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Planar repetitively pulsed microwave-pumped CO_2 laser

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Abstract. **A planar repetitively pulsed microwave-pumped CO_2 laser with discharge channel lengths of 250 and 470 mm is experimentally investigated. An average laser power of 60 W at a wavelength of 10.6 μm is attained. A peak power of 1300 W is reached in the repetitively pulsed regime. The dependences of the shape and energy of CO_2 laser pulse on the introduced power, working gas mixture composition and pressure, and pump-pulse repetition rate and width are analysed.**

Keywords: *planar waveguide CO_2 laser, microwave discharge, magnetron, peak power.*

1. Introduction

Currently, an important problem in studying planar waveguide CO_2 lasers excited by high-frequency and microwave discharges in the repetitively pulsed regime is the increase in the peak power and the decrease in the lasing pulse width. In particular, a sequence of laser pulses 10 – 50 μs wide, with a peak power of $\sim$ 1 kW and repetition rates in the kilohertz range, was obtained in experiments with high-frequency/microwave pumping of CO_2 lasers; the average laser power amounted to 10 – 100 W [1 – 5].

Many technological applications, for example, surface scribing or drilling holes, call for single- or periodic-pulse CO_2 lasers. A combination of high peak and low average powers is advantageous, because lowering the temperature of the irradiated zone reduces undesirable effects, for example, carbonization of organic materials. Changing mainly the repetition rate and pulse width and peak power, one can effectively control the heat supply to material and implement high-quality cutting.

In medicine, the use of controlled pulsed laser regime makes it possible to cut biological tissues using a series of microexplosions in their surface layer. This regime is characterised by minimum (or even zero) thermal damage. In contrast to the TEA CO_2 laser, whose pulse width is determined by physical processes and the average power can be changed by only varying frequency, the application of a magnetron as a high-power microwave generator (frequency 2.45 GHz) allows one to easily change the pump-pulse repetition rate and width. We used a 2M-130 magnetron with a pulse power to 8 kW and average power to 1.8 kW (in high-frequency generators the output signal amplitude is almost the same in both pulsed and cw regimes, whereas 10-kW high-frequency generators are rather expensive).

A number of studies [6 – 8] were devoted to compact planar waveguide CO_2 lasers with pulsed high-frequency pumping. In this context, it is of interest to analyse a microwave-pumped CO_2 laser operating in the repetitively pulsed regime.

In this paper, we report the results of studying the output characteristics of a planar waveguide laser pumped by a repetitively pulsed microwave discharge. The dependences of the characteristics of CO_2 laser pulse on the power introduced into the microwave discharge, working mixture composition and pressure, and pump-pulse repetition rate and width were experimentally studied. The characteristic times, shape of the output laser pulse, and its evolution were studied and recorded under different experimental conditions.

2. Experimental conditions

A schematic of the experimental setup for studying the microwave-pumped CO_2 laser is shown in Fig. 1.

The microwave cavity [waveguide (*1*) 90 × 45 × 800 mm in size with a rectangular cross section] is tuned by a short-circuiting plunger (*2*) from one side. From the side of magnetron (*3*) the cavity is tuned using a matching *E–H* transformer (*4*), which is based on a double T junction. The microwave-pump source is a pulsed power supply (*5*) of the RM-740T type with a 2M-130 magnetron (*3*). The active volume of laser head (*6*) is a cavity formed by two shaped aluminum plates, compressing a quartz plate (*13*) 2 × 30 × 300 (500) mm in size, with a long lateral side oriented along the microwave cavity slot. The dielectric plate is used as a distributed reactive ballast resistance (without power loss) to stabilise the discharge. The discharge channel, 2 × 25 × 250 or 2 2 × 25 × 470 mm in size (laser heads A or B, respectively), is formed by the gap between polished aluminum and quartz plates. Provision is made for head water cooling. The application of planar discharge has a number of advantages: effective heat removal from walls, laser head compactness, low breakdown voltage, high output beam quality, and high specific output laser power.

