. Experimental results and discussion

The power characteristics of the laser system (Fig. 1) at initiation of the gas mixture SF_6:H_2 = 7:1 by the *e*-beam with the characteristics given above were measured at the pressure varying from 0.1 to 1 atm. This mixture was close to optimal in the entire pressure range. The further increase of the H_2 concentration resulted in an insignificant increase in the energy and then in its fall off. The change in the *e*-beam energy absorbed by the gas medium was estimated by the equation

$$W_b = j_b \, (dE/dx) \, V \, t_b ,$$

where j_b is the *e*-beam current density, dE/dx is the mean energy loss per unit length, V is the volume of the active region of the gas cell, and t_b is the *e*-beam duration.

The value of 130 keV was taken as the mean energy of the electron velocity-distribution, and the mean *e*-beam energy loss per unit length was $1.8 \cdot 10^3$, $3.5 \cdot 10^3$, $6.48 \cdot 10^3$, $15.6 \cdot 10^3$, and $19 \cdot 10^3$ eV/cm (Ref. 9) at the pressures of 0.096, 0.184, 0.344, 0.82, and 1 atm of the gas mixture SF_6:H_2 = 7:1. The dynamics of emission power is caused by the power spectrum of the *e*-beam energy and tends to saturation. Such dependences were observed earlier,[6,7,10] and the maximum value of the emission energy at the pressure scale is fully determined by the increase in the rates of chemical reactions with the increasing pressure of the lasing medium, on the one hand, and with the increasing rate

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of collisional deactivation of the HF molecules, on the other hand. This results in a decreasing efficiency and, at the further increase of the pressure, in a decrease of the emission energy. Note that, from the viewpoint of achieving the maximum radiation efficiency, the optimal pressure can also depend on the spectrum of secondary electrons, that in its turn depends on the composition and pressure of the working mixture.[11]

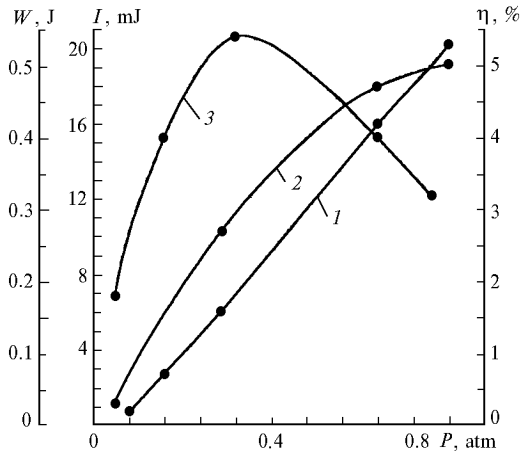

Fig. 1. Energy dissipated in a gas (*1*), emitted energy (*2*), and efficiency (*3*) as functions of the active medium pressure SF_6:H_2 = 7:1.

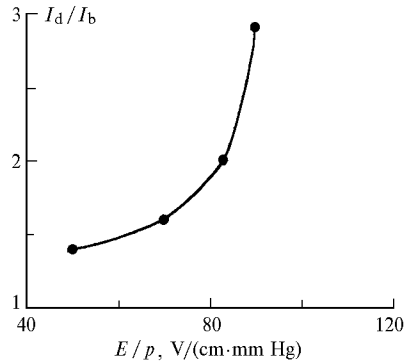

Fig. 2. Output laser energy as a function of E/p. I_b and I_d are the radiation energy in the case of active medium excitation by *e*-beam and by an *e*-beam-initiated discharge, respectively. Mixture SF_6:H_2 = 7:1, p = 0.184 atm.

To study the influence of the additional electric field on the efficiency, constant voltage was applied to the gas gap. The external electric field increases the energy of secondary electrons in the process of pulsed semi-self-maintained discharge and thus provides more intense generation of fluorine.[7] Figure 2 shows the dependence of the relative change of the laser radiation on E/p (E is the electric field strength, p is the pressure). It is seen that the laser energy increases by 2.8 times at the electric field strength close to the breakdown value. However, it should be noted that the energy scattered in a gas in the process of pulse discharge exceeds the absorbed *e*-beam energy by an order of magnitude. So, the laser efficiency decreases in this case. The increase in the total efficiency should be expected at the strength higher than the statistical breakdown value.

