Quantum Electronics **39** (9) 797 – 801 (2009)

PACS numbers: 42.55.Lt; 52.50.Jm; 42.62.–b
DOI: 10.1070/QE2009v039n09ABEH014063

Gas laser for efficient sustaining a continuous optical discharge plasma in scientific and technological applications*

V.P. Zimakov, V.A. Kuznetsov, A.Yu. Kedrov, N.G. Solov'ev, A.N. Shemyakin, M.Yu. Yakimov

***Abstract*. A stable high-power laser is developed for the study and technical applications of a continuous optical discharge (COD). The laser based on the technology of a combined discharge in a scheme with a fast axial gas flow emits 2.2 kW at 10.6 μm per meter of the active medium in continuous and repetitively pulsed regimes with the electrooptical efficiency 20 %. The sustaining of the COD plasma in argon and air is demonstrated at the atmospheric pressure. The emission properties of the COD plasma are studied and its possible applications are discussed.**

Keywords: *fast axial flowing, CO_2 laser, nonself-sustained discharge, combined discharge, continuous optical discharge.*

1. Introduction

A continuous optical discharge (COD) was first predicted theoretically and observed in experiments at the Institute for Problems in Mechanics, RAS in 1969 – 1970 [1, 2]. Since then, the theoretical and experimental investigations of the COD have been performed at the IPMech, RAS [3 – 5]. These works stimulated in turn extensive and successful developments in the field of high-power lasers, which formed an important direction of fundamental and applied investigations [6]. However, it seems that the discovery of the COD phenomenon has been somewhat ahead of time because the COD did not find wide technological and scientific applications so far despite the promising results obtained in the studies of its properties. It can be explained, in particular, by the fact that high-power cw IR lasers are not available for many research laboratories.

Thus, our first aim was to develop a low-cost and reliable IR laser with highly stable output parameters suitable to sustain a COD. Our developments are based on the technology of a combined discharge, namely, a dc (DC) discharge sustained by a capacitive repetitively pulsed discharge (CPD). The discharge of this type has been earlier successfully used in transverse-flow Lantan lasers emitting up to 5 kW in cw and repetitively pulsed regimes [6]. A nonself-sustained DC discharge is used in the DC – CPD technology for laser pumping, while a CPD sustains the quasi-stationary electric conduction of the active medium. The stability and homogeneity of the discharge plasma provided by the CPD ensures a more efficient input of the DC discharge energy compared to the input from a self-sustained DC discharge. The DC – CPD method, which has been verified in transverse gas flow CO_2 lasers, is also proposed here for use in rapid-axial gas flow lasers. Such laser systems will combine a high stability and a high symmetry of the output beam, inherent in the DC – CPD method, with unique possibilities for controlling and scaling radiation parameters offered by the axial gas flow scheme.

2. Properties of the DC – CPD

The vibrational lasing levels of molecules in the discharge tube of a fast axial-flow DC – CPD laser are excited in a nonself-sustained DC discharge between fourth pin anodes arranged upstream and a circular cathode located downstream. The electric field strength of the DC discharge in the combined discharge is lower than that required for ionisation and can be optimised to excite lasing levels more efficiently. In the case of low field strengths, ionisation instabilities are suppressed, and a high level of the gas flow turbulence is not required to sustain the DC – CPD homogeneity. In this case, the time-averaged CPD power is usually no more than 5 % of the DC discharge power.

An experimental laser for the working off and optimisation of the DC – CPD scheme and studying the parameters of the active medium was built based on a two-stage turbocompressor providing the pressure drop in the gas-dynamic circuit of the laser no more than by a factor of 1.4 in gas mixtures containing up to 75 % of helium.

The parameters of the DC – CPD in discharge tubes were investigated in broad range of parameters: the gas flow was changed up to 250 m s^{-1} and pressure was changed up to 90 Torr in mixtures of composition close to that of the $CO_2 : N_2 : He = 1 : 7 : 12$ mixture. After optimisation of the shape and mutual arrangement of the DC and CPD electrodes and the gas-flow parameters at the discharge tube input, the average power density supplied to the discharge achieved 17.5 W cm^{-3} in tubes with inner diameter 35 mm and the DC discharge cathode and anode separated by a distance of 400 mm.