To supply microwave power to discharge, we used an emitting slot (analog of slot antenna) in a hollow cavity tuned to the magnetron frequency, and the discharge

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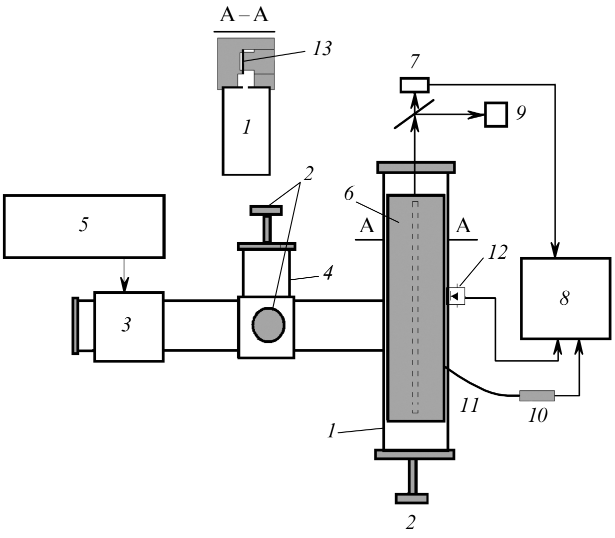

Figure 1. Schematic of the experimental setup: (*1*) waveguide; (*2*) short-circuiting plungers; (*3*) magnetron; (*4*) matching $E-H$ transformer; (*5*) power supply; (*6*) laser head; (*7*) pyrometer; (*8*) oscilloscope; (*9*) power meter; (*10*) photoelectron multiplier; (*11*) optical fibre; (*12*) microwave detector; and (*13*) discharge channel.

structure and optical cavity were beyond the microwave cavity [3].

The investigations were performed for gas mixtures of different compositions at pressures of 10 – 50 Torr, microwave-pump-pulse widths of 20 – 50 μs, and repetition rates of 0.4 – 10 kHz. The laser pulse shape was controlled by a BP-10 pyrometer (*7*) with a time resolution of 10^{-8} s and two-channel digital oscilloscope LeCroy-432 (*8*) with a transmission band of 350 MHz. The laser power was measured by a NOVA-2 facility (*9*) (Ophir) with a thermoelectric head (aperture 29 mm). The discharge glow in a wavelength range of 160 – 600 nm was recorded by a FEU-39A photoelectron multiplier (*10*), connected with the discharge gap through an optical fibre (*11*). The envelope of the rf pump pulse was recorded by a microwave detector head (*12*).

The laser cavity is formed by two mirrors: a highly reflecting spherical copper mirror with a curvature radius of 5 m and reflectance of 98.8 % and an output plane-parallel germanium mirror with a transmittance of 5 % or 10 %. The mirrors are located at a distance of 5 mm from the discharge channel and are thus somewhat protected from the gas-discharge plasma radiation.

The microwave radiation wavelength in the waveguide differs from the magnetron wavelength λ_{mag}. At a wide waveguide wall 9 cm in size and $\lambda_{\text{mag}} = 12.24$ cm, the waveguide wavelength is ~ 16.7 cm.

The simplest oscillations in a rectangular resonator are of the H_{101} type, which corresponds to H_{10} standing waves in a waveguide with a length of a half wavelength of the waveguide wave. The discharge channel length of 250 mm corresponds to three half-waves of the standing-wave electric field distribution. Thus, the field distribution along the discharge gap has three maxima and, therefore, is significantly inhomogeneous. An experimental study of the discharge glow showed that the dark spots along the discharge channel essentially decreased in size, up to their complete disappearance, with an increase in the power introduced into the discharge or a decrease in the gas pressure.

3. Experimental results

The laser efficiency and power depend strongly on the gas mixture composition. Figure 2 shows the oscillograms of laser pulses for a conventional working gas mixture and a nitrogen-free mixture and the shape of the microwave-pump-pulse envelope. Note some difference in the shapes of the corresponding laser pulses. The previous measurements [3] showed that addition of nitrogen increases the output laser power by a factor of 2.

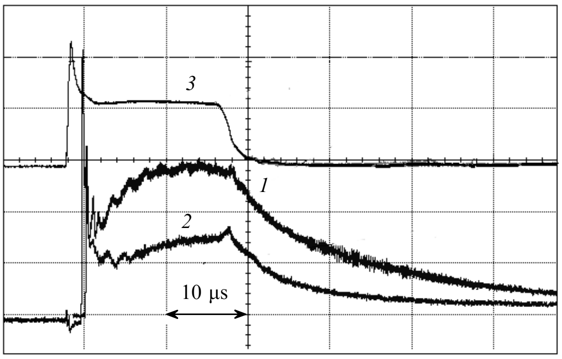

Figure 2. (*1, 2*) Oscillograms of laser pulses for (*1*) a working mixture $CO_2:N_2:He:Xe = 3:3:13:1$ and (*2*) a nitrogen-free mixture $CO_2:Ne:Xe = 4:15:1$ and (*3*) the pump-pulse envelope (mixture pressure 30 Torr, pump-pulse repetition rate 1000 Hz).

