PULSED REPETITIVE CO_2 LASER PUMPED WITH A COMBINED DISCHARGE

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In this paper we present some results of investigation into the performance of a technological CO_2 *laser experimental model developed on the basis of an original combined technique of a volume discharge formation. The active volume of the discharge zone, gas flow velocity through the discharge gap and discharge length along the optical axis in our experiments were* 1000 cm^3, 50 m/s *and* 80 cm, *respectively. We have studied the laser operation in different pumping modes and different pressure of helium-free and hydrogen containing gas mixtures. Long-term operation of a laser without change of the gas mixture containing* CO *was investigated, as well. It was shown that high lasing efficiency (up to 22% and up to 28% if the contribution from the cathode drop is reduced) and specific output power of several units of* W/cm^3 *could be achieved in such laser systems.*

At present development of highly efficient and scaleable CO_2 lasers still remains important both for solving technological problems and development of large-scale laser systems.

As a rule, excitation and, correspondingly, radiation emission in such devices occurs in continuous mode when the entire lasing medium passed through the discharge region is exited providing thereby high output parameters and economical relationship between the gas volume and output radiation energy. While in the pulse repetition mode the major part of the gas is blown through the discharge volume between pulses and thus remains unexcited.

Nevertheless, pulsed-periodic radiation has more efficient action on a target. In this connection active search for methods of active media repetitive pumping which could provide high specific output parameters, scalability and high lasing efficiency is being under taken long time (see Refs. 1–3).

The aim of this research was to investigate the power potentialities and efficiency of a repetitive CO_2 laser pumped using a combined discharge whose electrical circuits do not use elements fundamentally limiting the current in a self-maintained and a semi-self-maintained discharges.

To justify the choice of the pumping mode numerical simulation of the CO_2 laser operation has been performed. Therewith a set of balance equations for electrons, ions (O^-, CO_3^-, CO_2^+, N_2^+, He^+) and neutral components of the gas mixture (N_2, ν = 1–5; $CO_2(001)$; $CO_2(01-30)$; $CO_2(100)$) has been solved. The plasma chemical reactions used and the corresponding rate constants were taken from Refs. 4–6. The rate constants of the processes involving electrons and depending on the strength of the electric field were calculated from Boltzmann equation according to scheme of numerical solution from Ref. 4.

Most frequently used methods of laser pumping, namely, continuous self-maintained discharge, continuous semi-self-maintained one with the electric field across the gap providing optimal energy transfer to the upper lasing level, pulsed semi-self-maintained one with the exponential current decay (at constant and optimal electric field) were simulated. The value of the ratio E/N (where E is the electric field strength, N is the concentration of gas particles) for self-maintained discharge was chosen from the following condition:

$$K_O N_{CO_2} + \beta N_i = K_{iCO_2} N_{CO_2} + K_{iN_2} N_{N_2} + K_{iHe} N_{He}.$$

(Here K_O is the rate constant of the dissociative attachment, β is the recombination coefficient, K_{iCO_2}, K_{iN_2}, and K_{iHe} are the ionization constants of CO_2, N_2, He, respectively; N_{CO_2}, N_{N_2}, N_{He} are the concentrations of corresponding ions).

The data of calculations are presented in Fig. 1 as the lasing efficiency versus specific normalized energy deposited into the gas medium blown through the laser active zone. It is seen that the maximum efficiency is achieved in a pulsed mode of operation (see curve *1* in Fig. 1). The difference in efficiencies of pumping by pulsed and continuous semi-self-maintained discharges (curves *2*, *3*) are mainly determined by the V–T relaxation losses.

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The lasing efficiency experiences a further decrease when the medium is pumped with self-maintained discharge (see curve *4*), because of inoptimal E/N value in terms of the energy transfer to the upper lasing level. Nevertheless, it should be pointed out that the difference is to be decreased as the discharge gap increases (see Ref. 7).

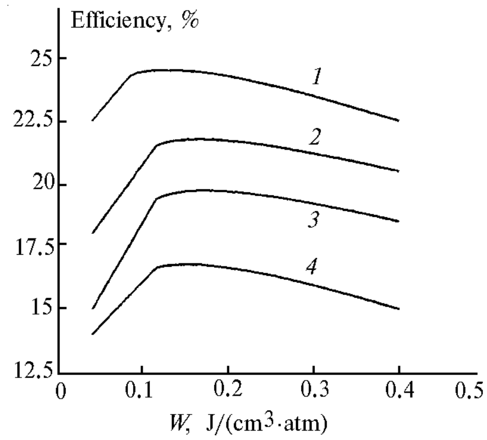

FIG. 1. Efficiency of a CO_2 *laser versus specific energy deposited into the active medium for different pumping methods obtained in* $CO_2:N_2:He = 1:4:8$ *mixture at a pressure* $p = 0.1$ Bar. *Combined pulsed discharge (1); semi-self-maintained discharge with the electrode width* 3.5 cm *(2); that with the electrode width* 5.5 cm *(3); continuous self-maintained discharge (4).*

To provide for optimal pulsed pumping we used a combined discharge. It is characteristic of this pumping method that no elements which limit current in circuits of semi-self-maintained and self-maintained discharges. Therewith as in the case of *e*-beam discharge initiation 90–97% of pumping power is deposited into the gas medium of semi-self-maintained discharge. This favors obtaining high efficiency and high specific output parameters of the laser emission and the discharge scalability. The circuitry facilitating the method is similar to that described in Ref. 8.

