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A Carbon-Dioxide Laser with Optical Pumping

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1. A laser operating on transitions between vibrational levels of the carbon-dioxide molecule is among the most powerful of existing lasers. The power extracted per unit length of the tube for a laser without flow reaches 70 W/m ([1,2]). Usually a carbon-dioxide laser is excited by a gas discharge. In the present article we investigate the properties of a carbon-dioxide laser excited by resonant radiation from an alkali-metal lamp. The advantages of such a method of excitation are connected, first, with the low voltage (several tens of volts) on the electrodes of the alkali-metal lamp as compared with the voltage (several kilovolts) required to sustain the discharge in an ordinary carbon-dioxide laser. Second, in this type of laser the noise level is much lower, so that it can be used to obtain monochromatic laser-radiation signals. The power per unit length and the efficiency of the laser considered are approximately the same as in an ordinary carbon-dioxide laser without flow.

2. Let us consider the operating principle of this laser. In its simplest design, to which we shall confine ourselves, the pump lamp, which is a cylinder of radius r_0, is placed at the center of a cylindrical laser tube of radius R_0. The alkali-metal lamp contains a mixture of an inert gas and an alkali metal, and to the working gas of the laser, which, as usual, consists of a mixture of helium, nitrogen, and carbon dioxide, we add an admixture of alkali-metal vapor of the same kind as in the lamp. Then the processes that provide the inverted population of the laser level proceed according to the scheme

$$\mathrm{M} + \hbar\omega \to \mathrm{M}^*, \tag{1}$$

$$\mathrm{M}^* + \mathrm{N}_2 \to \mathrm{M} + \mathrm{N}_2^{**}, \tag{2}$$

$$\mathrm{N}_2^{**} + \mathrm{N}_2 \to \mathrm{N}_2^* + \mathrm{N}_2^*, \tag{3}$$

$$N_2^* + CO_2 \to N_2 + CO_2^*. \tag{4}$$

Formula (1) corresponds to the absorption of a resonant photon by an atom of the alkali metal M. The electronic excitation of the alkali-metal atom is transferred to a nitrogen molecule, which is thereby brought into a vibrationally excited state. The cross section of such a process is found to be of the order of 10^{-15}–10^{-14} cm^2, and its values, determined in experiments ($^{3-15}$), are given in Table 1. Process (2) leads to the formation of a nitrogen molecule at a high vibrational level.

This excitation is exchanged among several vibrational excitations (process (3)) and is then transferred to the carbon-dioxide molecule (process (4)) and reaches the upper laser level 001. The subsequent processes of emission of the laser photon and destruction of the upper and lower laser levels occur in the same way as in an ordinary carbon-dioxide laser, so we shall not dwell on them. We note only that the scheme of laser operation presented is valid if the density of nitrogen considerably exceeds the density of carbon dioxide, which we assume to be fulfilled.

Table 1

Cross sections for transfer of resonant excitation of alkali-metal atoms to vibrational levels of nitrogen (10^{-16} cm^2)

Na	K $^2P_{1/2}$	K $^2P_{3/2}$	Rb $^2P_{1/2}$	Rb $^2P_{3/2}$	Cs $^2P_{1/2}$	Cs $^2P_{3/2}$
40.3 (^{3})	35 (^{8})	39 (^{8})	37 (^{14})	36 (^{14})	77 (^{15})	69 (^{15})
45.6 (^{4})	34 (^{9})	34 (^{9})				
36.6 (^{5})	20.2 (^{10})	20.2 (^{10})				
43 (^{6})	29.5 (^{11})	29.5 (^{11})				
10 (^{7})	17.6 (^{12})	17.6 (^{12})				
	19 (^{13})	19 (^{13})				

3. Let us determine the parameters of the laser under consideration. The working gas consists of a mixture of helium, nitrogen, carbon dioxide, and an alkali metal, with the densities of helium atoms N_{He}, nitrogen N_{N2}, carbon dioxide N_{CO2}, and alkali metal N_{M} being in the ratio

$$N_{\mathrm{He}} \gg N_{\mathrm{N2}} \gg N_{\mathrm{CO2}} \gg N_{\mathrm{M}}. \tag{5}$$

