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# High-frequency repetitively pulsed operating regime in high-power wide-aperture lasers

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***Abstract*. A technique for obtaining a repetitively pulsed operating regime in high-power wide-aperture lasers is proposed and experimentally realised. In this regime, the laser emits a train of pulses with a duration of 0.1 – 1 μs and a pulse repetition rate of several tens of kilohertz. The main properties of the pulsed regime are theoretically analysed and the proposed technique is tested in detail employing a test-bench gas-dynamic laser. The results of the test confirmed the conclusions of the theoretical analysis. The possibility of realising a repetitively pulsed regime in high-power wide-aperture lasers without a reduction in the average output power is experimentally demonstrated.**

***Keywords***: *gas-dynamic laser, wide-aperture resonator, Q-switching.*

## 1. Introduction

At present, interest is increasing in high-power lasers (50 – 100 kW) employed in the solution of a variety of research and production problems. The existing sources of high-power radiation operate only in the cw or quasi-continuous low-frequency (below 300 Hz) repetitively pulsed regime with a long pulse duration (tens of microseconds). The development of lasers operating in a high-frequency (tens of kilohertz) pulsed regime with a short pulse duration (hundreds of nanoseconds to few microseconds) or the conversion of the existing lasers to this regime will considerably extend the field of application of high-power lasers, improve the efficiency of their use by factors of several tens, and enable the realisation of qualitatively new effects [1]. For example, to attenuate the plasma screening in the radiation – material interaction, weaken the thermal radiation defocusing in long paths, improve the energy extraction efficiency in wide-aperture lasers, etc.

At a high output power exceeding several kilowatts, however, organising transient lasing modes based on high-frequency resonator modulation runs into several problems, which are caused by wide apertures of resonator elements and accordingly of the laser beam as well as by the high power density.

Presently known devices intended for resonator loss modulation may be conventionally divided into several classes: opto-mechanical, acousto-optic, electro-optical, and self-bleaching. In high-power lasers, only opto-mechanical devices can be used, which include transparent or reflective apertures. The remaining modulator types involve transmission optical elements.

In the ten-micrometer range, all optical materials possess a relatively high (up to several percent) absorption coefficient, which is responsible for a significant heat release and, in the long run, a fast degradation of these elements. The use of intracavity disc modulators in high-power industrial lasers is restricted by the output power of several hundred watts: due to the high power density inside the resonator, plasma is produced at the modulator aperture edges to cause modulator degradation or beam screening. In particular, the output power of the $CO_2$ laser investigated in Ref. [2] (a cw output power of 5 kW) lowered by two orders of magnitude when the laser was converted to the repetitively pulsed regime with the aid of a mechanical full-aperture modulator. The approach proposed in Ref. [3] appears to be more promising – modulating the gain of the active medium rather than the cavity loss. In this work, the gain of the active medium was modulated by imposing a strong external pulsed magnetic field. However, in this case there emerged almost insuperable difficulties related to setup scaling for larger volumes of the active medium as well as to increasing the modulation frequency and the pulse contrast ratio. The authors of Ref. [3] were able to raise the modulation frequency to only 10 Hz in a series of only several hundred pulses. This resulted in a reduction in the output power in the repetitively pulsed regime by almost an order of magnitude compared to the cw regime. In the injection of external signal, the methods of modulating the gain of the active medium appear to be the methods of choice [4].

Our work is concerned with a new technique of modulation of the gain of the active medium by radiation self-injection. This technique can be applied to obtain a repetitevely pulsed regime in the range of average output power of the order of 100 kW. The aim of our work is to theoretically substantiate and experimentally realise the repetitively pulsed regime of a gas-dynamic $CO_2$ laser.

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## 2. Substantiation of resonator design

In lasers with a high average output power, unstable resonator configurations are commonly used because of a large cross section of the active medium. In resonators of this type, externally injected low-power beams may exert a significant effect on the characteristics of output radiation [4, 5].

One way to realise the control regime is the self-injection of radiation – extraction from the resonator and return of a part of radiation after changing its spatio-temporal characteristics. The transition to the transient lasing mode is effected through the modulation of the self-injecting beam. Earlier, a study was made of laser versions with radiation self-injection into the paraxial resonator region [4]. However, analysis showed that the power of the beam injected into the paraxial beam region should be comparable with the output laser power to efficiently control the resonator of a continuously pumped laser, unlike pulsed systems with regenerative amplification [6].

