High energy high repetition rate P-P lasers.

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Introduction

A technique for obtaining of the repetitively pulsed operating regime in high-power wide-aperture lasers is proposed and experimentally realized. In this regime, the laser emits a train of pulses with duration of 100–150 ns and a pulse repetition rate of several tens of kilohertz. The main properties of the pulsed regime are theoretically analyzed 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 a repetitively pulsed regime in high-power wide-aperture lasers realization without significant reduction in the average output power is experimentally demonstrated.

In our days, interest is increasing in high-power lasers (> 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 (10–100 kHz) pulsed regime with a short pulse duration (100–150 ns) 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 eliminate the plasma screening effect in the radiation-material interaction process, 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 of wavelength, 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 inter-cavity 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 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 tull-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 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 and Nd YAG lasers.

Substantiation of resonator design

In the long wavelength 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 affected 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 w*as 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 $Nf >> 1$ 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 wave front 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].

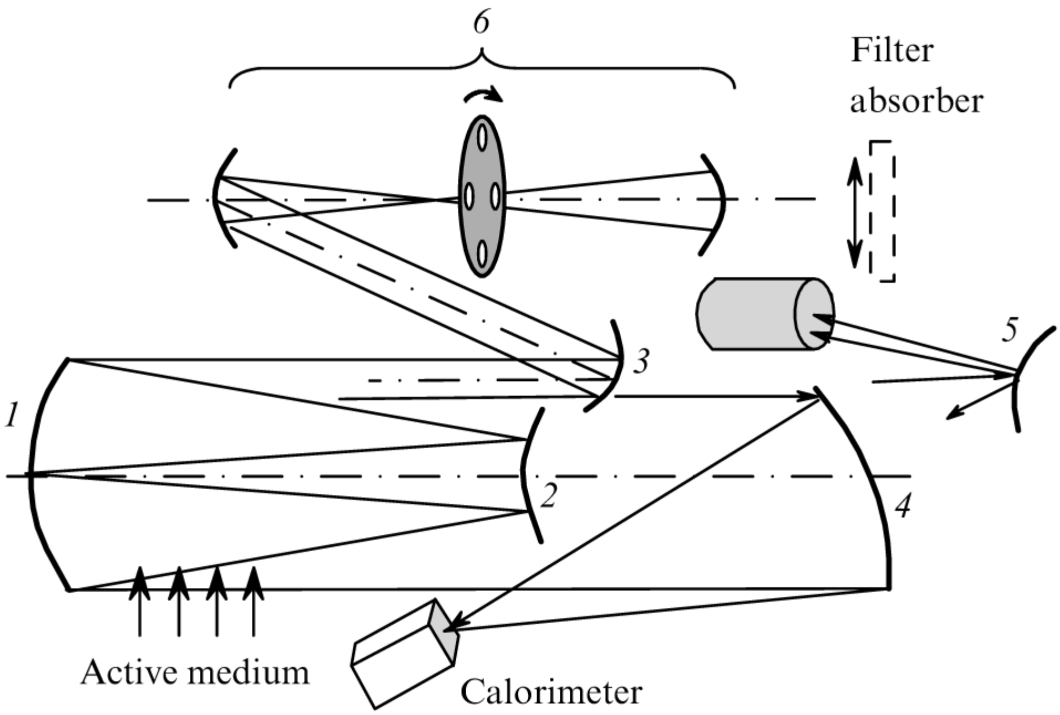

Figure 1. Scheme of the experimental setup: (*1, 2*) mirrors of the unstable resonator; (*3*) mirror coupler; (*4*) rotatory mirror; (*5*) deflecting mirror; (*6*) system for the formation of an injected beam.

The 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 m^{-l}, the time it takes the active medium to transit the resonator $\tau = 0.92\times10^{-4}$ s, the relaxation time $\tau_r = 2.76\times10^{-4}$ s, the total round-trip time in the resonator $\tau_c = 4.2\times10^{-9}$ 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 structure".

