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Overtone cw chemical HF laser with an extended active medium

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***Abstract*. The operation on the first overtone transition of the HF(v) molecule is demonstrated for a cw chemical laser with a three-jet nozzle unit using a nozzle – nozzle – nozzle reagent mixing scheme. The energy, spatial, and spectral characteristics of the laser, as well as the efficiency of conversion of the chemical energy of the pump reaction to the overtone radiation are experimentally estimated. Lasing with an output power of ~1.1 kW and a conversion efficiency of 18 % is obtained in the 1.321 – 1.34 μm wavelength range. The extent of the lasing region is 5.3 cm, which is several times longer than in a laser employing a two-jet nozzle unit with a radial expansion in a nozzle – injector scheme.**

Keywords: *chemical laser, three-jet nozzle unit, overtone, spatial and energy characteristics.*

1. Introduction

Our investigations reported in Refs [1–6] confirmed the conceptual possibility to produce a rather efficient overtone cw chemical HF laser emitting in the 1.313 – 1.351-μm range on the basis of a laser equipped with a two-jet nozzle unit with a radial expansion according to a nozzle – injector reagent mixing scheme. Our experimental studies and numerical estimates showed that the output characteristics of the overtone laser are very sensitive to the threshold gain because of a very low gain in the active medium. That is why extremely high requirements are imposed on the resonator mirrors from the viewpoint of their reflectivity: to obtain maximum energy characteristics of the overtone laser, the effective reflectivity $(r_1 r_2)^{0.5}$ of the resonator mirrors should be no less than 0.99, while the transmittance τ should be close to $1 - (r_1 r_2)^{0.5}$ [3, 4]. In addition, the overtone HF laser investigated in our work possesses a very short lasing region Δx_L, which does not exceed 1.1 – 2.5 cm according to various estimates [2].

The low transmittances of the mirrors, along with a very short lasing region, result in an extremely high radiation load on the resonator optics. The latter is among the limiting factors which hinder a further increase in the overtone radiation power. It may therefore prove to be expedient to use operating modes which ensure an extension of the lasing region, for instance, to employ a nozzle unit involving a three-jet reagent mixing scheme, which was successfully used in an HF laser operating on the fundamental mode [7 – 10]. In addition, a three-jet nozzle unit provides [due to the inert gas layer (He* molecules) introduced between the streams of oxidising gas (F atoms) and secondary fuel (H_2 molecules)] a reduction of the translational temperature of the active medium. As shown in Ref. [5], this reduction is highly beneficial to precisely the overtone laser.

Taking these circumstances into account, we formulated the aim of our research, which is to demonstrate the operation of a cw chemical laser with a three-jet nozzle unit on the first overtone transition of the HF(v) molecule, and to estimate its parameters and the conversion efficiency of the chemical energy of the pump reaction to the overtone radiation.

2. Experimental

A special feature of an overtone HF laser is that the gain of its active medium is extremely low, being 100 – 200 times lower than for operation on the fundamental mode. That is why, as noted above, its parameters are very sensitive to the threshold gain $G_{\text{th}} = (2L)^{-1} \ln (r_1 r_2)^{-1}$, where L is the length of the active medium along the optical axis of the resonator (the length of the nozzle unit). It is obvious that to provide conditions more favourable for laser operation in the overtone lasing mode, experimental models should be used whose nozzle units, on the one hand, form active media with the highest gain upon lasing on the fundamental transitions of working molecules, and on the other hand, ensure lowering of the gain G_{th}. We used this approach in Refs [1 – 6], in which the object of research was an efficient HF laser with a relatively long ($L = 70$ cm) two-jet nozzle unit with a radial expansion and a small mixing scale length ($l = 5$ mm).

In this paper, we studied the largest ($L = 40$ cm) HF laser model at our disposal having a three-jet nozzle unit. However, this model was so designed [8] that the mixing scale length afforded by its nozzle unit (nozzle – nozzle – nozzle reagent mixing scheme) was too long ($l = 16$ mm). This is directly reflected on the quality of reagent mixing and the gain of the active medium upon operation on the fundamental mode. This laser should therefore be considered as a device for conducting research of methodical

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Table 1. Optical and geometric characteristics of the elements of two-mirror resonators.