The self-injection of a part of output radiation through the resonator periphery is more efficient: on return to the paraxial resonator region, the injection power significantly rises due to the large number of passages to play the dominant part in the formation of output radiation.

The role of peripheral radiation was first investigated in Ref. [4]. In the case of a traditional resonator, the role of waves converging to the resonator axis was found to be insignificant, because their source is a narrow region with a small relative area at edge of the output mirror; accordingly, the power of the control wave injected into the resonator is low. This wave has a large divergence, and only its small part (of the order of $1/Nf$, where $Nf \gg 1$ is the Fresnel number) participates in lasing.

The effect of the injection wave on the resonator characteristics can be enhanced by matching the beam phase with the resonator configuration and increasing the radiation power returned. In this case, the propagation direction and the wavefront curvature of the injection beam should be so matched with the resonator configuration that the injection beam concentrates, after a relatively large number of passages through the resonator, near the optical resonator axis and transforms to a divergent wave that forms the output radiation. The injection beam energy should be high enough to exceed, after its arrival to the resonator axis, the saturation energy of the active medium. The experimental data of the investigation of the effect of this kind of self-injection on lasing in the stationary mode were reported in Ref. [5].

The schematic of the setup which realises the repetitively pulsed radiation self-injection is shown in Fig. 1. The radiation is extracted from the resonator past the edges of a mirror (*2*), the mirror coupler (*3*) directs a part of the output beam to a system intended for the injection beam formation (*6*); the beam is processed in the system (*6*), where it is modulated in power and acquires the requisite phase distribution, and is returned to the resonator with the aid of the same mirror. The above configuration was realised in a gas-dynamic $CO_2$ laser with the following parameters: the length of the active medium $L_a = 1.2$ m, the unsaturated gain $g_0 = 0.6\ \mathrm{m}^{-1}$, the time it takes the active medium to transit the resonator $\tau = 0.92 \times 10^{-4}$ s, the relaxation time $\tau_r = 2.76 \times 10^{-4}$ s, the total round-trip time in the resonator $\tau_c = 4.2 \times 10^{-9}$ s, the luminescence lifetime $\tau_{lum} = 5$ s, the resonator magnification factor $M = 1.45$, and the diameter of output laser aperture $a = 0.08$ m.

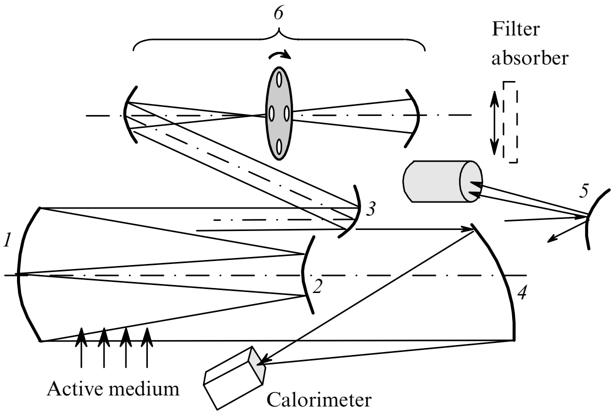

**Figure 1.** Scheme of the experimental setup: (*1, 2*) mirrors of the unstable resonator; (*3*) mirror coupler; (*4*) rotatory mirror; (*5*) deflecting mirror; (*6*) system for the formation of an injected beam.

The laser resonator is made of two spherical mirrors with rectangular apertures, which provided a geometrical amplification factor of 1.45. The active medium travels across the optical resonator axis. All theoretical and experimental data are given below for a laser with the above parameters.

## 3. Theoretical laser model and results of numerical analysis

For the initial theoretical treatment of lasing in a gas-dynamic laser with an unstable resonator and transmittance modulation, we will use the modified system of balance equations [7]. In the derivation of equations, the gain of the active medium was spatially averaged over the lasing volume. The gain was assumed to uniformly saturate, decreasing from its peak value (at the point of entry of the active medium into the resonator) to some minimal nonzero value (at the exit from the resonator) with the lateral coordinate. The resultant equations are written in the form coinciding with the form of equations in the case of quasistationary lasing mode:

