

# Numerical simulation of the main characteristics of a high-pressure DF–CO<sub>2</sub> laser for amplification of picosecond laser pulses

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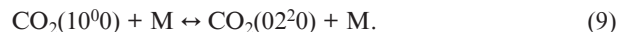
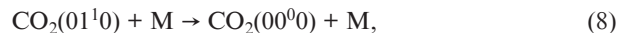
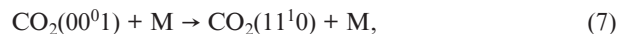
**Abstract.** The gain characteristics of the medium of a pulsed DF–CO<sub>2</sub> laser in the ten-micron region at the working gas pressures from 1 to 2.5 atm, which were experimentally determined in [4], are numerically simulated using a scheme that includes the main chemical and relaxation processes. It is shown that the chosen scheme of processes makes it possible (i) to numerically describe the experimental data on the temporal behaviour of gains; (ii) to explain the reason for early degradation of gains (at the degree of D<sub>2</sub> transformation of about 20%); (iii) from comparison of experimental and calculated temporal gain profiles, to determine the degree of photodissociation of F<sub>2</sub> molecules, which is an important parameter determining the operation of pulsed chemical DF–CO<sub>2</sub> lasers; and (iv) to predict the gain characteristics of working mixtures depending on their composition and pressure and on the initiation parameters. The predicted gains in the mixtures of the optimal composition at a pressure of 2.5 atm, a degree of dissociation of F<sub>2</sub> molecules per flash ~ 1%, and a flash duration at half-width of ~3 μs are ~7 m<sup>-1</sup>.

**Keywords:** DF–CO<sub>2</sub> laser, gain, simulation.

In [1–3], we proposed to use the active medium of chemical DF–CO<sub>2</sub> lasers for amplification of short (~1 ps) ten-micron pulses. An attractive feature of this system is the possibility of obtaining high gains and a high energy stored in the gain transition. In [4], we measured the gains in the active medium of a chemical DF–CO<sub>2</sub> laser on the P(20) line of the ten-micron band of the CO<sub>2</sub> molecule. The initial pressure of mixtures was 1, 1.5, 2, and 2.5 atm; the mixture contained 7%, 10%, or 15% of F<sub>2</sub>; 5% of D<sub>2</sub>; 35% of CO<sub>2</sub>; and 53%, 50%, or 45% of He. Fluorine contained 0.83% of oxygen as an impurity. Simultaneously, we measured two more parameters, the delay of the gain peak from the beginning of initiation and the full width at half maximum (FWHM) of the temporal gain profile. In the present work, we numerically simulate the mentioned characteristics of the system, compare them with experiment, and consider the possibility of optimising the system. In contrast to a large number of calculations concerning the energy parameters of DF–CO<sub>2</sub> lasers, we paid the main

attention to the gain characteristics of their active media at pressures exceeding 1 atm.

Based on the analysis of the literature data and the numerical simulation results (see below), we have chosen the following scheme of chemical and relaxation processes occurring in the active medium of the DF–CO<sub>2</sub> laser:



It can be shown that, under the conditions of work [4], there exist the following balances: between the concentrations of the D and F atoms, between the asymmetric mode of CO<sub>2</sub> molecules and vibrationally excited DF molecules, and between the symmetric and deformation modes of CO<sub>2</sub>. Taking into account these balances, we have

$$\frac{d[F_2]}{dt} = \frac{d[D_2]}{dt} = -0.5 \frac{d[DF]}{dt} = -W, \quad (10)$$

$$\frac{d[O_2]}{dt} = -k_4[D][O_2][M], \quad (11)$$

$$\frac{d[D]}{dt} = \frac{[2\alpha\beta[F_2]f(t) - k_4[D][O_2][M] + k_3^2[D]^2[F_2](1 - [F_2]/[D_2])/k_2[D_2]]}{(1 + k_3[F_2]/k_2[D_2])}, \quad (12)$$

$$\frac{d\varepsilon_2}{dt} = \frac{1.5W_{VV} - W_{VT}}{[CO_2][1 + 2(\varepsilon_1/\varepsilon_2)^2(1 + 1/\varepsilon_2)\exp(76/T)]}, \quad (13)$$

$$\frac{d\varepsilon_3}{dt} = \frac{(\varepsilon_0 - \varepsilon)W - k_5[DF]^2(\varepsilon - \varepsilon^0) - W_{VV}}{[CO_2] + (\varepsilon/\varepsilon_3)^2[DF]\exp(802/T)}, \quad (14)$$

