Excitation of fast-flow gas lasers by combined discharge methods

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In the combined discharge of DCD–CPD type, the pumping of laser levels is realized, using the direct current discharge (DCD) in the decaying plasma, created by the capacitive-coupled pulse-periodic discharge (CPD). Stability and homogeneity are characteristic of the DCD–CPD plasma. Therewith, the power consumption for the discharge stabilization constitutes only several percents of the CPD power, while this magnitude is equal to tens of percents, when using gas-dynamical methods. Authors have experimentally tested the possibility of efficient application of the DCD–CPD method to the development of high-power gas lasers. Experimental fast-axial-flow CO_2 lasers of 1.5 and 3 kW CW with pulse-periodic output power were built and investigated. Properties of the discharge and active medium were studied with two (1.5 kW) and four (3 kW) discharge tubes. Lasers demonstrate linear output power of 2 kW/m with 20% discharge efficiency. Power scaling up to 6 kW is possible. Possibilities of the DCD–CPD scheme in the laser mode selection are discussed.

Introduction

Gas-discharge lasers with the cooling of the active medium via the cavity fast-axial-flow are widely used in industry due to their small dimensions and high-quality radiation. Either the direct current discharge (DCD) or capacitive-coupled HF discharge are used in such lasers to excite the active medium. The discharge stability is provided for by gas-dynamical methods.[1,2] In this case, the power consumption for the gas flow can be the same as for excitation of the active medium, that decreases the laser efficiency. The use of combined DCD with ionization by capacitive-coupled pulse-periodic discharge (DCD–CPD) for solving of the above problems was proposed by us and developed for application to lasers with transverse gas flow.[3] The discharge plasma generated with the help of CPD, provides for the efficient and uniform excitation of the active medium by the non-self-sustained DCD. In this case, the power consumption for the discharge stabilization does not exceed several percents of the DCD total power.

The efficiency of the DCD–CPD technology for fast-axial-flow lasers is studied in this work.

1. DCD–CPD main characteristics

In the discharge tube of the laser with DCD–CPD the pumping is realized by DCD between plug anode and ring cathode (Fig. 1). The electric field intensity of the DCD–CPD is lower than it is required for ionization. The threshold current of the contraction significantly increases in this case; and DCD–CPD stability and spatial uniformity can be realized without additional energy consumption for generation of large or small-scale vortices unlike in discharges of other types. Time average power of CPD does not exceed 5% of DCD power and the pulse duration of CPD current at 10 kHz repetition rate is 40 ns.

An experimental CO_2 laser with fast-axial-flow, designed for studies of DCD–CPD characteristics is shown in Fig. 1. The laser was designed on the basis of two-step radial turbocompressor, which provides for less than 1.4 pressure differential. At the pressure in the $1CO_2 : 7N_2 : 12He$ mixture up to 90 Torr the speed of gas flow at the input of discharge tubes with 3.5 cm inner diameter is 200 m/s. As a result of optimization of the DCD and CPD electrode forms and flow characteristics, a DCD power density up to 15 W/cm^3 has been reached, averaged over the discharge tube volume.

The ultimate values of DCD–CPD power, at reaching and exceeding which the contraction of volume discharge occurs, are presented in Fig. 2. The increase of the ultimate power with the increase of pressure, as well as its almost linear decrease at the increase of time interval between CPD pulses (Fig. 2) indicate the ionization-overheating mechanism of the discharge instability, leading to the contraction.[2,4] Since the ionization is realized by CPD, there is a possibility to choose the electric field intensity of DCD, optimal for excitation of oscillations of CO_2 and N_2 molecules.[5]