*Reported at the Conference 'Laser Optics 2008', St. Petersburg, Russia.

V.P. Zimakov, V.A. Kuznetsov, A.Yu. Kedrov, N.G. Solov'ev, A.N. Shemyakin, M.Yu. Yakimov A.Yu. Ishlinskii Institute for Problems in Mechanics, Russian Academy of Sciences, prosp. Vernadskogo 101-1, 119526 Moscow, Russia;
e-mail: solovyov@lantanlaser.ru, shemyakin@lantanlaser.ru, yakimov@lantanlaser.ru

Received 20 January 2009; revision received 15 April 2009
Kvantovaya Elektronika **39** (9) 797 – 801 (2009)
Translated by M.N. Sapozhnikov

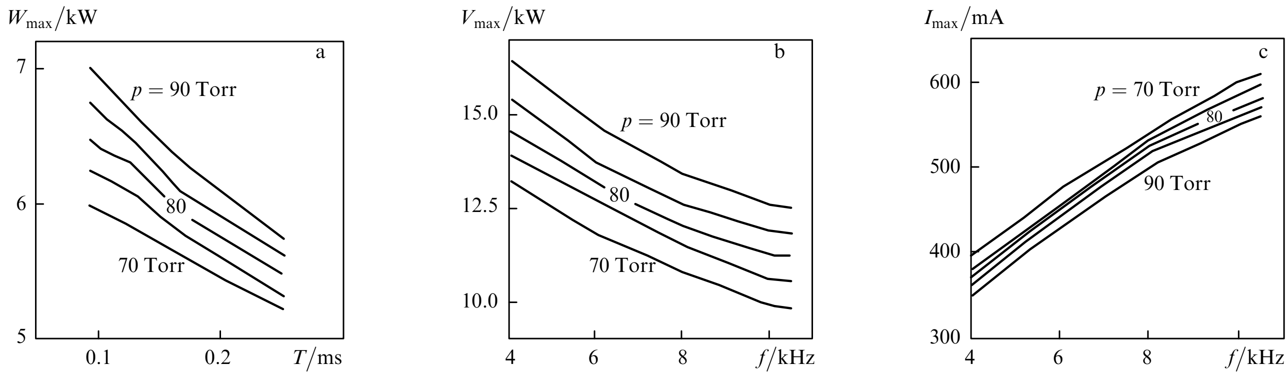

Figure 1. Dependences of the maximum power W_{max} of a homogeneous DC discharge on the period T between CPD pulses at different pressures p of the working gas mixture (a) and dependences of the maximum DC discharge voltage V_{max} (b) and current I_{max} (c) on the CPD pulse repetition rate f measured at different gas mixture pressures in one of the discharge tubes of a fast axial-flow CO_2 laser; the flow rate is 200 m s^{-1}.

Figure 1 presents the maximum output power, voltage, and current of the DC – CPD in one tube immediately before contracting, which appears when these values are exceeded. The maximum values were measured depending on the CPD pulse repetition rate f (or the time interval $T = 1/f$ between two successive pulses) at different gas pressures in the range typical for the laser operation. The achievement of the maximum values was determined by the appearance of the violations in the discharge emission homogeneity and by the appearance of irregular DC discharge current or voltage pulsations.

The increase in the maximum power of the discharge with increasing pressure (Fig. 1a) and its linear decrease with increasing T indicate to the ionisation-overheating mechanism of the discharge instability [7, 8]. The maximum current increases with increasing pulse repetition rate and decreases with increasing pressure (Fig. 1c). The maximum voltage increases with increasing pressure and decreases with increasing pulse repetition rate (Fig. 1b). This allows us to change the DC – CPD electric field with the aim to find its optimal value for excitation of the vibrational levels of CO_2 and N_2 molecules [9].

