EFFECT OF PARAMETERS OF THE DISCHARGE CIRCUIT ON THE MODE OF ENERGY INPUT INTO THE GAS IN A SELF-SUSTAINED DISCHARGE

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A model is proposed for calculating the characteristics of volumetric gas discharges used in the pumping of electric-discharge lasers. The dependence of the mode of energy input into the plasma of the gas discharge on the parameters of the discharge circuit is discussed.

Two types of powerful high-pressure pulsed lasers presently exist: electroionization lasers [1], in which a non-self-sustained discharge is maintained by an injected electron beam or a powerful ultraviolet light, and electric-discharge lasers having self-sustained discharges which are initiated by auxiliary discharges [2, 3]. The interest in such lasers is explained by the fact that because of the simplicity of their construction compared with electroionization lasers they can find wide application in technology and for scientific research.

It is known that the efficiency of a CO_2 laser essentially depends on the mode of energy input into the working gas, on the value of E/p in particular, where E is the field strength and p is the gas pressure [1, 4, 5]. In electroionization lasers, where the required electron density is achieved through an external ionizer, one can arbitrarily assign E/p and thus achieve a high laser efficiency. In electric-discharge lasers the multiplication of electrons is determined by impact ionization, and therefore rather high initial field strengths (no lower than the static breakdown strengths) are needed here which are not optimal from the point of view of the pumping of a CO_2 laser. However, E/p decreases as the storage capacitor discharges, so that the laser efficiency ultimately depends on what fraction of the energy of the storage was fed into the gas at optimal values of E/p. Thus, in a study of an electric-discharge CO_2 laser one must connect the parameters of the electrical circuit and the discharge gap with the mode of energy input into the active medium.

We will assume that the discharge has a volumetric nature and the cathode potential drop is small in comparison with the voltage applied to the gap [6]. Then the equations describing the discharge in a circuit consisting of a storage capacitor C, an inductance L, and a gas gap connected in series have the form

$$\begin{gathered} L\,di/dt = U_c - U; \\ dn/dt = (\alpha - \eta)vn - \beta n^2 + \psi_n(t); \\ dU_c/dt = -i/C + \psi_u(t); \\ dW/dt = iU/Sd;\ i = nevS, \end{gathered} \tag{1}$$

where n is the electron density; v is the electron drift velocity; α, β, and η are the coefficients of impact ionization, volumetric recombination, and capture; W is the energy applied per unit volume of gas; S is the area of the discharge; e is the electron charge; $\psi_n(t)$ is the rate of creation of electrons through the auxiliary discharge; $\psi_u(t)$ is the rate of supply of voltage to the capacitor C from the external storage; d is the interelectrode distance.

If the dependences of $(\alpha - \eta)/p$ on E/p are known for pure CO_2, N_2, and He gases [7, 8], then the determination of such dependences for CO_2-N_2-He mixtures is still a nontrivial task. Reports have recently appeared [4, 5] in which the electron energy distribution function and the electron energy balance during a discharge in CO_2-N_2-He mixtures are calculated and it is shown that the addition of even a small amount of molecular gas to the helium sharply alters the electron distribution function, shifting its maximum toward

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lower energies and "cutting off" the high-energy part. This is due to the larger ($\sim 10^{-16}$ cm^2) cross sections for excitation of vibrational levels of the molecules by low-energy electrons. By comparing the ionization cross sections of helium and molecular gases [14] one can note that electron multiplication in CO_2-N_2-He mixtures is due almost solely to collisions of electrons with the molecular component, while collisions with helium are unimportant in this case. Similar arguments can be made relative to the fraction of electron energy imparted to the excitation of different energy levels – almost all the energy goes into the excitation of the vibrational and electron levels of the molecular gases, with its distribution among the levels depending on E/p[4, 5].

In such a case one can assume that the pressure p^* of the molecular gas and the quantity E/p^* determine the energy balance and the electron distribution function during a discharge in a CO_2-N_2-He mixture. This is also indicated by the results of an experimental study of a gas discharge. It is shown [9] that an increase in the pressure of a CO_2-N_2-He mixture to 3.5 atm through the addition of helium to a constant amount of molecular gas does not affect the dependence of the energy input on the field strength. In analyzing the data on the static breakdown voltages obtained for CO_2-N_2-He mixtures (Fig. 1; curves 1-3 correspond to 1 : 1 : 0, 1 : 1 : 1, and 1 : 3 : 3 mixtures), we conclude that the breakdown field strengths are determined by the quantity p^* when the helium concentration in the mixture is less than 50%.

