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A microwave-pumped slab CO_2 laser

A.P. Mineev, S.M. Nefedov, P.P. Pashinin

***Abstract*.** **The radiation parameters of a diffusion-cooled compact slab CO_2 laser pumped by microwave discharge at a frequency of 2.45 GHz are studied. A magnetron from a domestic microwave oven is used as the pump source. An average output power of 25 W and an efficiency of $\sim$13 % are obtained at a wavelength 10.6 μm. A peak output power of 580 W is achieved for 20-μs pulses emitted at a pulse repetition rate of 400 Hz. The dependence of parameters of the CO_2 laser on the input pulse power in the range 0.8 – 8 kW, the composition and pressure of the working mixture and the pump pulse duration and repetition rate are studied experimentally. Optimal relations between these parameters are determined for the given design of the laser.**

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

1. Introduction

Laser systems based on a new generation of gas-discharge molecular lasers – slab waveguide CO_2 lasers pumped by high-frequency discharges with a hybrid waveguide-unstable resonator, are being developed rapidly at present. Diffusion-cooled lasers (without a cumbersome working-gas circulation system) are widely used for designing compact and high-power cw and repetitively pulsed devices having enhanced specific parameters and a high quality of optical radiation [1 – 8]. A specific energy output per unit area of the active medium of the planar structure of 20 kW m^{-2} has been experimentally achived upon diffusion cooling of the discharge.

In recent years, interest in the application of microwave discharge for pumping CO_2 lasers has grown considerably [9 – 12] mainly due to the availability of magnetrons operating at a frequency of 2.45 GHz (which are widely used in microwave ovens). In addition, the microwave discharge in the frequency range of 2 – 10 GHz used for laser pumping also has a number of advantages over dc and rf discharges, such as a high efficiency (more than 70 %) and a kW-level magnetron (microwave source) power; compact size of the magnetrons and their low cost and ability to operate in the pulsed mode; the absence of the active ballast impedance and the voltage drop in the electrode region, which alleviates an effective energy contribution to the microwave discharge plasma; the possibility of organising electrodeless discharge which resolves the problems associated with sputtering of the electrode material, plasma chemistry and service life of the working laser gas mixture; and the absence of a high discharge voltage and hence safety and reliability of the device. In addition, the high mechanical strength of the shell of the all-metal microwave discharge structure should also be noted.

An average output laser power of over 100 W achieved upon repetitively pulsed lasing [9] suggests that such systems are promising for the development of a new generation of compact, sealed, cheap and simple CO_2 lasers that do not require a cumbersome system of working gas circulation. Therefore, the study of diffusion-cooled, microwave-discharge-pumped, slab CO_2 lasers is undoubtedly of current interest.

This study is aimed at an analysis and solution of the problems associated with the use of microwave discharge for pumping slab CO_2 lasers. The following problems are of prime importance: (i) quest for new slab waveguide systems, perfection of the existing ones, as well as the search for structural materials for such systems; (ii) analysis of matching and design of the circuits for microwave power supply from the magnetron to the discharge system taking into account the magnitude and shape of the electromagnetic field in it; (iii) analysis of mechanisms of current flow, energy input, spatial structure, stability and scaling of high-power wide-aperture microwave discharges; and (iv) investigation of parameters and conditions for sustaining a low-temperature microwave discharge plasma, providing the efficient transformation of discharge energy into coherent optical radiation in molecular CO_2 laser mixtures at pressures up to the atmospheric pressure.

At present, the following approaches are used towards the solution of the above problems:

(i) Completely dielectric and metal – dielectric slab CO_2 laser structures made of materials traditional for rf technique that possess a high thermal conductivity and low distributed waveguide losses were used in [9, 10]. We believe that all-metal planar structures made of aluminium with a thin ($\sim$10 μm) Al_2O_3 layer deposited on it by oxidation are quite promising.