3. Laser parameters

Lasing can be obtained by using two, four or a greater number of discharge tubes combined in a two-mirror stable semi-confocal resonator. The optimal reflectance of the output mirror for two tubes was 70 % – 80 %, for four tubes – 50 % – 60 %, and for eight tubes – 30 % – 40 %. The gain was optimised for the minimal radiation load on resonator mirrors by performing calculations with the use of the measured parameters of the active medium [10]. The active-medium length in each discharge tube was 0.45 m.

The gain distribution in the active medium of each of the discharge tubes has the symmetry axis whose position is specified by the CPD electrodes [10]. The CPD electrodes in a laser with several discharge tubes were rotated through different angles around the axes of different tubes to provide the axial symmetry of the output beam.

The maximum output power obtained with two discharge tubes was 1.5 kW. The beam diameter, which was restricted by an aperture in these experiments, was 17 – 18 mm for the number of diffraction limits M^2 [11] about 10 at the maximum output power. The study of laser radiation parameters showed that the high homogeneity of the active medium, which is manifested in the output beam symmetry, can be achieved by selecting properly the shape of CPD electrodes [12]. The beam diameter was measured with an UFF-100 device by the ISO11146-1 : 2005 method [11], which gives correct results for the beams generated in stable resonators. The laser beam diameter, measured at different points outside the resonator, was then extrapolated inside the resonator by using a hyperbolic dependence [11]. We found by this method that the volume in which 90 % of the laser beam power was generated was no more than 50 % of the active-medium volume, taking into account the discharge gap and afterglow downstream.

Based on the results of experiments with two discharge tubes, we developed and built a considerably higher-power setup with four discharge tubes. The tubes were connected in parallel with a gas circulation system and in series with the optical resonator. The rectangular resonator had a length of 4800 mm and contained two additional fold mirrors. The highly reflecting concave mirror with the radius of curvature 10 m was used, while the output mirror was plane with the reflectance 50 %. The output beam diameter in the waist was 22 mm and the parameter M^2 characterising its divergence was equal to six. Figure 2 presents the dependences of the output laser power and the electrooptical lasing efficiency on the total electric power of the DC – CPD energy supply to all the four tubes. The maximum output cw power of the laser was 4 kW for the lasing efficiency of 20 % and the average power density of the energy supply to the active medium equal to 12.5 W cm^{-3}. Taking into account the active-medium volume filled with radiation, we find that up to 4.5 W cm^{-3} is extracted from the unity volume. This does not mean, of course, that the lasing efficiency achieves 36 % (4.5/12.5), but means only that the power density dissipated in the active-medium volume filled with radiation exceeds the average power density and, as shown below, can achieve 20 W cm^{-3}. There exist different mechanisms of power transfer into the laser beam, for example, the inhomogeneous contribution of the electric power or turbulent diffusion. These mechanisms are discussed below.

In our experiments, the volume filled with radiation in the resonator was purposeful restricted to 40 % – 50 % of the active volume. This relation between the volume filled with radiation and the entire active medium volume is also preserved in industrial lasers with longer resonators and with $M^2 < 2$. Calculations by the Rigrod formula [13] with

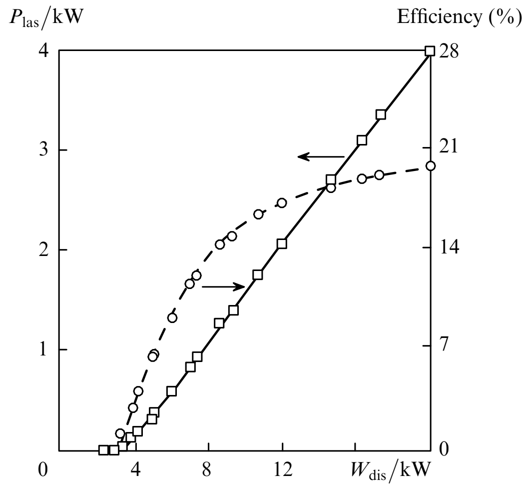

Figure 2. Dependences of the output power P_{las} and the electrooptical efficiency of a four-discharge tube laser on the DC – RCD power W_{dis}.

the experimental parameters of the active medium showed that the output power above 6 kW can be achieved by using eight discharge tubes and a resonator emitting a low-order transverse mode. Similar calculations performed for two [10, 11] and four discharge tubes were verified experimentally.