Theoretical laser model and results of numerical and experimental investigations

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:

$$\frac{dK}{dt} = \frac{2K}{\tau}\ln\frac{K_0}{K} - \frac{K[1 + I + (\tau_r/\tau_{\text{lum}})K]}{\tau_r},$$

$$\frac{dI}{dt} = \frac{I}{\tau_c}(K - \delta) + \eta\frac{\tau_r}{\tau_{\text{lum}}\tau_c}K, \qquad (1)$$

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; 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 equation (1) is the equation of vibrational kinetics [8] of a pre-excited 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

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

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,

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

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

where $\Delta I_s = (\Delta\delta/\delta_0)(\tau_r/\tau)$ are the quasi-stationary intensity fluctuations (for $\omega \to 0$), and $\omega_{\rm res} \approx (\mathrm{I}_s\delta_0/\tau_c\tau_r)^{1/2}$ 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 $\nu \ge 2/\tau$ and the second for

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

For the laser investigated, $\nu_{\rm res} \approx 100$ 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

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

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 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.

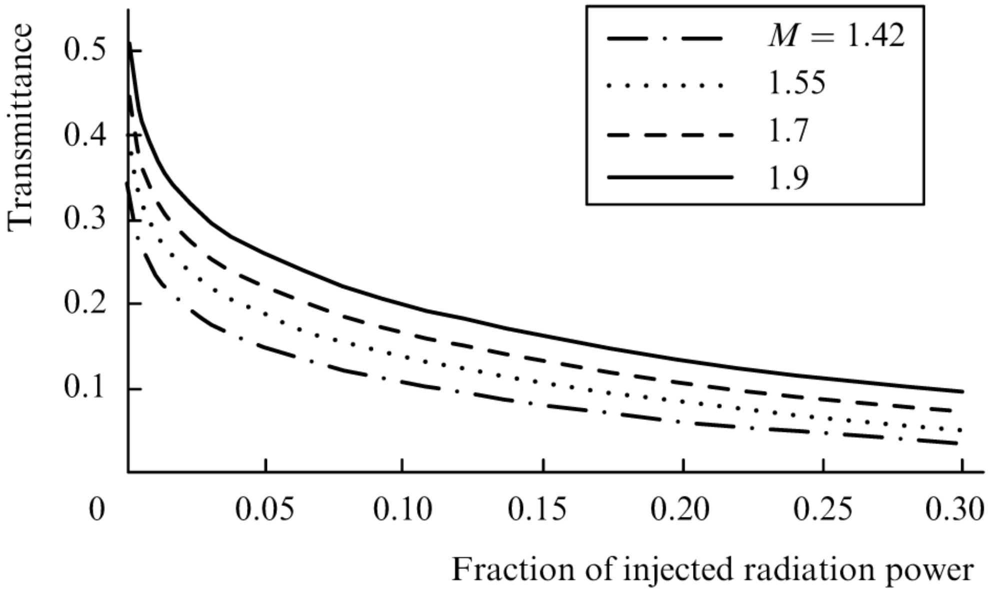

Figure 2. Dependence of laser resonator transmittance on the fraction of radiation power injected into the resonator for different values of resonator magnification factor *M*.

To derive qualitative estimates of laser operating modes with sdt-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. Figure 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].

