

CONTROL OF LASER RADIATION PARAMETERS

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Study of diffraction-coupled lasing in a set of lasers with self-pumped phase-conjugate mirrors on gain gratings in the case of short-range coupling

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***Abstract*. Compact schemes of a multichannel holographic laser system with short-range coupling and increased efficiency of single-mode lasing are developed for low-gain laser media operating not only at the fundamental laser transition but also at other laser transitions of the Nd : YAG crystal. The numerical simulation shows that the maximum possible number of laser channels can be increased by equalising their parameters. The possibility of phase locking of two loop Nd : YAG lasers without a nonreciprocal element with the free-running single-mode lasing efficiency up to 0.64 % and the contrast of the interference pattern of the output beams exceeding 0.5 is shown experimentally.**

Keywords: *short-range coupling, multichannel laser system, phase locking, interference pattern contrast.*

1. Introduction

We studied in [1 – 3] holographic laser systems with long-range coupling of self-pumped phase-conjugate oscillators on gain gratings. In the case of long-range coupling in a multichannel holographic laser system, the channel with the highest gain controls lasing in other channels, because of which all the controlled lasers are synchronised even at large gain mismatches and any number of lasers. However, the long-range coupling of N lasers occurs when the radiation of all the laser channels is mixed in a common active element, in which the radiation intensity can achieve $N^2 I$, where I is the intensity of one channel. Hence, an increase in the number of laser channels in a multichannel holographic laser system with long-range coupling is limited by the breakdown threshold of the common active element providing the interchannel coupling.

The aim of this paper is to search for a method for producing high-power solid-state multichannel holographic laser systems with a large number of channels and a high efficiency of their single-mode lasing without limitations related to the optical damage threshold of laser elements, which can be achieved in the case of short-range coupling of channels (coupling of neighbouring channels with each other) [4].

2. Schemes of a multichannel holographic laser system with short-range coupling by gain gratings

In a one-dimensional chain of lasers, each laser is coupled with two neighbouring ones. By coupling the end lasers with each other, we obtain a ring-type coupling instead of the chain-type coupling of lasers [5]. In the latter case, the end lasers are coupled only with one neighbouring laser, which makes it difficult to use standard coupling elements. In our case, the coupling elements are the active laser elements providing the four-wave mixing. Hence, we will consider the ring-type coupling of lasers.

The main advantage of the short-range coupling in multichannel laser systems is the absence of limitations associated with the optical damage threshold of laser elements. With increasing the number N of channels, we have, instead of one interchannel coupling element in the case of long-range coupling [2, 3], N coupling elements, in each of which only four waves interacts independently of the number of channels. In this case, the energy concentration in each channel can be increased up to the breakdown threshold of its optical elements, while the number of channels is not limited by the breakdown threshold if the radiation is separately coupled out from the multichannel system.

Studying the possibility of using loop lasers with highly efficient single-mode lasing in multichannel laser systems is important for application of low-gain laser materials operating in new promising spectral regions, for example, at wavelengths of 1.32 – 1.5 μm corresponding to laser transitions of Nd : YAG crystals.

As was shown in our studies [6 – 10], the highest efficiency of single-mode lasing is observed in Nd : YAG, Nd : GGG, and Nd : YA holographic lasers assembled according to loop schemes without a nonreciprocal element. We obtained the free-running single-mode lasing efficiency exceeding 1.2 % [6 – 8] for a Nd : YAG laser with two active elements (AEs) and degenerate four-wave mixing (DFWM) in each of them. Note for comparison that the efficiency of loop single-mode Nd : YAG lasers with a nonreciprocal element and long-range coupling did not exceed 0.2 % [1 – 3, 11].

The principal schemes of multichannel holographic laser systems without a nonreciprocal element and with short-

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range coupling are presented in Fig. 1. Figure 1a shows the scheme of a multichannel system based on our previously developed laser [6, 12] with increased single-mode lasing efficiency; each channel of this system has two AEs, one of which provides the DFWM feedback to form a loop oscillator and the second ensures the DFWM interchannel coupling of neighbouring loop oscillators. Figure 1b shows the scheme of a simplified multichannel holographic system with the minimum number of AEs, each of them providing simultaneously two DFWM couplings (the feedback for the oscillator formation and the interchannel coupling of oscillators). It is expected that the single-mode lasing efficiency of this system will be smaller than the efficiency of the scheme in Fig. 1a.

