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Study of the self-phase-locking of a pulsed three-channel holographic Nd : YAG laser by gain gratings

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***Abstract*. The conditions of phase locking of a three-channel holographic Nd : YAG laser system based on self-pumped phase-conjugate oscillators emitting giant 100-mJ, 60-ns monopulses in each of the channels are investigated experimentally. The pulse-to-pulse stable self-phase-locking of the laser system with a pulse repetition rate up to 20 Hz is obtained. The mutual coherence of laser channels was increased up to 0.87 by separating the controlling channel which initiates lasing in a set of controllable channels generating synchronous monopulses.**

Keywords: *holographic coupling, interference contrast, multichannel laser system, self-phase locking.*

Loop self-phase-conjugate solid-state lasers on holographic gain gratings can produce high-power single-mode pulses of high optical quality with a controllable spatiotemporal shape. Studies of the passive *Q*-switching [1] and self-*Q*-switching [2] of loop lasers have shown that the peak power of nanosecond pulses in pulse trains generated by these lasers can achieve 20 MW and the average power can exceed 100 W [1]. However, a further increase in the output power is restricted by the radiation damage threshold of laser media.

One of the most efficient methods for reducing the radiation load on active elements is the building of parallel multichannel laser systems. In this case, to preserve the high quality of radiation of holographic lasers and phase locking of individual channels, the feedback in each channel and coupling between channels in the system should be performed on gain gratings in active laser media.

We proposed in [3] a method for the phase locking of optically coupled lasers by gain gratings in the active medium, studied two-channel laser systems based on loop self-phase-conjugate lasers, and demonstrated their phase locking with a high phasing degree (up to 0.9).

In this paper, we studied the possibility of increasing the number of phase-locked channels to three by using the holographic coupling between laser channels (long-range type of coupling between lasers [4]). Figure 1 presents the optical scheme of the laser system. The phase locking of the channels and their optical holographic coupling are performed in a common active element AE0 due to the six-wave mixing of radiation directed from lasing channels to AE0 with the help of a system of fold mirrors. In addition, AE0, as in the two-channel system [3], serves as an intrachannel amplifier. Unlike the two-channel laser, the three-channel laser has three output channels with optical wedges OW1 – OW3. The output beams were then combined on a target in the far-field zone by using a set of mirrors (not shown in Fig. 1). To reduce the effect of backscattering of counter-propagating waves in each of the oscillators from 5 % – 10 % [3] to 0.1% and to reduce radiation losses through the open AE1 – AE3 output, the contrast of nonreciprocal elements NE1 – NE3 was increased from 80 [3] to 200 by using Faraday rotators based on rare-earth (NdFeB) permanent magnets and a FRG-25 magnetooptical glass with the high Verdet constant (0.111 ang min A^{-1}).

Optical wedges OW1 – OW3 also separate radiation between channels (stationary optical coupling), and by changing the angle of incidence of radiation on an optical wedge, we can change the Fresnel reflection coefficient and, hence, the value of the stationary coupling between lasing channels. This coefficient was 0.1 % in our scheme, which proved to be sufficient due to a higher contrast of nonreciprocal elements. In addition, feedback in a new optical