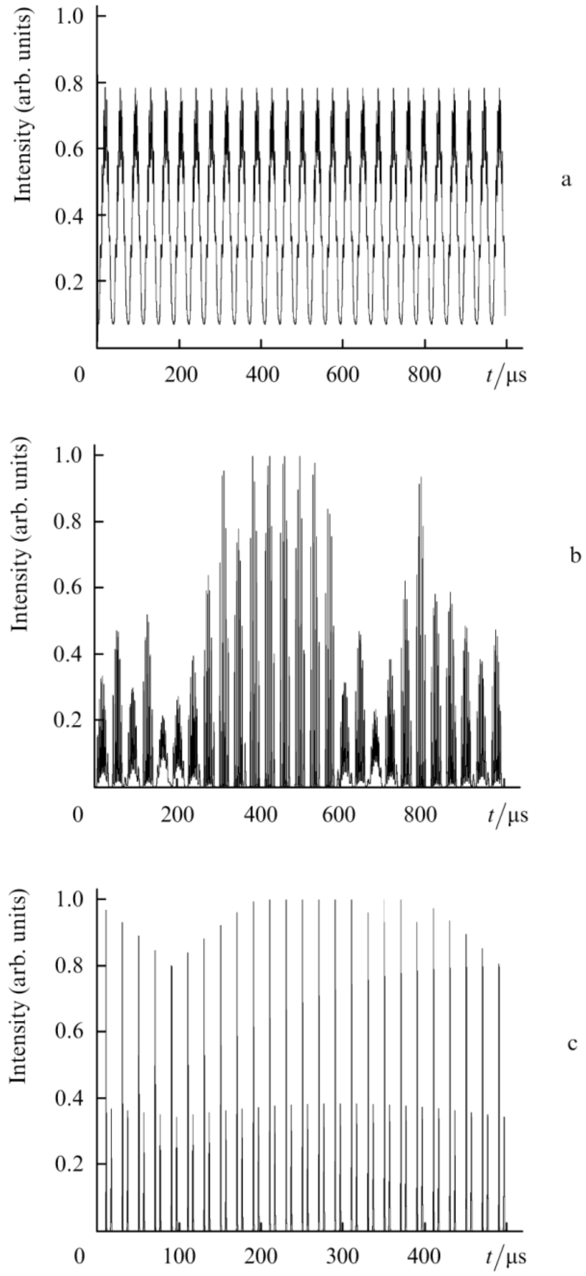

Figure 3. Rough pulse temporal structures of output laser radiation for a modulation depth of 5% and a modulation frequency of 27 kHz (a), 5.8% and 27 kHz (b), and 5% and 50 kHz (c); *M* = 1.45.

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 rased 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 $2/\tau < \nu < \nu_{\text{res}}$, 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 they're in tern till 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).

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. 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 dongs 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 fa convex deflecting mirror (5)] and optical attenuation filters. The signal generated by the photodetector entered a pre-am-pilfer. 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.