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$$T = 300 + (Q[\text{DF}] - q\varepsilon[\text{DF}] - (q_1\varepsilon_1 + 2q_2(\varepsilon_2 - 0.0425) + q_3\varepsilon_3)[\text{CO}_2])/c. \quad (15)$$

These equations should be supplemented by the equilibrium equations

$$\varepsilon = [(1 + 1/\varepsilon_3)\exp(802/T) - 1]^{-1}, \quad (16)$$

$$\varepsilon_1 = [(1 + \varepsilon_2)^2\exp(76/T) - 1]^{-1}, \quad (17)$$

$$\varepsilon^0 = [\exp(4182/T) - 1]^{-1}. \quad (18)$$

Here,  $f(t)$  determines the shape of the initiating pulse;  $\alpha$  is the degree of dissociation of F<sub>2</sub> molecules per pulse;  $\beta$  is the correction factor (see below);  $\varepsilon$ ,  $\varepsilon_1$ , and  $\varepsilon_3$  are the current average numbers of vibrational quanta in the DF molecules and in the symmetric and asymmetric modes of CO<sub>2</sub> molecules, respectively;  $\varepsilon_2$  is taken to be equal to half the current average number of vibrational quanta in the deformation mode of CO<sub>2</sub> molecules (introduced for convenience of writing equations);  $\varepsilon^0$  is the equilibrium average number of vibrational quanta in DF molecules at the instant  $t$ ;  $\varepsilon_0 = 4.6$  is the initial average number of vibrational quanta in DF molecules formed in reactions (2) and (3);  $Q = 64.2$  kcal mol<sup>-1</sup> is the thermal effect of the reaction of fluorine with deuterium calculated per DF molecule;  $q = 8.31$ ,  $q_1 = 3.97$ ,  $q_2 = 1.91$ , and  $q_3 = 6.72$  kcal mol<sup>-1</sup> are the energies of vibrational quanta in DF molecules and in the symmetric, deformation, and asymmetric modes of CO<sub>2</sub> molecules, respectively;  $c$  is the heat capacity of the mixture; [...] are the concentrations of particles in cm<sup>-3</sup>;  $W = k_3[\text{D}][\text{F}_2]$ ;  $W_{\text{VV}} = k_7[\text{CO}_2][\text{M}][1 + \varepsilon_1(1 + \varepsilon_2)\varepsilon_3 - \varepsilon_1\varepsilon_2(1 + \varepsilon_3)\exp(-392/T)]$ ; and  $W_{\text{VT}} = k_8[\text{CO}_2][\text{M}]\varepsilon_2[1 - (1 + 1/\varepsilon_2)\exp(-960/T)]$ .

The rate constants of the V–V' and V–T energy transfer processes are related to the vibrational relaxation times  $\tau$  by the formulas  $k_7[\text{M}] = (p\tau_{\text{VV}}^{\text{M}})^{-1}$ ,  $k_8[\text{M}] = (p\tau_{\text{VT}}^{\text{M}})^{-1}$ . The equations contain the following numerical parameters (in kelvins): 76 is the resonance defect of exchange process (9), 802 is the resonance defect of exchange process (6), 392 is the energy defect of process (7), 960 is the energy defect of process (8), 4182 is the energy of the DF molecule vibrational quantum, and 0.0425 is  $\varepsilon_2$  at the initial (room) temperature. In calculations, we used the following data:

