Quantum Electronics **34** (4) 333 – 340 (2004)

PACS numbers: 42.55.Lt; 42.62.Cf; 42.60.Fc
DOI: 10.1070/QE2004v034n04ABEH002677

Application of deformable mirrors in industrial CO_2 lasers. II. Intracavity power control and repetitively pulsed modulation of output radiation

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***Abstract*. Industrial CO_2 lasers of various types with stable cavities, which contain deformable mirrors with a controllable curvature of the reflecting surface, are studied experimentally. Stable and reproducible control of the output power of industrial CO_2 lasers is achieved in both single-mode and multimode regimes until the complete lasing quenching. Stable repetitively pulsed lasing regimes with a pulse repetition rate varied from a few to several hundred hertz are obtained in cw CO_2 lasers. The shapes of the output laser pulses and the dependence of the mean output power on the frequency – time parameters of the control voltage applied to the intracavity deformable mirror are studied.**

Keywords: *industrial CO_2 lasers, output power control, repetitively pulsed modulation, deformable mirrors with a controlled curvature.*

1. Introduction. Repetitively pulsed operating mode in cw lasers

Single-channel deformable mirrors with a controlled curvature of the reflecting surface, which were considered in the first part of this work (see Ref. [1]), are simple, reliable, and convenient adaptive optical elements. Their placement into laser cavities allows the following:

(1) A real-time compensation for the parabolic component of thermooptic distortions appearing in the laser [2, 3].

(2) A real-time control of the laser output power until the complete lasing quenching.

(3) Implementation of repetitively pulsed lasing modes in cw lasers, including a regime in which the radiation pulse (peak) power exceeds the cw lasing power.

When controlling the output power of a laser with a repetitively pulsed modulation of the output radiation, the cavity's geometry is varied by controlling the curvature of the reflecting surface of its one or several mirrors. As a result, the cavity Q factor and, consequently, the laser output power change. Under a dynamic control at a certain frequency, this leads to a repetitively pulsed operating mode of a cw laser.

An intracavity modulation of the CO_2-laser output radiation was considered in several works. A limited control range of the output power (by a factor of < 2 relative to the nominal level) of a 1-kW cw CO_2 laser was obtained for a statically changing voltage applied to the deformable mirror [4]. Lasing was not quenched even at mirror resonance frequencies of 3.8 and 7.6 kHz, at which the maximum deformations were achieved: the radiation modulation depth at the resonance frequencies was 50 % – 70 %. A similar mirror was used in an unstable cavity of a 5-kW cw CO_2 laser [5]. A repetitively pulsed lasing mode was observed close to the same resonance frequencies of the deformable mirror. A static or low-frequency control was not analysed.

Hence, a repetitively pulsed lasing mode in cw CO_2 lasers has been implemented by now using deformable mirrors only at resonance frequencies and actually only in an unstable cavity. However, most of domestic and foreign low- and medium-power industrial lasers (< 5 kW) utilise stable cavities [6], so that the reliable realisation of a repetitively pulsed mode in them is of special interest. It is primarily important to achieve this mode not only at separate fixed frequencies but also over as wide spectrum as possible: from a static and low-frequency (tens of hertz) control to a high-frequency (tens of kilohertz) control. The possibility of tuning the modulation frequency is naturally required. In the latter case, the processing complex based on such a laser acquires new technologically important capabilities of processing new materials, extending the set of processed materials, introducing new technological operations, improving their quality, etc.

The possibility of modulating the radiation of a particular laser in a low-frequency repetitively pulsed mode is unambiguously and reliably determined by the possibility of lasing quenching by controlling statically a deformable mirror. Indeed, if the mirror deformations in this mode are sufficient for controlling the output power over the entire possible range (from zero to the nominal value), then, by controlling the mirror curvature at a low frequency within the same range, we can implement a repetitively pulsed radiation modulation. This is valid for a frequency range with a constant sensitivity, in which mirror deformations are the same as in the static mode [7]. For example, this range is 0 – 1 kHz for uncooled single-channel deformable controlled-curvature mirrors [7]. Thus, static quenching of laser oscillation using deformable mirrors is essentially important for achieving repetitively pulsed lasing regimes with low modulation frequencies.

In addition, when Q-switching is performed, an important condition is an excess of the pulse (peak) power over

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Received 28 May 2003; revision received 3 November 2003
Kvantovaya Elektronika **34** (4) 333 – 340 (2004)
Translated by A.S. Seferov

the cw lasing power. When the cavity is switched to the high-Q state, the energy stored in the cavity during the period of the low-Q state is emitted at the onset of the laser pulse. This initial power surge may substantially exceed (by several times) the nominal output cw power. The peak power is determined not only by the Q-switching rate (the mirror response speed) but also by the value of the residual power in the low-Q state, when the cavity is shut incompletely. It is obvious that, the higher the residual radiation power in the low-Q state, the lower the peak laser-pulse power, all other factors being the same.

