Quantum Electronics **32** (2) 107 – 111 (2002)

PACS numbers: 42.55.Lt; 42.60.Jf; 42.60.Lh
DOI: 10.1070/QE2002v032n02ABEH002138

Numerical simulation of a CO laser pumped by a medium-pressure combined discharge

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***Abstract*.** **A model of a pulsed CO laser pumped by a medium-pressure combined discharge at room temperature is discussed. The optimum parameters of the active medium (pressure, specific energy input, and the ratio E/p for different mixtures) at which the calculated efficiency for a mixture with the composition CO : He = 1 : 3 amounts to 14 % are calculated. The dependence of the output parameters on the additions of nitrogen and xenon to the working mixture is analysed.**

Keywords: *repetitevely pulsed CO laser, combined discharge, numerical simulation.*

1. Introduction

The interest in CO lasers is explained by their high specific characteristics, high quantum efficiency (~ 80 %), and an almost twice shorter wavelength compared to that of carbon dioxide lasers, which have gained the widest application in technology. However, applications of CO lasers are restricted by the fact that they operate at cryogenic temperatures. In this case the highest efficiency attained with such lasers is 63 % [1]. At room temperature, the efficiency drops by more than an order of magnitude even under the most favourable conditions, when the laser is pumped by an electron-beam-controlled nonself-sustained discharge [2].

We believe that the efficiency of a CO laser operating at room temperature can be increased by using the pressure range $p \leqslant 100$ Torr (when the effect of the collisional broadening of spectral lines is insignificant) and by selecting the pump-pulse duration that provides a sufficiently high population of the vibrational levels of CO along with a small gradient of the operating plateau of the distribution function.

In our opinion the above conditions can be most fully met if the working medium is excited by a medium-pressure combined discharge, which combines a short ($\sim 10^{-7}$ s) stage of self-sustained discharge and a long ($\sim 10^{-4}$ s) stage of nonself-sustained discharge. The main amount of energy is pumped during the nonself-sustained stage in an optimal electric field. The advantages of such an approach manifest themselves most fully in CO_2 lasers, where the excitation scheme contains no elements that would substantially limit the discharge current [3]. This type of discharge ensures the pumping of CO_2 lasers comparable in efficiency to the electroionisation method. The lasers excited by such a discharge are less complicated in design and have a number of advantages in performance.

The above discussion suggests that the use of medium-pressure combined discharges will make it possible to build a highly efficient TE CO laser operating at room temperature. It would be interesting to calculate the characteristics of a CO laser excited in this way.

2. Description of the model

We calculated the population dynamics of the vibrational levels of a CO molecule (36 levels were accounted for) in CO – He mixtures by employing a system of kinetic equations describing energy exchange between the different vibrational levels of the CO molecule (VV exchange), the conversion of vibrational energy to heat as a result of collisions (VT relaxation), excitation of vibrational levels by electron impact, and transitions related to stimulated emission and absorption of radiation. The distribution over the rotational sublevels was assumed to be of the Boltzmann type. A system of equations of this type can be found in Ref. [4]. If the mixtures contained nitrogen, we added a similar equation for the first vibrational level of the N_2 molecule, while into the equation for CO we incorporated terms responsible for VV exchange with N_2. The effect of higher vibrational levels of nitrogen on the kinetic of the medium was ignored due to the low population of these levels. The VV-exchange and VT-relaxation constants were calculated by the method developed in Refs [4, 5]. The temperature of the gas mixture needed for calculating these constants was determined by solving a temperature balance equation similar to that used in Ref. [6]. The electron-impact constants were calculated by using the Boltzmann equation, whose form and method of numerical solution were taken from Ref. [7].

To allow for lasing, into the system of equations we incorporated balance equations (similar to those used in Ref. [4]) for the photons that correspond to the vibrational–rotational transitions at which the gain higher than the threshold value is achieved. The stimulated emission and absorption cross sections were calculated by the method discussed in Refs [8, 11].

