OPTIMIZATION AND LIMITING CHARACTERISTICS OF CO_2 LASERS

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It is shown that the limiting characteristics of CO_2 lasers are determined mainly by two parameters: the specific power of the electric discharge, referred to the square of the active medium pressure, and the product of the pumping time and the gas pressure. An investigation is made of the dependence of the efficiency and the radiation pulse shape over a wide range of the parameters. For the first time it is noted that the energy from the lower laser level can be given to the upper vibrational states of the symmetric and deformed modes, which allows high radiation density, ~0.2 J/cm^3·atm, to be achieved, as is shown by calculation. Because of energy redistribution in the asymmetric mode the limiting gain coefficient in C_{02} lasers is $\simeq 0.12$ cm^{-1}.

Published experiments [1-6] have established limiting values of the most important quantities characterizing the efficiency of CO_2 laser systems in which the optically active medium is generated by means of an electric discharge. It has been shown that in the electric-ionization type of laser the gain factor K reaches 12% with a specific power of absorbed electrical energy $Q/p \simeq 1$ J/cm^3·atm. In lasers with a twin transverse discharge (TEA systems), because of the higher initial value of the parameter E/p, necessary to create a volume discharge, the limiting gain factor does not exceed 5% with $Q/p = 1$ J/cm^3·atm. However, as is shown by experiment, independently of the method of generating the inversion medium by means of an electric field, there is a limiting energy absorbed in the electrical discharge $Q/p = 0.8-1$ J/cm^3·atm, beyond which one observes the development of instability and transition of the discharge into a spark. The minimum time for instability development at a pressure of 1 atm is $t^* = 2\cdot 10^{-7}$ sec. Preliminary experiments conducted with very rapid pumping, accomplished in a time less than the instability development time, i.e., $t_{ins} < t^*$, have shown that there is a real possibility of reaching very high values of $Q/p = 3-5$ J/cm^3·atm. It is clear that the prospects for further development of compact amplifying and generating systems with CO_2 are determined by the possibility of using the limiting characteristics of the inversion medium obtained.

The present paper addresses mathematical modeling of the processes governing the dynamics of creating an inversion medium in CO_2, the object being to establish a more general approach in solving practical problems associated with the investigation and production of specific laser systems.

1. In order to seek optimal and limiting characteristics of CO_2 lasers in which the active medium is excited by an electrical discharge, we conducted computer solution of the system of equations describing a volume discharge and the active medium in a laser radiation field. The calculations were made for pulsed systems with constant power level added to the discharge of electrical energy. Experiments conducted with electric ionization and TEA lasers have shown that this regime may be realized in most cases.

The program examined the following scheme: at time zero an electron beam with constant current density and 100 keV energy was injected into the discharge gap, filled with a mixture $CO_2:N_2 = 1:2$ at a pressure of p = 1-10 atm. Simultaneously, a voltage was applied to the discharge from a source capable of

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TABLE 1

Constants	$W_{3.4}$	$W_{1.2}$	$W^{+}_{3.1}$	$W^{-}_{3.1}$	$W^{+}_{2.0}$	$W^{-}_{2.0}$
Relaxation-rate constants; Literature	$4{,}8\cdot10^{6}$ 30, 22, 24	$7{,}2.10^{8}$ 30, 26	$2\cdot10^{5}$ 30, 23—25	$7\cdot10^{4}$ 30, 23—25	$1{,}5\cdot10^{5}$ 30, 27, 28	$7\cdot10^{4}$ 30, 29

W_j[sec^{-1}, atm^{-1}]

maintaining a constant level of E/p =21 V/cm · torr during the whole time of application of the electron beam. A resonator of length l = 1 m was formed by two mirrors (fully reflecting and semitransparent) with a reflectance of R = 0.38, and the active medium length L was 70 cm.

As was established from the above calculations, the limiting power of radiative energy $Q_r/p = 0.2$ J/cm^3 · atm can be achieved only in mixtures without helium for rather fast pumping over a time less than the instability development time of ~200 nsec. The value E/p = 21 V/cm · torr assumed in the calculation satisfies the requirement of efficient transfer of electrical energy to the CO_2 and N_2 molecules [7, 8] and makes it possible, for a high discharge power level, to achieve limiting energy characteristics and to expand the region of application of these calculations for other laser systems. Thus, in TEA lasers the best regime for absorption of electrical energy is accomplished with E/p = 25 V/cm · torr [6].

