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Q-switched chemical cw HF laser

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Abstract. **The characteristics of a cw chemical HF laser mechanically *Q*-switched at a frequency of up to 1000 Hz are studied. It is shown that the peak power of laser pulses increases by a factor of at least five for modulation frequencies from 17 to 250 Hz. The mean output power in the repetitively pulsed mode is appreciably lower than that in the cw lasing mode, but, as the modulation frequency increases (within the same frequency range), the mean power rises more rapidly than the peak power does. The possible factors causing the revealed discrepancies between the experimental and calculated laser characteristics are considered.**

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

1. Introduction

A repetitively pulsed operating mode can be realised in continuously pumped flow-type lasers under certain conditions discussed below. In this regime, the peak pulse power is many times higher than the continuous radiation power, while the mean power decreases to a much smaller degree. It seems that the most suitable technique for achieving the repetitively pulsed lasing is the resonator *Q*-switching [1 – 3].

The efficiency of the repetitively pulsed lasing depends on the kinetic characteristics of the processes occurring in an active medium (such as the radiation-field-intensity rise rate, the inversion-recovery rate, the rate of relaxation processes, etc.) and on the *Q*-switching technique. A repetitively pulsed operating mode of cw chemical lasers (CCLs) on HF(DF) was proposed for the first time in [4], where it was pointed out that the efficiency of resonators could possibly be raised by using phase conjugation in gases, because the phase-conjugation efficiency rapidly increases with increasing the radiation intensity [5].

There are other benefits of chemical lasers operating in the repetitively pulsed mode that are associated with specific features of the interaction between radiation and physical objects, features of the radiation propagation in the atmosphere, and with the possibility of attaining a pulse repetition rate that cannot be ensured by conventional pulse-pumping methods but can be realised by switching the resonator *Q* factor. A repetitively pulsed lasing mode at a pulse repetition rate equal to the rate of replacing the medium in the HF(DF) CCL resonator was proposed in [4]. However, calculations showed that the mean output power substantially decreased (by a factor of ~ 5) as compared to continuous lasing.

The repetitively pulsed operating mode for an HF CCL was simulated in [6] on the basis of a combination of calculation methods and computer simulation using programs for analysing processes in continuous and pulsed chemical lasers, and possible ways to realise this regime experimentally were proposed. The calculations of the energy parameters of laser pulses confirmed the conclusions drawn in [4], although the theoretical models used in [4] and [6] differed considerably. In addition, the energy, temporal, and spectral characteristics of output radiation were calculated in [6], and a method for simulating the dynamics of recovering the amplification properties of the HF CCL active medium after its saturation was proposed. This enabled the authors to obtain the first estimates of the upper limit of the pulse repetition rate, which does not yet lead to a decrease in the pulse energy, and the rate ensuring the maximum mean output power in the repetitively pulsed lasing mode.

Note that a *Q*-switched mode is rather difficult to realise experimentally. Therefore, in this work, we solved the following preliminary problems: to show that the resonator *Q*-switched mode actually leads to an increase in the peak pulse power in a cw HF laser, to estimate the temporal characteristics in the repetitively pulsed lasing mode as applied to the active medium of an actual HF laser, and to obtain experimental data for optimising the *Q*-switching method and arranging experiments on determining the gain-recovery time in the HF-laser active medium.

To realise the resonator *Q*-switched mode, we chose a method of a rotating mirror combined with stationary resonator mirrors [7]. This method has such advantages as the use of existing high-speed electrical spindles, a 100 % modulation depth, a quite high radiation resistance, and the possibility of using comparatively wide apertures of modulated beams. This method has such drawbacks as a difficulty of independently changing the speed of *Q*-switching and resonator lifetime and also the incomplete filling of the resonator with the active medium.