This paper presents the results of experimental studies of static control of the output radiation power and repetitively pulsed lasing modes in industrial CO_2 lasers with standard stable cavities. We used cooled single-channel deformable mirrors with a controllable curvature of the reflecting surface, which were considered in detail in Refs [1, 8].

To have a more complete picture, note that a repetitively pulsed modulation of CO_2-laser radiation can also be achieved without using deformable optical elements: e.g., by controlling the discharge current or the transmission of the cavity output mirror. However, these methods have certain limitations: the response speed and the output radiation power for the first and second methods, respectively.

2. CO_2 laser with an axial mixture circulation and output power of 2.5 kW

A Garpun-2000 industrial gas-discharge cw CO_2 laser (SNPP 'Istok-Laser', Fryazino, Moscow region) with a rapid axial circulation of the working mixture (CO_2-N_2-He) was used in the experiments. Its main characteristics are listed in Table 1.

Table 1. Parameters of the Garpun-2000 CO_2 laser.

Radiation wavelength	10.6 μm
Maximum output power:	
Multimode lasing	2500 W
Single-mode lasing	1000 W
Power-control range	200 – 2000 W
Relative radiation-power instability	$\leqslant 5\,\%$
Maximum output-beam diameter:	
Multimode lasing	45 mm
Single-mode lasing	20 mm
Radiation divergence (single-mode lasing)	2 mrad
Water temperature at the cooling-system inlet	25 °C
Excess pressure in the water cooling system	0.15 – 0.2 MPa

The stable laser cavity consists of an end concave mirror with a −30-m radius of curvature and the output semitransparent (50 %) mirror with either a −30-m (for multimode lasing) or −15-m (for single-mode lasing) radius of curvature. The cavity also includes six flat deflecting mirrors. All of these optical elements are cooled and vacuum-tightly mounted in the cavity housing. The diameter of the end and output mirrors is 60 mm; the total length of the cavity is 6.5 m.

Instead of the end mirror, a cooled single-channel deformable mirror with a controllable curvature of the reflecting surface was mounted in the laser cavity. The detailed characteristics of this mirror are listed in Table 1 from Ref. [1]. A controllable mirror with a flat initial optical surface was used in our experiments. A scheme of the Garpun-2000 laser cavity with a controlled-curvature mirror is shown in Fig. 1.

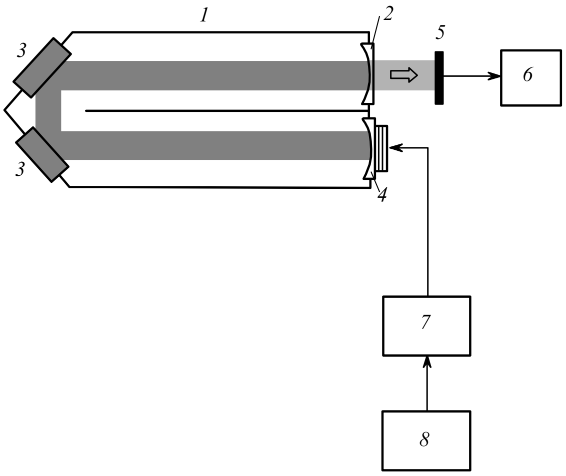


Figure 1. Garpun-2000 CO_2 laser with a controlled-curvature mirror in the cavity: (*1*) cavity housing; (*2*) semitransparent output mirror; (*3*) six deflecting mirrors; (*4*) single-channel deformable mirror with a controlled curvature of the reflecting surface; (*5*) TI-4 thermoelectric sensor of the laser output power; (*6*) V7-38 voltmeter; (*7*) electronic unit for controlling the deformable mirror; and (*8*) control computer.

After the controlled mirror (*4*) is mounted in the laser, the mirror is exposed to an external atmospheric pressure and undergoes deformations during the subsequent cavity evacuation and its filling with the working gaseous mixture. The sag of our deformable mirror at a pressure of 1 atm is 3.1 ± 0.1 μm, which corresponds to a change from the flat mirror surface to a convex one with a radius of curvature of 71 ± 2 m. These measurements were performed using the collimator from an OSK-2TsL optical bench. These deformations are fully elastic: as the pressure is removed, the reflecting surface recovers its initial profile.

When the control voltage changes from −300 to +210 V, the radius of curvature of deformable mirror (*4*), which is vacuum-tightly mounted in the evacuated volume, changes from +9.7 m (a convex shape) to −23.6 m (concave).

2.1 Static control of the output radiation power

Experiments were performed in both single- and multimode lasing regimes. Using a thermoelectric sensor (*5*) and voltmeter (*6*), cw laser output power was monitored as a function of the control voltage across the deformable mirror (*4*). The voltage was formed in an electronic unit (*7*) in response to commands from a control computer (*8*). The measurements were conducted at a nominal output power $P_{\text{nom}} = 200 - 2100$ W [the output power within the control range (see Table 1) is considered as the nominal power for the cavity with a flat end mirror]. A signal value of 1 mV at the sensor (*5*) output corresponds to an output power of 680 W. The TI-4 sensor error is ±5 %, and its time constant is 1 min.