In our experiments the discharge volume was 1 l. The gas flow velocity through the gap was 50 m/s, the discharge length along the optical axis was 80 cm. For determining the laser output parameters radiation was sampled using the simplest stable optical cavity consisting of a concave copper mirror ($R = 20$ m, reflectivity 98%) and a coated plane mirror of ZnSe (reflectivity 80%). The cavity length was 1.4 m.

We have investigated the laser operation modes providing maximum output energy in various gas mixtures and at different pumping conditions. Further increase of the output energy was limited by the discharge constriction.

Deposited pumping power and output one versus pumping pulse repetition rate (PRR) are shown in Fig. 2. Since at low PRR (up to 400–500 Hz) the pumping power increases linearly with PRR, the output power is linear with PRR, as well. As the PRR is further increased saturation and fall in deposited power and, hence, output one is evident. It experiments performed stable maximum of the energy deposited at the stage of semi-self-maintained discharge into hydrogen-free and hydrogen containing gas mixtures was found to be at PRR of ~900 Hz and ~600 Hz, respectively. Note that self-maintained discharge was stable at PRR up to 3–4 kHz. This appears to be due to the process of intensive energy deposition into the most unstable discharge region, namely, cathode layer, which results in formation of inhomogeneities in that region. Calculation performed indicates that in conditions of our experiments the length of the cathode fall region is close to the width of Prandtl boundary layer. Therefore interpulse interval exceeding the time taken for one-fold gas change in discharge gap is determined by the necessity of total gas change in boundary near-electrode layer wherein conditions of gas circulation are pure. At the same time development of acoustic processes appears to be evident (see Ref. 9). At the instant a current starts to flow through the discharge gap shock wave enhanced in the zone of semi-self-maintained discharge begins to propagate in both directions along gas flow. Hence, the interpulse interval is required for all appeared inhomogeneities in gas density to be completely removed by gas flow.

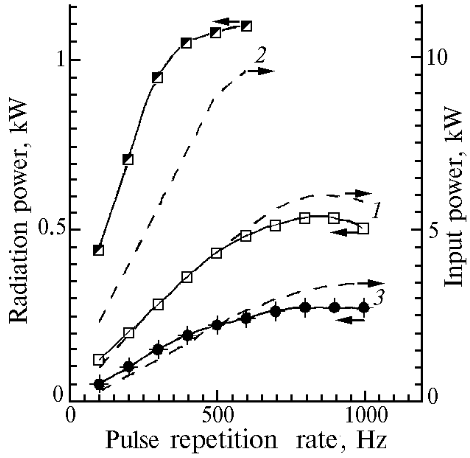

FIG. 2. Deposited and output power as a function of pulse repetition rate. Gas mixture $CO_2:N_2:He = 1:2:4$, *pressure* $p = 90$ Torr *(1);* $CO_2:N_2:He:H_2 = 3:10:26:3$, $p = 90$ Torr *(2);* $CO_2 : N_2 = 1:3$, $p = 40$ Torr *(3).*

Evidently, the difference in output radiation peaks obtained in hydrogen-free (800–900 Hz) and hydrogen-containing (400–600 Hz) mixtures is caused by gas heating at high pumping power level which in mixtures with hydrogen is achieved at low PRR.

Figure 3 depicts maximum deposited and output radiation power versus gas mixture pressure. Such a behavior of the curves can be explained by a number of competitive processes which make the laser output power either to increase or fall. On the one hand, the increase of pressure results in an increase of the power deposited into the discharge plasma and a number of excited molecules providing an improvement of output power parameters and on the other hand, pressure rise produces enhancement of the V–T relaxation rate and the laser line broadening which decreases the lasing gain and, correspondingly, the output power. At an enhanced pressure of the gas mixture (especially, its molecular component) stability of the discharge lowers and, correspondingly, the power dissipates in the gas poorer and the discharge plasma homogeneity also worsens.