The processes of deactivation have a pronounced effect on the power characteristics of HF lasers. The efficiencies of deactivation of different particles can differ widely; molecules, attraction in which is determined by the hydrogen bond and results in formation of long-lived complexes, deactivate most efficiently. Thus, several collisions are needed for H_2O molecule to deactivate any molecule, whereas HF molecule deactivates HF* molecule after roughly 60 collisions.[12] That is why the fall off of energy is observed as HF molecules are generated in the process of multiple turns-on. Figure 3 shows the dependence of the radiation energy on the number of accelerator turns-on in the gas mixture SF_6:H_2 = 7:1 with (curves *1* and *2*) and without (curve *3*) absorber. A zeolite based absorber was homogeneously distributed over the surface of a Ti base set along the entire active volume. It is seen that the use of the zeolite based absorber allows the relative radiation energy drop to be decreased from 40 to 13% in the studied range of the turns-on number.

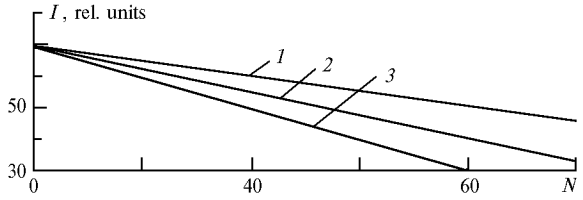

Fig. 3. Relative change of the radiation energy vs. number of accelerator turns-on in the presence of an absorber of 4 (*1*), 6 (*2*), and 0 cm^3 (*3*) in volume.

The spectral-temporal characteristics were studied for both the total laser signal and for separate lines at the pressure varying from 0.1 to 1 atm. Figure 4 shows the typical oscillogram of the radiation pulse (*a*) and the pressure dependence of the pulse duration at halfmaximum (*b*). The duration varied from 150 ns at 1 atm to 600 ns at 0.1 atm. The moment of the lasing start also varied depending on the pressure from 20 ns at 1 atm to 97 ns at 0.1 atm relative to the beginning of the *e*-beam action on the gas medium. Such a dynamics of the duration is caused by the increasing rate of energy input with increasing pressure and rate of chemical reactions.

The spectral distribution of energy for the laser mixture SF_6:H_2 = 7:1 is given in Table 1. At the pressure of 0.82 and 0.344 atm, lasing was observed at the transitions of the p-branch (P_1, P_2, P_3, P_4, P_5, P_6), and the maximum energy corresponded to the P_2 transition. The pressure decrease down to 0.096 atm led to lasing at the transitions P_1, P_2, P_3, P_4, and P_5 and shifted the maximum to the P_1 transition.

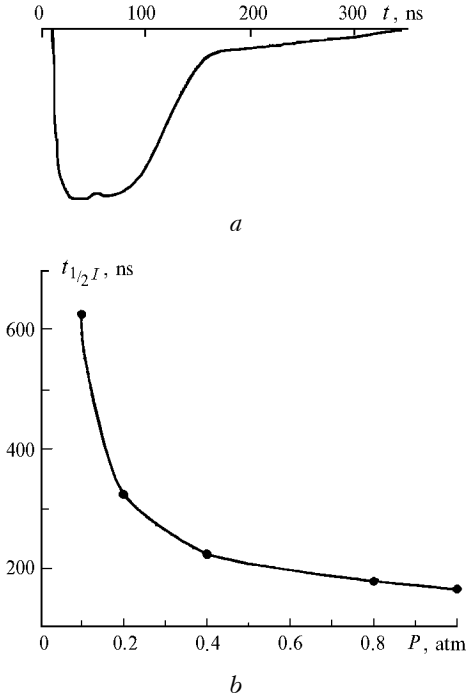

Fig. 4. Oscillogram of radiation pulse (*a*) (p = 0.344 atm) and pressure dependence of the pulse duration at halfmaximum (*b*) in the mixture SF_6:H_2 = 7:1.