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(ii) Microwave power was supplied to the discharge through a slit in the volume resonator in which a standing wave was excited, and the discharge structure and the optical resonator were located outside the microwave cavity [9, 10]. In the power supply circuit formed by the magnetron, volume resonator and the discharge structure, losses due to reradiation and matching are inevitable. Hence, it is expedient to combine the volume microwave resonator and discharge for reducing these losses and simplifying the microwave power supply circuit.

(iii) To obtain a wide-aperture and homogeneous discharge, it is important to use repetitively pulsed microwave power generation at higher pulse power levels.

(iv) To increase the efficiency of conversion of microwave power into laser radiation, the active laser medium should be pumped by 10 – 100-μs pulses at a repetition rate of up to 60 kHz.

2. Scheme of a microwave-pumped laser

Figure 1 shows the scheme of a microwave-pumped slab CO_2 laser. A PM-740T pulse power supply with the conversion efficiency of line voltage into magnetron power supply voltage exceeding 90 % was used to control magnetron (*1*). We used a 2M-130 magnetron from a microwave oven with a pulse power up to 8 kW and average power up to 1.8 kW.

A rectangular waveguide of size $90 \times 45 \times 500$ mm forms volume microwave resonator (*6*) closed on one side and adjusted by short-circuiting plunger (*2*). The magnetron is matched with the resonator on the microwave power input side with the help of an impedance transformer based on hybrid tee (*5*) with two similar movable plungers (*2*). Microwave power is extracted from the volume resonator through an extended slit in the narrow wall of the waveguide (analogue of the slot antenna) and is supplied to laser head (*3*).

The laser head cross section (Fig. 2) is a gas-discharge structure formed by two profiled aluminium plates (*2*) and (*3*) pressing $2 \times 30 \times 300$ mm quartz plate (*4*) whose lateral side faces the microwave resonator slit. Discharge channel (*5*) of size $2 \times 25 \times 250$ mm is formed by the gap between

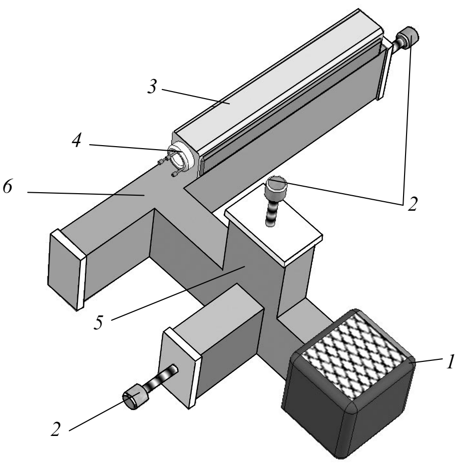

Figure 1. Scheme of a slab CO_2 laser: (*1*) magnetron; (*2*) short-circuiting plungers; (*3*) laser head; (*4*) output mirror; (*5*) hybrid waveguide tee; (*6*) microwave resonator.

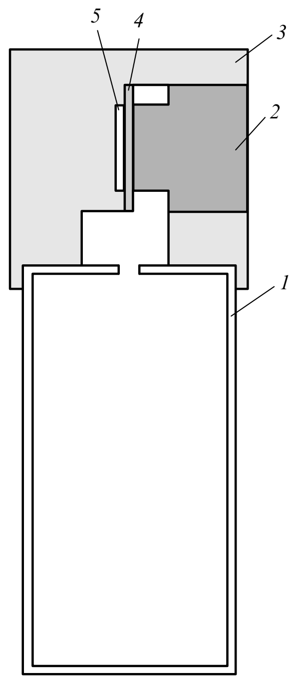

Figure 2. Section of the laser head of a slab CO_2 laser: (*1*) 90×45-mm rectangular waveguide; (*2*, *3*) profiled aluminium plates; (*4*) quartz plate; (*5*) $2 \times 25 \times 250$-mm discharge channel.

polished aluminium and quartz plates. Water cooling of aluminium plates is envisaged in the construction. The advantages of planar discharge include the efficient heat removal from the walls, small size, a low breakdown voltage, a high quality of the output beam, and a high output power of laser radiation extracted per unit volume.