The computer calculations are based on a model in which the CO_2 and N_2 molecules are considered as a set of harmonic oscillators with a Boltzmann distribution of vibrational level populations [9, 10]; the relaxation of vibrational energy is accounted for in the scheme proposed in [11]. The relaxation levels are identified with regard to the mean number of vibrational quanta e_i of the CO_2 and N_2 molecules, where i = 1, 2, and 3 corresponds to the symmetric, deformed, and asymmetric vibrational CO_2 modes, i = 4 corresponds to N_2, and the following processes are taken into account:

$$CO_2(00^00)+N_2(1) \rightleftarrows CO_2(00^01)+N_2(0) \quad W_{3.4};$$
$$CO_2(00^01)+X \rightleftarrows CO_2(11^10)+X \quad W_{3.1};$$
$$CO_2(00^01)+X \rightleftarrows CO_2(03^00)+X \quad W_{3.2};$$
$$CO_2(01^10)+X \rightleftarrows CO_2(00^00)+X \quad W_{2.0};$$
$$CO_2(10^00)+CO_2 \rightleftarrows CO_2(02^00)+CO_2 \; W_{1.2};$$
$$CO_2(00^01)+h\nu \rightleftarrows CO_2(10^00)+2h\nu \quad W_{\nu}.$$

The $CO_2(00^01)$ relaxation rate constants, well known in the literature, equate $W_{3.1} = W_{3.2}$, which is impossible, since $W_{1.2} \gg W_{3.1}$. Here X is any of the CO_2 or N_2 particles, the subscripts + and − refer to CO_2 and N_2 molecules, respectively, and $W_{3.1} = W^{-}_{3.1} + W^{+}_{3.1}$; $W_{3.2} = W^{-}_{3.2} + W^{+}_{3.2}$; $W_{2.0} = W^{-}_{2.0} + W^{+}_{2.0}$; the temperature dependence of the relaxation-process rate constant W_j was chosen from the papers cited in Table 1, in which the values of W_j are referred to T = 300°K and 1 atm pressure. In describing the heating of the gas the basic channel is taken into account, i.e., relaxation of vibrational energy into translational energy.

The radiative intensity was calculated on the assumption of a single-mode lasing regime to a single 20-fold rotational–vibrational R-branch transition [12, 13]. In forming the volumetric discharge plasma a homogeneous distribution of electric field and electron concentration [1] was assumed, calculated with allowance for ionization by the electron beam in the electric field, as well as recombination and capture.

The vibrational state population is determined by the energy contained in the mode and the concentration of molecules, and therefore the pumping M_i of the active medium can be expressed in terms of the specific discharge power M = enVE and the fraction of energy going to excite the i-th vibrational mode; $M_i = B_iM$, where e, n, and V are the charge, concentration, and drift velocity of the electron; E is the electric field intensity. The dependence of B_i on the mixture composition and E/p were given in [8]. For $Q/p > 1$ J/cm^3 · atm one must take into account the deexcitation by discharge electrons of the N_2 and CO_2 vibrational states. The values of the rate constants $\nu_{\lambda i}$ of multiquanta transitions of molecules on collision with an electron were determined approximately from the known cross sections [14] and the distribution function for electrons in N_2 [7], and this is evidently permissible, since the energy balance is determined mainly by nitrogen for the given values of E/p and the given gas mixture. The rate of change of the mean number of vibrational quanta of the i-th mode has the form

$$g_i = M_i/E_i N_{\pm} \quad n\sum_{\lambda=1} \lambda \nu_{\lambda i} \exp(\lambda E_i/U) \sum_{m=\lambda} N_{mi},$$

where T_i and E_i are the temperature and energy of the vibrational quanta of the i-th mode; N_+ and N_- are the concentrations of CO_2 and N_2 molecules; λ is the number of vibrational quanta excited per unit electron collision; U is the mean effective electron energy; N_{mi} is the ratio of the population of the m-th vibrational level to N_+ for CO_2 and to N_- for N_2. In CO_2 $\lambda = 1$, since the excitation cross section for $\lambda = 2$ is small; in nitrogen we accounted for processes with $\lambda = 1-6$. With the above assumptions the system of equations describing the dynamics of the laser processes has the following form:

