INVESTIGATION OF THE INVERTED MEDIUM OF A QUASI-STATIONARY CO_2 LASER WITH PULSED EXCITATION

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The results of an investigation of the inverted medium of a quasi-stationary CO_2 laser is presented. The medium is distinguished by the fact that the time of flight of individual molecules through the discharge gaps is less than the relaxation time of the 00°1 CO_2 laser level. The emitted power, the gain, the saturation intensity, and the gas temperature are measured. Using the experimental data, the distribution of the molecules in the vibrational and rotational states of the inverted medium is calculated. The maximum power density attained in this experimental model is 25 W/cm^3. For comparison, the characteristics of a model in which cold CO_2 is added to the flow of excited nitrogen are investigated. It is shown that in this case the output power level is determined by the efficiency with which the jets are mixed.

In [1] we briefly described a model of a quasi-stationary CO_2 laser with pulsed pumping. The main characteristic of this method of exciting the medium is that the time of flight of the separate molecules through the region of the quasi-stationary discharge is less than the relaxation time of the upper laser level of CO_2, and for each small element of volume of the gas the excitation process has a pulse form. As calculations [2] and preliminary experiments [1] have shown, the inversion is considerably higher than that attained under stationary conditions. The purpose of the present investigation was to make a detailed study of the properties of the inverted medium.

The experimental arrangement used is shown in Fig. 1, in which 1-5 are the components of the pulse valve, 6 is the critical section of the nozzle 7, 9-10 are electrodes, 8 is an insulator, 11 are the voltage supplies to the discharge electrode, 12 is the distributor chamber of the mixer system, 13 are the tubes of the mixer section, 14 is the chamber for investigating the state of the inverted medium, 15 are guides for limiting the gas flow, 16 is the booster volume, 17 is the resonator mirror, and 18 is a window of NaCl. The working mixture of gases CO_2-N_2-He was made in chamber 1. The high-speed valve opened the

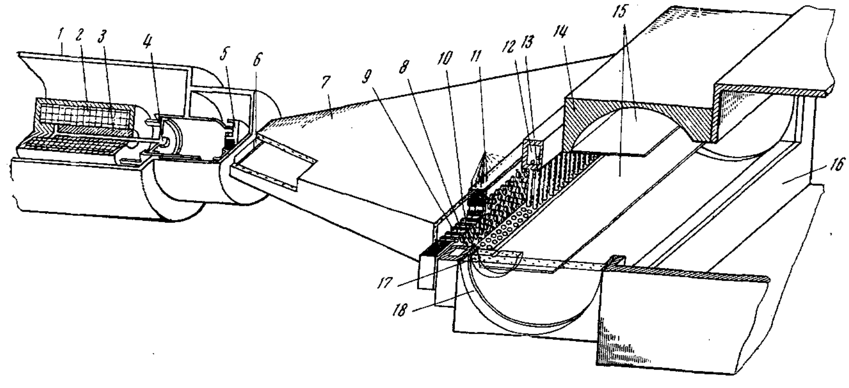

Fig. 1

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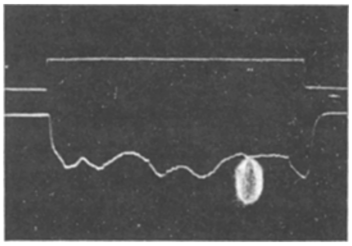

Fig. 2

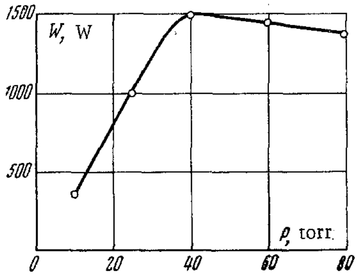

Fig. 3

chamber 1, connecting it to the nozzle 7. The gas mixture passing through the nozzle was accelerated up to a velocity $v_0 = 5 \cdot 10^4$ cm/sec. After reaching steady flow conditions in the discharge gap 8, of length $l = 1$ cm, a rectangular voltage pulse of duration $\tau = (5\text{-}20) \cdot 10^{-3}$ sec was applied. The maximum length of the pulse was determined by the geometrical dimensions of the vacuum volume 16, which acts as a pump of large capacity.

The rate of gas flow and the length of the channels determine the time $\tau_l = l/v_0$ the separate molecules reside in the discharge, and the range of concentrations for which the condition $\tau_l < \tau_{00°1CO_2}$ is satisfied.

The characteristics of the gas which passes through the discharge gaps were analyzed in the chamber 14. We measured the gas density and the flow velocity, and we also estimated the temperature and the state of inversion. The main diagnostic methods used were optical interferometry, the observation of Rayleigh scattering of light which has passed through the gas flow, probing of the medium with low-power and high-power sources of radiation at a wavelength of 10.6 μ, observation of lasing, and measurement of the energy of stimulated emission.