In such a structure, the electric field in the discharge region is perpendicular to the surface of the dielectric plate. Because the microwave power enters the discharge region from one side only, the discharge current is closed on the other side through an aluminium plate. Therefore, the microwave discharge is not concentrated only in the vicinity of the dielectric plate surface, but is distributed uniformly over the entire thickness of the discharge region. The active medium has a volume of 12.5 cm^3, and hence the average input power density amounts to 160 W cm^{-3}.

3. Experimental conditions

The above design of the laser head led to the development of a compact diffusion-cooled CO_2 laser. The experiments were performed with various gas mixtures in a working gas pressure range of 10 – 50 Torr for a microwave pump pulse duration of 20 – 100 μs and a pulse repetition rate of 0.4 – 10 kHz. The laser pulse shape was recorded with a BP-10 pyroelectric detector with a time resolution of 10^{-8} s and a 350-MHz LeCroy-432 two-channel digital oscilloscope. The laser radiation power was measured with a NOVA-2 (OPHIR) power meter with a thermoelectric head (with an aperture of 29 mm) calibrated to the wavelength 10.6 μm. The plasma emission in the discharge was detected with a FEU-39A photomultiplier (spectral range of 160 – 600 nm) connected with the discharge gap through an optical fibre.

The radiation field structure in a slab laser is of hybrid type. In the direction perpendicular to the slit, radiation propagates as in a waveguide, while along the slit, a mode corresponding to the chosen cavity is formed.

We used the conventional design of a stable optical cavity formed by two mirrors: a highly reflecting spherical gold-plated copper mirror (with a radius of curvature 5 m and a reflectance of 98.8 %), and an output flat germanium mirror with an antireflection coating (with a transmittance of 5 % or 10 %). The mirrors are mounted at distances of 5 mm from the discharge gap, which protects them to a certain extent from the action of the gas-discharge plasma. The laser radiation field structure corresponds to the multimode generation.

The wavelength of microwave radiation in the waveguide for the main type of oscillations H_{10} depends on the size a of the broad wall of the rectangular waveguide. It is known that the radiation wavelength in the waveguide differs from the radiation wavelength generated in the magnetron. For $a = 9$ cm and $\lambda_0 = 12.24$ cm, the wavelength λ_w in the waveguide will be equal to 16.7 cm. Note that waves can propagate in the waveguide if the condition $\lambda < \lambda_{cr}$ is fulfilled, where $\lambda_{cr} = 2a$ for the H_{10} wave.

Figure 3 shows the experimentally obtained distribution of the electromagnetic field power along the slit of the tuned volume resonator in the absence of a discharge. To obtain a more uniform power distribution along the discharge gap, the size of the broad wall of the waveguide must be reduced from 90 to approximately 62 mm. In this case, the wavelength in the waveguide

$$\lambda_w = \lambda_0 \left[1 - \left(\frac{\lambda_0}{2a} \right)^2 \right]^{-1/2} \quad (1)$$

is about 80 cm, and half the wavelength fits in the microwave resonator (the so-called half-wave resonator). Figure 4 shows the dependence of the wavelength in the waveguide on the size of the broad wall of the waveguide [13].

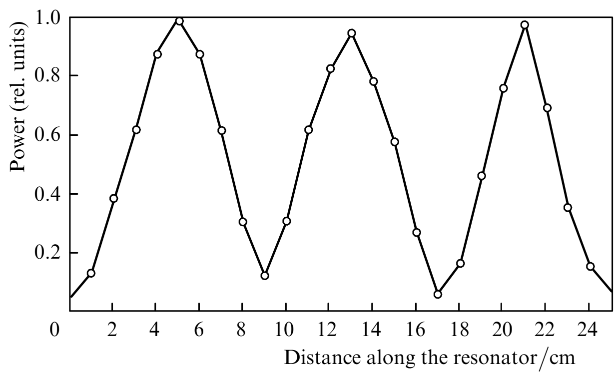

Figure 3. Distribution of the electromagnetic field power (in the absence of discharge) along the slit of an adjusted volume resonator.