$$de_1/dt = -W_{3.1}\Gamma_3 + W_{1.2}\Gamma_2 + g_1 + KI/C_0 p;$$
$$de_2/dt = -3W_{3.2}\Gamma_1 - W_{3.1}\Gamma_3 + 2W_{2.0}\Gamma_4 - 2W_{1.2}\Gamma_2 + g_2;$$
$$de_3/dt = -W_{3.4}(e_3 - e_4)\psi_- + W_{3.2}\Gamma_1 + W_{3.1}\Gamma_3 + g_3 - KI/C_0 p;$$
$$de_4/dt = W_{3.4}(e_3 - e_4)\psi_+ + g_4;$$
$$dT/dt = \frac{N_+\left[-\left(E_3 - E_1'\right) W_{3.1}\Gamma_3 - 3\left(E_3 - E_2'\right) W_{3.2}\Gamma_1 - 2E_2 W_{2.0}\Gamma_2\right]}{p\left(c_+\rho_+\psi_+ + c_-\rho_-\psi_-\right)};$$
$$dI/dt = CI(K - |\ln R|/2L)L/l;$$
$$dn/dt = (\alpha - \alpha')Vn + <\sigma_0 V_0> n_0 N - \beta n^2;$$
$$e_i = r_i \exp(-E_i/k'T_i)/(1 - \exp(-E_i/k'T_i).$$
$$\text{for} \quad t=0 \;\; e_i = e_{i0};$$
$$\Gamma_1 = {}^1/_2[\exp(-500/T)(1+e_3)(e_2/2)^3 - e_3(1+e_2/2)^3;$$
$$\Gamma_2 = \exp(-80/T)(1+e_1)(e_2/2)^2 - e_1(1+e_2/2)^2;$$
$$\Gamma_3 = 1/2[\exp(-420/T)(1+e_3)e_1 e_2/2 - e_3(1+e_1)(1+e_2/2)];$$
$$\Gamma_4 = (e_{02} - e_2)/(2+e_{02}),$$

where r_i, E_+, T, I are the level of degeneracy of the oscillations, the radiative quantum energy, the gas temperature of the active medium, and the radiative intensity in the resonator, respectively; c_+, c_-, ρ_+, ρ_- are the heat capacity and density of CO_2 and N_2; $\psi_+ = N_+/N$, $\psi_- = N_-/N$; $C_0 = 2.4 \cdot 10^{19}\psi_+ E_+$; and σ_0 is the cross section for ionization of active-medium molecules by an electron beam with electron concentration n_0 and speed V_0. With a constant E/p = 21 V/cm · torr the ionization coefficients in nitrogen are $\alpha/p = 5 \cdot 10^{-4}$ cm^{-1} [15], in CO_2 $\alpha/p = 4 \cdot 10^{-3}$ cm^{-1} [16], for capture in $CO_2 - \alpha'/p = 10^{-3}$ cm^{-1} [17], for recombination $\beta = 2 \times 10^{-7}$ $sec^{-1} \cdot cm^{-3}$, and the drift speed of the electrons in the discharge $V = 6 \cdot 10^6$ cm/sec [8]. The gain factor can be expressed in the form [13]

$$K = \sigma[N(00^01) - N(10^00)]/p;$$
$$\sigma = 10^{-17}(25.8 - 8.98 \cdot 10^{-2}T + 1.2 \cdot 10^{-4}T^2 - 5.8 \cdot 10^{-8}T^3). \tag{1.1}$$

The vibrational state populations are expressed in terms of the mean number of vibrational quanta and the quantum numbers v, v_1, v_2, v_3 for nitrogen and CO_2, respectively, for the symmetric, deformed, and asymmetric modes:

$$N(v) = N_- e_4^{v}/(1 + e_4)^{v};$$
$$N(v_1 v_2 v_3) = \frac{4N_+(1 + v_2)\, e_1^{v_1} e_2^{v_2} e_3^{v_3}}{(1 + e_1)^{1+v_1}(2 + e_2)^{2+v_2}(1 + e_3)^{1+v_3}}.$$

The system of differential equations constituting the mathematical program was solved on a computer by a Runge–Kutta method. The efficiency of the model was checked [4] by comparing it with known experimental results (1, 3, 18, 19]. It was shown that, in spite of a certain indeterminacy in the values of constants used in the model, the results of the computations differed from the experimental values by not more than 25%, which can be considered satisfactorily at the present time.

2. The analysis and optimization of CO_2 lasers is appreciably simplified by introducing parameters determining the efficiency and the gain factor, independent of the pressure and method of maintaining the electrical discharge. In fact, the equation of the mathematical code can be represented in structural form, by dividing the right side by the concentration of the appropriate molecules, expressed in terms of the initial