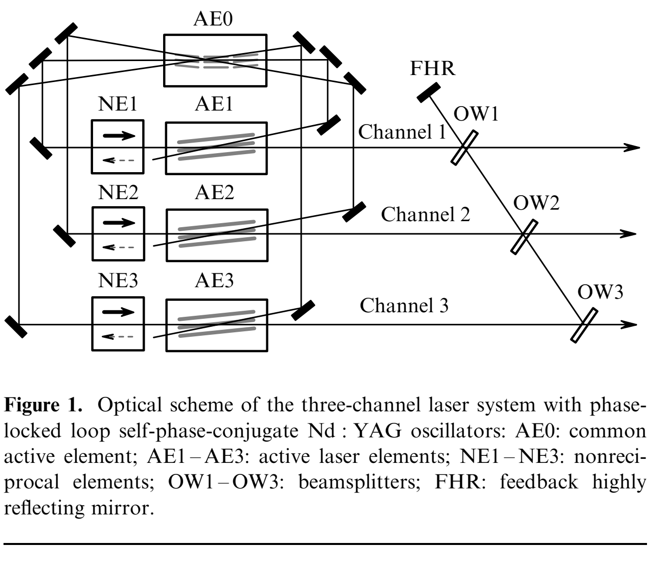

Figure 1. Optical scheme of the three-channel laser system with phase-locked loop self-phase-conjugate Nd : YAG oscillators: AE0: common active element; AE1 – AE3: active laser elements; NE1 – NE3: nonreciprocal elements; OW1 – OW3: beamsplitters; FHR: feedback highly reflecting mirror.

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scheme (Fig. 1) is performed by using a highly reflecting mirror (HR) rather than a partially reflecting mirror, as in [3]. We used a Sagnac interferometer [2, 5] as a HR, which provided the efficient angular selection of radiation, improved the Q factor of linear [6] and loop [1, 2, 5] laser resonators, and also separated the TEM_{00} mode without using an intracavity aperture.

Note that simulation of the lasing dynamics of a multichannel holographic system phase-locked by gain gratings with the long-range holographic coupling performed in [7] showed the following. The mismatch between gains in different channels can cause a strong time shift of generated nanosecond pulses. For equal relative mismatches of the field amplitude gains between the first, strongest channel, and the next-in-gain second (controllable) channel, and between the controllable second and third channels ($\Delta\alpha_{12} = \Delta\alpha_{23} = 0.003$ cm^{-1}), the relative time shift $\Delta\tau_{12}$ of laser pulses in the first and second channels ($\Delta\tau_{12}/\tau = 0.4$, where τ is the laser pulse duration) proved to be greater than the time shift $\Delta\tau_{23}$ for a pair of controllable channels ($\Delta\tau_{23}/\tau = 0.15$) by a factor of 2.7. The values of $\Delta\tau_{12}$ and $\Delta\tau_{23}$ increase up to the duration τ of laser pulses when $\Delta\alpha_{12}$ is increased up to 0.017 cm^{-1} and $\Delta\alpha_{23}$ up to 0.055 cm^{-1}, i.e. the single-pass small-signal gain in controllable laser channels can differ by a factor of three ($e^{2\times 0.055L} = 3$, where $L = 10$ cm is the active element length). In this paper, we studied the conditions of phase-locking of the three-channel laser system by selecting an active element in which the gain in one of the lasing channels was somewhat higher than in other channels, and used this channel as the control channel with respect to other (controllable) laser channels.

Experiments were performed by using a Nd:YAG laser with active elements of size ⌀6.3 × 100 mm. The maximum small-signal gain was no less than 80. Optical pumping was carried out with a GDN-13 four-channel power supply. The pump pulse duration was 250 μs, its maximum energy achieved 63 J per each quantron, and the pulse repetition rate was 5 Hz.

The phase-locking in each pair of the lasing channels and in the entire three-channel laser system was estimated from the interference of radiation beams in the Young experiment scheme by combining the output beams in the far-filed zone. Figure 2 shows the typical photographs of the interference patterns of output beams obtained with a TM1010 CCD camera in the accumulation regime for 2 min. Figure 2a demonstrates the interference pattern for a pair of the output beams from the first and second channels, Fig. 2b shows the interference pattern for a pair of output beams from the second and third channels, and Fig. 2c illustrates the interference pattern for all the three output beams of the laser system.

One can see from Fig. 2 that the interference pattern in all cases is well reproducible from pulse to pulse, i.e. the grating phase remains invariable, which demonstrates good phase locking of lasing channels in the repetitively pulsed regime. The increase in the pump pulse repetition rate from 5 to 20 Hz without the additional adjustment of resonators reduced the output energy of the laser system by 30 % (due to the thermally induced lens effect), however, the phase-locking of channels was not violated.