A typical form of the voltage oscillograms (the upper trace) across the discharge gap and the emission pulse (the lower trace) are shown in Fig. 2. Lasing reaches a maximum $(5\text{-}100) \cdot 10^{-6}$ sec after the voltage is applied to the electrodes and stays at the same level throughout the pulse. The length of the voltage pulse considerably exceeds the characteristic time of the process (the relaxation time of the upper and lower laser levels and the time of flight of the gas through the discharge region and the resonator), i.e., steady-state conditions are satisfied.

Figure 3 shows the output power as a function of the pressure of the working mixture for a ratio of components $CO_2 : N_2 : He = 1 : 3 : 6$. The experimental points were obtained at the optimum discharge current for each pressure of the mixture, which increases in proportion to the pressure. For $N_\Sigma \approx 1.3 \cdot 10^{18}$ cm^{-3} (which corresponds to a pressure $p^* = 40$ torr at room temperature) the curve reaches saturation, and a further increase in the density leads to a slight fall in the output power.

The small-signal gain (α_0) was measured using a low-power steady CO_2 laser on the P20 transition. For optimum operation ($p^* \approx 40$ torr) the gain $\alpha_0 = 1.3 \cdot 10^{-2}$ cm^{-1}. A small ($\sim 3\%$) reduction in α_0 with distance from the discharge channels was observed in the resonator.

The temperature in the gas flow was found from interferometric measurements. The estimates were made assuming that $N_\Sigma T$ is constant over the cross section of the chamber. The temperature distribution can then be established from the density distribution. Under optimum conditions the temperature of the gas in the resonator $T = 500°K$.

To determine the limiting power characteristics of the inverted medium, simultaneously with α_0 we measured in each cycle of operation the saturation intensity I_H. The maximum power densities of the beam in these experiments reached 2 kW/cm^2 for steady operation of the probing laser (the diameter of the iris which cut off the beam was 2 mm) and 3 kW/cm^2 (iris diameter 4 mm) under pulsed conditions ($\tau \approx 5 \cdot 10^{-2}$ sec). For $p^* = 40$ torr the measured saturation intensity was 2.8 kW/cm^2.

The results of the experiments enable certain conclusions to be drawn regarding the properties of the inverted medium. When the resonator radiates maximum power, $\alpha_0 = 1.3 \cdot 10^{-2}$ cm^{-1} and $T_g = 500°K$. The gas temperature is in equilibrium with the rotational temperature. It can also be assumed that equilibrium exists between the excited molecules of N_2 and CO_2, since the time scale for transmitting the excitation from N_2^* (v = 1) to CO_2 (00°0) in this case is of the order of several microseconds, while the time of flight through the resonator $d/v_0 = 80 \cdot 10^{-6}$ sec.

From the available data we can find the distribution of the molecules in the vibrational and rotational levels in the inverted medium (Table 1).

For the calculations of the populations we took the probability of spontaneous emission with respect to the P20 transition as $A^{00°1,19}_{10°0,20} = 0.17$ sec^{-1} [3], while the value of the form factor for the center of the line, determined in this case by collision broadening, is $S(\nu_0) = 1.9 \cdot 10^{-9}$ sec.

TABLE 1

Δn, cm^{-3}	$n^{19}_{00^\circ 1}$, cm^{-3}	$n^{20}_{10^\circ 0}$, cm^{-3}	$N_{00^\circ 1}$, cm^{-3}	$N_{10^\circ 0}$, cm^{-3}	$N_{CO_2^\circ}$, cm^{-3}	$N_{N_2^*}$, cm^{-3}	$\frac{N_{00^\circ 1}}{N\,CO_2^0}$
$9.1 \cdot 10^{14}$	10^{15}	$9.3 \cdot 10^{13}$	$1.7 \cdot 10^{16}$	$1.6 \cdot 10^{15}$	$8.6 \cdot 10^{16}$	$6.45 \cdot 10^{16}$	0.2

TABLE 2

Injection of CO_2	Concentration, cm^{-3}			Power supplied to discharge, W	$\alpha_0 L$	I_H, $\mathrm{kW/cm^2}$	$\alpha_0 I_H$, $\mathrm{W/cm^3}$
	CO_2	N_2	He				
Combined	$1.3 \cdot 10^{17}$	$3.9 \cdot 10^{17}$	$7.8 \cdot 10^{17}$	$2.7 \cdot 10^{5}$	0.39	2.8	36
Independent	$1.5 \cdot 10^{17}$*	$4 \cdot 10^{17}$	—	$2.7 \cdot 10^{5}$	0.59	2.15	50
Independent	$3 \cdot 10^{17}$*	$8 \cdot 10^{17}$	—	$4 \cdot 10^{5}$	0.41	2.8	36

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*The mean values of the concentration of CO_2 are presented from interferometric measurements $N_{CO_2} = \frac{1}{L}\int_0^L N(x)\,dx$.