$$k_2 = 2.66 \times 10^{-10} \exp(-1970/RT) \text{ cm}^3 \text{ s}^{-1} [5];$$

$$k_3 = 1.13 \times 10^{-10} \exp(-2460/RT) \text{ cm}^3 \text{ s}^{-1} [5];$$

$$k_4(300 \text{ K}) = 1.7 \times 10^{-32} \text{ cm}^6 \text{ s}^{-1} (\text{M} = \text{He}), 15.9 \times 10^{-32} \text{ cm}^6 \text{ s}^{-1} (\text{M} = \text{CO}_2), 7.1 \times 10^{-32} \text{ cm}^6 \text{ s}^{-1} (\text{M} = \text{D}_2), 31.1 \times 10^{-32} \text{ cm}^6 \text{ s}^{-1} (\text{M} = \text{F}_2) [6] [\text{we used the relation } k_4(T) = k_4(300 \text{ K})300/T];$$

$$k_5 = 2 \times 10^{-10}/T + 2.326 \times 10^{-22} T^{2.96} \text{ cm}^3 \text{ s}^{-1} [5];$$

$$(p\tau_{\text{VV}}^{\text{He}})^{-1} = \exp(15.995 - 236.107T^{-1/3} + 736.685T^{-2/3});$$

$$(p\tau_{\text{VV}}^{\text{CO}_2})^{-1} = \exp(25.409 - 351.419T^{-1/3} + 1151.264T^{-2/3});$$

$$(p\tau_{\text{VV}}^{\text{D}_2})^{-1} = \exp(-0.55 - 5.253T^{-1/3});$$

$$(p\tau_{\text{VV}}^{\text{DF}})^{-1} = (0.182 - 390.967T^{-1.47})^{-1};$$

$$(p\tau_{\text{VT}}^{\text{He}})^{-1} = \exp(-0.947 + 59.465T^{-1/3} - 307.632T^{-2/3});$$

$$(p\tau_{\text{VT}}^{\text{CO}_2})^{-1} = \exp(8.461 - 109.177T^{-1/3} + 267.152T^{-2/3});$$

$$p\tau_{\text{VT}}^{\text{D}_2} = 0.072,$$

where  $p\tau$  are given in  $\mu\text{s atm}$ . The temperature dependences of  $(p\tau_{\text{VV}}^{\text{M}})^{-1}$  and  $(p\tau_{\text{VT}}^{\text{M}})^{-1}$  in the range 300–650 K were determined by us by averaging available data from the literature.

The initiating pulse used in experiments of [4] is given in the form  $f(t) = 0.51t^4\exp(-1.65t)$ , where  $t$  is measured in  $\mu\text{s}$ , and the pulse duration at half maximum is 2.88  $\mu\text{s}$ .

Due to the absorption of initiating light by molecular fluorine, initiation in large-aperture DF–CO<sub>2</sub> amplifiers is inhomogeneous over the reactor cross section. This circumstance was taken into account in calculations. Table 1 presents the calculated correction factors  $\beta$ , which take into account the dependence of the degree of dissociation of F<sub>2</sub> molecules in the measurement region [4] on the concentration of F<sub>2</sub> molecules in the mixture and on the mixture pressure.

**Table 1.** Dependence of the coefficient  $\beta$  on the F<sub>2</sub> concentration and the mixture pressure.

Concentration of F <sub>2</sub> in the mixture	Coefficient $\beta$			
	Mixture pressure/atm			
	1	1.5	2	2.5
7	1	0.955	0.913	0.871
10	0.962	0.902	0.845	0.799
15	0.902	0.822	0.754	0.693