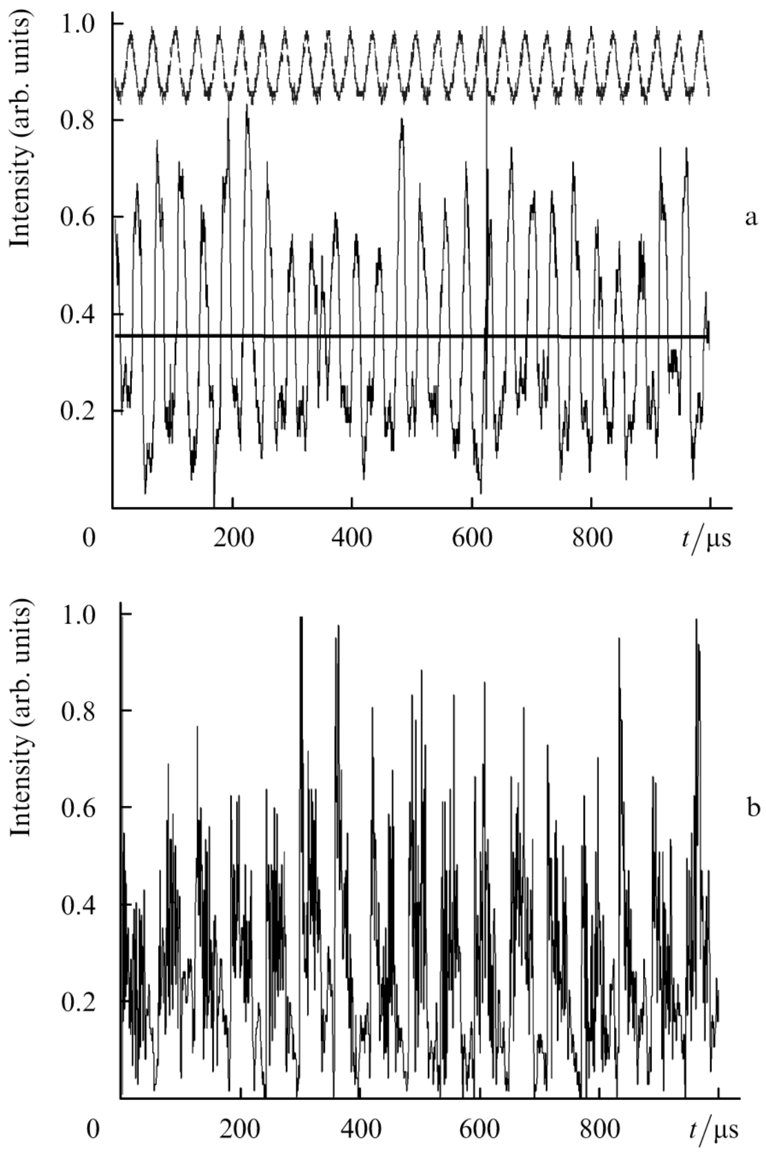

Figure 4. Rough pulse temporal structures of laser radiation for a modulation Depth-3% and A modulation frequency of-27KHZ (top-modulating Signal, Bottom-output laser signal) (a) and for a modulation depth of 7% and a modulation frequency of -25KHZ(b)

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 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

(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 the high-frequency modulation modes realization 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 operation to the operating mode with regular pulses structure. Round trip time of the resonator geometry and repetitively pulsed 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 [9-11]. 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 peak 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 are open.

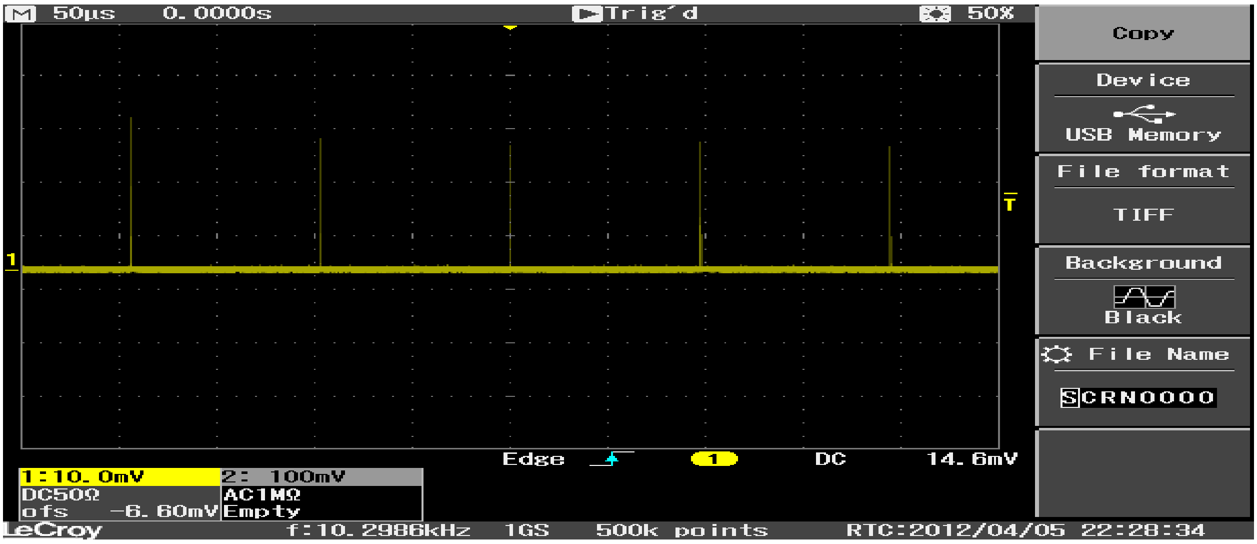

Figure 5. High repetition rate P-P mode of operation for high power Nd YAG laser.