The first condition that the gas parameters must satisfy is connected with the requirement that the photon emitted by the lamp be absorbed by an alkali-metal atom in the laser. Although the outer wall of the laser reflects resonant photons, these photons are not used if they return again to the lamp. Hence the mean free path of the resonant photons emitted by the lamp is smaller than the transverse dimensions of the laser,

$$K_{\Delta\omega} N_{\mathrm{M}} \Delta r > 1, \qquad \Delta r = R_0 - r_0.$$

Here $K_{\Delta\omega}$ is the absorption coefficient of the resonant photon emitted by the lamp. The width of the absorption line is determined by collisions of the absorbing atom with helium atoms and is therefore proportional to the helium density. Thus this condition has the form

$$N_{\mathrm{He}} N_{\mathrm{M}} (R_0 - r_0) > A, \tag{6}$$

where the quantity A depends on the width of the radiation line of the alkali-metal lamp.

An excited alkali-metal atom M*, formed in the laser as a result of absorption of a photon from the pump lamp, fluoresces more rapidly than process (2) has time to occur. However, the mean free path of this photon is considerably smaller than that of the photon from the pump lamp, so that it will have time to be re-emitted many times before returning back to the lamp. The second condition whose fulfillment is necessary in order that the photon not return to the pump lamp is that the resonantly excited state of the alkali-metal atom be destroyed by collisions with nitrogen before the photon returns to the lamp. The time for a photon with a Lorentzian line shape to traverse a distance l is equal to (^{16}) $1.4\,\tau\sqrt{K_0 l}$, where K_0 is the absorption coefficient at the line center and τ is the fluorescence lifetime of the resonant photon; therefore this condition has the form

$$\tau\sqrt{K_0(R_0 - r_0)} \gg 1/N_2 K_{\mathrm{qu}},$$

where K_{qu} is the constant of process (2). Since the Lorentzian broadening is determined by collisions with helium atoms ($K_0 \sim N_{\mathrm{M}}/N_{\mathrm{He}}$), this condition can be represented in the form

$$\frac{N_{\mathrm{N2}}^2}{N_{\mathrm{He}}} N_{\mathrm{M}} (R_c - r_0) \gg B, \tag{7}$$

where the quantity B is determined by the parameters of the working gas and turns out to be of the order of 10^{28} cm^{-5}.

Finally, the third condition is connected with the requirement that the nitrogen molecules transfer their excitation to the carbon dioxide molecules, rather than carry it away to the walls of the discharge tube. Since a nitrogen molecule, as a result of diffusion, traverses the distance $R_0 - r_0$ in a time of order $(R_0 - r_0)^2/D$, this condition has the form $(R_0 - r_0)^2/D \gg (N_{\mathrm{CO2}} K_{\mathrm{tr}})^{-1}$, where K_{tr} is the constant for transfer of vibrational excitation from nitrogen to carbon dioxide. Since the diffusion coefficient is determined by collisions with helium atoms and is inversely proportional to its density, this condition may be represented in the form

$$N_{\mathrm{CO2}} N_{\mathrm{He}} (R_0 - r_0)^2 \gg C, \tag{8}$$

where the parameter C is of order 10^{32} cm^{-4}.

4. Let us examine questions related to the power of this laser. Its power is, first of all, connected with the power of the alkali-metal lamp, which exceeds 1 kW/m (^{17,18}). More than 1/3 of the power of this lamp is emitted in the form of resonance radiation; approximately the same fraction of the resonance-radiation energy can be converted into laser-radiation energy. Therefore this laser is capable of giving the same radiation power as an ordinary carbon-dioxide laser with a sealed-off tube (100 W/m) at a somewhat lower efficiency ($\sim 10\%$).