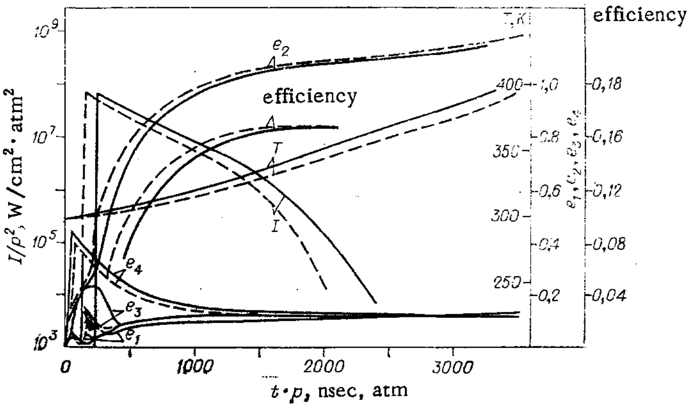

Fig. 1

pressure p of the working medium:

$$de_i/d\tau = \sum_j \varphi_j f_j(e_1, e_2, e_3, e_4) + g_i/p + \delta K I^*/C_0; \tag{2.1}$$

$$dI^*/d\tau = I^*(K - |\ln R|\ /2L)cL/lp; \tag{2.2}$$

$$dT/d\tau = f(e_1,\ e_2,\ e_3,\ e_4), \tag{2.3}$$

where τ = pt, $I^* = I/p^2$, $\delta = \pm 1$ for i = 1, 3 and $\delta = 0$ for i = 2, 4.

In Eqs. (2.1)-(2.3) it was assumed that the concentration of CO_2 and N_2 molecules, expressed in terms of the initial pressure, does not change throughout the radiative pulse, since we are considering processes whose time is considerably less than the time for the gas to expand due to heating. Expressions of the type $\sum_j \varphi_j f_j$ determine the relaxation in terms of the j-th channel, the probability for which is represented in the form $W_j = p\varphi_j\psi_\pm$, where φ_j is the temperature dependence of the relaxation probability in terms of the j-th channel; f_j are coefficients depending on the vibrational temperatures of the CO_2 and N_2 molecules. Thus, the right sides of the equations governing the dynamics of the inversion and laser transitions consist of terms of the following type: $\varphi_j f_j$, g_i/p, KI^*/C_0, f. Clearly, the solution will not depend on the pressure, if the quantities $g_i/p \sim M/p^2$ and KI^* remain constant during transition to another value of p, as well as the time of action M/p^2 i.e., pt_{inst}. By choosing M and the time of action of the pumping, one can hold M/p^2 and pt_{inst} constant, and, as will be shown below, the quantity KI^* will then also be independent of p, since $I \sim p^2$, and $K \sim Q/p = M/p^2 pt_{inst}$.

Therefore, for $I^* = 0$, the solution of the system (2.1)-(2.3) will not depend on the gas pressure and is determined by two parameters: the ratio of the specific electric discharge power to the square of the active-medium pressure M/p^2, and the product of the pumping time by the pressure pt_{inst}. For $I^* \neq 0$ the self-similarity may first be perturbed, since the factor M/p^2 which depends on p enters into the equation for I^*, and transition to a different pressure is equivalent to change in the ratio between the lengths of the active medium and the resonator. Figure 1 shows the solution of the system of equations for two pressures, 5 and 10 atm, and the constant values of M/p^2, pt_{inst}. It can be seen that the increase in pressure leads to delay in the radiative pulse and to displacement of the other solutions. However, after a time τ, depending on the pressure, the solutions practically coincide.

The calculations performed have shown that the efficiency and the specific energy characteristics of CO_2 lasers in the region where the linewidth of the rotational-transition (p = 0.1-10 atm) depends linearly on pressure are, in fact, determined by the quantities M/p^2 and pt_{inst}. The ratio of the energy injected into the discharge to the pressure is expressed in terms of these same parameters.

The equation for electron concentration does not enter into the system (2.1)-(2.3), since the dynamics of laser processes and the specific energy characteristics in the approximation used in the model are given by the quantities M/p^2 and pt_{inst}. The solution was carried out in order to determine the effectiveness of using an electron beam as a means of ionizing the active medium.

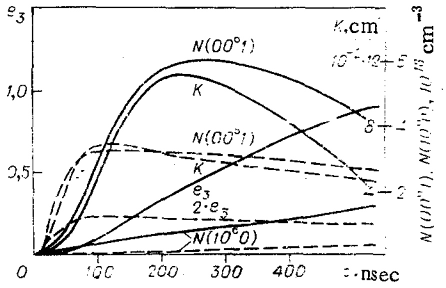

Fig. 2

As will be shown below, in the region $Q/p = 0.2-1\ J/cm^3 \cdot atm$ the efficiency is not very sensitive to change in M/p^2 and pt_{inst}, and therefore for many CO_2 lasers one can use average values for these quantities. Continuous-wave CO_2 lasers can be considered as pulsed with pumping duration determined by the time for heating and cooling of the active medium. This considerably simplifies analysis of CO_2 lasers: Optimization reduces to choice of values of M/p^2 and pt_{inst} for which the efficiency is a maximum. One can vary M/p^2 by means of the applied electric field or the external source of ionization.