Laws of Scaling of Disk Lasers

Well known that the power of disk lasers is limited not only by the power of the pump and overheating of the medium but also by the losses due to the ASE and the background radiation losses in the resonator. To avoid overheating, the size of the active medium should vary in accordance with the law of power scaling. Then, to avoid large losses caused by their exponential growth during the ASE, amplification of radiation corresponding to transverse round trips should not be large. This requires a reduction in gain G. Gain is determined by the reflectivity of the output mirror and disk thickness. Amplification of radiation per round trip, however, should not be substantially greater in magnitude than the radiation loss per round trip along the same optical path. The difference between the gain and losses per round trip of radiation determines the optical energy that is coupled out from the laser cavity. Reduction of the gain at this loss level requires an increase in the disk thickness. In this case, at a certain critical size, the disk becomes optically too thick and cannot be pumped above the threshold without overheating. Some features of scaling can be shown on a simple model. Suppose M is the saturation intensity of the medium. The corresponding optimal thickness of the disk can be estimated as h~T/Mb. The corresponding optimal lateral dimensions of the disk can be represented in the form: D~T/Mb2, where *T* is a parameter of the heat load. Roughly speaking, the loss per round trip of radiation must be scaled inversely proportional to the cube root of the power required: P~ n T2 / M b3.

An additional problem is the efficient delivery of pump energy. In cases with a small-signal gain, single-pass absorption of the pump is also low. It follows that the effective utilization of the pump energy is very necessary for the effective operation of the laser disk. To scale the output power, the medium must be optically thin, which requires a large number of passes of the pump energy through the medium. Besides, the pump energy coupled in through the lateral side of the disk can also be a possible solution for efficient pumping.

To reduce the effects of the ASE, it was proposed to use an optical cover consisting of an undoped material on the surface of the laser disk. This cover allows the spontaneously emitted photons to escape from the active layer and prevents their resonance in the bulk of active material. Rays cannot be reflected from the surface, as in the case of an open disk. This allows the maximum power achievable by the disk laser to be increased by an order of magnitude. Reflection of the ASE from the disk edge should also be suppressed. This can be done through the absorbing layer at the generatrix of the disk cylinder. In the regime when output power is close to maximal, much of the energy is used in the ASE; therefore, the absorbing layers must also have radiators accumulating heat. In the case of the maximum pump density of the disk laser its efficiency is quite low: Most of the pump power is used in the ASE and is absorbed at the edges of the device. In this case, the distribution of the pump energy between several disks can significantly improve the performance of the laser system. Indeed, lasers, consisting of several modules with disk elements in a single cavity, have been repeatedly reported. One of these lasers, fabricated by the TRUMPF Group [12] − a world leader in this class of laser systems − is presented at Fig. 6.

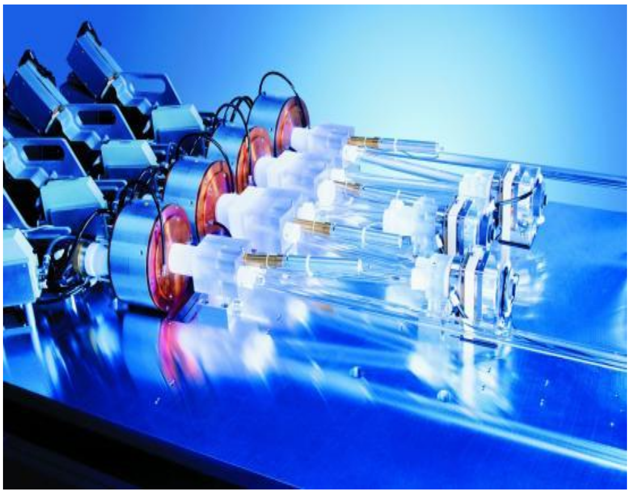

Figure 6. " Zig-Zag" disk Laser consisting of a series of disk modules in a single cavity (TRUMPF [5]).

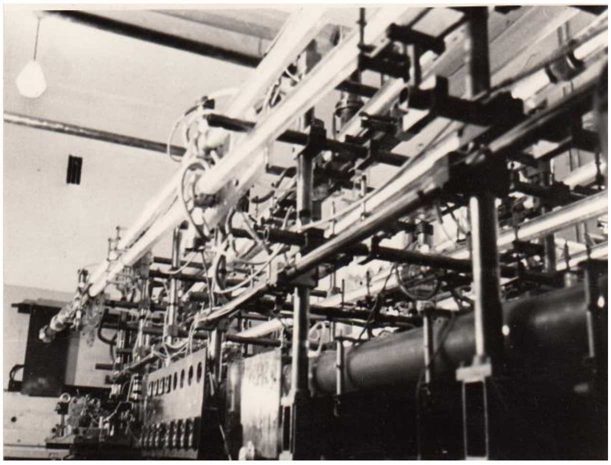

Figure 7. "Zig-Zag"- CO_2-laser created by A.I. Barchukov FIAN 1970.

