EFFECT OF LASER RADIATION ON THE VIBRATIONAL DISTRIBUTION OF CO_2

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In connection with progress in the field of CO_2 lasers, questions of the vibrational kinetics of molecules of CO_2 have been discussed in many communications. In a majority of cases of practical importance, the distribution of CO_2 is due to processes of vibrational exchange (V−V) on which is based the well-known thermodynamic model [1]. In other cases, the V−V exchange does not determine the vibrational distribution, since the perturbation is small; therefore, it is found sufficient to consider a small number of levels of CO_2 (usually three), whose populations satisfy the linear equations of the balance [2]. There is the possibility of conditions where the vibrations are strongly excited and, at the same time, V−V processes are insignificant (a very small CO_2 impurity in the inert gas, with a high degree of ionization). Then the number of equations becomes large. The present article discusses one such case: the excitation of a steady-state vibrational distribution in a glow discharge by laser radiation, whose solution is rather graphic.

The article considers conditions where the excitation of an antisymmetric mode of CO_2 by electrons takes place far more frequently than damping by heavy particles, and in paired modes (symmetrical longitudinal bending vibrations), the contrary, i.e., a Boltzmann distribution is established in the antisymmetric mode, with the temperature of the electrons, and in paired modes, with the temperature of the gas. Let us examine the variation of the distribution under the action of rather strong laser radiation, leading to induced transitions between the levels 00^01 and 10^00.

Let us formulate the problem in more detail. In a harmonic investigation, digressing from the splitting of the levels due to Fermi resonance, the vibrational levels of CO_2 can be given by the vibrational number of the paired modes $v = 2v_1 + v_2$ (v_1, v_2 are the vibrational numbers of symmetrical longitudinal and bending vibrations) and the vibrational number of the antisymmetric mode u. Under these conditions, the levels are degenerate with a multiplicity factor

$$g_v = \begin{cases} (v+2)^2/4, & v - \text{ even}, \\ (v+1)(v+3)/4, & v - \text{odd}. \end{cases}$$

The vibrational levels form a square grid in the plane vu (Fig. 1). Adjacent vibrational levels in the grid are connected by transitions along the u axis with collisions with electrons, and along the v axis with collisions with heavy particles. A laser transition is illustrated on the grid by the diagonal 01-20. By definition, other transitions are unimportant. In the absence of laser radiation the vibrational distribution is obviously the product of the Boltzmann distributions along u with the temperature of the electrons, and along v with the temperature of the gas. It is required to find the distribution over the levels with a given intensity of the laser radiation.

We define the current between two mesh points of the grid of the vibrational levels as the difference in the number of direct and reverse transitions between them in unit volume in unit time. The condition of the steady-state character of the populations then degenerated in accordance with the Kirchhoff rule: the

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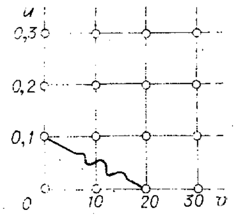

Fig. 1

Fig. 2

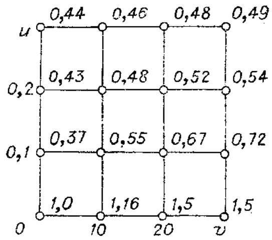

Fig. 3

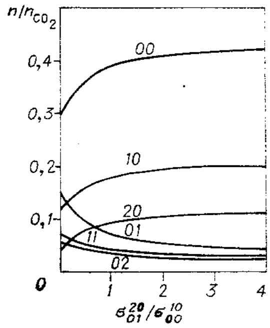

Fig. 4

algebraic sum of the currents at every mesh point is equal to zero. We introduce the potentials φ_{vu} with respect to the distribution unperturbed by laser radiation

$$\varphi_{vu} = \frac{n_{vu}}{n_{00} g_v \alpha_c^v \alpha_a^u}, \tag{1}$$

where n_{vu} is the population of the level vu; $\alpha_c = e^{-\hbar\omega_c/T}$; $\alpha_a = e^{-\hbar\omega_a/T_e}$; $\hbar\omega_c$, $\hbar\omega_a$ are the vibrational quanta of the paired and antisymmetric modes; T_e, T are the temperatures of the electrons and the gas. We adopt the normalization $\varphi_{00} = 1$. We note that the formulas for the currents between neighboring mesh points have the form of Ohm's law, for example;

$$J_{vu}^{v+1,u} = \sigma_{vu}^{v+1,u}(\varphi_{vu} - \varphi_{v+1,u}),$$

where the conductivity is equal to $\sigma_{vu}^{v+1,u} = g_v n_{00} \alpha_c^v \alpha_a^u W_{vu}^{v+1,u} n_M$, $W_{vu}^{v+1,u}$ is the rate constant of the transition vu → v+1, u with a collision with heavy particles; n_M is the density of the heavy particles.

