High Repetition Rate High-Power Wide-Aperture Lasers

14.1 Introduction

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.

In our days, interest is increasing in high-power lasers (up to 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

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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, laser investigated in [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 tull-aperture modulator. The approach proposed in [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 [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 repetitively 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.

14.2 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 selt-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 [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 [5].

The schematic of the setup which realises the repetitively pulsed radiation self-injection is shown in Fig. 14.1. 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

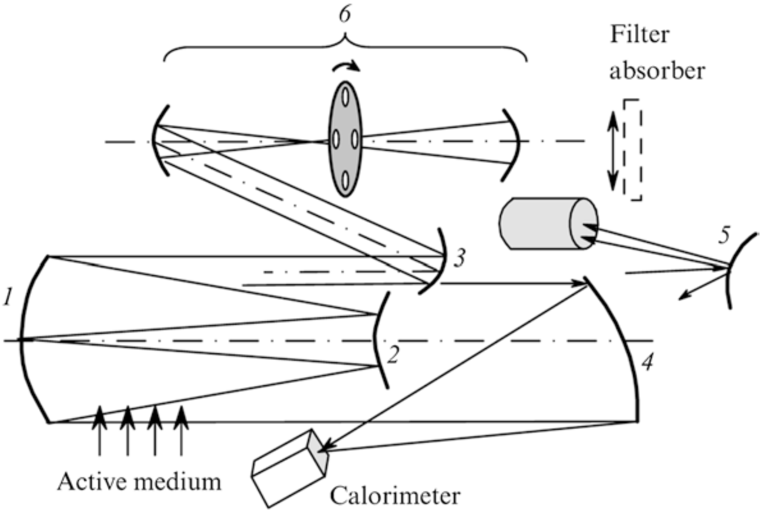


Fig. 14.1 Scheme of the experimental setup: *1, 2* mirrors of the unstable resonator; *3* mirror coupler; *4* rotatory mirror; *5* deflecting mirror; *6* system for the formation of an injected beam

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 $\tau_{\text{lum}} = 5$ s, the resonator magnification factor $M = 1.45$, and the diameter of output laser aperture $a = 0.08$ m.

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. Such a temporal structure of radiation in the case of quazicontinuous mode of operation for pulsed lasers has a name—“rough pulse”.

14.3 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:

$$\begin{aligned} \frac{dK}{dt} &= \frac{2K}{\tau} \ln \frac{K_0}{K} - \frac{K[1 + I + (\tau_r/\tau_{\text{lum}})K]}{\tau_r}, \\ \frac{dI}{dt} &= \frac{I}{\tau_c}(K - \delta) + \eta \frac{\tau_r}{\tau_{\text{lum}}\tau_c} K, \end{aligned} \tag{14.1}$$

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; ν is the modulation frequency; and η is the fraction of spontaneous radiation power that remains inside the resonator after tracing around the resonator.

The first of (14.1) 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 equation (14.1) 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 ΔI 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; ΔK 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 ω is the circular frequency. The last-named quantity is related to the above-introduced modulation frequency ν in the usual way: $\omega = 2\pi\nu$.

In this approximation,

$$\frac{\Delta I}{\Delta I_s} = \left(\frac{\omega_{\text{res}}\tau}{2}\right)^2 \left\{\frac{(\omega\tau/2)^2 + 1}{(\omega\tau/2)^2 + [(\omega\tau/2)^2 - (\omega_{\text{res}}\tau/2)^2]^2}\right\}^{1/2}, \tag{14.2}$$

$$\frac{\Delta I}{\Delta I_s} = \frac{\Delta\delta\tau}{\tau_c} \left\{\frac{(\omega\tau/2)^2 + 1}{(\omega\tau/2)^2 + [(\omega\tau/2)^2 - (\omega_{\text{res}}\tau/2)^2]^2}\right\}^{1/2}, \tag{14.3}$$

where $\Delta I_s = (\Delta\delta/\delta_0)(\tau_r/\tau)$ are the quasi-stationary intensity fluctuations (for $\omega \to 0$), and $\omega_{\text{res}} \approx (\mathrm{I}_s\delta_0/\tau_c\tau_r)^{1/2}$ 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 ΔI should be large enough for the radiation intensity to be modulated to a near-zero value.