The study of the contrast of the interference pattern $V = (U_{max} - U_{min})/(U_{max} + U_{min})$ (where $U_{max,\,min}$ are the energy densities at the interference maximum and minimum, respectively) with the help of the CCD camera showed that the contrast V_{12} of interference of the controlling (first) and controllable (second) laser channels (Fig. 2a) did not exceed 0.5, as in our similar experiments with the two-channel system [3]. By measuring the temporal parameters with an LFD-2A avalanche photodiode and an Agilent 54641A oscilloscope, we found (Fig. 3a) that a low value of V_{12} was observed because the output laser monopulse of the controlling channel was ahead of synchronous laser monopulses of controllable channels. The time shift $\Delta\tau_{12}$ between these laser monopulses varied from 70 to 100 ns from pulse to pulse. The duration of the output monopulses of the system was 60 ns and exceeded the duration of the laser monopulse (40 ns) in each of the laser channels when the rest of the channels were switched off. This points to the appearance of a longer collective resonator in a phase-locked multichannel laser system [8]. The energy of laser pulses in individual lasing channels was approximately the same (about 120 mJ) upon pumping by 63-J pulses in each quantron with a pulse repetition rate of 5 Hz.

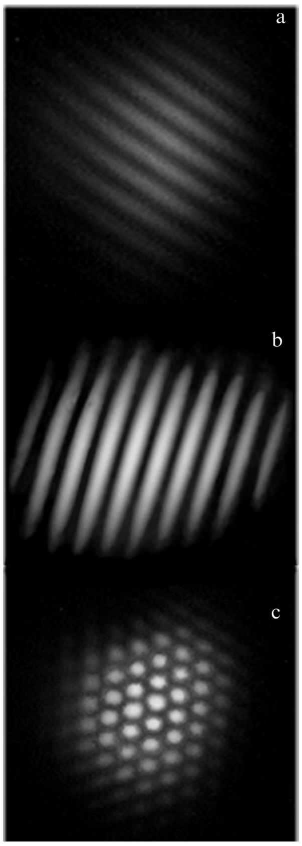

Figure 2. Photograph of the interference pattern for phased output radiation beams in the first and second (a), second and third (b), and three (c) channels.

Similar studies of phasing of a pair of controllable (second and third) channels in the Young experiment showed that their interference pattern has a higher contrast $V_{23} = 0.87$, which was close to the maximum value (Fig. 2b) and coincided with the degree γ_{23} of mutual coherence when the intensities of monopulses were equalised. The degree of mutual coherence was determined in the following way. By using the method described in [9, 10], the expressions for the energy density in the region of interference of two laser pulses can be written in the form

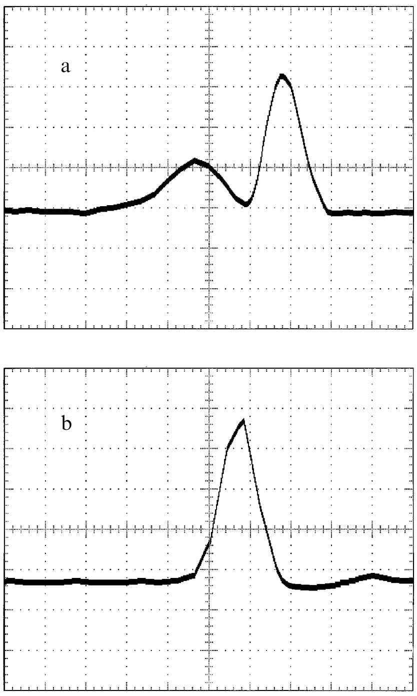

Figure 3. Oscillograms of radiation pulses for the pulse intensity ratios $I_2/I_1 \approx I_3/I_1 < 0.8$ (a) and $I_2/I_1 \approx I_3/I_1 > 0.8$ (b).

