*Quantum Electronics* **41** (11) 1033–1036 (2011)

PACS numbers: 42.55.Lt; 41.75.Fr; 52.80.–s
DOI: 10.1070/QE2011v041n11ABEH014626

# Carbon dioxide laser with an e-beam-initiated discharge produced in the working gas mixture at a pressure up to 5 atm

V.M. Orlovskii, S.B. Aleskeev, V.F. Tarasenko

---

***Abstract.*** **A high-pressure $CO_2$ laser with a discharge initiated by an electron beam of sub-nanosecond duration in the laser gas mixture at a pressure up to 5 atm is fabricated. For the 20-ns pulses the energy from the active volume ~4 $cm^3$ amounted to 40 mJ. The laser operation at a pulse repetition rate up to 5 Hz is demonstrated. In the gas mixture $CO_2:N_2:He = 1:1:6$ at a pressure 5 atm, the specific energy deposition of ~0.07 J $cm^{-3}$ $atm^{-1}$ is obtained in the process of a non-self-sustained discharge with ionisation amplification.**

***Keywords:*** *$CO_2$ laser, electron beam, high pressure.*

## 1. Introduction

At present significant attention is paid to the problem of formation of short high-power $CO_2$-laser pulses and their applications. Thus, high-power radiation (2 kW) in the range from 0.5 to 3 THz was produced by mixing two frequencies of $CO_2$-laser radiation in a nonlinear GaAs crystal [1], and superpower fields in the IR range may be used to obtain high-energy particles [2].

To produce high-power optical fields, the oscillator–amplifier system is used. In the case of the atmospheric-pressure active medium, the transmission bandwidth of the amplifying cascade is not high, because the amplification spectrum consists of individual rotational lines and does not allow amplification of pulses shorter than a few nanoseconds. It was proposed [3] to produce radiation pulses by amplifying picosecond $CO_2$-laser pulses in high-pressure active media of $CO_2$ amplifiers. In [4] this method made it possible to obtain the peak power of 15 TW from the $CO_2$-laser pulse (45 J, 3 ps). The active medium pressure of the last amplifier of the system was 2.5 atm. The transmission bandwidth, required for amplification of a 3-ps pulse in the active medium under the pressure 2.5 atm, was provided by the field broadening of the medium spectrum under the action of radiation with the intensity up to 140 GW $cm^{-2}$. The saturation energy for the 3-ps pulse was 120 mJ $cm^{-2}$. The laser generated radiation at six rotational lines. A further increase in the peak power of such $CO_2$-laser systems is associated with greater pressures of the active medium and the corresponding increase in the transmission bandwidth for amplifying short pulses.

Increasing the active medium pressure is most efficient when using an electron beam to initiate the discharge in compressed media of pulsed and repetitively pulsed $CO_2$ lasers [5–7]. It is shown [8, 9] that to implement a non-self-sustained discharge, one can use a beam current pulse with the duration up to ~1 ns. Owing to an increase in beam current density, this duration makes it possible to provide a high electron concentration at atmospheric pressure of the mixture and an efficient regime of laser operation. When the pressure is increased beyond the atmospheric one, it is possible to use beam current pulses shorter than 1 ns. In the case of small duration of the electron flow (~1 ns), the major part of energy is introduced at the stage of plasma decay, and the electron beam ensures preliminary ionisation in the active volume. Reducing the duration of the electron beam pulse used to initiate the discharge in $CO_2$ lasers allows substantial lowering of the energy spent to create conductivity in the gas discharge gap. Under optimal conditions, the energy does not exceed 1% of the energy, deposited into the active medium in the course of the main discharge [7]. It was shown [8, 9] that the use of sealed-off vacuum diodes to produce a beam of accelerated electrons allows $CO_2$-laser dimensions to be considerably reduced, which is promising for producing small-duration pulses and implementing continuous tuning of the radiation frequency.