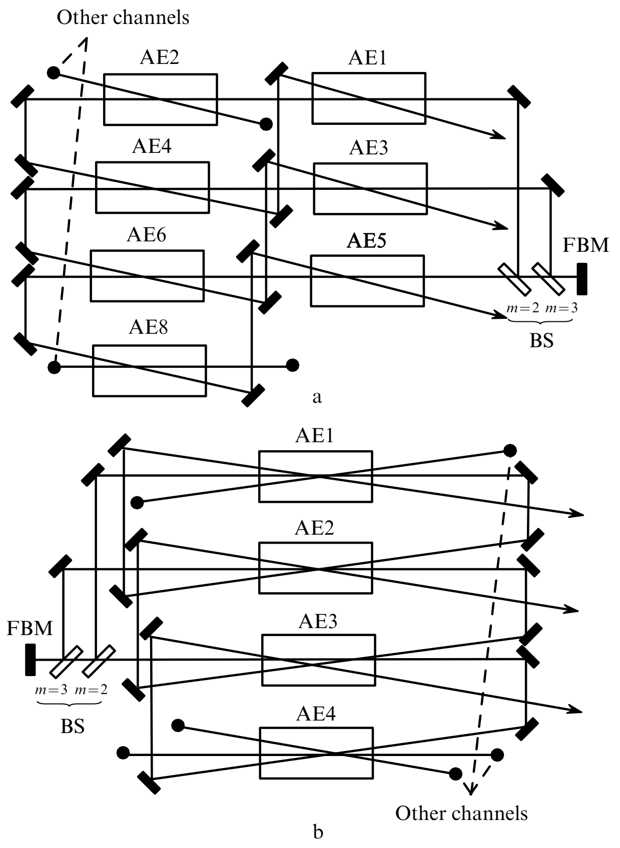

Figure 1. Principal schemes of multichannel holographic laser systems with short-range coupling and a large number of AEs: (FBM) feedback mirror; (BS) beamsplitters with reflection coefficients $R_m = 1/m$.

Note that the linear radiation exchange in these schemes (Fig. 1) occurs at the feedback mirror (FBM) due to the coaxial summation of beams of each laser channel with the help of beamsplitters with reflection coefficients $R_m = 1/m$, where m is the laser channel number [3].

3. Mathematical model of the kinetics of diffraction-coupled lasing of a multichannel laser system

Let us construct a mathematical model of the kinetics of diffraction-coupled lasing of a laser system with short-range coupling. While the main mechanisms of phase locking of channels in a multichannel holographic laser system with long-range coupling were clarified by us even for a small (three) number of channels [3], the short-range ring coupling requires to take into account more than three laser channels and correspondingly to increase the model size. This is explained by the fact that, in the case of less than four channels, each channel is coupled with two neighbouring channels, i.e. we have a long-range coupling arranged according to the ring type.

Hence, to study the short-range holographic coupling of channels, it is necessary to increase their number. We will study the synchronisation conditions of laser channels by introducing a gain mismatch: the larger the channel number, the smaller its gain. The first laser channel is controlling and directly coupled to two neighbouring controlled channels. The other controlled channels are not directly coupled to the control (first) channel, because of which it is these channels for which the short-range coupling in the laser system is adequately described. The features of this coupling manifest themselves when the number of controlled channels that are not directly coupled to the control channel exceeds the number of controlled channels (two) directly coupled to the first channel.

Thus, to investigate the short-range coupling, the number of laser channels in the laser system should be no less than six: one control channel, two neighbouring controlled channels, and three more controlled channels that are not directly coupled to the control channel.

The lasing equations in the model with a large number of degrees of freedom should be simplified to make the analysis of the considered processes more convenient and to eliminate the model instability factors that are not related to the object under study, i.e. to the short-range holographic coupling. The simplest model is the point laser model described by the Statz–De Mars equations [13]. In this model, the space inside a laser (the laser cavity completely filled by an active material) is reduced to a point, due to which the mathematical model represents a system of ordinary differential equations. The drawbacks of this simple model in our case are as follows: first, the cavity configuration is important and, second, the loop cavity length usually considerably exceeds the AE length. Thus, we will use the approximation of a point laser medium (the space occupied by the active medium is reduced to a point). The wave equation for the amplitude A of a plane wave propagating in the free space of the cavity can be written in the form

$$\frac{\partial A}{\partial z} + v^{-1}\frac{\partial A}{\partial t} = 0, \tag{1}$$