Experiment number	Element type	Element code	$\tau_{1.3}$ (%)	$r_{2.8}$ (%)	R/m	d/cm	Substrate material
1	I	15S-2, sphere	0.025	1.6	15	13	Quartz KV glass
	II	K4, wedge	0.040	1.6	∞	12	– " –
2	I	15S-6, sphere	0.025	2.0	15	13	– " –
	II	K4, wedge	0.040	1.6	∞	12	– " –
3	I	15S-2, sphere	0.050	2.2	15	12	– " –
	II	5SG-1, sphere	0.025	2.0	5	12.8	– " –
4	I	No. 4, sphere	0.220	5.0	5	10	Calcium fluoride
	II	15S-4, sphere	0.040	1.8	15	12	Quartz KV
5	I	No. 4, sphere	0.220	5.0	5	12	– " –
	II	15S-4, sphere	0.040	1.8	15	13	– " –
6	I	IK-003 No. 3, plate	0.650	1.3	∞	13	– " –
	II	15S-4, sphere	0.025	2.0	15	13	– " –

Notes: (I) output mirror; (II) highly reflecting mirror; ($\tau_{1,3}$) average transmittance for the radiation in the overtone transition range (1.32 – 1.34 μm); ($r_{2.8}$) peak reflectivity in the fundamental transition range (2.63 – 2.95 μm); (R) radius of curvature of an element; (d) diameter of an element.

nature, which does not pretend to attain the limiting output characteristics. In the course of such investigations [7–10], we optimised its parameters and measured its characteristics (including the gain) upon lasing on the fundamental transitions of the HF(v) molecule.

As for the overtone lasing, crucially important for its realisation (along with the length of the nozzle unit) is the proper choice of the parameters of resonator optics. To do this, the information is required on the gains G_0^* (on the fundamental mode) and G_0 (on the overtone), which can be obtained, for instance, by using calculational-experimental method proposed in our earlier paper [11]. Our estimates yielded $G_0^* \sim 0.9 \times 10^{-2}$ cm^{-1} and $G_0 \sim 0.57 \times 10^{-4}$ cm^{-1}.

Knowledge of these parameters allows us to formulate the requirements on the optics of the overtone laser with a two-mirror resonator. To solve this problem, it is necessary to suppress lasing on the fundamental mode and provide the conditions for overtone lasing. The lasing on the fundamental mode is suppressed when the reflectivity of the output resonator mirror is

$$r_1 = \left(\mathrm{e}^{2LG_0^*}\right)^{-0.5}, \tag{1}$$

For $L = 40$ cm and $G_0^* \sim 0.9 \times 10^{-2}$ cm^{-1}, the reflectivity is $r \leqslant 0.7$. The overtone lasing is possible when

$$r_1 r_2 \geqslant \left(\mathrm{e}^{2LG_{\mathrm{th}}}\right)^{-1} \geqslant \left(\mathrm{e}^{2LG_0}\right)^{-1}. \tag{2}$$

For $L = 40$ cm and $G_0 \sim 0.57 \times 10^{-4}$ cm^{-1}, the product $r_1 r_2 \geqslant 0.99545$. Since the reflectivity of the highly reflecting resonator mirror (taking into account that the typical total loss factor due to scattering and absorption measured in our work is $a = 0.0015$) is $r_2 = 1 - a = 0.9985$, the reflectivity of the output mirror is $r_1 \geqslant 0.99545\, r_2^{-1} \geqslant 0.99695$ and the transmittance is $\tau_1 \leqslant 1 - r_1 - a \leqslant 0.00155$. A calculation made according to Ref. [12] gave the estimates of the optimal parameters of the output mirror as $r_1^{\mathrm{opt}} = 0.9977$ and $\tau_1^{\mathrm{opt}} = 0.0008$, and of the output overtone radiation power $N \sim 0.5$ kW, which can be expected in the experiments. Taking into account the requirements formulated above, we assembled five variants of two-mirror resonators out of the overtone optical components at our disposal, which were employed in our experiments. The characteristics of the optical components used in the resonators are presented in Table 1.