Figure 2 shows typical measurement results. A stable reproducible control of the output radiation power was achieved in all the experiments at a nominal power of 200–1900 W for both single- and multimode lasing regimes. At an output power of ~ 2 kW [curves (*7*) and (*8*)], curves $P(U)$ could not be measured over the entire control-voltage range, since an electric-discharge pinching was observed in the cavity [12]. For the single-mode laser operation [curve (*1*)], a cooling liquid at an elevated temperature of ~ 30 °C was used for purely technical reasons.

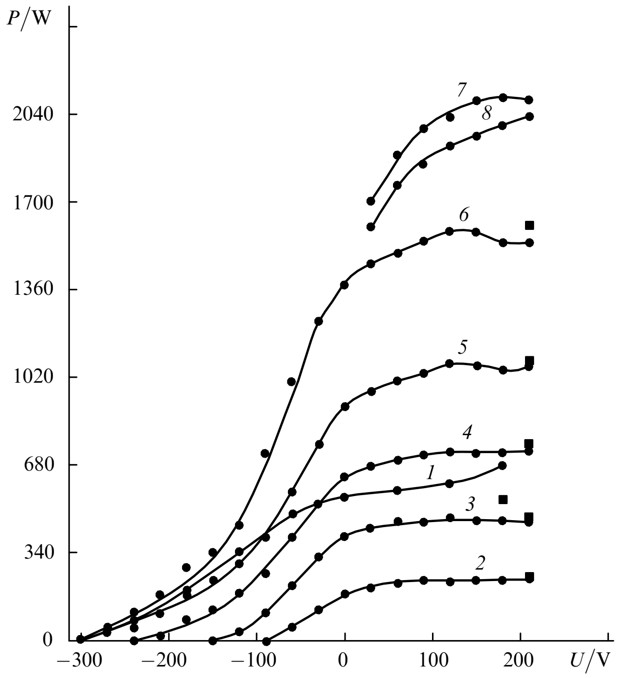


Figure 2. Output power P of the Garpun-2000 CO_2 laser as a function of the voltage U applied to the intracavity deformable mirror with a controlled curvature of the reflecting surface for single-mode lasing at a nominal output power $P_{\rm nom} = 680$ W (*1*) and multimode lasing at $P_{\rm nom} = 240$ (*2*), 470 (*3*), 750 (*4*) 1070 (*5*), 1580 (*6*), 2100 (*7*), and 2000 W (*8*); (■) return of the controlled mirror to the initial state (a transition from −300 to +210 V).

The dependences obtained have a slight stable peak in the voltage range of 120–150 V, which is clearly seen at $P_{\rm nom} \geqslant 750$ W (Fig. 2). This peak evidently corresponds to an optimal geometry of the cavity. In fact, when the control voltage changes from 150 to 120 V, the radius of curvature of the deformable mirror in use, which is vacuum-tightly mounted in the cavity, changes from −29.7 to −38.2 m. This agrees well with the curvature of the standard cavity mirror (−30 m).

The data in Fig. 2 show that, for $P_{\rm nom} \leqslant 1.6$ kW, the amplitude of the controlled mirror deformations is sufficient for completely disabling the cavity. If the output power is higher, lasing is quenched incompletely and the residual output power is within 100 W. In this case, lasing can be quenched completely using the following procedure. As is seen in Fig. 2, a segment of 120–210 V is insignificant for controlling the output power for all of the experimental curves; for the range of $-300\ldots+120$ V, the output power changes from zero to the possible maximum. By selecting an appropriate initial curvature of the deformable mirror, the peak of curves $P(U)$ can be shifted to a point of 210 V. The output-power peak then corresponds to the limiting positive control voltage (210 V), which in turn corresponds to the optimal curvature of the deformable mirror (−30 m). However, at the maximum negative voltage, the mirror curvature exceeds that obtained in the experiments with the initially flat mirror. This makes it possible to completely quench lasing in the cavity at $P_{\rm nom} > 1.6$ kW. Using the results obtained in the first part of this paper (see Table 1 and Fig. 2 from Ref. [1]) and simple algebraic calculations, it can be shown that the desired shape of the deformable mirror has a convex profile with a radius of curvature of ~ 270 m.