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

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

For the laser investigated, $\nu_{\text{res}} \approx 100$ 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 super-position 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 δ 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 relation-ships

$$\delta = 1 - |\gamma^2|, \quad |\gamma^2| = \frac{1}{M^2} + \frac{s}{|\gamma^{4N}|}, \tag{14.4}$$

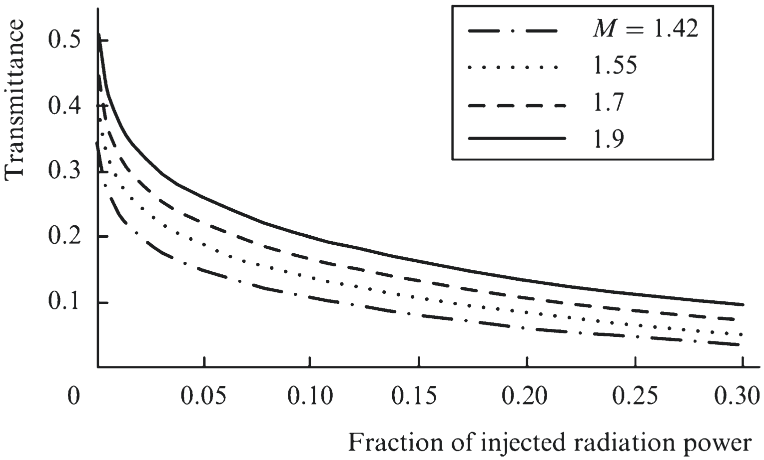


Fig. 14.2 Dependence of laser resonator transmittance on the fraction of radiation power injected into the resonator for different values of resonator magnification factor *M*

where

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

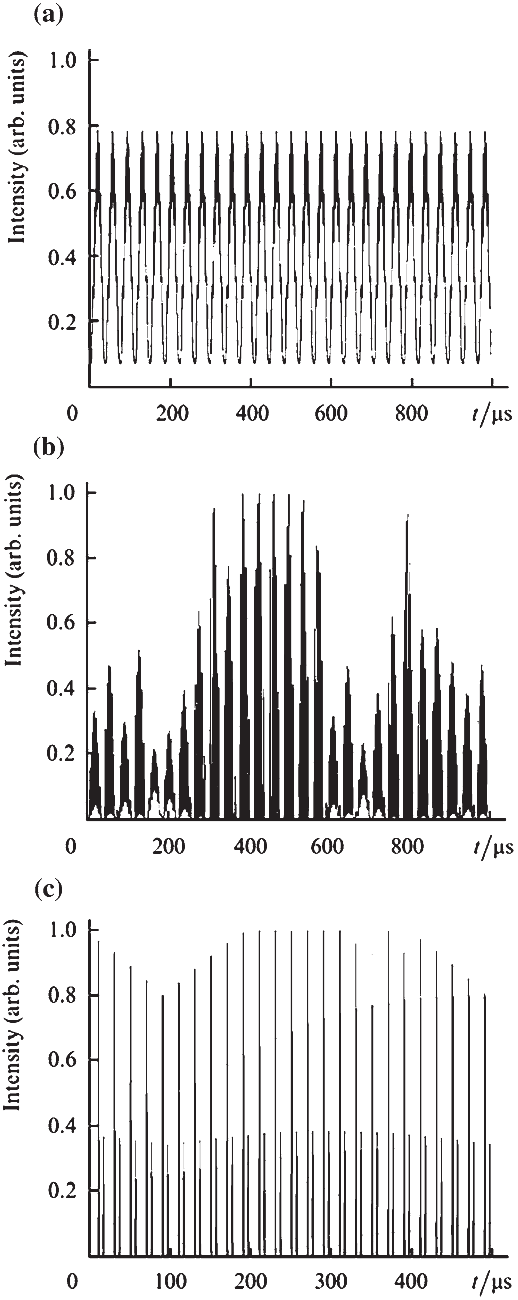
is the number of transits required of the beam injected into the resonator to find itself in the region of paraxial diffraction transformation; $s = S/\pi a^2$ is the relative injection beam area; S is the injection beam area; and λ is the radiation wavelength.

