

On the possibility of simultaneous emission of an autonomous cw HF – DF chemical laser in two spectral ranges

A.S. Bashkin, L.V. Gurov, B.I. Katorgin, S.N. Petrova, D.V. Polinovsky

Abstract. The efficiencies of different fuel compositions used in the combustion chamber of an autonomous cw chemical HF–DF laser for obtaining high specific energy parameters during simultaneous lasing in HF and DF molecules in two spectral ranges are theoretically analysed. It is shown that mirrors with the reflectance above 99% in these spectral ranges can be manufactured in principle.

Keywords: active medium generator, cw chemical HF–DF laser, two-wavelength laser, multilayer dielectric mirrors, fuel composition.

1. Introduction

Continuous-wave chemical lasers (CCLs) usually emit in one spectral range depending on the fuel composition and, hence, on molecules in excited vibrational states employed (HF, DF, HCl, HBr, CO₂) [1]. Because simultaneous lasing in several spectral ranges is of interest for a number of applications, theoretical calculations of the possibility of obtaining simultaneous lasing in two different spectral ranges by using different pairs of molecules were reported in the literature: HF–HCl [2], HF–HBr [3], DF–CO₂ [4]. In this paper, we calculated processes proceeding in the combustion chamber and active zone of a laser taking into account their interrelation and analysed the possibility of obtaining efficient simultaneous lasing in an autonomous HF–DF CCL in two spectral ranges in molecules HF and DF.

Such a laser can be used for studying the propagation of radiation at different wavelengths under the same climatic and weather conditions in different regions over sea, in near the ground and high-altitude atmospheric layers, as well as in the near cosmic space (the properties of propagation of radiation from different lasers through atmosphere, in particular, HF and DF CCLs were considered, for example,

in [5, 6]). These data can be used for laser location and communication. Such data were obtained in experiments at near the ground [7] and space [8] paths by using HF and DF CCLs emitting in one spectral range. Because the multi-frequency emission spectra of HF and DF CCLs overlap with the absorption spectra of most atmospheric gases (such as CO₂, N₂O, NO, SO₂, HCl, C₃H₈, HDO, H₂O, HF, etc. [9, 10]), these lasers are promising for studying the gas composition of the atmosphere. The HF and DF CCLs were used for remote gas analysis of some impurities to control the environment. Thus, a HF CCL was used for highly sensitive (0.2 mg m⁻³) measurements of the HF impurity concentration in exhaust gases appearing in the production of aluminium [11]. A DF CCL was employed for measuring the concentration of HCl molecules in the atmosphere [12].

Discharge-pumped repetitively pulsed HF(DF) lasers can be also used for these purposes (see, for example, [13], where concentrations of different hydrocarbons in the atmosphere were measured by employing these lasers). However, such lasers require the use of high-power discharge power supplies, while their average output power is at present considerably lower than the output power of autonomous CCLs, which do not require electric power supplies. In addition, the size and output power of CCLs can be increased more simply. Because of this, the use of HF(DF) CCLs operating in the repetitively pulsed regime can be expedient at sufficiently large sensing ranges.

The applications of HF and DF CCLs could be expanded by obtaining lasing in HF and DF molecules simultaneously in two spectral ranges. However, this is not simple to achieve. To obtain vibrationally excited HF and DF molecules in the lasing region, H₂ or D₂ should be added as a secondary fuel at the nozzle array section to a flow containing atomic fluorine and issuing from the combustion chamber to the lasing region. However, H₂ or D₂ is also commonly used as a primary fuel for obtaining atomic fluorine. As a result, a flow issuing from the combustion chamber contains, along with atomic fluorine, unexcited HF or DF molecules in great amounts. Because of this, the absorption coefficient of these molecules in the $v = 0 \rightarrow v = 1$ vibrational band usually exceeds the gain, which can reduce the output lasing power more than by half. To avoid this situation, different primary and secondary fuels are used in HF and DF CCLs emitting in one spectral range: for example, D₂ as a primary fuel and H₂ as a secondary fuel, or vice versa.

In the case of HF–DF CCLs emitting in two spectral ranges, both H₂ and D₂ should be used as the secondary fuel. To reduce absorption at the $v = 0 \rightarrow v = 1$ transition in

A.S. Bashkin, L.V. Gurov, B.I. Katorgin, S.N. Petrova Open Joint-Stock Company, V.P. Glushko Energomash Research and Production Association, ul. Burdenko 1, 141400 Khimki, Moscow region, Russia; e-mail: energo@online.ru;

D.V. Polinovsky Moscow Aviation Institute (State Technical University), Volokolamskoe sh. 4, 125871 Moscow, Russia

Received 23 November 2007; revision received 20 February 2008

Kvantovaya Elektronika 38 (8) 429–435 (2008)

Translated by M.N. Sapozhnikov

this case, it is necessary to use alternative fuel compositions (FCs) whose combustion products would contain the minimal amount of unexcited HF and DF molecules at the optimal content of atomic fluorine.

