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CONTROL OF LASER RADIATION PARAMETERS

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Computational and experimental study of a *Q*-switched cw chemical HF/DF laser

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***Abstract*. The energy and temporal parameters of radiation from a cw chemical medium-size HF/DF laser mechanically *Q*-switched by a mirror rotating at a frequency of up to 1 kHz are calculated and studied experimentally. The peak power of laser pulses in the repetitively pulsed regime exceeds the cw output power of the HF laser at least by a factor of four. The average power in the repetitively pulses regime is lower than that in the cw regime, but it increases (approximately doubles) with increasing modulation frequency. The time of the complete recovery of the gain profile in the active medium is measured to be 6 – 7 μs. Two numerical models are developed which describe the dynamics of *Q*-switched HF and DF lasers. Some specific features of the operation of these lasers are analysed with the help of these models.**

Keywords: *chemical laser, cavity Q-switching, repetitively pulsed lasing, pulse peak power*.

1. Introduction

Continuously pumped lasers operating in the repetitively pulsed regime (RPR) due to cavity *Q*-switching can produce output peak powers exceeding the cw output power by an order of magnitude, retaining at the same time the average power (or only slightly reducing it) [1].

The repetitively pulsed regime, providing high pulse peak powers, offers advantages compared to the cw regime both in technological processes (laser isotope separation, cutting of materials, ablation) and from the point of view of increasing the efficiency of nonlinear processes (frequency conversion, phase conjugation). In recent years the idea of using light-detonation waves to produce the jet thrust attracts the attention of researchers [2 – 4]. It is assumed that this can be realised by employing high-power lasers emitting short pulses of duration less than 100 ns at high pulse repetition rates. In particular, a gas-dynamic CO_2 laser was proposed for this purpose in [4, 5]. The repetitively pulsed regime was realised in a 10-kW CO_2 laser by the method of self-injection of modulated radiation to an unstable resonator [5]. The authors of paper [6] obtained the RPR in an electric-discharge CO_2 laser by using both an electrooptical modulator and a mechanical shutter. The laser emitted 200 – 300-ns pulses at a pulse repetition rate of 10 – 40 kHz. In [7], it was shown theoretically that the peak output power of an e-beam sustained CO laser emitting pulses at a pulse repetition rate of 50 kHz can be increased more than by three orders of magnitude by preserving its average power (up to 96 %). In [8], the operation of a cw oxygen – iodine laser in the RPR was achieved by using the Zeeman effect. For the repetition rate of magnetic-field pulses of $\sim$2 kHz, the excess of the peak power P_{peak} over the average power P_{av} was $k = P_{peak}/P_{av} = 16$.

The parameters of a supersonic repetitively pulsed HF laser were calculated in [9]. It was predicted that under certain conditions for pulse repetition rates of 150 – 200 kHz, the coefficient k can achieve 30, while the average output power decreases by half. Also, experiments with a small 1-kW HF laser were performed [10]. However, the experimental setup used in [10] did not allow the authors to measure the inversion recovery time in the active medium after a giant pulse (this time was set equal to 4 μs in calculations). In addition, a disadvantage of the experiment was that the filling of the cavity by the active medium was 1/26, whereas the filling factor used in calculations was set equal to unity. Another disadvantage was that the RPR scheme with a rotating mirror strictly connected the switch on time of the cavity *Q* factor and the lifetime of the high-*Q* cavity. As a result, it was impossible to compare experimental and calculated results.

To remove partially the drawbacks of experiment [10] and to understand in more detail the RPR mechanism with mechanical *Q*-switching, we studied experimentally and theoretically a higher-power 8-kW HF/DF laser (with the active medium of length 400 mm) and measured, in particular, the inversion recovery time in the active medium.