Figure 14.2 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.

To derive qualitative estimates of laser operating modes with sdt-injection, we considered the energy and time characteristics of the laser with the parameters specified above. The system of (14.2) was numerically investigated employing the Runge–Kutta method. Figure 14.3 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. 14.3a). When the transmittance modulation depth is rased above

Fig. 14.3 Rough train 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**); $M = 1.45$



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. 14.3b). For modulation frequencies $2/\tau < \nu < \nu_{\text{res}}$, the laser goes over to a mode close to the Q-switching mode (Fig. 14.3c). 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 in tern til 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).

Therefore, when the modulation frequency is lower than ν_{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 ν_{res}. When the modulation frequency is made greater than ν_{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 arc indicative of the feasibility of the repetitively pulsed regime in wide-aperture lasers described by the model (1).

14.4 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 dements of the test-bench structure were not cooled, the duration of rims 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. 14.1. 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 шar 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 dong 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

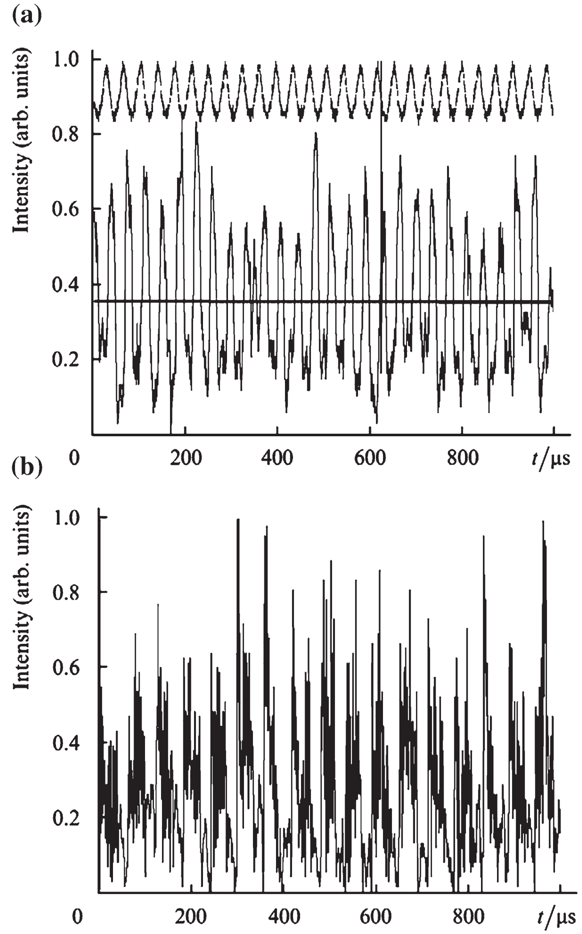


Fig. 14.4 Rough train temporal structures of laser radiation for a modulation depth of ~3 % and a modulation frequency of ~27 kHz (*top* modulating signal, *bottom* output laser signal) (**a**) and for a modulation depth of 7 % and a modulation frequency of ~25 kHz (**b**)

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 fa 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 ~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