To explain the discrepancy between the volume-averaged DC discharge power density (12.5 W cm^{-3}) and the average laser power (4.5 W cm^{-3}) extracted from the unit volume filled with radiation, it is necessary to consider the possible mechanisms of the additional supply of excited particles to the laser beam region. According to our estimate, this discrepancy can be explained if the DC discharge power density in the laser beam region exceeds 20 W cm^{-3}. It is known that the concentration of active particles in the region of intense lasing in the active medium considerable decreases [14 – 16]. The estimates of the role of the turbulent diffusion of excited particles into the lasing region, as in [16], showed that turbulent transfer can explain approximately half the observed increase in the pump power density. Another mechanism of its increase can be the interaction between the DC discharge and CPD during discharge plasma formation. This effect is manifested experimentally in a change in the laser beam configuration with changing the radiation power [10, 12]. When the radiation power was close to the threshold, the beam cross section in a laser with two discharge tubes, in the case when CPD electrodes were oriented in both tubes identically, was strongly elliptic and compressed in the vertical direction, i.e. along the CPD current direction. The number of transverse modes in the vertical direction was also smaller than in the horizontal direction. As the radiation power was increased, the beam width increased and the number of modes in the vertical direction increased, being almost invariable in the horizontal direction. When the radiation power achieved 1 kW, the beam became symmetric, and as the radiation power was further increased, the beam broadened already in the vertical direction.

These observations can be explained taking into account that ionisation in the CPD in cold gas occurs nonuniformly, mainly near the tube walls. The pumping of the DC discharge at low powers also will occur near tube walls, which makes the beam cross section elliptic in this case. At high pumping powers, the effects of gas heating and slowing down of the loss of free electrons in a constant electric field come to play. In this case, the CPD plasma breaks away from the walls and can even concentrate near the tube axis, as the DC discharge current corresponding to the ionisation degree. The negative influence of these effects on the axial symmetry of the generated beam can be easily eliminated in a laser with a great number of tubes if the CPD electrodes in differently tubes are oriented differently. In addition, the shape of CPD electrodes can be specially selected to obtain the maximum ionisation namely in the volume filled with radiation, thereby increasing the efficiency and stability of lasing at a small number of transverse modes [12].

4. Sustaining of a COD

The power of a laser with four DC – CPD tubes (up to 4 kW in the cw regime) is quite sufficient for sustaining a COD in different gases at the atmospheric and higher pressures. Nevertheless, it was not clear before the beginning of experiments whether the focused beam intensity will be sufficient to produce plasma in the vapour of a metal evaporated from the target surface for initiating a COD. However, despite a comparatively low intensity of focused radiation (the cross-sectional area of the beam in the focus was measured to be 0.1 mm^2), plasma was readily produced by inserting a metal wire to the focus of a lens with a focal distance of 100 mm in air, or even easier, in argon at the atmospheric pressure and the cw laser power of 3 – 3.5 kW.

The simplest scheme for focusing and gas supply to sustain a COD is shown in Fig. 3. The laser beam is focused by an AR-coated plano-convex ZnSe lens with the focal distance $F = 100$ mm. The laser beam axis passes through a nozzle of diameter 19 mm, through which different gases can be supplied to the focal region, except toxic gases and gases yielding toxic products upon decomposition (CO_2 almost completely decomposes in a COD to produce CO). The focal point is located at a distance of 19 mm from the nozzle edge, so that the COD would be located completely in the supplied gas atmosphere. The gas flow rate was usually 1 – 2 m s^{-1}, but it could be increased up to 10 m s^{-1} and more. At flow rates exceeding several metres per second, the atmospheric air could admix into the supplied gas jet.