2. Selection of the optimal fuel composition in a combustion chamber

The fuel composition used in the active medium generator (AMG) of autonomous HF and DF CCLs includes a fluorine-containing oxidiser, primary and secondary fuels, and a diluent. We used in our study nitrogen trifluoride (NF₃) and molecular fluorine (F₂) as oxidisers and helium as a diluent. In the combination of its operating characteristics, nitrogen fluoride surpasses all other oxidisers [14], but its energy characteristics in the case of HF and DF CCLs emitting in one spectral range are 20%–25% worse than those of molecular fluorine, which is the most efficient of them.

As a primary fuel, different substances can be used. In theoretical and experimental studies of HF and DF CCLs performed earlier [14–16], apart from H₂ and D₂ a number of other gases and liquids were used: CO and CS₂ for a HF CCL and C₂H₄, C₂H₂, CO, and CS₂ for a DF CCL. In this paper, we analysed theoretically and compared the efficiencies of using these primary fuels for obtaining lasing in two spectral ranges.

The method of selecting the optimal FC in a combustion chamber is described in paper [16]. It was shown that the dependence of the specific energy output (the ratio of the laser radiation power to the total mass consumption of components) on the relative molar content χ_F of atomic fluorine in the flow of oxidising gas from the combustion chamber in HF and DF CCLs with a slot nozzle array when different FCs were used had a broad maximum, the specific energy output varying only slightly (within $\pm 5\%$) in the range $\chi_F = 0.09 - 0.166$. According to [16], the maximum

specific energy output was achieved for $\chi_F^{\text{opt}} = 0.118$ after variations of many initial conditions. For this reason, this value was used in further calculations. The content of HF(DF) molecules in the oxidising gas for the specified molar fraction of atomic fluorine $\chi_F^{\text{opt}} = 0.118$ can be reduced, apart from using alternative primary fuels, by lowering the temperature of combustion products. In this case, to provide a high enough degree of dissociation of a fluorine-containing oxidiser (more than 97%), the gas temperature in the combustion chamber should be no lower than 1600 K.

Table 1 presents the main parameters of the usual FC based on H₂ or D₂ as primary fuels and alternative FCs in the combustion chamber calculated thermodynamically for determining the optimal chemical composition satisfying the conditions presented above. One can see from Table 1 that FCs based on CO and CS₂, whose combustion products do not contain HF or DF molecules in the ground state, are most favourable for obtaining simultaneous lasing in HF and DF molecules in two spectral regions. Among hydrogen-containing fuels, the best results were obtained for a FC based on acetylene. The molar fraction χ_{HF} of HF molecules in this case was approximately 4.5 times smaller than that for a hydrogen-based FC.

Another important parameter characterising a FC in the combustion chamber is its mean molecular mass. As this mass is increased, the mass flow rate of the fuel through the nozzle array increases and the specific energy output of the laser decreases. One can see from Table 1 that FCs based on H₂ and D₂ have the minimum molecular mass, while FCs based on CO and CS₂ have the maximum molecular mass. Note that the use of the nitrogen trifluoride oxidiser instead of molecular fluorine considerably deteriorates the properties of a FC. Thus, the replacement of NF₃ by F₂ in the combustion chamber in the case of a FC based on C₂H₂, the molar fraction of HF decreases by 1.4 times and the molecular mass by 1.3 times (Table 1, variant 4).

Table 1. Basic parameters of optimised usual and alternative (in parentheses) FCs providing the degree of fluorine dissociation in the combustion chamber equal to 97% for the molar fraction of atomic fluorine equal to 0.118.

Variant	Fuel composition	Molar fraction of HF or DF	Molar fraction of other products	Molecular mass of the mixture/g mol ⁻¹
1	H ₂ :NF ₃ :He = 1:1.1:6.7	0.19	–	10.1
	H ₂ :F ₂ :He = 1:1.9:11	(0.139)	–	(8.1)
2	D ₂ :NF ₃ :He = 1:1.1:6.7	0.190	–	10.2
	D ₂ :F ₂ :He = 1:1.9:11	(0.138)	–	(8.2)
3	H ₂ S:NF ₃ :He = 1:3.9:21	0.068	SF ₆ –0.034	13.3
	H ₂ S:F ₂ :He = 1:6.6:35	(0.046)	(SF ₆ –0.022)	(9.9)
4	C ₂ H ₂ :NF ₃ :He = 1:5.3:36	0.042	CF ₄ –0.042	11.3
	C ₂ H ₂ :F ₂ :He = 1:9.1:35	(0.030)	(CF ₄ –0.030)	(8.8)
5	C ₂ H ₄ :NF ₃ :He = 1:6.2:39	0.074	CF ₄ –0.037	11.5
	C ₂ H ₄ :F ₂ :He = 1:11:62	(0.052)	(CF ₄ –0.026)	(8.9)
6	CO:NF ₃ :He = 1:1.9:9.2	0	CF ₄ –0.076 O ₂ –0.037	15.0
	CO:F ₂ :He = 1:3.2:16	(0)	(CF ₄ –0.050 O ₂ –0.025)	(10.7)
7	CS ₂ :NF ₃ :He = 1:7.6:43	0	CF ₄ –0.018 SF ₆ –0.035	13.9
	CS ₂ :F ₂ :He = 1:13:74	(0)	(CF ₄ –0.012 SF ₆ –0.023)	(10.1)

