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Abstract**Full Text**

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PHYSICS

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A CARBON DIOXIDE LASER IN THE SINGLE-PULSE MODE*(Presented by Academician M. A. Leontovich, 17 VI 1969)*

1. The CO₂ laser is the most powerful laser operating in the continuous mode. At present there exists a laser ⁽¹⁾ whose power is 9 kW. Such a high power of a carbon dioxide laser is due to the fact that in it the conditions for producing population inversion on the vibrational levels of the molecule are fulfilled in the best possible way. In this situation one may hope to obtain pulses of high energy with the aid of this laser. The first experimental attempts in this direction have been made and give a value for the energy of the radiation pulse reaching 5 J. ^(2,3). Although these values are considerably smaller than the value attained with a neodymium laser (1000 J. ⁽⁴⁾) and a photodissociation laser (65 J. ⁽⁵⁾), Hill ⁽²⁾ asserts that a pulsed carbon dioxide laser is capable of giving a large output. In the present work we shall continue the discussion begun by Hill ⁽²⁾, connected with clarifying the possibilities of a pulsed carbon dioxide laser, and shall determine the optimal operating conditions of such a laser. This problem is facilitated by the fact that the processes occurring in this laser have been studied in sufficient detail and the constants of these processes are known.
2. An increase in the energy of a laser-radiation pulse can be achieved by increasing the volume occupied by the gas, or the output per unit volume. For a laser operating in the continuous mode, a substantial increase in the radius of the discharge tube does not lead to an increase in the output power of the laser, which is due to effects of heating of the gas by the discharge current. For a laser operating in the single-pulse mode, such a problem does not arise. However, when the laser is excited by a pulsed discharge, another problem arises, connected with the fact that the discharge current occupies part of the volume. In this case only a part of the volume occupied by the gas is usefully employed, and this part is the smaller the larger the dimensions of the system or the higher the gas pressure. To overcome this difficulty it is proposed to create free electrons independently and uniformly throughout the volume. The best method in comparison with others (irradiation of the gas with hard radiation, ad-

dition of a radioactive additive) is the addition to the gas of an easily ionized additive. Photoionization of the atoms of the additive leads to the formation of free electrons of the required density. The most suitable additive is cesium. We give the density of saturated cesium vapor in the range of temperatures of practical interest.

Temperature, °K	300	320	340	360	380	400
Saturated vapor pressure of cesium, torr	$1.8 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$	$0.9 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
Density of cesium atoms, cm^{-3}	$5.8 \cdot 10^{10}$	$3.5 \cdot 10^{11}$	$1.6 \cdot 10^{12}$	$6.2 \cdot 10^{12}$	$2.3 \cdot 10^{13}$	$6.6 \cdot 10^{13}$

The same value limits the density of free electrons that can be attained at the temperatures under consideration. Since

Since the density of the additive is very small, it does not affect the properties of the working gas.

- Thus, we have a gas in which we can uniformly create the required electron density. By acting on the electrons with an electric field, we excite the vibrational levels of the molecule and create an inverse population of the vibrational levels of the molecules. Let us determine the optimal conditions (gas composition and pressure, electron density, electric-field strength) that ensure the maximum energy extraction per unit volume. We shall first discuss the composition of the mixture. A high-power laser in continuous operation works on a $\text{CO}_2\text{--N}_2\text{--He}$ mixture. Helium performs two functions: it increases the thermal conductivity of the mixture and thereby makes it possible to reduce the influence of thermal effects and, in addition, promotes the depopulation of the lower laser level. Helium plays the same role in a pulsed laser as well. Therefore the optimal ratio between the helium density N_{He} and the carbon-dioxide density N_{CO_2} should be chosen the same as in a continuous-wave laser⁽⁸⁾, $N_{\text{He}} : N_{\text{CO}_2} \approx 10$. The addition of nitrogen to a laser operating in the continuous regime greatly increases its power. This is associated with the large cross section for excitation of the vibrational levels of nitrogen by electron impact, whose maximum value at an electron energy of 2.3 eV is⁽⁶⁾ $5 \cdot 10^{-16} \text{ cm}^2$. However, the maximum cross section for direct excitation of the upper laser

level of the carbon-dioxide molecule by electron impact is of the same order ⁽⁷⁾, and is reached at an electron energy of 0.9 eV. The mean electron energy in the positive column of the discharge is determined by the charge-particle balance condition (the number of charged particles formed as a result of ionization is equal to the number of recombining particles at the walls and in the volume), and in a carbon-dioxide discharge under optimal laser operating conditions is 2-3 eV. For this reason, the addition of nitrogen to carbon dioxide greatly increases the power of a laser operating in the continuous regime ⁽⁸⁾. Therefore, by lowering the mean electron energy in a single-pulse laser, we use the carbon dioxide effectively, and there is no need to add nitrogen to it.

4. Let us choose the optimal operating conditions of the laser. First, the ratio of the electric-field strength to the pressure of the carbon dioxide should be chosen so that the mean electron energy is about 1 eV, which corresponds to the maximum cross section for excitation of the CO₂ vibrational level by electron impact. Assuming that helium does not change the properties of the discharge, we find $E/p \approx 7$ V/torr · cm. The same value is obtained from the energy-balance equation, taking into account that all the energy transferred to the electron goes into excitation of vibrational levels:

$$\hbar\omega K N_e N m = jE = ew N_e E. \quad (1)$$

Here $\hbar\omega$ is the excitation energy of the 001 level; K is the constant for excitation of this vibrational level of CO₂ by electron impact, and w is the electron drift velocity. Using the experimental values of w ⁽¹¹⁾, K ⁽⁷⁾, we find $E/p = 8$ V/cm · torr.