2. Experimental setup

Experimental studies were performed with a bench model of a HF laser with a nozzle – nozzle reagent mixing unit. Figure 1 shows the experimental setup. The laser with nozzle unit (*3*) was placed inside low-pressure chamber (*1*). On the two opposite walls of the chamber, spherical highly reflecting aluminium-coated glass mirror (*2*) (with

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the radius of curvature $R = 10765$ mm and the light diameter 160 mm) and output coupler (*4*) (plane–parallel fluorite plate) were mounted in flanges. Two plane cavity mirrors (*6*) and (*7*) (aluminium-coated glass plates of diameter 40 mm) were located at a distance of $L =$ 3890 mm from highly reflecting cavity mirror (*2*). The optical axis of cavities formed by mirrors (*2*), (*6*), and (*7*) passed at a distance of $x = 12$ mm from the cut of nozzle unit (*3*). Laser radiation was coupled out and directed to measuring channels through output coupler (*4*) inclined at angle 3° with respect to the cavity axis. The length l of the active medium along the optical axis (determined by the nozzle unit size) was 400 mm, and its length along the flow direction was 40 mm.

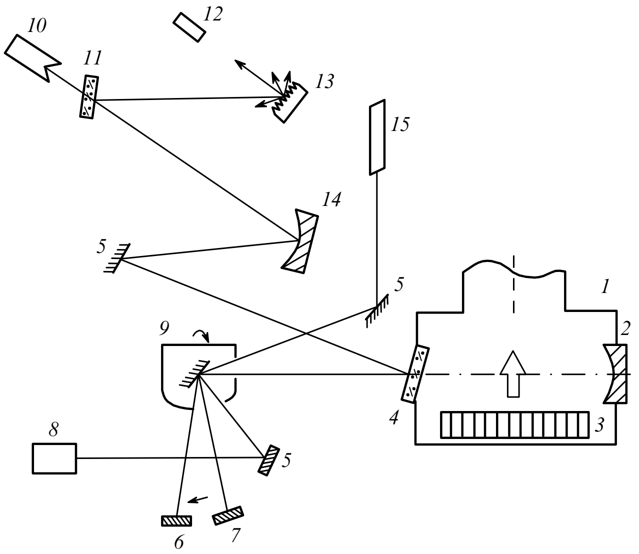

Figure 1. Scheme of the experimental setup: (*1*) low-pressure chamber with an HF laser; (*2*) highly reflecting spherical cavity mirror; (*3*) laser nozzle unit; (*4*) fluorite output coupler; (*5*) plane fold mirrors; (*6*, *7*) plane cavity mirrors; (*8*) photomultiplier; (*9*) rotating mirror Q-switch of a fast photodetector setup; (*10*) calorimeter; (*11*) plane–parallel fluorite beamsplitter; (*12*) photoresistor; (*13*) mat radiation scatterer; (*14*) spherical mirror; (*15*) alignment helium–neon laser.

The laser was Q-switched with the help of rotating mirror (*9*) with the 24×24-mm aperture mounted on the cavity axis between plane mirrors (*6*) and (*7*) and output coupler (*4*). The displacement of the cavity axis from mirror (*6*) to mirror (*7*) caused the generation of a pair of pulses per revolution of mirror (*9*). The time interval between pulses in a pair was determined by the distance (40 mm) between the centres of mirrors (*6*) and (*7*) and by the distance (1720 mm) from these mirrors to the axis of rotating mirror (*9*). The calculated misalignment angle (the angle of rotation of the mirror leading to Q-switching) was $\theta_{\rm calc} = 1.16 \times 10^{-3}$ rad.

The average laser radiation power was measured with a M201 Coherent Radiation calorimeter (*10*) with the time constant 1 s. A part of radiation reflected from plane fluorite plate (*11*) was scattered by mat aluminium plate (*13*). Scattered radiation was detected with gold-doped germanium photodetector (*12*). The output signal of photodetector (*12*) was recorded with a TDS-3052B Tektronix storage oscilloscope (USA). The oscilloscope was triggered by a pulsed signal from a photomultiplier on which a beam from helium–neon laser (*15*) reflected from mirror (*9*) was incident.

The rotation period of the mirror Q-switch was determined by the duration of the time interval between adjacent electric pulses, which were generated by an electromagnetic sensor placed on the drive of the mirror during its each rotation. Pulses from the sensor were recorded in real time with a Type 535 Tektronix electron-beam oscilloscope, to the second channel of which a signal from calorimeter (*10*) was fed.