The formula for the diagonal current 01-20 has another form:

$$J_{01}^{20} = \sigma_{01}^{20}\left(\varphi_{01} - \frac{\alpha_c^2}{\alpha_a}\varphi_{20}\right),$$

where $\sigma_{01}^{20} = n_{00}\alpha_a \sigma_0 I$; σ_0 is the cross section of the induced radiation; I is the intensity of the laser radiation divided by the energy of a photon.

As can be seen, the problem is analogous to calculation of the electric circuit from a source included between the mesh points 01 and 20 (the analogy, however, is incomplete from the point of view that the emf is not determined previously). We note that the values of

$$a_{vu} = \frac{\varphi_{vu} - \varphi_{20}}{\varphi_{01} - \varphi_{20}} \tag{2}$$

are determined only by the conductivities of the grid and do not depend on the source. The a_{vu} obviously coincides with the distribution of the potential in the grid with fixed potentials $\varphi_{01} = 1$ and $\varphi_{20} = 0$. This distribution is most conveniently measured in an analog machine, selecting the appropriate grid of the resistances. With values of a_{vu} known from measurements, it is sufficient only to determine φ_{01} and φ_{20} in order to be able to use (2) to calculate the potential at all the other mesh points.

Let us consider the equivalent circuit, illustrated in Fig. 2. The heavy line with the effective conductivity σ_{ef} replaces the grid. Thus, σ_{ef} is the resistance of the grid (without diagonal) between the mesh points 01 and 20. This value is determined by the set of coefficients a_{vu}, but can be measured fairly well in an analog machine.

The equation of continuity of the current has the form

$$\sigma_{01}^{20}\left(\varphi_{01}-\frac{\alpha_c^2}{\alpha_a}\varphi_{20}\right)+\sigma_{\text{ef}}\left(\varphi_{01}-\varphi_{20}\right)=0. \tag{3}$$

The insufficient equation for determining φ_{01} and φ_{20} gives the normalization of the potential

$$\varphi_{00}=a_{00}\varphi_{01}+(1-a_{00})\,\varphi_{20}=1. \tag{4}$$

We write the solution of the system (3), (4):

$$\varphi_{01}=\frac{1+\dfrac{\sigma_{01}^{20}}{\sigma_{\text{ef}}}\dfrac{\alpha_c^2}{\alpha_a}}{1+\dfrac{\sigma_{01}^{20}}{\sigma_{\text{ef}}}\left[1-a_{00}\left(1-\dfrac{\alpha_c^2}{\alpha_a}\right)\right]}; \tag{5}$$

$$\varphi_{20}=\frac{1+\dfrac{\sigma_{01}^{20}}{\sigma_{\text{ef}}}}{1+\dfrac{\sigma_{01}^{20}}{\sigma_{\text{ef}}}\left[1-a_{00}\left(1-\dfrac{\alpha_c^2}{\alpha_a}\right)\right]}. \tag{6}$$

The potentials of the remaining mesh points are determined from (2),

$$\varphi_{vu}=a_{vu}\,\varphi_{01}+(1-a_{vu})\varphi_{20} \tag{7}$$

and have an intermediate value between φ_{01} and φ_{20}.

Using formulas (5)-(7), taking account of (1) and the normalization $n_{CO_2}=n_{00}\sum\limits_{v,u}g_v\alpha_c^v\alpha_a^u\varphi_{vu}$, we obtain the final formula for the populations:

$$n_{vu}=n_{CO_2}g_v\alpha_c^v\alpha_a^u\frac{1+\dfrac{\sigma_{01}^{20}}{\sigma_{\text{ef}}}\left[1-a_{vu}\left(1-\dfrac{\alpha_c^2}{\alpha_a}\right)\right]}{A+\dfrac{\sigma_{01}^{20}}{\sigma_{\text{ef}}}\left[A-B\left(1-\dfrac{\alpha_c^2}{\alpha_a}\right)\right]}, \tag{8}$$

where $A=\dfrac{1}{(1-\alpha_a)(1-\alpha_c)^2\left(1-\alpha_c^2\right)}$; $B=\sum\limits_{v,u}g_v\alpha_c^v\alpha_a^u a_{vu}$. With $\sigma_{01}^{20}/\sigma_{\text{ef}}\gg 1$, the populations tend toward a constant limit, connected with equalization of the populations of the laser levels.