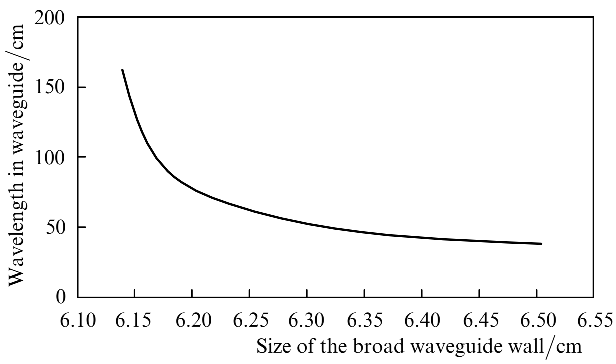

Figure 4. Dependence of wavelength in the waveguide on the size of the broad wall of the waveguide; magnetron generation frequency is 2.45 GHz.

4. Experimental results

The efficiency and output power of the laser depend considerably on the total pressure due to an increase in the concentration of working molecules in the gas mixture.

Figure 5 shows the dependence of the output power of a microwave-pumped laser on the pressure of the working gas mixture. The decrease in the output power with increasing the pressure is due to a deterioration of the discharge homogeneity and an increase in the gas temperature. A standing wave is formed in the microwave cavity, and the presence of the electric field minima causes an increase in the plasma inhomogeneity along the discharge channel with increasing pressure. The discharge can be initiated at the field minima simply by increasing the microwave pump power, but this may cause a considerable overheating in regions with the maximum intensities of the microwave field and may lead to discharge contraction.

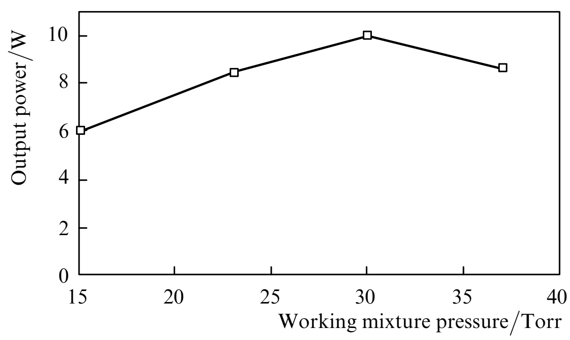

Figure 5. Dependence of the output laser power on the working mixture pressure. The gas composition is $CO_2:N_2:He:Xe = 3:3:13:1$. The average input power is 80 W, the pump pulse duration is 20 μs, and the pulse repetition rate is 1000 Hz.

The rate of electron generation depends drastically on the average energy (temperature) of the electron gas which is determined by the parameter E/N (E is the field strength and N is the density of the gas molecules). This parameter (reduced electric field) is proportional to the mean free path and the higher the value of this parameter, the higher the energy acquired by the electron. It follows hence that the ionisation rate increases sharply with the parameter E/N (i.e., with a decrease in N with increasing the gas temperature T). The dependence of the electron loss rate on E/N is weaker. This leads to ionisation-overheating instability which in turn causes a heat-induced population of the lower energy level and, hence, a decrease in the laser output power. Thus, an optimal value of pressure exists for a given composition of the gas and for given parameters of the microwave pump pulses.