Under optimum conditions a considerable portion of the energy of the vibrational excitation of the molecule $[N_2^* \ (v = 1) + CO_2\ 00^\circ 1]$ is converted into radiation in the resonator. This is confirmed by the fact that when working with two resonators spaced 25 cm apart, the power radiated by the second (further) resonator is reduced by an order of magnitude when the first resonator is connected. The density of the excited molecules which can participate in lasing is $N_{N_2^*} + N_{CO_2 00^\circ 1} = 8.2 \cdot 10^{16}\ \mathrm{cm}^{-3}$. Note that taking into account the contribution of the upper vibrational levels of the excited nitrogen ($v = 2$–8) and CO_2 $00^\circ m$ ($m > 1$) should lead to a correction of approximately 20%. If we assume that the energy of all the excited molecules is converted into stimulated emission inside the resonator, we can estimate the maximum power which the inverted medium is capable of developing. This is

$$P_{\max} = 10^{-7} h\nu_0 dL v_0 (N_{N_2^*} + N_{CO_2 00^\circ 1}) = 9.4 \cdot 10^3 \ \mathrm{W},$$

where d is the diameter of the resonator.

The limiting power which can be produced by the system is assumed to be governed by the product $\alpha_0 I_H V$ (where V is the volume of the resonator). For optimum operation $P_{\alpha_0 I_H} = 14 \cdot 10^3$ W. The fact that $P_{\alpha_0 I_H}$ is greater than $P_{\max}$ is due to the fact that under the experimental conditions the reserve of vibrational energy of $(N_{N_2^*} + N_{CO_2 00^\circ 1})$ is limited, and there is no boosting mechanism. This leads to a change in parameters of the inverted medium over the diameter of the resonator.

As can be seen from Fig. 3, the maximum power recorded in the experiment is 1.5 kW. If we assume that the parameters of the inverted medium do not change appreciably during its motion through the resonator, then, taking into account the losses in the latter, the limiting power which should be extracted from the laser is

$$W_1 = \frac{\pi d^2 I_H \tau}{4(2-\tau)} \left[\frac{\alpha_0 L}{\ln[(1-\tau)(1-\eta)]^{-1/2}} - 1 \right].$$

Here η is the total dissipative loss in the resonator ($\eta \approx 10 \cdot 10^{-2}$), and τ is the transmittance of the exit mirror of the resonator ($\tau \approx 20 \cdot 10^{-2}$). The coefficient $(2 - \tau)$ takes into account the two directions of propagation of the radiation.

With the above-mentioned parameters of the resonator $W_1 = 5.4 \cdot 10^3$ W. The difference between W_1 and the experimental value W_2 is due to the fact that when calculating W_1 we ignored the considerable change in the inversion when the medium moves through the resonator.

The correspondence between experiment and the above estimates enables us to designate the quantity $W_{\max} = 25\ \mathrm{W/cm^3}$ as the limiting power density which this medium is capable of delivering.

We will compare the above method of excitation with the method of independent injection of cold CO_2 into a jet of excited nitrogen [3]. The advantages of the latter method of excitation are obvious: in this case the danger of dissociation of CO_2 molecules disappears and one can increase the power in the discharge, thereby increasing the concentration of vibrationally excited nitrogen.

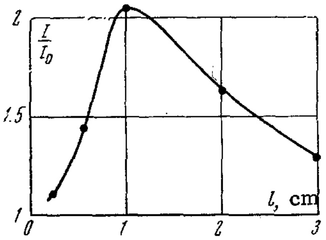

Fig. 4

Cold CO_2 was injected into the above-mentioned arrangement. The principles of operation of the mixing system employed can be understood from Fig. 1. Nitrogen (with or without the addition of helium) was excited in the channels 8. CO_2 was pumped into the tube 13 and discharged into the chamber through an opening in this tube (the diameter of the opening was 1 mm). The jet of excited nitrogen absorbed the CO_2, and the excitation was transferred as the mixture of gases traveled downstream.

Table 2 shows the main characteristics of the optimum operating conditions of the model with combined and independent injection of CO_2.

As can be seen from the table, the parameters of the optimum operating conditions are quite close. It should be noted that in the case of independent mixing, helium is not an essential component of the working mixture.

The maximum value of the product $\alpha_0 I_H$ is reached at comparatively low densities. As the density increases the saturation intensity increases somewhat, but a reduction in the small-signal gain leads on the average to a reduction in the product $\alpha_0 I_H$. The addition of helium to the excited nitrogen increases the small-signal gain, but the saturation intensity decreases, and the product $\alpha_0 I_H$ is less than without helium.

The parameters attained in the arrangement with independent gas mixing are not the limiting ones. The efficiency with which vibrational energy excitation is transferred is quite low due to poor mixing of the gases.