The pulse duration τ_{imp} should be chosen from the condition that during this time the gas is heated to the temperature $T_{\text{pr}} = 800^\circ\text{K}$, since at this gas temperature lasing ceases ^(9,10). This gives

$$^{3/2}(T_{\text{pr}} - T_0)N_{\text{He}} = N_e N_{\text{CO}_2} K 0.6\hbar\omega\tau_{\text{imp}}, \quad (2)$$

where T_0 is the initial gas temperature; $0.6\hbar\omega$ is the excitation energy of the lower laser level, which is given up to the translational degrees of freedom. Hence we obtain

$$\tau_{\text{imp}} \approx \frac{3}{N_e K} \text{ sec}. \quad (3)$$

Let us note that under these conditions each molecule of carbon dioxide has time to be excited and to emit three times. At the same time, the density of helium is sufficiently high, so that the destruction of the lower laser level due to collision with a helium atom and the establishment of equilibrium over the

translational degrees of freedom occur much faster than the excitation of the vibrational level by electron impact.

The density of carbon dioxide should be limited by the condition that breakdown not have time to develop during the pulse,

$$\tau_{\text{imp}} \ll \frac{4}{N_{\text{CO}_2} K_{\text{ion}}(E/p)}, \quad (4)$$

where K_{ion} is the ionization constant of carbon dioxide by electron impact. Comparing formulas (3), (4), we find the optimum relation between the electron density and the carbon dioxide density:

$$N_e/N_{\text{CO}_2} \simeq 3 \frac{K_{\text{ion}}}{K_{\text{exc}}} \sim 2 \cdot 10^{-5}. \quad (5)$$

Under these conditions we obtain, for the energy of the laser radiation ξ per pulse and per unit volume of the active medium,

$$\xi = 3N_{\text{CO}_2} 0.4\hbar\omega \approx 10^{-14} N_e \text{ J}. \quad (6)$$

5. In studying the operation of this laser, one should take into account the possibility of recombination of electrons and ions. If a cesium ion forms a bound state with an atom or molecule, then recombination proceeds intensively over times of the order of $\sim 1/N_e\beta$, where the recombination coefficient is $\beta \sim 10^{-6} \text{ cm}^3/\text{s}$. This time is always less than the pulse time $\tau_{\text{imp}} \lesssim 3/N_e K_{\text{exc}}$, since $K_{\text{exc}} \sim 10^{-8} \text{ cm}^3/\text{s}$. This effect cannot be overcome by ionizing the gas, since that would lead to a nonuniform distribution of electrons. Therefore the cesium photoionization pulse should be continued for the entire operating pulse of the laser.
6. Let us summarize. The basic scheme of the laser under consideration is as follows. Cesium is evaporated into the volume occupied by the working gas, and the temperature of the walls of this system must be considerably higher than room temperature, so that the cesium density in the volume is sufficiently high. Before the discharge pulse, a pulse of ultraviolet radiation is switched on, acting throughout the entire operating pulse of the laser. Under the action of the radiation, cesium atoms and the molecules of which it is a constituent are ionized. Since each electron, during the action of the laser, has time to excite $\sim 2 \cdot 10^5$ molecules (see formula (2)), the energy losses for photoionization are relatively small. Since the drift velocity of the electrons under optimum conditions is $w_{\text{dr}} \approx 5 \cdot 10^6 \text{ cm/s}$, during this time they will travel a distance of $\approx 50 \text{ cm}$. In order that this effect not influence the operating conditions of the laser, it is necessary that the distance between the electrodes L be sufficiently large. Otherwise, over times shorter than the pulse time, the internal field of

the plasma screens the external field, which leads to nonuniform use of the volume and to a sharp decrease in the output energy of the laser. On the other hand, increasing the distance between the electrodes leads to additional difficulties associated with a large potential difference between the electrodes. It may also prove convenient to switch on the discharge in the transverse direction. These difficulties can be overcome by using an alternating-current discharge (connecting an inductance to the discharge plates).

The implementation of the proposed pulsed-laser design is associated with great technical difficulties. Namely, to create a plasma of uniform density in the active medium we use a photoionization source, and the photon mean free path is several orders of magnitude greater than the system dimensions usually used, so that for optimum utilization

the photoionization source, the walls of the discharge tube should be made highly reflective. Further, a relatively high plasma density is possible at high temperatures of the gas and the walls. Problems arise that are associated with the evaporation of cesium into the gas. Further, in order to carry out the discharge it is necessary to create a uniform field of high intensity in a large volume, and the direction of the field intensity must be changed during the discharge. Although each of the difficulties listed is not fundamental, taken together they make the problem technically very complex. Nevertheless, a pulsed carbon dioxide laser deserves attention already because this laser has a high efficiency ($\sim 10\%$); thus, when it is used for large volumes of working gas, the problem of creating a powerful pumping source and the problem of extracting uselessly used energy from the working volume prove to be simpler than in other cases.

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