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High-power supersonic CO laser on fundamental and overtone transitions

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Abstract. **Lasing parameters of a rf discharge-pumped CO laser in a subsonic gas flow with subsequent cooling of the laser medium in a supersonic flow are studied. The output power of the laser achieved 2.1 kW for the efficiency up to 21 % in the spectral range 4.9 – 5.7 μm corresponding to the $V + 1 \to V$ fundamental vibrational transitions in the CO molecule. The laser output power at the $V + 2 \to V$ first vibrational overtone transitions (2.6 – 2.7 μm) was 50 W. Possible ways of improving the laser design for generating radiation at higher overtone transitions of the CO molecule are discussed.**

Keywords: *supersonic CO laser, rf discharge, overtone transitions, gain.*

1. Introduction

A molecular CO laser [1 – 3] operating on the $V + 1 \to V$ fundamental vibrational transitions is a highly efficient, high-power source of laser radiation. The active medium of this laser is an essentially multilevel system allowing lasing at the vibration – rotation transitions of the CO molecule in a broad wavelength range from 4.6 μm [4, 5] to 8.2 μm [6], as well as at the $V + 2 \to V$ first overtone vibrational transitions [7, 8]. Lasing in an overtone CO laser is possible at more than 400 vibration – rotation transitions in the 2.5 – 4.2-μm spectral range [9 – 11], which covers the transparency window of the atmosphere (3 – 4 μm). It was pointed out in [7 – 11] that the efficiency of an overtone CO laser increases upon cooling the laser medium and may achieve 11 % [9 – 11].

A high peak power of the overtone emission (up to 10^5 W) was obtained in pulsed electroionisation (EI) lasers [9 – 13] in which a high voltage $\sim 10^5$ V was used for the operation of the electron accelerator. The use of an rf discharge leads to a considerable lowering of voltage and simplifies the excitation of the active medium of the CO laser [14 – 17]. The output power of a supersonic CO laser operating in the fundamental band upon excitation of the active medium in the subsonic gas flow by an rf discharge was found to be 0.33 kW [14] for a single-pass laser cavity. The use of a three-pass cavity increased the output power to 0.99 kW, the efficiency of the laser amounting to 7 % of the input power [15].

In this paper, we studied the lasing parameters of a CO laser operating at the fundamental and overtone vibrational transitions of the CO molecule upon excitation of the active medium in the subsonic gas flow by an rf discharge and cooling the laser medium in a supersonic flow. The possibility of extending the emission range of the overtone CO laser to the wavelength range 3 – 4 μm corresponding to higher ($V > 15$) overtone transitions is considered.

2. Supersonic rf-discharge-excited CO laser

The lasing parameters of a CO laser upon excitation of the active medium by an rf discharge in a subsonic gas flow and cooling of the laser medium in a supersonic flow were experimentally studied at the Air Force Research Laboratory, USA. Figure 1 shows the schematic diagram of such a laser.

The length of the active medium, equal to the width of the supersonic gas flow, was 10 cm. To eliminate the effect of the boundary layers formed near the optical elements of laser cavity (*6*), a system of blowing of these elements by an inert gas (helium) was used. The length of the gas- dynamic channel from supersonic nozzle (*4*) to vacuum pumping system (*5*) was 50 cm. The design of the equipment envisaged five spots for fixing the optical elements of the laser cavity at various distances from the nozzle. Thus, the time of passage of the excited gas from the nozzle to the laser cavity could be changed by changing the position of the cavity.

Note that the highest output power at the fundamental and overtone transitions of the CO molecule was observed for the maximum distance ($\sim$ 45 cm) between the supersonic nozzle and the laser cavity axis. Calculations made while designing the gas-dynamic channel and the measurements of the gas flow pressure with a Pitot tube showed that the supersonic gas flow was preserved at a distance of 50 cm from the nozzle. The Mach number for the supersonic flow was 2.7 and the temperature of the gas in the flow was $\sim$ 100 K. The gas pressure in the subsonic part of the gas-