3. Results of calculations

3.1 Calculation of energy characteristics

To determine the validity of the model, we calculated the characteristics of an electroionisation laser operating at room temperature under the experimental condition described in

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Received 8 February 2000; revision received 10 December 2001
Kvantovaya Elektronika **32** (2) 107 – 111 (2002)
Translated by E.M.Yankovsky

Ref. [2]. The results of our calculations of the laser efficiency as a function of the specific pump energy and the calculated shape of the radiation pulse are depicted in Fig. 1. Clearly, there is satisfactory agreement between the calculated and experimental efficiencies for the pressures $p = 0.4$ and 0.5 atm and between the shapes of the radiation pulses. This suggests that the results of our calculations are reliable when combined discharge pumping is used.

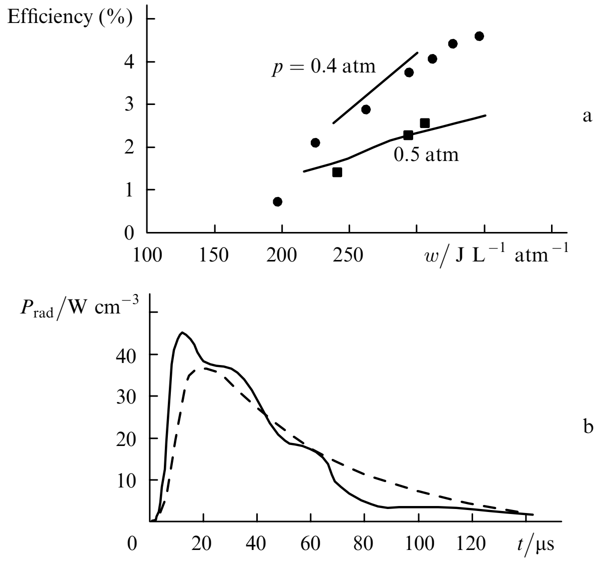

Figure 1. (a) Efficiency of a laser pumped by an electron-beam-controlled discharge as a function of the specific energy input w for two pressures of a mixture with the composition $CO:N_2:He = 1:6:7$ (the circles and squares are experimental results; the solid curves are calculations); (b) the shape of the radiation pulse for a mixture of the same composition at $p = 0.4$ atm and $w = 275$ J L^{-1} atm^{-1} (the dashed curve is the experimental; the solid curve is calculations).

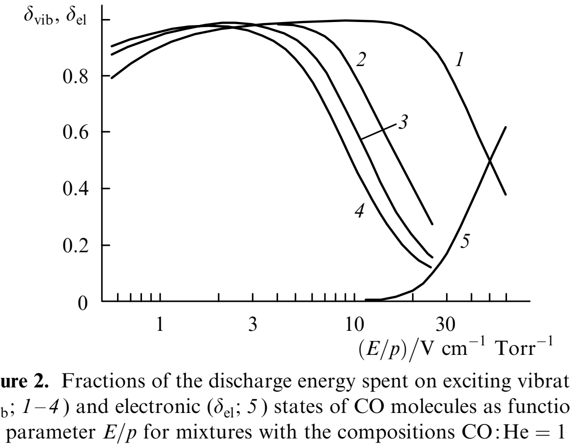

Figure 2. Fractions of the discharge energy spent on exciting vibrational (δ_{vib}; *1–4*) and electronic (δ_{el}; *5*) states of CO molecules as functions of the parameter E/p for mixtures with the compositions $CO:He = 1:0$ (*1* and *5*), 1:3 (*2*), 1:6 (*3*), and 1:9 (*4*).

One of the advantages of the combined discharge is that the main energy input occurs when the electric field is optical for laser pumping. To determine the energy input, we calculated the fraction of the discharge energy spent on vibrational excitation of CO, as a function of the reduced electric field strength E/p for different mixtures (Fig. 2). One can see that the optimal value of E/p increases from 1.5 to 12 V cm^{-1} Torr^{-1} as the fraction of CO in the mixture grows from 10 % to 100 %. However, for all the mixtures considered this value is within the region of nonself-sustained discharge, since at electron concentrations 10^{11}–10^{12} cm^{-3} characteristic of the experiments described in Ref. [3] the conditions needed for a nonself-sustained discharge to occur are met, i.e., recombination dominates ionisation:

$$K_{ion}N \ll n_e\beta\,, \tag{1}$$

where

$$K_{ion} = \sum_i \chi_i K_i \tag{2}$$

is the total gas mixture ionisation constant, N is the molecular number density, β is the recombination coefficient, and K_i and χ_i are ionisation constant and the fraction of the ith component of the mixture. Below, we assume that the pumping is performed in the optimal and fixed electric field.

