

CONTROL OF LASER RADIATION PARAMETERS

PACS numbers: 42.55.Rz; 42.65.Hw; 42.60.By; 42.40.Eq
DOI: 10.1070/QE2011v041n03ABEH014490

Control of phase locking in a set of lasers with self-pumped phase-conjugate gain-grating mirrors using a passive *Q*-switch

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***Abstract*.** **We studied the possibility of controlling phase-locked lasing of a set of lasers with self-pumped phase-conjugate gain-grating mirrors by using a passive *Q*-switch and selecting the gain of one of the lasers. The ranges of stable operation are calculated by mathematical simulation and well agree with the experimental results. Single-mode radiation in the form of trains of phase-locked laser pulses are experimentally obtained for the first time in a three-channel diffraction-coupled gain-grating Nd : YAG laser system with a LiF : F_2^- passive *Q*-switch. The space-time pattern of the trains of 1.064-μm nanosecond pulses is the same in the channels with and without *Q*-switch and their interference pattern contrast reaches 0.81.**

Keywords: *multichannel laser system, phase locking, passive laser Q-switch, interference pattern contrast.*

1. Introduction

The development of high-power solid-state lasers based on small-size crystals is a complicated scientific and engineering problem of modern laser physics. One of the possible solutions of this problem consists in the use of multichannel laser system. This solution involves numerous problems related to the synchronisation and phase locking of separate laser channels, as well as to the control of the synthesised space-time structure of multichannel laser radiation [1].

In [2], we proposed to phase lock diffraction-coupled loop laser cavities [3, 4], which ensure self-compensation of optical distortions due to the phase conjugation on holographic gain gratings. We experimentally demonstrated phase-locked multichannel holographic Nd : YAG laser systems with long- [5] and short-range [6] coupling by gain gratings. In contrast to laser systems with long-range coupling (each channel with each one), in which the number of laser channels is limited due to their optical coupling in one common active element (AE), the laser system with short-range coupling (coupling of neighbouring channels) allows one to realise an unlimited number of laser channels, since each pare of neighbouring channels in this case has its own coupling active element. However, the interference pattern contrast for this scheme of a two-channel Nd : YAG laser system operating in the free-running regime did not exceed 0.6 [6]. At the same time, it was experimentally found that the introduction of a passive *Q*-switch (PQS) based on a LiF : F_2^--crystal into this laser system leads to an increase in the interference contrast of the output beams up to 0.81 [7].

In this work, we study the possibility of controlling the phase locking of radiation in a multichannel Nd : YAG laser system with self-pumped self-conjugate gain grating mirrors using a passive *Q*-switch introduced into one of the laser channels to ensure the synchronous start of the entire system.

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Received 19 November 2010
Kvantovaya Elektronika **41** (3) 202–206 (2011)
Translated by M.N. Basieva

2. Mathematical simulation of lasing kinetics

We used our previously developed point model of the active medium [6]. The point model of the PQS was written in a similar form. The material rate equation for the resonance absorption coefficient μ of a PQS has the form [8]

$$\frac{d\mu}{dt} = -\frac{I_1 + I_2 + I_3 + I_4}{U_Q}\mu + \frac{\mu_0 - \mu}{\tau_Q}, \quad (1)$$

where μ_0 is the initial resonance absorption coefficient of the PQS; U_Q is the PQS absorption saturation energy density; τ_Q is the lifetime of the upper working level of the PQS; and $I_1 - I_4$ are the intensities of waves interacting with the PQS. The point parameter of a PQS is its optical transmittance

$$T = \exp(-\mu d - kd), \quad (2)$$

where k is the parasitic (nonresonance absorption and scattering) loss coefficient; d is the length; $\ln(1/T)$ is the total loss increment; and kd is the parasitic loss increment of the passive *Q*-switch. If the signal is weak, $\mu = \mu_0$, and the initial point parameter of a PQS is its initial transmittance

$$T_0 = \exp(-\mu_0 d - kd). \quad (3)$$

Figure 1 shows the optical scheme of the studied three-channel holographic laser system. Each laser channel is a loop laser cavity with a self-pumped phase-conjugate mirror formed in the active element. In each AE, the six-wave interaction involves three degenerate four-wave mixing processes, one of which is responsible for the feedback forming the loop cavity and the other two processes create the diffraction coupling with the neighbouring loop cavities. A passive Q-switch placed in one of the laser channels synchronously switches lasing in all the laser channels, which emit trains of giant nanosecond phase-locked pulses. The radiation of channels is linearly summed on a reference mirror (RM) and equally distributed over the channels using beam splitters with the reflectances $R_i = 1/i$, where i is the channel number. The boundary conditions of the laser kinetics model are determined according to this scheme.