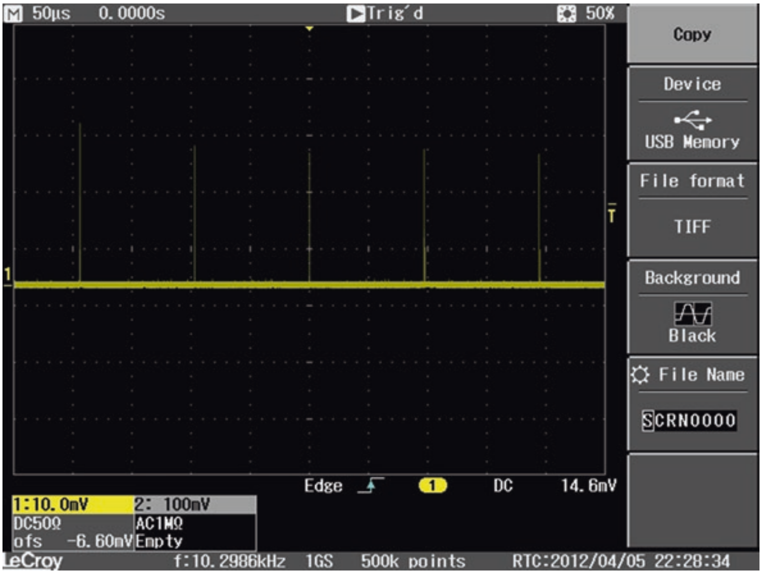


Fig. 14.5 P–P mode of operation for high power Nd YAG laser

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. 14.4. For a modulation frequency of about 27 kHz and a modulation depth of 2–3 %, the quasi-stationary modulation regime is realised (Fig. 14.4a). 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. 14.3a. When the modulation depth was increased to 7–8 %, the laser passed to the repetitively pulsed operating regime (Fig. 14.4b). 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 band-width, 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 regime calculated by expressions (14.1) and presented in Fig. 14.3b. 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. 14.3c. 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 operation to the operating mode with regular pulses structure. Round trip time of the resonator geometry and P–P regime frequency of pulses matching should be taken into account. The efficient method of regular structure for P–P operating regime for CO_2 and LD pumped Nd YAG lasers has been realized. The studies of the power and temporal characteristics of the laser radiation show that the developed lasers have a very high efficiency of energy extraction close to that of a CW laser mode of operation. The pulse power to average power ratio of more than two orders of magnitude after transformation of CW into P–P mode of operation had been demonstrated. The prospects of efficient and compact P–P/CW laser systems is open (Fig. 14.5).

14.5 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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Chapter 16
Pulse-Periodic Lasers for Space Debris Elimination

16.1 High Repetition Rate P–P Mode of Laser Operation

For the lasers with a high average output power (GDL, HF/DF, COIL, Nd YAG) is very common to use an unstable resonator configurations having a large cross section of the active medium. In the resonators of this type, externally injected low-power beam may exert a significant effect on the characteristics of output radiation.

One way to realize the radiation control regime is the self-injection regime of radiation, extracted from the resonator and returned back to resonator as a part of radiation after changing its spatial-temporal characteristics [1, 2]. 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. However, analysis showed that the power of the beam injected into the paraxial beam region should be about the same value or comparable with the output laser power to efficiently control the resonator of a continuously pumped laser, unlike pure pulsed systems with regenerative amplification.

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.

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 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 wave front

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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.

P–P mode of operation was realized in two type of lasers theoretically and experimentally, in a gas-dynamic CO_2 and Nd YAG lasers [3]. CO_2—laser had the following parameters: the length of the active medium $L_a = 1.2$ m, the unsaturated gain coefficient $g_0 = 0.6\ \mathrm{m}^{-1}$, 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 go-round resonator time $\tau_{rt} = 4.2 \times 10^{-9}$ s, the luminescence lifetime $\tau_{\mathrm{lum}} = 5$ s, the resonator magnification factor $M = 1.45$, the diameter of output laser aperture $a = 0.08$ m. Nd YAG—laser was above of 1 kW level, with two heads geometry.

The CO_2-laser resonator is made up 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. In what follows all theoretical and experimental data are given for a laser with the above parameters.

A part of the output laser radiation 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 the modulator. The maximal modulation frequency in our experiments has reached 50 kHz.

A mirror 4 focused the radiation onto the calorimeter. The duration of an individual pulse was about 100–150 ns. We emphasize that the recorded pulse duration was limited by the measuring path bandwidth equal, as noted above, to 50 MHz. The amplitudes of individual pulses exceeded the average value of output power by factor -10. The average output power was measured with a calorimeter cooled by running water. It is noteworthy that the average output power in the pulse-periodic mode was equal to the output power in the CW laser-operating mode. Good agreement between the experimental and theoretical data for frequencies ranging up to 25–50 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.