For the sake of convenience, we calculated the excitation frequency of the kth vibration level of the CO and N_2 molecules by the expression

$$Q_k = P_{sp}(t)\delta_k/\varepsilon_k\,, \tag{3}$$

where P_{sp} is specific power supplied to the gas, δ_k is the fraction of the discharge energy spent on the excitation of the kth vibrational level, and ε_k is the energy of the kth vibrational level. The initial value of P_{sp}, with the pulse shape remaining unchanged, was chosen from the condition:

$$\int_0^\infty P_{sp}(t)\mathrm{d}t = w\,, \tag{4}$$

where w is the given specific energy input.

The length of the active medium was set, according to the experimental conditions described in Ref. [3], equal to 80 cm, and the reflectivity of the output mirror R_{out} (with the exception of Fig. 5; see below) was set equal to 97 %. We assumed that the total losses due to the cavity mirrors were 2 %. Using these data, we calculated the threshold gain, which proved to be equal to 3.1×10^{-4} cm^{-1}.

To answer the question of whether lasing at 300 K is possible in principle upon excitation by a combined discharge, we calculated the small-signal gain in a medium-pressure active medium. Curve (*1*) in Fig. 3 represents the maximum smal-signal gain g_{max} (for all possible vibrational–rotational transitions; in most cases this is the $10 \rightarrow 9$ transition), as a function of the specific energy input w for a mixture with the composition $CO:He = 1:3$ at $p = 62$ Torr. The initial increase in $g_{max}(w)$ with w is caused by the increase in the energy stored in the vibrational degrees of

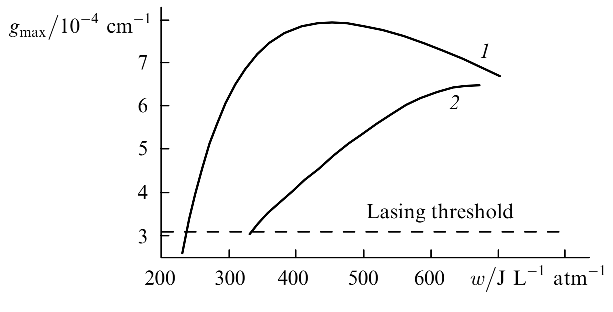

Figure 3. Maximum gain g_{max} as a function of the specific energy input w for mixtures with the compositions $CO:N_2:He = 1:0:3$ (*1*) and 1:3:1 (*2*) at $p = 62$ (*1*) and 78 Torr (*2*) and $T = 300$ K.

freedom of CO, which leads to a general rise in the population of the vibrational levels. However, the temperature of the gas also rises in the process, which increases the VT relaxation rate and, as a result, lowers the gain with increasing w. The maximum gain $g_{\max}(w) = 8\times 10^{-4}$ cm^{-1}, attained at $w = 423$ J L^{-1} atm^{-1}, is greater than the threshold gain by a factor of 2.7. This is a good basis for attaining high laser efficiencies.

The curves representing the dependence of the efficiency on w for the conditions specified in Fig. 3 are depicted in Fig. 4a. One can see that these are fairly flat curves, but the efficiency strongly depends on the temperature of the gas mixture and the presence of nitrogen. The maximum efficiency is achieved in all cases with the same specific energy input.