The increase in the laser power with an increase in the power introduced into discharge is limited by the rise in the working mixture temperature. The change in the laser pulse shape and width with a change in the pump-pulse width in the range of 20 – 45 μs is shown in Fig. 3. One can see that an increase in the pump-pulse width above 30 μs reduces both the amplitude and width of laser pulse because of the active-medium superheating.

Figure 4 shows the dependences of the average output laser power on the average pump power for several pump-pulse repetition rates. The average power was varied by

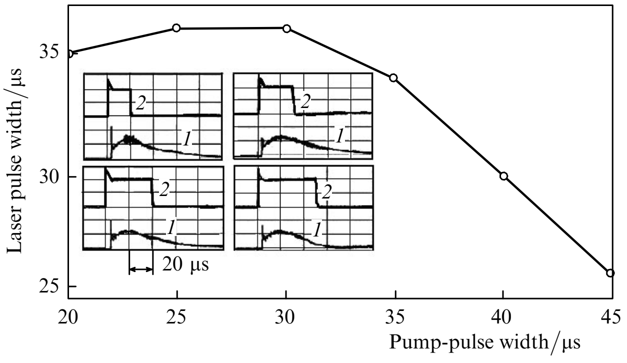

Figure 3. Dependences of the laser pulse width (at half maximum) on the pump-pulse width. The inset shows the oscillograms of (*1*) laser pulses and (*2*) microwave-pump-pulse envelopes (gas pressure 30 Torr, pulse repetition rate 500 Hz).

changing the microwave pulse width in the range of 20–50 µs. The pump-pulse power was 4 kW. One can see in Fig. 4 that, at the same introduced microwave power but different pulse repetition rates, output laser powers differ. Hence, pumping by shorter pulses with a higher repetition rate is preferred.

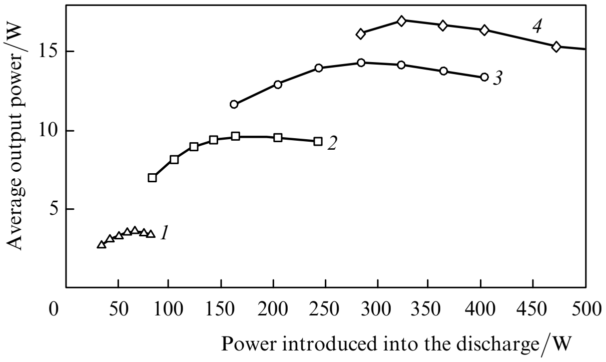

Figure 4. Dependences of the average output laser power (laser head A) on the pump power at pump-pulse repetition rates of (*1*) 400, (*2*) 1000, (*3*) 2000, and (*4*) 3300 Hz ($CO_2:N_2:He:Xe = 3:3:12:2$ mixture at a pressure of 30 Torr).

The dependence of the laser pulse width (at half maximum) on the working gas pressure, as well as the pulse shape evolution are shown in Fig. 5. The pulse width is determined to a great extent by the relaxation time of excited molecules. This time decreases with an increase in pressure; therefore, the pulse width also depends on pressure: an increase in this parameter yields shorter pulses with a higher energy and peak power. Hence, the working pressure must be maximally high; however, in this case it is necessary to take into account that the discharge becomes unstable with increasing pressure.

Figure 6a shows the dependence of the laser pulse delay time τ on the average microwave-pump power. The shape of the sharp peak in the leading edge of laser pulse (Fig. 6b) is similar to that of the TEA-laser output pulse in the so-called switched-on amplification regime. This peak arises when the pump-pulse leading edge is sufficiently steep [9]. The oscillograms in Fig. 6c indicate that, with an increase in the power introduced into the discharge, the laser pulse shape changes from almost flat [curves (*1*, *2*)], as under cw pumping, to a curve with a characteristic hump [curve (*3*)]. The laser pulse delay time with respect to the pump pulse ranges from 4 to 10 µs.