$$\begin{aligned} \frac{\mathrm{d}K}{\mathrm{d}t} &= \frac{2K}{\tau}\ln\frac{K_0}{K} - \frac{K[1 + I + (\tau_r/\tau_{lum})K)]}{\tau_r}, \\ \frac{\mathrm{d}I}{\mathrm{d}t} &= \frac{I}{\tau_c}(K - \delta) + \eta\frac{\tau_r}{\tau_{lum}\tau_c}K, \end{aligned} \qquad (1)$$

where $K_0 = 2L_a g_0$ is the averaged unsaturated gain–length product calculated in tracing around the resonator; $K = 2L_a g$ is the averaged saturated gain–length product in tracing around the resonator; $I = J/J_s$; $J$ is the volume-averaged intensity; $J_s$ is the saturation intensity; $t$ is the current time; $\delta = \delta_0(1 + \Delta(\nu))$ are the losses per round trip; $\delta_0 = -\ln(|\gamma^2|)$; $\Delta(\nu)$ is the modulating function; $\nu$ is the modulation frequency; and $\eta$ is the fraction of spontaneous radiation power that remains inside the resonator after tracing around the resonator.

The first of Eqns (1) is the equation of vibrational kinetics [8] of a preexcited one-component (the lower working levels is not populated) active medium of a gas-dynamic $CO_2$ laser. The second equation describes the formation of radiation in the propagation through the resonator. The characteristics of active medium and radiation are averaged over the volume, and that is why the equations do not contain directional derivatives and depend only on time.

To determine the conditions ensuring the repetitively pulsed operating regime, the system of equations (1) was considered in the perturbation-theory approximation relative to the small parameters

$$\frac{\Delta I}{I_s}, \quad \frac{\Delta K}{\delta_0}, \quad \frac{\Delta\delta}{\delta_0},$$

where $\Delta I$ is the amplitude of the deviation of output radiation intensity from the stationary value; $I_s = 2(\tau_r/\tau) \times \ln(K_0/\delta_0) - 1$ is the normalised output radiation intensity for the stationary lasing; $\Delta K$ is amplitude of the deviation of the gain–length product from the stationary value; $\Delta\delta$ is the transparency modulation amplitude; $\delta = \delta_0 + \Delta\delta\cos\omega t$; and $\omega$ is the circular frequency. The last-named quantity is related to the above-introduced modulation frequency $\nu$ in the usual way: $\omega = 2\pi\nu$.

In this approximation,

$$\frac{\Delta I}{\Delta I_s} = \left(\frac{\omega_{res}\tau}{2}\right)^2 \left\{\frac{(\omega\tau/2)^2 + 1}{(\omega\tau/2)^2 + [(\omega\tau/2)^2 - (\omega_{res}\tau/2)^2]^2}\right\}^{1/2}, \quad (2)$$

$$\frac{\Delta I}{I_s} = \frac{\Delta\delta\tau}{\tau_c}\left\{\frac{(\omega\tau/2)^2 + 1}{(\omega\tau/2)^2 + [(\omega\tau/2)^2 - (\omega_{res}\tau/2)^2]^2}\right\}^{1/2}, \quad (3)$$

where $\Delta I_s = (\Delta\delta/\delta_0)(\tau_r/\tau)$ are the quasi-stationary intensity fluctuations (for $\omega \to 0$), and $\omega_{res} \approx (I_s\delta_0/\tau_c\tau_r)^{1/2}$ is the resonance circular frequency.

The transition to the repetitively pulsed regime necessitates the fulfilment of two conditions: (i) the transmittance fluctuations should be fast enough, because otherwise the output radiation power will vary in the quasi-stationary manner; (ii) the value of $\Delta I$ should be large enough for the radiation intensity to be modulated to a near-zero value.

The former condition is satisfied for $\nu \geqslant 2/\tau$ and the second for

$$\frac{\Delta I}{I_s} \geqslant 1 \to \Delta\delta \geqslant \frac{\tau_c}{\tau}\left\{\frac{(\omega\tau)^2 + [(\omega\tau)^2 - (\omega_{res}\tau)^2]^2}{(\omega\tau)^2 + 1}\right\}^{1/2}.$$

For the laser investigated, $\nu_{res} \approx 100$ kHz, and the repetitively pulsed regime is realised for $\nu > 20$ kHz, $\Delta\delta/\delta_0 > 0.02$.