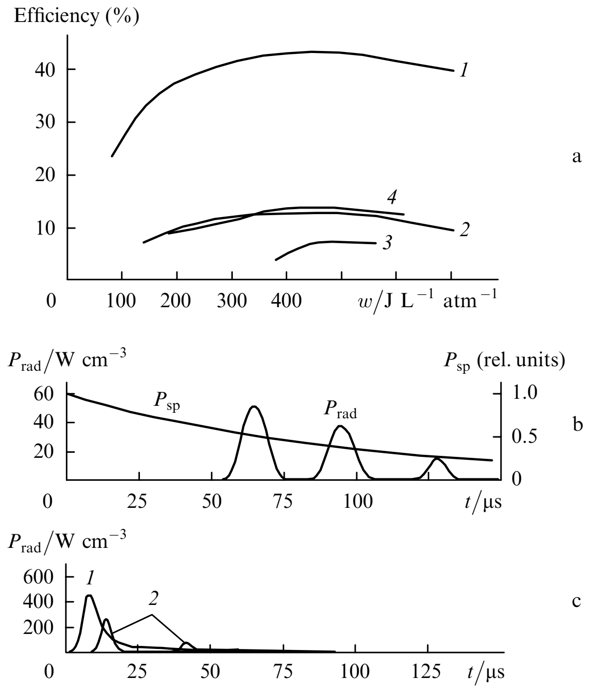

Figure 4. (a) Efficiency of a laser excited by a combined discharge as a function of the specific energy input w (*1* – CO:He = 1:3, $p = 62$ Torr, and $T = 170$ K; *2* – CO:He = 1:3, $p = 62$ Torr, and $T = 300$ K; *3* – CO:N$_2$:He = 1:3:1, $p = 78$ Torr, and $T = 300$ K; and *4* – CO:Xe = 0.25:0.75, $p = 62$ Torr, and $T = 300$ K); (b) curves representing the time dependence of the specific output radiation power $P_{\rm rad}$ and the specific pump power $P_{\rm sp}$, calculated for a combined discharge (CO:He = 1:3, $p = 62$ Torr, $w = 423$ J L^{-1} atm^{-1}) (b); and (c) the radiation pulses (CO:N$_2$:He = 1:6:7 (*1*) and CO:He = 1:1 (*2*) at $p = 0.4$ atm and $w = 350$ J L^{-1} atm^{-1}).

Fig. 4b shows the time dependence of the specific pump power $P_{\rm sp}(t)$ upon excitation by a combined discharge; which corresponds to the shape of the current pulse that approximates the experimental oscillograms of Ref. [3]. We also present in this figure the shape of the radiation pulses $P_{\rm rad}(t)$. It is interesting that radiation is generated as a train of pulses. This is explained by the fact that first lasing involves lower transitions (levels with $v = 8 - 10$), then medium transitions ($v = 12$, 13), and later upper transitions ($v = 16$, 17) and simultaneously lower transitions. Note that the addition of N$_2$ can make the radiation pulse continuous [curve (*1*) in Fig. 4c; see Sec. 3.2 for more detail]. The dependence of the efficiency on w coincides qualitatively with the dependence $g_{\max}(w)$ (Fig. 3) and is determined by the number of transitions involved in lasing. The efficiency varies for the same reason that $g_{\max}(w)$ does, with the result that maximum efficiency is attained at approximately the same value of w.

The results of calculations on the optimisation of the cavity Q factor for a specific energy input of 423 J L^{-1} atm^{-1} and a pressure of 62 Torr are presented in Fig. 5 (curve *1*). One can see that at $R_{\rm out} = 9.35\,\%$ the curve exhibits a weak maximum caused primarily by radiation absorption by the cavity mirrors. Fig. 5 also shows the variation in the efficiency with the increase in the initial temperature of the gas mixture [curve (*2*)].

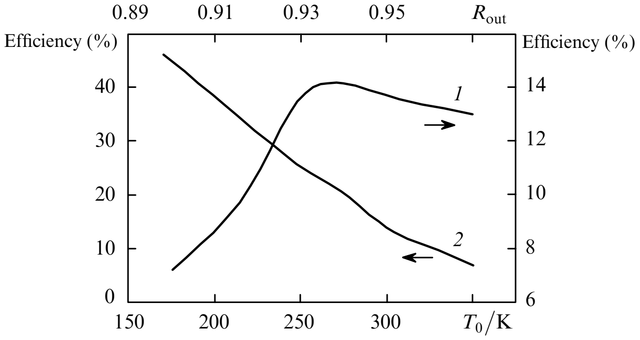

Figure 5. Dependences of the laser efficiency on the output mirror reflectivity $R_{\rm out}$ (*1*) and the initial gas temperature T_0 (*2*) for a mixture with the composition CO:He = 1:3 at $p = 62$ Torr and $w = 423$ J L^{-1} atm^{-1}.

