CO_2-LASER BASED ON A THREE-ELECTRODE DISCHARGE FORMING ELECTRIC CIRCUITRY

V.V. Borovkov, S.L. Voronov, B.V. Lazhintsev, V.A. Nor-Arevyan, and G.I. Fedorov

Federal Nuclear Center of Russia,
the All-Russian Scientific-Research Institute for Experimental Physics,
Sarov, Nizhegorodskaya Region

Received October 9, 1997

We have developed a TEA CO_2-laser operating at the atmospheric pressure in which the electric discharge occurs inside the region confined by three electrodes that make up two discharge gaps connected in a series, with the storage capacitor being coupled to two outer electrodes. The initiation of a self-maintained volume electric discharge (SMVED) is performed, in this scheme, by applying successively in time of high-voltage pulses to the central electrode. As shown in this paper the electric discharge circuitry and that type of the operation mode enable one to form the SMVED that provides for depositing up to 250 J/(l·atm) energy density at a high efficiency of the active medium excitation. In this arrangement of the electric circuitry the voltage for charging the capacitor storage to the voltage at which the SMVED is formed is from 0.6 to 0.9 of the static breakdown voltage that makes only 1 to 3% of the pumping energy. The use of that type of electric circuitry in a pulse-periodic mode of operation would allow one to drastically (about ten-fold) decrease the load of the SMVED power supply commutators while simultaneously providing for an efficient excitation of the laser active medium.

INTRODUCTION

A lot of practical applications of the pulse-periodic TEA CO_2-lasers, such as isotope separation, photochemistry, lidars, and the like, need for lasers delivering some kilowatts of the mean power. Although many types of the electric circuitry and power supplies for excitation of the TEA CO_2-laser active media have been developed up to now (see, e.g., Refs. 1 and 2), there is still an urgent need for long lasting and reliable power supplies for technological TEA CO_2-lasers. The difficulties in constructing such power supplies are especially urgent regarding the energy commutators to be used in that sort of systems.

In recent years the electric circuitry that uses the magnetic compression of power supply pulses[3,4] is often being implemented, along with the dual discharge excitation scheme,[5,6] to facilitate the operation of power commutators in the laser power supplies. Potentially, the magnetic compression of a discharge current pulse provides for high reliability and almost infinite lifetime of power supplies since it uses solid state commutators. However, certain difficulties[3,4] in their implementation to supply SMVED still restrict their wide use in practice. Among the drawbacks of such a circuitry there are the large specific mass of a magnetic material (about 1 kg per one Joule) as well as the necessity of using a separate capacitor battery in each cascade of the magnetic compression.

The excitation schemes based on the dual-discharge circuitry that are now widely used in the electric-discharge lasers in various active media use both two- and three-electrode configurations of the laser chamber.[5–10]

The excitation scheme that uses a dual-discharge configuration is most widely used now in excimer lasers.[5,6] Example of a successful implementation of that sort of the excitation scheme in a CO_2-laser has been reported in Refs. 7 and 8. Decoupling of the electric circuitry initiating the discharge and the circuitry that maintains the excitation discharge is achieved by use of a nonsaturating inductance (2 to 25 μH). The decoupling inductance of the excitation discharge circuitry makes the time of power deposit into the volume discharge longer that, in turn, makes the output laser pulse longer than 1 μs. Such a long duration of the laser pulse imposes certain restrictions on their use in isotope separation, photochemistry, and lidar applications. Moreover, this inductance may negatively affect the stability of the discharge in its volume phase, especially in a pulse-periodic mode of operation.