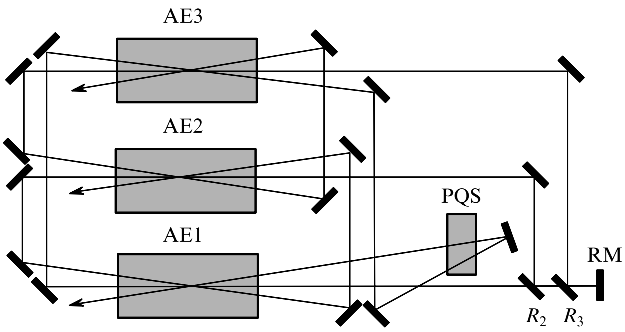

Figure 1. Optical scheme of the studied three-channel holographic laser system: (AE1, AE2, AE3) active elements of the first, second, and third channels; (PQS) passive Q-switch in the first laser channel; (RM) reference mirror; (R_2, R_3) reflectances of beamsplitters ($R_i = 1/i$).

We performed numerical simulation for a system with a Nd^{3+} : YAG active element and a LiF : F_2^- passive Q-switch with the following saturation energy densities and lifetimes of the upper working levels [9, 10]: $U_s = 0.53$ J cm^{-2}, $\tau_s = 250$ μs for the AE and $U_Q = 0.0029$ J cm^{-2}, $\tau_Q = 55$ ns for the PQS. The parasitic loss increments of the AE and PQS were taken to be 0.1.

To determine the conditions of the diffraction-coupled lasing of a three-channel laser system, we introduced into our calculations the mismatch between the gain increments of neighbouring AEs (or laser channels)

$$\Delta\alpha L = (\alpha_0^{(1)} - \alpha_0^{(2)})L = (\alpha_0^{(2)} - \alpha_0^{(3)})L,$$

where $\alpha_0^{(i)}$ is the unsaturated gain of the ith AE and L is the AE length. Figure 2 presents the results of computer calculations of the lasing kinetics of the three-channel laser system with a PQS ($\alpha_0^{(1)}L = 4.4$, $T_0 = 60\,\%$) in the first laser channel for different mismatches between the gain increments of neighbouring laser channels.

It is well known that a laser can operate in a Q-switched regime if the initial transmission of the PQS is sufficiently low to prevent lasing until the PQS is unsaturated, which determines the upper boundary of the region of acceptable initial transmissions of PQSs. Figure 2 also points to the existence of the low boundary of this region at which the multichannel laser system does not operate in a stable regime. One can see that, at the chosen mismatches $\Delta\alpha L$, the output laser pulses of all the laser channels are generated synchronously, while the pulses of the second and third laser channels even have similar intensities; however, the intensity and shape of the output pulses depend on the gain mismatch. In particular, the passive Q-switching regime observed at $\Delta\alpha L = 0.3$ changes to the free-running regime,