HF/DF-laser and COIL are waiting for the experimental efforts to be applied. Theoretically P–P modes of regenerative amplification for high power lasers have been investigated and modeled by computer. The output parameters are very much dependable on parameters of media, way of pumping and resonator geometry. The summary of the radiation temporal structure is presented:

COIL	P–P mode starts at frequencies >20 kHz
	Depth of modulation—100 % at frequencies >100 kHz
	Pulse duration <250 ns. Ratio P peak./P aver. = 100–1,000
HF/DF	P–P mode starts at frequencies >100 kHz
	Depth of modulation—100 % at frequencies >250 kHz
	Pulse duration <100 ns. Ratio P peak./P aver. = 100–10,000
Nd YAG	P–P mode starts at frequencies >4 kHz
	Depth of modulation—100 % at frequencies >40 kHz
	Pulse duration <250 ns. Ratio P peak./P aver. = 100–1,000
CO	P–P mode starts at frequencies >10 kHz
	Depth of modulation—100 % at frequencies >100 kHz
	Pulse duration <250 ns. Ratio P peak./P aver. = 100–1,000

16.2 New Application for Space

Last years the increasing of attention has been given to the study of possibility of lasers use for cleaning of the space from elements of space debris (ESD) which have collected within more than four decades of operation of space and create in some cases the big threat for space vehicles (SV). By expert estimations in the space by 1996 was about 3.5 million not traced ESD in the size less than 1 cm, more than 100,000 splinters in the size in a diameter from 1 to 10 cm, the size nearby 8,000 ESD exceed 10 cm [4–6]. Large ESD with a diameter more than 10 cm are found out by modern watch facilities and are brought in special catalogues. The most effective method of protection from such ESD is maneuvering of SV. By estimations of experts splinters in diameter less than 1 cm do not represent special danger for existing SV because of presence of passive constructional protection though it considerably makes SV much more heavier. The most unpleasant diameter of splinters is 1 … 10 cm when the necessary degree of passive protection does not manage to be carried out because of its unacceptably big weight, and to avoid collision at the expense of maneuvering SV it is impossible, as on the radar screen such splinters are not visible.

In low orbits under the influence of atmosphere quickly enough there is their self-clearing as time of life ESD in orbits with height about 200 km averages about 1 week. In higher orbits in height their self-cleaning can occupy of 600 km 25–30 years, and at heights about 1,000 km—2,000 years [5]. The estimations executed in work [6], have shown that the probability of collision SV in diameter of 10 m within 1 year of its operation makes 0.45×10^{-2} for ESD with a size 2 … 4 cm and 0.4 for ESD with a size <0.4 cm, and frequency of collisions with the catalogued objects (≥ 10 cm) is at level of one collision for 30 years. And every year number ESD regularly increases. From here the reality of threat of collision with ESD for all period of operation SV is clear.

Thus withdrawal ESD from an orbit protected SV is rather actual problem. For this purpose it is necessary to reduce speed of its movement. As it will be shown further, it is possible to reach at the expense of pulse irradiation ESD and reception on its surface of the plasma creating an impulse of return. Such impulse arising in a mode of laser ablation of ESD material, should reduce height of orbit ESD so that it has flown by SV or, finally, would enter into dense layers of atmosphere and has burnt down.

In a number of works earlier it was offered to use the Nd YAG ground based laser installations for space clearing, but such laser has the essential lacks connected with necessity of passage of 1 mkm radiation of the big capacity through atmosphere that can lead to loss of optical quality of a bunch of radiation and occurrence of nonlinear effects. They have small mobility, therefore number ESD which it is possible to influence on by their radiation, will be limited. At influence of laser on ESD from the Earth surface the return impulse will be directed upwards and the apogee of orbit ESD will be increased, but the perigee is going to be decreased and stopped by dense atmosphere. And the most important thing—requirements to power of the land based laser should be increased in comparison with the space laser as the distance from a terrestrial surface to ESD is much more. For these reasons for the most expedient arrangement of Nd YAG 100 kW laser installation directly in space is recommended. Thus it is desirable, that in such installation power consumption should be minimal. To this condition satisfies Nd YAG with LD pumping, capable to work independently in P–P mode of operation with very small expenses of power for the system service control. But for the case of the ground based laser we have suggested the DF-laser, which radiation propagation through the atmosphere is much more effective and the output power of existing systems (>1.5 MW) and technology are more advanced.