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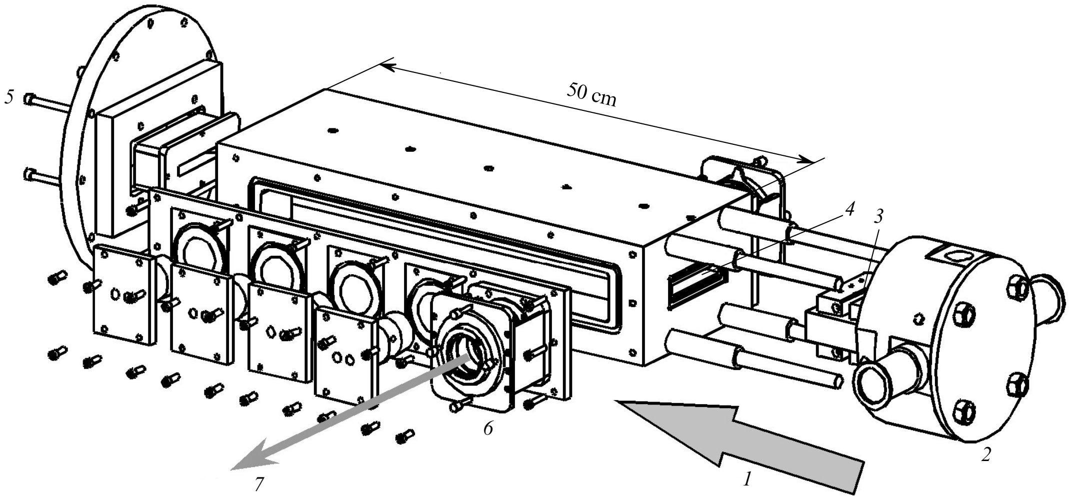

Figure 1. Scheme of a supersonic rf CO laser: (*1*) direction of gas flow, (*2*) gas mixing chamber, (*3*) rf electrodes, (*4*) supersonic nozzle, (*5*) vacuum pumping system, (*6*) adjusting optical elements blown by helium, and (*7*) laser radiation.

dynamic channel varied from 160 to 290 Torr, which corresponded to a pressure of 2–9 Torr in the supersonic gas flow. Experiments were carried out on the gas mixture CO : He = 1 : 7 with a small admixture of oxygen. Special attention was paid to the purity of the gases. For example, carbon monoxide used in the experiments (the volume fraction of CO was not lower than 99.99 %) was stored in aluminium (and not steel) cylinders to prevent the formation of iron pentacarbonyl which deteriorates the electric discharge and lasing parameters of the CO laser (see, for example, [18]).

The gas was excited by an rf discharge of frequency 13.6 MHz between electrodes (*3*) in a ceramic tube of inner cross section 10 mm $\times$ 100 mm mounted right in front of supersonic nozzle (*4*). The length of the discharge region was $\sim$ 75 mm along the gas flow. The power supplied to the rf discharge could be varied from 4 to 20 kW.

In a system with a single-pass laser cavity, the output power at fundamental vibrational transitions was 2.1 kW and the maximum efficiency was 21 % (Fig. 2). Lasing was observed in the fundamental vibrational transition band from 4 $\rightarrow$ 3 to 18 $\rightarrow$ 17 in the spectral range 4.9 to 5.7 μm (Fig. 3a). For the same geometry of the laser cavity in [14], the output power of a supersonic rf CO laser was 0.33 kW. Thus, the output power in the fundamental band increased by a factor of 6 due to an increase in the time of flow of the gas from the nozzle to the laser cavity, the use of a system of inert gas blowing around the optical elements of the cavity and the use of pure gases.

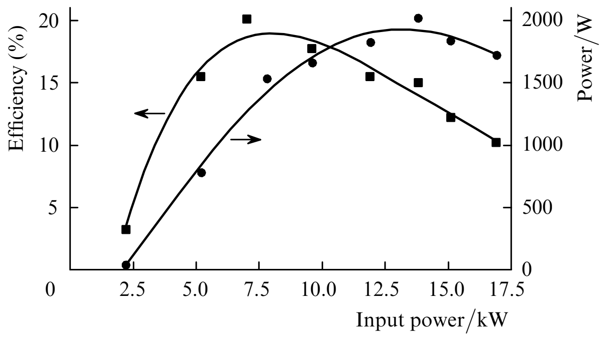

Figure 2. Efficiency and power of a supersonic rf CO laser operating on the fundamental band, as a function of the energy input.