i.e. the wave amplitude A (and intensity $I \sim |A|^2$) does not change during the propagation through an empty laser cavity, and we can use the time $t = z/v$, for which light propagates the distance z with the velocity v, instead of the empty cavity coordinate. In this case, the wave equation for the intensity of the ith wave in the free space is reduced to the form (in ordinary derivatives)

$$\frac{\mathrm{d}I_i}{\mathrm{d}t} = 0. \tag{2}$$

Consider now the parameters of a point laser medium upon DFWM (taking into account only the transmission gain grating). Then, the rate constitutive equation for the gain α

corresponding to the mean intensity in the medium will have the form

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t} = -\frac{I_1 + I_2 + I_3 + I_4}{U_\mathrm{s}}\alpha + \frac{\alpha_0 - \alpha}{T_1}, \tag{3}$$

where α_0 is the maximum gain in the absence of laser radiation, which is determined by pumping (the pump parameter); U_s is the saturation energy density; T_1 is the longitudinal relaxation time; and I_i is the intensity of the wave involved in the four-wave interaction in the active medium ($i = 1 - 4$). For the gain α_m corresponding to the intensity in the interference maximum in the medium, we have

$$\frac{\mathrm{d}\alpha_\mathrm{m}}{\mathrm{d}t} = -\frac{I_1 + I_2 + I_3 + I_4 + 2\sqrt{I_2 I_3 - I_1 I_4}}{U_\mathrm{s}}\alpha_\mathrm{m} + \frac{\alpha_0 - \alpha_\mathrm{m}}{T_1}. \tag{4}$$

Next, the expressions for the point parameters of the active medium, namely, for the one-pass gain G in the AE and the diffraction efficiency η [14] of the transmission grating in the AE, will be written in the form

$$G = \mathrm{e}^{\alpha L}, \tag{5}$$

$$\eta = G \sinh^2\left(\frac{\alpha - \alpha_\mathrm{m}}{4} L\right), \tag{6}$$

where L is the AE length. The intensities of four waves involved in DFWM at the AE exit are determined as

$$I_{1-3}^{\mathrm{out}} = I_{1-3}^{\mathrm{in}} G,$$
$$I_4^{\mathrm{out}} = I_4^{\mathrm{in}} G + I_1^{\mathrm{in}} \eta, \tag{7}$$

where I_{1-4}^{in} and I_{1-4}^{out} are the wave intensities at the AE entrance and exit. Expressions (7) are used in the boundary conditions for the system of equations (2)–(4) for specific schemes of AE coupling in each laser and of laser coupling with each other.

The calculated scheme of a six-channel holographic laser system with short-range coupling is shown in Fig. 2. This scheme contains twelve AEs.

The intrinsic DFWM process, during which lasing in each channel develops, occurs in odd AEs, while the interchannel DFWM occurs in even AEs. The subscript at the intensity $I_i^{(j)}$ in Fig. 2 is the wave number in the DFWM processes and the superscript is the AE number.

Let us write the boundary conditions for the scheme shown in Fig. 2. For odd AEs, we have

$$I_1^{(1,3,5,7,9,11)}(t) = I_2^{(1,3,5,7,9,11)}(t - t_1) G^{(1,3,5,7,9,11)}(t - t_1),$$

$$I_2^{(1,3,5,7,9,11)}(t) = I_2^{(2,4,6,8,10,12)}(t - t_2) G^{(2,4,6,8,10,12)}(t - t_2), \tag{8a}$$

$$I_3^{(1,3,5,7,9,11)}(t) = I_3^{(4,6,8,10,12,2)}(t - t_3) G^{(4,6,8,10,12,2)}(t - t_3),$$