We also studied the effect of the gas mixture pressure on the energy characteristics of the laser. The curves representing the pressure dependence of the maximum gain and the laser efficiency for a specific energy input of 423 J L^{-1} atm^{-1} are depicted in Fig. 6. Competing processes determine the shape of the curves. On the one hand, with the specific energy input fixed, an increase in pressure leads to a rise in the population of the vibrational levels of the carbon monoxide molecule and, hence, to an increase in the vibrational–rotational inversion, gain, and laser efficiency. On the other hand, an increase in gas pressure leads to a situation in which the effect of the collisional mechanism of broadening of spectral lines becomes more pronounced. This results in a decrease in the gain, laser efficiency, and the stimulated emission cross section $\sigma(v, j)$ calculated by the

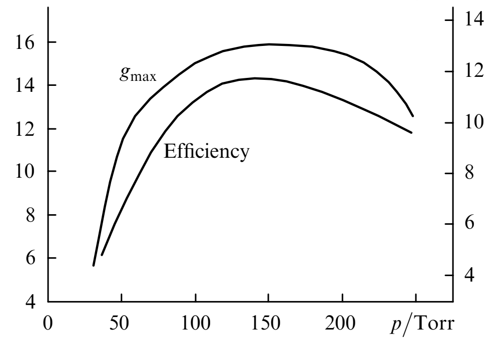

Figure 6. Maximum small-signal gain $g_{\max}$ and laser efficiency as functions of the gas pressure p at $w = 423$ J L^{-1} atm^{-1} and $T = 300$ K for a mixture with the composition CO:He = 1:3.

expression of Ref. [11]:

$$\sigma(\upsilon,j)=\frac{1}{8\pi^2}\left(\frac{\ln 2}{\pi}\right)^{1/2}\lambda^2(\upsilon,j)\,\frac{A(j+1)}{2j+1}\,\frac{\Delta\nu_{\rm st}}{\Delta\nu_{\rm d}^2}$$

$$\times\int_{-2(y+1)}^{+2(y+1)}\frac{\exp(-z^2\ln 16)}{y^2/4+z^2}\,{\rm d}z\,, \qquad (5)$$

where

$$y=\frac{\Delta\nu_{\rm st}}{\Delta\nu_{\rm d}};\quad z=\frac{\nu_0-\nu_0'}{\Delta\nu_{\rm d}};$$

$$\Delta\nu_{\rm st}=41.40(\chi_{\rm CO}+1.46\chi_{\rm He}+\chi_{\rm N_2}+1.18\chi_{\rm Xe})\frac{p(T)}{\sqrt{T}}, \qquad (6)$$

with $\Delta\nu_{\rm st}$ measured in MHz, p in Torr, and T in kelvins, and

$$\Delta\nu_{\rm d}=2\nu_0\left(\frac{2kT}{m_{\rm CO}c^2}\ln 2\right)^{1/2}. \qquad (7)$$

Fig. 7 shows the dependences of the stimulated emission cross sections on the pressure p for different transitions, which confirm the above viewpoint. One can see that the decrease in the cross section caused by collisional broadening begins at pressures of about 80 Torr. At pressures higher than 130 Torr, the increase in inversion to the energy supplied to the gas is unable to compensate for the decrease in the stimulated emission cross section. This explains the drop in the gain and efficiency at high pressures. Thus, medium pressures are optimal for the active medium of a CO laser, because it is at these pressures that the greatest energy input can be provided along with the small effect of collisional broadening.