Formation of nanosecond electron beams is a rather difficult problem, including generation of electron beams and their output through the window between the vacuum and gas cells. It was shown in Ref. [10] that by applying nanosecond high-voltage pulses to a gas diode, one can get an electron beam with the values of the parameter $E/p$ ($E$ is the electric field strength in the gas discharge gap, and $p$ is the pressure) essentially lower than the critical ones, necessary for production of runaway electrons [11]. In [12] the electron beam at atmospheric pressure was obtained in different gases: in helium – with the beam current amplitude 200 A (the beam current density greater than 10 A $cm^{-2}$, the mean energy of electrons ~150 keV); in air – with the beam current amplitude 10 A (the beam current density greater than 1 A $cm^{-2}$, the mean energy of electrons ~95 keV); in nitrogen – with the beam current amplitude 3.5 A (the beam current density greater than 0.35 A $cm^{-2}$); and in the $CO_2 – N_2 – He$ mixture – with the amplitude 12 A. Thus, an atmospheric-pressure $CO_2$ laser was fabricated with the e-beam-initiated discharge produced in the same gas medium [13]. The further increase in the pressure in such laser systems is associated with the possibility of volume discharge formation in the diode gap and generation of a sub-nanosecond electron flux in compressed laser media.

---

**V.M. Orlovskii, S.B. Aleskeev, V.F. Tarasenko** Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, prosp. Akademicheskii 2/3, 634055 Tomsk, Russia;
e-mail: orlovskii@loi.hcei.ru

Received 6 April 2011; revision received 2 August 2011
*Kvantovaya Elektronika* **41** (11) 1033–1036 (2011)
Translated by V.L. Derbov

The aim of the present work is to produce a repetitively pulsed high-pressure (up to 5 atm) $CO_2$ laser pumped by an e-beam-initiated discharge produced in the same gas mixture.

## 2. Experimental setup and measurement techniques

The scheme of the experimental setup is presented in Fig. 1. An additional built-in transmission line with the wave impedance 40 Ω was used in the pulse generator (*1*) (SINUS) [14]. This allowed increasing the pressure in the gas diode up to 6 atm. On the matched load of 40 Ω the generator produced a voltage pulse with the amplitude ~180 kV, the half-maximum width ~1.5 ns and the pulse front duration ~ 0.5 ns. The cathode (*2*) consisted of a set of three cylinders with the diameters 12, 22, and 30 mm made of 50-μm-thick titanium foil, inserted into each other such that the smallest cylinder with the diameter 12 mm was higher by 2 mm than the middle one having the diameter 22 mm and by 4 mm than the largest outer one. The setup had two gas discharge gaps, connected with each other and filled with the $CO_2-N_2-He$ gas mixture. The first 17-mm-long gap was formed by the cathode (*2*) and the steel grid (*3*) with the mesh size 0.5×0.5 mm. In some experiments the grid was replaced with a 40-μm-thick AlBe foil in order to equalise the electric field in the laser gap. The results of experiments with the grid and with the AlBe foil were identical. The voltage pulse from the pulse generator (*1*) was applied to the cathode (*2*). The electron beam, produced in the process of the pulsed discharge in the first gap, was coupled through the grid or the foil into the second gap. The second 6-mm-wide gap was formed by the grid (or the foil) and the profiled stainless-steel electrode (*4*) of size 70×10 mm. The diameter of the electron beam at the distance 1 cm from the grid was equal to 80 mm, which provided the ignition of the discharge along the entire electrode (*4*). The voltage $U_0$ was applied to the gap between the electrodes from an additional dc-voltage power supply and could be varied from 10 to 35 kV. The total capacity $C_0$ of the storage device was equal to 6.6 nF. The resonator consisted of the copper mirror (*6*) (radius of curvature 2.5 m) and ZnSe mirror with multilayer coating (*7*) (reflection coefficient 90 %). The parameters of the electron beam were registered using a collector based on a standard double-ended connector. The area for measuring the parameters of the electron beam (brass, diameter 20 mm) was placed in a cylinder having the inner diameter 25 mm (the movable part of the connector) mounted in the centre of the connector from one side, the other side being connected to a cable.