We turn now to one important fact which must be taken into account for practical use of the model, particularly for large values of Q/p. The system of equations describing the dynamics of inversion-medium generation and laser transition does not contain the energy-conservation law in explicit form. This indicates that the use of the drift approximation and the expression for the rate of energy transfer from the external electric field to vibrational states of N_2 and CO_2 molecules requires further justification.

As the calculations have shown, even for $Q/p = 1\ J/cm^3 \cdot atm$ a considerable number of molecules are in an excited vibrational state, so that the process of exciting them with an electron beam is real. This process, as was shown in [7], leads to an increase in the high-energy part of the electron-distribution function, and it therefore becomes possible to develop a volumetric discharge instability [2, 5]. To account correctly for the effect of the level of population of vibrational states and their temperatures on the electron-distribution function one must rigorously solve the Boltzmann equation to find the correct values of the quantity M/p^2, pt_{inst}. However, it was shown in [7] that the drift approximation can be used even for high vibrational temperatures, up to $T \doteq 4000°K$ (this corresponds to $Q/p = 0.8\ J/cm^3 \cdot atm$), since, in spite of the appearance of the high-energy part of the distribution function, the average effective electron energy varies very little with increase of vibrational temperatures.

3. Most of the theoretical and experimental investigations dealing with an analysis of CO_2 lasers [1, 3, 5, 10, 18, 19] were performed for regimes which do not have a high enough level of energy absorbed in the discharge $Q/p = 0.2-0.5\ J/cm^3 \cdot atm$, nor high enough N_2 and CO_2 vibrational temperatures $T_i < 4000$ K.

The present paper attempts to study the possibilities of CO_2 lasers over a wide range of injected energy densities $Q/p = 0.01-3\ J/cm^3 \cdot atm$, which corresponds to higher vibrational temperatures.

The region $Q/p > 1\ J/cm^3 \cdot atm$ is characterized by the fact that in the process of pumping the active medium a considerable fraction of the CO_2 and N_2 molecules exists in an excited vibrational state. Starting at a certain time when depletion of the zero vibrational level occurs, subsequent increase in the energy of a given type of oscillation can occur because of increase in the average vibrational energy of the molecules, i.e., increase in the population of the higher vibrational states from transition of molecules from lower levels, which leads to a reduced population of the latter. When there is a Boltzmann distribution of vibrational levels within a mode the population of any vibrational state has a maximum for a specific vibrational temperature, above which the population diminishes. The presence of a maximum population of vibrational level can cause two effects that are important for CO_2 lasers: the existence of a limiting available gain factor $\sim 0.12\ cm^{-1}$ and the possibility of obtaining high absorbed-energy densities.

Figure 2 illustrates the existence of a limiting gain factor and the dependence of the characteristic time for variation in the gain factor on Q/p. Two regimes are shown in the absence of lasing: the solid lines correspond to $Q/p = 2.5\ J/cm^3 \cdot atm$ and the broken lines, to $Q/p = 0.26\ J/cm^3 \cdot atm$. In the first case the active medium is pumped throughout the whole time shown in Fig. 2, and therefore e_3, the average numver of vibrational quanta of the asymmetric CO_2 mode, increases, while the N (00^01) population, and, consequently, the gain factor, having reached a maximum, diminish. This occurs because the $CO_2(00^00)$ population decreases in the $CO_2(00^00) + N_2(1) \rightleftharpoons CO_2(00^01) + N_2(0)$ processes and even for $e_3 \approx 0.5$ a considerable number of molecules are already excited. Further increase in e_3 can proceed because of excitation of higher $CO_2(00^0\ v_3)$, vibrational states, $v_3 > 1$, which leads to a reduction in the $CO_2(00^01)$ population and in the gain factor. For $Q/p > 1\ J/cm^3 \cdot atm$ a considerable number of molecules with asymmetric types of oscillation are in bound states $CO_2(01\ v_3)$, $CO_2(02\ v_3)$, etc. Calculations show that the limiting gain factor of CO_2 lasers ($K = 0.12\ cm^{-1}$) is reached with $Q/p = 1\ J/cm^3 \cdot atm$. This result was first obtained experimentally in [2]. The maximum gain factor depends on the value of E/p exciting the active medium. For example, in TEA CO_2