By solving the system of Eqns (10)–(18), we found the dependences  $\varepsilon_1(t)$ ,  $\varepsilon_2(t)$ ,  $\varepsilon_3(t)$ , and  $T(t)$  and used them to determine the temporal profile of the gain at the P(20) line of the ten-micron CO<sub>2</sub> emission upon probing the active medium of a DF–CO<sub>2</sub> laser. Of course, the main contribution to the gain is made by the P(20) transition of the 00<sup>0</sup>1–10<sup>0</sup> band. The population inversion of the levels responsible for this transition is  $\Delta N(t) = N_u(t) - (g_u/g_{\text{low}})N_{\text{low}}(t)$ , where  $N_u(t) = n_{001}(t)r_{j=19}(t)[\text{CO}_2]$  and  $N_{\text{low}}(t) = n_{100}(t)r_{j=20}(t)[\text{CO}_2]$  are the time-dependent populations of the upper (00<sup>0</sup>1,  $j = 19$ ) and lower (10<sup>0</sup>,  $j = 20$ ) states;  $g_u$  and  $g_{\text{low}}$  are the statistical weights of these states;  $n_{001}(t) = \varepsilon_3(t)/[(1 + \varepsilon_1(t))(1 + \varepsilon_2(t))^2(1 + \varepsilon_3(t))^2]$  and  $n_{100}(t) = \varepsilon_1(t)/[(1 + \varepsilon_1(t))^2(1 + \varepsilon_2(t))^2(1 + \varepsilon_3(t))]$  are the populations of the 00<sup>0</sup>1, 10<sup>0</sup> vibrational states;  $r_{j=19}(t)$ ,  $r_{j=20}(t)$  are the populations of rotational states with  $j = 19$  and 20; and  $r_j = (2j + 1)(300/TQ_r)\exp(-Bhcj(j + 1)/kT)$ . The rotational constant is  $B = 0.387$  cm<sup>-1</sup>, and the rotational statistical sum is  $Q_r = 267$  at 300 K. The gain in the line centre is  $\sigma(v_0) \times \Delta N(t)$ , where  $\sigma(v_0) = \{8\pi^2 v_0 d^2 / [3hc(\Delta v)_{1/2}]\} \{ (j + 1) / (2j + 1) \}$  is the stimulated emission cross section;  $v_0$  is the transition frequency (cm<sup>-1</sup>);  $(\Delta v)_{1/2}$  is the half-width at half maximum (HWHM) of the transition line;  $d = 3.83 \times 10^{-20}$  CGSE units is the transition dipole moment [7]; and  $j = 19$  is the number of the rotational level of the upper state of the transition.

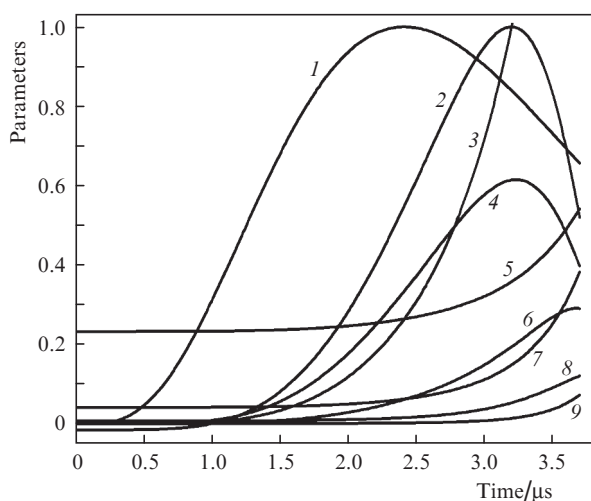
The HWHM of the spectral line was calculated by the formula  $(\Delta v)_{1/2} = \gamma p(300/T)^m$ , where  $p$  is the gas pressure (atm) and  $\gamma$  is the HWHM of the line at a pressure of 1 atm and a temperature of 300 K (cm<sup>-1 atm<sup>-1</sup></sup>). It is usually assumed that  $m = 0.75$  (see, for example, [8]). Then,  $(\Delta v)_{1/2} \sim (T/300)^{0.25}$ , because  $p \sim T/300$ . In calculations, we assumed that  $\gamma = 0.01$  cm<sup>-1 atm<sup>-1</sup></sup> for collisions between CO<sub>2</sub> molecules [7] and 0.07 cm<sup>-1</sup> for collisions of CO<sub>2</sub> with the other molecules.

Under some conditions (high vibrational excitation of CO<sub>2</sub> molecules, high pressures), some contribution to amplification is made by the lines lying near the P(20) line. In the

calculations, we took into account the contribution of the P(17) and P(19) lines of the  $00^02-10^01$  band with frequencies 944.57 and 942.81  $\text{cm}^{-1}$  and the R(21), R(22), R(23), R(24), and R(25) lines of the  $01^11-11^10$  band with frequencies 942.9, 943.41, 944.2, 944.67, and 945.47  $\text{cm}^{-1}$ , respectively. The calculations show that, under the experimental conditions of [4], the contribution of ‘hot’ bands to the gain can reach 20%.

From the temporal profile of the gain, we found the profile peak delay  $t_{\text{del}}$  from the beginning of initiation, the profile FWHM  $t_{1/2}$ , and the gain  $K$  in the profile peak.