2.2 Repetitively pulsed modulation of the output radiation

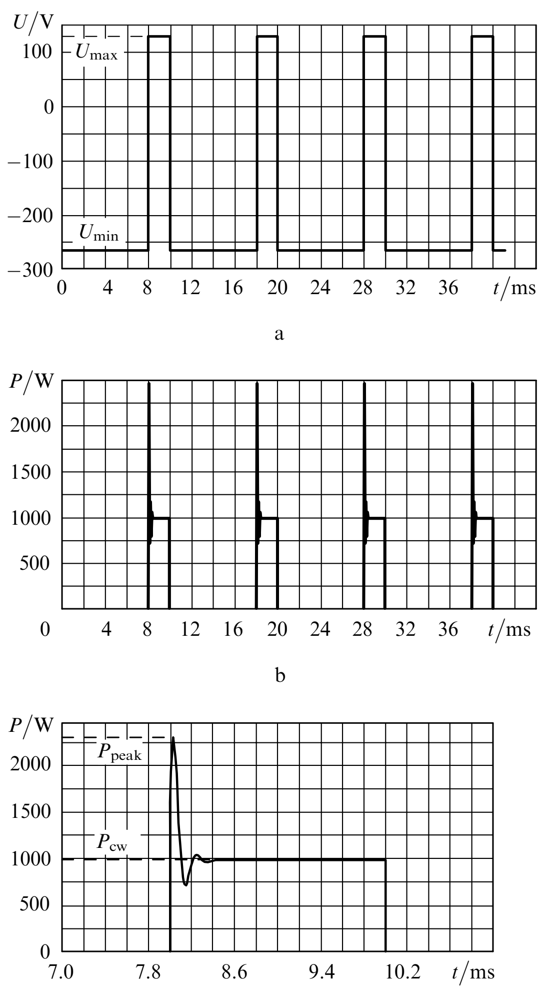
These experiments were performed in a multimode lasing regime. The mean and pulse power of repetitively pulsed radiation were recorded. The mean-power measurement procedure was identical to that in the cw lasing mode, including the same instruments (Fig. 1). In pulse-power measurements, a Ge–Au photoresistor (FSG-22-3A1 with a time constant of $< 10^{-7}$ s) cooled with liquid nitrogen and a C1-98 dual-beam oscilloscope were used instead of the sensor (*5*) and voltmeter (*6*), respectively. The oscilloscope recorded the output signal of the photoresistor and also monitored the pulse control voltage applied to the deformable mirror (*4*). This voltage was generated by the unit (*7*), which, instead of the computer (*8*), was controlled by a G5-54 pulse generator. The Ge–Au photoresistor was calibrated using a TI-4 sensor and a light chopper.

The experiments were performed at a nominal output power of 470–1020 W. When a rectangular pulse voltage was applied to the deformable mirror (*4*) (Fig. 1), a cw lasing mode changed to a repetitively pulsed mode. Figure 3 shows schematically typical measurement results. Repetitively pulsed lasing modes with pulse repetition rates $f = 10 - 400$ Hz and durations $\tau_{\rm p} = 0.6 - 50$ ms were achieved at various control voltages applied to the mirror. The frequency–time parameters of pulse CO_2-laser radiation are thus determined by the frequency–time characteristics of the control voltage at the deformable mirror. During all of these tests, the controlled-curvature mirror operated stably and the experimental data were fully reproducible.

As is shown in Fig. 3, the laser-pulse profile is not strictly rectangular. When the control voltage applied to the deformable mirror changes jumpwise from −265 to +130 V, a power surge occurs, which corresponds to a transition to the high-Q cavity state at the beginning of each pulse as a result of changing the curvature of the reflecting mirror surface. After the energy stored in the active medium in the low-Q state is emitted, ordinary cw lasing occurs, until the high Q factor is removed again by the controlled mirror. Measuring the surge amplitude, i.e., the peak power $P_{\rm peak}$ (Fig. 3c), at various repetitively pulsed lasing modes (the average number of measurements was 20) has shown that

$$P_{\rm peak}/P_{\rm cw} = 2.5 \pm 0.2,$$

where $P_{\rm cw}$ is the corresponding power in the cw mode. The error of this result is determined mainly by the laser-radiation instability and is obviously below 10 % at a confidence level of 0.99.



a

b

c

Figure 3. Time dependences of (a) the control voltage U applied to the intracavity deformable mirror and (b) the laser output power P and (c) the shape of the output laser pulses in a repetitively pulsed mode of the Garpun-2000 cw CO_2 laser at a nominal output power $P_{nom} = 90$ W, pulse repetition rate $f = 100$ Hz, and pulse duration $\tau_p = 2$ ms.

Another effect that also determines the shape of laser pulses is the damped oscillation of the reflecting surface of the deformable mirror after a control-voltage jump, which in turn leads to power oscillations in the laser pulse (Fig. 3c). These oscillations are most clearly observed on the oscilloscope at short cavity-shutting voltage pulses. The power-oscillation frequency corresponds to the natural frequency of the deformable mirror as a dissipative vibrating system [11]. The natural frequency of this mirror is 4.7 kHz, which agrees well with the period of damped power oscillations in the laser pulse (slightly longer than 0.2 ms, Fig. 3c). The total duration of the damped oscillations is no longer than 0.4 ms (no more than two oscillation periods).

If the period of damped power oscillations in the laser pulse is known, one can estimate the speed (time) of switching the Garpun-2000 laser cavity to the high-Q state using the deformable mirror under study. Figure 3c shows that the pulse radiation power rises from zero to the peak value in a quarter-period of damped oscillations lasting ~ 50 μs. This is the maximum Q-switching time. As was expected, it is much shorter than the active-medium lifetime in our laser ($\sim 10^{-3}$ s).