Figure 3 also presents the photographs of a COD in laboratory air and argon at different laser powers. The COD sustaining thresholds measured under these conditions were $P_0^{Ar} = 1.2$ kW in argon and $P_0^{Air} = 2.3$ kW in air. Thus, CODs in argon at the radiation power $P = 2$ kW and in air at $P = 4$ kW have close values of P/P_0 and close sizes of the emitting region (Fig. 3). The difference is that in the argon plasma a greater absorbed laser power is dissipated and, in addition, argon moves at a rate of about 1 m s^{-1}, while air is immobile. The contour plots in insets in Fig. 3 represent the equal-brightness lines for the optical emission of plasma. The plots were obtained from photographs taken through a filter in a narrow spectral range in the 512-nm region, where the plasma emission spectrum is mainly continuous. Because the COD plasma is virtually transparent for its own emission in this spectral region, these data give, after Abel transformations, the radial distributions of the emissive power of the COD plasma in the continuous spectrum. These radial distributions can be recalculated by using the

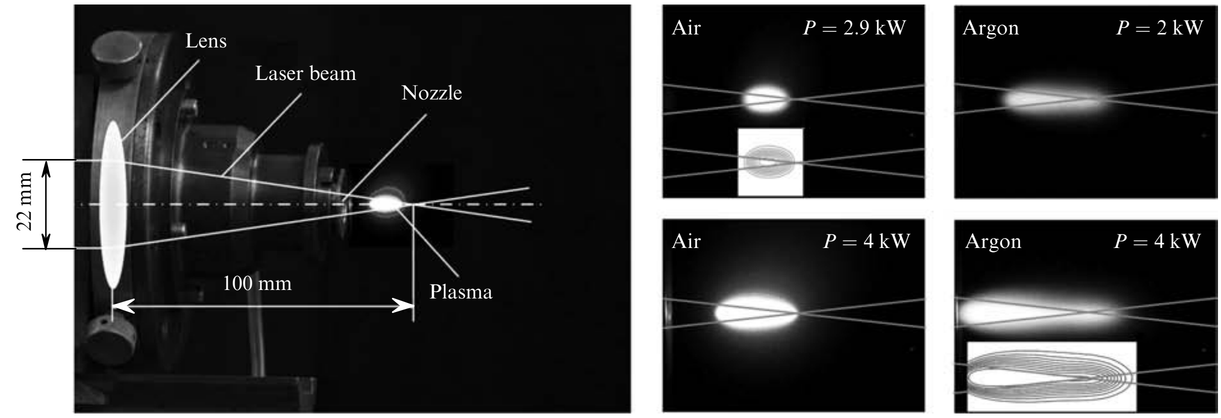

Figure 3. Experimental scheme for COD sustaining (at the left) and COD photographs in argon and air (at the right) taken through an optical filter to study the brightness and temperature distributions inside a plasma cloud (the frame size is 30×40 mm). The contour plots in insets are formed by the equal-brightness lines of laser emission in the 512-nm region.

known temperature dependence of the emissive power to obtain the temperature distribution in the COD [3].

The COD plasma has the following basic properties. The hottest region is located on the laser beam axis and is somewhat displaced to the laser from the centre of a region occupied by plasma. The maximum temperature depends on the gas type and pressure and is $(15 - 20) \times 10^3$ K at the atmospheric pressure. The typical concentrations of free electrons in the plasma are $10^{17} - 10^{18}$ cm^{-3} in the pressure range from 1 to 10 atm. The plasma volume heated above 10000 K (corresponding approximately to the sizes of emitting regions in Fig. 3) depends on the gas type and radiation power and lies in the range from 0.1 to 1 cm^3.

Figure 4 presents the emission spectra of a COD in air and argon at the atmospheric pressure. The spectra were obtained to study the possibility of the COD application as a high-power UV radiation source. One can see from Fig. 4 that both spectra exhibit an intense continuum in the UV region, which makes them similar to the solar spectrum at the top of the atmosphere (which is simulated by the black-body radiation spectrum with temperature 5800 K). Because the COD plasma in mainly transparent in the spectral region studied, the COD emits much weaker than the black body at the temperature 15×10^3 K typical for the COD.