The resonance field can be represented as a superposition of two waves – the ordinary divergent wave and the convergent one, which transforms to a divergent wave in the incoherent summation in the paraxial resonator region. The transparency $\delta$ of the resonator with laser-radiation self-injection, taking into account the diffraction transformation of the convergent wave to the divergent wave in the paraxial resonator region, is defined by the relationships

$$\delta = 1 - |\gamma^2|, \quad |\gamma^2| = \frac{1}{M^2} + \frac{s}{|\gamma^{4N}|}, \quad (4)$$

where

$$N \simeq \ln\left[\frac{a^2}{\lambda L_r}\left(1 - \frac{1}{M}\right) + 1\right]\Big/ 2\ln M$$

is the number of transits required of the beam injected into the resonator to find itself in the region of paraxial diffraction transformation; $s = S/\pi a^2$ is the relative injection beam area; $S$ is the injection beam area; and $\lambda$ is the radiation wavelength.

Fig. 2 shows the calculated resonator transmittance against beam fraction returned to the resonator. One can see that the modulation amplitude of resonator losses amounts to 30 % – 50 % of the losses of the basis resonator (without self-injection) when the power of the beam returned to the resonator is about 5 % of the output beam power. This loss modulation amplitude is sufficient to ensure the repetitively pulsed operating regime.

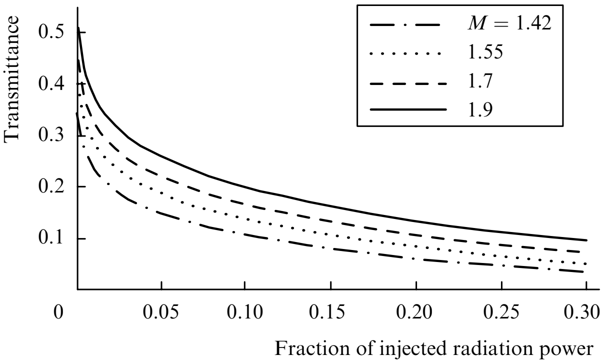

**Figure 2.** Dependence of laser resonator transmittance on the fraction of radiation power injected into the resonator for different values of resonator magnification factor $M$.

To derive qualitative estimates of laser operating modes with self-injection, we considered the energy and time characteristics of the laser with the parameters specified above. The system of equations (2) was numerically investigated employing the Runge–Kutta method. Fig. 3 gives the time dependences of the output power for several values of the modulation frequency and depth; the geometrical resonator amplification factor is $M = 1.45$. The calculated data are in qualitative agreement with the notions of the dynamics of quantum processes occurring in lasers [8].

Numerical calculations indicate that the pulses of output radiation power reproduce the modulation pulses in shape and duration for modulation frequencies up to 20–25 kHz (Fig. 3a). When the transmittance modulation depth is raised above the critical value, within the modulation pulse length there emerge separate power peaks, whose total number (4–8) is close to the resonance-to-modulation frequency ratio. Their modulation depth amounts to 100 % (Fig. 3b). For modulation frequencies $2/\tau < \nu < \nu_{res}$, the laser goes over to a mode close to the $Q$-switching mode (Fig. 3c). In this case, there occurs not only an increase in the modulation depth of output radiation power, but a change in the characteristic pulse structure – the envelopes of individual pulses and their internal peak structure become more regular. The peak intensity in this mode exceeds the stationary intensity by more than a factor of 10. In the $CO_2$ laser case, the duration of an individual peak of the structure is comparable with the pulse duration of a free-running pulsed $CO_2$ laser (hundreds of nanoseconds).