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2. Experimental setup

The repetitively pulsed operating mode of a cw HF laser was studied using a well-developed test-bench prototype with a radial-expansion nozzle assembly [8]. The optical scheme of the experiment is shown in Fig. 1. The test-bench model was placed into low-pressure compression chamber (*11*). The resonator was composed of highly reflecting aluminium-coated mirror (*1*) (with a radius of curvature $R = 10765$ mm and an optical diameter of 170 mm) and output fluorite window (*10*), which were attached to the opposite walls of the chamber. Output mirror (*3*) (an dielectric-coated fluorite plate with a transmission $\tau = 0.05$) was positioned at a distance $L = 4560$ mm from highly reflecting mirror (*1*). Q-switching was performed by rotating a flat aluminium-coated mirror [unit (*2*) of a fast photochronograph (FPC)] installed inside the resonator between output dielectric mirror (*3*) and output window (*10*). The optical diameter of the rotating mirror of the FPC was 25 mm. The calculated resonator misalignment angle θ^* (the angle of mirror rotation corresponding to switching the high Q factor off and assumed equal to the angle of beam divergence) was $\sim 1.5 \times 10^{-3}$ rad. The resonator was aligned using a He–Ne laser.

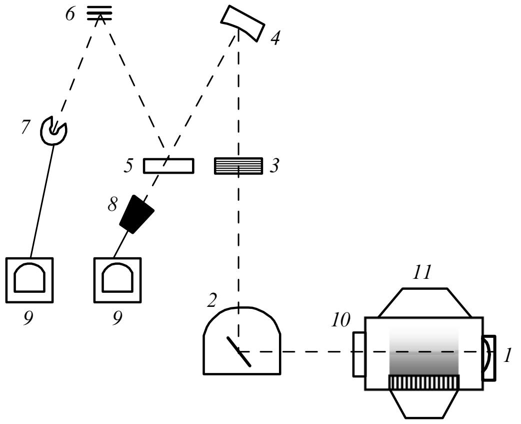

Figure 1. Optical scheme of the setup with the Q-switched HF laser: (*1*) highly reflecting resonator mirror; (*2*) FPC; (*3*) output mirror; (*4*) focusing mirror; (*5*) beamsplitter; (*6*) diffuser; (*7*) photodetector; (*8*) calorimeter; (*9*) oscilloscope; (*10*) output window; and (*11*) pressure chamber containing the active medium of the HF laser.

The mean laser-radiation power was measured with M201 calorimeter (Coherent Radiation, USA) (*8*) with a time constant of 1 s, whose sensitive area received 94 % of the focused output energy. The remaining part of the radiation reflected from flat fluorite plate (*5*) was scattered by matted aluminium plate (*6*) and detected by photodetector (*7*), for which an FSG-22-3A1 photoresistor based on Au-doped Ge was used. Electrical signals from calorimeter (*8*) and photodetector (*7*) were recorded by an S1-64A light-beam oscillograph and an S8-14 cathode-ray oscilloscope operating in a storage mode. To achieve the maximum temporal resolution, the FSG-22-3A1 photoresistor was loaded into a resistor with a 50-Ω rated resistance. An identical resistor was connected in parallel to the oscilloscopes' inputs in order to prevent distortions in pulse electrical signals transmitted through a long (10 m) coaxial cable.

The period between two successive resonator Q-switchings was assumed to be equal to the rotational period of the FPC mirror and defined as the time interval between neighbouring electrical pulses that were fed from an electromagnetic transducer. The latter was installed on the drive of the rotating mirror and generated pulses in each revolution. Pulses from the transducer were displayed in the real time on the screen of the S1-68 oscilloscope.

The resonator and the optical system as a whole were preliminarily adjusted with the open pressure chamber. The optical axis of the resonator was set at a distance of 13 mm from the end of the nozzle assembly; the pressure chamber was then closed and evacuated to a pressure of ~ 0.1 Torr. After the resonator was precisely aligned, the drive for rotating the FPC mirror was started and, when the chosen speed of mirror rotation was reached, the HF laser was enabled. Three–four seconds after the fuel components began to arrive at the nozzle assembly, the mean laser output power reached a steady-state level that was maintained for 3 s. The characteristics of ten pulses with the maximum amplitudes were measured. The dynamics of an increase in the pulse amplitudes was visually monitored using photodetector (*7*) and S1-64A light-beam oscillograph. The repetitively pulsed lasing mode was studied experimentally with parameters of the test-bench laser, the majority of which were close to the parameters of the calculated prototype. These parameters are presented in Table 1.