Other possible applications of the COD can be based on the fact that the COD can be readily obtained in chemically pure media because it is removed from the walls and electrodes are absent, i.e. impurities that can strongly affect the emissive power and other properties of plasma are excluded. Therefore, the COD is an ideal object for studying the spectroscopic properties of gases at high temperatures (up to 25×10^3 K in helium) and for verifying the computer models of radiative heat exchange. Continuous optical discharges can be also used in the fields of high-temperature gas dynamics, the development of a laser rocket engine, thermoelectric phenomena, plasma chemistry, the deposition of films, the preparation of finely divided powders, etc.

These discharges can be also applied for obtaining high-

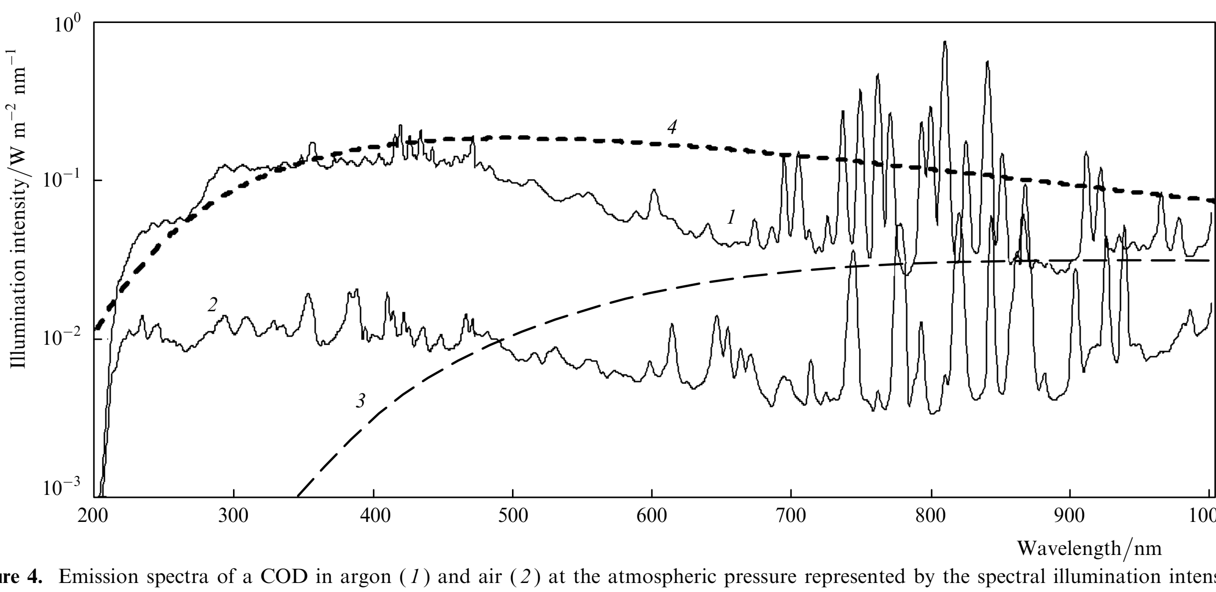

Figure 4. Emission spectra of a COD in argon (*1*) and air (*2*) at the atmospheric pressure represented by the spectral illumination intensity at a distance of 55 cm from the COD compared to these produced by a ribbon tungsten lamp with temperature 3000 K (*3*) and a black body at temperature 5800 K (*4*). The laser power is 3.2 kW.

enthalpy gas flows by blowing gas through a nozzle located near the discharge. The discharge is stable at flow rates in cold gas up to $10-12$ m s^{-1} and gas pressures from 1 to 10 atm and above [3, 4]. For the cw output power of a laboratory laser up to 6 kW, the gas flow enthalpy achieved by this method can be estimated as 2.5×10^4 J g^{-1} for the mass rate of $0.1-0.2$ g s^{-1}. To obtain supersonic flows, a low-pressure chamber is required to which gas, heated at a high pressure in the COD, is supplied through a nozzle. The composition of the plasma produced in this way corresponds to the initial gas flowing into the discharge, taking into account that during heating by laser radiation, the dissociation and ionisation of gas occur. The plasma composition at an elevated pressure is close to the thermally equilibrium composition. In pure molecular gases (O_2, N_2, CO_2, etc.), a COD can be produced at laser powers up to 6 kW.