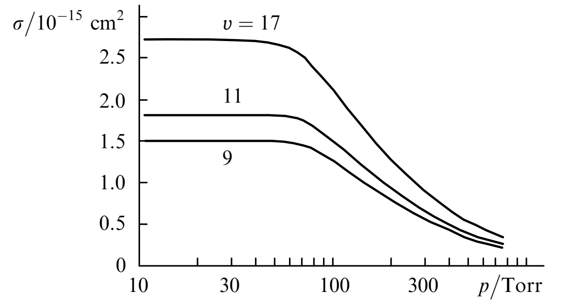

Figure 7. Dependences of the stimulated emission cross section σ on the pressure p in the optical transition of the P branch for levels with different vibrational numbers υ.

An important advantage of using combined discharges for pumping gas lasers is the possibility of realising the train pumping regime, i.e., a regime in which packets (trains) of several consecutive pulses are delivered to the discharge gap, with the intervals between the pulses being controllable and much shorter than the intervals between the trains [2]. In the case of a CO_2 laser, such pumping made it possible to achieve a radiation pulse with a variable duration.

We studied the possibility of increasing the pulse duration and changing the type of radiation by employing the train pumping of a CO laser. In our calculations, as in the experiment described in Ref. [12], we set the interval between the pulses in a packet equal to 100 μs. The calculations were performed for fairly large (but attained in experiments) energy inputs ($\sim$ 800 J L^{-1} atm^{-1}) [13].

Fig. 8b shows the time dependence of the specific output radiation power upon pumping the active medium by trains consisting of one or three pulses. One can see that lasing occurs in both cases in the form of three short pulses, with the lasing time (the interval between the first and last pulse) varying insignificantly. This is explained by the fact that at a fixed pump energy supplied into the gas by a train of pulses, the average pump power decreases with increasing number of pulses. As a result, despite the increase in the duration of pumping, the duration of lasing (when $g_{\rm max}$ exceeds the threshold) almost does not increase. As the number of pulses in a train increases, the laser efficiency decreases (for a fixed energy input per train), as shown in Fig. 8c.

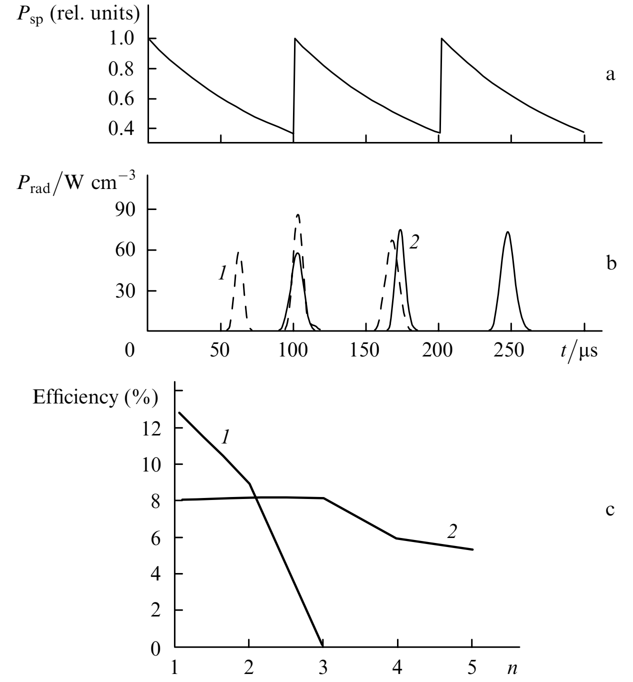

Figure 8. Time dependences of the specific pump power $P_{\rm sp}$ upon pumping the active medium by a train consisting of three pulses (a) and of the specific output radiation power $P_{\rm rad}$ for a specific energy input of 846 J L^{-1} atm^{-1} per train consisting of one (dashed curve) and three (solid curve) pulses (b), and the dependence of the laser efficiency for specific energy inputs per train of 423 (*1*) and 846 J L^{-1} atm^{-1} (*2*) on the number n of pulses in the packet (c).