In the paper [5] the most possible variants of rapprochement ESD, flying, as a rule, on elliptic orbits, with various SV, moving on circular orbits at heights 200–700 km have been analyzed. Two variants when SV moves on a circular orbit at height of 400 km have appeared the worst, and ESD fly on elliptic orbits with height of apogee −2,000 and −4,000 km. In this case in a perigee there are areas where planes of orbits SV and ESD coincide, and speed of their rapprochement is maximum, and in this area vectors of speed SV and ESD lie along the same direction, i.e., by influence of the laser radiation it is impossible to give to ESD a lateral component of speed, as in more opportunity of an inclination of planes of orbits SV and ESD under the relation to each other.

The maximum speeds of rapprochement calculated for these two variants have made accordingly −395 and −2,463 m/s. For circular orbits with height 200, 400 and 700 km settlement of rapprochement ESD speeds, flying on circular orbits, with SV do not exceed 343 m/s, therefore these variants can be neglected.

Let's consider process of rapprochement ESD which is catching up SV, after influence on ESD of the laser radiation. Before the laser influence force of an attraction of the Earth and centrifugal force are equal:

$$\frac{m\upsilon_0^2}{R+H} = \gamma \frac{mM}{(R+H)^2},$$

where υ_0—speed of movement ESD on a trajectory before influence of a laser impulse, *R*—radius of the Earth, *H*—height ESD over the Earth, *M*—weight of the Earth, γ—a gravitational constant, *m*—weight ESD after such influence on ESD this balance will be broken; then the reduction of ESD speed $\Delta\upsilon$ will force the normal acceleration in the direction to the centre of the Earth:

$$a_{\mathrm{H}} = -\frac{\gamma M}{(R+H)^2} + \frac{(\upsilon_0 - \Delta\upsilon)^2}{R+H}$$

where $\Delta\upsilon$—change of ESD speed after laser pulse influence (typical value $\Delta\upsilon$ makes ~200 km/s [7]). After simple transformations from (1) we will receive

$$a_{\mathrm{H}} = \frac{-2 \cdot \upsilon_0 \cdot \Delta\upsilon + \Delta\upsilon^2}{R+H}.$$

Through the time—*t* the radius-vector of ESD orbit will be changed:

$$\Delta H = \frac{a_{\mathrm{H}} t^2}{2} = \frac{\Delta\upsilon \cdot (\Delta\upsilon - 2\upsilon_0)}{R+H} t^2$$

By knowing the initial distance—*L* from SV to ESD and a tangential component of rapprochements speed of ESD to SV after influence of a laser pulse:

$$t = \frac{\ell}{\upsilon_{\mathrm{T}}} = \frac{\ell}{\upsilon - \Delta\upsilon}$$

Then for change of size of a radius-vector of ESD orbit we will receive the following expression:

$$\Delta H = \frac{\Delta\upsilon \cdot (\Delta\upsilon - 2\Delta\upsilon_0)}{R+H} \frac{\ell^2}{(\upsilon - \Delta\upsilon)}$$

From here it is possible to find the distance between ESD and SV when it is necessary to start the influence on ESD by laser:

$$\ell = (\upsilon - \Delta\upsilon)\sqrt{\frac{\Delta H \cdot (R+H)}{\Delta\upsilon \cdot (\Delta\upsilon - 2\upsilon_0)}}$$

Proceeding of the SV dimensions, we will be set by size $\Delta H = 30$ m. Then for the first variant of rapprochement ESD to SV at V rapp = 395 m/s, $\Delta\upsilon = 200$ m/s, Vo = 8 km/s, $H = 400$ km, R ≈ 6,300 km the distance between will make 4.1 km. This way will be passed in time ~20 s. Then for metal ESD at typical values $C_{\mathrm{m}}^{0\Pi\mathrm{T}} = 4\,\mathrm{din} - \mathrm{s/J}$ and *S/m* = 0.15 sm2/g we will receive $\Delta\upsilon = 6$cm/s, and the necessary number of pulses for the value $\Delta\upsilon = 200\,\mathrm{m/s}$ will make 3,300 pulses at frequency of high repetition rate Nd YAG laser—3,000 Hz necessary time of influence 1.1 s, which is much less than time of rapprochement to SV found before (20 s). It shows that with the same laser it is possible to reject ESD from SV with rapprochements having much greater speed.