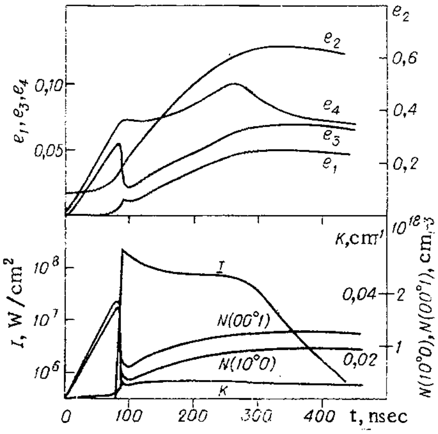

Fig. 3

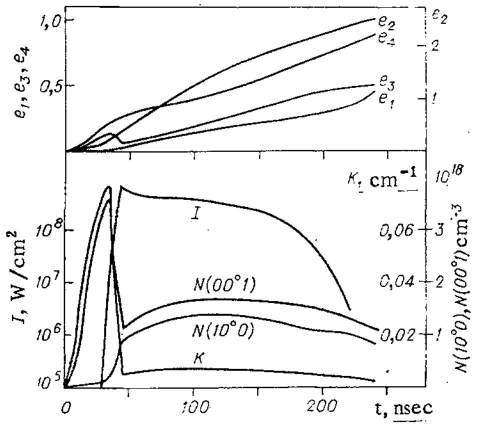

Fig. 4

lasers, where $E/p \simeq 30$ V/cm·torr, $K = 0.03$-0.05 cm^{-1}, which is due to a decrease in the efficiency of nitrogen excitation.

For comparison, Fig. 2 shows a regime where the energy $Q/p = 0.26$ J/cm^3·atm is absorbed for a time $t_{inst} = 50$ nsec. For small values of Q/p the CO_2 (00^01) population and the gain factor reach their highest values at the maximum of e_3, and then diminish with a characteristic relaxation time. Figure 2 shows that the gain factor $K \sim Q/p$, and the lifetime of the gain diminishes with increase of Q/p. The latter is connected with the fact that for large of values of Q/p the rate of energy transition from N_2 to CO_2 (00^01) is greater, and, consequently, the N (00^01) population decreases more rapidly. The dependence of the characteristic lifetime of the gain on the density of injected energy was first noted in the experiments of [20]. The dependence of the gain lifetime on Q/p must lead to a limitation in the duration of a probing signal when an active medium with $Q/p > 1$ J/cm^3·atm is used an an amplifier.

We consider operation of CO_2 lasers in a lasing regime in order to determine the processes governing the efficiency and the radiative pulse shape for various values of M/p^2 and pt_{inst}. Figure 3 shows variation of the lasing characteristics during the pulse for conditions frequently realized in CO_2 lasers: $Q/p \doteq 0.2$ J/cm^3·atm, $M/p^2 = 0.27$ V/cm·torr, $p = 5$ atm.

Figure 3 shows that during lasing one obtains an almost constant gain factor, determined by losses in the resonator and by the population of the lower lasing level. The value of CO_2 (10^00) is determined by equilibrium between two processes: the rate of population $CO_2\ (00^01) + h\nu \rightarrow CO_2\ (10^00) + 2h\nu$, which is proportional to $(e_3 - e_4)$, i.e., to Q/p, and the opposite process, the emptying of the symmetric and deformed CO_2 modes. It is clear that the greater the population of the CO_2 (10^00) level, the larger is the value of $e_3 = e_4$ remaining after lasing ceases and the smaller the efficiency. Therefore, for small Q/p addition of the gases H_2, He, and H_2O can reduce the CO_2 (10^00) population, and therefore the efficiency must be higher.

The processes occurring in CO_2 lasers at high $Q/p > 1$ J/cm^3·atm are illustrated by the example of Fig. 4 ($M/p^2 = 2.7$ W/cm^3·torr^2, $Q/p = 2$ J/cm^3·atm, $p = 5$ atm). The main special feature of lasing in this region of Q/p is the presence of a maximum in the population of the lower lasing level, which allows high densities of energy absorbed per unit volume of active medium, using the CO_2 states CO_2 (v_100), CO_2 $(0v_20)$, $(v_1 > 1,\ v_2 > 2)$ as a reservoir, to which energy is given from CO_2 (10^00). Figure 4 shows the regime when relaxation in the thermal energy of the symmetric and deformed modes lags behind the population because of radiation. This leads to an increase in the average number of vibrational quanta e_1 and e_2 and to a corresponding increase in the population of the lower lasing level, but at 150 nsec the CO_2 (10^00) begins to diminish, although lasing continues and e_1 and e_2 increase. The reason is that the zero vibrational CO_2 state is depleted during the lasing because of the above processes, and at $t = 150$ nsec only 30% of the CO_2 molecules remain in the zero vibrational CO_2 (00^00) level. Therefore, the CO_2 (10^00) molecules collide mainly with excited molecules and energy is transferred from the CO_2 (10^00) to higher vibrational states. For the same reason the CO_2 (00^01) population diminishes for $t > 150$ nsec, although e_3 increases. For $t > 240$ nsec the gas is already heated enough, the losses from relaxation of CO_2 (00^01) exceed the pumping power, and, therefore, e_3 diminishes. The lasing is curtailed for $t > 200$ nsec because of overheating of the gas (T = 600 K) and reduction in the population of the upper lasing level.

