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OPTIMIZATION OF PULSED-PERIODIC NEODYMIUM GLASS LASERS

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Results of an investigation aimed at improving the efficiency of pulsed-periodic neodymium glass lasers are presented. The choice of the efficiency criterion of the laser system as the product of the radiation power and the Strehl number made it possible to formulate and substantiate several practical recommendations on the choice of optimum operating-mode–structure parameters of a pulsed-periodic laser.

Thermooptical effects are known to affect substantially the radiation parameters of solid-state lasers [1, 2]. In isotropic media such as neodymium glass these effects are the main reason for wave-front distortion, since they lead to an increase in the divergence of the radiation and, as a consequence, to a drop in the intensity in the utilization zone.

To date, several main methods of decreasing the level of thermooptical distortions in the active medium of solid-state lasers are known [3], including the use of matrices with certain physical properties or subjected to a special treatment, that provide an optimum thermal regime for the active element, and, of course, dynamic correction of the wave front [1, 3], etc. However, despite the large number of these methods, none of them can pretend to be a universal method, since the efficiency of using each of them should be determined by the particular requirements on the laser parameters.

The present work is aimed at extending the number of possible ways of improving the optical quality of the radiation of pulsed-periodic lasers with cylinder-shaped glass active elements by reducing the effect of thermooptical aberrations.

The following quantity can be a possible combined criterion of the efficiency of a laser system:

$$I = P\mathrm{Sh}\,,$$

where P is the radiation power, equal to the product of the mean specific energy output (per unit mass of the active medium) and the active-element mass, and Sh is the Strehl number, considered as an integral criterion of optical homogeneity [4]. For a one-pass laser amplifier, the quantity I is proportional to the maximum radiation intensity in the Fraunhofer diffraction zone (or in the focal plane of the lens system) [4].

The energy output and the heat liberation for each point of the active medium are proportional to the pumping energy. With increase in the latter, on the one hand, the specific energy output and, therefore, the radiation power P increase, and on the other hand, the heat liberation increases, which leads to an increase in the inhomogeneity of the thermally stressed state of the active element and, as a consequence, to a drop in the optical quality of the radiation, i.e., the Sh number. The evident ambiguity of the pumping-energy dependence of the criterion I also occurs for pulsed-periodic lasers in which superposition of the phase perturbation due to the new pumping pulse on the current aberration state of the active medium additionally occurs.

Numerical simulation of a pulsed-periodic laser was carried out with account for the two main factors: cooling of the active element along its side surface and inhomogeneous distribution of the pumping energy along the radial direction [5]. The temperature, stress, and deformation fields provided recovery of the wave front, for which deviations from the plane shape were mainly induced by the temperature dependence of the refractive index

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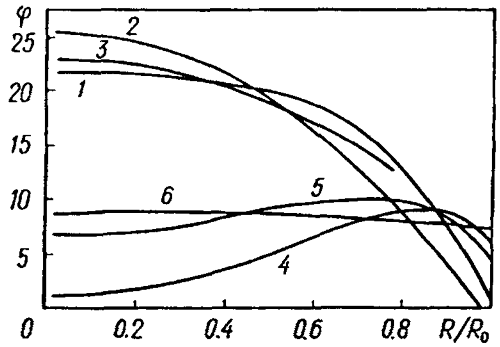


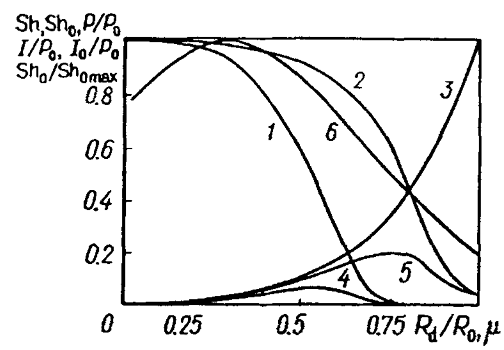


Fig. 1. Radiation phase fronts (1, 4, 5) and their spherical components (2, 3, 6) for an opaque active element with $R_0 = 0.0255$ m at $\nu = 0.05$ Hz and $W = 0.3$ J/g: $L = 1$ m, Bi = 20 (1, 2, 3), $L = 1$ m, Bi = 0 (4); optimum combination of cooled (Bi = 20) and thermally insulated (Bi = 0) rods with a total length $L = 1$ m (5, 6). φ, rad.

