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On the possible nature of high-frequency modulation of a CO laser pulse

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***Abstract*. It is shown that the temporal modulation of a pulse from an electron-beam-controlled CO laser can be caused by the periodic modulation of losses caused by the monotonic heating of the active medium.**

Keywords: *laser, pulse shape, heat release, high-frequency modulation.*

CO lasers attract interest due to their high energy parameters and a broadband emission spectrum. By now the kinetics of CO lasers and the methods of producing the population inversion and obtaining the high energy release have been studied in many theoretical and experimental papers [1 – 13]. At the same time, the temporal radiation characteristics of these lasers have not been investigated completely so far. It is known that the radiation pulse of a selective cavity CO laser has a complex temporal structure [3, 6, 7, 9]. In particular, high-frequency oscillations and spikes are observed, the spike regime being more typical for low-pressure lasers.

The oscillation frequency in electric-discharge low-pressure (~ 1 Torr) lasers is $\sim 10^5$ Hz, which is comparable with the resonance acoustic frequency in discharge tubes of diameter ~ 1 cm. In this connection it was assumed [6] that it is the resonance sound that is responsible for the radiation pulse modulation.

Typical oscillograms of radiation pulses from an electron-beam-controlled high-pressure (~ 100 Torr) CO laser are shown in Fig. 1. They are obtained in [7] by using a setup [4] cooled down to ~ 100 K. A selective cavity with a diffraction graying and intracavity mirrors was used. The cavity length L was 1.7 m, the active region length was 0.9 m, and the discharge region width was 6 – 8 cm. The initial concentration of working gas mixtures was 0.5 amagat.

Laser pulses of duration ~ 200 μs in Fig. 1 were irregularly modulated at a frequency of $(0.5-1)\times 10^6$ Hz, which greatly exceeds the resonance acoustic frequency ($\sim 10^4$ Hz) of a discharge chamber used in experiments. In addition, acoustic perturbations could not affect cavity mirrors during the time equal to the duration of laser and pump pulses because this is possible only at times $L/c_s \sim 10^{-3}$ s (c_s is the sound speed), i.e. after the laser pulse end. Thus, the high-frequency modulation is not related to acoustic perturbations at least under experimental conditions in [7]. It is also not related to the beats of longitudinal modes because the characteristic beat frequency exceeds the modulation frequency by two orders of magnitude. The beats of transverse modes can in principle contribute to the observed modulation. However, the high-frequency modulation of pulses from a CO laser is also observed in unstable resonators (Fig. 2) [9], where transverse modes are suppressed. Therefore, the nature of this modulation is not clear so far, and investigations in this direction are still of current interest.

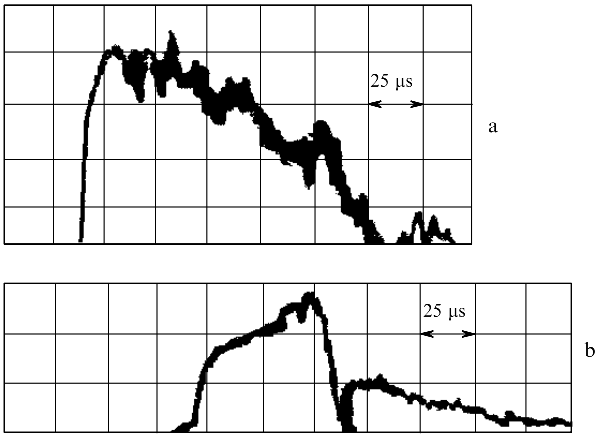

Figure 1. Typical oscillograms of a radiation pulse from a high-pressure $CO:N_2:He = 1:9:10$ mixture laser for the energy input $Q = 388$ J L^{-1} amagat^{-1}, the pump pulse duration $\tau_p = 55$ μs, and the laser wavelength $\lambda = 5.2$ μm (a) and from a $CO:N_2 = 1:9$ mixture laser for $Q = 447$ J L^{-1} amagat^{-1}, $\tau_p = 125$ μs, and $\lambda = 5.4$ μm (b).

In this paper, we consider the Q-switching of a resonator caused by heat release in the active medium as the possible reason for high-frequency oscillations. It is known that the periodic modulation of losses (Q-switching of a resonator) in solid-state lasers appears even during a monotonic increase in temperature. This is explained by the temperature dependence of the refractive index n and, hence, the optical length nL of the active element [14]. We will show below that such modulation can be also observed in gas lasers, in particular, in a CO laser.

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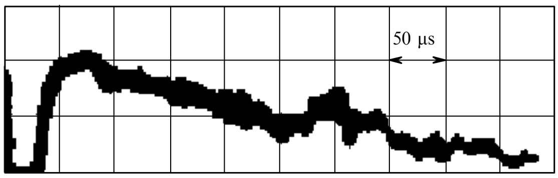

Figure 2. Oscillogram of a radiation pulse from an unstable cavity $CO:N_2 = 1:9$ mixture laser (with magnification $M = 1.5$) for $\rho_0 = 0.5$ amagat, $T_0 = 140$ K, the power input 2.4 kW cm^{-3} amagat^{-1}, and $\tau_p = 42$ μs.