The dependences of the mean laser-output power on the repetition rate and duration of the rectangular voltage pulse applied to the intracavity deformable mirror were studied in the implemented repetitively pulsed modes for constant control-voltage amplitudes: $U_{max} = 130$ V and $U_{min} = -265$ V (Fig. 3a). Figures 4 and 5 show the mean output power as a function of the absolute and relative durations of the cavity-blocking pulse for various repetitively pulsed lasing modes. All the experimental curves are linear. As the duration of the cavity-shutting pulse increases, the mean output power decreases. The functions $P(\tau_{cl}/T)$ for different pulse repetition rates almost coincide (Fig. 5) at least within the limits of the measurement error. These measurements were performed at a constant nominal radiation power in the cw lasing mode ($P_{nom} = 1020 \pm 50$ W). This power corresponds to the point of intersection of the obtained straight lines with the ordinate axis in Figs 4 and 5. The error corresponds to the error of the TI-4 thermoelectric sensor.

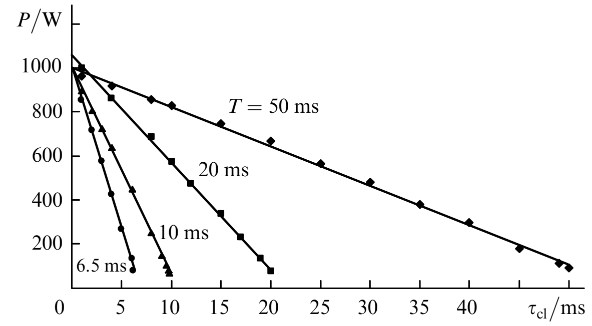


Figure 4. Mean output power P of the repetitively pulsed Garpun-2000 CO_2 laser as a function of the duration τ_{cl} of the cavity-shutting pulse at various pulse repetition periods T.

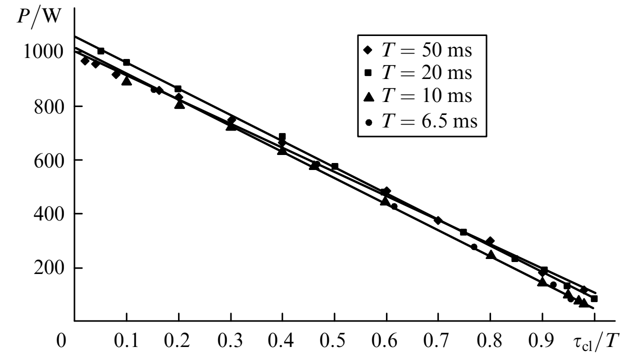


Figure 5. Mean output power P of the repetitively pulsed Garpun-2000 CO_2 laser as a function of the relative duration τ_{cl}/T of the cavity-shutting pulse at various pulse repetition periods T.

Hence, for a given P_{nom} in a cw lasing mode, the mean power of repetitively pulsed radiation is unambiguously governed by the relative duration (or the off-duty factor) of the pulses shutting or enabling the laser cavity. Changing the pulse duration of the control voltage applied to the intracavity deformable mirror allows a linear control of the mean laser-output power. The slope of the control characteristics can be changed by selecting the voltage-pulse repetition rate (Fig. 4).

Table 2. Parameters of the Hebr-1A CO_2 laser.

Radiation wavelength	10.6 μm
Number of beam modes	2
Maximum output power	1000 W
Power-control range	200 – 1000 W
Output-beam diameter	< 28 mm
Radiation divergence	< 3 mrad

3. A transverse-flow CO_2 laser with an output power of 1 kW

A Hebr-1A (Bulgaria) industrial gas-discharge cw CO_2 laser with a rapid transverse flow of the working mixture was used in our experiments. Its main characteristics are listed in Table 2.

A stable laser cavity (Fig. 6) consists of an end concave mirror with a −30-m radius of curvature and an output semitransparent (45 % transmission) flat mirror. The cavity also includes two flat deflecting mirrors 50 mm in diameter and four diaphragms. The end and deflecting mirrors are made of silicon with copper or gold reflecting coatings, and the output mirror is made of zinc selenide. The cavity optical elements are placed on water-cooled substrates. The diameter of the end and output mirrors is 28 mm, and the total cavity length is 3 m.

As was in earlier experiments, a controlled-curvature deformable mirror similar to that described above [1] was mounted vacuum-tightly instead of the end mirror (*11*) (Fig. 6) in the Hebr-1A-laser cavity. This deformable mirror also had a flat initial shape of the optical surface and an almost the same sensitivity (45 instead of 46 μm kV^{-1} in the range of ±100 V, see Table 1 in Ref. [1]). In addition, the control voltage of this mirror was inverted with respect to the previous one: [−200 V, 300 V] instead of [−300 V, 200 V]; at negative and positive voltages, the mirror profile was concave and convex, respectively. A standard laser-cooling system was used to cool the deformable mirror.