For more exact calculations at the big speeds of rapprochement it is necessary to consider dynamics of change of values $\Delta \upsilon$ and current distance between ESD and SV after influence of each laser pulse of P–P irradiation of ESD.

For the second variant with very great speed of rapprochement V rapp $= 2{,}463$ m/s at $\Delta \upsilon = 200\ \mathrm{m/s}$ and much bigger distance—20 km the rejection is possible as well. However, maintenance of $\Delta \upsilon$ at the distance—20 km will meet some changes of parameters due to the bigger size of the focal point on such a distance.

The problem of ESD withdrawal from SV orbit that ESD has flown by SV has been above considered. Other problem is important also—to create such impulse of return to achieve decrease ESD to an orbit in height of 200 km when at the expense of the further braking in atmosphere of particles of ESD will be burn down, and the space will be cleared from ESD. In other words, SV with laser installation will carry out onboard a role of "cleaner" of the most used orbits. That particle ESD has decreased to 200 km over the Earth surface, its speed needs to be reduced by certain value $\Delta \upsilon$ which will allow it to pass from a circular orbit on elliptic which exact value can be calculated as follows:

$$\Delta \upsilon = \mathrm{V}_{\mathrm{apogee}} - \mathrm{V}_{\mathrm{start}},$$

where Vapogee—ESD speed in apogee of a transitive elliptic orbit, V start—speed ESD in an initial circular orbit. Speed in apogee is:

$$\mathrm{V}_{\mathrm{apogee}} = \sqrt{\frac{2 \cdot \gamma \cdot M \cdot R_{start}}{r_{200} \cdot (r_{200} + R_{start})}},$$

where R 200—radius of a circular orbit in height of 200 km, R start—radius of an initial orbit. ESD speed in an initial circular orbit is defined as:

$$\mathrm{V}_{start} = \sqrt{\frac{\gamma \cdot M}{R_{start}}}.$$

On the basis of given by [5] data, the graphic dependence of demanded reduction of speed ESD in apogee of an elliptic orbit from height of an initial circular orbit has been constructed. The similar dependence has been resulted in the work [5] without explanations. It is clear that ESD, being in the orbit with height ~900 km, will decrease it to the height of 200 km if to reduce the speed by 200 m/s.

Change of ESD speed $\Delta \upsilon$ after the influence of laser radiation pulse with energy density E [J/cm^2] on ESD is defined from the following expression:

$$\Delta \upsilon = \mathrm{Cm\,E\,S/m};$$

where S—the interaction area, m—weight of ESD, Cm [din s/J]—proportionality factor between $\Delta \upsilon$ and E, depending on the ESD type. Characteristics of the most widespread of them are presented in the Table 16.1 [5]. Such ESD are formed as a result of SV explosions, or their collisions with ESD. Spheroids of Na and K are formed after destruction of reactors, splinters of phenol-carbon plastics and

Table 16.1 Cm(opt) and S/m for different ESD

	Type Of ESD				
	Na(K)	"C"-based materials	Organics-based materials	"Al"-based materials	"Fe"-based material
Angle (degre.)	65	87	99	30	82
Apogee (km)	930	1,190	1,020	800	1,500
Perigee (km)	870	610	725	520	820
S/m (cm^2/g)	1.75	0.7	2.5	0.37	0.15
size (cm)	1.0	1 × 5	0.05 × 30	1 × 5	1 × 10
Reflectivity	0.4	0.02	0.05/0.7	0.05/0.7	0.5
$C_m^{opt}\left(\frac{\text{Din s}}{\text{j}}\right)$	(6 ± 2)	(7.5 ± 2)	(5.5 ± 2)	(4 ± 1.5)	(4 ± 1.5)

Table 16.2 LEO /MEO ESD removal data for Nd YAG laser

λ	τ	D_b	W	f	<P>	d_s	Z	I
1.06 μm	10 ns	30 m	60 J	3,000 Hz	360 kW (0.5)	5.2 cm 2 Dif	300 km	3.0 J/cm^2

fragments of "plastics-aluminum" are the fragments of thermal protection; splinters of aluminum based materials can appear after explosion of tanks and covers of SV; steel bolts—fragments of connecting blocks armature.