The HF laser under study was described in detail in Ref. [8] and the measuring equipment in Ref. [10]. In addition, here we employed an AGEMA (Sweden) 'Thermovision 880' infrared imager to evaluate the real-time temperature field distribution (adequate to the distribution of radiation power density) arising on the target surface heated by a laser beam. The working reagents were supplied in the molar ratio: $D_2 : F_2 : \mathrm{He} : H_2 : \mathrm{He}^* = 1 : \alpha_1 : \psi_1(\alpha_1 - 1) : \alpha_2(\alpha_1 - 1) : \psi_2(\alpha_1 - 1)$. Because the main objective of our study was to demonstrate a new effect of the overtone lasing in an extended active HF medium, we abandoned the idea of optimising both the chemical fuel composition and the flow rate load of the nozzle unit. Following the results of previous investigations [7–10], the chemical fuel composition was taken to be close to the optimal one in the case of lasing on the fundamental mode ($\alpha_1 \sim 1.6$, $\psi_1 \sim 11$, $\alpha_2 \sim 30$) and the total mass flow rate of the reagents was maintained close to the rated one ($m = 90 - 100$ g s^{-1}), all the above parameters remaining constant.

To change the conditions for overtone lasing, we varied the transmittances of resonator mirrors τ_1 and τ_2 ($\tau_1 = 0.025\,\%$, $0.05\,\%$, $0.22\,\%$, $0.65\,\%$, and $\tau_2 = 0.025\,\%$ and $0.04\,\%$), the position of optical resonator axis relative to the cut of the nozzle unit x_{c} (3.5 and 4.5 cm), and the coefficient of secondary dilution of the active medium with helium ψ_2. Every $\sim$ 10-s long test run comprised two equally long operating laser modes – with ($\psi_2 = 5 - 6$) and without ($\psi_2 = 0$) secondary dilution of the active medium with helium.

3. Experimental results and discussion

To evaluate the reproducibility and reliability of experimental results and also to determine the efficiency of conversion of the chemical energy of the pump reaction to the overtone radiation, we first conducted a control experiment with the HF laser operating on the fundamental mode. The resultant output powers N^* were equal to 6.07 kW for $\psi_2 = 0$ and 6.22 kW for $\psi_2 = 5 - 6$. Within the limits of experimental error, these data well agree with those obtained earlier [10].

The output power N of overtone radiation was defined as the sum of output powers N_1, N_2 (transmitted through the first and second mirrors, respectively) and N_a (absorbed and scattered by the mirrors):

$$N = N_1 + N_2 + N_a, \qquad (3)$$

$$N_a = (N_1 + N_2)/a, \; a = a_{ab} + a_{sc}, \qquad (4)$$

where a_{ab} and a_{sc} are the radiation loss factors due absorption and scattering in the mirrors, respectively; and $a = 0.15\,\%$ for each mirror. The data of test runs are collected in Table 2. As expected, the output power level of overtone radiation proved to be low: the highest power $N \sim 1.1$ kW for $\psi_2 \sim 6$ was obtained for the lowest transmittance of the output mirror $\tau_1 = 0.025\,\%$ (test runs No. 1 and No. 2). When the coefficient τ_1 was increased two-fold (test run No. 3), the output power became 11 times lower.