$$U_{ij} = \int_0^t \{I_i g(t') + I_j g(t' - \Delta\tau_{ij}) + 2[I_i g(t') I_j g(t' - \Delta\tau_{ij})]^{1/2} \gamma_{ij} \cos\Delta\Phi_{ij}\} \mathrm{d}t', \quad (1)$$

where I_i and I_j are the relative peak intensities of the ith and jth laser pulses; $g(t)$ is the form factor of the time envelope of a pulse normalised to the unit amplitude, which is assumed a Gaussian; and $\Delta\Phi_{ij}$ is the phase difference for interfering waves. Then, the degree of mutual coherence γ_{ij} (when it is constant in time and under the condition that $\cos\Delta\Phi_{ij} = \pm 1$ in the interference maximum and minimum, respectively) can be estimated by the contrast of the interference pattern and the degree of time synchronisation [3] as

$$\gamma_{ij} = V_{ij}/f_{ij}, \quad (2)$$

where

$$f_{ij} = \frac{2\int_0^t [I_i g(t') I_j g(t' - \Delta\tau_{ij})]^{1/2} \mathrm{d}t'}{\int_0^t [I_i g(t') + I_j g(t' - \Delta\tau_{ij})] \mathrm{d}t'} \simeq \frac{2(I_i I_j)^{1/2}}{I_i + I_j} \exp[(-\Delta\tau_{ij}^2 \ln 2)/\tau^2] \quad (3)$$

is the degree of time synchronisation or the degree of the mutual overlap of laser pulses of the same duration shifted in time with respect to each other.

The high contrast V_{23} can be explained by the fact that the laser pulses of controllable channels are generated synchronously. The second pulse of the oscillogram in Fig. 3a is formed by the mutual overlap of synchronous pulses of controllable channels. This confirms the results of numerical simulations [7] according to which the time shift between the output laser pulses of controllable channels (second and third) was virtually absent in the case of the same gain mismatch between the first and second and between the second and third channels.

The relative time shift $\Delta\tau$ between the laser pulse of the first (controlling) channel and pulses of the second and third (controllable) channels was changed by varying the triggering time of the pump pulses in the controlling channel with respect to the synchronised pump pulses of controllable channels in the interval from 10 to 100 ns with the help of an electronic delay line. In this case, the lasing regime in each controllable channel was changed from the near-threshold regime to a regime close in intensity to the lasing regime of the controlling channel. Figure 4 presents the dependence of the time shift $\Delta\tau_{12}$ between the output pulses of the coupled lasing of the first and second channels on the intensity ratio of their own lasing. A similar dependence was obtained for the coupled lasing of the first and third channels. One can see from Fig. 4 that in the case of the near-threshold lasing intensity in controllable channels, the time shift $\Delta\tau_{12}$, as before, falls in the interval 70 – 100 ns. As the intensity of the output pulses in channels is equalised, the relative time shift $\Delta\tau_{12}$ decreases, and pulses are generated in fact synchronously when $I_2/I_1 = 0.8 - 1.0$. Figure 3b shows the oscillogram corresponding to the synchronous generation of pulses in all the three channels for the intensity ratio $I_2/I_1 \approx I_3/I_1 > 0.8$.

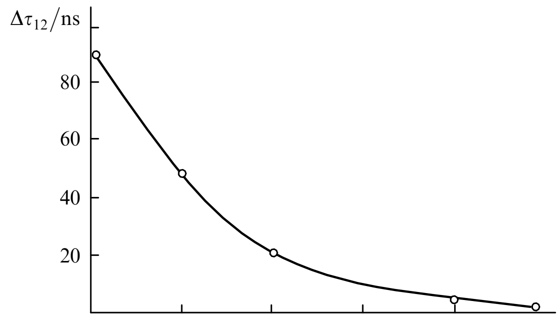

Figure 4. Dependence of the time shift $\Delta\tau_{12}$ between the output pulses of coupled lasing of the first and second channels on the ratio I_2/I_1 of their lasing intensities.