3. Brief description of the model for calculating the energy parameters of a HF–DF CCL

We calculated gas flows in the nozzles of the oxidising gas and secondary fuel by using the following parameters: the nozzle array step was 6 mm, the height of the oxidiser nozzle section at the array cut was 3.4 mm, the expansion degree was 17, the height of the secondary fuel nozzle section at the array cut was 1.6 mm, and the expansion degree was 22. The nozzle wall temperature was set equal to 400 K and the deceleration temperature of the secondary fuel was 300 K. The gas flow through the nozzle was calculated by using the Ansys CFX 5.7 software solving this problem based on the complete system of Navier–Stokes equations.

Due to a large calculation time, the parameters of the active medium were calculated by using the two-dimensional mathematical model of a supersonic HF–DF CCL based on the system of equations of Navier–Stokes equations written in the narrow-channel approximation for multicomponent gas mixtures in the presence of nonequilibrium physiochemical processes in the active medium, including multicomponent diffusion, nonequilibrium chemical reactions, the VV exchange and VT relaxation processes, and lasing. We suppose that the use of the narrow-channel approximation is also justified because we only compared the energy parameters of a two-spectral range HF–DF CCL for different primary fuels in the combustion chamber rather than attempted to determine them accurately.

The flow velocities and temperatures in the output section of the nozzle array in the narrow-channel model were calculated by using the Ansys CFX 5.7 software package, and pressures were set equal to pressures on flow axes. All the calculations were performed at a pressure of 5 Torr at the nozzle array section by selecting the corresponding mass consumptions of components.

We assumed in calculations that transfer processes are laminar. Diffusion flows were described by the Fick law. The transfer coefficients were calculated by using semi-empirical expressions from [17]. To simplify calculations of the energy parameters of the laser, we used the Fabry–Perot resonator model in the software program. The program was developed by the method [17] by using the rate constants of chemical and relaxation processes proceeding in the lasing region taken from [18].

This program allows us to calculate small-signal gains and radiation intensities for vibration–rotation transitions of the P branch of HF and DF molecules. The program was tested by comparing the obtained gas-mixture-flow distributions of small-signal gains maximal over the rotational quantum number, which were averaged over the nozzle array period, with similar distributions calculated in [19]. The comparison showed that these distributions are virtually coincident.

4. Analysis of the possibility of obtaining high specular reflectance simultaneously in two spectral emission ranges of a HF–DF CCL

The high reflectance of radiation at one wavelength or within a narrow spectral band can be achieved by the deposition of dielectric coatings of width $\lambda/4$. However, it was not obvious beforehand that it is possible to select film thicknesses providing the high reflectance (above 99%) simultaneously in two well separated broad spectral ranges by using an acceptable number of layers.

We calculated the reflectance of layered media consisting of thin homogeneous nonabsorbing films by the method described in [20]. All the calculations for selected materials of dielectric layers and a substrate were performed in two stages. First we calculated the reflectances at the central wavelengths of each of the spectral ranges (separately for $\lambda = 2.8$ and $3.8 \mu\text{m}$) by varying the layer thickness with a step of 2×10^{-9} m. The results were processed by selecting thicknesses providing high reflectances of a multilayer coating, which were close at both emission wavelengths.

By sorting many possible combinations of materials with low (CaF₂, BaF₂, MgF₂, ThF₄, NaCl, KCl) and high (ZnSe, CdTe) refraction indices, we selected pairs of materials for dielectric coatings providing the reflectance above 99% simultaneously at wavelengths 2.8 and $3.8 \mu\text{m}$ by using the minimum number of layers. A transparent substrate was made of silicon, which was earlier used for manufacturing dielectric mirrors for HF(DF) CCLs (see, for example, [21]). Metal mirrors had silver coatings, which were earlier used in a number of experimental papers [22, 23]. The reflectances of mirrors calculated for pairs ThF₄–CdTe and ThF₄–ZnSe (Table 2) show that to obtain the reflectance exceeding 99%, it is sufficient to deposit from 13 to 21 layers on a silicon substrate (taking into account the 0.1- μm -thick upper protective ThF₄ layer). These pairs of materials were chosen based on the results of experiments [22, 23] on the development of multilayer dielectric coatings with the reflectance up to 99.9% for a DF CCL and up to 99.88% for a CO₂ laser. These covering materials are also transparent in the emission range of the HF CCL. One can see that even a slight decrease in the refractive index n after the replacement of one of the components of the pair (at $\lambda = 2.8 \mu\text{m}$, we have $n = 2.69$ for CdTe and $n = 2.44$ for ZnSe) leads to the increase in the required number of coatings. A smaller number of layers is obviously required for metal mirrors with silver coatings (5–7 layers).