3.2 Effect of adding nitrogen and xenon to the gas mixture

N_2 and Xe are often added to the gas mixture of a CO laser (along with CO and He), with nitrogen being the most widespread addition. However, in contrast to the CO_2 laser, the need for N_2 in the mixture of the CO laser is not obvious. The point is that the excitation cross sections of the vibrational degrees of freedom of CO and N_2 by electron impact have maxima of the same order of magnitude within the same energy range [8], i.e., CO and N_2 compete with each other upon excitation of vibrational states during discharge. Therefore, nitrogen accumulates a fraction of the pump energy, which lowers the rate at which this energy is supplied to the vibrational degrees of freedom of CO. This, in turn, reduces the gain of the active medium and the efficiency in the case of combined discharge pumping [curve (*3*) in Fig. 4a].

However, upon pumping by a short high-power discharge, when the population distribution of CO with a small gradient over the vibrational states has no time to be established, for example, in the case of an electroionisation laser [2], the addition of nitrogen is useful. Nitrogen accumulates the energy of the short pump pulse and gradually transfers it to all the vibrational levels of the carbon monoxide molecules.

The above reasoning is clearly demonstrated by the results of our calculations of the distribution function of the population of the vibrational levels of CO molecules, which are shown in Fig. 9. One can clearly see that adding N_2 to the CO – He mixture accelerates the formation of a plateau for this function [curves (*1*) and (*3*)], which is required for efficient lasing. The difference in the shape of the distribution functions with and without N_2 diminishes with time [curves (*2*) and (*4*)]. As a result, when a gas mixture with the composition $CO_2:N_2:He = 1:6:7$ at a pressure of 0.4 atm is excited by a nonself-sustained 10-μs discharge with a specific energy input of 350 J L^{-1} atm^{-1}, the efficiency is 2.7 %, while for a gas mixture with the composition CO: He = 1:1 under the same conditions, the efficiency is only 1.7 %. At the same time, for a pump-pulse duration ~ 150-μs in a mixture with the composition CO:He = 1:3 at a pressure of 60 – 130 Torr, the lasing efficiency exceeds 10 %.

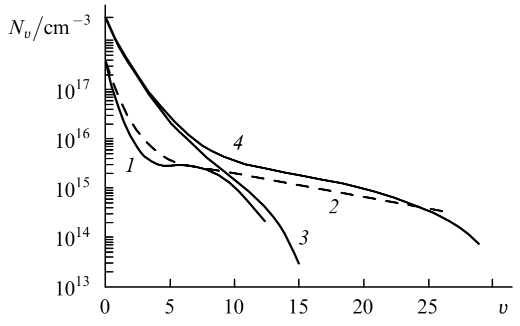

Figure 9. Distribution N_v of CO molecules over the vibrational levels v in the absence of cavity mirrors with a pump-pulse duration of 10 μs and $p = 0.4$ atm for mixtures with the compositions $CO:N_2:He = 1:6:$ (*1*, *2*) and 1 : 0 : 3 (*3*, *4*) at times $t = 10$ (*1*, *3*) and 15 μs (*2*, *4*).

The effect of adding nitrogen also manifests itself in the time dependence of the specific output radiation power (see Fig. 4c). For a mixture with nitrogen pumped by a nonself-sustained ~ 10-μs discharge, the output radiation power is much higher than for a mixture without nitrogen. More than that, for a low CO-to-N_2 concentration ratio, for example, for a mixture with the composition $CO:N_2:He = 1:6:7$, the laser pulses are long and continuous (an order of magnitude longer than the pump pulse). In mixtures without nitrogen (CO:He = 1:1) under the same conditions, radiation is generated in the form of pulse trains.

When the active medium is pumped by a combined discharge and the value of the parameter E/p is optimal, replacing He by Xe has no significant effect on the efficiency, provided that the energy input is the same [curves (*2*) and (*4*) in Fig. 4a].

It was found experimentally [9] that the presence of xenon reduces the rate of degradation of the working gas mixture. It is known that the dissociation of CO may occur due to the following reactions [10]:

$$CO(X^1\Sigma) + e \rightarrow C + O + e, \qquad (8)$$

$$CO(X^1\Sigma) + CO(A^3\Pi) \rightarrow CO_2 + C + 0.4 \text{ eV}. \qquad (9)$$

The dependences of the constants of dissociation of CO by electron impact and of excitation of the electronic level $CO(A^3\Pi)$ on E/p are presented in Figs 10 and 11. One can see that the addition of xenon to the working medium reduces these constants and, thereby, reducing the rate of CO dissociation by direct electron impact and through the excited $CO(A^3\Pi)$ state.