In the history of electrical discharge CO2-lasers output power scaling a very similar geometry had been investigated carefully. This is a "Zig-Zag" –CO_2 laser which was created in FIAN by A.I. Barchukov in the beginning of 70`s.The future of "Zig-Zag" multi– module geometry disk laser probably will be the same. At the Fig. 7 "Zig-Zag"- CO2-laser created by A.I. Barchukov FIAN 1970 is presented. With the help of this laser we have forecasted a lot of new effects which later on made significant difficulties to the scientists involved into high power mono-module laser creation. There are: deformation of the high power laser mirrors surface and distortion of phase front of the beam during propagation and as the result-high power static and adaptive optics, big scale water cooled optics for telescopes based on SiC, high power CW plasmotrone in air and as the result – crusibleless growing of crystals, high quality laser beam and as the result- high quality laser based hard materials welding and cutting and so on.

In the quasi-continuous regime, the power can be estimated by scaling the saturation intensity with a duty cycle of the pump and by multiplying the duration of the pump by the pulse repetition rate. At moderate repetition rates (e.g., higher than 1 Hz), the maximum energy of the output pulses is approximately inversely proportional to the cube of background losses b. The undoped cover can increase the average output power by an additional order of magnitude, provided that this cover does not increase the background loss. At low pulse repetition rates (in the single-pulse regime) and sufficient pump power, there is no general limitation on the energy, but the required size of the device increases rapidly with increasing pulse energy, thereby establishing a practical limit of energy. One active element, according to the estimates, can generate an optical pulse with energy of a few thousand joules, depending on the level of internal signal loss in the disk.

Disk lasers, as well as fiber lasers, have a large ratio of the cooling surface area to the gain of the laser. However, these two different concepts of the laser design also differ by the values of the achievable peak power. Beam quality of fiber lasers is determined by properties of waveguides, the refractive index difference between the core and the cladding, and the size of the internal diameter of the fiber that transmits light. On the other hand, beam quality of disk lasers depends on the design of the resonator. With increasing size of the optical pump region (its diameter is usually a few millimeters) at a constant optical power density on the disk surface, scaling of the output power becomes possible. Adjustment of the resonator also has similar features. Self-phase modulation defines the typical limit of nonlinear amplification of ultra short pulses. It leads to an extension of the spectral line proportional to the ratio of the effective optical path in the material with nonlinear characteristics to the effective cross-sectional area of the beam multiplied by the square of the pulse duration. An electro-optical switch in a regenerative amplifier of the disk laser makes a substantial contribution to the nonlinear characteristics of the gain which is greater than the contribution from the disk. It must be emphasized that the values of the peak power, achieved today in single disk modules, are much smaller than the values obtained in 'rod' and 'slab' solid-state laser systems. However, the level of the average power generated by a single disk module also leaves much to be desired.

Regenerative Amplification of Pulses

At present, in the scientific and technical research and manufacturing processes relying on the use of high average power lasers, only sources operating in two regimes find applications, i.e., CW and P-P laser sources with a pulse repetition rate up to hundreds of Hz and pulse duration from tens of microseconds to tens of milliseconds. In most processes, purely thermal mechanism of action is mainly implemented, since use is made of the possibility of a laser source to deliver quite a lot of energy to a small area of the surface of the work piece. High-frequency, high-average-power laser systems operating in the Q-switched regime, which provides the pulse duration in a periodic train from a few to hundreds of nanoseconds, allows for a fundamentally different mechanism of interaction of radiation with matter, i.e., ablation, ensuring local release of energy not only in space but also in time [13]. This results in an explosive local evaporation of the substance without an intermediate liquid phase. This mechanism can significantly extend the range of technological applications of laser sources. Today, it has found a real use in practice, only at an insignificant level of output power in the range of 1000 W. However, there arises a reasonable question: Why are high-power P-P lasers not available at the international laser market? The answer is simple: The complexity of their manufacturing consists in the inability of application of the classical modulation methods to laser systems with high average and peak powers. At the same time, it is quite clear that the creation of high-power (>1 kW) P-P lasers with frequencies up to 100 kHz or higher (with a peak power exceeding the average power by two to three orders of magnitude) would significantly expand the field of application of laser sources, increase their efficiency, and implement qualitatively new effects [14].