Thus, the quantity $(\alpha - \eta)$, which figures in Eqs. (1) and (3), is determined as follows:

$$\alpha - \eta = p^*(\alpha - \eta)/p^* \cdot (E/p^*), \qquad (2)$$

where $(\alpha - \eta)/p^*$ for the mixture of molecular gases CO2 – N2 is determined by interpolation between the values of $(\alpha - \eta)/p^*$ for pure CO2 and N2 [7, 8]. The volumetric recombination coefficients β were determined from [10, 11], while the electron mobilities M were determined from the data of [5] for CO_2-N_2-He mixtures.

Let us go on to the calculation of the mode of energy input into the gas for concrete circuits. The time dependences of E/p^* in the discharge gap, the current density, and the energy put into the gas are shown in Fig. 2 for nitrogen with $p^* = 1$ atm, $d = 1$ cm, $S = 1$ cm^2, and $C = 3 \cdot 10^{-10}$ F; The values of E_0/p^* are 41, 53, and 65 V·cm^{-1}·mm Hg^{-1} for curves 1-3, respectively; $L = 10^{-7}$ H and 10^{-6} H for the solid and dashed curves, respectively. The initial conditions for Eqs. (1) were assigned in the form $n(0) = 10^{10}$ cm^{-3}, $U(0) = U_C(0) = U_0$, $W(0) = 0$, and $E_0/p = U_0/pd$ and we took $\psi_n = \psi_u = 0$. It is seen that the field strength in the plasma is almost independent of the inductance for small overvoltages, although the effect of the inductance on the nature of the time variation in E/p^* becomes ever stronger in proportion to the increase in the overvoltage. A transition to an oscillatory discharge mode is observed at overvoltages approaching twofold. A characteristic property of the $E/p^*(t)$ dependences is the presence of the following principal phases: a surge in E/p^* to values roughly corresponding to static breakdown, a more or less prolonged holding of E/p^* at this level (the "step"), and a decline in E/p^* with the possible transition to an oscillatory mode. The presence and duration of the separate phases is determined by the quantity $E_0/p^* = U_0/p^*d$ and to a lesser extent by the characteristic impedance of the circuit. We note that in the circuit under consideration even at overvoltages of $E_0/E_{st} \approx 1.3$ almost all the energy is put into the gas at high field strengths ($E \gtrsim E_{st}$, where E_{st} is the static breakdown field strength).

The mode of energy input into a CO_2-N_2-He mixture was calculated for a circuit with the parameters $C = 4 \cdot 10^{-10}$ F and $L = 1.5 \cdot 10^{-6}$ – $2 \cdot 10^{-5}$ H. Since in a real circuit the voltage on the capacitor C was supplied with a front of $\tau \approx 2.5 \cdot 10^{-8}$ sec and during this time the gas ionization was accomplished by an auxiliary discharge [12] which gave an initial number of electrons $n_0 \approx 10^{11}$ – 10^{12} cm^{-3}, the initial conditions for Eqs. (1) were written in a form permitting the modeling of the breakdown of the gas gap: $n(0) = 0$; $U(0) = U_C(0) = 0$;

$$\psi_n(t) = \begin{cases} n_0/\tau; & t \leqslant \tau \\ 0; & t > \tau; \end{cases} \qquad \psi_u(t) = \begin{cases} U_0/\tau; & t \leqslant \tau \\ 0; & t > \tau. \end{cases}$$