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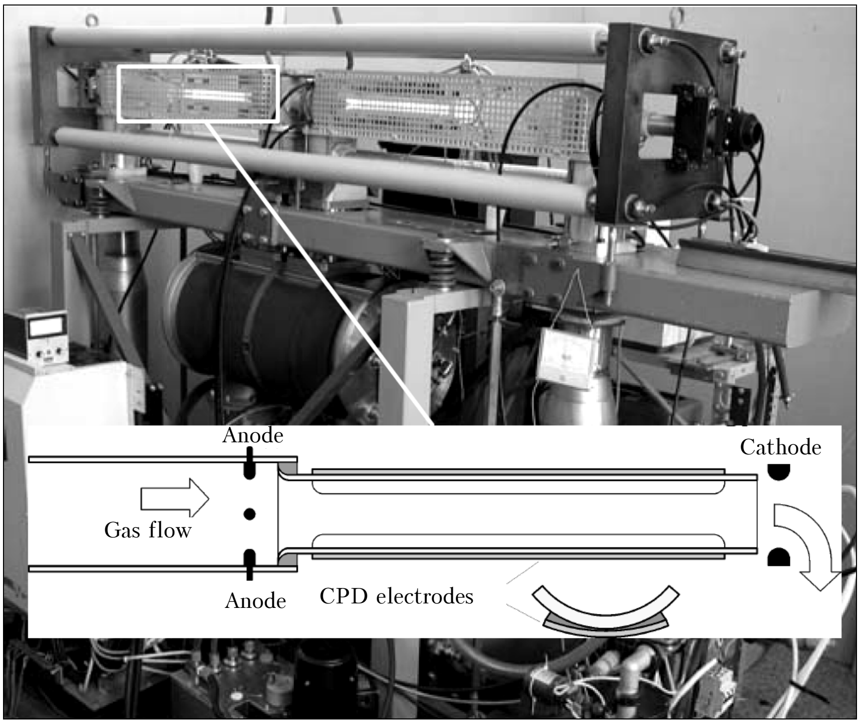


Fig. 1. Experimental CO_2 laser with fast-axial-flow with two DCD–CPD discharge tubes. The output power is equal to 1.5 kW. The discharge tube is schematically shown. The arrows show the gas direction. DCD electrodes serve as anode and cathode.

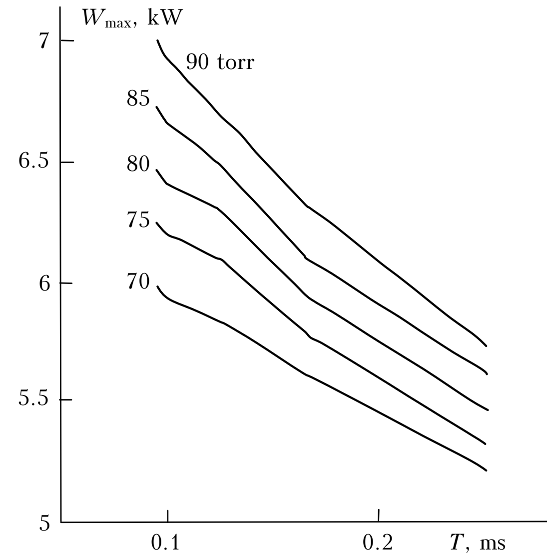


Fig. 2. DCD ultimate power W_{max} depending on the time interval T between CPD pulses at different pressures p (Torr) of the $1CO_2:7N_2:12He$ mixture in the discharge tube of the CO_2 laser with fast-axial-flow. Flow speed is 200 m/s.

2. Laser radiation characteristics

To study laser generation, two or four discharge tubes were connected sequentially in the semi-confocal stable cavity (see Fig. 1). Active length of each tube consisted of a 40-cm discharge share and 5-cm share of the excited gas downstream from the discharge zone. The experiments were aiming at determination of optical characteristics of the active medium, necessary for estimation of laser scaling capabilities (Fig. 3), and the discharge structure influence on the laser generation.

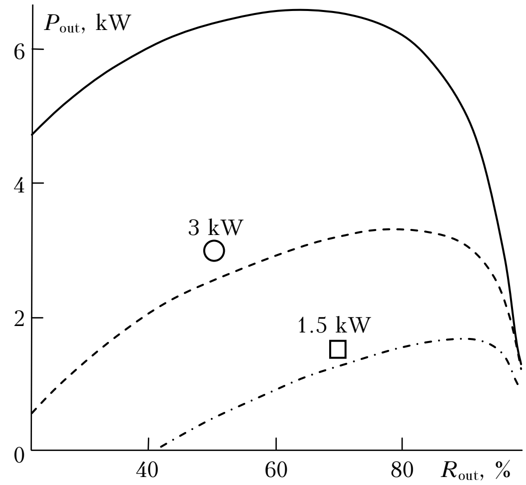


Fig. 3. Laser output power P_{out} depending on the reflection coefficient of the output mirror R_{out} for lasers with 2, 4, and 8 discharge tubes calculated by the Rigrod formulae[7] with measured parameters of the active medium. The points were obtained experimentally at lasers with two (1.5 kW) and four (3 kW) discharge tubes.