Figure 6 presents the dependences of the output power of a CO_2 laser on the pump pulse repetition rate for various compositions of the working gas mixture. The output power

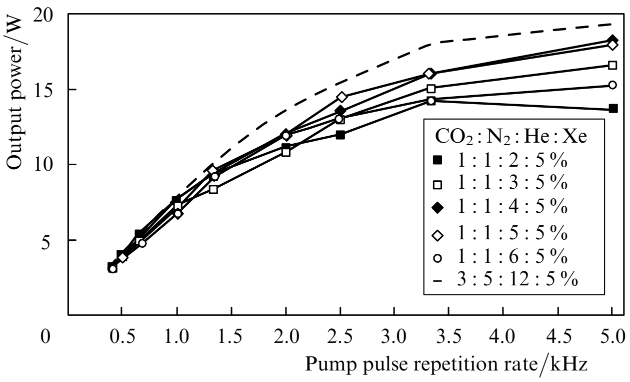

Figure 6. Dependences of the output power of a CO_2 laser on the pump pulse repetition rate for various compositions of the $CO_2:N_2:He:Xe$ working gas mixture. The pulsed microwave power is 4 kW, the pump pulse duration is 20 μs, and the gas pressure is 30 Torr.

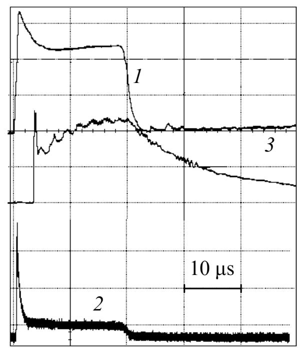

Figure 8. Oscillograms of (*1*) the envelope of the microwave pump pulse, (*2*) the photomultiplier signal pulse corresponding to plasma emission in the gas discharge gap, and (*3*) the laser pulse.

increases with the pump pulse repetition rate (the average input power increases). For the first mixture (with the lowest concentration of helium), the output laser power decreases sooner than for other mixtures. This is probably caused by its overheating due to a lower partial concentration of helium.

Figure 7 shows the effect of xenon impurity on the laser output power. One can see that addition of 10 % xenon increases the output laser power by 40 %, while a 5 % addition increases the output power by $\sim$21 % (similar results were obtained in [14]). It is well known that one of the main mechanisms restricting the output power of sealed lasers is the inevitable dissociation of CO_2 by electron impact in the gas-discharge plasma. The output power increases due to a decrease in the reduced field E/N in the discharge plasma and due to a partial increase in the CO_2 pressure caused by slowing down of the dissociation of CO_2 molecules. This occurs because the mean electron energy also decreases with E/N, which leads to an increase in the rate of vibrational excitation of CO_2 and N_2 molecules. The low ionisation potential of xenon facilitates the generation of new electrons for sustaining the discharge.

Figure 8 shows the oscillograms of envelopes of the microwave pump pulse and the photomultiplier signal corresponding to the plasma emission in the discharge gap. One can see that plasma emission begins almost immediately after switching-on the microwave generator. The decay of the envelope of the microwave pump pulse corresponds to the time of discharge formation. The beginning of lasing is delayed with respect to the pump pulse by several microseconds, while the laser pulse duration exceeds the pump pulse duration.

The laser efficiency depends on the parameters of the active medium and the optical cavity and, in particular, on the transmission coefficient of the output mirror. Figure 9 shows the dependence of the output power of a microwave-pumped laser on the pump pulse repetition rate for the output mirror transmittances of 5 % and 10 %. In the simplest case, the gain of the CO_2 laser can be determined by using the experimental dependences of the output power on the output mirror transmission.

By measuring the output power for two values of transmission of the output mirror and using the Rigrod formula [15]

$$P = P_s \frac{t_1\sqrt{r_2} + t_2\sqrt{r_1}}{\left(\sqrt{r_1} + \sqrt{r_2}\right)\left(1 - \sqrt{r_1 r_2}\right)} \left(Lg_0 + \ln\sqrt{r_1 r_2}\right) \qquad (2)$$

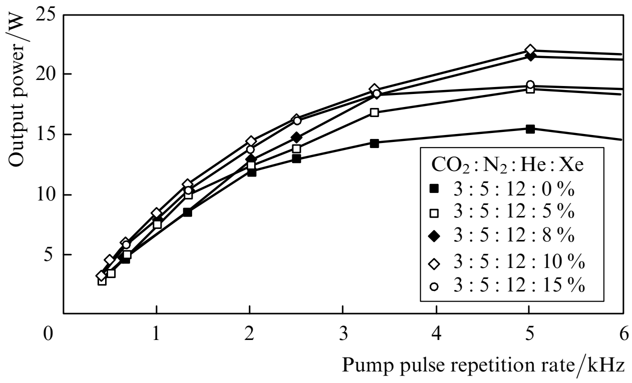

Figure 7. Dependence of the output power of a CO_2 laser on the pump pulse repetition rate for various admixtures of xenon (%) in the $CO_2:N_2:He:Xe$ working gas mixture. The parameters are the same as in Fig. 6.