Figure 1 presents the calculated time dependences of various characteristics of the active mixture of the composition  $\text{F}_2$  (10%) +  $\text{D}_2$  (5%) +  $\text{O}_2$  (0.083%) +  $\text{CO}_2$  (35%) + He (49.9%) at a pressure of 2.5 atm. This figure also shows the intensity profile of the initiating pulse.



**Figure 1.** Time dependences of (1) initiating pulse intensity, (2) gain, (3) relative concentration of DF molecules (normalised to the DF concentration at the instant of the maximum gain), (4) relative population of the state  $(00^01, j = 19)$  (multiplied by a factor of 100), (5) medium temperature, (6) average number of vibrational quanta  $\varepsilon_3$  in the asymmetric mode, (7) half the average number of vibrational quanta  $\varepsilon_2$  in the deformation mode, (8) relative population of the state  $(10^00, j = 20)$  (multiplied by a factor of 100), and (9) average number of vibrational quanta  $\varepsilon_1$  in the symmetric mode. The mixture composition at a pressure of 2.5 atm is  $\text{F}_2$  (10%) +  $\text{D}_2$  (5%) +  $\text{O}_2$  (0.083%) +  $\text{CO}_2$  (35%) + He (49.9%);  $\alpha = 0.75\%$ . Curves (1, 2, 5) are normalised to the maximum values. Parameters:  $t_{\text{del}} = 3.2 \mu\text{s}$ ,  $t_{1/2} = 1.37 \mu\text{s}$ ,  $K = 6.18 \text{ m}^{-1}$ ; the temperature and the degree of  $\text{D}_2$  transformation in the gain profile peak are 460.5 K and 0.215, respectively. The fraction of the flash energy released to the moment corresponding to the gain peak is 60%.

The gain profile [curve (2)] is formed by several processes changing the populations of the upper and lower levels of the transitions involved in amplification. On the rising part of the profile, the dominant role is played by the increase in the population of the upper levels due to an increase in the average number of vibrational quanta  $\varepsilon_3$  in the asymmetric mode of the  $\text{CO}_2$  molecule [curve (6)] due to accelerating formation of DF molecules [curve (3)] in reaction (3). On the descending part of the profile, the main role belongs to the processes decreasing the population of the upper levels and increasing the population of the lower levels of transitions.

For illustration, Fig. 1 also presents the time behaviour of the population of the upper  $(00^01, j = 19)$  [curve (4)] and lower  $(10^00, j = 20)$  [curve (8)] levels of the P(20) transition of the  $00^01-10^00$  band, which makes the main contribution to the

gain of the active medium. The population of the upper levels decreases due to two reasons – heating of the medium and VV' relaxation. Upon formation of the DF molecule, 40% of the reaction energy is immediately spent on the translational degrees of freedom. The resonance defect in the fast energy transfer (6) from the vibrationally excited DF molecule to the  $\text{CO}_2$  molecule increases this fraction of energy to 52%. The vibrational relaxation of  $\text{CO}_2$  molecules also contributes to heating of the medium. Due to the fast VT-relaxation process (8) with  $\text{M} = \text{He}$ , the distribution of population over the vibrational modes of the deformation mode is close to equilibrium and is determined by the translational temperature. With increasing temperature,  $\varepsilon_2$  increases and the population of all the states with the zero vibrational level of the deformation mode decreases as  $1/(1 + \varepsilon_2)^2$ . As  $\varepsilon_2$  increases, the population of the level  $(00^01, j = 19)$  [curve (4)] also decreases, which finally causes a decrease in the gain [recall that the  $(00^01, j = 19) - (10^00, j = 20)$  transition makes the main contribution to the gain of the active medium]. An additional decrease in the gain occurs due to the VV' relaxation, which decreases the population of the upper levels of the transitions participating in amplification, and due to an increase in the population of the level  $(10^00, j = 20)$  [curve (8)] resulted from an increase in the average number of vibrational quanta  $\varepsilon_1$  in the symmetric mode [curve (9)].