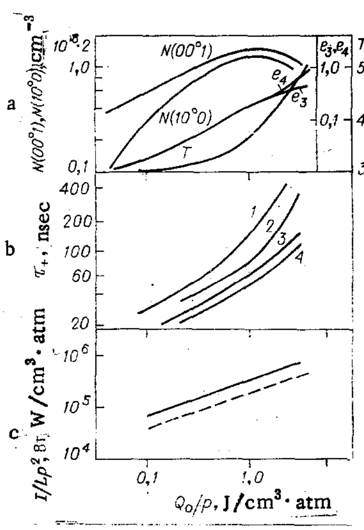

Fig. 5

Thus, to achieve high specific characteristics of radiated energy the excitation of the active medium and conversion of vibrational CO_2 and N_2 energy into radiation must be accomplished rapidly enough so that the energy from the symmetric and deformed CO_2 modes is not able to relax and the gas does not become heated. It is clear that He, H_2O, and H_2 empty the lower lasing level effectively, and the efficiency will decrease for $Q/p > 1$ J/cm³ · atm.

The second important peculiarity of lasing at high Q/p is the high and almost constant level of radiative intensity. This results from a high rate of energy transmission from N_2 to CO_2 $(00^0\ v_3)$, and from the fact that the high radiated power level does not lead to an increase in population of the lower lasing level, but, starting at a certain time, when the CO_2 (00^00) is emptied noticeably, leads to a decrease in CO_2 (10^00).

For various values of Q/p these processes determine the efficiency and the moment when lasing stops, as can be seen in Fig. 5a, which shows the dependence on Q/p of the quantities N (10^00), N (00^01), e_3, e_4 and T at the time when lasing ceases.

For $Q/p \leqslant 0.1$ J/cm · atm the lower lasing level can empty, since the radiative power is small, and therefore N (10^00) does not affect the lasing, which is stopped by reduction in the upper level populations. For larger values $Q/p = 0.1-0.5$ J/cm³ · atm the rate of energy transmission from N_2 to CO_2 (00^01) and the radiative intensity are greater, which leads to a larger value of the N (10^00) population level. Since N (00^01) − N (10^00) = const, which is determined by the gain factor in the lasing being equal to the losses in the resonator, the N (00^01) population and e_3 at the moment when lasing ceases will be larger, which leads to reduced efficiency for $Q/p > 0.2$ J/cm³ · atm. In a given range of Q/p the efficiency depends on the lower lasing-level population and, to a certain degree, on the gas heating; therefore, the efficiency may be increased by adding gases to the mixture which will efficiently quench the CO_2 (10^00). For $Q/p > 1$ J/cm³ · atm the N (10^00) population diminishes and lasing is stopped by gas heating and reduction in N (00^01). At the moment lasing ceases e_3 increases $(e_4 > e_3)$, but N (00^01) decreases, since mainly high-energy vibrational CO_2 $(00^0\ v_3)$ states are excited. With increase of Q/p the values of e_3 and e_4 remaining after lasing stops increase, which leads to a reduction in efficiency.

We now investigate the shape of the radiative pulse as a function of M/p^2 and pt_{inst}. Figure 5c shows the dependence of the peak rate of intensity, referred to the product of the square of the pressure p^2 and the length of the active medium, on Q/p (the solid line is for $M/p^2 = 30$ W/cm³ · torr², and the broken line is for