3. Experimental results

Table 1 presents the results of measurements of the period T and rotation frequency of the mirror Q-switch. Also are presented the average power $\bar{P}_{\rm r}$ of repetitively pulsed radiation depending on T, the duration $t_{\rm r}$ of the leading edge of the pulse, the pulse FWHM $t_{0.5}$, the pulse duration $t_{0.1}$ at the 0.1 level, the peak power $P_{\rm peak}$ for a pair of laser pulses, the interval $\Delta t_{2,1}$ between pulses, the cavity switching time $t_{\rm sw}$, and the rise time t_Q of the cavity Q factor. Figure 2 shows the temporal parameters of pulses obtained after the processing of their oscillograms.

In the quasi-stationary lasing regime (at a small rate of the Q-factor switching), the time dependences of the cavity Q factor and radiation pulse probably coincide, i.e. $t_{0.1} = t_{\rm sw}$. By assuming that these dependences are symmetric in time, we can determine the experimental misalignment angle (mirror rotation) of the cavity $\theta_{\rm exp} = 2\pi f t_{\rm sw}$. The oscillogram in Fig. 2a corresponds to this regime. We found that the misalignment angle $\theta_{\rm exp} = 2.62 \times 10^{-3}$ rad differed from its calculated value $\theta_{\rm calc} = 1.16 \times 10^{-3}$ rad. If the radiation divergence remained constant, the misalignment angle was independent of the rotation frequency of the mirror Q-switch. The oscillogram in Fig. 2a can be used to calibrate the channel for recording laser pulse shapes.

By assuming that the cavity misalignment angle is constant ($\theta_{\rm exp} = 2.62 \times 10^{-3}$ rad), we can estimate the cavity switching time $t_{\rm sw} = T\theta_{\rm exp}/(4\pi)$ and the rise time $t_Q = t_{\rm sw}/2$ of the cavity Q factor. The energy and temporal parameters of the RPR obtained after processing experimental data by the method described in [10] are presented in Table 1.

Table 1. Energy and temporal experimental parameters of a repetitively pulsed HF laser.

T/ms	f/Hz	$\bar{P}_{\rm r}$/W	First pulse				Second pulse				$\Delta t_{2,1}$/μs	$t_{\rm sw}$/ms	t_Q/μs
			$t_{\rm r}$/μs	$t_{0.5}$/μs	$t_{0.1}$/μs	$P_{{\rm peak}_1}$/W	$t_{\rm r}$/μs	$t_{0.5}$/μs	$t_{0.1}$/μs	$P_{{\rm peak}_2}$/W			
45.5	22	0.100	3.30	6.80	9.40	430	3.10	6.60	9.50	380	82	9.5	4.7
8	125	0.121	0.45	0.64	1.43	910	0.43	0.65	1.33	800	15.5	1.7	0.83
4	250	0.198	0.26	0.36	0.71	1700	0.17	0.32	0.65	1780	7.7	0.83	0.42
2	500	0.133	0.18	0.22	0.36	1370	0.087	0.15	0.25	430	4.0	0.42	0.21
1	1000	0.045	0.046	0.09	0.16	640	0.036	0.09	0.15	33	1.94	0.21	0.11