At the second stage of calculations, we calculated reflectances at different wavelengths in two emission ranges of the HF–DF CCL (2.64– $3.0 \mu\text{m}$ and 3.7 – $4.05 \mu\text{m}$), which allowed us to select the ratio of widths of dielectric layers so that to provide the high reflectance in the entire required wavelength range. Figure 1 presents the wavelength dependence of the reflectance of a mirror in the lasing ranges

Table 2. Reflectances of mirrors (in percent) at wavelengths of 2.8 and $3.9 \mu\text{m}$ for normally incident radiation.

Variant	Structure of the multilayer coating with a ThF ₄ protective layer	Substrate material	Number N of layer pairs					
			2	3	5	6	8	10
1	(ThF ₄ –ZnSe) N + ThF ₄	Si	–	–	–	–	–	99.1
2	(ThF ₄ –CdTe) N + ThF ₄	Si	–	–	–	99.3	99.8	99.9
3	(ThF ₄ –ZnSe) N + ThF ₄	Ag	99.0	99.4	99.8	–	–	–
4	(ThF ₄ –CdTe) N + ThF ₄	Ag	99.3	99.7	99.9	–	–	–

for HF and DF molecules obtained by using three pairs of ThF₄–CdTe layers (with the upper protective ThF₄ layer) deposited on a silver-coated metal substrate. One can see from Fig. 1 that the reflectance of this mirror with a multilayer dielectric coating is quite satisfactory in the entire required wavelength range. Similar wavelength dependences of the reflectance were calculated for multilayer dielectric coatings on a silicon substrate. In this case, a slight decrease in the reflectance (by 1 %–2 %) was observed only in the short-wavelength edge of the emission spectrum of the HF CCL (2.64 μm). However, the contribution of radiation in this range to the output power of CCLs is usually quite small.

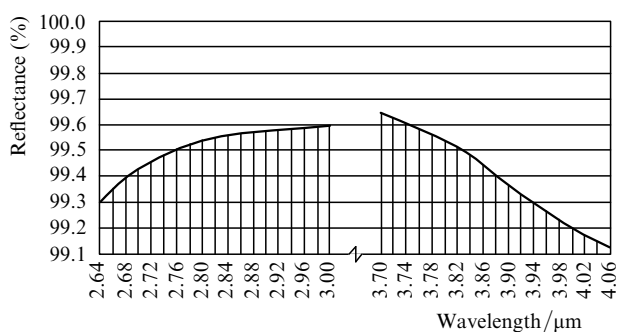


Figure 1. Wavelength dependence of the reflectance calculated for three pairs of ThF₄–CdTe layers (with the upper protective ThF₄ layer) deposited on a silver-coated metal substrate for normally incident radiation.

In some cases, mirrors are oriented so that radiation is incident on their surface not normally but at a certain angle to it. Such a situation can appear when it is necessary to change the propagation direction of radiation, for example, in measuring systems or when a multipass resonator is used. For comparison Table 3 presents the thickness of mirror coatings calculated for radiation incident at 45° to the normal to the resonator mirror surface.

One can see from Table 3 that the problem of obtaining the reflectance above 99 % simultaneously in two spectral ranges can be also solved in the case of radiation incident at an angle to the normal to the mirror surface. In this case, the number of dielectric coating layers required to obtain high reflectances is even slightly smaller than that in the case of normal incidence.

5. Calculation of the energy parameters for different variants of HF–DF CCLs

HF(DF) cw chemical lasers are usually characterised by their specific energy output and reduced radiation power (the ratio of the output power to the nozzle array section area). These parameters were compared for two variants of

the active-medium formation in the two-range HF–DF CCL (Fig. 2), when H₂ was supplied as the secondary fuel into one part of the AMG (the first AMG module) and D₂ was supplied to the other part (the second AMG module) (Fig. 2a) or when the H₂–D₂ mixture was supplied as the secondary fuel into both modules (Fig. 2b). The length of the active medium in each module was set equal to 50 cm in calculations, so that the total length of the active medium along the optical axis of the resonator was the same in both variants (100 cm). The reflectance of the highly reflecting resonator mirror was set equal to 99.4 % according to [20], and the reflectance of the output mirror was 90 %, the absorption coefficient of each mirror being 0.6 %. The fuel compositions in the combustion chamber are indicated in Table 1.