Fig. 2. Dependences of Sh (1), Sh_0 (2), relative radiation power P/P_0 (3), and normalized characterististic number I/P_0 (4) and I_0/P_0 (5) on the relative radius of the aperture diaphragm R_d/R_0, and the dependence of the normalized Strehl number Sh_0/Sh_{0max} (6) on the number μ for $R_0 = 0.0255$ m at $\nu = 0.05$ Hz and $W = 0.3$ J/g: $L = 1$ m, Bi = 20 (1-5); combination of cooled (Bi = 20) and thermally insulated (Bi = 0) rods.

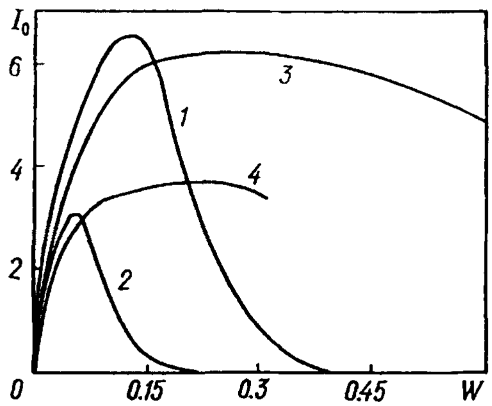
and by the photoelasticity phenomenon [6]. It should be noted that in what follows, all results of simulations are presented only for matrices made of GLS-6 laser glass.

After a certain number of pulses that depends on the thermophysical properties of the matrix, its shape, and the pumping and cooling intensities, the pulsed-periodic laser starts functioning in the quasistationary mode, when by the instant of the start of each successive pumping pulse the thermally stressed state of the active element and, therefore, the structure of the wave front of the optical radiation become independent of the pulse number.

For a rod of radius R_0 and length L, a certain specific pumping energy averaged over the volume of the active element for which the quantity I will be maximum corresponds to a particular pulse rate ν. The pumping energy unambiguously determines the corresponding power P and mean heat liberation W in the volume of the active medium. Thus, when the radius of the active medium $R_0 = 0.0225$ m and $L = 1$ m, the pulse rate $\nu = 0.01$ Hz, and Bi = 20, the pumping providing the heat liberation $W = 0.2$ J/g will be optimal. Exceeding this value with the aim of providing a further increase in the energy output will necessarily lead to an increase in the inhomogeneity of the heat liberation in the active medium with a corresponding sharp drop in the Sh number and a decrease in the quantity I compared to its maximum possible value.

If the spherical component is selected from the wave front, the optical quality of the radiation will be characterized by the residual phase scatter and, therefore, the residual Strehl number Sh_0. In the simulation, the choice of the optimum sphere was carried out by the method of least squares [7]. In practice, compensation for spherical aberration can be achieved by special adjustment of the cavity with spherical mirrors [7]. Upon carrying out this operation, the operating-mode parameters of the laser that provide the maximum of the new function $I_0 = PSh_0$ (with account for the sphere selection) have different values. For example, in the above case ($R_0 = 0.0225$ m, $L = 1$ m, $\nu = 0.01$ Hz) compensation for the spherical component of the radiation wave front makes it possible to increase the optimum value of the heat liberation to $W = 0.9$ J/g. In this case the maximum value of the intensity in the far-field zone increases by almost a factor of five for the mode of a one-pass amplifier.

Figure 1 presents the wave front of the radiation (curve 1) upon one passage through the active medium in the quasistationary regime ($R_0 = 0.0225$ m, $L = 1$ m, $\nu = 0.05$ Hz, $W = 0.3$ J/g, Bi = 20). The same figure presents the spherical component of the wave front (curve 2). In an active element with an opaque side surface, the zone of maximum phase perturbations is concentrated near the side surface. Therefore, use of aperture diaphragming – shielding of a portion of the near-surface region of the active element in the radial direction – is efficient. It can



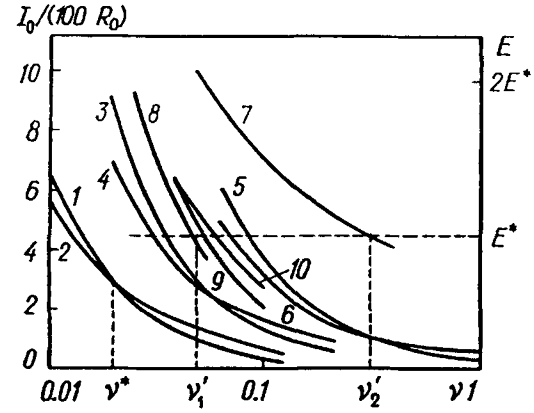


Fig. 3. Dependence of the characteristic number I_0 on the average heat liberation W in an active medium with (3, 4) and without (1, 2) aperture diaphragming: $\nu = 0.05$ Hz (1, 3); $\nu = 0.1$ Hz (2, 4). I_0, arb. units; W, J/g.