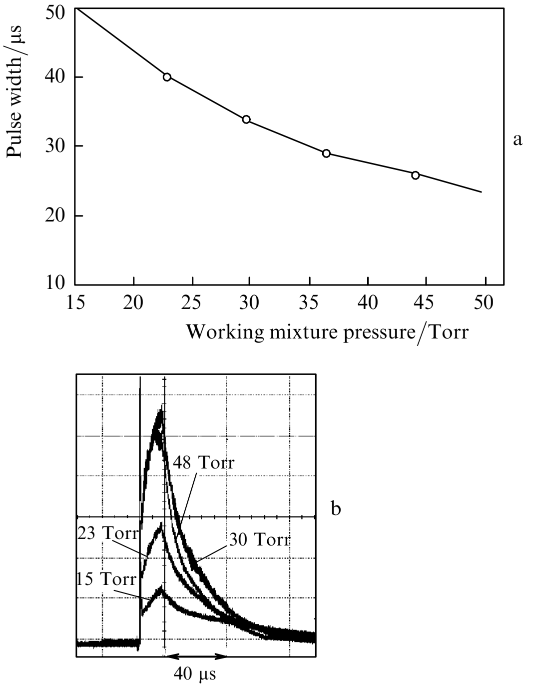

Figure 5. Dependences of the laser pulse (a) width (at half maximum) and (b) shape on the pressure of $CO_2:N_2:He:Xe = 3:3:13:1$ mixture (pump-pulse width and repetition rate are 20 µs and 1000 Hz, respectively).

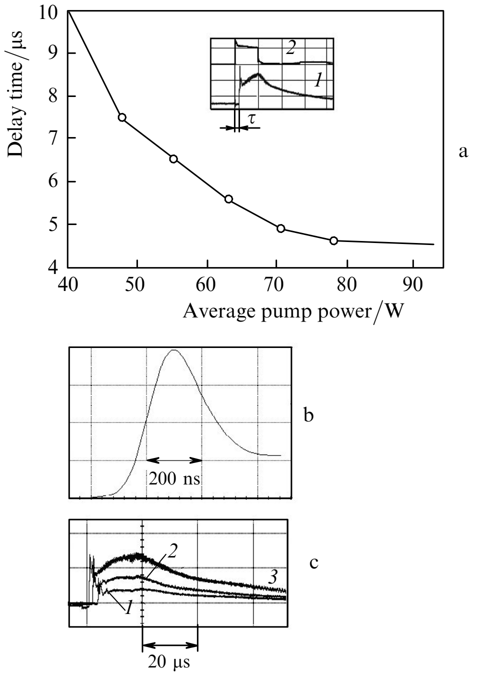

Figure 6. (a) Dependence of the laser pulse delay time τ on the microwave power introduced into the discharge; (b) the leading edge shape; and (c) the laser pulse shapes at microwave-pump powers of (*1*) 50, (*2*) 70, and (*3*) 90 W (pump-pulse width 20 µs, repetition rate 1000 Hz, $CO_2:N_2:He:Xe = 3:3:13:1$ mixture at a pressure of 23 Torr). The inset shows the oscillograms of the (*1*) laser pulse and (*2*) pump-pulse envelope.

Figure 7 presents the dependence of the pulsed output CO_2 laser power on the pulsed microwave-pump power. It can be seen that, for the given mixture composition, gas pressure, and volume of the active medium (laser head B), saturation is absent, and, therefore, the output power may exceed 1.3 kW.

The dependences of the average output power of microwave-excited laser on the pump-pulse repetition rate at different working gas pressures are shown in Fig. 8. It can be seen that maximum laser powers are obtained at pump-pulse repetition rates of 3–5 kHz.

For the case under consideration we will estimate the temperature relaxation time $\tau_T = \Lambda^2/\chi$ of the gas mixture for an interelectrode gap $h = 2$ mm using the formula $\tau_T = \Lambda^2/\chi$ [10], where $\Lambda = h/\pi$ is the diffusion length and χ is the gas thermal diffusivity (20 $cm^2\ s^{-1}$ for a