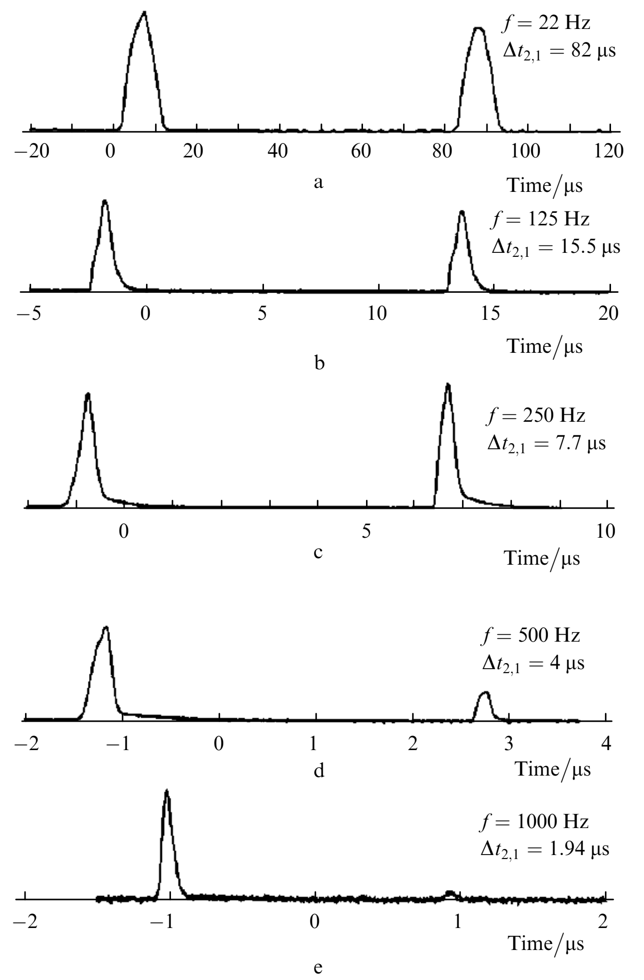

Figure 2. Oscillograms of radiation pulses from a Q-switched HF laser for different rotation frequencies of the mirror Q-switch and different time intervals between two pulses.

The gain recovery time of the active medium was determined by comparing the peak laser radiation powers P_{peak_1} and P_{peak_2} (see Table 1) obtained for the same rotation frequency of the mirror. The variant when P_{peak_1} considerably exceeds P_{peak_2} corresponds to the situation in which the gain of the active medium has not been recovered yet. The inversion recovery time estimated from the interval $\Delta t_{2,1}$ between pulses was 6 – 7 μs.

4. Results of calculations

Calculations were performed by using two models which are not intended for a detailed description of the gas-dynamic, chemical, and radiative processes in the active medium of a Q-switched HF/DF laser because it would require great computational resources. Within the framework of these models, the active medium is assumed homogeneous and its laser parameters change only along the gas flow. In the first model [11], the gain profile is calculated by constructing the equation for the gain containing generalising terms describing pumping and relaxation. By varying these terms, the gain profile is matched with the profile obtained in [12] by using the numerical model of a HF/DF laser in the 'narrow channel' approximation. In the second model, the fitting parameter is the production rate of molecules HF(υ) and DF(υ) in excited vibrational states (where υ is the vibrational quantum number) along the flow direction, which is specified by 'injecting' artificially a certain amount of fluorine atoms into the active medium. Such a procedure allows one to match the time dependence of the production of molecules in excited vibrational states with data obtained in [12]. The criterion for the validity of the model can be its agreement with the experimental data. In this sense, both models correctly predict the excess $k = P_{peak}/P_{av}$ of the peak power of the Q-switched laser over the average cw power of this laser, and, which is even more important, they correctly predict the recovery time of the gain in the active medium.

Figure 3 presents the output power P at the HF/DF($\upsilon = 2$) $\rightarrow$ HF/DF($\upsilon = 1$) transition calculated for different rotation frequencies of the mirror Q-switch used in experiments. Also, the time dependences of the gain g in the active medium at the point $x = 12$ mm on the cavity axis are presented. The energy and power of two successive laser pulses in the Q-switching regime are given in Table 2.

The results of calculations are in good agreement with experimental data. As in the experiment, the energy of the second pulse decreases compared to that of the first pulse when the rotation frequency of the mirror Q-switch increases from 250 to 500 Hz (Figs 2, 3). The maximum