The temporal structure of lasing appearance was so that lasing was observed consequently at the most intense lines of the transitions $P_2 \to P_1 \to P_3 \to P_4 \to$ $\to P_5 \to P_6$, and the lines of the P_4, P_5, and P_6 transitions were observed in the second half of the total time interval of the laser pulse.

Figure 5 shows the time dependence of the radiation energy at separate lines observed at the transitions of the P_2 band at different pressure. It is seen that lasing at P_2 transitions with high and low values of the rotational quantum number J is observed simultaneously, what is indicative of a significant nonequilibrium in the energy distribution over rotational levels.

Table 1. Spectral distribution of energy for the laser mixture SF_6:H_2 = 7:1

P	J	I, relative units		
		0.82 atm	0.344 atm	0.096 atm
P_1	2	9	–	–
	3	5	–	–
	4	4	2	13
	5	4.5	13	24
	6	5	16	110
	7	30	31	140
	8	8	9	41
	9	9	11	16
	10	2	2	0.5
	11	1	0.5	–
	12	0.5	–	–
P_2	2	28	7	9
	3	40	6.5	113
	4	50	258	94
	5	240	250	18
	6	16	64	4
	7	42	50	4
	8	28	6	0.5
	9	4	4	0.5
	10	2	2	–
	11	1	0.5	–
P_3	4	–	–	2
	5	10	4	11
	6	19	21	8
	7	12	20	6
	8	12	7	0.5
	9	6	4	–
	10	1	–	–
P_4	4	10	–	1
	5	20	3	2
	6	18	6	0.5
	7	24	2	–
	8	8	–	–
P_5	4	6	2	1
	5	22	–	1
	6	20	0.5	–
	7	10	–	–
	8	4	–	–
P_6	4	4	0.5	–
	5	6	–	–
	6	2	–	–

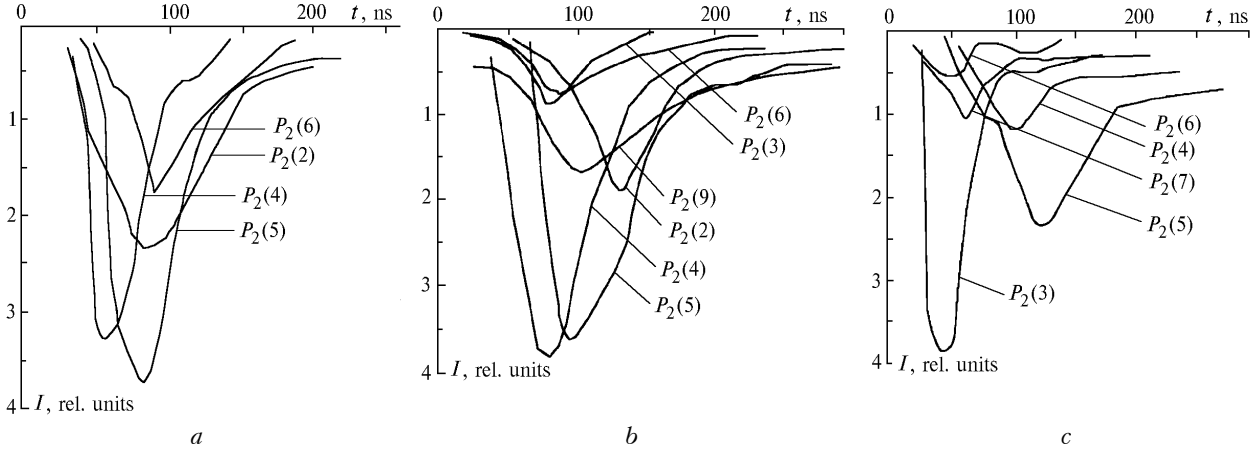

Fig. 5. Time behavior of intensity of separate lines of the P_2 transition in the mixture SF_6:H_2 = 7:1 at different pressure: 0.82 (*a*), 0.344 (*b*), and 0.096 atm (*c*).

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