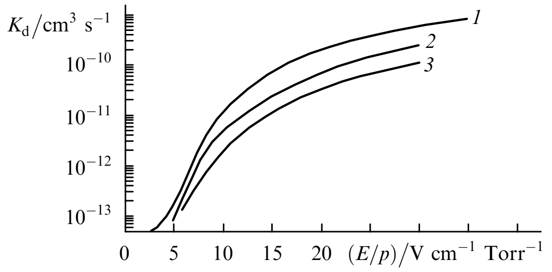

Figure 10. Total constant K_d of CO dissociation by electron impact as a function of the parameter E/p for mixtures with the compositions CO:He:Xe = 1 : 3 : 0 (*1*), 1 : 2 : 1 (*2*), and 1 : 0 : 3 (*3*).

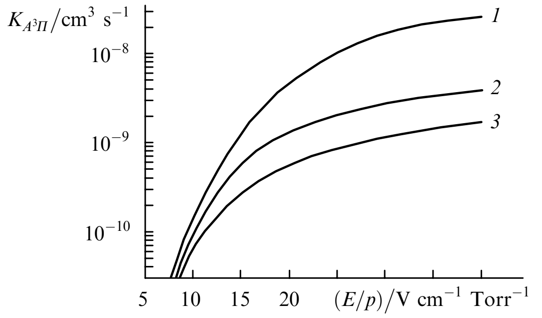

Figure 11. Rate constant $K_{A^3\Pi}$ for excitation of the electronic level $A^3\Pi$ of CO molecules in a discharge as a function of the parameter E/p for mixtures CO:He:Xe = 1 : 3 : 0 (*1*), 1 : 2 : 1 (*2*), and 1 : 0 : 3 (*3*).

References

1. Mann M.M., Rice D.K., Eguchi R.G. *IEEE J. Quantum. Electron.*, **10**, 682 (1974).
2. Ionin A.A., Mayerhofer W., Walter S., Zeyfang E. *Kvantovaya Elektron.*, **22**, 883 (1995) [*Quantum Electron.*, **25**, 851 (1995)].
3. Osipov V.V., et al. *Opt. Atmos. Okeana*, **10**, 1266 (1997).
4. Rocwood S.D., Brau J.E., Proctor W.A., Canawan G.H. *IEEE J. Quantum. Electron.*, **9**, 120 (1973).
5. Gordiets B.F., Osipov A.I., Shelepin L.A. *Kinetic Processes in Gases and Molecular Lasers* (New York: Gordon & Breach, 1988; Moscow: Nauka, 1980].
6. Basov N.G., Dolinina V.I., Kovsh I.B., et al. *Preprint FIAN No. 183* (Moscow: P.N.Lebedev Physics Institute, 1984).
7. Smith K., Thompson R. *Computer Modeling of Gas Lasers* (New York: Plenum, 1978; Moscow: Mir Publishers, 1981).
8. Witteman W.J. *The CO₂ Laser* (Berlin: Springer, 1987; Moscow: Mir Publishers, 1990].
9. Aleinikov V.S., Masychev V.I. *Kvantovaya Elektron.*, **12**, 1932 (1985) [*Sov. J. Quantum Electron.*, **15**, 1274 (1985)].
10. Polak L.S. *Neravnovesnaya khimicheskaya kinetika i ee primenenie* (Nonequilibrium Chemical Kinetics and its Application) (Moscow: Nauka, 1979).
11. Svelto O. *Principles of Lasers* (New York: Plenum Press, 1989; Moscow: Mir Publishers, 1990].
12. Osipov V.V., Ivanov M.G., Lisenkov V.V. *Zh. Tekh. Fiz.*, **69** (5), 33 (1998) [*Tech. Phys.*, **44**, 508 (1998)].
13. Basov N.G., Ionin A.A., Kotkov A.A., et al. *Kvantovaya Elektron.*, **30**, 859 (2000) [*Quantum Electron.*, **30**, 859 (2000)].