Fig. 4. Maximum value of the characteristic number I_0 (1-6, 9, 10) normalized to the active-element radius and the optimum pumping energy (7, 8) as functions of the pulse rate ν with (2, 4, 6, 7, 10) and without (1, 3, 5, 8, 9) aperture diaphragming for rods with an opaque (1-8) and a polished (9, 10) side surface (Bi = 20, L = 1 m): R_0 = 0.05 m (1, 2); R_0 = 0.0225 m (3, 4, 7, 8); R_0 = 0.01 m (5, 6, 9, 10). ν, Hz; R_0, m.

provide a certain increase in the total optical quality of the laser radiation. In this case, the Sh and Sh_0 numbers will always increase with decrease in the diaphragm radius R_d (see curves 1 and 2 in Fig. 2).

An increase in the optical quality of the radiation upon aperture diaphragming is inevitably accompanied by a loss in the total power P with vignetting of the part of the radiation coming from the region of the active medium with the strongest phase perturbations. In rods with an opaque surface, the near-surface region has the highest inversion parameters, since this region absorbs a substantial share of the pumping radiation [5]. Curve 3 in Fig. 2 shows the variation of the relative radiation power $P(R_d/R_0)/P_0$ with the aperture diaphragm radius R_d, where P_0 is the power at $R_d/R_0 = 1$. The optimum value of R_d/R_0 corresponds to a maximum of the function I and to that of the function I_0 upon selecting the spherical component of the wave front (curves 4 and 5 in Fig. 2). Curve 3 in Fig. 1 presents the spherical component selected from the portion of the wave front upon optimum diaphragming of the beam at $R_d/R_0 = 0.78$. It is evident from Fig. 2 that in the case of this optimum aperture diaphragming the radiation intensity in the far-field zone upon compensation for the spherical component increases by approximately a factor of 7.5 compared to the original value (i.e., at $R_d/R_0 = 1$).

At low pulse rates ν, aperture diaphragming proves to be inefficient. In this case the maximum value of the intensity I reached at a particular pumping energy without a diaphragm always proves to be higher than upon aperture diaphragming. On the other hand, the optimum values of the pumping energy and, therefore, the optimum energy liberation in the active medium with and without aperture diaphragming are different. This situation is illustrated in Fig. 3, where the dependence of the quantity I_0 on the mean specific heat liberation W in the active medium is shown for two values of the pulse rate ν with and without the optimum diaphragm (R_0 = 0.0225 m, L = 1 m). Thus, at ν = 0.05 Hz there is no point in carrying out aperture diaphragming of a rod with the specified dimensions, since the maximum value of the quantity I_0 without a diaphragm achieved at W = 0.14 J/g exceeds the maximum I_0 upon aperture diaphragming, which in turn corresponds to the value W = 0.3 J/g (curves 1 and 3 in Fig. 3). At this pulse rate, optimum operation of a pulsed-periodic laser without diaphragming is achieved at a pumping energy providing the specific heat liberation W = 0.14 J/g. The situation changes with an increase in the pulse rate ν, since use of an aperture diaphragm can markedly increase the efficiency criterion chosen (see curves 2 and 4 in Fig. 3 at ν = 0.1 Hz).

Figure 4 shows the dependence of the maximum value of the quantity I_0 divided by the active-element radius R_0 on the pulse rate for active elements with different radii with and without aperture diaphragming. At pulse rates lower than a certain critical value ν^* use of aperture diaphragming is inefficient. If $\nu > \nu^*$, the radiation intensity is always higher upon optimum diaphragming. As an example, the pulse rate ν^* corresponding to $R_0 = 0.05$ m is shown in Fig. 4. In the general case, the value of the pulse rate depends on the active-element radius and shifts to lower frequencies with an increase in the radius.