In the three-electrode schemes of a dual-discharge excitation the capacitor energy storage of the main discharge that has minimal inductance is connected to

0235-6880/98/02-03 106-05 $02.00

two outer electrodes, while the discharge initiation is performed through the central electrode. This type of the laser chamber has been used in Ref. 9 to study the performance parameters of a XeCl-laser while in Ref. 10 this same scheme was used to study a combined discharge in a CO_2-mixture operated in a quasi-cw mode at the pressure ≤ 0.1 atm. In the experimental study reported in Refs. 9 and 10 the discharge has been being formed in both discharge gaps simultaneously. This is achieved by choosing proper ratio between the lengths of the two discharge gaps, as well as of the voltage applied to the gaps to maintain the SMVED, and primarily this happens due to short rise time and high amplitude of pulsed voltage applied to the central control electrode. However, it is very difficult to maintain such an operation mode both in the excimer and CO_2 lasing media, especially at atmospheric pressures.

The authors of Refs. 11 and 12 have proposed a three-electrode construction of the laser chamber, in which the dual-discharge excitation of an active medium is performed by initiating the electric discharge in two gaps in a succession. In this way, the additional, decoupling inductance is removed from the discharge power supply circuitry in contrast to the schemes described in Refs. 7 and 8. As a result, it becomes possible to achieve a shorter duration of the excitation pulse that, in turn, promises a higher stability of the SMVED in a wider range of the active medium composition. The latter circumstance is especially important when lasers operate in a pulse-periodic mode. Moreover, in this scheme one may arrange two synchronized laser channels that allows the master oscillator-amplifier operation mode to be realized. In Refs. 13 to 15 one may found a description of successful experiments on implementing such an approach to excitation of the Ar-Xe and CO_2 mixtures in the configurations with the discharge gaps of both equal and different spacings.

In this paper we present the results of investigation of a CO_2-laser constructed based on the three-electrode scheme of the SMVED formation.[15]

EXPERIMENTAL SET UP

In our experiments we have used a cylinder-shaped laser chamber made from a stainless steel tube 240 mm in diameter. The electrode assembly is a set of three nickel electrodes that form two 250-mm-long discharge gaps, with the spacing between the electrodes being $d_1 = 32$ mm and $d_2 = 24$ mm. All the four working surfaces of the electrodes have the same shape close to the Chang profile. The electrodes are supported, in the laser chamber, with the teflon bushings. A series of 12 spark gaps along a lateral side of each electrode provided for the discharge volume preionization.

The laser cavity optical components are mounted on the end flanges of the chamber thus serving as the end windows of the resonator. The plane-parallel resonators of both resonators consist of plates from BaF_2 with a dielectric coating ($R = 80\%$ at $\lambda = 10.6$ μm) and totally reflecting mirrors from copper.

We have been measuring the output power of the laser emission with two calorimetric power-meters IMO–2N. The laser generation pulse has been recorded with a FPU–50 photodetector. When measuring the volt-ampere characteristics of the discharge we used a current bypass and ohmic dividers. In the experiments we used He of a high purity and N_2 and CO_2 of a technical purity.

Set out in Fig. 1 is the block-diagram of the electric circuitry of a three-electrode laser chamber with the central control electrode. The power supply of the SMVED is provided with two LC-generators that involve capacitors of K15–10 type (4700 pF, 30 kV) that are charged from two sources of high voltage up to ± 20 kV. The initial capacitance, $4C_0$, of the LC-generators has been being varied in the experiments from 200 to 510 nF. The wave impedance of the SMVED power supply was about 1 Ω, at the impact capacitance $C_0/4 = 32$ nF.

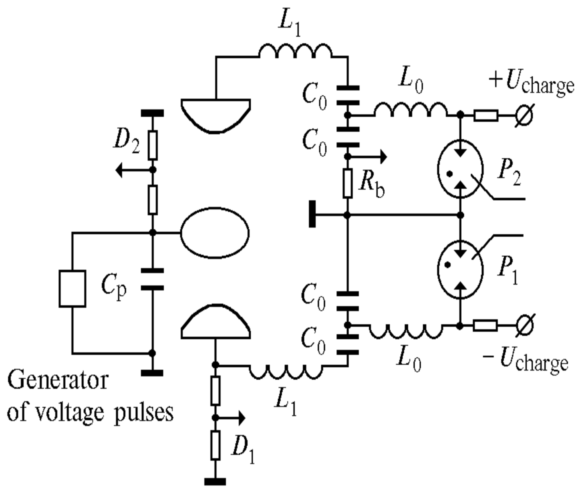

FIG. 1. Block-diagram of the electric circuitry of the installation. D_1 and D_2 are the ohmic voltage dividers; R_b is the current bypass.