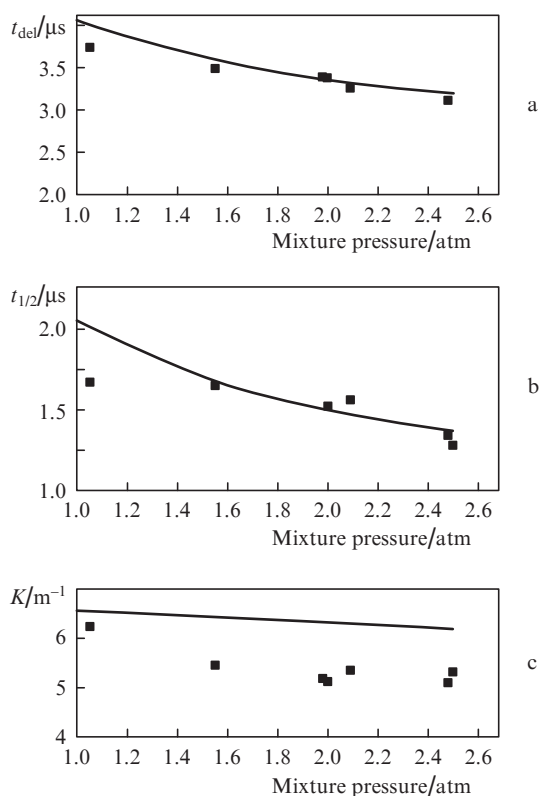
From Fig. 1 one can see that the population of the level  $(00^01, j = 19)$  [curve (4)] begins to considerably decrease when the average number of vibrational quanta  $\varepsilon_3$  in the asymmetric mode of  $\text{CO}_2$  molecules still continues to increase [curve (6)]. At the same time, the population of the lower level  $(10^00, j = 20)$  [curve (8)] increases not so strongly. All this indicates that the main role in the decrease in the gain under the conditions of calculations is played by the decrease in the population of the level  $(00^01, j = 19)$  due to increasing temperature of the medium. This is also evidenced by the fact that the maxima of curves (2) and (4) are reached almost simultaneously.

The calculations showed that the delays of the gain peaks from the beginning of initiation  $t_{\text{del}}$  and the FWHMs of the gain profiles  $t_{1/2}$  only slightly depend on the VV'-relaxation rate when it changes within reasonable limits. For example, for the mixture  $\text{F}_2$  (10%) +  $\text{D}_2$  (5%) +  $\text{O}_2$  (0.083%) +  $\text{CO}_2$  (35%) + He (49.9%) at a pressure of 2.5 atm, the formal increase in the total rate of VV' processes by two times (note that the processes disregarded in the considered scheme can hardly cause a stronger increase in the total VV'-relaxation rate) leads to a decrease in  $t_{\text{del}}$  by 6.5%, 5%, and 3.4% at the degree of dissociation of  $\text{F}_2$  molecules of 0.375%, 0.75%, and 1.5%, respectively. In this case, the parameter  $t_{1/2}$  decreases by 8.5%, 7.3%, and 6%, respectively. Simultaneously with this increase in the relaxation rate, the gain for all the mentioned dissociation degrees decreases by  $1.67 \text{ m}^{-1}$ , i.e., the gain of the active medium 1 m long decreases approximately fivefold.

We can conclude that the parameters  $t_{\text{del}}$  and  $t_{1/2}$  depend only on the experimental conditions, i.e., on the composition and pressure of mixtures and on the degree of dissociation of  $\text{F}_2$  molecules. Therefore, comparing the calculated values of these parameters with experimental data, one can find the value  $\alpha$ . If the scheme of VV' processes is chosen correctly, then the calculated gains corresponding to the found  $\alpha$  must not strongly differ from experimental values.