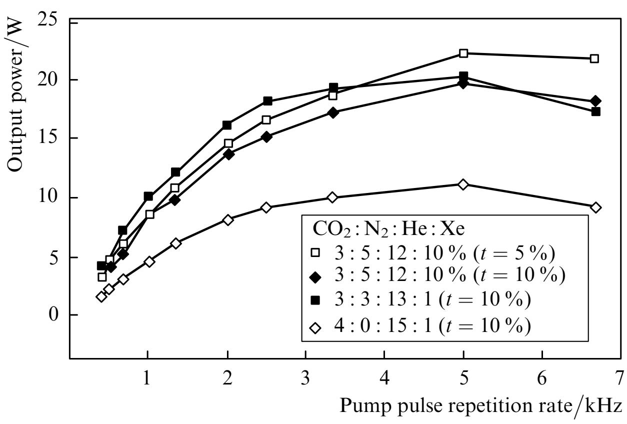

Figure 9. Dependences of the output power of a laser operating on the $CO_2:N_2:He:Xe$ = 3 : 5 : 12 : 10 gas mixture for an output mirror transmittance of 5 % and 10 %, as well as on the gas mixtures $CO_2:N_2:He:Xe$ = 3 : 3 : 13 : 1 and $CO_2:He:Xe$ = 4 : 15 : 1 for an output mirror transmittance of 10 %, on the pump pulse repetition rate. The parameters are the same as in Figs 6 and 7.

(here t_1, t_2, r_1, r_2 are the transmission and reflection coefficients respectively of the resonator mirrors; L is the active length of the laser; and P_s is the saturation power), we can estimate the unsaturated gain g_0 (by neglecting the distributed losses and losses due to matching of waveguide and free space modes, assuming that the discharge is homogeneous). The estimated value of g_0 is $\sim 1.2 - 1.3$ m^{-1} for a pump pulse repetition rate of 5 kHz.

Unlike pulsed (repetitively pulsed) pumping of the active medium of the laser, the gain in the cw mode (upon rf pumping) is lower (0.5–0.7 m^{-1}) [16]. This is caused by overheating of the working medium which lowers inversion due to collisional relaxation on the one hand, and drastically reduces the concentration of CO_2 molecules due to plasma chemical reactions on the other hand. In the pulse regime, the gain of the medium is almost double this value for the same average pump powers extracted from the power supply, since the input pulse power is also twice as high while a part of the dissociated CO_2 molecules are recovered during the interval between pulses.

Nitrogen molecules are used as an additional channel for pumping energy to the working oscillation mode of CO_2 in almost all CO_2 lasers. Figure 9 shows the dependence of the output power of a CO_2 laser on the presence of N_2 molecules in the working gas mixture. One can see that the addition of nitrogen doubles the output power of the laser. The oscillograms of the laser pulse shapes are almost identical in these cases, and CO molecules formed due to dissociation of CO_2 probably play the role of nitrogen molecules. The vibrational excitation cross section for CO molecules is quite high, while the energy difference between the vibrational levels of CO and CO_2 is lower than the mean kinetic energy kT. As a result, the working mode of the CO_2 molecule can be excited, although not so efficiently, because, unlike N_2 molecules, CO molecules are capable of spontaneous radiative decay.