Table 2. Overtone HF-laser test data

Experiment number	τ_1 (%)	x_c/cm	ψ_2	N/W
1	0.025	3.5	0	1233
			5.7	1124
2	0.025	4.5	0	954
			6.2	1097
3	0.050	4.5	0	36
			4.9	101
4	0.220	3.5	0	100
			5.9	50
5	0.220	4.5	5.4	21
6	0.650	4.5	5.9	13

Note: x_c is the distance between the resonator axis to the cut of the nozzle unit

This effect can be explained by the fact that for $\tau_1 > 0.025\,\%$, the overtone laser operates near the lasing threshold, so that its energy output depends only slightly on the degree of secondary dilution, the resonator transmittance, and the location of the resonator axis. Nevertheless, we were able to demonstrate the feasibility of an overtone HF laser with a three-jet nozzle unit based on a nozzle–nozzle–nozzle scheme and obtain an output power $N \sim 1.1$ kW under the conditions of secondary dilution of the active medium with helium ($\psi_2 = 6.2$) for a flow rate load of the nozzle unit $g_n = 0.25$ g s^{-1} cm^{-2}. This corresponds to a specific energy extraction $N_\Sigma \sim 10$ J g^{-1} and the efficiency of conversion of the chemical energy of the pump reaction to the overtone (the ratio between the peak output power at the overtone to the output power at the fundamental mode obtained under similar condition) $\varepsilon_2 = 18\%$.

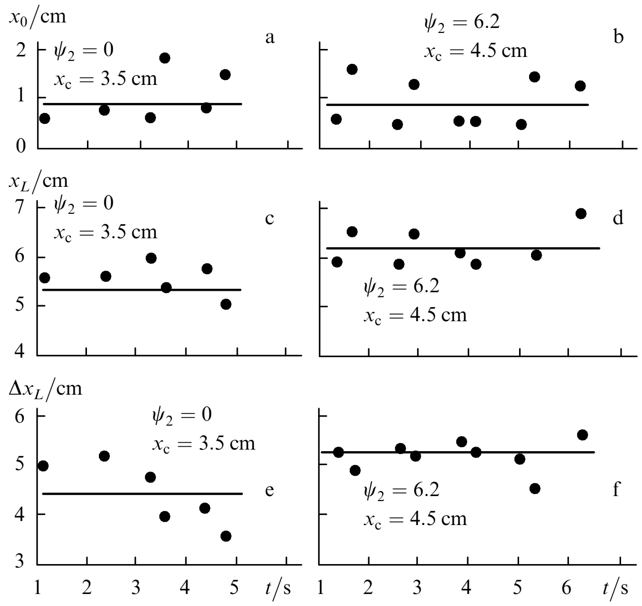

Figure 1. Effect of the coefficient of secondary dilution of the active medium on the spatial 'detachment' of the lasing region from the cut of the nozzle unit (a, b), the location of the far boundary of the region (c, d), and its extent (e, f) for $\tau_1 = 0.025\,\%$.

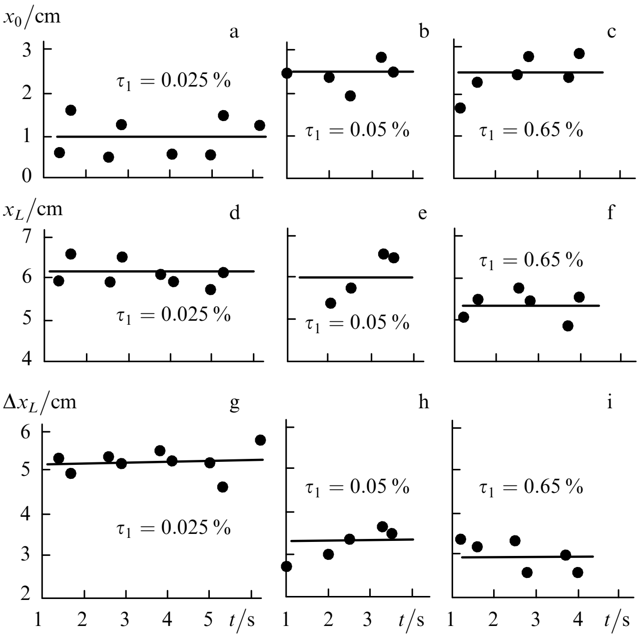

Figure 2. Effect of the transmittance of the output resonator mirror on the spatial 'detachment' of the lasing region from the cut of the nozzle unit (a–c), the location of the far boundary of the region (d–f), and its extent (g–i) for $\psi_2 \sim 5$ and $x_c = 4.5$ cm.