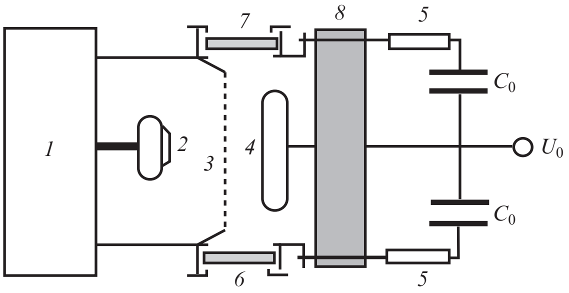

**Figure 1.** Scheme of the experimental setup: (*1*) pulse generator; (*2*) cathode; (*3*) AlBe foil (steel grid); (*4*) anode; (*5*) current shunt; (*6*) mirror; (*7*) output window; (*8*) pulse isolator.

To perform measurements, a flange with a collector was mounted in the working cell instead of the electrode (*4*) with isolator. The instability of the electron beam density in the vicinity of the electrode (*4*) did not exceed 15 %. To record the signals from the capacitance divider, collectors and shunts, we used the TDS-7405 oscilloscope with the 4-GHz bandwidth and the 20-GHz sampling rate or the TDS-334 oscilloscope with the 0.3-GHz bandwidth and the 2.5-GHz sampling rate. The IMO-2N calorimeter was used to measure the pulse energy and the mean power of laser radiation. The pulse duration of the laser was determined using the FP-1 or FSG-22-3A2 photodetector. The discharge glow was photographed with a digital camera.

## 3. Experimental results and discussion

As shown earlier [15], in an inhomogeneous electric field at a short rise time of the voltage applied to the gap in different gases, an electron beam is produced with the amplitude amounting to tens and hundreds of amperes. Under these conditions, a volume discharge is observed in the gap, i.e., jets having the form of a cone or several cones with bright spots on the cathode. Using the SINUS generator with an additional transmission line and ring profiled cathode allowed formation of a regular structure of cathode spots and of a volume charge in the form of cones at pressures higher than the atmospheric one. It allowed also considerable widening of the range of pressures, under which the electron beam is produced.

Figure 2 shows the voltage amplitude at the first gas-discharge gap, the beam current density, and the FWHM duration of the current pulse vs. pressures of helium and nitrogen. The beam current density for He slightly increases with increasing pressure and tends to saturation; for $N_2$ a decrease in the current density with an increase in pressure is observed. The decrease in the beam current density in nitrogen at pressures 2 – 4 atm is due to the decrease in the volume, occupied by the discharge, and to the beginning of the discharge contraction at a pressure ~ 4 atm. The FWHM pulse durations of the beam current in measurements with the resolution up to 0.14 ns in helium and nitrogen were ~ 0.2 ns (Figs 3, 4). It was

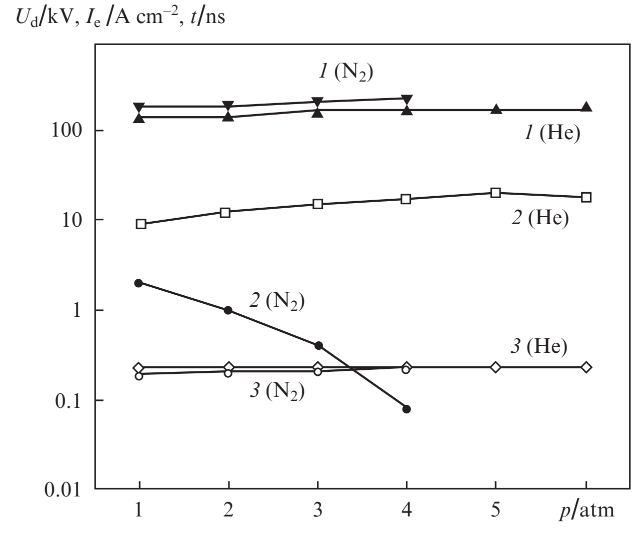

**Figure 2.** Voltage amplitude (*1*), current density (*2*) and FWHM pulse duration of the electron beam current (*3*) vs. helium and nitrogen pressure for the first gap.

established that the recorded pulse duration of the beam current depends on the collector diameter and is minimal when this diameter is small. The plasma, diverging from the cathode, at different points reaches the anode at different moments of time. Correspondingly, the time needed to achieve the critical field also has statistical dispersion, and the total current pulse duration is greater than that for a small part of the anode area. The mean energy of the beam electrons in the optimal regime is ~ 60% of the energy, corresponding to the maximal voltage applied to the gap. All these data confirm the assumption [12, 15] about formation of the electron beam between the plasma front expanding from the cathode and the anode upon achieving the critical field value.