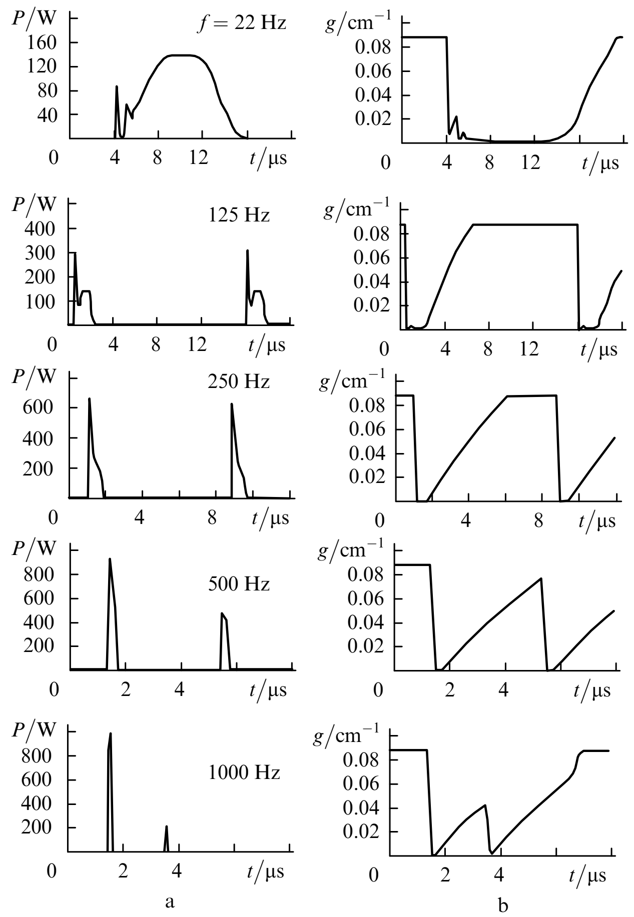

Figure 3. Profiles of laser pulses at the (HF/DF($\upsilon = 2$) $\rightarrow$ HF/DF($\upsilon = 1$) transition for different rotation frequencies of the mirror Q-switch used in experiments (a) and the time dependences of the gain in the active medium at the point $x = 12$ mm located on the cavity axis (b).

Table 2. Calculated energy parameters of two successive laser pulses.

Pulse	Rotation frequency of the mirror Q-switch/Hz	Pulse energy/mJ	Maximum pulse power/W
First	22	1	141
	125	0.23	298
	250	0.24	695
	500	0.22	954
	1000	0.093	993
Second	22	1	141
	125	0.23	297
	250	0.24	689
	500	0.11	480
	1000	0.022	208

output power can be considerably increased in the Q-switching regime. According to calculations, for the rotation frequency of the mirror Q-switch equal to 22 Hz, after relaxation oscillations continuing for ~ 4 μs, output radiation power becomes stationary at the level $P \sim 140$ W. As the rotation frequency is increased up to 250 Hz, the peak power increases by a factor of five (up to the level $P \sim 700$ W) (see Table 2).

The difference in the output powers presented in Tables 1 and 2 is explained by the fact that calculations were performed taking into account only one $v = 2 \to v = 1$ vibrational band, whereas lasing occurs in experiments at two vibrational bands $v = 1 \to v = 0$ and $v = 2 \to v = 1$. According to [13], the power ratio for the $v = 1 \to v = 0$ (P_{1-0}) and $v = 2 \to v = 1$ (P_{2-1}) bands in cavities with similar parameters is $P_{1-0}/P_{2-1} = 0.57/0.43$. Taking this ratio into account, we see that the calculated and experimental output powers prove to be close enough. Note also that in the case of lasing at the $v = 1 \to v = 0$ transition, the $v = 1$ level is rapidly depopulated; taking this process into account, the calculated power in the $v = 2 \to v = 1$ band should increase.

The calculation of the Q-switched DF laser showed that its operation is similar to that of the HF laser. The somewhat lower output pulse energy and its shorter duration are related to the lower gain in the active medium of the DF laser.

An interesting result was obtained by using the first model for calculating the radiation pattern of the Q-switched HF laser. We found that the mirror Q-switch produces a poor spatial structure of the output beam: the angular divergence of laser radiation for the stable cavity used in our experiments proved to be an order of magnitude higher than the diffraction-limited divergence.

5. Discussion of the results

Direct measurements show that in some region of modulation frequencies the average output power of a repetitively pulsed HF laser increases with decreasing the switching time of the Q factor. This fact suggests the existence of the giant pulse regime (i.e. the inversion accumulation regime). Indirect data obtained by processing experimental data show that the peak power of laser pulses in the repetitively pulsed regime exceeds the cw power at least by a factor of four. The average power of the repetitively pulsed laser is lower than the cw power, but it increases almost twice with increasing modulation frequency. This result agrees with the data that we obtained for a small HF laser [10]. In addition, the energy parameters of laser radiation obtained here exceed those reported in [10] by more than twice (proportionally to the increase in the length of the active medium along the cavity optical axis).