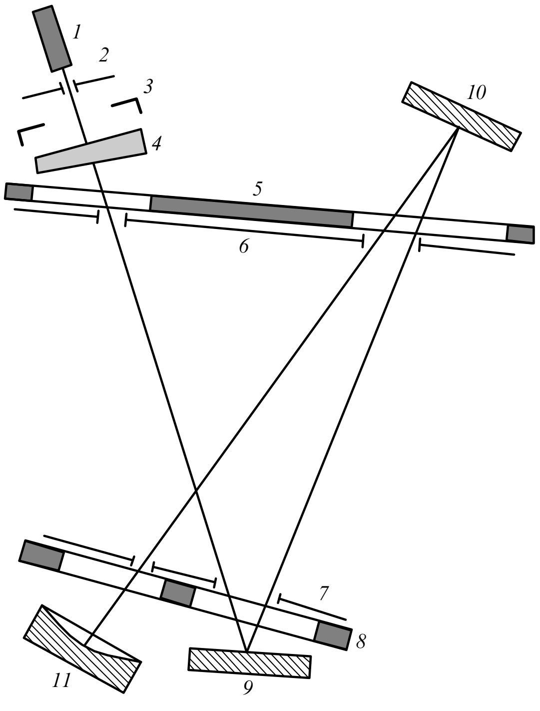


Figure 6. Optical layout of the Hebr-1A CO_2-laser cavity: (*1*) alignment He – Ne laser; (*2*) screen; (*3*, *5*, *8*) diaphragms; (*4*) output mirror; (*6*, *7*) replaceable diaphragm plates for alignment; (*9*, *10*) deflecting mirrors; (*11*) end mirror that was replaced by a controlled-curvature deformable mirror.

The scheme of the experiments with the Hebr-1A laser compared to that in Fig. 1 has the following differences. The number of the deflecting mirrors in the cavity is two. Instead of a voltmeter, a laser output-power meter (a standard instrument of the Hebr-1A complex) is used, in which a bolometer on a copper wire serves as a sensor. The experiments were performed at a nominal laser output power of 490 – 940 W. Like in the previous case, the radiation output power was measured as a function of the control voltage applied to the deformable mirror.

Typical measurement data are shown in Fig. 7. As was in earlier experiments, a stable reproducible control of the laser output power was achieved in these experiments. For example, the reproducibility of the results (the limiting power values) for $P_{\text{nom}} = 590$ W is characterised by the data listed in Table 3. Note that the power value marked with an asterisk is not quite reliable, since it was recorded experimentally only once, and the residual output power was within 30 W even for the highest nominal laser power (see below).

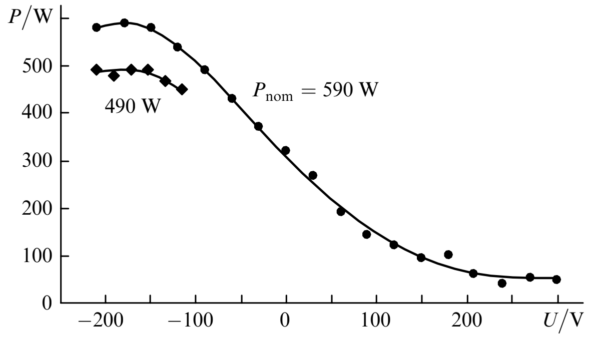


Figure 7. Output power P of the Hebr-1A industrial CO_2 laser as a function of the voltage U applied to the intracavity deformable mirror with a controlled curvature of the reflecting surface at various P_{nom}.

The obtained curves $P(U)$ have a maximum at a control voltage close to −180 V, which evidently corresponds to the optimal cavity geometry. For our deformable mirror mounted vacuum-tightly in the evacuated laser cavity, a control voltage of −180 V corresponds to a mirror radius of

Table 3.

Control voltage/V	Output power/W
−210	580
+300	40 – 50*
−210	580
+300	20 – 30
−210	560 – 570

curvature of -31 m. This almost coincides with the radius of curvature of the standard laser mirror ($R = -30$ m).

Static tests have shown that Hebr-1A-laser oscillation is not quenched completely at a positive (blocking) voltage at the controlled mirror; the residual radiation power is 20–30 W. For example, for an optimal laser alignment corresponding to the maximum output power (940 W) (in this case, the mirror control voltage is -210 V), the residual output power at $+300$ V was < 30 W. The residual output power (at the blocking voltage applied to the mirror) obviously decreases, as the nominal laser-output power decreases. Using the same reasoning as in Section 2 and taking into account the identical curvature ($R = -30$ m) of the standard end mirrors in the both cavities, we can assume that Hebr-1A-laser oscillation will be quenched at the same initial convex profile of the deformable mirror (with a radius of 270 m).