Figure 3 shows the distribution of the potential (c_{vu} is easily reduced with respect to the potential on a 4×4 grid, for the following conditions: $\alpha_a=0.5$; $\alpha_c=0.2$; $\sigma_{00}^{01}/\sigma_{00}^{10}=0.25$ (here $\sigma_{\text{ef}}/\sigma_{00}^{10}=0.225$) and $\sigma_{01}^{20}/\sigma_{00}^{10}=1$. In calculating the conductivities of the grid, it was assumed that the dependence of the rate constant on the vibrational numbers is determined by the square of the matrix element of the oscillator coordinate. For paired modes, the degeneration of the levels was taken into consideration. Figure 4 shows the dependence of the populations of several levels on the intensity of the radiation (the intersection of the curves of the populations of 01 and 02 is connected with the fact that n_{20} is the population of the multiplet 20, exceeding by four times the population of the lower laser level 10^00).

The change in the populations of the vibrational levels under the action of laser radiation is the reason for the saturation of the amplification of the laser radiation. The dependence of the amplification coefficient on the intensity of the radiation is determined by the well-known formula

$$K=\frac{K_0}{1+\dfrac{I}{I_s}},\quad K_0=\sigma_0\frac{n_{CO_2}}{A}\left(\alpha_a-\alpha_c^2\right),$$

where K_0 is the amplification coefficient of a weak signal, and the intensity of the saturation is calculated using the expression (8):

$$I_s=\frac{\hbar\omega\left(\sigma_{\text{ef}}/\sigma_{00}^{10}\right)W_{00}^{10}n_M}{\sigma_0\alpha_a\left[1-\dfrac{B}{A}\left(1-\dfrac{\alpha_c^2}{\alpha_a}\right)\right]}.$$

It is assumed that, with a change in the intensity of the radiation, the intensity of the electrical field in the discharge varies in such a way that the temperature of the electrons remains fixed.

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ACCELERATION OF IONS IN A VACUUM DIODE

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An investigation was made of the time, mass, and energy characteristics of the collective acceleration of ions in a vacuum diode. Acceleration of ions was observed only with the presence of surges on the oscillogram of the current density. The maximal energies of the ions in axial and radial directions are equal and depend on the multiplicity of the charge. It is shown that ions of the near-cathode plasma are drawn into acceleration conditions.

With a study of the explosive emission of electrons in a vacuum diode, two sets of current-takeoff conditions are observed: stable and unstable. Unstable conditions are accompanied by considerable surges on the oscillogram of the total current [1] and the density of the electron current [2]. The method of autographs has been used to find that, with unstable current takeoff, electron jets are formed, localized in space. With the presence of surges on the oscillogram of the total current, an acceleration of positive ions in the direction of the anode is recorded [1]. Since there exists an interconnection between these phenomena, it is necessary to study the time, mass, and energy characteristics of the accelerated ions, as well as the localization of the region of acceleration of the ions, in order to study the mechanism of unstable current takeoff.

A more detailed investigation of explosive conditions of electron and current-takeoff conditions was made with a voltage in the diode of $\sim 10^4$V. Due to their contradictory nature, it is practically impossible to bring in data on the collective acceleration of ions in a vacuum diode, obtained with higher voltages [1, 3-5]. Therefore, it is necessary to study the characteristics of the acceleration process with the abovementioned voltage.

Experiments were made with a pressure of 10^{-5} mm Hg. Breakdown was effected between a sharp cathode (Cu, W) and a flat anode (Cu, Ta, W). The interelectrode gap was established within the limits $d = 1$-5 mm. Single voltage pulses with an amplitude $U_0 = 25$ kV and a duration of 5-150 nsec were fed to the diode. The density of the electron current was investigated using a collector installed in back of an opening with a diameter of 0.1d at the center of the anode. The time characteristics were investigated by the method of a broken discharge. Provision was made for heating the anode up to a temperature of ~ 2000°C. The ion currents were recorded using a Thompson mass-spectrograph with an electron-optical recorder, whose sensitivity is $\sim 10^4$ times greater than with photographic recording. The resolving power did not exceed 25. The mass-spectrograph could be arranged at a distance of 20 mm from the axis of the diode, as well as along the axis of the diode behind an opening in the anode with a diameter of 1 mm, or behind an opening of the same diameter in the cathode holder.

In the experiments on study of the density of the electron current j_e at the center of the anode, it was observed that considerable surges on the oscillogram were recorded with a duration of the voltage pulse $\tau_p \geqslant 1/2t_k$ (t_k is the duration of the high-voltage stage of the vacuum discharge). The maximal increase in

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