The results of investigation show a high optical uniformity of the active medium. Maximal output power at the continuous mode of operation reaches

1.5 kW in the experiments with two discharge tubes and more than 3 kW with four discharge tubes. The magnitude M^2, which characterizes the radiation direction diagram,[6] was approximately equal to 10 at two tubes and 6.5 at four tubes.

Values of coefficients of amplification of the weak signal G_0 and saturation intensity I_S, averaged over the active medium length were obtained by the method of calibrated losses as functions of the volume-average DCD power density $<jE>$. When calculating the dependence of laser power on the output mirror reflection coefficient for 2, 4, and 8 discharge tubes (see Fig. 3) by the Rigrod formulae,[7] the following values were used: $G_0 = 0.5$ m^{-1}, $I_S = 1.3$ kW/cm^2, corresponding to $<jE> = 10$ W/cm^3.

3. The peculiarities of combined discharge in fast-axial-flow scheme

An important feature of fast-axial-flow lasers is the cylindrical geometry of their active medium, favorable for laser radiation generation, however, complex in providing for CPD uniformity in the discharge tube section. Nevertheless, this geometry affords new possibilities for controlling laser radiation parameters.

Mutual positions of electrodes of the transverse CPD and longitudinal DCD in the laser discharge tube are shown in Figs. 1 and 4.

At an invariable form of the pulse discharge electrodes it is impossible to simultaneously provide for the uniformity of the pulse-periodic discharge both in the absence and in the presence of DCD electric field, because the plasma conductivity strongly depends on the DCD voltage closer to the moment of the next pulse. The CPD glow pattern in the absence of electrostatic field is shown in Fig. 4. At a low initial concentration of electrons in the beginning of each pulse the breakdown develops in the form of a surface discharge along the tube walls, therefore, the middle part of the tube is dark. The pattern differs, when the direct voltage is applied along the tube axis, because in this case the recombination rate of free electrons sharply decreases and plasma conductivity significantly increases to the beginning of the next pulse.

Figure 4 also shows the change of the outgoing laser beam configuration, the pattern discharge glow, and pulse current distribution $j(x)$ at the increase of radiation power and the corresponding decrease of mean specific electric resistance ρ of the medium.

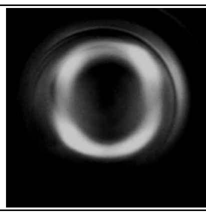
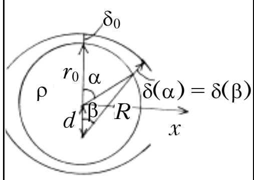
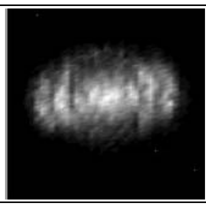
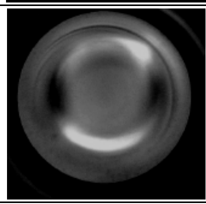
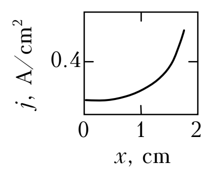
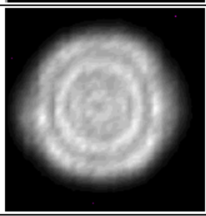
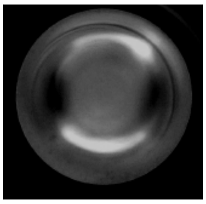
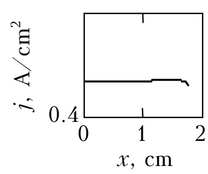
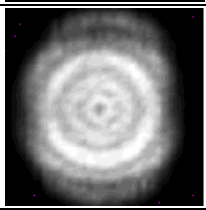
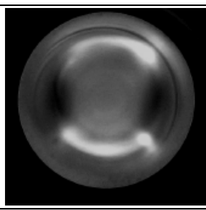
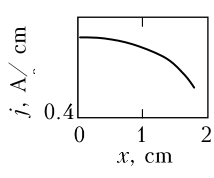
Laser operation regime, average plasma resistance	The distribution of radiation intensity over 2×2 cm field	CPD glow image. Inner tube diameter is 3.5 cm	Current density distribution CPD $j = j(x)$ [Ref. 8]
No DCD ($\rho \approx 10^5$ Ω · cm)	No radiation		
Generation threshold ($\rho \approx 10^4$ Ω · cm)			
Radiation power 0.5 kW ($\rho \approx 7 \cdot 10^3$ Ω · cm)			
1.25 kW radiation power ($\rho \approx 5.5 \cdot 10^3$ Ω · cm)			