The development dynamics of the spatial characteristics of the lasing region (the geometrical dimensions of the active medium) is demonstrated in Figs 1 and 2. As upon lasing at the fundamental mode [10], in the overtone version there occurs, regardless of the degree of secondary dilution of the active medium with helium, a spatial 'detachment' of the lasing region from the cut of the nozzle unit characterised by a coordinate $x_0 = 0.9$ cm (Figs 1a and 1b). The far boundary of the active region x_L and its extent $\Delta x_L = x_L - x_0$ for $\psi \sim 6$ are respectively equal to 6.2 and 5.3 cm (Figs 1d and 1f). As expected, they exceed the x_L and Δx_L values for the $\psi_2 = 0$ mode by 15 %–18 % (Figs 1c and 1e). The dynamics outlined above corresponds to the minimal transmittance of the output mirror ($\tau_1 = 0.025\%$).

As the resonator is 'opened' (as τ_1 is increased), the geometrical dimensions of the active medium change. While the far boundary of the lasing region is hardly changed ($x_L \sim 6$ cm, Figs 2d–2f), its spatial 'detachment' from the cut of the nozzle unit increases to $x_0 \sim 2.5$ cm (Figs 2b and 2c) to reduce the extent of the region Δx_L to ~ 3 cm (Figs 2h and 2i). The reason for this change may lie with the growth of threshold gain and the lowering of radiation density in the active medium. The latter circumstance results in the fact that the role of collisional deactivation of the HF(υ) molecules increases and a lower fraction of vibrational energy is converted to radiation.

These data, which were obtained with the aid of a scanning-type beam analyser, are confirmed by infrared imaging data obtained with the 'Thermovision 880' imager. The respective Δx_L values obtained by these techniques for $\tau_1 = 0.025\,\%$ are 5.3 and 5.4 cm; for $\tau_1 = 0.65\,\%$ they are equal to 3.0 and 2.4 cm. These data show that the extent of the active medium $\Delta x_L = 5.3 - 5.4$ cm produced by the three-jet nozzle unit based on a nozzle–nozzle–nozzle scheme in the mode of highest output power (for $\tau_1 = 0.025\,\%$) is two-to-five times greater than the $\Delta x_L = 1.1 - 2.5$ cm value characteristic of the overtone HF laser with a two-jet nozzle unit with a radial expansion in a nozzle–injector scheme [2].

In our previous investigation of the laser of the latter type, we recorded the oscillation spectra containing three-four lines ($P_2(3-6)$ [2] and $P_2(5-7)$ [5]) covering the 1.313–1.351-μm wavelength range. An analysis of the HF-laser spectral measurement data revealed the following. A typical lasing spectrum (the relative output powers of the laser lines N_J/N proportional to their intensities) with the secondary dilution of the active medium with helium comprises two lines: $P_2(4)$ with $\lambda = 1.321$ μm and $P_2(5)$ with $\lambda = 1.331$ μm or $P_2(5)$ and $P_2(6)$ with $\lambda = 1.340$ μm. The specific form of the spectrum depends on the operating parameters of the HF laser – τ_1, x_c, and τ_2.

As the transmittance τ_1 increases (Fig. 3), there occurs a transfer of power to spectral lines with lower rotational quantum numbers J and accordingly their shift to the blue. For $\tau_1 = 0.05\,\% - 0.22\%$, the $P_2(5)$ line accounts for 90 % of output laser power. Moving the optical resonator axis away from the cut of the nozzle unit (increasing x_c) is also accompanied by a shift of the spectrum (as regards the relative intensities of spectral lines), though to the red, this being independent of the output mirror transmittance (Fig. 4). This is caused by the influence of translational temperature of the active medium, which increases with distance to the cut of the nozzle unit (a similar effect was also observed when this laser was operating by the fundamental transitions [10]).