5. Conclusions

We have demonstrated experimentally the possibility of the efficient use of a combined DC – CPD discharge in a fast axial-flow CO_2 laser. The properties of the active medium, the operation parameters and the possibilities of scaling of the laser have been investigated. The output laser power of more than 2.2 kW per active-medium meter with the electrooptical efficiency 20 % has been achieved. The principles of the design of lasers with the output power up to 6 kW and high efficiency and high radiation quality have been developed.

The possibility of the ignition and sustaining of a COD in argon and air in a laser beam with $M^2 = 6$ has been demonstrated. A stable and symmetric beam obtained in a fast axial-flow laser can sustain a stable and symmetric plasma region favourable for performing diagnostics and various applied studies, despite the fact that the laser radiation divergence strongly exceeds the diffraction limit.

References

1. Raizer Yu.P. *Pis'ma Zh. Eksp. Teor. Fiz.*, **11**, 195 (1970) [*Sov. JETP Lett.*, **11**, 120 (1970)].
2. Generalov N.A., Zimakov V.P., Kozlov G.I., Masyukov V.A., Raizer Yu.P. *Pis'ma Zh. Eksp. Teor. Fiz.*, **11**, 447 (1970) [*Sov. JETP Lett.*, **11**, 302 (1970)].
3. Gerasimenko M.V., Kozlov G.I., Kuznetsov V.A. *Kvantovaya Elektron.*, **10**, 709 (1983) [*Sov. J. Quantum Electron.*, **13**, 438 (1983)]; *Fiz. Plazmy*, **9**, 1269 (1983).
4. Generalov N.A., Zakharov A.M., Kosynkin V.D., Yakimov M.Yu. *Fiz. Goreniya Vzryva*, **22**, 91 (1986) [*Combustion, Explosion, Shock Waves.*, **22**, 214 (1986)].
5. Surzhikov S.T. *Fizicheskaya mekhanika gazovykh razryadov* (Physical Mechanics of Gas Discharges) (Moscow: Bauman Moscow State Technical University, 2006).
6. Generalov N.A., Gorbulenko M.I., Solov'yov N.G., Yakimov M.Yu., Zimakov V.P., in *Gas Lasers – Recent Developments and Future Prospects* (Netherlands: Kluwer Academic Publishers, 1996) p. 323.
7. Wiegand W.J., Nighan W.L. *Appl. Phys. Lett.*, **26**, 554 (1975).
8. Raizer Yu.P. *Gas Discharge Physics* (Berlin: Springer-Verlag, 1991; Moscow: Nauka, 1987).
9. Lowke J.J., Phelps A.V., Irwin B.W. *J. Appl. Phys.*, **44**, 4664 (1973).
10. Generalov N.A., Shemyakin A.N., Solov'yov N.G., Yakimov M.Yu., Zimakov V.P. *Proc. SPIE Int. Soc. Opt. Eng.*, **6611**, 6611K (2007).
11. International standard ISO 11146-1:2005 (2005).
12. Zimakov V.P., Kedrov A.Yu., Kuznetsov V.A., Solov'ev N.G., Shemyakin A.N., Yakimov M.Yu. *Opt. Atmos. Okean.*, **21**, 669 (2008) [*Atmospheric and Ocean Optics*, **21**, 575 (2008)].
13. Rigrod W.W. *IEEE J. Quantum Electron.*, **14**, 377 (1978).
14. Losev S.A. *Gazodinamicheskie lazery* (Gas-dynamic Lasers) (Moscow: Nauka, 1977).
15. Witteman V.J. *The CO_2 Laser* (Berlin: Springer-Verlag, 1987; Moscow: Mir, 1990).
16. Galushkin M.G., Golubev V.S., Zavalova V.E., Novodvorskii O.A., Panchenko V.Ya. *Kvantovaya Elektron.*, **22**, 485 (1995) [*Quantum Electron.*, **25**, 461 (1995)].