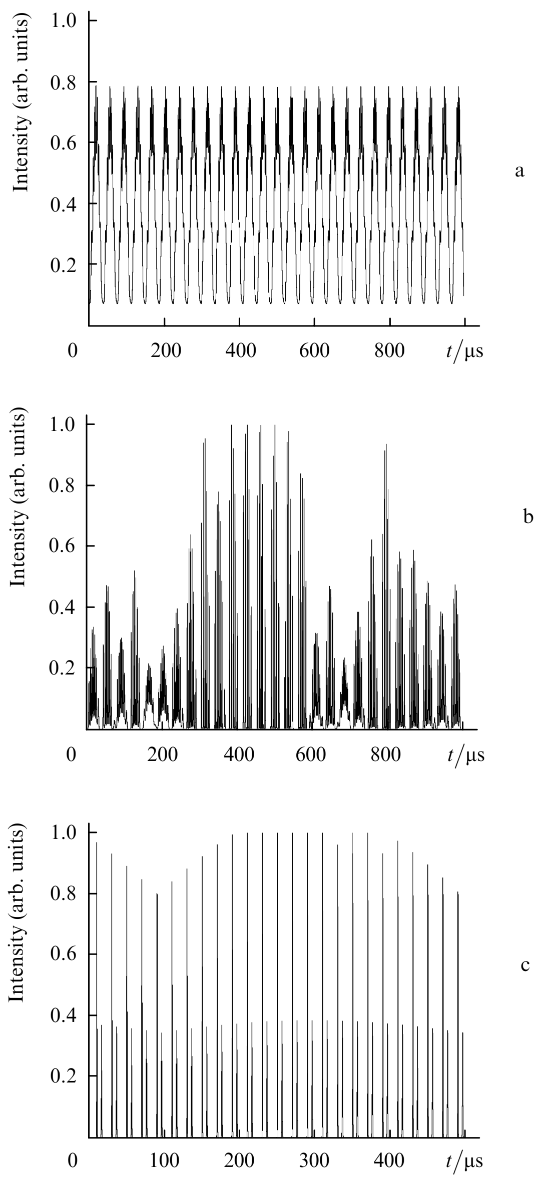

**Figure 3.** Temporal structures of output laser radiation for a modulation depth of 5 % and a modulation frequency of 27 kHz (a), 5.8 % and 27 kHz (b), and 5 % and 50 kHz (c); $M = 1.45$.

Therefore, when the modulation frequency is lower than $\nu_{\rm res}$, the lasing exhibits two characteristics oscillation constituents – the low-frequency oscillation, defined by the modulation frequency, and the high-frequency oscillation, defined by the eigenmodes of the resonator – active medium system, whose frequency is close to $\nu_{\rm res}$. When the modulation frequency is made greater than $\nu_{\rm res}$, the forced oscillations manifest themselves in the form of the high-frequency component, while the slow oscillations are the natural oscillations of the system at the resonance frequency. The results of numerical calculations are indicative of the feasibility of the repetitively pulsed regime in wide-aperture lasers described by the model (1).

## 4. Experimental results

The results of numerical calculations were experimentally verified on a test-bench $CO_2$ gas-dynamic laser whose parameters were given in the foregoing. For a fuel, use was made of carbon monoxide (CO), with air as the oxidiser. The typical output power was equal to 50 kW. To preclude the damage to optical elements of the laser, the output power was lowered by lowering the flow rate of the working components. When the laser was operated in the cw mode, the output power was equal to about 10 kW. Since the elements of the test-bench structure were not cooled, the duration of runs was limited by the heat capacity of resonator elements and combustion chamber and was equal to 3 s, the nominal power settling time was 0.3 s from the onset of mixture combustion.

The optical configuration of the experimental setup was similar to that diagrammed in Fig. 1. A part of the output laser radiation (about 20 %) was diverted by an inclined metallic mirror to the injection beam formation system consisting of two spherical mirrors with conjugate focal planes. In the vicinity of the focal plane there formed the waist of the branched part of the laser beam, and a modulator was placed near the waist. The modulator location was so selected that the laser beam completely filled the aperture of every round hole in the modulator disk. The modulator was a rotating metal disk with openings along its perimeter. In experiments, use was made of disks with 150 and 200 drilled holes with respective diameters of 4 and 2 mm and a filling factor (the ratio between the open state duration and the total period) of 1 : 2. The maximal modulation frequency was equal to 33 kHz.

A VIGO SYSTEM PD-10.6-3 photodetector was used as a radiation detector of the measuring system. The detector enabled measuring both the temporal structure of the signal and its constant component. Because the output beam is characterised by a high power density, which is many times higher than the optical breakdown threshold and upper bound of dynamic range of the detector, the radiation was attenuated employing the geometrical factor [a convex deflecting mirror (*5*)] and optical attenuation filters. The signal generated by the photodetector entered a preamplifier. After the preamplifier and a cable line, the signal was recorded by a broadband digital storage Tektronix THS710 oscilloscope. The transmission band of the path was limited primarily by the preamplifier and was equal to $\sim$ 50 MHz.