The inductance L_1 is determined by the design of laser chamber and of the capacitor energy storage. The value of the inductance L_0 is chosen so that it provides for a reliable decoupling between the SMVED power supply and circuitries that provide for charging the LC-generators. The commutation between LC-generators is being done by the dischargers D_1 and D_2 of RU–73 type. In this experiment time of the LC-generators recharging were 10 to 20 μs. In control experiments we have increased the recharging time to 50 μs, but that does not affect the output laser parameters. It is obvious, in this connection, that such an increase of the recharging time would significantly decrease the load of commutators in the SMVED power supply circuitry once this scheme is used in a pulse-periodic mode. The discharge forming circuitry is a generator of the voltage pulses that charges the peaking capacitor, $C_p = 1$ nF. The preionizing sparks are supplied with power from a separate generator not shown in the block-diagram. The energy stored in the preionization unit amounted to 3% of the energy stored in the SMVED power supply. The operation of the laser has been triggered by high-voltage pulses from a pulse-generator by initiating the discharge breakdown in the dischargers D_1 and D_2 that, in turn, enable recharging of the LC-generators. Preionization of the discharge volume is switched on just before the voltage at the discharge gaps reaches its maximum then, in 80 ns time lag, the circuitry forming the ignition pulse is set to operate. This time lag was kept constant in all the experiments conducted.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 presents typical oscillograms of the voltage pulse at the central electrode and of the current pulses through the discharge gaps that illustrate the initial stage of the SMVED formation. As seen from Fig. 2 there appears a pulse of positive polarity at the central electrode with the rise time of 40 ns when charging the peaking capacitor C_p. As a result, a volume electric discharge is being formed in the gap d_1 at the electric field strength of 22 kV/cm. Then, during about 30 ns, the capacitor C_p recharges, the voltage at the central electrode changes its polarity and, at the field strength of 24 kV/cm, a discharge is being formed in the second gap, d_2, accompanied by a simultaneously growing electric current of the main discharge. The current density at the stage of the discharge formation was comparable in value to that of the SMVED and reached 40 to 100 A/cm^2, depending on the composition and total pressure of the mixture. Recharging of the C_p through the resistance of plasma in the first gap and creating as high as possible voltage at the second gap requires high-density discharge current at the stage of the SMVED formation.

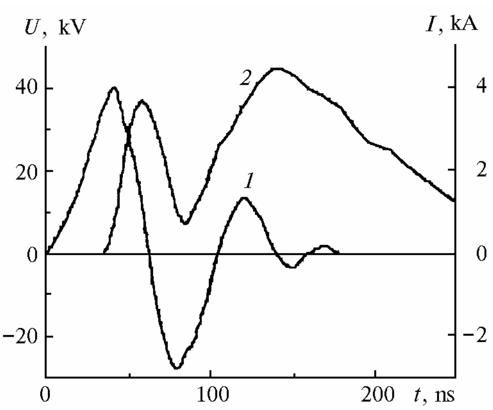

FIG. 2. Oscillograms of the voltage pulses (1) at the central electrode and of the discharge current (2). The gas mixture used is CO_2:N_2:He = 1:1:3, *total pressure* $P_{mix} = 0.8$ atm, $U_{charg} = \pm 15$ kV.