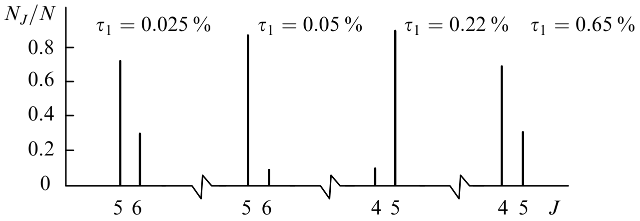

Figure 3. Effect of the transmittance of output resonator mirror on the overtone laser spectrum for $\psi_2 \sim 5$ and $x_c = 4.5$ cm.

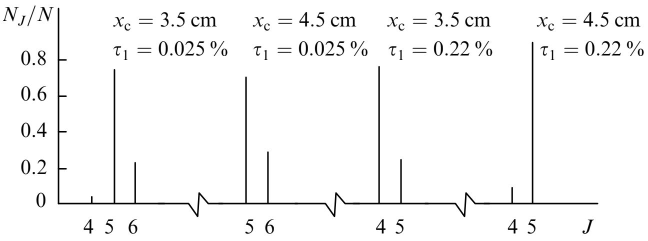

Figure 4. Effect of the position of optical resonator axis relative to the cut of the nozzle unit on the overtone laser spectrum for $\psi_2 \sim 5$.

As for the effect of secondary dilution coefficient ψ_2, the lasing spectrum shifts to the blue due to a reduction of the translational temperature of the active medium upon its dilution with helium (Fig. 5). Therefore, by varying the operating parameters of the overtone HF laser with a three-jet nozzle unit, it is possible to control, to a certain degree, the spectral composition of its radiation. In this case, it is possible to select a mode that ensures lasing at only one wavelength, for instance, at 1.340 μm (Fig. 5).

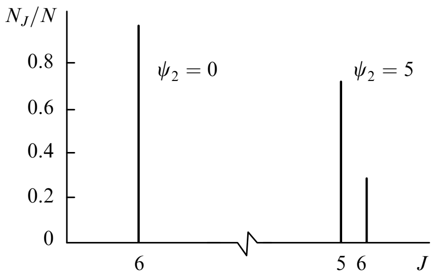

Figure 5. Effect of the coefficient of secondary dilution of the active medium with helium on the overtone laser spectrum for $x_c = 4.5$ cm and $\tau_1 = 0.025\,\%$.

This fact is of significance from two viewpoints. First, it is indicative of the feasibility of lasing (like in an oxygen-iodine laser) at a single line without employing special selective elements. Second, it gives hope for the realisation of an HF laser operating in the master oscillator–power amplifier configuration. This operating mode does not generally require that the master oscillator should possess a high output power.

4. Conclusions

Therefore, lasing was obtained for the first time in an overtone HF laser with a three-jet nozzle unit in a nozzle–nozzle–nozzle reagent mixing scheme in the 1.321–1.340-μm wavelength range. An output power of ~ 1.1 kW was obtained for an efficiency of conversion of the chemical energy of the pump reaction to the overtone of 18 %. Varying the coefficient of secondary dilution of the active medium with helium ψ_2 showed that for $\psi_2 \sim 5$ the extent of lasing region is equal to 5.3 cm, which exceeds that for the $\psi_2 = 0$ mode by nearly 20 %. In comparison to a laser with a two-jet nozzle unit with radial expansion in the nozzle–injector scheme, the extent of lasing region is two-to-five times greater.

We have demonstrated the feasibility of spectral line selection by varying the transmittance of the output resonator mirror, the position of the optical resonator axis, and the coefficient of secondary dilution of the active medium with helium. As a result, we were able to obtain lasing at a single line – $P_2(6)$ with $\lambda = 1.34$ μm. To further improve the output energy characteristics, a change-over should be made to an HF-laser model whose nozzle unit provides a better reagent mixing due to a smaller nozzle spacing (for instance, to a nozzle – nozzle – injector scheme [13]) and produces an active medium with a higher gain. Also, there is good reason to optimise the maximum possible number of operating laser parameters.

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