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THEORY OF A STEADY CO LASER

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The kinetic equations describing the operation of a CO laser, which is one of the most promising in terms of efficiency and specific characteristics, consist of a nonlinear system of high order (30-60). The numerical studies which have been made of the parametric functions of the generation power are inadequate for the analysis of experimental data and the design of new systems. In the present report we propose a simple model of a CO laser which makes it possible to find the power and the generation spectrum as functions of the parameters of the instrument.

An approximate analytical theory of the distribution of diatomic molecules by vibrational levels under the conditions of strong separation of the effective vibrational temperature T_1 from the gas temperature T was constructed in [1, 2]. The condition of applicability of the resonance approximation used in [1, 2] has the form

$$\exp(-\delta_{VV}v^*) \ll C\frac{6\Delta E}{T\delta_{VV}^3},$$

where $C = (v^* + 1)f(0)\exp[-(\Delta E/T)(v^*)^2 - 1/2]$ [$f(0)$ is the fraction of molecules in the ground state]; ΔE is the anharmonicity of a molecule; v^* is a number corresponding to the Treanor minimum [3]; δ_{VV} is a number which depends on the gas temperature and characterizes the rate of exchange with the resonance defect [2].

Allowance for radiative transitions within the framework of [1, 2] gives the equation

$$\frac{3Q_{10}}{\delta_{VV}^3}\frac{d}{dv}\left[(v+1)^2 f^2\left(\frac{2\Delta E}{T} - \frac{d^2\ln f}{dv^2}\right)\right] + P_{10}(v+1)f\exp(\delta_{VT}v) + \\ + A_{10}(v+1)f + \frac{I_v}{\hbar\omega_v}\sigma(v)\left[\gamma_v f + \frac{df}{dv}\right] = 0, \qquad (1)$$

where P_{10} and A_{10} are the probabilities of the collisional and radiative transitions ($1 \to 0$); Q_{10} is the probability of exchange in a collision of CO molecules; I_V is the light intensity in the transition $v + 1 \to v$; $\hbar\omega_V = E_1 - 2\Delta Ev$; $\gamma_V = 1 - \exp[-2B_V(j_V + 1)/T]$; B_V is the rotational constant; j_V is the rotational quantum number at which generation in the band $v + 1 \to v$ takes place; $\sigma(v)$ is the cross section for stimulated emission. The remaining notation is as in [2].

The independence of T_1 from the presence of generation follows from Eq. (1). This conclusion is confirmed by the numerical calculations of [4]. The loss rate is determined by the quantum flux formed in the region of the Treanor minimum by V—V processes and depends only on T_1 and the gas temperature. The connection between T_1 and T, if the pumping is concentrated in the lower levels, is found from the equation

$$q = \eta_V\frac{jE}{N_{CO}E_1} = \frac{6Q_{10}}{\delta_{VV}^3}\frac{\Delta E}{T}C^2(T_1),$$

where $q \ll (6Q_{10}/\delta_{VV}^3)(\Delta E/T)^3$. Here jE is the power released in the discharge; η_V is the portion expended on the excitation of vibrations; N_{CO} is the density of CO molecules.

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With steady generation the inversion is determined by the condition

$$\sigma(v)(\gamma_v f + df/dv) = \Delta_0, \tag{2}$$

where $\Delta_0 = \ln(1/R)/2LN_{CO}$; $R = \sqrt{R_1 R_2}$; $R_{1,2}$ are the coefficients of reflection of the mirrors; L is the length of the active medium; in (2) the resonator is assumed to be nonselective.

Solving (2) for $l \leqslant v \leqslant r$, we find

$$f_0(v) = f(l)\exp\left(-\int_l^v \gamma_v dv\right) + \Delta_0 \exp\left(-\int_l^v \gamma_v dv\right)\left[\int_l^v \frac{dv' \exp\left(\int_l^{v'} \gamma_v dv\right)}{\sigma(v')}\right], \tag{3}$$

where l and r are the lower and upper limits of the generation spectrum. Near the lower limit we use the approximate solution ($I_v = 0$) [1, 2], and joining it with (3) at $v = l$ we find $f(l) = C/(l+1)$ if $l > v^*$ (otherwise it must be joined with the corrected Treanor distribution).