One of the successful trends in implementation of new methods of high-frequency modulation of the output from high-power laser sources is due to the regenerative amplification of a small signal injected into the cavity of a high-power gas or solid-state laser with the classical rod geometry. Use of intra cavity modulators in high-power laser systems is hindered, because high power density inside the cavity leads to the appearance of plasma on the surface elements of the modulator, to the screening of radiation and to the destruction of the optical elements of the modulator. Quite promising is the method of realization of the P-P regime in high-power lasers, which is based on the use a self-filtering cavity. This cavity is a confocal resonator consisting of two spherical mirrors of different curvatures; in the common focal plane there is an annular output mirror with a hole. Because of the high degree of discrimination of the higher modes with respect to the resonator losses, the lower mode is reliably generated. The spherical resonator mirror is placed outside the active medium and contains a modulation unit comprising spherical mirrors. The laser mode should be formed quickly enough in the leading edge of a giant pulse. The problem of laser micromachining usually involves cutting, drilling, surface cleaning and polishing, as well as removal of thin layers due to the ablation of the material. Micromachining relies on lasers emitting pulses of different duration. The geometry of the beam and the pulse repetition rate are crucial: usually the pulse duration does not exceed a few tens of nanoseconds, and in some cases reaches several hundreds of picoseconds. Disk laser technology provides excellent flexibility in the scaling of the output power by combining it with a high pulse energy and excellent beam quality.

Prospects for scaling the power of disk lasers

As mentioned above, the design of the disk laser generating a continuous and relatively high power is ideal for cutting and welding metals, where high optical quality of the beam is required. It is important for such industries as automotive, transportation, aerospace and heavy engineering. However, the design of the disk laser is more suitable for a range of new technologies that are currently in demand. Today, a multi-module laser with a power up to 16 kW and beam quality of ≥2 mm mrad, fabricated by the TRUMPF Group, is the undisputed leader in this class of laser systems. CW solid-state diode-pumped disk lasers demonstrate highly efficiency. Beam quality of the laser disk is outstanding, which makes it possible to work with a target from a large distance, while providing an extremely high concentration of radiation in the interaction region with the help of the focusing optics. In this design of the laser module the disk size is no more than 4−5 mm, because at larger sizes the energy loss due to the amplified spontaneous emission increases at an absolutely unacceptable rate. The above-presented laser system consists of a set of disk modules in a single cavity. This geometry of the laser system allows implementation of the P-P regime with a fairly high peak power, but the average power lies within a kilowatt. Parallel operation of disk lasers can increase the peak power of the entire system, but the phase-locking of the disk channels in the P-P regime requires additional scientific research. Further expansion of the power to the megawatt level of both the average and peak power in both geometries is very problematic.

At the same time, a different approach is known to the implementation of scalable solid-state laser systems, which consists of a set of active elements in the form of 'slabs', followed by phase-locking of the generated radiation. The team of the Northrop Grumman Corporation has created a laser with a power of >100 kW and high laser beam quality equal to the diffraction limit of 1.5 (averaged value) with the exposure time of 300 seconds [15]. The laser efficiency reaches 30%. The authors of the project point to the easy replacement of individual laser channels in case of failure. They also mention some of the advantages of the parallel structure of the amplifying channels in terms of ease of further increasing output power, if necessary, to 100 kW. Besides, the laser assembled according to this scheme provides the divergence at the level of two diffraction limits from the common (composite) aperture. From general physical considerations, we can assume that for a given power level and a reasonable value of radiation resistance of optical elements, the divergence of the laser radiation at the level of 2×10-5 rad can be achieved for the CW generation regime and 0.6×10-5 rad for the P-P regime. A further increase in the number of channels in order to obtain an output power of 1 MW will require the coherent summation of the power from at least 80 channels, which seems an elusive task.