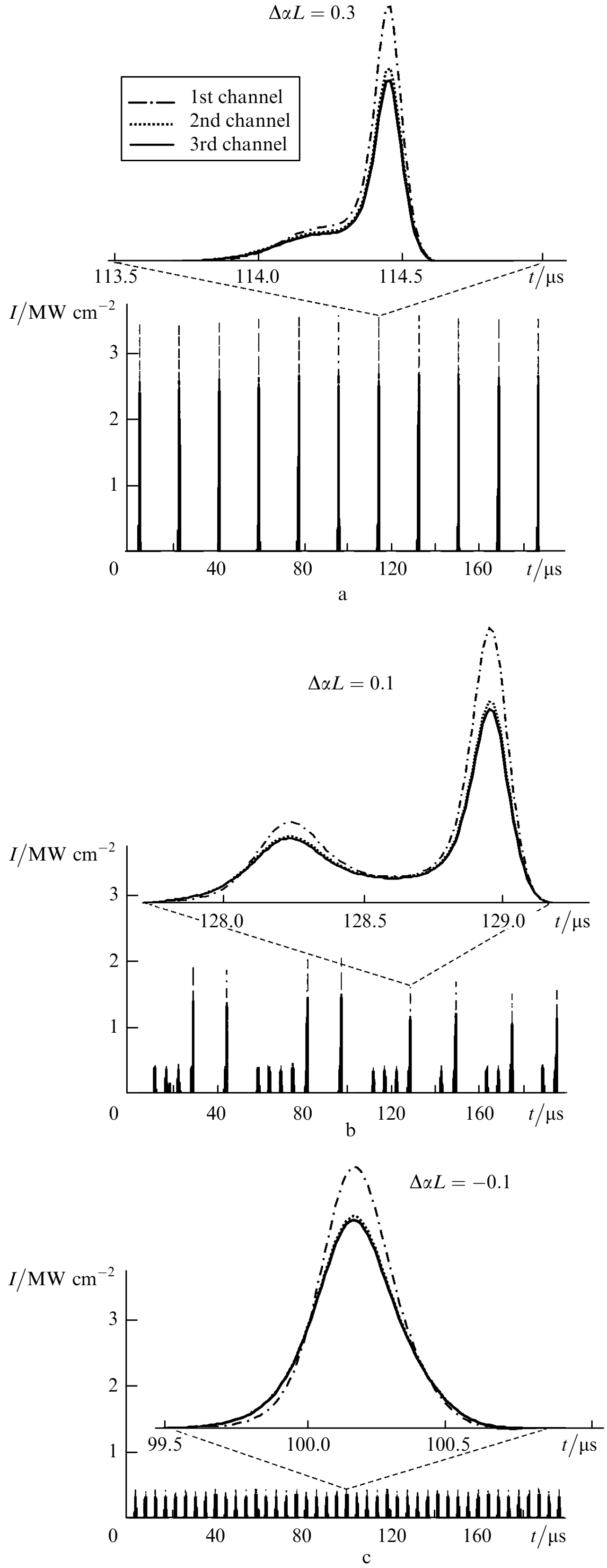

Figure 2. Results of computer calculation of the lasing kinetics of a three-channel laser system with a PQS in the first laser channel at $\Delta\alpha L = 0.3$ (a), 0.1 (b), and -0.1 (c); $\alpha_0^{(1)}L = 4.4$, $T_0 = 60\,\%$.

which does not depend on the PQS, at $\Delta\alpha L = -0.1$. On the contrary, at a large positive mismatch ($\Delta\alpha L = 0.3$), the first laser channel injects its Q-switched radiation into all the laser channels, because of which the radiation is phase locked.

At a large gain mismatch, $\Delta\alpha L = 0.3$ ($\alpha_0^{(1)}L = 4.4$, $\alpha_0^{(2)}L = 4.1$, $\alpha_0^{(3)}L = 3.8$), Fig. 2a shows the most stable Q-switching regime, when the train consists of giant laser pulses with an intensity of ~ 4 MW cm^{-2}, a duration of ~ 100 ns, and a period of ~ 20 µs. Figure 2b shows that the decrease in the gain mismatch to $\Delta\alpha L = 0.1$ ($\alpha_0^{(1)}L = 4.4$, $\alpha_0^{(2)}L = 4.3$, $\alpha_0^{(3)}L = 4.2$) leads to a spread in the intensity and repetition rate of laser pulses. In this case, each giant pulse with an intensity of 1.5–2 MW cm^{-2} and a duration of 150 ns is preceded by several free-running spikes with an identical intensity (~ 0.5 MW cm^{-2}), a duration of ~ 200 ns, and a period of 5 µs, whose number within the interval between neighbouring giant pulses chaotically changes. In addition, the giant pulses have a lower intensity, a smaller pulse repetition rate, and a worse stability.

Figure 2c, which is plotted for the gain mismatch decreased to $\Delta\alpha L = -0.1$ ($\alpha_0^{(1)}L = 4.4$, $\alpha_0^{(2)}L = 4.5$, $\alpha_0^{(3)}L = 4.6$), i.e., when the controlling first laser channel (with the PQS) has a smaller gain than the channels without PQS, demonstrates the complete absence of giant pulses. One observes only free-running pulses with an intensity of 0.5 MW cm^{-2}, a duration of ~ 200 ns, and a period of 5 µs, which are typical for separate laser channels without PQS.

Our calculation allowed us to determine the regions of gain increment mismatches corresponding to the completely stable and phase-locked diffraction-coupled lasing, which was found to be $(\Delta\alpha L)_Q \geqslant 0.3$ for $T_0 = 60\,\%$. We can conclude that the completely stable operation with the use of a PQS with $T_0 = 60\,\%$ is observed when the gain of the AE of the first channel exceeds the gain of the other AEs by a value that compensates the initial losses in the PQS [their increment is $\ln(1/T_0) \approx 0.5$]. The simulation of lasing with optically denser PQSs confirmed this conclusion, since a decrease in the initial transmittance of the PQS lead to an increase in the minimum $(\Delta\alpha L)_Q$. In particular, at $T_0 = 40\,\%$ ($\ln(1/T_0) \approx 0.9$) we have $(\Delta\alpha L)_Q \geqslant 0.5$, and at $T_0 = 20\,\%$ ($\ln(1/T_0) \approx 1.6$) we have $(\Delta\alpha L)_Q \geqslant 1.0$.