$$I_4^{(1,3,5,7,9,11)}(t) = 0,$$

and for even AEs, we can write

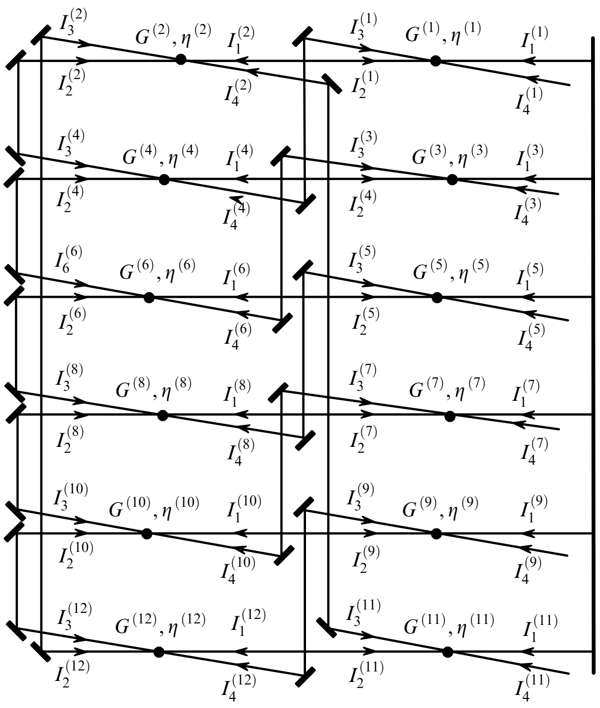

Figure 2. Calculated scheme of a six-channel holographic laser system with short-range coupling: $I_i^{(j)}$ is the intensity of the ith wave in the jth active element; $G^{(j)}$ and $\eta^{(j)}$ are the single-pass gain and the diffraction efficiency of the grating of the jth AE.

$$I_1^{(2,4,6,8,10,12)}(t) = I_2^{(1,3,5,7,9,11)}(t - t_2) G^{(1,3,5,7,9,11)}(t - t_2),$$

$$I_2^{(2,4,6,8,10,12)}(t) = I_4^{(4,6,8,10,12,2)}(t - t_4) G^{(2,4,6,8,10,12)}(t - t_4)$$
$$+ I_1^{(4,6,8,10,12,2)}(t - t_4) \eta^{(2,4,6,8,10,12))}(t - t_4), \tag{8b}$$

$$I_3^{(2,4,6,8,10,12)}(t) = I_1^{(12,2,4,6,8,10)}(t - t_4) G^{(12,2,4,6,8,10)}(t - t_4),$$

$$I_4^{(2,4,6,8,10,12)}(t) = I_1^{(11,1,3,5,7,9)}(t - t_3) \eta^{(11,1,3,5,7,9)}(t - t_3),$$

where t_1 is the time of light double pass between an odd AE and the feedback mirror; t_2 is the time of light pass between the even and odd AE of each laser channel; t_3 is the time of light pass between the odd AE of a channel and the even AE of the neighbouring channel; and t_4 is the time of light pass between the even AE of a channel and the even AE of the neighbouring channel.

4. Results of numerical simulation

The calculation results of the kinetics of diffraction-coupled lasing in a six-channel holographic laser system with the short-range coupling of AEs for the single-pass small-signal gain $G_0 = 80$, length $L = 10$ cm, times $t_1 = t_3 = t_4 = 4$ ns and $t_2 = 2$ ns and different $\Delta\alpha$ are shown in Fig. 3. In this case, the gain mismatches between neighbouring lasers are $\Delta\alpha_{12} = \Delta\alpha$, $\Delta\alpha_{13} = 2\Delta\alpha$, $\Delta\alpha_{14} = 3\Delta\alpha$, $\Delta\alpha_{15} = 2\Delta\alpha$, $\Delta\alpha_{16} = \Delta\alpha$. One can see from Fig. 3 that unlike the synchronisation of lasers with a nonreciprocal element [3], when the gain mismatch disrupted the synchronisation and