To compare the characteristics of the two-range CCL based on two separate modules (Fig. 2a), we performed a series of calculations of the parameters of the laser with the active medium length 50 cm emitting only in one spectral range of HF or DF molecules (Table 4). The highest specific lasing parameters were obtained for the CS₂-based FC (Table 4, variants 6 and 12), which had the lowest rates of vibration–translation relaxation due to the absence of relaxant HF molecules in the oxidising gas flow. The CO-based FC having similar relaxation properties only slightly inferior to the CS₂-based FC. When hydrogen-containing primary fuels were used in the case of lasing in DF molecules (variants 7–10), the acetylene-based FC was the most efficient. In the case of HF CCL, alternative FCs based on hydrogen-containing primary fuels (variants 3–4) rank below the usual FC (variant 1) in specific parameters, except variant 2 with the C₂H₂ primary fuel. This can be explained by the fact that the concentration of unexcited HF molecules in the combustion chamber is four times lower than that of unexcited DF molecules in the case of the usual FC (variants 2 and 4 in Table 1).

Note that the energy parameters of the CCL increase when the oxidiser NF₃ is replaced by F₂. The increase in the energy parameters is especially noticeable when hydrogen-containing FCs are used in the HF CCL because the replacement of NF₃ by F₂ not only improves the relaxation properties of the FC and reduces its molecular mass but also reduces the absorption of radiation by unexcited HF molecules.

The efficiencies of different FC combinations in the case of simultaneous lasing in HF and DF molecules obtained by using two independent AMGs [HF and DF modules (Fig. 2a)] can be compared based on the results of calculations presented in Table 5 where usual primary and secondary fuels in variant 1 in each of the two modules are different, while in variants 2–5 alternative primary fuels are the same in each module and the secondary fuel in one module is H₂ and in the other – D₂. It is obvious that FCs based on CO and CS₂ are free from the negative influence of absorption of radiation in the $\nu = 1 \rightarrow \nu \rightarrow 0$ band by

Table 3. Reflectances of mirrors (in percent) at wavelengths of 2.8 and 3.9 μm for radiation incident at 45° to the normal to the mirror surface.

Variant	Structure of the multilayer coating with a ThF ₄ protective layer	Substrate material	Number <i>N</i> of layer pairs					
			2	3	4	5	6	7
1	(ThF ₄ –ZnSe) <i>N</i> + ThF ₄	Si	–	–	–	98.7	99.4	99.7
2	(ThF ₄ –CdTe) <i>N</i> + ThF ₄	Si	–	–	99.1	99.7	99.9	–
3	(ThF ₄ –ZnSe) <i>N</i> + ThF ₄	Ag	99.5	99.8	99.9	–	–	–
4	(ThF ₄ –CdTe) <i>N</i> + ThF ₄	Ag	99.7	99.9	–	–	–	–