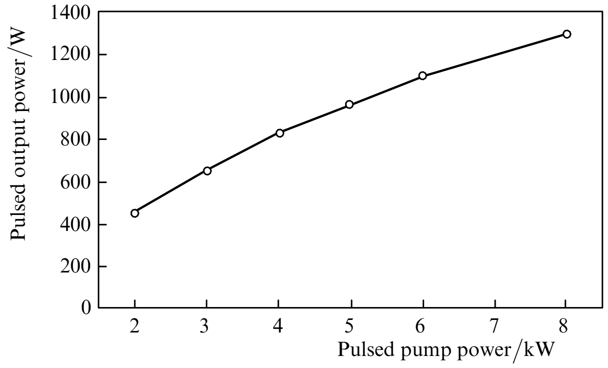

Figure 7. Dependence of the pulsed output laser power on the pulsed microwave-pump power (laser head B) ($CO_2 : N_2 : He : Xe = 3:3:13:1$ mixture at a pressure of 50 Torr, gas mixture circulation rate 0.1 L s^{-1}, pump-pulse width 20 μs, repetition rate 400 Hz).

pressure $p = 30$ Torr). For the reverse time $1/\tau_T$ of diffusive heat removal we have the following values: 4.9, 3.9, and 3.2 kHz at $p = 30$, 37, and 45 Torr, respectively. These values are very close to the threshold pump frequency, above which the laser power begins to rapidly decrease. With a decrease in pressure the output power peak shifts to higher pump-pulse repetition rates because of the increase in the gas thermal diffusivity.

With an increase in gas pressure [Fig. 8, curve (*3*)], an atypical output power peak arises at a pump frequency of 3.8 kHz. This effect is likely to be related to the acoustic resonance in the laser head. The reason for the occurrence of the acoustic effect is the change in the gas temperature due to the repetitively pulsed regime of microwave-pump-power modulation. As was noted above, the electric field distribution along the discharge channel is nonuniform for the design under consideration. The discharge nonuniformity increases with an increase in the mixture pressure (see the photograph of plasma glow along the discharge channel in Fig. 8). The sound wavelength for an excitation frequency of 3.8 kHz was estimated to be multiple of the microwave cavity length. The existence of acoustic resonance may improve the discharge uniformity. One should take into account that an increase in the pump power may transform the discharge into the so-called γ phase, which is undesirable for efficient CO_2 laser operation [10].

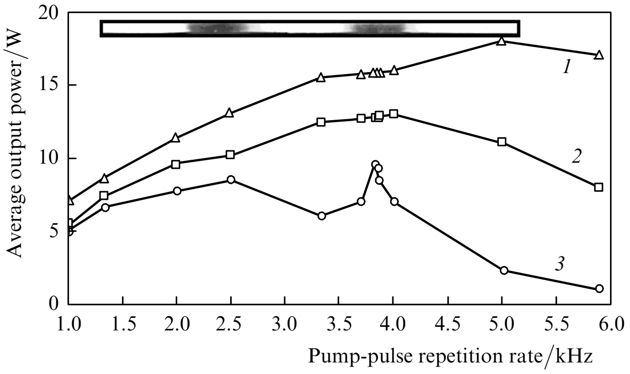

Figure 8. Dependences of the average output microwave-excited laser power (laser head A) on the pump-pulse repetition rate at working gas pressures of (*1*) 30, (*2*) 37, and (*3*) 45 Torr (the pulsed power and pump-pulse width are 3 kW and 20 μs, respectively; $CO_2 : N_2 : He : Xe = 3:3:13:1$ mixture). The top inset is a photograph of plasma glow along the discharge channel at a gas pressure of 30 Torr, pulse repetition rate of 1 kHz, and average pump power of 50 W.

To determine the optimal (with respect to the output power) operation conditions for the planar repetitively pulsed microwave-pumped CO_2, we performed a series of experiments with variation in the pump regime and working-gas mixture composition and pressure. Based on the results of these experiments, we concluded that, to increase the output power of the heads under study, the pump pulses must be shortened. Unfortunately, the existing magnetron power supply cannot provide pump pulses shorter than 20 μs.

The maximum output powers for laser heads A and B were 25 and 43 W, respectively (at a working mixture pressure of 30 Torr, without circulation). Thus, the scaling of such microwave-pumped lasers is fairly good. At a gas circulation rate of ~ 0.1 L s^{-1} and mixture pressure of 30 Torr, we obtained output powers of 37 and 51 W for the first and the second laser heads, respectively. Further experiments showed that the optimal pressure changes in the case of mixture circulation, and the laser power reaches a maximum at a pressure of 50 Torr (Fig. 9).