The question arises as to how the average power of a few megawatts can be achieved on the basis of solid-state lasers. And it is this power that is needed to address many problems associated with the removal of debris from near-Earth space, with launching of missiles with the help of lasers, with the creation of long-range conducting channels and others. Fiber lasers are not applicable for these purposes because of the smallness of the area of the exit pupil of the fibers and hence the impossibility of operation of such lasers in the high-frequency P-P regime with high peak power at an average power of a few megawatts [16, 17]. The laser system based on 'slabs' also seems hard to implement as adjustment of the system and its maintenance in a safe operation mode are comparable to the complexity of working with a multi-element system for the solution to the problem of controlled thermonuclear fusion (CTF) at Livermore (USA). Proceeding from the above, the answer is quite clear: Such a laser can and should be based on the mono-module disk laser geometry!

This is due to the indisputable advantages of the disk geometry in terms of the minimal thermal lens in the active media and the high radiation resistance of the disk in the P-P regime because of the large area of the optical surface to couple out the radiation. So, the necessity to find a solution to the problem of the ASE suppression along the diameter of the disk was the major problem (matter of patent). In our case, the size of the disk at a megawatt level of the average power output should be at least 50 cm, i.e., at least hundred times bigger the size of the disk that is used today in existing systems. Radiation from such a laser, obtained during generation in the active medium of a single disk, does not require additional phase-locking. At the same time, such a laser in a mono- module geometry will be very well combined with a large-diameter telescope for ensuring high peak power density of the laser pulse on space debris. It is well known that the disk geometry of a laser was proposed 54 years ago [18], but only now the solution to the problem of the ASE suppression with increasing transverse dimensions of the active medium in the mono-module disk geometry is found! Thus, the prospects of new versions of the mono-module disk laser creation for new class of cutting-edge problems of our days are open [19-20].

In conclusion it is necessary to say several words about a new set of applications for high energy high repetition rate P-P lasers. Many years were undertaken attempt at the creation of the conducting channels of large length for studying the upper air and solution of special problems. In this connection is of great interest our program, which in the combination with the high-voltage high-frequency Tesla type source can be useful in the solution of the enumerated above problems. At the same time, one should say that as a result of the conducted investigations laser jet engine is possible the passage to the solution of the following completely interesting problems:

1. Creation of the interceptor of manmade space debris and other dangerous space objects, such as asteroids, comets, meteorites and so on;
2. Launch of micro-objects with the super-high acceleration to the space;
3. Realization of orbital scale conducting channels for energy delivery from space to the ground.
4. Powerful pulsed lasers are capable to create a large-scale current conducting channel, which can be located at the arbitrary distances from the source of radiation. Channel with the length about hundred of meters can be achieved with low energy of single laser pulse. Beginning from the 70's, successful attempts of the problems: interception of lightning bolts and blocking of over voltage waves on the electric power lines were undertaken.

Successful developments of high repetition rate P-P powerful lasers technology and technology of laser system make it possible to foresee the possibility of well conducting channels realization with the length up to several ten and hundred of kilometers for the purpose of energy transfer for significant distances, creation of new and promising systems for the mastering of outer space power engineering and motivation for significant contribution to be done on that basis to an essential improvements of the global ecology of our planet [21, 22].

Conclusions

We have demonstrated both theoretically and experimentally, the feasibility of converting a high-power wide-aperture CO_2 and Nd YAG lasers 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 100 ns, a peak output power greater than 100 kW and an average output power coinciding with the power of stationary lasing (10 kW for CO_2 and 1 kW for Nd YAG) were experimentally obtained. The applicability of the proposed method of laser conversion to the repetitively pulsed lasing regime is limited by the threshold of optical breakdown on the modulator aperture only, which can be easily eliminated by decreasing of the injected signal. New set of applications for high energy high repetition rate P-P lasers is suggested.

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