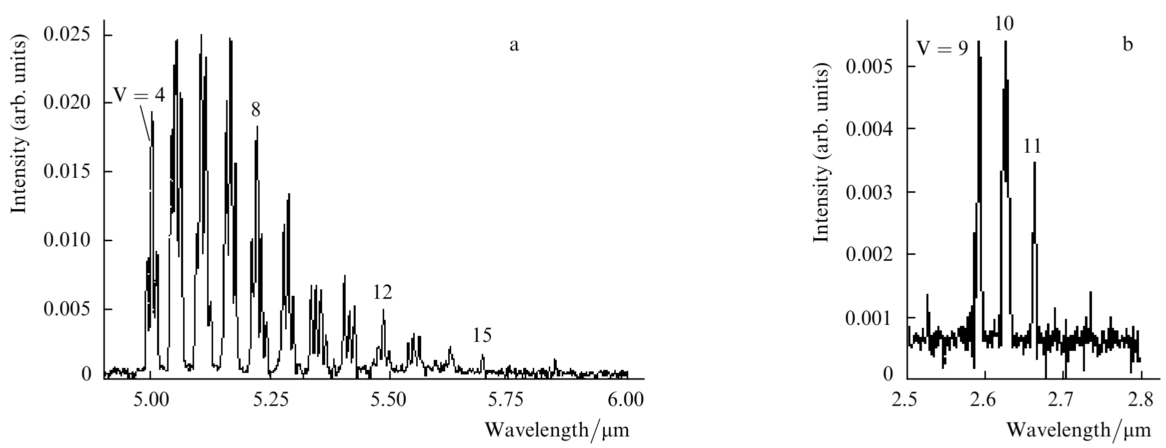

Figure 3. Emission spectrum of a supersonic rf CO laser operating on (a) fundamental and (b) overtone vibrational transitions.

At the overtone vibrational transitions of the CO molecule, the output power in the supersonic rf CO laser achieved ~ 50 W. The overtone emission spectrum corresponds to relatively low overtone transitions from 9 → 7 to 11 → 9 in the spectral range 2.6 – 2.7 μm (Fig. 3b). Overtone lasing upon rf excitation of the gas followed by supersonic cooling of the laser medium was observed for the first time.

In these experiments, overtone lasing was realised in a laser with a single-pass cavity formed by two mirrors with reflectivities exceeding 99.9 % (the threshold gain was ~ 0.01 m^{-1}) in the spectral range ~ 2.7 μm. The study performed with a liquid-nitrogen-cooled EI laser showed that the gain achieved its highest value in the region of high overtone transitions of the CO molecule. For example, it may exceed 0.2 m^{-1} in the CO – He mixture and 0.4 m^{-1} in the CO – N_2 mixture at the 33 → 31 transition [19]. However, lasing threshold was not reached in a supersonic rf CO laser using laser mirrors with reflectivities ~ 99 % (the threshold gain was ~ 0.1 m^{-1}) in the spectral range 3 – 4 μm corresponding to high overtone transitions V = 20 – 35. Apparently, this is due to the fact that population inversion at high vibrational levels is formed over a period exceeding the time of flow of the gas from the supersonic nozzle to the laser cavity.

3. Temporal dynamics of the gain and discussion of results

In an electric-discharge CO laser, the population of the higher vibrational levels of the CO molecule occurs due to the VV exchange [20, 21] whose rate depends on the frequency of molecular collisions, i.e., on the temperature and pressure of the gas mixture. In a supersonic flow at a temperature ~ 100 K of the gas, its pressure was rather low (2 – 9 Torr) and hence the rate of VV exchange was not high. The effect of the pressure of the gas mixture on the time of formation of inverse population was studied in our model experiments performed with a pulsed EI laser described in [9 – 11, 19].

In our experiments, we measured the delay between the onset of the EI discharge pulse and the lasing pulse at the overtone transitions of the CO molecule (27 → 25, 31 → 29 and 35 → 33). This time corresponds to the time interval during which the gain in the active medium attains its threshold value in the laser cavity. The frequency-selective laser cavity consisted of a spherical copper mirror and a diffraction grating (200 grooves mm^{-1}) working in the self-collimation mode. For the vibrational transitions 27 → 25, 31 → 29 and 35 → 33, the threshold gain in such a cavity was 0.06, 0.07 and 0.08 m^{-1}, respectively.

Figure 4 shows the dependence of the delay in the onset of lasing on the gas mixture density measured for the mixtures CO : He = 1 : 4 (used normally for EI CO lasers [9 – 11, 19]) and CO : He = 1 : 7 (used normally for supersonic rf CO lasers) at an initial gas temperature of 100 K. A decrease in the gas density led to an increase in the delay time which increased sharply for a gas density below 0.06 amagat (1 amagat is the gas density under normal conditions). For such a density of the gas, the collisional broadening of the gain lines becomes smaller than the Doppler broadening for which the gain varies proportionally to the pressure (density) of the gas. Note that the maximum density in the active medium of a supersonic CO laser was ~ 0.03 amagat (9 Torr at a gas temperature ~ 100 K), which corresponds to the Doppler broadening of the gain lines.