Table 1. Parameters of the calculated model and the experimental setup for the Q-switched HF laser.

Parameter	Calculated model	Experimental setup
Oxidiser-excess factor α	1.7	1.5–1.6
Degree of oxidiser dilution ψ	10	11–13.5
Oxidiser-deceleration pressure p_0/Pa	1.2×10^5	1.4×10^3
Fuel-deceleration temperature T_f/K	300	300
Temperature of the combustion-chamber wall T_w (K)	300	300
Pressure at the entrance to the resonator p_r/Pa	532	664
Mach number in the oxidiser flow M_0	4.8	4.3
Mach number in the fuel jet M_f	1	2.8
Average flow velocity in the resonator $u/\mathrm{m\ s^{-1}}$	2500	2000
Width of the generation zone along the flow d/mm	35	50
Length of the active medium along the resonator axis l/mm	250	180
Resonator length L/mm	250	4650
Maximum gain g/m^{-1}	9.5	7
Loss factor k/m^{-1}	0.21	0.9
Resonator filling $\mu = l/L$	1	~ 0.04

3. Experimental results

Table 2 lists the results from measurements of the rotational period T and frequency f of the FPC mirror and the following characteristics depending on T: the mean power $\bar{P}_R$ of repetitively pulsed radiation, the pulse rise time τ_r, the FWHM $\tau_{0.5}$ of the pulse, and the pulse duration $\tau_{0.1}$ at a level of 0.1 of its height. The time-averaged characteristics

Table 2. Characteristics of repetitively pulsed radiation from the Q-switched HF laser.

T/ms	f/Hz	$\bar{P}_R/\mathrm{W}$	$\tau_r/\mu\mathrm{s}$	$\tau_{0.5}/\mu\mathrm{s}$	$\tau_{0.1}/\mu\mathrm{s}$
60	17	0.056	10	–	–
8	125	0.084	0.9	1.2	2.6
4	250	0.146	0.6	0.55	1.3
2	500	0.106	0.4	0.45	0.75
1	1000	0.008	0.05	–	0.10

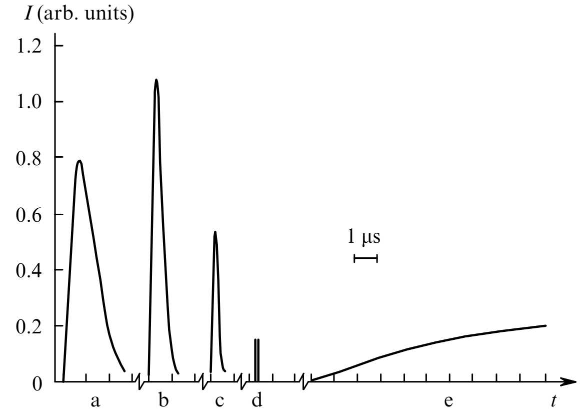

Figure 2. Averaged oscillograms of Q-switched HF-laser pulses for modulation frequencies of (a) 125, (b) 250, (c) 500, (d) 1000, and (e) 17 Hz.

of pulses were obtained by processing their oscillograms. Examples of averaged oscillograms are shown in Fig. 2.