Analysis of the experimental data showed that the recovery time of the gain in the active medium (or the storage of its vibrational energy) is $6-7$ μs. Therefore, to obtain the maximum output power of the HF laser under study, the modulation frequency should not exceed 150 kHz. The average output power can be preserved at the expense of the pulse peak power (by operating in the regime of incomplete inversion recovery in the active medium). As shown in [9], this can be achieved by using the modulation frequency of 250 kHz, having lost half the average power compared to the cw regime.

Experiments showed that the pulse shape is preserved as a whole upon cavity Q-switching and their duration decreases with increasing the rotation frequency of the mirror Q-switch. In the optimal case (when the excess of the pulse power over the cw power is maximal), the pulse FWHM is ~ 350 ns.

In this paper, we did not attempt to optimise completely in calculations the cavity Q-switching regime. However, some preliminary results were obtained. Thus, we have shown within the framework of both calculation models that the coefficient k depends on the switching time of the cavity Q factor (which was simulated in calculations by the time of change of cavity losses). We simulated the situation when cavity losses were changed not due to rotation of a mirror but with the help of an ideal modulator whose transmission τ was changed instantly from 0 to 1. The opening time of such a modulator was set equal to 1 μs in calculations, which approximately corresponds to the operating regime with the mirror rotating at a frequency of 250 Hz. We found that, by increasing the rate of changing cavity losses, it is possible to increase the peak pulse power almost by a factor of one and a half.

Calculations of the amplifying properties of the active medium of the HF laser showed that for the rotation frequency of the mirror Q-switch equal to 250 Hz, the stationary gain profile is almost completely recovered during the time interval between two pulses $\Delta t_{2,1} \sim 7.5$ μs. This means that the pulse energies in the pulsed and repetitively pulsed regimes with the modulation frequency $\nu = 1/\Delta t_{2,1} \sim 133$ Hz are the same. When the rotation frequency of the mirror Q-switch is equal to 1000 Hz, the population inversion in the active medium has no time to recover by the onset of the second pulse, resulting in a considerable decrease in the second-pulse energy on passing from pulsed lasing to repetitively pulsed lasing.

The pulse profile of a Q-switched laser depends on the rate of changing cavity losses: the faster the cavity is 'open', the higher the expected instant power of the pulse. The calculation of the time dependence of radiation losses for rotation frequencies of the mirror Q-switch equal to 125 and 1000 Hz showed that the front of loss variations in the cavity during rotation of the mirror Q-switch is comparatively smooth and its length amounts to ~ 25 % of the laser pulse duration.

Another factor affecting the peak power in the RPR is the cavity length, which determines the lifetime of photons for the given level of losses. As losses are reduced, the period of relaxation oscillations of the output power decreases, and under certain conditions, an increase in the instant pulse power can be achieved for fixed gain parameters of the active medium. This fact is confirmed by the calculation.

As mentioned above, our calculations have shown that the angular divergence of radiation for the stable resonator used in our experiments exceeds the diffraction-limited divergence by an order of magnitude. The use of an unstable telescopic resonator is not efficient because in this case the angular spectrum of the beam is expanded almost by an order of magnitude (at the modulation frequency 250 Hz) and the centre of gravity of the beam shifts with respect to the axis of the aligned resonator due to its dynamic misalignment. In this connection the scheme with a rotating mirror Q-switch in an unstable resonator of another type was proposed [11], in which the displacement of the beam axis does not cause the cavity misalignment. This scheme and a detailed theoretical analysis of the spatial-angular characteristics of radiation of a Q-switched HF laser will be considered in our future studies.

6. Conclusions

We have demonstrated the operation of a medium-size cw chemical HF laser (with the active medium of length 400 mm along the cavity optical axis) in the repetitively pulsed regime with a pulse repetition rate up to 250 kHz. For the modulation frequency $\sim$150 kHz, the peak radiation power in the RPR exceeds the cw power at least by a factor of four. The influence of the modulation frequency on the average RPR power has been determined and the complete recovery time of the gain profile of the active medium has been measured to be 6 – 7 μs. Two numerical models describing the dynamics of the Q-switched HF/DF laser have been developed. The models are in good agreement with experiments. In particular, they correctly predict the excess of the peak power over the average cw power and the time interval during which the gain in the active medium is recovered.

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