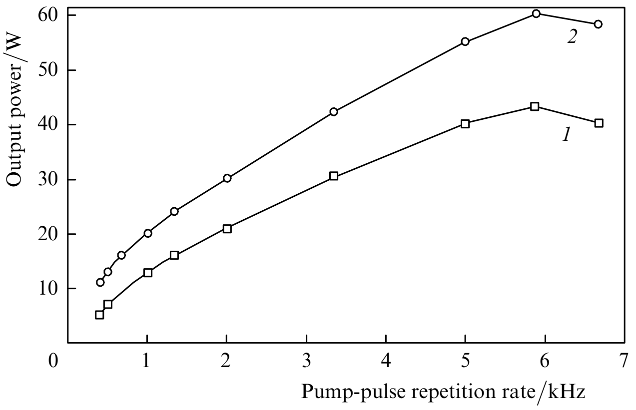

Figure 9. Dependences of the output laser power on the microwave-pump-pulse repetition rate (laser head B). $CO_2 : N_2 : He : Xe = 3:3:13:1$ mixture (*1*) at a pressure of 30 Torr without gas circulation and (*2*) at a pressure of 50 Torr with ~ 0.1 L s^{-1} circulation (pump-pulse width 20 μs, output mirror transmittance 10 %).

Table 1 contains the output characteristics of two types of laser heads.

Table 1.

Mixture pressure/Torr		Laser power/W	
Without gas circulation	With circulation	Head A	Head B
30		25	43
50		22	38
	30	37	51
	50	41	61

Thus, circulation of the working gas mixture even at a low rate makes it possible to increase the maximum output laser power by 40 % – 50 %.

4. Conclusions

We investigated two designs of a planar repetitively pulsed microwave-pumped CO_2 laser. The pulsed-pump density reached 400 W cm^{-3}. The shape of the output laser pulse and its evolution were experimental studied under different conditions. The laser pulse characteristic delay with respect to the pump pulse was 4 – 10 μs. With a decrease in the mixture pressure the peak of output laser power shifted to higher pump-pulse repetition rates. It was experimentally confirmed that pumping by shorter pulses with a higher repetition rate is preferred. The possibility of obtaining a high peak power was established for a planar CO_2 laser. In our experiments, in the case of slow working-mixture circulation, the pulsed peak power reached 1300 W at a pump-pulse width of 20 μs and repetition rate of 400 Hz (laser head B). The maximum average laser power was 60 W. The comparison of the two laser heads differing by the discharge channel length showed the possibility of scaling such lasers. Slow circulation of the working gas mixture makes it possible to increase the maximum output laser power by 40 % – 50 %.

References

1. Nishimae J., Yoshizawa K. *Proc. SPIE Int. Soc. Opt. Eng.*, **1225**, 340 (1990).
2. Shahadi A., Sintov Y., Jerby E. *Microwave Opt. Technol. Lett.*, **36** (2), 115 (2003).
3. Mineev A.P., Nefedov S.M., Pashinin P.P. *Kvantovaya Elektron.*, **37**, 950 (2007) [*Quantum Electron.*, **37**, 950 (2007)].
4. Wester R., Seiwert S. *J. Phys. D: Appl. Phys.*, **24**, 1102 (1991).
5. Mineev A.P., Nefedov S.M., Pashinin P.P. *Proc. SPIE Int. Soc. Opt. Eng.*, **5137**, 288 (2003).
6. Lapucci A., Mascalchi S., Rossetti F. *Opt. Laser Technol.*, **28** (3), 187 (1996).
7. Plinski E.F., Witkowski J.S., Majewski B.W., Abramski K.M. *Appl. Phys. B*, **76**, 375 (2003).
8. Dutov A.I., Evstratov I.Yu., Ivanova V.N., Kuleshova A.A., Motovilov S.A., Novoselov N.A., Semenov V.E., Sokolov V.N., Yur'ev M.S. *Kvantovaya Elektron.*, **23**, 499 (1996) [*Quantum Electron.*, **26**, 479 (1996)].
9. Witteman W.J. *The CO_2 Laser* (Berlin: Springer, 1987; Moscow: Mir, 1990).
10. Raizer Yu.P., Shneider M.N., Yatsenko N.A. *Vysokochastotnyi emkostnoi razryad* (High-Frequency Capacitive Discharge) (Moscow: Nauka, 1995).