Under quasi-steady-state lasing conditions (at a low speed of switching on the high-Q regime), the temporal dependences of both the resonator Q factor and the output pulse power evidently coincide; i.e., $\tau_{0.1} = t_{\mathrm{sw}}$ (where t_{sw} is the duration of the high-Q resonator regime). Additionally assuming that these dependences are symmetrical in time, one can determine the experimental resonator misalignment (mirror rotation) angle $\theta_0 = 2\pi f t_{\mathrm{sw}}$. Such a regime is shown in Fig. 2e. The misalignment angle is independent of the rotational frequency of the modulating mirror, provided that the radiation divergence remains constant. These oscillograms can serve to determine the off-duty factor $q = T/t_{\mathrm{sw}}$ of Q-switching in the repetitively pulsed mode. The q value relates the quasi-steady-state mean power $\bar{P}_R$ in the repetitively pulsed mode to the power P_{cw} in the cw lasing mode as follows:

$$q\bar{P}_R = P_{\mathrm{cw}}. \tag{1}$$

For $T = 60 \times 10^{-3}$ s and $\tau_{0.1} = 20 \times 10^{-6}$ s, the off-duty factor is $q = 3000$, $\bar{P}_R = 0.056$ W, and $P_{\mathrm{cw}} = 170$ W.

In a general case of a repetitively pulsed lasing mode,

$$E_{\mathrm{p}} = \bar{P}_R T = \int_0^{\tau_{0.1}} P_R \mathrm{d}t = P_{\mathrm{peak}} \tau_{\mathrm{eff}}, \tag{2}$$

$$P_{\mathrm{peak}} = \frac{\bar{P}_R T}{\tau_{\mathrm{eff}}}, \tag{3}$$

where E_{p} is the pulse energy, P_{peak} is its peak power, and

$$\tau_{\mathrm{eff}} = \frac{1}{P_{\mathrm{peak}}} \int_0^{\tau_{0.1}} P_R \mathrm{d}t \tag{4}$$

is the effective pulse duration, which is determined from a pulse-power oscillogram. If the resonator misalignment angle $\theta_0 = 2 \times 10^{-3}$ rad does not depend on a change in the mirror rotation speed, the time of the high-Q resonator state $t_{\mathrm{sw}} = \theta_0/(4\pi f)$ and the Q-factor rise time $t_Q = t_{\mathrm{sw}}/2$ can then be evaluated.

The pulse peak power P_{peak}, the time of the high-Q resonator state t_{sw}, and the Q-factor rise time t_Q obtained in this way are listed in Table 3.

Table 3. Characteristics of the resonator Q-switching in the HF laser.

T/ms	f/Hz	$t_{\mathrm{sw}}/\mu\mathrm{s}$	$t_Q/\mu\mathrm{s}$	$\tau_{\mathrm{eff}}/\mu\mathrm{s}$	$P_{\mathrm{peak}}/\mathrm{W}$
60	17	20	10	20	168
8	125	1.33	0.66	1	672
4	250	0.67	0.34	0.65	898
2	500	0.33	0.16	0.46	476
1	1000	0.17	0.08	0.05	160

4. Discussion

The data from direct measurements presented in Table 2 demonstrate that, within a certain range of pulse repetition rates in the Q-switched HF-CCL lasing mode, the mean power increases with decreasing the time of the high-Q resonator state. This proves the existence of a giant-pulse lasing mode (i.e., accumulation of inversion) for such active media. The results of indirect measurements (Table 3), which were obtained from processing the experimental data, demonstrate that, under our experimental conditions, the peak output power in the repetitively pulsed mode is at least five times higher than the output power in the cw mode. However, the mean output power in the repetitively pulsed lasing mode is lower than that in the cw mode, but it increases with an increase in the modulation frequency.

Calculations performed in [6] however predict a 30-fold excess of the peak power in the repetitively pulsed mode over the power generated in the cw HF lasing mode. In addition, other discrepancies between the calculated and experimental results came to light. It occurred that the resonator misalignment angle $\theta_0 = 2\pi f t_{\mathrm{sw}} \approx 2 \times 10^{-3}$ rad differs from the calculated angle of divergence $\theta^* \approx 1.5 \times 10^{-3}$ rad. The intensity-rise time t_I for the lasing field in the Q-switched mode calculated for the instantaneous Q-switching-on was 14 ns. The experimental laser-pulse rise time $\tau_{\mathrm{r}} = 600$ ns at a modulation frequency of 250 Hz (Fig. 2b) exceeded the Q-factor rise time $t_Q = 340$ ns. An increase in the modulation frequency from 500 to 1000 Hz (with a corresponding decrease in the Q-factor rise time) resulted in a drop of the peak power in the repetitively pulsed mode, which also differs from the calculation.