The average output power was measured with a calorimeter cooled by running water. A mirror 4 focused the radiation onto the calorimeter. In the cw mode, the constant-level signal was recorded with a noise component, which did not exceed 5 % of the constant signal level. The oscilloscope traces of laser output in the case of radiation modulation are depicted in Fig. 4. For a modulation frequency of about 27 kHz and a modulation depth of 2 % – 3 %, the quasi-stationary modulation regime is realised (Fig. 4a). In this case, the laser radiation exhibits intensity fluctuations consistent with the modulating signal, with the output power departing from the average value by a factor of three. This regime agrees well with the operating regime shown in Fig. 3a. When the modulation depth was increased to 7% – 8%, the laser passed to the repetitively pulsed operating regime (Fig. 4b). In this case, lasing took place in the form of a train of 5 – 10 pulses within one cycle of the open modulator state. The duration of an individual pulse was about 200 ns. We emphasise that the recorded pulse duration was limited by the measuring path bandwidth, which was equal, as noted above, to 50 MHz. The amplitudes of individual pulses exceeded the average value by factors of 6.5 – 11. This regime agrees well with the

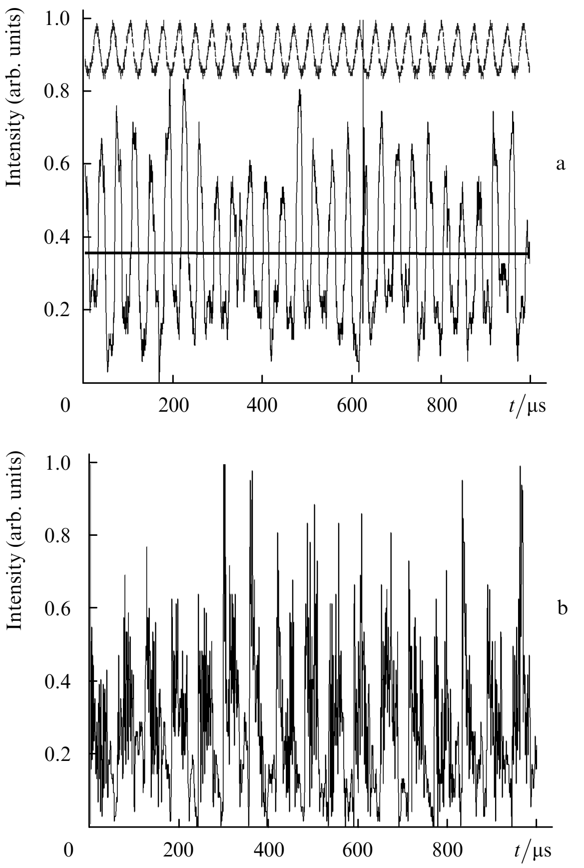

**Figure 4.** Temporal structures of laser radiation for a modulation depth of $\sim 3$ % and a modulation frequency of $\sim 27$ kHz (top – modulating signal, bottom – output laser signal) (a) and for a modulation depth of $\sim 7$ % and a modulation frequency of $\sim 25$ kHz (b).

regime calculated by expressions (1) and presented in Fig. 3b. Note that the average output power in the repetitively pulsed regime was equal to the output power in the cw laser operating mode.

The technical characteristics of the modulator in use (the maximal modulation frequency was 33 kHz) did not permit realising the high-frequency modulation modes presented in Fig. 3c. Good agreement between the experimental and theoretical data for frequencies ranging up to 25–30 kHz testifies to the adequacy of the proposed model and the possibility of employing this method at higher frequencies to convert a cw laser to the operating mode similar to the *Q*-switching mode.

## 5. Conclusions

We have demonstrated, both theoretically and experimentally, the feasibility of converting a high-power wide-aperture $CO_2$ laser to the repetitively pulsed lasing regime by self-injecting the modulated fraction of output radiation without decreasing the output power compared to the stationary lasing. In this case, the peak output power can exceed the average output power by more than an order of magnitude. Repetitively pulsed modulation with a pulse length of 200 ns to 1 μs, a peak output power greater than 100 kW, and an average output power coinciding with the power of stationary lasing (10 kW) were experimentally obtained. The applicability of the proposed method of laser conversion to the repetitively pulsed lasing regime is limited only by the threshold of optical breakdown on the modulator aperture, which is attained for an average output power of the order of 100 kW in the laser configuration investigated.

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