Substituting the solution (3) into Eq. (1), we find the power of the radiative losses

$$\Delta_0 I_v \simeq \hbar\omega_v \frac{12\Delta E}{T\delta_{VV}^3} Q_{10}(v+1) f_0(v)\left[(\gamma_v(v+1)-1) f_0(v) - (v+1)\Delta_0/\sigma(v) - \lambda \exp(\delta_{VT} v) - \mu\right], \tag{4}$$

where

$$\lambda = P_{10} T\delta_{VV}^3/12\Delta E Q_{10} \ll 1; \quad \mu = A_{10} T\delta_{VV}^3/12\Delta E Q_{10} \ll 1.$$

In deriving (4) we omitted the contribution from terms of $\sim d^2 \ln(f_0/dv^2)$, which are small according to estimates. The edge of the generation spectrum is found from the conditions

$$I(l) = I(r) = 0.$$

The total emission power is determined by the equation

$$P = \int_l^r I_v dv = \frac{\hbar\bar{\omega}_v}{\Delta_0} \frac{6\Delta E Q_{1v}}{T\delta_{VV}^3}\left[f_{0l}^2 (l+1)^2 - f_{0r}^2 (r+1)^2 - \right.$$
$$\left. - 2\int_l^r (\lambda \exp(\delta_{VT} v) + \mu)(v+1) f_0 dv\right].$$

The equations derived are considerably simplified with the additional assumptions $\gamma_v \equiv \gamma$ and $\sigma(v) = (v+1)\sigma_0$.

In this case the total emission power is determined by the equation ($k = \Delta_0/\gamma\sigma_0$):

$$P = \frac{6\Delta E \hbar\bar{\omega}_v Q_{10}}{T\delta_{VV}^3 \Delta_0}\left[C^2 - k^2 - \frac{2\lambda k}{\delta_{VT}} \exp(\delta_{VT} r)\right].$$

In the absence of V—T losses the lower edge of the spectrum, the power, and the efficiency are

$$l = 1/\gamma(1 - k/C) - 1;$$

$$P = \frac{6\Delta E \hbar\bar{\omega}_v Q_{10}}{T\delta_{VV}^3 \Delta_0}(C^2 - k^2); \tag{5}$$

$$\eta = \frac{\Delta_0 \int_l^r I_v dv}{q N_{CO} E_1} = \frac{\hbar\bar{\omega}_v}{E_1}\left(1 - \frac{k^2}{C^2}\right) = \frac{\hbar\bar{\omega}_v}{E_1}\left[1 - \left(1 - \frac{1}{\gamma(l+1)}\right)^2\right]. \tag{6}$$

The latter equation connects the generation efficiency with the lower end of the spectrum.

To find the upper end r of the spectrum one must allow for the effect of anharmonism on the quantity $\sigma(v)$. The expressions obtained allow one to calculate the emission spectrum, the power, and the efficiency as functions of the pumping rate, the gas temperature, the gas composition, and the quality of the resonator. For a comparison of the theory constructed here with experiment we use the report [5], neglecting the effect of the flux across the resonator. The dependence of the total emission power on the pumping power is well described by Eq. (5). The "threshold" pumping rate is estimated by the equation

$$P_{\text{thr}} = 6\Delta E N_{\text{CO}} \hbar\bar{\omega}_v Q_{10} k^2 V T \delta_{VV}^3,$$

and for the experimental conditions of [5] P_{thr} = 60 kW, p = 0.76 mm Hg, T = 100°K, CO:Ar = 1:9, $(-\ln R)/L = 0.12$, V = 500 cm^3, and for Q_{10} we take the values which follow from [6]. The experimental value is P_{thr} = 70 kW. The slope of the dependence of P_{out} on the pumping rate P is determined by the quantity $\eta_{qu}\eta_v S_{dis}/S$, where $\eta_{qu} = \hbar\bar{\omega}_v/E_1 = 90\%$, η_v is the excitation efficiency of $\leqslant 80\%$, and S_{dis}/S is the ratio of the area of the output window to the area of the discharge, ≈ 0.29, i.e., the slope is ≈ 0.2. In the experiments this value is ≈ 0.17. Using (6) the theoretical efficiency at a pumping rate of 152 kW gives $\eta \leqslant 0.12$, while in the experiment the efficiency is $\approx$ 0.08. The quantity $\zeta_{theor} \approx 5.5$ while $\zeta_{exp} = 4$. Allowing for the approximations used in constructing the theory, the agreement achieved must be considered satisfactory.

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