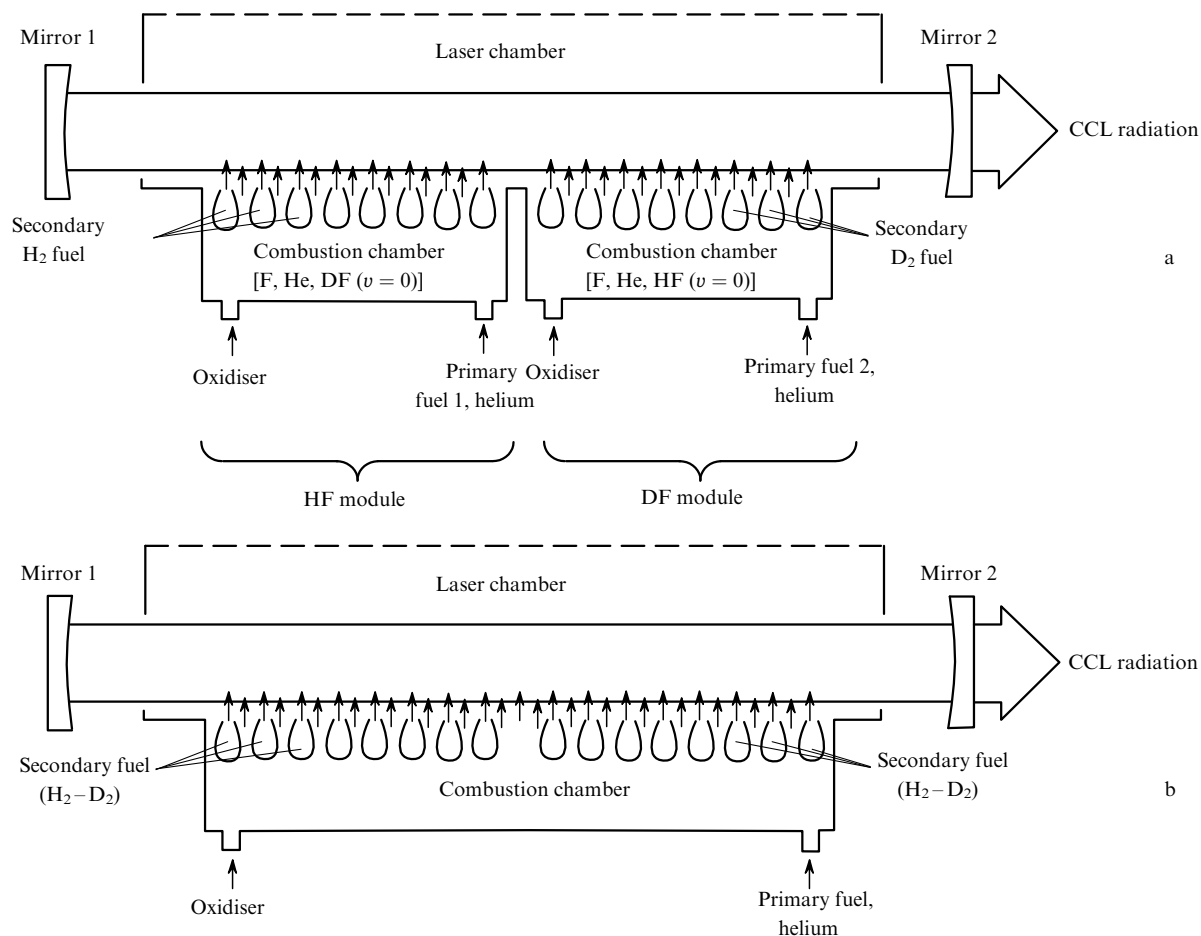


Figure 2. Possible laser schemes providing simultaneous lasing in HF and DF molecules by using two independent HF and DF AMG modules (a) and one double HF/DF AMG module (b).

unexcited HF or DF molecules flowing out from the combustion chamber. As a result, these FCs offer the best specific characteristics in the case of simultaneous lasing in two spectral ranges. The efficiency of hydrogen-containing FCs decreases with increasing concentration of HF molecules in combustion products flowing out of the combustion chamber. Thus, the worst results were obtained when usual FCs were employed in both AMGs (Table 5, variant 1): the output power decreased approximately by half compared to the output power during lasing in one

spectral range only (Table 4, variant 1 and 7). It is preferable to use alternative primary fuels in both AMGs, especially acetylene (Table 5, variant 2) because absorption losses in this case are compensated due to the reduced rates of vibration–translation relaxation of the FC, and the parameters of simultaneous lasing in two spectral ranges are not inferior to the parameters of lasing in one spectral range.

Even better results on simultaneous lasing in HF and DF molecules in two spectral ranges can be obtained by using the double HF/DF AMG module (Fig. 2b), when the H₂–

Table 4. Energy parameters for lasing in one spectral range with the use of one AMG module with the active medium of length 50 cm.

Variant	Primary fuel	Oxidiser	Secondary fuel	Reduced power/W cm ⁻²	Specific energy output/J g ⁻¹
1	D ₂			85 (111)	128 (173)
2	C ₂ H ₂			84 (122)	131 (194)
3	C ₂ H ₄			44 (84)	68 (134)
4	H ₂ S	NF ₃ (F ₂)	H ₂	48 (96)	74 (152)
5	CO			147 (186)	217 (282)
6	CS ₂			156 (192)	235 (302)
7	H ₂			75 (93)	100 (127)
8	C ₂ H ₂			106 (128)	145 (178)
9	C ₂ H ₄			95 (119)	128 (165)
10	H ₂ S	NF ₃ (F ₂)	D ₂	92 (126)	126 (174)
11	CO			98 (127)	128 (168)
12	CS ₂			109 (137)	144 (188)

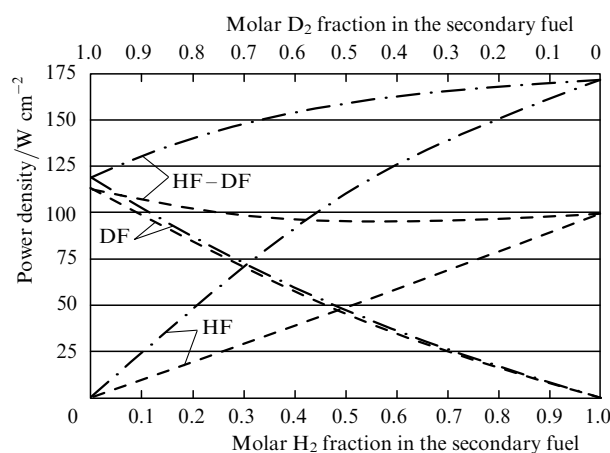
Table 5. Energy parameters for lasing in HF and DF molecules in two spectral ranges with the use of two independent HF and DF AMG modules. The total active medium length is 100 cm.