An important direction in modern research and development of slab waveguide CO_2 lasers is associated with an increase in the peak power and a decrease in the laser pulse duration. Figure 10 shows the dependence of the output pulsed laser power on the pulsed microwave pump power. The curve is plotted taking into account the laser pulse shape and duration. One can see that for such a composition of the gas mixture, pressure and volume of the active medium (12.5 cm^3), saturation of the output power is not observed. Therefore, such a design of the CO_2 laser can provide kilowatt peak powers.

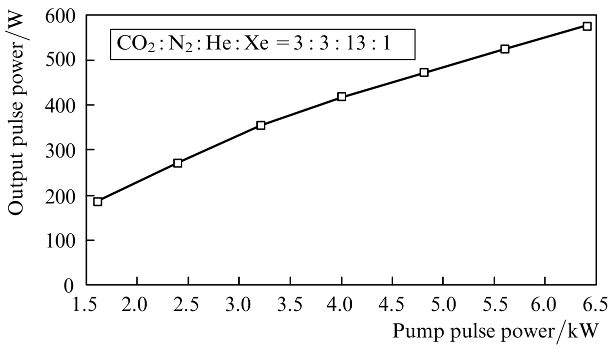

Figure 10. Dependence of the pulsed output power of a laser on the microwave pump pulse power; the composition of the working gas is $CO_2:N_2:He:Xe = 3:3:13:1$. The pump pulse duration is 20 μs, the pump pulse repetition rate is 400 Hz; the gas pressure is 30 Torr; the output mirror transmittance is 10 %.

The increase in the output power with increasing the power supplied to the discharge is limited by the increase in the temperature of the working mixture. Figure 11 shows the dependence of the output laser power on the pump pulse duration, and hence on the average power supplied to the discharge. One can see that an increase in the pump pulse duration above 25 μs (for the given lasing regime) reduced the output laser power. Apparently, this is due to overheating of the active medium, which leads to population of the lower laser level and, hence, to a decrease in the output power.

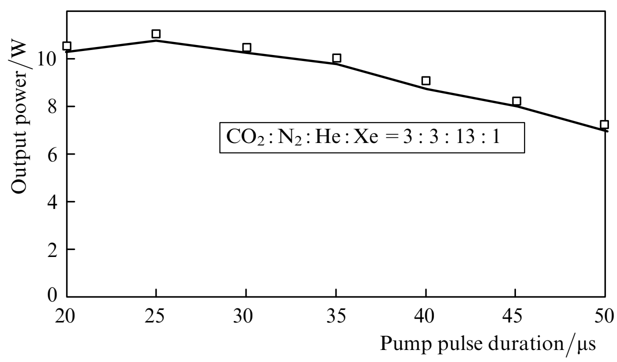

Figure 11. Dependence of the output power of a laser on the pump pulse duration; the gas composition is $CO_2:N_2:He:Xe = 3:3:13:1$. The gas pressure is 30 Torr; the pump pulse power is 4 kW; the pulse repetition rate is 1000 Hz; and the output mirror transmittance is 10 %.

Figure 12 shows the dependence of the efficiency of a microwave-pumped laser on the pulse repetition rate. The efficiency was determined by neglecting the transformation of the line voltage into the microwave signal. An increase in the pump pulse repetition rate leads to an increase in the average microwave power supplied to the discharge. The degree of dissociation and temperature of the gas also increase, which ultimately leads to a decrease in the efficiency of the laser. Figure 12 also shows the dependence of the output power of the microwave-pumped laser on the pump pulse repetition rate. The maximum output power achieved for such pump parameters and partial composition of the gas is 25.2 W.