The optimum pumping energy providing the maximum I_0 should decrease with increasing pulse rate in both the case of use of aperture diaphragming and without it (curves 7 and 8 in Fig. 4 for $R_0 = 0.0225$ m). At a certain pulse rate ν^* the optimum pumping energy becomes equal to the threshold value E^*, which is the lower boundary of the energies at which lasing takes place. Therefore, the optimum operating mode of the laser setup cannot be provided at pulse rates $\nu > \nu_1'$ (see Fig. 4).

Optimum diaphragming assumes a higher pumping energy in the region of the maximum of the function I_0 than in the case of an undiaphragmed rod at the same pulse rate (curve 7 in Fig. 4). Therefore, the critical pulse rate ν^* shifts to higher values (e.g., the value ν_2' is higher than ν_1' in Fig. 4). In other words, use of aperture diaphragming makes it possible to extend substantially the pulse-rate range of optimum functioning of a solid-state laser for given dimensions of the active element.

Use of cylindrical active elements with a polished side surface leads to a shift of the critical pulse rate ν^* to lower values. Thus, for a rod with $R_0 = 0.01$ m the efficiency of aperture diaphragming becomes evident already at $\nu^* = 0.04$ Hz, whereas for an identical opaque rod of same radius the critical pulse rate is $\nu^* = 0.4$ Hz (curves 9, 10 and 5, 6, respectively). This situation is connected with the strong dependence of the transverse distribution of the pumping radiation on the diffuseness of the side surface of the active element [5]. Indeed, whereas in rods with an opaque cylindrical side surface the density of the pumping radiation always decays exponentially from the surface to the center of the rod, in polished active elements the radiation density may prove to be higher in the center of the rod than at the surface due to focusing of radiation [5]. This is the reason why aperture diaphragming in polished active elements does not lead to as sharp a decrease in the output energetics of the laser radiation as in opaque rods.

It should be noted that curves 9 and 10 in Fig. 4 correspond to the case where the cooling liquid has a refractive index equal to unity. In real cases, the relative refractive index of glass and water has a value of order of 1.2, and therefore, the pulse rate ν^* for a polished rod will shift to the right along the pulse-rate axis due to a change in the distribution of the pumping radiation over the cross section of the active element. In this case it still has a lower value than the corresponding quantity for an opaque rod of the same dimensions.

Aperture diaphragming of polished active elements leads to the use of just the central region of the rod, which is characterized by a more uniform distribution of the inverse population in optical pumping. In this regard aperture diaphragming is identical to the well-known method of placing a rod in a transparent concentric cylinder or using a special immersing liquid as the cooling agent.

The effect of the surface opaqueness on the pumping-energy distribution over the volume of the active medium decreases with increasing rod radius [5]. This tendency leads to the fact that the difference between the character of the heat liberation in opaque and polished active elements and between the corresponding pulse rates ν^* vanishes with increasing R_0.

One of the possible ways of compensating for thermooptical aberrations is the phase-conjugation principle, consisting in directing the radiation successively through two portions of the active medium with different structures of the phase inhomogeneity. In other words, the distortions of the wavefront of the radiation upon propagating through the first portion of the active medium should be at least partially compensated by the phase distortions in the second portion.

For a cylindrical active element with phase conjugation the radial phase distribution in the wavefront will consist of two components:

$$\varphi(\sigma) = \varphi_1(\sigma) L_1 + \varphi_2(\sigma) L_2,$$

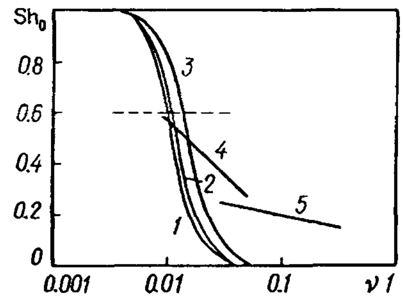


Fig. 5. Dependences of Sh_0 for different construction schemes of the laser (1, 2, 3) and optimum μ (4, 5) on the pulse rate ν at $W = 0.73$ J/g: Bi = 20, L = 1 m (1); Bi = 0, L = 1 m (2); optimum combination of cooled (Bi = 20) and thermally insulated (Bi = 0) rods with a total length L = 1 m (3); $R_0 = 0.0225$ m (1-4); $R_0 = 0.01$ m (5).

where $\varphi_1(\sigma)$ and $\varphi_2(\sigma)$ are the phase changes per meter of the first and second portions of the active medium, respectively, and $\sigma = R/R_0$. The ratio of the lengths L_1 and L_2 of the first and second portions of the active medium is determined based on providing the maximum Strehl number [4]

$$\mathrm{Sh} = \exp(-D),$$

where D is the phase variance with respect to its mean.