Thus, the results of experiments on the static control of the output power of the Hebr-1A and Garpun-2000 lasers basically coincide, but certain differences still exist. In particular, the function $P(U)$ for Hebr-1A with the high-Q cavity (at negative control voltages) has no horizontal region. In addition, the dependence $P(U)$ for this laser is less steep (2.0 W V^{-1} compared to 3.9 W V^{-1} for Garpun-2000) in the maximum-cavity-sensitivity region at the same nominal output power. This is clear from the comparison of Figs 2 and 7. These differences in the curves $P(U)$ are evidently conditioned by the geometry of the laser cavities, such as their different lengths and curvatures of the output mirrors, as well as by different gain-to-loss ratios in these lasers.

The repetitively pulsed modulation of the Hebr-1A-laser output radiation was effected in the same manner as for Garpun-2000. The only difference was that the amplitude ($U_{\max}$, $U_{\min}$) and frequency–time (f, τ) control-voltage parameters (Fig. 3a) were set by a computer (*8*) program (Fig. 1). The experimental results fully correspond to those in Section 2.2. Moreover, the experiments in the repetitively pulsed mode have shown that, for all factors being equal, the spatial distribution of the radiation intensity over the output aperture improves (becomes smoother) compared with that for the Hebr-1A laser operating in a cw mode. This was observed visually from a print of the radiation spot on an organic-glass plate placed at the laser output.

This effect is probably caused by a radiation and discharge-current redistribution in the cavity during deformations of the controllable mirror (*4*) (Fig. 1), which, in turn, changes the ratio between the modes in the output laser beam. Since the Hebr-1A-laser radiation consists of two modes (TEM_{00} and TEM_{01}), radiation power is probably transferred from the higher to zero mode during pulsed lasing. In other words, the TEM_{01} mode is suppressed, thus leading to a smoother radiation-intensity distribution over the output aperture.

Another possible factor that improves the spatial intensity distribution is evidently a decrease in thermal deformations of the laser intracavity optics in a repetitively pulsed lasing mode. In fact, for other factors being equal, thermal deformations of the mirrors are determined by the mean radiation power incident on them. At a certain nominal output power, a transition from a cw lasing mode to a repetitively pulsed mode means that the mean radiation power at the mirror decreases by a factor of $\sim q$, where q is the off-duty factor for laser pulses (Fig. 5 shows this for the output beam). Hence, the thermal deformations of the intracavity optics in a repetitively pulsed mode are smaller than in the cw mode. This may lead to an improved spatial radiation-intensity distribution in the output beam. Since the actual thermal deformations of the laser optics are small, it can be evidently presumed that, of the two aforementioned causes, the first one predominates.

The tests of the Garpun-2000 and Hebr-1A lasers with the controlled cavities considered above were repeated multiply under a static control of the output power and in repetitively pulsed lasing modes. In all of the experiments, the deformable mirrors placed in the cavities stably operated under radiative loads: the cw power and the peak power in repetitively pulsed modes reached values of 4.2 and 6 kW, respectively. Comparative interferometric measurements of the mirrors showed that their optical characteristics remained unchanged even in experiments under unfavourable thermal conditions (cooling with warm water). Figure 8 shows examples of interferograms of the controlled-curvature mirror before and after tests in the Garpun-2000 laser. As is seen, the maximum optical-surface distortions do not exceed a quarter-wavelength of the interferometer ($\lambda =$

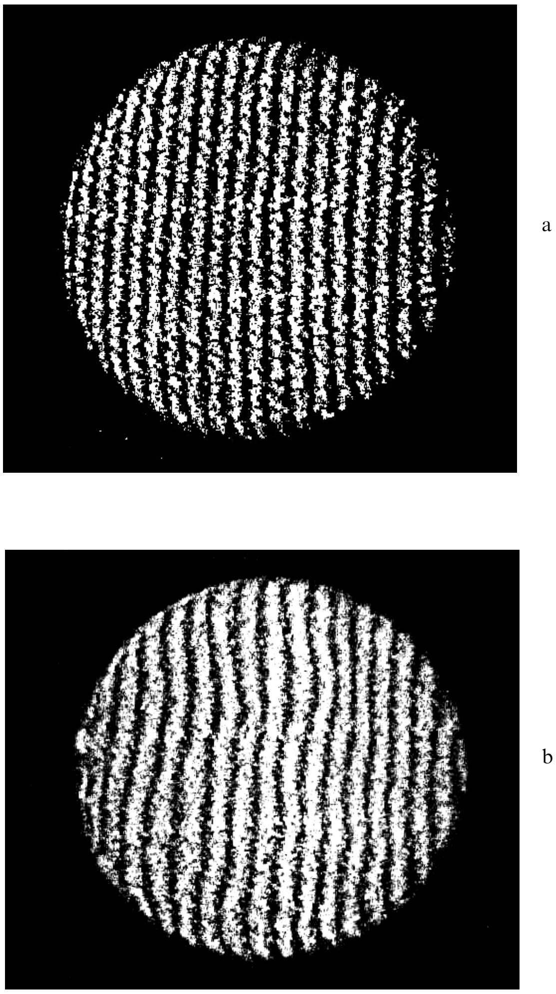


Figure 8. Interferograms of the initial shape of the controlled-curvature mirror surface (light diameter is 42 mm) (a) before and (b) after multiple tests in the CO_2-laser cavity at an output power of > 2 kW. The interferometer wavelength is 632.8 nm.