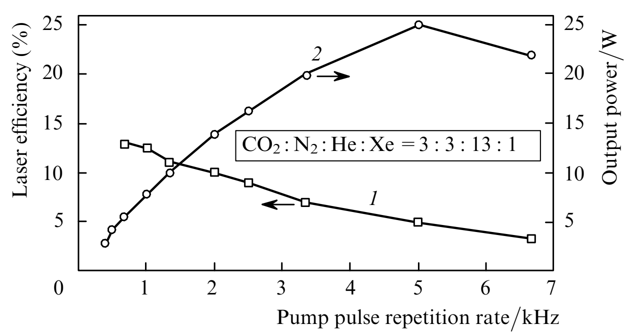

Figure 12. Dependences of the efficiency (*1*) and the output power (*2*) of a laser on the pump pulse repetition rate; the gas composition is $CO_2:N_2:He:Xe = 3:3:13:1$; the pressure is 30 Torr; the pump pulse power is 4.8 kW; and the pump pulse duration is 20 μs.

5. Conclusions

We have studied the parameters of a microwave-pumped slab CO_2 laser as functions of the pump power, composition of the working mixture, pressure, pump pulse repetition rate and duration. All the experiments were performed without circulation of the working gas mixture. The experimentally achieved specific energy output from a unit area of the active medium was about 0.4 W cm^{-2}. The average output power of 25 W and the efficiency of about 13 % were obtained at a wavelength of 10.6 μm. The peak power of laser radiation in the repetitively pulsed regime was 580 W. The design of the CO_2 laser can provide kilowatt peak powers. To reduce losses and to simplify the microwave power supply, it is expedient to combine the microwave volume resonator and the laser head. The output beam quality can be improved by passing to an optical scheme using a confocal hybrid waveguide-unstable resonator in the positive and negative branches of the stability diagram.

The results of this research can be used for designing and developing CO_2 lasers with an average output power up to 100 W, a laser pulse duration of 10 – 100 μs at pump pulse repetition rates up to 10 kHz with a peak power of about 1 kW.

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References

1. Jackon P.E., Baker H.J., Hall D.R. *Appl. Phys. Lett.*, **54**, 1950 (1989).
2. Colley A.D., Baker H.J., Hall D.R. *Appl. Phys. Lett.*, **61** (2), 136 (1992).
3. Kuznetsov A.A., Ochkin V.N., Udalov Yu.B., Witteman W.J. *Laser Phys.*, **4** (6), 1106 (1994).
4. Leont'ev V.G., Mol'kov S.I., Sukhanova N.P., Shishkanov E.F. *Kvantovaya Elektron.*, **21**, 931 (1994) [*Quantum Electron.*, **24**, 869 (1994)].
5. Mineev A.P., Nefedov S.M., Pashinin P.P. *CLEO/Europe'96* (Hamburg, 1996) paper CTuN6.
6. Lapucci A., Labate A., Rossetti F., Mascalchi S. *Appl. Opt.*, **35**, 3185 (1996).
7. Mineev A.P., Nefedov S.M., Pashinin P.P. *Proc. SPIE Int. Soc. Opt. Eng.*, **3686**, 35 (1999).
8. Mineev A.P., Nefedov S.M., Pashinin P.P. *Kvantovaya Elektron.*, **36**, 656 (2006) [*Quantum Electron.*, **36**, 656 (2006)].
9. Nishimae J., Yoshizawa K. *Proc. SPIE Int. Soc. Opt. Eng.*, **1225**, 340 (1990).
10. Shahadi A., Sintov Y., Jerby E. *Microw. Opt. Techn. Letts*, **36** (2), 115 (2003).
11. Mineev A.P., Nefedov S.M., Pashinin P.P. *Proc. SPIE Int. Soc. Opt. Eng.*, **5137**, 288 (2003).
12. Wester R., Seiwert S. *J. Phys. D: Appl. Phys.*, **24**, 1102 (1991).
13. Lebedev I.V. *Tekhnika i pribory SVCh* (Microwave Technology and Devices) (Moscow: Vysshaya Shkola, 1970).
14. Grudszus S., Marz M. *J. Phys. D: Appl. Phys.*, **26**, 1980 (1993).
15. Rigrod W.W. *Appl. Phys.*, **36**, 2487 (1965).
16. Dutov A.I., Evstratov I.Yu., Ivanova V.N., Kuleshov 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**, 484 (1996)].