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Efficiency of an $H_2 - SF_6$ laser with electron-beam initiation of chemical reactions

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Abstract. The spectral and amplitude – time characteristics of HF lasers pumped by a nonchain chemical reaction and initiated by radially convergent and planar electron beams were investigated. The principal channels leading to the formation of vibrationally excited HF molecules were analysed. It was confirmed that high efficiencies (~ 10%) of a nonchain HF laser may be attained only as a result of the simultaneous formation of atomic and molecular fluorine when the active mixture is acted upon by an electron beam and of the participation of molecular fluorine in population inversion. It was shown that a laser pulse has a complex spectral – temporal profile caused by the successive generation of *P*-lines and the overlap during the radiation pulse of both the rotational lines of the same vibrational band and of individual vibrational bands.

1. Introduction

The use of an electron beam in the initiation of chain and nonchain chemical reactions in hydrogen lasers makes it possible to excite large volumes of the active medium and to obtain considerable energies and (or) radiation efficiencies [1 – 8]. The highest radiation efficiencies and energies are attained in chemical lasers pumped by chain reactions. However, in the practical applications of hydrogen fluoride lasers, the latter must have high energy characteristics in an individual-pulse regime. The lasers must also be safe and convenient to operate and in certain cases the possibility of working in a repetitively pulsed regime is needed. Nonchain lasers based on mixtures of SF_6 with hydrogen, deuterium, or their compounds under conditions permitting the attainment in them of fairly high efficiencies (10% and more) are more promising from this point of view. The achievement of such high lasing efficiencies when a $H_2 - SF_6$ mixture is pumped by an electron beam has been reported [3, 4, 8] and their attainment in a nonchain HF laser has been explained [4, 8] by the participation of molecular fluorine in population inversion. The presence in the lasing spectrum of an HF molecule of vibrational transitions with $v \geqslant 4$ and the generation of lasing pulses of fairly long duration (long duration of the pump pulse) should serve as proof of the validity of this hypothesis.

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This communication presents the results of a study of hydrogen fluoride lasers pumped by a nonchain chemical reaction initiated by radially convergent and planar electron beams and analyses the influence of these characteristics on the lasing efficiency. The study is a continuation of investigations described in Refs [7, 8].

2. Experimental devices and methods of measurement

Two devices were used in the experiments. In device 1 with an active volume of ~ 30 litres, use was made of excitation by a radially convergent electron beam, the energy and temporal characteristics of the HF-laser radiation obtained with the aid of the device, as well as the pump-pulse parameters described in Refs [7, 8].

Device 2 was used previously to investigate broad-band emission and was similar to that described in Ref. [9]. The accelerator made it possible to generate an electron beam with a 42 cm × 1.5 cm cross section, 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 laser cavity included only part of the volume in the laser chamber, having a diameter of 2.5 cm, and was formed by a spherical copper mirror with a radius of curvature of 2.5 mm and a plane-parallel KRS-5 plate with a reflection of the order of 33% in the region of 3 μm. IMO-2N or IKT-1N calorimeters were used to determine the radiation energy. The temporal characteristics of the radiation pulse were recorded by a liquid-nitrogen-cooled FSG-22-3A2 photodetector or an FP-1 photodetector (the spectral-sensitivity range was 1.5 – 11 μm). The signal from the photodetectors was applied to an S8-14 oscilloscope. The spectral characteristics of the radiation were investigated with the aid of an MDR-12 monochromator in which a reflecting diffraction grating with 300 lines mm^{-1} (plate scale 9.6 nm mm^{-1}) was used as a dispersive component.

3. Experimental results and their discussion

It has been shown [4, 8] that the efficiency of an electron-beam-pumped HF laser is influenced by the formation of not only atomic but also molecular fluorine. Both particles are formed as a result of the dissociation of SF_6 molecules when an electron beam is injected into the active mixture. The vibrationally excited HF molecules may be formed in this case as a result of two main processes:

$$F + H_2 \rightarrow HF\,(v \leqslant 3) + H + Q_1\ (31.8\ \text{kcal mol}^{-1})\ , \quad (1)$$

$$F_2 + H \rightarrow HF\,(v \leqslant 6) + F + Q_2\ (98\ \text{kcal mol}^{-1})\ , \quad (2)$$

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 [4, 8]. 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 the population of the HF molecules with $v \leqslant 3$. This in fact leads to the appearance of lasing as a result of vibrational transitions with $v \leqslant 3$. 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 vibrational transitions ($4 \leqslant v \leqslant 6$). Furthermore, the atomic fluorine formed in the second reaction can again participate in the population inversion as a result of transitions with $v \leqslant 3$ [see reaction (1)]. Thus, short chains leading to an increase in the HF-laser efficiency may occur in the active mixture, whereas vibrational 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 electron-beam pulse.