632.8 nm), which is insignificant for IR optics ($\lambda =$ 10.6 nm).

4. Conclusions

Using the mirrors with a controlled curvature of the reflecting surface considered earlier [1], a stable reproducible control of the output power of industrial CO_2 lasers with stable cavities and differently circulating working mixtures was achieved in both single- and multimode regimes until the complete lasing quenching. This allows single-channel bimorph mirrors to be used as peculiar switches of laser radiation [9] with a response time no longer than 0.5 ms. For example, such a switch is a useful element in a medium-power laser setup in which the processed workpieces are replaced frequently and quickly and where radiation must be quenched for the time during which a workpiece is absent from the working zone or the processing laser head moves from one object (operation) to another.

The dependences $P(U)$ obtained experimentally make it possible to use the intracavity single-channel deformable mirrors under study for stabilising the laser output power, when it randomly changes for some reasons. As a result, intracavity mirrors with a controlled curvature of the reflecting surface can also be used to stabilise the energy characteristics of the focal spot in a laser complex performing any technological operations based on controlling the laser output power. For example, they can be used in laser welding for stabilising the temperature in the focal spot, which may change as a result of fluctuations of the laser output power, surface and bulk inhomogeneities of the processed materials (workpieces), gaps between the processed plates, etc.

Repetitively pulsed lasing modes at pulse repetition rates of a few to hundreds hertz were achieved in the stable-cavity cw CO_2 lasers considered. The following experimental facts have been established.

(1) The frequency – time parameters of pulse radiation are determined by the frequency – time characteristics of the control voltage applied to the intracavity deformable mirror; at the leading edge of each pulse, there are damped power oscillations at a frequency corresponding to the natural vibration frequency of the deformable mirror.

(2) At the beginning of each laser pulse, a power surge is observed being caused by a transition to the high-Q cavity state; the pulse amplitude is 2.5 times higher than the cw lasing power.

(3) The time of transition to the high-Q cavity state is limited by the vibration decay time of the deformable mirror's reflecting surface after the control-voltage jump and amounts to ~ 50 μs (the total duration of damped vibrations is < 0.4 ms).

(4) The mean power of repetitively pulsed radiation is unambiguously determined by the relative duration τ/T (off-duty factor) of pulses that shut or enable the laser cavity; the function $P(\tau)$ is linear within the range considered, and its slope depends on the pulse repetition rate f.

(5) The intensity distribution of repetitively pulsed laser radiation over the exit aperture is more uniform than that for the cw lasing mode.

In our experiments, the frequency of repetitively pulsed modulation was limited from above by the capabilities of the control electronics. If more powerful electronics is used, the application of the intracavity mirrors considered in cw CO_2 lasers will evidently help implement repetitively pulsed modes with higher frequencies, up to the resonance frequency of the controlled mirror ($F_{\text{res}} = 4.7$ kHz, the resonance-peak width $\Delta F = 0.42$ kHz at a $1/\sqrt{2}$ level). The more so as the controlled-mirror deformation amplitude at the resonance frequency far exceeds the static mirror deformations [7]. Taking into account a typical character of the optical arrangements of the stable cavities considered and the stable reproducibility of the results, the use of these mirrors in other CO_2 lasers will presumably lead to similar results.

As to low-power CO_2 lasers, uncooled deformable mirrors of similar type and design [7] can be used in them. Their sensitivity is higher than that of cooled mirrors (compare the numerical data from Refs [7] and [8]). Consequently, for other factors being equal, these mirrors will ensure a higher efficiency of the intracavity radiation control and a repetitively pulsed modulation at lower voltage amplitudes at the deformable mirror.

In our experiments, the mirror with a controlled curvature of the reflecting surface was mounted in the cavity instead of the end mirror. However, if necessary, any deflecting mirror in the cavity can be replaced by a deformable one (in view of a compensation for possible astigmatism). The more so as these controlled mirrors easily ensure this substitution thanks to their mass and size characteristics [1]. For example, deformable mirrors can be set up instead of deflecting mirrors (*9*) and (*10*) in the Hebr-1A-laser cavity (Fig. 6). Together with the replacement of the end mirror, this will lead to the formation of a controlled cavity with several deformable mirrors [10]. The radiation control efficiency in such a cavity obviously improves. Moreover, the presence of a number of controlled-curvature mirrors in the cavity offers new possibilities, such as a reduction of the output voltage of the control electronics and, thus, its simplification, a compensation for the electromechanical hysteresis of one deformable mirror at the expense of another, etc. Lasing in a repetitively pulsed mode makes it possible to extend the modulation frequency range by selecting and combining frequency regimes for individual deformable mirrors.

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