The presence of poorly mixing gas jets with different refractive indices leads to refraction effects which are easily detected when investigating lasing. Despite the high gain of the medium, under most circumstances lasing is not observed in the first resonator and is observed in the second (further) resonator. If τ, α_0, and I_H are known, then by measuring the laser power one can estimate the effective distributed losses due to refraction. For the mode of operation corresponding to the third line in Table 2, the loss level $\delta \sim 10^{-2}\ cm^{-1}$ in the far resonator.

The presence of nonuniformities due to poor mixing is most clearly shown at high pressures. Figure 4 shows the small-signal gain as a function of the distance to the output of the discharge channels for a jet with p = 1 atm. The existence of a maximum on the curve is due to competition between two processes: mixing of the jets, which leads to an increase in the inversion, and combined relaxation of the molecules of excited N_2 and CO_2. Estimates of the relaxation time of the mixture ($CO_2 : N_2 = 1:1$) show [4] that the inversion should disappear at a distance of several millimeters from the outlet. The existence of a high gain at a distance $l = 3$ cm confirms the very poor mixing. Note that at a high gain α_0 ($\alpha_0 = 3.5 \cdot 10^{-2}\ cm^{-1}$) lasing, in general, is not observed. This can only be explained by the presence of high-density gradients which lead to detuning of the resonator. For a characteristic jet size of $2R \approx 0.3$ cm the deflection of the beam due to the difference in refractive index of CO_2 and N_2 in a length L = 20 cm, $\varphi \sim L(n_{CO_2} - n_{N_2})/R$ may reach a degree (n_{CO_2}, n_{N_2} are the refractive indices of CO_2 and N_2 and R is the scale of the inhomogeneities).

It follows from the above data that in systems with independent mixing it is not possible to use completely the store of vibrational excitation energy due to poor interpenetration of the jets. To improve the energy efficiency, it is necessary to reduce the diameter of the initial jets and attempt to achieve turbulent mixing.

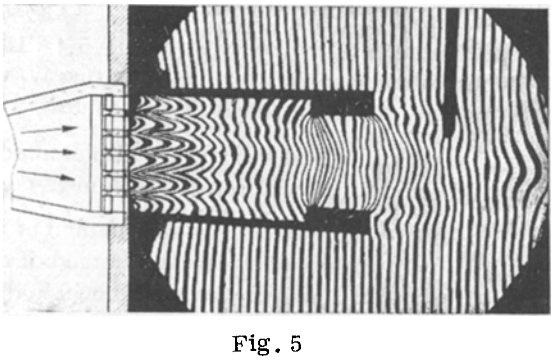

Fig. 5

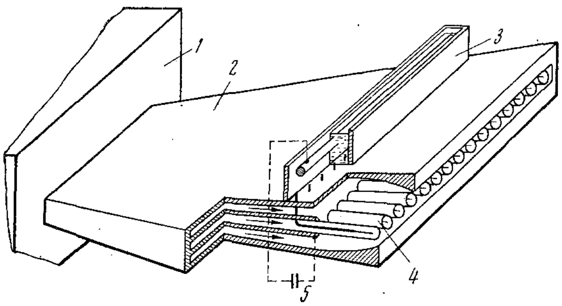

Fig. 6

When a previously prepared mixture is forced through discharge gaps, the situation is simplified considerably since N_2^* ($v = 1$) and $CO_2^{00^\circ 1}$ are in equilibrium at any point of the medium. It is worth noting a difficulty of another kind, which arises when exciting a mixture in discharge channels of the kind shown in Fig. 1. This difficulty arises due to the nonuniformity of the current distribution over the channel radius.

Figure 5 shows an interferogram of the flow field for $p^* = 40$ torr, which illustrates the inhomogeneity of the density distribution at the output of the discharge gap. The gas density along the axis of the channel is approximately twice that at the periphery, which indicates the lower temperature on the axis. This form of gas density distribution forces us to the conclusion that the discharge is heated mainly in the boundary region, as a result of which the heat transfer to the walls may be considerable and the excitation efficiency of the mixture therefore reduced. As estimates show, the ratio of the total energy contained in the gas (vibrational, rotational, and thermal) to the energy introduced into the discharge is 50% in this case.

The nonuniformity of the current distribution over the cross section of the channel is not a fundamental effect. The nonuniformity disappears in the construction shown in Fig. 6, which was used at high pressures with the gas jet emerging directly into the atmosphere. The component parts of the apparatus in Fig. 6 are as follows: 1 is the gas reservoir, 2 are the accelerating sections, 3 is a water resistance to decouple the separate channels, 4 are the discharge electrodes, and 5 is the system of discharge channels. The use of this construction at moderate pressures ($p \sim 0.1$ atm) should considerably improve the power characteristics of the laser.

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