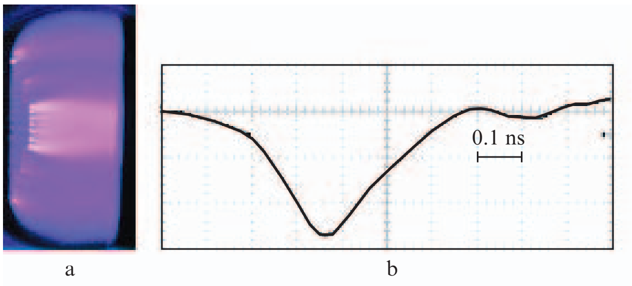

**Figure 3.** Integral discharge glow in helium at the ressure 6 atm (a) and the beam current pulse (b).

In the first gas-discharge gap the ~ 0.2-ns electron beam was produced after applying the voltage pulse. The maximum of the electron energy distribution in the beam depended on the gas type and corresponded to the electron energy 70 – 100 keV; the beam current density was also gas-dependent and amounted to 5 – 20 A cm$^{-2}$. The electron beam was used to initiate the discharge in the second gas-discharge gap. Both the first and second gaps had the same $CO_2 : N_2 : He$ = 1 : 1 : 6 mixture and pressure. Both gaps were communicated via the grid meshes or the holes in the foil. The latter were located aside from the discharge zone. The time of the discharge current pulse rising up to the maximal value was ~ 25 ns at the gas-mixture pressure of 5 atm, and practically all the energy was imparted to the gas within ~ 50 ns. The amplitude of the discharge current was ~ 1200 A. The rise of the radiation pulse was delayed by 500 ns with respect to the beginning of the current pulse, and its duration at half-maximum level was equal to ~ 20 ns at the pressure 4 atm. The energy of radiation amounted to 40 mJ, the efficiency ratio with respect to the stored energy being 2.8%.

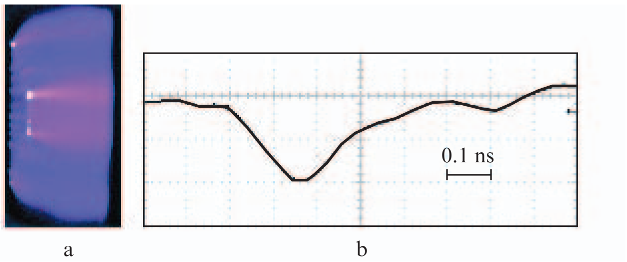

**Figure 4.** Integral discharge glow in nitrogen at the pressure 2 atm (a) and the beam current pulse (b).

Figure 5 shows the oscillograms of the discharge current pulses in the second gap and the laser pulse at the working-mixture pressure of 4 atm. After the end of the beam current and discharge, the capacitors $C_0$ still kept voltage (nearly 1/3 of the initial one), which indicates the volume discharge formation. The comparison of the measured voltage reduction on the capacitors and oscillograms of the current pulse passing through the gas-discharge gap shows, that practically all the energy is imparted to the gas approximately within 50 ns.

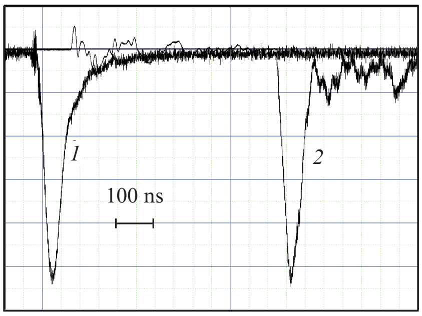

**Figure 5.** Oscillograms of the discharge current pulses (*1*) and the laser radiation pulse (*2*) at the working-mixture pressure of 4 atm.

Figure 6 presents the dependence of the radiation energy on the pressure of the working mixture. The maximal energy was obtained at a pressure of 5 atm in the $CO_2 : N_2 : He = 1 : 1 : 6$ gas mixture and the specific energy, dissipated in the gas 0.067 J cm$^{-3}$ atm. The laser operated at a pulse repetition rate up to 5 Hz; for higher repetition rates the measurements were not performed.