The above discrepancies in the results can be explained by a comparative analysis of the experimental and calculated models of the repetitively pulsed operating mode in the HF laser. The most significant discrepancy is observed between the experimental and calculated resonator-filling factors μ (Table 1). The difference between the threshold gains is evidently less.

The expression for the rate of the increase in the photon-flux density I in the resonator upon instantaneous Q-switching in the two-level model approximation under the assumption that relaxation is absent is written in the form

$$\frac{1}{c}\frac{\mathrm{d}I}{\mathrm{d}t} = \mu(g-k)I, \qquad (5)$$

$$\frac{\mathrm{d}g}{\mathrm{d}t} = -2\sigma g I, \qquad (6)$$

where c is the velocity of light, g is the gain in the active medium, k is the radiation loss factor, and σ is the induced-emission cross section. The characteristic field-intensity rise time t_I [neglecting the saturation described by Eqn (6)] is estimated from formula $t_I \sim (g-k)/c$. The quantities involved in Eqn (5) are averaged over the resonator length. In the calculated model, it was assumed that the resonator is completely filled with the generating medium, while in the experiment, the medium fills only a part of the resonator volume of length l with a filling factor $\mu = 3.85 \times 10^{-2}$ (Table 1). As a result of averaging the quantities in field-transfer equation (5), the field-intensity rise rate in the experimental model turns out to be lower by a factor of $\mu^{-1} \approx 26$ than in the calculated model (for $\mu = 1$). With allowance for the Q-factor rise time (Table 3), the field-intensity rise time becomes comparable to the laser-pulse rise time in the repetitively pulsed mode (Fig. 2).

The incomplete filling of the resonator volume with the active medium was the main reason for a decrease in the output power in the repetitively pulsed lasing mode at modulation frequencies of 500 and 1000 Hz. In fact, the times t_{sw} for which the high-Q-factor resonator exists (or the resonator lifetimes) for these frequencies are 330 and 170 ns, respectively. Since the field-intensity rise time at $\mu = 3.85 \times 10^{-2} \approx 1/26$ cannot be shorter than $t_I/\mu = 14\ \mathrm{ns} \times 26 = 364$ ns (neglecting the Q-factor rise time), the resonator lifetime is then too short for saturating the medium.

The results from studying the repetitively pulsed mode of an HF laser by switching the resonator Q factor using an opticomechanical modulator allow one to expect the attainment of the calculated parameters of laser pulses and implementation of a repetitively pulsed lasing mode upon agreement between the experimental and calculated Q-switching parameters. The 50 % energy efficiency of the repetitively pulsed mode relative to the cw mode, which is predicted by calculations and depends on the inversion-recovery rate in the HF-laser medium, must be additionally confirmed.

5. Conclusions

It has been found experimentally that the peak output pulse power of the cw HF chemical laser operating in the Q-switched mode increases at pulse repetition rates of 17 – 250 Hz. The mean power emitted in the repetitively pulsed mode using the opticomechanical modulation of the resonator Q-factor increases with shortening the duration of the high-Q regime (with an increase in the modulation frequency) more rapidly than the peak power does. The revealed differences between the experimental and calculated characteristics in the Q-switched mode, such as a decrease in the peak and mean powers at frequencies of 500 – 1000 Hz, are mainly due to the incomplete filling of the resonator volume with the active medium. In the subsequent studies, it is therefore suggested to improve the agreement between the parameters in the experimental and calculated HF-laser models, to attain higher peak and mean output powers, and to determine the inversion-recovery rate in the lasing medium. This will enable one to approach the implementation of a repetitively pulsed lasing mode [7].

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