In practice, in the simplest case the phase conjugation method can be implemented in different ways, in particular, by using two active elements of identical radii and lengths L_1 and L_2, one of which is cooled and the other is thermally insulated. In this case the side surface of both rods should necessarily be opaque. After a certain number of pulses this system of active elements starts to operate in a quasi-steady-state mode, and the only restriction will be connected with a steady increase in the volume-averaged temperature of the thermally insulated active element, which in turn is determined by the thermal stability of the glass and the temperature dependence of the spectral luminescence properties of the activator ions.

Figure 1 presents the radial phase distribution for cooled (curve 1) and thermally insulated (curve 4) rods with $R_0 = 0.0225$ m and $L = 1$ m. The radial phase gradients in these active elements have opposite signs, except for a certain near-surface region with $\sigma > 0.85$ in the thermally insulated active element, where the temperature gradient tends to zero upon approaching the outer surface. This structure of each of the wavefronts makes it possible to reduce substantially the level of phase aberrations of the radiation using a pair of active elements with the optimum ratio of their lengths L_1 and L_2 within a single amplifier stage. In particular, for the example considered, the optimum length ratio will be equal to $\mu = L_1/(L_1 + L_2) = 0.273$ (see curve 6 in Fig. 2), provided that $L_1 + L_2 = 1$ m. In this case the Sh_0 number is almost 30% higher than in use of a single thermally insulated rod (the case $\mu = 0$). The wavefront of radiation propagating in this combined active element at $\mu = 0.273$ is shown by curve 5 in Fig. 1. The same figure also presents the optimum sphere selected from this wavefront (curve 6). It is evident that the sphere radius becomes rather large, i.e., the spherical component is virtually not present in the wavefront at the given operating-mode parameters and $\mathrm{Sh} \approx \mathrm{Sh}_0$.

Investigations showed that the optimum value of μ depends only weakly on the pumping energy but is a function of the active-element radius R_0 and the pulse rate ν. Figure 5 shows the dependence of the optimum value of μ on the pulse rate ν for different rod radii. As is evident from the plots, the value of μ decreases with increasing pulse rate ν, i.e., the contribution of the cooled portion to the total length of the active element decreases. This is connected with faster growth of thermally induced inhomogeneities with increasing ν in the cooled rod compared to the thermally insulated one.

Figure 5 shows dependences of St_0 on the pulse rate at a specific heat release in the active medium of $W = 0.73$ J/g and a radius $R_0 = 0.0225$ m for three laser schemes: with a cooled active element of length $L_1 = 1$ m, with a thermally insulated active element [2] of length $L_2 = 1$ m, and with a combined active element with the optimum ratio of the lengths L_1 and L_2, provided that $L_1 + L_2 = 1$ m (curves 1, 2, and 3, respectively). If the value

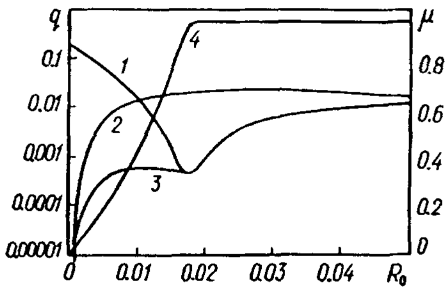


Fig. 6. Dependence of the variance of the relative pumping energy (1, 2, 3) and the optimum μ (4) on the active-element radius R_0 for a polished rod (1), an opaque rod (2), and the optimum combination of polished and opaque rods (3).

$Sh_0 = 0.6$ is considered as the threshold level of the total optical inhomogeneities of the active medium, a certain pulse rate ν_{thr} such that $Sh_0 > 0.6$ when $\nu < \nu_{thr}$ will unambiguously correspond to each construction scheme at a particular level of heat release. For the considered case of cooled and thermally insulated active elements, the critical pulse rates are approximately the same and equal to $\nu_{thr} = 0.011$ Hz, and their optimum combination can provide a certain increase in the pulse rate to the value $\nu_{thr} = 0.014$ Hz (Fig. 5). Therefore, phase conjugation with simultaneous use of cooled and thermally insulated rods extends somewhat the pulse-rate range of laser operation.