In a pulsed CO laser, temperature increases during the pump pulse and subsequent relaxation processes. The refractive index in a gas laser weakly depends on temperature, its variation being determined by a change in the medium density. The expansion of the working medium to a buffer volume reduces the medium density ρ, which is accompanied by a decrease in the refractive index n and, hence, by a change in the optical length of the medium. The latter causes the periodic modulation of the effective Q factor of the resonator at the frequency

$$\Omega(t) = \frac{4\pi L}{\lambda}\frac{\mathrm{d}n}{\mathrm{d}\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t}. \tag{1}$$

To obtain the modulation frequency corresponding to the observed experimental frequency $\Omega_{exp} \sim 10^6$ Hz, it is necessary that for $L \sim 2$ m, variation in the refractive index $\rho \mathrm{d}n/\mathrm{d}\rho \sim 2\times10^{-4}$ and $\lambda \sim 5$ μm, the rate of density variation $\mathrm{d}\rho/(\rho \mathrm{d}t)$ would be $\sim 10^3$ s^{-1}, which is quite real for high-power lasers with high energy input and high heat release.

As an example Fig. 3 presents the experimental time dependences of the active medium temperature, oscillograms of the radiation pulse from a $CO:N_2 = 1:9$ mixture laser [7], and the calculated change in the modulation frequency (1). The calculation was performed for $L = 1.7$ m and $\rho \mathrm{d}n/\mathrm{d}\rho = (n-1)\rho/\rho_0 \sim 1.4\times10^{-4}\rho/\rho_0$. The value of n for this mixture was determined from data [15]. The time dependence of the density has the form [16, 17]

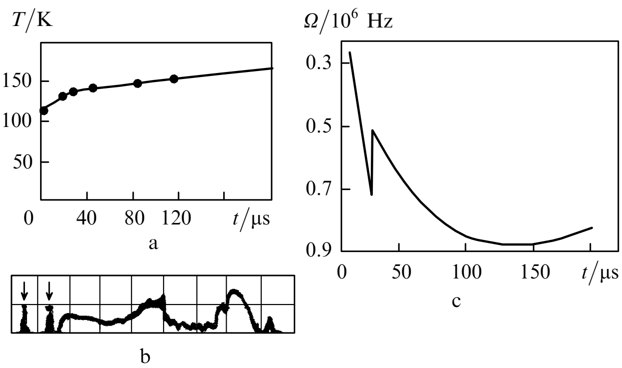

Figure 3. Time dependence of the mixture temperature (a), the oscillogram of a radiation pulse from a CO laser at the wavelength $\lambda = 5.3$ μm (b) and the time dependence of its modulation frequency (c). The $CO:N_2 = 1:9$ mixture, $\rho_0 = 0.5$ amagat, energy input 210 J L^{-1} amagat^{-1}, $\tau_p = 25$ μs, time base 25 μs div^{-1}. The arrows show the onset and end of the pump pulse.

$$\rho(t) = \rho_0 \exp\left(-\frac{t}{\tau}\right) + \rho_0\frac{T_0}{T}\left[1 - \exp\left(-\frac{t}{\tau}\right)\right], \tag{2}$$

where τ/c_s and d is the characteristic transverse size of the active medium. Expression (2) qualitatively describes the passage from isochoric to isobaric expansion.

The region of high-frequency temporal oscillations in Fig. 3b at the frequency $\Omega_{exp} \sim 10^6$ Hz, which is determined visually from the oscillation period, corresponds to the time $100-170$ μs after the pump pulse onset. One can see that this region well correlates with the corresponding high-frequency region in Fig. 3c.

The modulation depth of the resonator Q factor is determined by the ratio of the intermode distance to the laser linewidth. The smaller number of resonator modes is located within the laser linewidth, the sharper is decrease in the gain on passing from one mode to another. Therefore, an increase in the modulation depth should be expected when the mixture pressure is decreased (the linewidth decreases) and the aperture is reduced (the number of transverse modes decreases). It is known that, when the modulation depth is increased, the spike lasing regime and chaotic lasing with the doubled period can appear [14].

In addition, the amplitude of high-frequency oscillations depends on the ratio Ω/Ω_r, where $\Omega_r = [(A-1)/t_{inv}t_{ph}]^{1/2}$ is the frequency of relaxation oscillations [14]. Here, A is the dimensionless pump parameter normalised to the absorption coefficient, which takes into account electron impact pumping and all vibrational relaxation processes increasing the inversion population of levels on the transition under study; t_{inv} is the relaxation time of the inverse population; and t_{ph} is the photon lifetime in the resonator. The modulation will be more efficient if the resonance condition $\Omega \sim \Omega_r$ is fulfilled. The typical parameters of high-pressure (~ 100 Torr) selective cavity $CO-N_2$ lasers are $\Omega_{exp} \sim 10^6$ Hz, $1/t_{inv} \sim 5\times10^5$ Hz, and $\Omega_r \sim 10^7$ Hz, and therefore the oscillation amplitude in such laser is insignificant.

It follows from the above discussion that the high-frequency modulation in helium-containing mixtures should be observed earlier than in $CO-N_2$ mixtures, all other factors being the same. This is related to a faster passage from the isochoric to isobaric expansion regime in a medium with a greater sound speed (i.e. with lighter molecules). In addition, the amplitude of high-frequency oscillations in helium-containing mixtures will be greater because the relaxation frequency in them is lower and, therefore, the ratio Ω/Ω_r is closer to unity. This corresponds qualitatively to oscillograms of radiation pulses from CO lasers with the helium-containing mixture (Fig. 1a) and with the mixture without helium (Fig. 1b): the radiation pulse profile in the helium-containing mixture has a more irregular shape.

Thus, the mechanism of high-frequency oscillations considered above can be important and should be further investigated. This mechanism should be taken into account in the studies of temporal characteristics of high-power gas lasers with a great heat release.

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