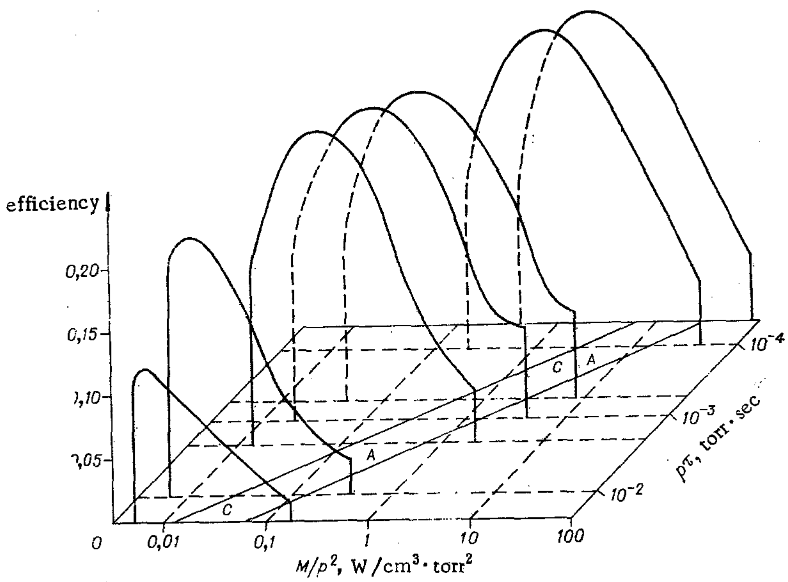

Fig. 6

$M/p^2 = 2$ W/cm$^3 \cdot$torr^2). The increase in intensity is determined by the fact that the N_2 population and the rate of energy transmission from N_2 to CO_2 ($00^0 v_3$) increase with increase in Q/p. For the same reason the quantity I/Lp^2 increases with increase of M/p^2. Calculations show that the quantity I/Lp^2 is practically independent of pressure.

The dependence of radiative pulse width on Q/p for various values of $M/p^2 = 2$; 5; 10; 20 W/cm$^3 \cdot$torr^2 is shown in Fig. 5b (curves 1-4). For a fixed M/p^2 the transition to large Q/p means an increase in the active-medium pumping time, which leads to an increased width in the radiative pulse. An increase in M/p^2 for Q/p = const leads to a reduction in the pulse width, since the vibrational energy cannot be transmitted from N_2 to CO_2 ($00^0 v_3$) and pumped into N_2; therefore, the rate of this process increases and vibrational energy is transformed more rapidly into radiation.

4. The investigation of the dependence of efficiency on M/p^2 and pt_{inst} is shown in Fig. 6.

We consider the basic relations shown in Fig. 6. The lines A−A and C−C corresponds to constant values of Q/p, 1; 0.2 J/cm$^3 \cdot$atm. For Q/p > 0.01 J/cm$^3 \cdot$atm there is lasing and an increase of efficiency with increase of Q/p, and for pt_{inst} = const this is associated with an increase in the excess energy injected into the discharge above the threshold value. The increase in the threshold value of Q/p and the decrease in efficiency for $pt_{inst} > 10^{-3}$ arise from an increase in the loss to relaxation of vibrational energy of the CO_2 asymmetric mode. The efficiency reaches the maximum value for Q/p = 0.18 J/cm$^3 \cdot$atm, and for $pt_{inst} < 10^{-3}$, where the CO_2 (00^01) relaxation is weak, the efficiency is practically independent of pt_{inst} and is ~0.24. The reduction of efficiency in the region Q/p = 0.2-1 J/cm$^3 \cdot$atm is due, for $pt_{inst} > 10^{-3}$, to gas heating, and for $pt_{inst} < 10^{-3}$ to the population of the lower lasing level during lasing, since the pt value of the CO_2 (10^00) relaxation is greater than 10^{-3} sec$\cdot$torr, even in a gas heated to this specific level. For Q/p> 1 J/cm$^3 \cdot$atm the efficiency decreases appreciably because of energy loss due to deactivation by discharge electrons of CO_2 and N_2 vibrational levels and because of a decrease in the CO_2 (00^01) population due to depletion of the zero CO_2 vibrational state. For Q/p > 1 the CO_2 (10^00) population at the maximum ceases to grow, since the energy is given to the higher vibrational states of the symmetric and deformed CO_2 modes. This circumstance allows us to achieve high radiative density values, $Q_r/p = 0.2$ J/cm$^3 \cdot$atm at an efficiency of 0.1, which may be important in the design of compact CO_2 lasers.

Thus, the investigations conducted have shown that the efficiency and the specific energy characteristics of CO_2 lasers are determined, for a given mixture of gases, by two parameters: M/p^2 and pt_{inst}. This simplifies the search for optimum conditions for CO_2 laser operation. Analysis of the properties of CO_2 lasers at high values of Q/p has shown that the limiting attainable gain factor of CO_2 lasers is ~0.12 cm^{-1}. If excitation of the active medium is sufficiently fast and for Q/p > 1 J/cm$^3 \cdot$atm one can achieve high values of radiative energy, 0.2 J/cm$^3 \cdot$atm at an efficiency of 0.1. In this case one should not add the vapor of He, H_2, and H_2O, since this will lead to heating of the gas and a decrease in efficiency. The optimum parameters of the external circuit can be chosen, using the dependence of the efficiency on M/p^2 and pt_{inst}.

The experiments confirm the basic conclusions of this work [3, 6, 21], but one should treat the dependence of efficiency for Q/p > 2 J/cm$^3 \cdot$atm with caution, since the model does not take into account the effect on the distribution function of quenching of the vibrational level of the CO_2 molecules by electrons.

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