The energy distribution over the spectrum for the $SF_6 : H_2 = 7 : 1$ laser mixture is illustrated in Fig. 1. for the three pressures investigated, lasing was observed as a result of the transitions with $v > 3$. At higher pressures (0.82 and 0.344 bar), 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 [10]. A decrease in pressure to 0.096 bar led to lasing as a result of the P_1, P_2, P_3, P_4, P_5 transitions (there was also lasing as a result of transitions with $v > 3$) and a shift of the lasing maximum to the P_1 transition. This indicates the participation of molecular fluorine in the population inversion in the HF laser.

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 bar for the $SF_6 : H_2 = 7 : 1$ laser mixture. Fig. 2a presents an electron-beam current pulse and a laser radiation pulse obtained on the apparatus with pumping by a radially convergent electron beam. The lasing threshold was attained 40 ns after the injection of the electron-beam current, whereas the radiation-pulse duration significantly exceeded the pump-pulse duration and had a complex spike structure. This is apparently also associated with the fact that different vibrational transitions, including the transition with $v > 3$, as a result of which lasing has long delay times, participate in the lasing process.

Fig. 2b shows electron-beam current and lasing pulses obtained on the apparatus with pumping by a planar electron beam. These pulses have evidently similar structures. The pressure dependence of the half-amplitude duration of the radiation pulse is shown in Fig. 2c. An increase in pressure increases the specific energy imputs into the active mixture and the rates of the chemical reactions, which in fact leads to a decrease in the radiation-pulse duration, but at a pressure of 1 bar the latter exceeded the pump-pulse duration. Thus, when the pressure in the mixture changed from 1 to 0.1 bar, the laser-radiation pulse duration changed from 150 to

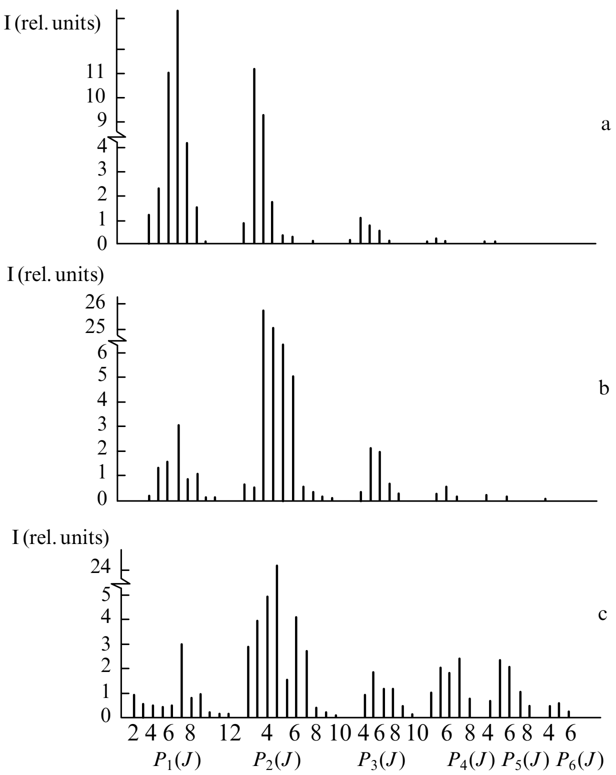

Figure 1. Intensity distributions over the lasing spectrum at pressures in the $SF_6 : H_2 = 7 : 1$ laser mixture of 0.096 bar (a), 0.344 bar (b), and 0.82 bar (c) obtained on device 2.