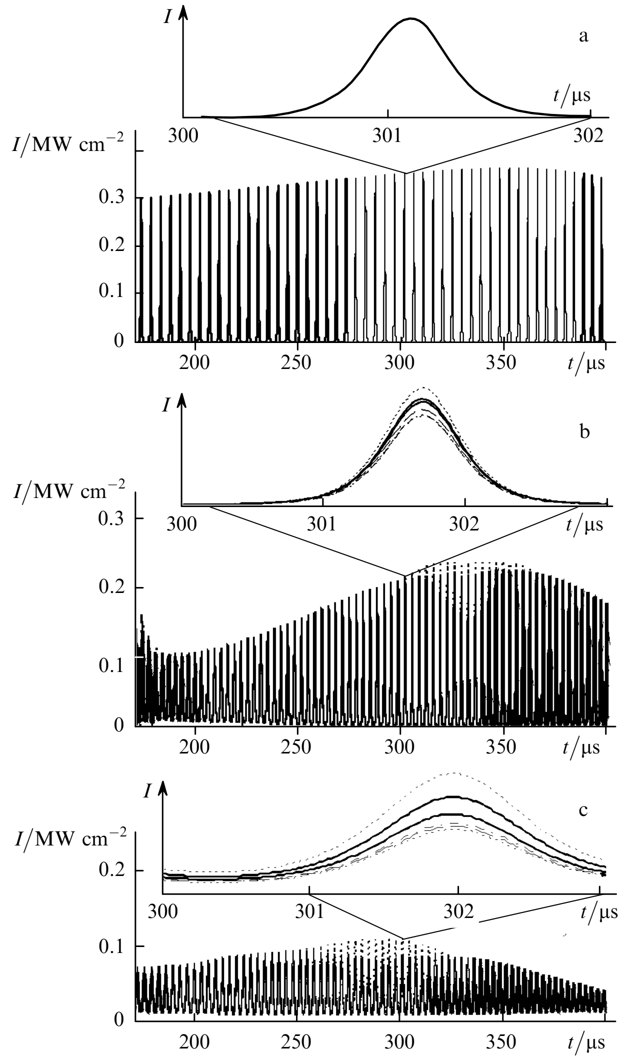

Figure 3. Calculated lasing kinetics of the six-channel holographic laser system with short-range coupling at $\Delta\alpha = 0$ (a) 0, (b) 0.012, and (c) 0.024 cm^{-1}.

lead to a time shift of laser pulses, we have in our case only a difference in the amplitudes of laser pulses. In this case, an increase in the gain mismatch results in the passage from the regime of regular undamped pulsations, which corresponds to the periodic Q-switching on gain gratings and was experimentally observed in [7], to the regime of free-running spikes decaying with decreasing the laser radiation intensity and single-mode lasing efficiency.

The absence of pulse shifts is explained by the short linear stage in the development of each laser pulse in contrast to the monopulse regime when a nonreciprocal element is used [3]. Unlike the case of long-range coupling [3], in our case, we do not observe better synchronisation of controlled channels (compared to the synchronization of the control laser and a set of controlled lasers) provided by the control channel. The amplitudes of laser pulses of any neighbouring channels differ by approximately the same value. Hence, it is possible to study the influence of the gain mismatch on the synchronisation of many lasers with short-range holographic coupling by considering any pair of neighbouring channels of the holographic laser system, because the behaviour of synchronisation of all the neighbouring lasers with short-range coupling is revealed even in an individual pair of channels.

Let us choose a criterion of desynchronisation of a laser system. In our case, the synchronisation of lasers is violated if the radiation pulses have different amplitudes, and, hence, we will assume that the system is desynchronised if the intensities of laser pulses of any channel pair differ by a factor of two, i.e. the desynchronisation condition has the form

$$I_{\max}/I_{\min} = 2. \tag{9}$$

Let the radiation intensity difference ΔI for any pair of neighbouring channels be identical in modulus (this is observed for the short-range coupling). In this case,

$$I_{\max} = I_{\min} + (N-1)\Delta I. \tag{10}$$

Then, by substituting chosen desynchronisation condition (9) in (10), we obtain the maximum number $N_{\max}$ of laser channels which can be synchronised at short-range coupling:

$$N_{\max} = \frac{I_{\max}/2}{\Delta I} + 1. \tag{11}$$

Let us study the dependence of the difference ΔI in the radiation intensities of the first and second channels on the gain mismatch $\Delta\alpha$ in neighbouring channels. This dependence in a multichannel system remains valid for any pair of neighbouring channels, and, hence, it is possible to directly calculate $N_{\max}$ from the radiation intensity ratio of the second and first channels I_{ch2}/I_{ch1} (note that here $\Delta I = I_{ch1} - I_{ch2}$ and $I_{\max} = I_{ch1}$) corresponding to the given value of $\Delta\alpha$:

$$N_{\max} = \frac{1/2}{1 - I_{ch2}/I_{ch1}} + 1. \tag{12}$$

Figure 4 shows the calculated dependence of $N_{\max}$ (12) on $\Delta\alpha$ at the input parameters given above. This dependence demonstrates that the gain mismatch in AEs should be decreased with increasing the number of laser channels,

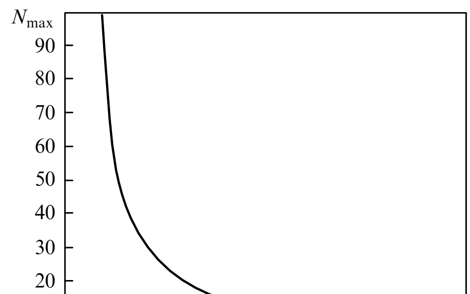

Figure 4. Dependence of the maximum number $N_{\max}$ of channels of a system with short-range coupling on the gain mismatch $\Delta\alpha$ between neighboring channels. The horizontal dashed line corresponds to $N_{\max} = 6$.