The limitation on the power of an ordinary laser is connected with thermal effects. Specifically, if the gas temperature exceeds 800° K (^{19}), then, owing to the large population of the lower laser level, inversion of the level populations cannot be created. This gives a limiting value of the power for a laser in a cylindrical tube of $\sim$ 100 W/m* and a somewhat higher value for the limiting power if the discharge and the working gas are concentrated between two coaxial cylindrical surfaces (^{21}). A similar situation also occurs in our case. Let us determine the size of the laser region from the heat-conduction equation, assuming that the main heat is released by the lamp. We have:

$$-\chi \, dT/d\rho = P/2\pi r_0,$$

where P is the thermal energy released per unit length of the lamp; χ is the thermal conductivity coefficient of helium. Solving this equation and assuming that $\chi \sim T^{1/2}$, we obtain:

$$\frac{2}{3} \left[\chi(T_1)T_1 - \chi(T_2)T_2\right] = P(R_0 - r_0)/2\pi r_0,$$

where T_1 is the gas temperature at the inner cylindrical surface, and T_2 at the outer surface of the laser. Taking $T_1 = 800^\circ$ K, we find from this

$$\frac{R_0}{r_0} - 1 = \frac{4\pi}{3P} \left[T_1 \chi(T_1) - T_2 \chi(T_2)\right] \simeq \frac{6}{P \text{ (W/cm)}}. \tag{9}$$

As follows from this, at the maximum attainable powers of the alkali-metal lamp the quantity $R_0 - r_0$ is comparable with r_0, so that no problem associated with the choice of resonator for the laser arises. In this case the laser power can be increased by increasing the power of the alkali-metal lamp.

5. Let us give specific parameters of a laser based on a cesium lamp ([17]) with power $P = 12.5$ W/cm, resonance-radiation power 4 W/cm, and tube radius $r_0 = 2.5$ cm. In this case the radius of the laser tube, according to formula (8), is $R_0 = 5$ cm, and the parameter A in formula (6) is $A = 3 \cdot 10^{32}$ cm^{-5}. The helium density must be limited—

* With rapid transverse pumping of the gas, the attainable powers (1 kW/m) ([20]) are higher, since this circumstance plays no role.

so that it does not destroy the upper laser level; moreover, the constant of this process is ([22]) $K_p \approx 3 \cdot 10^{-15}$ cm^3/sec. The time of induced emission in a carbon dioxide laser is $N_{\mathrm{He}}/2 \cdot 10^{24}$ cm$^3 \cdot$ sec, and since it must be less than the time for destruction of the upper laser level in collisions with helium, $1/N_{\mathrm{He}}K_p$, it follows that $N_{\mathrm{He}} \ll 10^{19}$ cm^{-3}. Then it follows from formula (5) that $N_{\mathrm{Cs}} \gg 10^{14}$ cm^{-3}, and this is possible if the gas temperature is not below 400°K; otherwise the cesium will condense. This condition is fulfilled with a double outer wall and air placed in the gap. The branch tube with cesium is led outside; moreover, the amount of cesium in the gas is small and, in the example given, amounts to fractions of a milligram per meter of tube length. Conditions (6) and (7), for real values of the nitrogen and carbon dioxide densities—for example, for $N_{\mathrm{CO_2}} \sim 10^{16}$ cm^{-3} and $N_{\mathrm{N_2}} \sim 10^{17}$ cm^{-3}—are satisfied with a large margin.

Thus, the proposed continuous-wave carbon dioxide laser with optical pumping, using existing alkali-metal lamps, is capable of generating the same powers per unit length as an ordinary laser and, in some cases, may prove more convenient in use than an ordinary laser in a discharge tube. We note that the described pumping principle may prove very convenient for excitation of a CO laser, for which the problem of simplifying the excitation method is even more acute than in the case of a CO_2 laser. The practical value of a CO laser is indicated by the fact that its continuous-wave power at a wavelength of $5\,\mu$ reaches 90 W ([23]).

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