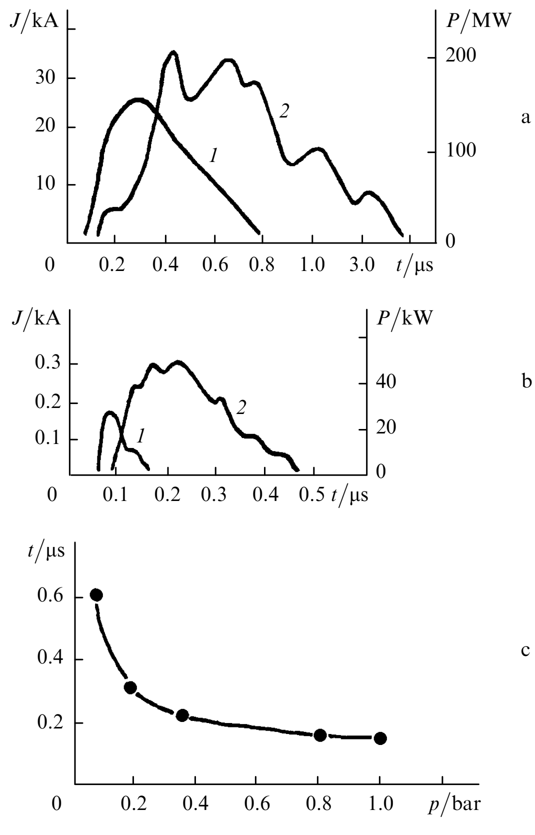

Figure 2. Electron-beam current-pulse (1) and lasing-pulse (2) oscillograms with the $SF_6 : H_2 = 7 : 1$ mixture pumped by radially convergent (a) and planar (b) electron beams at pressures of 0.45 bar (a) and 0.344 bar (b) and dependence of the radiation-pulse duration, obtained on device 2, on the pressure in the same mixture (c).

600 ns, whereas the laser-emission delay time relative to the instant when the gas medium was acted upon by the electron beam changed from 20 to 97 ns.

The order in which lasing appeared as a result of individual vibrational 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 on the most intense transition lines, whereas the P_4, P_5, and P_6 transition lines were detected only in the second half of the radiation pulse. Fig. 3 presents the time dependences of the lasing energies of individual lines detected as a result of the transitions of the P_2 band at a pressure of 0.344 bar. Evidently, lasing as a result of P_2 transitions with a high 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.

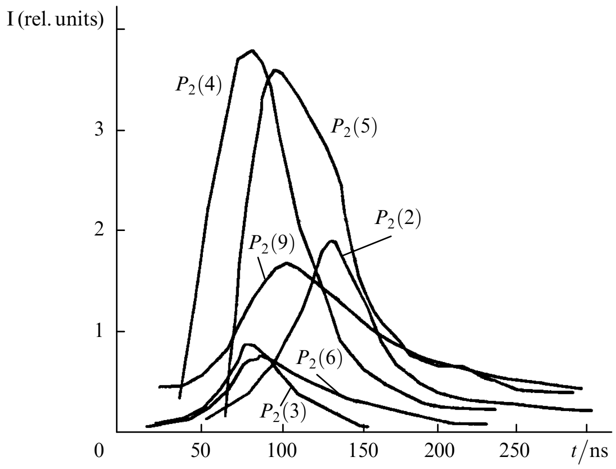

Figure 3. Time variation of the intensities of individual P_2 transition lines at a pressure of 0.344 bar in the $SF_6 : H_2 = 7:1$ mixture (device 2).

According to Refs [4, 8], the limiting efficiency of a nonchain HF laser with participation of only atomic fluorine in population inversion cannot exceed 9% and is determined by the relationship $\eta = 0.88 \times 10^{-2} h\nu$, where $h\nu = 10.2$ kcal mol^{-1}. In the present study, we obtained an efficiency greater than 10% on the apparatus with pumping by a radially convergent electron beam. The possibility of achieving a radiation efficiency of a nonchain HF laser of 10% and above was reported in Refs [3, 4, 8], which demonstrates the involvement of molecular fluorine in the population inversion in a nonchain HF laser.

We may note an important advantage of the use of a radially convergent electron beam for the pumping of an HF laser. The efficiency of hydrogen fluoride lasers pumped by a planar electron beam is known to be significantly influenced by the electrical field of the induced space charge. For a radially convergent electron beam (device 1), the energy deposited in the gas and determined from the pressure jump [7] is approximately equal to the energy calculated by the Monte Carlo method [7] (without taking into account the influence of the space charge) by means of the program described in Ref. [11] over the entire range 0.25 – 1.25 bar in the $H_2 : SF_6 = 1:8$ active mixture.

On the other hand, measurements have shown that the electric field and the radiation-energy density in the centre of a laser chamber 20 cm in diameter and at a distance of 4.5 cm from the side wall differ by more than 15% during the injection of the electron beam (at a pressure in the mixture of 0.45 bar). The attainment of high lasing energies [7, 8] for a fairly uniform radiation-energy distribution over the output-beam cross section as well as the satisfactory agreement between the results of the calculations of the energy input into the gas and the experimental data show that the devices with a radially convergent geometry of the injection of electron beams into the active mixture are optimal for the attainment of high radiation energies and efficiencies in nonchain HF (DF) lasers and for the generation of high-quality laser beams. In this geometry, the electric field of the negative-ion space charge generated is apparently significantly weaker than in the injection of electrons from one or two sides owing to the rapid discharge on the cylindrical wall of the laser chamber.

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