In the single-pulse mode of laser operation, phase conjugation can be achieved by using two active elements with different outer surfaces in a single amplifier stage: a polished rod of length L_1 and an opaque rod of length L_2. Indeed, as has been noted above, the structure of the distribution of the pumping radiation can differ substantially in polished and opaque rods [5]. Therefore, one may expect that the optimum ratio of the rod lengths L_1 and L_2, i.e., the quantity $\mu = L_1/(L_1 + L_2)$, will be determined based on the minimum variance of the relative density of the pumping energy q [5].

Figure 6 shows the dependence of the variance of q on the radius R_0 for polished and opaque active elements and for their optimum combination: curves 1, 2, and 3, respectively. As is evident from the plots, the quantity q is smaller for an active element with an opaque surface within the range of $0 < R_0 < 0.011$ m than for a polished rod; the reverse picture is observed when $R_0 > 0.011$ m, i.e., it is evident that it is advisable to polish large rods (curve 4). Within the range of $0 < R_0 < 0.018$ m, the combination of rods with the optimum ratio of lengths provides the smallest variance of q as compared to both polished and opaque active elements with the same geometrical path of the radiation in the active medium. When $R_0 > 0.018$ m, radiation focusing becomes insufficiently pronounced to provide efficient use of the phase-conjugation principle. In this case the efficiency of use of just polished rods increases.

The following has been shown as a result of the investigations carried out.

1. The total efficiency criterion I of a laser system, equal to the product of the radiation power and the Strehl number, is quite applicable to performing a partial parameter optimization of pulsed-periodic lasers. For a single-pass laser amplifier this quantity is proportional to the maximum radiation intensity in the Fraunhofer diffraction zone.

2. For cylindrical glass active elements with particular dimensions used at a particular pulse rate ν, there exists an unambiguous optimum pumping energy averaged over the active-element volume at which the quantity I is maximum. Exceeding this value with the aim of achieving a further increase in the energy output will necessarily lead to an increase in the inhomogeneity of the heat liberation in the active element with a corresponding sharp drop in the Sh number and a decrease in the quantity I compared to its maximum attainable value.

3. In active elements with an opaque side surface, use of aperture diaphragming is efficient, since it will always provide an increase in the integral criterion of the optical quality of the active medium expressed by the Sh number and, under certain conditions, also an increase in the quantity I. The efficiency of aperture diaphragming for these active elements increases substantially with any increase in the pumping energy, radius of the optical element, or pulse rate. In active elements with a polished side surface, aperture diaphragming proves to be more efficient than in rods with an opaque surface as a result of additional radiation focusing. Here aperture

diaphragming, providing an increase in the total optical quality of the active medium, does not lead to as sharp a decrease in the output energetics of the laser radiation as in opaque rods.

4. Aperture diaphragming is efficient at pulse rates exceeding a critical value ν^* that depends mainly on the rod dimensions. In the case $\nu > \nu^*$, the maximum value of the quantity I in optimum aperture diaphragming always exceeds the corresponding quantity for an undiaphragmed rod.

5. For an arbitrary pulse rate ν, the maximum of the quantity I is achieved at higher pumping energies in aperture diaphragming than in the case of an undiaphragmed active element. At the same time, an increase in the pulse rate ν leads to a decrease in the optimum pumping energy both with and without aperture diaphragming. Therefore, use of a diaphragm makes it possible to increase the value of the critical pulse rate ν^* at which an optimum pumping energy exceeding the threshold value will still be achieved.

6. In certain cases simple and rather efficient method of partial compensation for thermooptical aberrations is the use of the phase-conjugation principle, which consists in directing the radiation successively through at least two portions of the active medium having opposite directions of the curvature of the lateral phase distribution. In practice, this is implemented by using a sequence of a pair of opaque active elements in a single amplifier stage of a pulsed-periodic laser, for which the length ratio is specially adjusted and for one of which cooling of the outer side surface is intentionally precluded.

7. In the single-pulse operating mode, the phase-conjugation principle can be implemented under certain conditions by a similar combination of two active elements one of which is polished and the other has an opaque outer surface. The efficiency of using particular cylindrical active elements (polished, opaque, or combined) in the single-pulse mode depends unambiguously on the active-element radius.

NOTATION

R_0 and L, radius and length of the active element; ν, lasing pulse rate; W, average specific heat liberation in the active element; R_d, opening radius in the aperture diaphragm; φ, phase in the wave front; D, phase variance in the wave front; σ, relative radial coordinate; q, relative density of the pumping energy; Bi, Biot number.

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