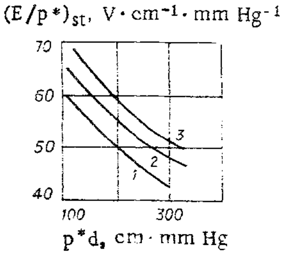

Fig. 1

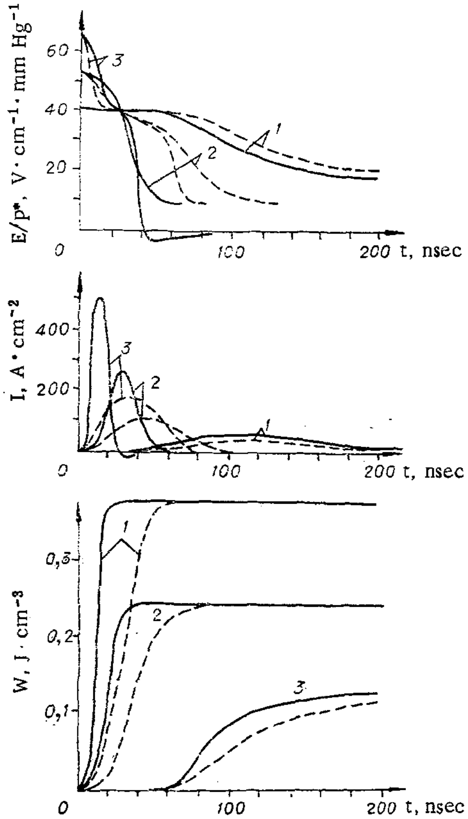

Fig. 2

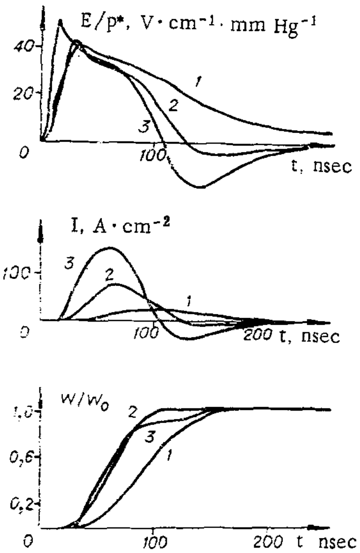

Fig. 3

In Fig. 3 we present the results of the calculation for the mixture $CO_2 : N_2 : He = 1 : 2 : 5$ at a pressure of 1.5 atm, which corresponds to $p^* = 420$ mm Hg, $d = 3$ cm, $S = 9$ cm^2, $C = 4 \cdot 10^{-10}$ F, and $L = 1.5 \cdot 10^{-6}$ H; the values of E_0/p^* are 42, 62, and 92 V·cm^{-1}·mm Hg^{-1} for curves 1-3, respectively. With overvoltages on the order of twofold the voltage and current have an oscillatory nature. At overvoltages $E_0/E_{st} \approx 2.3$ about 90% of the stored energy is fed into the gas in the first "half-period" and at overvoltages of ~1.6, all the stored energy.

The experimental results were obtained with the use of a voltage pulse generator, built on the Marx scheme [15], as the capacitor C. The capacitance of the generator "at best" was $4 \cdot 10^{-10}$ F and the self-inductance was $L_0 = 3 \cdot 10^{-7}$ H. In the course of the experiment the parameters were varied within the following limits: inductance $L = (1.5\text{-}2) \cdot 10^{-6}$ H, $U_0 = (157\text{-}225)$ kV, pressure of gas mixture 1-5 atm, helium concentration in mixture 45-80%, and active volume not more than $3 \times 1.5 \times 9$ cm^3. The preliminary ionization of the mixture was accomplished with an auxiliary discharge along the surface of the dielectric. The technique of accomplishing the preliminary ionization is presented in [12]. We introduced μ-xylene vapor, the partial pressure of which was 1-3 mm Hg [13], into the working volume to increase the degree of preionization.

The effect of the initial values of E/p on the nature of the energy input into the gas was studied in the mixture $CO_2 : N_2 : He = 1 : 2 : 5$ with $U_0 = 157$ kV and $d = 2$ cm. Voltage oscillograms are presented in Fig. 4. It is seen that the voltage on the plasma in the quasisteady phase is proportional to the pressure, as follows from the calculations; the nature of the discharge also varies as a function of the initial overvoltage: at overvoltages above twofold the discharge has an oscillatory nature, while below twofold it has an aperiodic nature.

Since the processes responsible for the appearance of an arc channel in the gap are insufficiently studied, the transition of the discharge from the volumetric to the arc stage was not analyzed in the calculations and the results of the calculations are only applicable to a volumetric discharge. The region of applicability of such calculations was determined experimentally. For this we studied the limiting energy density which can be put into the gas without the formation of an arc channel as a function of the rate of energy input into the gas, determined by the product ρS (ρ is the characteristic impedance of the circuit), and of the composition and pressure of the gas. The limiting energy inputs at which the discharge still has a volumetric nature at atmospheric pressure, as a function of the parameter ρS for $d = 2.6$ cm, are presented in Fig. 5a. The