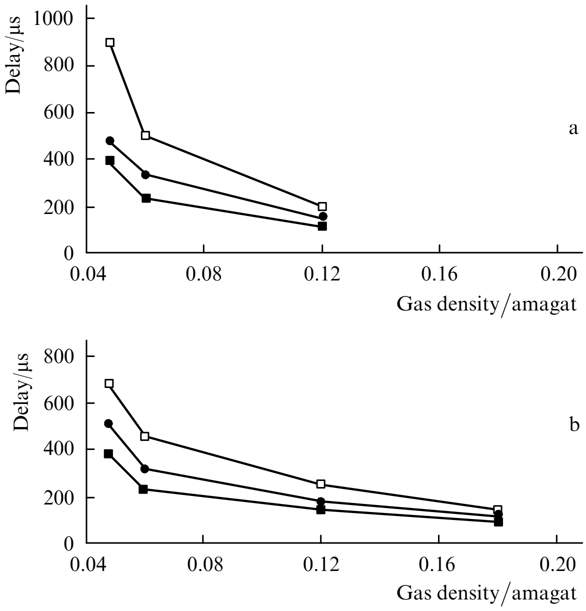

Figure 4. Dependence of the delay in lasing at the 27 → 25 (■), 31 → 29 (●) and 35 → 33 (□) overtone transitions on the density of the gas mixtures CO : He = 1 : 7 (a) and CO : He = 1 : 4 (b) for a specific energy input ~ 250 J L^{-1} $amagat^{-1}$

Thus, a decrease in the density of the gas mixture lowers the VV exchange rate. Moreover, the gain decreases as the density falls below 0.06 amagat, which leads to a sharp increase in the time required for achieving the threshold value of the gain. For the mixture CO : He = 1 : 7, for example, the delay at the transition 35 → 33 achieved ~ 900 μs for a gas density of 0.048 amagat (~ 13 Torr at 100 K). In the supersonic CO laser, the time in which the gas flows from the nozzle to the farthest laser cavity was found to be ~ 400 μs. Although the gain apparently achieves its threshold value at lower overtone transitions during this period of time, it is still not sufficient for initiating lasing on higher transitions.

In order to determine the conditions under which lasing can be initiated on higher overtone transitions, we studied the temporal dynamics of the gain in the active medium of a pulsed CO laser. The gain was measured in the master oscillator – amplifier mode by the calibrated loss method. The optical scheme of the experiments and the measuring technique are described in [19, 22]. Figure 5 shows the temporal dynamics of the gain, measured at the fundamental [20 → 19 P(14)] and overtone [20 → 18 P(12)] transitions [19] with the same upper vibrational level. The temporal dynamics of the gain in the medium can be characterised by determining t_0, the instant at which the gain reverses its sign (the time corresponding to the emergence of population inversion) and $t_{0.9}$, the time at which the gain attains 0.9 level of its peak value. These instants of time are shown in Fig. 5 for the dynamics of the gain at the 20 → 19 P(14) fundamental transition. In spite of the difference in the peak values of the gain for the basic and overtone transitions (the scales of the G_1 and G_2 axes in Fig. 5 differ by a factor of 4.5), the time $t_{0.9}$ is virtually the same for both of them. Such a coincidence is due to the fact that the temporal dynamics of the gain at the vibrational transitions of the CO molecule

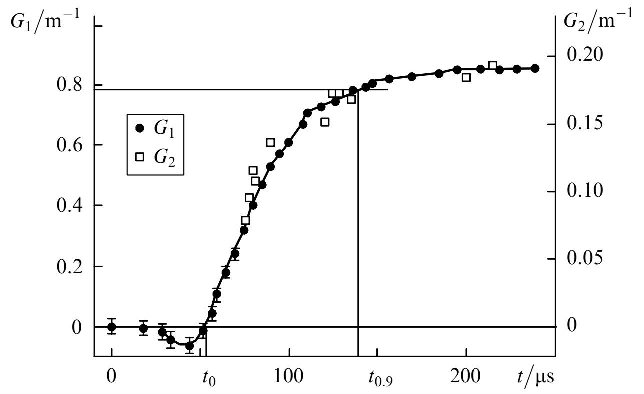

Figure 5. Temporal dynamics of the gains G_1 and G_2 for the $20 \to 19$ P(14) fundamental and $20 \to 18$ P(12) overtone transitions for a specific energy input of 300 J L^{-1} amagat^{-1} and density 0.15 amagat (gas mixture CO : He = 1 : 4). The times t_0 and $t_{0.9}$ correspond to the $20 \to 19$ P(14) transition.

is determined by the processes of formation of the vibrational distribution function in the active medium [20, 21]. In particular, the theoretical analysis carried out in [23] indicates that the characteristic times t_0 and $t_{0.9}$ for the overtone transitions must be close to the corresponding values for the fundamental transitions.