because the synchronisation region of a multichannel holographic laser system with short-range coupling lies below the dependence $N_{max}(\Delta\alpha)$ in Fig. 4. For example, for ten laser channels, it is necessary to have the gain mismatch $\Delta\alpha$ in lasing channels no higher than 0.015 cm^{-1}, i.e. the single-pass small-signal gain in our AEs can differ no stronger than by a factor of $e^{\Delta\alpha L}$ ($e^{\Delta\alpha L} \leqslant 1.162$) (we take $L = 10$ cm); in the case of a hundred laser channels, the allowable gain mismatch should be decreased to 0.0023 cm^{-1} ($e^{\Delta\alpha L} = 1.023$).

Our estimates agree well with the calculated value $\Delta\alpha = 0.024$ cm^{-1} (corresponding to Fig. 3c), at which condition (9) is fulfilled for our model of a six-channel system, i.e. $N_{max} = 6$. This N_{max} satisfies the dependence of N_{max} on $\Delta\alpha$ with a good accuracy (Fig. 4).

5. Experiment

The experiments were performed using a Nd : YAG laser with two AEs of size ⌀6.3 × 120 mm, 200-μs pump lamp pulses, and a pulse repetition rate of 5 Hz. The two-channel laser system was assembled according to the scheme shown in Fig. 1b. At the pump energy of each AE equal to 63 J, the single-mode radiation energy at the exit of each channel was 0.4 J, i.e. the laser system efficiency was 0.64 %. The phase locking of two channels of the laser system was estimated by the interference of output beams combined in the far-field zone. Figure 5 presents a typical radiation interference pattern with a contrast of 0.51, which confirms the existence of phase locking in the set of diffraction-coupled loop lasers without a nonreciprocal element at short-range coupling.

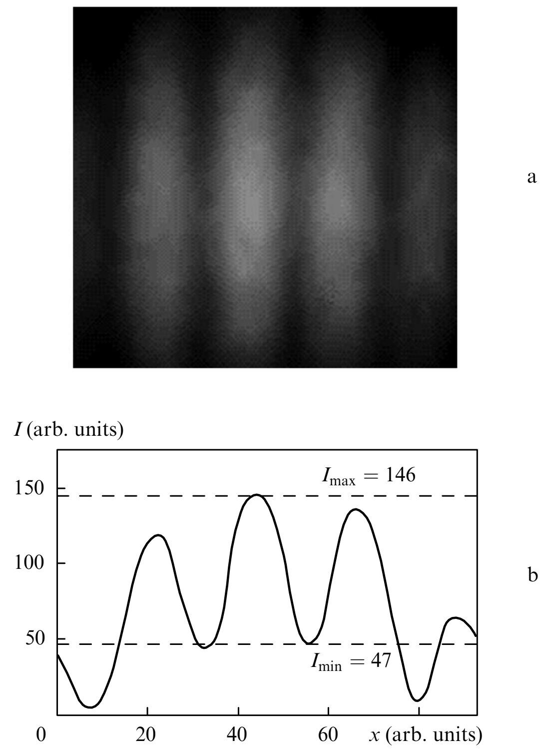

Figure 5. Interference pattern of radiation of the two-channel Nd : YAG laser system with sort-range coupling (a) and its intensity distribution (b).

6. Conclusions

Thus, a new method for improving the energy parameters of multichannel holographic laser systems has been developed based on the use of short-range coupling of laser channels and elimination of limitations related to the optical breakdown threshold of laser elements. This method allows one not only to increase the number of laser channels but also to increase the output energy of individual channels.

A compact scheme of a multichannel laser system with short-range coupling and increased lasing efficiency has been developed, which is important for application of low-gain laser materials operating in new promising spectral regions, for example, at wavelengths of 1.32 – 1.5 μm, corresponding to some laser transitions of the Nd : YAG crystal.

The numerical simulation has shown that the maximum possible number of laser channels can be increased (even above the maximum number of channels limited by the breakdown threshold in the case of the long-range coupling) by equalising the parameters of laser channels.

The test experiment have demonstrated not only the principal possibility of the phase locking of two loop Nd : YAG lasers without a nonreciprocal element, but also the increase in the lasing efficiency from 0.2 % to 0.64 % with the contract of the interference pattern of output radiation beams better than 0.5.

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