Satisfactory agreement between the calculated and experimental [4] values of the parameters  $t_{\text{del}}$  and  $t_{1/2}$  was achieved at  $\alpha = 0.75\%$ . As an example, Figs 2a, 2b show the calculated

and experimental parameters  $t_{\text{del}}$  and  $t_{1/2}$  for the mixture F<sub>2</sub> (10%) + D<sub>2</sub> (5%) + O<sub>2</sub> (0.083%) + CO<sub>2</sub> (35%) + He (49.9%) in the pressure range from 1 to 2.5 atm, while Fig. 2c shows the experimental and calculated gains for the same mixture at  $\alpha = 0.75\%$ . One can see that calculated gains are slightly higher than the experimental values, but the maximal difference between them does not exceed 20%. It seems that, in general, the calculated data satisfactorily agree with experimental parameters. This indicates that the scheme of processes (1)–(9) and the corresponding system of equations (10)–(18) adequately describe pumping of CO<sub>2</sub> molecules in a chemical DF–CO<sub>2</sub> laser and, hence, the system (10)–(18) can be used to optimise the gain characteristics depending on the composition of working mixtures and on the initiation parameters.



**Figure 2.** (a) Delay of the gain peak from the beginning of initiation, (b) FWHM of the gain profile, and (c) gain in the profile peak vs. the pressure of the mixture F<sub>2</sub> (10%) + D<sub>2</sub> (5%) + O<sub>2</sub> (0.083%) + CO<sub>2</sub> (35%) + He (49.9%) at the flash duration at half maximum of 2.88  $\mu\text{s}$  and  $\alpha = 0.75\%$ . The points and solid curves correspond to the experimental data of [4] and calculations, respectively.

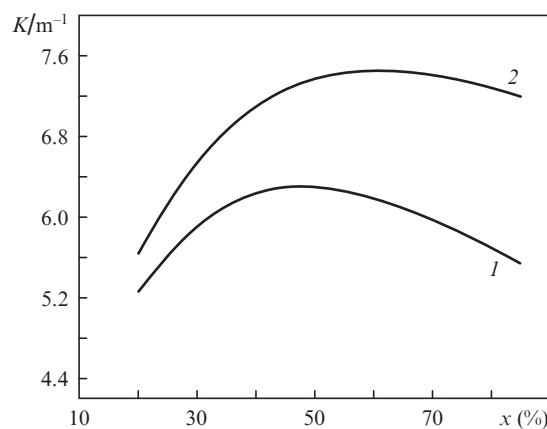
Note that the choice of the mixture composition depends on some purely practical considerations. The use of the active medium of the DF–CO<sub>2</sub> laser for amplifying short pulses is most efficient beginning for initial pressures of 2–2.5 atm [3]. For large-aperture amplifiers operating at such pressures, the fraction of F<sub>2</sub> can hardly be higher than 10% due to the appearance of a strong initiation inhomogeneity over the reactor cross section.

The final temperature of the reaction products and, hence, the pressure in the reactor after the explosive transformation increase proportionally to an increase in the D<sub>2</sub> concentration. Therefore, the strength of reactors and their windows becomes a topical problem. At the same time, the gain in the

case of D<sub>2</sub> fraction exceeding 5% increases not very strongly. From the practical viewpoint, the five-percent concentration of deuterium in the mixture is sufficiently high.

According to calculations, to obtain the maximum possible gains, one should decrease the concentration of oxygen in the mixture. It is known that the reaction of fluorine with deuterium occurs according to the energy branching mechanism:  $\text{DF}(v) + \text{D}_2(v') \rightarrow \text{DF}(v-1) + \text{D}_2(v'+1)$ ,  $\text{D}_2(v) + \text{F}_2 \rightarrow \text{D} + \text{F} + \text{DF}$ . The O<sub>2</sub> molecules decrease the chain length due to the trimolecular termination [4] and, at a sufficiently high concentration of O<sub>2</sub>, the mixtures become stable. With addition of CO<sub>2</sub> molecules in the mixture, branching can be completely suppressed because the vibrational energy of DF molecules is transferred to CO<sub>2</sub> molecules and lost due to the VT relaxation. In this case, even a small amount of oxygen is enough to stabilise the prepared mixtures. Our experiments showed that, at the O<sub>2</sub> concentration of 0.083%, the mixtures are stable in the entire studied range of pressures. At the same time, the calculations revealed that further decrease in the oxygen concentration does not substantially increase the gain of the medium.