We studied the effect of the gas mixture density on the gain dynamics for the $19 \to 18$ P(11) fundamental vibrational transition. Figure 6 shows the dependences of t_0 and $t_{0.9}$ on the density of the gas mixture CO : He = 1 : 4 for the same specific energy input 150 J L^{-1} amagat^{-1}. An increase in the density of the gas mixture from 0.04 to 0.12 amagat reduces the times t_0 and $t_{0.9}$ from 300 to 100 and from 1400 to 400 μs, respectively, i.e., almost inversly proportional to the change in the gas density. These results show that the rate of the processes of formation of the vibrational distribution function depends considerably on the density of the active medium. Hence, to obtain lasing at higher overtone transitions in the supersonic CO laser, we must increase either the density of the active medium, or the time of flow of the gas from the supersonic nozzle to the laser cavity.

An increase in the gas density increases the VV exchange rate and reduces the time required for the attainment of the threshold gain in the active medium of the CO laser. However, if the gas density in the subsonic part of the gas-dynamic channel begins to exceed 0.4 amagat (~ 300 Torr under normal conditions), the gas excitation becomes problematic due to instability of the self-sustained rf discharge. Hence, for a gas density exceeding 0.4 amagat, the active medium must be excited by a non-self-sustained discharge. In [18, 24–28], for example, the gas was excited by the non-self-sustained EI discharge in a supersonic flow with a gas density ~ 1 amagat (200 Torr at 80 K) [28].

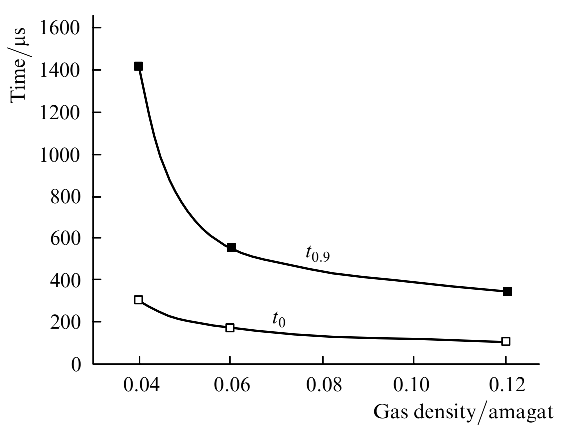

Figure 6. Dependence of t_0 and $t_{0.9}$ for the $19 \to 18$ P(11) transition on the density of the gas mixture CO : He = 1 : 4 for a specific energy input of 150 J L^{-1} amagat^{-1}.

In the case of excitation by a self-sustained discharge, lasing at high overtone transitions in a supersonic CO laser can occur due to an increase in the time of the gas flow from the supersonic nozzle to the laser cavity. This time period can be increased in two ways: by increasing the length of the supersonic part of the gas-dynamic channel, or by decreasing the supersonic flow velocity (Mach number). However, an increase in the length of the gas-dynamic channel increases the boundary layer thickness, and the absorption of radiation by molecules of the insufficiently excited gas may become comparable with the gain in the active medium. A decrease in the Mach number, for example, by changing the profile of the supersonic nozzle, increases not only the time of the gas flow to the laser cavity, but also the temperature and density of the gas in the supersonic flow. In order to maintain the gas temperature in the supersonic flow at the level ~ 100 K, the gas must be cooled in the subsonic part of the gas-dynamic channel.

Thus, simulation of the working conditions for a supersonic CO laser in a pulsed laser device leads to the methods of improving its design to achieve lasing at high overtone transitions of the CO molecule.

4. Conclusions

Our experiments have shown that the output power and efficiency of a supersonic CO laser operating in the fundamental band achieve 2.1 kW and 20 %, respectively in the case of excitation of the medium by an rf discharge in the subsonic gas flow, followed by a cooling of the laser medium in the supersonic flow. Lasing at the overtone transitions of a CO molecule with an output power of 50 W was achieved for the first time in such a laser. The effect of parameters of the medium on the processes of formation of population inversion in it was studied in model experiments in a pulsed EI CO laser. The results of these experiments reveal that the time taken by the gas to reach the laser cavity in a supersonic flow is not sufficient for realising population inversion at higher overtone transitions in a supersonic CO laser. Ways have been suggested for improving the design of the supersonic CO laser in order to obtain overtone lasing in the spectral range 3–4 μm, which is important for various applications.

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