High power high repetition rate P–P laser should generate a temporally, and spectrally effective pulse designed for high transmission through the atmosphere, as well as for efficient ablative coupling with the target.

The space based Nd YAG laser with output power less than 100 kW that we propose is the best tool for fast re-entering of the ESD to the dense layers of atmosphere.

The DF ground-based laser system that we have proposed is capable to get a rapid engagement of targets whose orbits cross over the site, with potential for kill on a single pass. Very little target mass is ablated per pulse so the potential to create additional hazardous orbiting debris is minimal.

The laser system would need to be coupled with a target pointing and tracking telescope with guide-star-like wave-front correction capability.

Table 16.2 presents the LEO /MEO ESD removal data for Nd YAG laser. ESD have a size 1–10 cm and fly below 300 km altitude. Cm = 4 dyn-s/J in average for polymer and "Al"—based materials response. Typical S/m data for ESD: NaK-1.75; Al-0.37; Fe-0.15 are taken from the Table 16.1. For I = 3.0 J/cm^2, S /g = 0.15 cm^2/g, we need N = 7,000 laser pulses for ESD re-entry. Nd YAG—laser operating at 3,000 Hz can re-enter small object from the gap 1–10 cm in 2.3 s. Such a level of average output power (360 kW) for CW/P–P Nd YAG lasers has not been demonstrated up to now. To get such effective results for clearing we need not the laser only but a 30 m in diameter telescope to deliver the laser pulses to a target at 300 km range or more with 10 ns time duration:

Table 16.3 presents the LEO /MEO ESD removal data for DF laser. ESD have the same size 1–10 cm and fly below 300 km altitude. Cm = 4 dyn-s/J in average

Table 16.3 LEO /MEO ESD removal data for DF laser

λ	τ	D_b	W	f	<P>	d_s	Z	1
3.8 μm	10 ns	30 m	0.150 J	10 kHz	1.5 MW	18 cm 2Dif	300 km	0.6 J/cm^2

for the same materials: polymer and aluminum. With I = 0.6 J/cm^2, t = 10 ns, S/g = 0.15 cm^2/g, we need N = 35,000 pulses for ESD re-entry. Ground based 1.5 MW DF—laser operating at 10 kHz can re-enter any small object from the same size gap in 3.5 s. This operation requires a 30 m in diameter telescope to deliver 2 J/cm^2 (Cm = 0.2 Cm opt) to a target at 300 km range with a 10 ns pulse at 3.8 mkm: Here is important to note that with 1 min delay for retargeting all objects of this height and below can be re-entered during—0.5 year only. It should be noted as well here that the level of output power for CW regime had been demonstrated and technology is mature enough. The realization of P–P mode of operation for this type of laser is the question of time. Motivation is completely available. New tasks for high repetition rate high power lasers generated during last few years are very much important [7–9] and definitely should be solved during upcoming years.

16.3 Conclusion

1. In the paper the questions of SV protection and of orbits clearing from dangerous ESD with diameter from 1 to 10 cm by means of high power high repetition rate P–P Nd YAG with average power 100 kW and DF-lasers with average power about 1.5 MW are considered;
2. Possibility of applying mentioned above installations not only for dangerous ESD withdrawal from SV orbit, but also for planned clearing of the most maintained orbits from these ESD when the given installations will carry out a role of "cleaner" of these orbits is analyzed. For this purpose under the influence of radiation it is necessary to translate ESD from a circular orbit to elliptic, which perigee is in the dense atmosphere beds where ESD should be burn down. As a result of the decision of a ballistic problem, dependence of necessary reduction of speed ESD from height of their orbit over the Earth is received. It is found that for orbits with heights up to ~300 km the demanded influence can be provided by 1.5 MW DF-laser installation with a telescope with diameter −30 m and duration of pulses about 10 ns;
3. It is shown that for the worst variant in case of influence on metal ESD with the greatest speed of their rapprochement with SV ~2.5 km/s angular divergence of radiation of space based 100 kW Nd YAG laser should be not worse than two diffraction limits at use of a telescope with diameter of main mirror $D = 1$ m is admissible.