Fig. 4. The change of the discharge glow structure, laser radiation spot configuration, and CPD current density distribution $j(x)$ in the process of DCD power increase and the accompanied decrease of plasma discharge resistance. The data were obtained in the experiment with two DCD tubes.

It is possible to derive a relation, connecting the duration of pulse voltage increase with geometrical characteristics of electrodes and discharge tube under the condition of uniformity of the CPD current density distribution over the tube section.[8] This relation can be used in the design of lasers and other devices, using the DCD–CPD.

4. Discussion

In our experiments, the share of volume in the active medium, occupied by radiation, did not exceed 50% of the total active medium volume and was limited by diaphragm in the optical cavity. Such ratio of the volumes was chosen as typical for the cavity designed for generation of a small number of transverse modes. Thus, the data obtained in short cavities with multimode operation can be used for the cavities operating in two or three transverse modes as well.

The results of the calculation by the Rigrod formulae[7] at measured parameters of the active medium (see Fig. 4) for the cases of 2, 4, and 8 discharge tubes are presented in Fig. 3. Experimental data for 2 (1.5 kW) and 4 tubes (3 kW) are shown by dot curves. The data presented allow the conclusion that the output power exceeding 6 kW can be obtained when using eight discharge tubes and the output mirror with a 50% reflection coefficient. In this case, the greater length of the cavity is favorable for generation of transverse modes of low orders, thus providing the radiation quality $M^2 = 2$–2.5 at maximal discharge efficiency of 20% and higher.

There are two reasons for relatively high generation efficiency in the above experiments. It is known that in the presence of laser radiation at the pumping power exceeding by several times the generation threshold, the concentration of excited particles in the volume with radiation is much lower than in the surrounding active volume.[9,10] Analysis of the mechanism of transfer of excited molecules from the surrounding volume to the radiation zone has shown that the process is caused by the turbulent diffusion. According to our calculations, about 50% of the efficiency increase is due to the turbulence diffusion.

Another possible mechanism, selectively increasing the pumping efficiency within the region occupied by radiation, can be interaction between DCD and CPD. As it is shown in Fig. 4, in case of DCD–CPD low voltage and power, plasma is concentrated on the tube walls. The DCD current in this case flows non-uniformly, causing a strong ellipticity of the laser beam near the generation threshold. The increase of the DCD power leads to increasing the plasma conductivity. This results in a more uniform distribution of the CPD current and, at maximal power, even its concentration along the tube axis, which also influences the change of the laser radiation spot configuration. Thus, following CPD, DCD current can provide for the increase of the pumping power in the volume occupied by radiation.

Current redistribution along the tube section, caused by the generation power increase, at first glance is harmful for the laser, because it leads to violation of the beam axial symmetry at varying power. However, the axial symmetry can be restored by rotating at some angle outer pulse charge electrodes around the optical axis, when going from one tube to another. The concentration of CPD and DC near the axis at the increase of power favors the stability of radiation mode structure. Thus, the choice of the form of the CPD outer electrodes can provide for the maintenance of high-quality radiation at increasing DCD power. The form of CPD electrodes can be optimized in such a way that to provide the increase of pumping power in the radiation zone in a maximally wide power range. This is very important for increasing the laser efficiency when generating a small number of transverse modes.

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