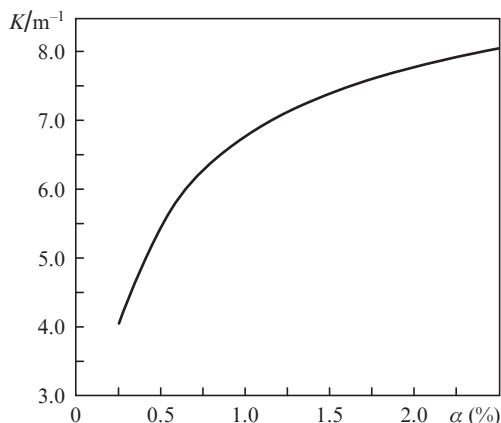
As follows from calculations, for each degree of dissociation of F<sub>2</sub> molecules  $\alpha$ , there exists an optimal concentration of CO<sub>2</sub> in the mixture. With increasing  $\alpha$ , the optimal concentration of CO<sub>2</sub> increases. Figure 3 shows the dependences of  $K$  on the fraction of CO<sub>2</sub> in the mixture at  $\alpha = 0.75\%$  and 1.5%. The optimal concentrations of CO<sub>2</sub> at these  $\alpha$  are 50% and 60%, respectively.



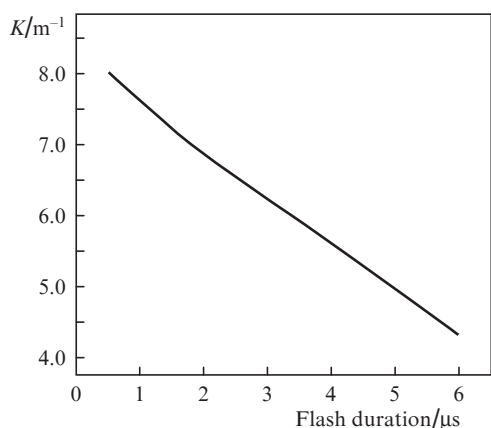
**Figure 3.** Dependences of the gain on the fraction of CO<sub>2</sub> in the mixture F<sub>2</sub> (10%) + D<sub>2</sub> (5%) + O<sub>2</sub> (0.083%) + CO<sub>2</sub> ( $x\%$ ) + He [(84.9 –  $x\%$ )] at a pressure of 2.5 atm and a flash duration at half maximum of 2.88  $\mu\text{s}$  for  $\alpha = 0.75\%$  (1) and 1.5% (2).

Figures 4 and 5 show the dependences of the gains on the degree of dissociation of F<sub>2</sub> molecules and on the flash duration. As is seen, a decrease in the flash duration strongly increases the gain. From the data in Figs 3–5 one can conclude that the gains of the active medium of a DF–CO<sub>2</sub> laser with the optimal composition and the initial pressure of 2.5 atm at realistic initiation parameters (degree of dissociation of F<sub>2</sub> molecules  $\sim 1\%$ , flash duration at half maximum  $\sim 3 \mu\text{s}$ ) can reach  $\sim 7 \text{ m}^{-1}$  for ten-micron radiation. Under these conditions, the energy stored in the gain band for a picosecond pulse reaches  $\sim 50 \text{ J L}^{-1}$ .

Thus, we can conclude that the simplified scheme of chemical and relaxation processes (2)–(9) adequately



**Figure 4.** Dependence of the gain on the degree of dissociation of  $F_2$  molecules for the mixture  $F_2$  (10%) +  $D_2$  (5%) +  $O_2$  (0.083%) +  $CO_2$  (50%) + He (34.9%) at a pressure of 2.5 atm and a flash duration at half maximum of 2.88  $\mu s$ .



**Figure 5.** Dependence of the gain on the flash duration for the mixture  $F_2$  (10%) +  $D_2$  (5%) +  $O_2$  (0.083%) +  $CO_2$  (50%) + He (34.9%) at a pressure of 2.5 atm and  $\alpha = 0.75\%$ .

describes the amplification of ten-micron radiation by the active medium of a chemical DF– $CO_2$  laser. Comparison of the experimental and calculated delays of the gain peak from the beginning of initiation, as well as of experimental and calculated FWHMs of the gain profile, makes it possible to determine the degree of dissociation of  $F_2$  molecules, which is an important parameter characterising the operation of chemical DF– $CO_2$  lasers. The expected gains exceed  $7\ m^{-1}$ .

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