Figure 3 shows the oscillograms of the voltage pulse at the second discharge gap, as well as the pulses of discharge current and the laser emission pulse recorded at the capacitance of pumping generator $4C_0 = 510$ nF. As is seen the discharge is aperiodic, with more than 85% of the amount of energy stored in the pump generator of the main discharge being deposited during first 500 ns from the discharge initiation moment. The plasma resistance reaches its minimum, about 10 Ω, at the moment when the electric current is maximum and then it grows up to 30 Ω when the current drops down to $0.1 \cdot I_{max}$. By the moment of the discharge termination the capacitor energy storage of the pump circuitry is exhausted but only down to the level of 3% of the initially stored amount of energy. The level of that residual energy increases, at a constant voltage of charging, with increasing total pressure of the mixture and content of the molecular components. It also increases subject to the decrease of the charging voltage occurs. The reduced value of the electric field strength, E/N, is, at the stage of energy deposition into the SMVED, within the range from $1.5 \cdot 10^{-16}$ to $4 \cdot 10^{-16}$ V·cm^2. According to data from Ref. 16 that level of the electric field strength well provides for an efficient excitation of the active media in CO_2-lasers. Sufficiently high resistance of the SMVED plasma and the absence of additional conductance in the discharge power supply circuitry should enable a relatively simple design of the latter based on a line with distributed parameters matched with the resistance of the discharge plasma. In this way an optimal, for efficiently exciting the active medium, value of quasi-constant voltage at the discharge gap will be provided during the entire pump pulse. In this case the duration of the pump pulse will be the same as that in the power supply based on a lumped capacitance.

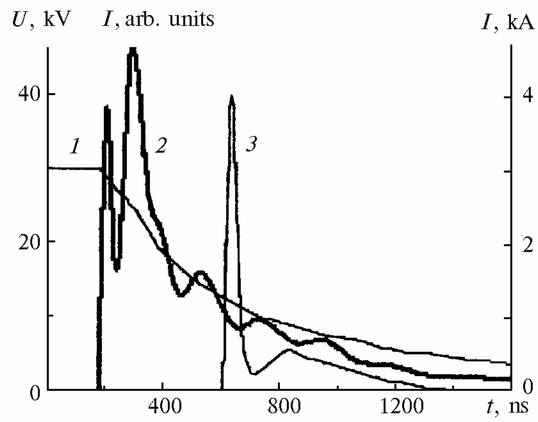

FIG. 3. Oscillograms of the voltage pulses at the second gap (1), discharge current pulses (2), and of the generation pulse (3). The gas mixture used is CO_2:N_2:He = 1:1:3, *total pressure* $P_{mix} = 0.8$ atm, $U_{charg} = \pm 15$ kV.

The generation pulse shape follows the profile characteristic of a TEA CO_2-laser. The first peak of the emission that has duration of 50 ns, at the half maximum level, concentrates about 50% total energy of lasing. Time delay between the emission pulse and the beginning of the discharge current pulse increases with decreasing content of N_2 in the mixture and in our experiments it amounted to about 400 ns.

Figure 4 presents the energy of generation in the first, E_1, and second, E_2, gaps, the values of specific energy of generation produced in each gap and total output energy of the laser as functions of the energy stored in the capacitor storage of the SMVED power supply. The composition of the mixture was $CO_2:N_2:He = 1:1:3$, the pressure equaled to 0.8 atm, and the product $R_1R_2 \sim 0.8$. One can see from this figure that the lasing energy is practically a linear function of the energy stored in the capacitors up to 75 J that corresponds to about 250 J/(l·atm) energy deposition from a power supply. It is worth noting that a uniform diffuse discharge is being formed in the entire range mentioned above. At the same time, further increasing of the amount of stored energy did not yield any increase in the output energy because of a significant deterioration of the discharge homogeneity. Moreover, at the energy level of 80 to 90 J practically all the discharges observed ended by the spark breakdown. Replacing of the output mirror with $R = 80\%$ for the ones with $R = 53\%$ resulted in a significant drop of the generation energy. The energy generated in the wider gap decreased by 1.7 times and by 1.4 times in the narrower gap. This circumstance is indicative of the fact that only small excess of the generation threshold has been achieved in both discharge gaps.