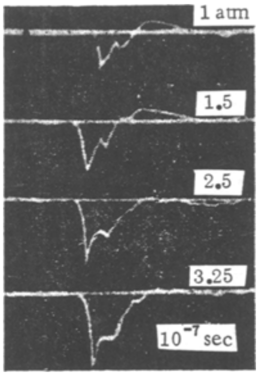

Fig. 4

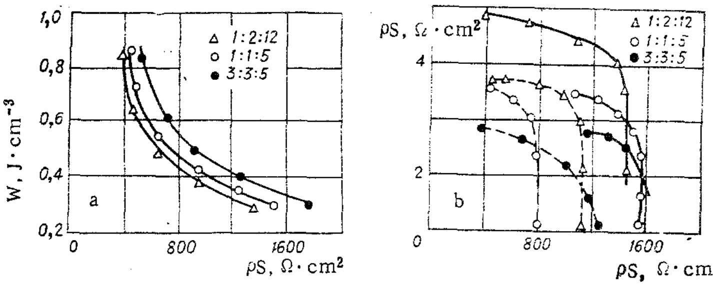

Fig. 5

dependence on ρS of the pressure at which the limiting energy input is reached in the volumetric stage of the discharge is shown in Fig. 5b with $U_0 = 200$ kV for $d = 3$ and 2.6 cm by solid and dashed curves, respectively. The ratios of components of the CO_2-N_2-He mixture are given in Fig. 5a, b. It is interesting to note that at high energy inputs and a pressure of 1-2 atm the energy put into the volumetric discharge grows with the heat capacity of the gas mixture.

Thus, a model and a method of calculation are proposed for the mode of energy input into the gas, the use of which gives results in satisfactory agreement with the experimental data. The region of applicability of the method is determined experimentally. The results obtained can be used to calculate the characteristics of electric-discharge carbon dioxide lasers.

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LITERATURE CITED

1. N. G. Basov, É. M. Belenov, V. A. Danilychev, and A. F. Suchkov, "Electroionization lasers on compressed carbon dioxide," Usp. Fiz. Nauk, 114, No. 2, 213-247 (1974).
2. A. K. Laflamme, "Double discharge excitation for atmospheric pressure CO_2-laser," Rev. Sci. Instrum., 41, 1578-1582 (1970).
3. M. C. Richardson, A. J. Alcock, N. Leopold, and P. Burtin, "A 300-J multigigawatt CO_2-lasers," IEEE J. Quant. Electron., QE-9, 236-243 (1973).
4. W. L. Nighan and J. H. Bennet, "Electron energy distribution functions and vibrational excitation rates in CO_2-lasers mixture," Appl. Phys. Lett., 14, 240-242 (1969); W. L. Nighan, "Electron energy distributions and collisional excitation rates in N_2, CO, CO_2 and their mixtures," Phys. Rev. A, 2, 1989-2000 (1970).
5. A. N. Lobanov and A. F. Suchkov, "Distribution function and energy balance of electrons in an electroionization CO_2 laser," Kvant. Élektron., 1, 1527-2535 (1974).
6. N. G. Basov, É. M. Belenov, V. A. Danilychev, O. M. Kerimov, I. B. Kovsh, and A. F. Suchkov, "Electric current in compressed N_2, CO_2, and their mixtures under conditions of strong ionization by an electron beam," Zh. Tekh. Fiz., 42, 2540-2549 (1972).
7. V. L. Granovskii, Electric Current in a Gas (Steady Current) [in Russian], Nauka, Moscow (1971).
8. H. Raether, Electron Avalanches and Breakdown in Gases, Butterworths, Washington, D. C. (1964).
9. Yu. I. Bychkov, I. N. Konovalov, Yu. A. Kurbatov, and V. M. Orlovskii, "An electroionization CO_2 laser with a radiation energy of 2.5 J per pulse," Prib. Tekh. Éksp., No. 3, 165-167 (1974).
10. G. A. Mesyats, Yu. I. Bychkov, V. V. Kremnev, Yu. D. Korolev, Yu. A. Kurbatov, and V. V. Savin, A Volumetric Discharge Excited by a Short Electron Beam in a Gas at High Pressure [in Russian], Preprint No. 3, IOA, Sibirsk. Otd., Akad. Nauk SSSR, Tomsk (1972).
11. S. J. Kast and C. Cason, "Performance comparison of pulsed discharge E-beam controlled CO_2-lasers," J. Appl. Phys., 44, 1631-1637 (1973).
12. Yu. I. Bychkov, V. V. Osipov, and V. F. Tarasenko, "A pulsed CO_2 laser excited by the double discharge method," Kvant. Élektron., No. 3 (15), 122-129 (1973).
13. Handbook of Chemistry [in Russian], Vol. 1, Khimiya, Moscow–Leningrad (1966).
14. A. T. Jusick, C. E. Watson, L. R. Peterson, and A. E. S. Green, "Electron impact cross sections for atmospheric species," J. Geophys. Res., 72, 3943-3953 (1967).
15. G. A. Mesyats, A. S. Nasibov, and V. V. Kremnev, Formation of High-Voltage Pulses [in Russian], Énergiya, Moscow (1970).