Figure 2c shows the interference pattern for three output beams observed upon synchronous lasing in three laser channels in the case of equal intensities of lasing in these channels provided by the electronic control of delays of pump pulses. The contrast of the interference patterns produced by all pairs of the beams $V_{12} \approx V_{23} \approx V_{13}$ did not exceed ~ 0.55. Then, in the case of the total time synchronisation, the degree of mutual coherence of pairs of laser channels has the same value (~ 0.55) according to (2). However, in the presence of the time shift between pulses, the degree of mutual coherence was large even for shifted pulses because for parameters $\Delta\tau_{12} \approx 70$ ns and $V_{12} \approx 0.5$ measured in experiments, we obtain the value $\gamma_{12} \approx 1$ from (2) and (3). The decrease in the mutual coherence of radiation beams can be explained by the fact that in the case of efficient lasing in controllable lasing channels, the competition between lasing in controllable (second and third) channels and radiation in the controlling (first) channel increases. As a result, the diffraction efficiency of gain gratings decreases first of all in the controlling channel, while the laser system is completely synchronised. As the time delay between controlling and controllable pulses is increased, gain gratings are written predominantly by controlling radiation, and their diffraction efficiency is higher than that of gratings written by radiation of controllable channels. As a result, lasing in the controlling channel dominates, thereby increasing the degree of mutual coherence of radiation in laser channels.

Figure 5 presents the typical dependences of the interference contrast V_{12} of radiation pulses in the first and second laser channels and the degree of their time (the degree f_{12} of overlap of pulses [3]) and frequency (the degree γ_{12} of mutual coherence) synchronisation on the shift $\Delta\tau_{12}$ of these laser pulses. One can see that, as $\Delta\tau_{12}$ is increased, the value of γ_{12} increases but f_{12} decreases, which results in a decrease in the interference contrast V_{12}. As $\Delta\tau_{12}$ is decreased, the degree of frequency synchronisation slightly decreases but the degree of time synchronisation increases. For this reason, for $\Delta\tau_{12} < 50$ ns, the maximum contrast $V_{12} \approx 0.55$ of the interference pattern for the controlling (first) and controllable (second) channels is observed. At the extreme point of this interval ($\Delta\tau_{12} \approx 50$ ns), the degree of mutual coherence $\gamma_{12} \approx \gamma_{23} \lesssim 0.76$ corresponds to the maximum value of V_{12}, which conforms to the optimal degrees of the time and frequency synchronisation of the three laser channels. In the case of the maximum shift $\Delta\tau_{12} \approx 100$ ns, the degree of mutual coherence $\gamma_{12} \approx \gamma_{23}$ increases up to its maximum value ~ 0.87.

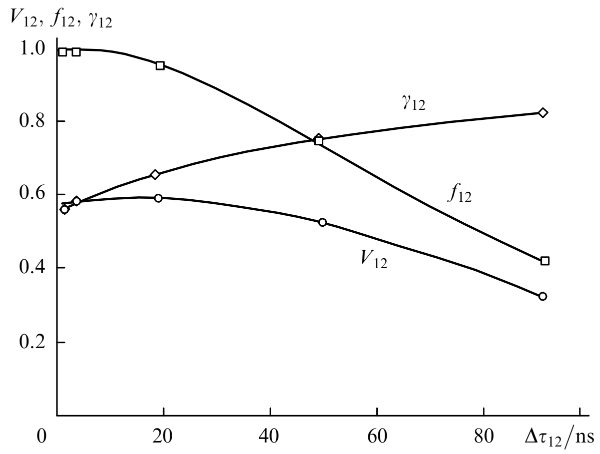

Figure 5. Dependences of the interference contrast V_{12} for the output pulses of the first and second channels and the degrees of their time (f_{12}) and frequency (γ_{12}) synchronisation on the time shift $\Delta\tau_{12}$ of these laser pulses.

Thus, we have obtained the pulse-to-pulse stable self-phase-locking of the three-channel holographic Nd : YAG laser system based on self-pumped phase-conjugate oscillators emitting 60-ns, 100-mJ pulses in each channel with a pulse repetition rate up to 20 Hz.

The increase in the degree of mutual coherence of radiation in laser channels to the value close to unity achieved by separating the controlling channel, which triggers lasing in a set of synchronously lasing controllable channels, demonstrates the efficiency of phase-locking by the gain gratings in the active laser medium and suggests that the number of phased lasing channels can be further increased.

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