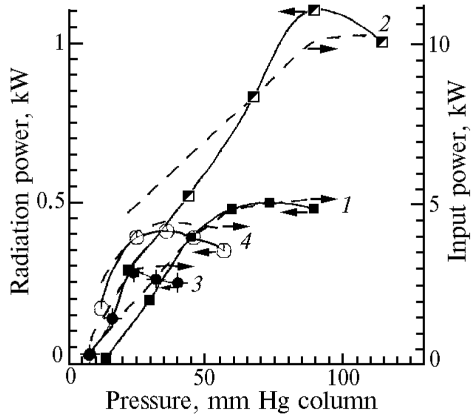

FIG. 3. Input and output power versus gas mixture pressure. Pulse repetition rate is 700 Hz *(1, 2, 3), gas mixture* $CO_2:N_2:He = 1:2:4$ *(1);* $CO_2:N_2:He:H_2 = 3:10:26:3$ *(2);* $CO_2:N_2 = 1:3$ *(3);* $CO_2:N_2:H_2 = 1:3:0.3$, *PRR is* 300 Hz *(4).*

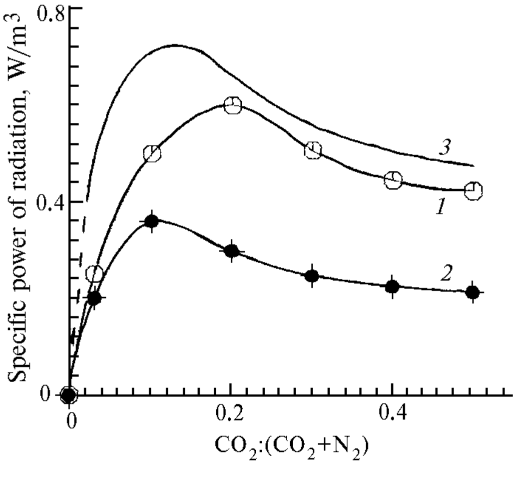

FIG. 4. Specific output power as a function of CO_2 *content in the gas mixture. PRR is* 700 Hz, *Helium and* $CO_2:N_2$ *mixture are* 40 *and* 30 Torr, *respectively. Initial shots (1); after* 10^6 *shots (2); calculated curve (3).*

For determining optimal composition of a gas mixture experiments on choosing the ratio between the CO_2 and N_2 concentrations in a gas mixture were performed (see Fig. 4). The measurements were made in the initial laser shots (curve *1*) and after 10^6 shots (curve *2*). Partial pressure of Helium and $CO_2:N_2$ mixture were 40 Torr and 30 Torr, respectively.

It is seen that the deposited power decreased as the fraction of CO_2 in gas mixture increased.

Maximum output power in the initial shots was obtained in the mixture $CO_2:N_2 = 1:4$. However, after 10^6 laser shots the gas mixture with $CO_2/(CO_2 + N_2) \le 0.1$ was found to be the optimal. It is apparent that at low CO_2 concentration decomposition of CO_2 molecules affects the laser operation to a lesser degree.

Relationship between the maximum specific power and $CO_2/(CO_2 + N_2)$ proportion was calculated for the condition mentioned above (see curve *3* in Fig. *4*). An increase in the specific radiation power at low partial pressure of CO_2 is caused by the efficiency increase due to a decrease in V–T relaxation losses and an increase in the gain.

At $CO_2/(CO_2 + N_2) > 0.15$ the lasing efficiency is no longer increased with the CO_2 fraction, while the fall in the specific power is evident. The latter can be explained by a decrease in the deposited energy associated with a more intense associative attachment of electrons to CO_2 molecules decreasing the current pulse duration.

In our experiments we found that the gas mixture $CO_2:N_2:He = 1:4:8$ at a pressure $p = 80$ Torr, which provides maximum efficiency of 28% in the initial shots (without considering the energy portion deposited into the cathode drop region). But, during the laser operation its efficiency rapidly falls due to CO_2 dissociation and production of new components (CO and O_2) in the mixture. Therewith the production of O_2 molecules results in a decrease of pumping power owing to an increase of the rate of electron attachment to these molecules and fall off of the current of semi-self-maintained discharge, other conditions being the same.

For a long-term operation of the laser to be studied the gas mixtures containing CO molecules which made it possible to maintain the initial gas composition due to the reverse chemical reaction $CO + O \rightarrow CO_2$. For instance, the fall in the laser output power in the mixture $CO_2:CO:N_2:He = 1:1:3:7.5$ does not exceed 10% after 10^6 shots.

Thus, a new pulse-periodic pumping mode was realized in an experimental model of a technological CO_2 laser. It was shown that high efficiency (up to 22% and up to 28% at a reduced fraction of cathode drop) can be achieved in such laser systems. Therewith the specific output power can reach several W/cm^3. The laser can operate (with some decrease in its efficiency) in a helium-free mixture. Besides, long-term operation without the gas change is possible using mixtures with CO.

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