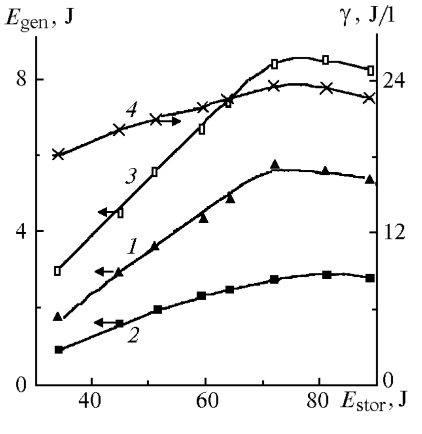

FIG. 4. Energy of generation in the first (1) and second (2) discharge gaps, total output energy of the laser (3), and total specific energy of output laser emission (4) as functions of energy stored in the capacitors of the SMVED power supply. The gas mixture used is $CO_2:N_2:He = 1:1:3$, *total pressure* $P_{mix} = 0.8$ atm.

Among the specific features of this laser operation we should like to note that there occurs a significant variation of the lasing region width and, as a consequence, of its volume. The width of the lasing region has been monitored by recording generation spots from each gap. The growth of the lasing zone width, w occurred almost linearly with increasing pump energy, with the broadening being observed in both laser channels. The ratio w_1/w_2 is approximately 1.5 in the whole range of the pump energy variation. That difference in the widths of lasing zones observed in two gaps is primarily due to the same profile of all the four working surfaces of electrodes while using different gap spacing.

The maximum energy of 8.4 J, at the efficiency of 11.5% with respect to the energy stored in the SMVED power supply capacitors, was obtained in the mixture $CO_2:N_2:He = 1:1:3$ at a total pressure of 0.8 atm. As it follows from the electrotechnical properties of the discharge as well as from the energy distribution in the gaps, the actual lasing efficiency in the first gap amounted to more than 13%. To make use of the full potentialities of forming the discharge with three-electrode systems one should use the discharge zones of equal width in both discharge gaps. This task may be achieved by decreasing the curvature of working surfaces of electrodes in the second gap and use of equally spaced gaps. Preliminary experiments conducted with identical discharge gaps showed that it is possible to form uniform, diffuse discharges in a wide range of the voltage applied to the SMVED.

It should be noted here that the electric circuitry proposed in Refs. 7 and 8 with no commutators used in the power supply of SMVED may appear to be much promising for use in CO_2-lasers. In that scheme the capacitor energy storage of the SMVED power supply is charged directly from a dc-voltage source. In our experiments such a circuitry has enabled the formation of a uniform diffuse discharge in CO_2 mixtures, at the charging voltage of 0.6 to 0.95 the static breakdown voltage. When using this approach in the mixture $CO_2:N_2 = 1:2$ at the total pressure of 0.2 atm we have recorded the same results as in the case with using LC-generators. We obtained 0.6 J generation energy, at the efficiency of 4.5% and ~190 J/(l·atm) energy deposition into the discharge.

CONCLUSION

The three-electrode configuration of a pump electric discharge has been analyzed for the first time in application to pumping CO_2-lasers. In the circuitry proposed the discharge is being formed in two discharge gaps in a succession. The experiments conducted have shown that such an electric circuitry and the operation mode enable forming the SMVED at the energy deposition from a power supply up to 250 J/(l·atm) that provides for lasing efficiency above 11%. The charging voltage of the capacitor energy storage enabling the maintenance of the SMVED is from 0.6 to 0.9 the static breakdown voltage. The laser pulse duration of 50 ns achieved is the minimum possible, for the gas mixture composition used, duration. The discharge ignition is performed by fast commutation only of the energy stored in the circuitry of the discharge pulse shaper and preionization that amounts to less than 5% total pump energy. These results show that constructing of UV preionization units and pulse discharge shapers with a long lifetime is quite realistic. The electric circuitry proposed enables one not only to drastically (by tens of times) decrease the working load of the commutators in the main discharge power supply, but to exclude it at all, if necessary. The use of two discharge gaps makes it possible to arrange the operation of such a device in the master oscillator-amplifier mode. The construction of the discharge chamber allows one to vary the ratio between the gap spacings in a wide range.