Variant	Oxidiser	Primary fuel	Secondary fuel	Reduced power of each module/W cm ⁻²		Average reduced power of each module/W cm ⁻²	Total specific energy output/J g ⁻¹
				2.64–3.0 μm	3.7–4.05 μm		
1	NF ₃ (F ₂)	D ₂	H ₂	32 (42)	46 (62)	43 (57)	62 (83)
			H ₂	D ₂	54 (72)		
2	NF ₃ (F ₂)	C ₂ H ₂	H ₂	64 (103)	92 (150)	81 (110)	118 (163)
			H ₂	D ₂	98 (117)		
3	NF ₃ (F ₂)	C ₂ H ₄	H ₂	34 (61)	49 (90)	61 (85)	88 (126)
			H ₂	D ₂	88 (109)		
4	NF ₃ (F ₂)	CO	H ₂	147 (186)	204 (270)	123 (157)	173 (225)
			H ₂	D ₂	98 (127)		
5	NF ₃ (F ₂)	CS ₂	H ₂	156 (192)	224 (280)	133 (165)	190 (245)
			H ₂	D ₂	109 (137)		

D₂ mixture is supplied as the secondary fuel to both modules (Table 6). For comparison with the results presented in Table 5, acetylene is used as the primary fuel in Table 6 because it has the best energy characteristics among all hydrogen-containing primary fuels. One can see that in this case the specific energy parameters increase by 15%–25%. This can be explained by the fact that when the H₂–D₂ mixture is used as the secondary fuel, the amplification of radiation is observed over the entire length of the active medium rather than over its half, as in the case of the scheme with two independent AMGs (Fig. 2a). For example, the product of the gain and the active medium length for the HF molecule in the case of using the H₂–D₂ mixture in the double AMG is larger by 40% than in the scheme with two independent AMGs. Thus, to obtain efficient lasing simultaneously in HF and DF molecules, it is preferable to use the H₂–D₂ mixture as the secondary fuel.

The results presented in Table 6 suggest that the replacement of the primary fuel CS₂ by C₂H₂, when F₂ is used as an oxidiser, reduces the energy characteristics by ~30%, and when NF₃ is used – the reduction is even more considerable (by ~40%).

By using the H₂–D₂ mixture as the secondary fuel, it is possible to change the ratio of output powers in emission ranges of HF and DF molecules by varying the ratio [H₂]/[D₂] (Fig. 3). In this case, the total output power for the C₂H₂–NF₃–He FC in the combustion chamber somewhat decreases with increasing ratio [H₂]/[D₂], while the lasing power in DF molecules exceeds that in HF molecules due to the presence of unexcited HF molecules in the oxidising gas flow, when C₂H₂ is used as the primary fuel. The approximately equal output powers in both spectral ranges can be obtained in this case for the molar ratio H₂:D₂ ≈ 1:1. When CS₂ is used as the primary fuel (Fig. 3), the total output power, on the contrary, increases with increasing the ratio [H₂]/[D₂], while the lasing power in DF molecules is

**Figure 3.** Dependences of the radiation power density upon lasing in HF and DF molecules on the molar fraction of H₂ and D₂ in the secondary fuel in the scheme with a double AMG module (Fig. 2b) for the C₂H₂–NF₃–He (dashed curves) and CS₂–NF₃–He (dot-and-dash curves) FCs. The active medium length is 100 cm.

lower than in HF molecules due to the absence of unexcited HF molecules.

6. Conclusions

(i) The replacement of the usual FC based on H₂ or D₂ by the C₂H₂-based FC reduces by 4–5 times the concentration of strongly absorbing products flowing out of the combustion chamber, which can provide the efficient simultaneous lasing in two spectral ranges in HF and DF molecules, especially by using the H₂–D₂ mixture as the secondary fuel. In this case, the specific energy parameters are as good as the lasing parameters for the usual FC in one spectral range.

Table 6. Energy parameters for lasing in HF and DF molecules in two spectral ranges with the use of a double HF/DF AMG module and the secondary H₂–D₂ fuel. The total active medium length is 100 cm.

Variant	Primary fuel	Oxidiser	Secondary fuel	Reduced power/W cm ⁻²		Specific energy output/J g ⁻¹	
				2.64–3.0 μm	3.7–4.05 μm	2.64–3.0 μm	3.7–4.05 μm
1	C ₂ H ₂ (C ₂ H ₂)	NF ₃ (F ₂)	H ₂ :D ₂ = 1:1	49	46	70	65
				(77)	(57)	(111)	(83)
2	CS ₂ (CS ₂)	NF ₃ (F ₂)	H ₂ :D ₂ = 1:1	112	48	154	66
				(140)	(57)	(200)	(82)

(ii) The higher calculated energy parameters were obtained for the two-range HF–DF CCL by using CO and CS₂ as the primary fuel in the combustion chamber, which is caused by the complete absence of absorbing HF or DF molecules in the oxidising gas flowing from the combustion chamber.