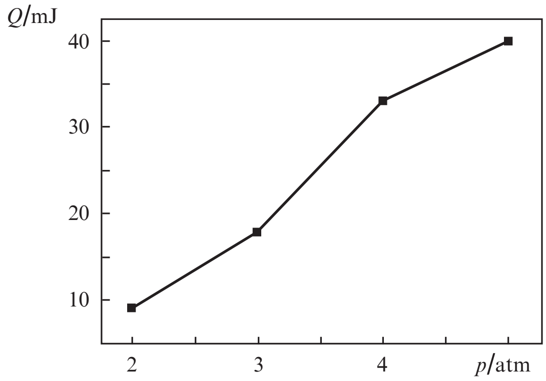

**Figure 6.** Dependence of the radiation energy upon the pressure of the working mixture.

Thus, in the present paper we have demonstrated for the first time the possibility of fabricating a $CO_2$ laser with a subnanosecond-electron-beam-initiated discharge produced in the working mixture at a pressure of 5 atm. This active-medium production method is promising for designing lasers with small pulse duration and continuous frequency tuning.

## References

1. Tochitsky S.Ya., Sung Chieh, Trubnick S.E., Joshi Chan, Vodopyanov K.L. *J. Opt. Soc. Am. B*, **24** (9), 2509 (2007).

2. Pogorelsky I., Shkolnikov P., Chen M., Pukhov A., Yakimenko V., McKenna P., Carroll D., Neely D., Najmudin Z., Willingdale L., Stolyarov D., Stolyarova E., Flynn G. *AIP Conf. Proc.,* **1086**, 532 (2009).
3. Corkum P.B. *IEEE J. Quantum Electron*., **21** (3), 216 (1985).
4. Haberberger D., Tochitsky S., Joshi C. *Opt. Express*, **18** (17), 17865 (2010).
5. Basov N.G., Belenov E.M., Danilychev V.A., Kerimov O.M., Kovsh I.B., Podsosonnyi A.S., Suchkov A.F. *Zh. Eksp. Teor. Fiz.*, **17** (3), 147 (1973).
6. Orlovskii V.M. *Izv. Vyssh. Uchebn. Zaved., Ser. Fiz.*, (8), 74 (1999).
7. Karpov V.M., Konev Yu.G., Orlovskii V.M., Osipov V.V., Ponomarev V.B. *Kvantovaya Elektron.*, **15**, 465 (1988) [*Sov. J. Quantum Electron.*, **18**, 294 (1988)].
8. Bychkov Yu.I., Orlovskii V.M., Osipov V.V., Poteryaev A.G. *Prib. Tekh. Eksp.*, (5), 185 (1983).
9. Karpov V.M., Mesyats G.A., Orlovskii V.M., Osipov V.V., Poteryaev A.G. *Zh. Tekh. Fiz.*, **57** (12), 2335 (1987).
10. Alekseev S.B., Gubanov V.P., Orlovskii V.M., Stepchenko A.S., Tarasenko V.F. *Prib. Tekh. Eksp*., (4), 81 (2003).
11. Korolev Yu.D., Mesyats G.A. *Physics of Pulsed Breakdown in Gases* (Ekaterinburg: URO-Press, 1998).
12. Alekseev S.B., Gubanov V.P., Orlovskii V.M., Tarasenko V.F. *Pis'ma Zh. Tekh. Fiz.*, **30** (20), 35 (2004) [*Tech. Phys. Lett.*, **30**, 859 (2004)].
13. Alekseev S.B., Orlovskii V.M., Tarasenko V.F. *Kvantovaya Elektron.*, 33 (12), 1059 (2003) [*Quantum Electron*., **33** (12), 1059 (2003)].
14. Gubanov B.P., Korovin S.D., Pegel' I.V., et al. *Izv. Vyssh. Uchebn. Zaved., Ser. Fiz.*, (12), 110 (1996).
15. Alekseev S.B., Orlovskii V.M., Tarasenko V.F., et al. *Pis'ma Zh. Tekh. Fiz.*, **29** (10), 29 (2003). [*Tech. Phys. Lett.*, **29**, 411 (2003)].