REFERENCES:

1. E.P. Velikhov, V.Yu. Baranov, V.S. Letokhov, E.A. Ryabov, and A.N. Starostin, *Pulsed* CO_2-*Lasers and Their Application to Isotope Separation* (Nauka, Moscow, 1983), 304 pp.
2. *Technological Lasers. Handbook* (Mashinostroenie, Moscow, 1991), Vol. 7, 432 pp.
3. H. Tanaka, H. Hatanaka, M. Obara, K. Midorikawa, and H. Tashiro, Rev. Sci. Instr. **61**, No. 8, pp. 2092–2096 (1990).
4. H. Hatanaka, K. Midorikawa, M. Obara, and H. Tashiro, Rev. Sci. Instr. **64**, No. 11, 3061–3065 (1993).
5. Y. Sato, M. Inoue, K. Haruta, H. Nagai, and Y. Murai, Appl. Phys. Lett. **64**, No. 6, 679–680 (1994).
6. F.A. Goor, W.J. Witteman, J.C.M. Timmermans, J.Spijker, and J.Couperus, Proc. SPIE **2206**, 30–40 (1994).
7. P.K. Bhadani, A. Sylvan, and R.G. Harrison, Rev. Sci. Instr. **62**, No. 6, 1404–1407 (1991).
8. P.K. Bhadani and R.G. Harrison, Rev. Sci. Instr. **65**, No. 3, 563–566 (1994).
9. S. Bollanti, P.Di. Lazzaro, F. Flora, G. Giordano, T. Letardi, C. Patrucci, G. Schina, and C.E. Zheng, Proc. SPIE **2206**, 144–152 (1994).
10. V.V. Osipov, V.V. Savin, and V.A. Tel'nov, Zh. Prikl. Mekh. Tekh. Fiz. No. 2, 10–16, (1982).
11. V.V. Borovkov, V.V. Voronin, S.L. Voronov, B.V. Lazhintsev, V.A. Nor-Arevyan, V.A. Tananakin, and G.I. Fedorov, "*Pump up Device for a Continuous Flow Laser*,B Patent No. 2017289 RF Invention Bull. No. 14, 153 (1994).
12. V.V. Borovkov, V.V. Voronin, S.L. Voronov, V.E. Zherebtsov, V.V. Ivanov, B.V. Lazhintsev, V.A. Nor-Arevyan, V.A. Tananakin, and G.I. Fedorov, "*The Method to Gain Generation in a Gas, Electric-Discharge Laser and a Gas Electric-Discharge Laser*,B Patent No. 2029423 RF the Invention Bull. No. 5, 213 (1995).
13. V.V. Borovkov, V.V. Voronin, S.L. Voronov, D.I. Zenkov, B.V. Lazhintsev, V.A. Nor-Arevyan, V.A. Tananakin, and G.I. Fedorov, Pis'ma Zh. Tekh. Fiz. **21**, No. 4, 36–39 (1995).
14. V.V. Borovkov, V.V. Voronin, S.L. Voronov, D.I. Zenkov, B.V. Lazhintsev, V.A. Nor-Arevyan, V.A. Tananakin, G.I. Fedorov, and I.M. Yutkin, Kvant. Elektron. **22**, No. 5, 439–440 (1995).
15 V.V. Borovkov, V.V. Voronin, S.L. Voronov, B.V. Lazhintsev, V.A. Nor-Arevyan, V.A.Tananakin, and G.I. Fedorov, Kvant. Elektron. **23**, No. 1, 41–42 (1996).
16. G.A. Mesyats and Yu.D. Korolyov, Usp. Fiz. Nauk **148**, No. 1, 101–122 (1986).