(iii) If F₂ is used as an oxidiser in the two-range HF-DF CCL (the secondary fuel is the H₂–D₂ mixture), the replacement of the primary CS₂ fuel by C₂H₂ reduces energy characteristics by ~30%; in the case of the NF₃ oxidiser, the reduction is even more considerable (by ~40%).

(iv) By using the H₂–D₂ mixture as the secondary fuel, it is possible to change in a broad range the ratio of output powers in the emission ranges of HF and DF molecules in one laser setup by varying the [H₂]/[D₂] ratio.

(v) It has been shown that the high reflectances (more than 99%) can be obtained in principle simultaneously in two well-separated emission ranges of HF and DF molecules by using multilayer dielectric coatings based, for example, on the ThF₄–ZnSe and ThF₄–CdTe pairs (with the upper protective ThF₄ layer) deposited on a silicon or a silver-coated metal substrate.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 06-08-01335-a).

References

- Bashkin A.S., Igoshin V.I., Oraevskii A.N., Shcheglov V.A. *Khimicheskie lazery* (Chemical Lasers) (Moscow: Nauka, 1980).
- Stepanov A.A., Shikanov V.L., Shcheglov V.A. *Kvantovaya Elektron.*, **8**, 765 (1981) [*Sov. J. Quantum Electron.*, **11**, 462 (1981)].
- Aleksandrov B.P., Stepanov A.A., in *Trudy NPO Energomash* (Proceedings of the Energomash Research and Production Association) (Moscow, 2001) Vol. 19, pp 318–334.
- Martyshchenko V.V., Stepanov A.A., in *Trudy NPO Energomash* (Proceedings of the Energomash Research and Production Association) (Moscow, 2001) Vol. 24, pp 315–328.
- Gebhardt F.G. *Appl. Opt.*, **15** (6), 1479 (1976).
- Bashkin A.S., Beznodnev V.N., in *Trudy NPO Energomash* (Proceedings of the Energomash Research and Production Association) (Moscow, 2001) Vol. 20, pp 300–311.
- Watkins W.R., White K.O. *Appl. Opt.*, **15** (5), 1114 (1976).
- King S.R. *Appl. Opt.*, **15** (5), 1116 (1976).
- Zuev V.E. *Rasprostranenie vidimyykh i IK voln v atmosfere* (Propagation of visible and IR wave in the atmosphere) (Moscow: Sov. Radio, 1970).
- Strohbehn J.W. (Ed.) *Laser Beam Propagation in the Atmosphere* (New York: Springer-Verlag, 1978; Moscow: Mir, 1981).
- Toenniben A. et al. *Appl. Opt.*, **18** (6), 297 (1979).
- Krüger G. *Appl. Opt.*, **18** (15), 281 (1979).
- Velikanov S.D., Frolov Yu.N., Sin'kov S.N., et al. *Kvantovaya Elektron.*, **24**, 279 (1997) [*Quantum Electron.*, **27**, 273 (1997)].
- Roback R., Lynds L. *AIAA Paper* 674–1142 (1974).
- Voignier F., Regnier P. *J. Phys.*, **41** (11), C9-45 (1980).
- Fedorov I.A. *Nepřerывnye khimicheskie lazery na rabochikh molekulakh ftoristogo vodoroda i ftoristogo deiteriya. Uchebnoe posobie* (Manual on Continuous-wave HF and DF Lasers) (St. Petersburg: Baltiiskii State Technical University, 1994) Vol. 1.
- Katorgin B.I., Stepanov A.A., Shcheglov V.A. *Osnovy kinetiki, gazodinamiki i optiki neravnovesnykh sred* (Fundamentals of Kinetics, Gas Dynamics and Optics of Nonequilibrium Media) (Moscow: MAI, 2002) Vol. 2.
- Cohen N.J., Bott J.F. *Review of Rate Data for Reactions of Interest in HF and DF Lasers TR-0083(3603)-2* (El Segundo, Cal., USA, The Aerospace Corporation, 1982).
- Aleksandrov B.P., Stepanov A.A., in *Trudy NPO Energomash* (Proceedings of the Energomash Research and Production Association) (Moscow, 2001) Vol. 23, pp 332–351.
- Born M., Wolf E. *Principles of Optics* (Oxford: Pergamon Press, 1969; Moscow: Nauka, 1970).
- Gross R.W., Bott J.F. (Eds) *Handbook of Chemical Lasers* (New York: Wiley, 1976; Moscow: Mir, 1980).
- Wilson L.E. *J. Phys.*, **41** (11), C9-1 (1980).
- Braunstein M. *Low-Absorption Coating Technology. Final Report AD0917927* (Malibu, Cal., USA, Hughes Research Laboratories, 1974).