Additional calculations showed that the gain mismatch ($\alpha_0^{(2)} - \alpha_0^{(3)}$) between the second and third channels (without PQS) slightly affects the lasing regime of the multichannel laser system. It was found that the laser regimes described above (see Fig. 2) are determined mainly by the gain or loss mismatch between the first and the other channels, i.e., we can take $\Delta\alpha = \alpha_0^{(1)} - \alpha_0^{(2)}$, while the mismatch between $\alpha_0^{(2)}$ and $\alpha_0^{(3)}$ can take any value rather than only $\Delta\alpha$, and we will obtain a kinetics similar to the kinetics shown in Fig. 2.

3. Experimental investigations of the possibility of controlling the phase-locked regime of laser operation

We experimentally studied the three-channel 1.06-µm Nd : YAG laser system whose scheme is shown in Fig. 1. We used K301V pump cavities with elliptical mirror reflectors, AEs $\varnothing 6.3 \times 100$ mm in size, and pumping by lamp pulses with an energy of 63 J, a duration of 200 µs, and a repetition rate of 5 Hz. We used PQSs based on $LiF:F_2^-$ crystals with the initial transmittances $T_0 = 20\,\%$, 40 %, and 60 %. The AE in the first channel had the highest small-signal gain (about 80), which corresponds to the gain increment $\alpha_0^{(1)}L \approx 4.4$, which was used in our simulation. The small-signal gains of the AEs in the second and third channels were smaller, of about 55 and 50, respectively, which correspond to $\alpha_0^{(2)}L \approx 4.0$ and $\alpha_0^{(3)}L \approx 3.9$, i.e., the difference between the gain increments of the first and second channels was $\Delta\alpha L \approx 0.4$. To equally divide the laser radiation energy between the channels, the beamsplitters for the second and third channels had the reflectances $R_2 = 1/2$ and $R_3 = 1/3$, respectively ($R_i = 1/i$). Between the beamsplitters and the reference mirror (see Fig. 1), we placed an aperture diaphragm with a diameter of 3.5 mm [2], which separated the main lasing mode and ensured the coaxial summation of the beams of laser channels in the region of the reference mirror.

The time profiles of laser pulses were measured by an LFD-2A avalanche photodiode connected to an Agilent 54641 A oscilloscope, and the energy parameters were measured with an Ophir power meter. The interference pattern of the output beams of laser channels was recorded using a CCD camera. The interference pattern contrast V was determined by the formula $V = (I_{max} - I_{min}) \times (I_{max} + I_{min})^{-1}$, where I_{max} and I_{min} are the maximum and minimum intensities in the interference pattern.

We studied the specific features of phase locking of single-mode beams of the second and third laser channels (without PQS) for different initial transmittances of the PQS placed in the first laser channel. Figure 3 shows the recorded oscillograms and interferograms for the second and third laser channels.

As is seen from Fig. 3, the decrease in the PQS initial transmittance from 60 % to 20 % leads to a suppression of the train of giant laser pulses, which were generated due the use of the PQS, and to the appearance of chaotic free-running pulses, which well agrees with the calculated lasing kinetics (see Fig. 2), since the gain mismatch $\Delta\alpha L \approx 0.4$ realised at $T_0 = 60\,\%$ satisfies the calculated stable operation range $(\alpha L)_Q \geqslant 0.3$, the mismatch at $T_0 = 40\,\%$ lies near the lower boundary of this range $(\alpha L)_Q \geqslant 0.5$, and the mismatch at $T_0 = 20\,\%$ lies outside the stable operation range $(\alpha L)_Q \geqslant 1.0$. At the same time, the decrease in T_0 also decreases the interference pattern contrast from 0.81 to 0.59, the latter value being close to the contrast in the case of the free-running operation of the laser system without PQS, which is 0.51 [6].

In the case of $T_0 = 60\,\%$, the energies of all the three output laser beams were similar to each other, while the total energy of the single-mode output laser radiation reached 0.5 J, which corresponds to the laser efficiency of 26 %. The interference pattern contrast was high not only for the second and third laser channels, but also for the first channel with the others. Figure 4 shows a typical interference pattern of all the three output laser beams at $T_0 = 60\,\%$, which demonstrates phase-locked operation of the entire laser system with $V > 0.8$. The decrease in the initial transmittance of the PQS lead to an increase in the energy of the single-mode radiation of the second and third laser channels with respect to the energy of the first channel, because of which the contrast of the interference between the first and the other channels decreased stronger than between the second and third channels. The total energy of the single-mode output laser radiation decreased and did not exceed 0.3 J at $T_0 = 20\,\%$, only 20 % of this value belonging to the first channel, while the other channels contributed

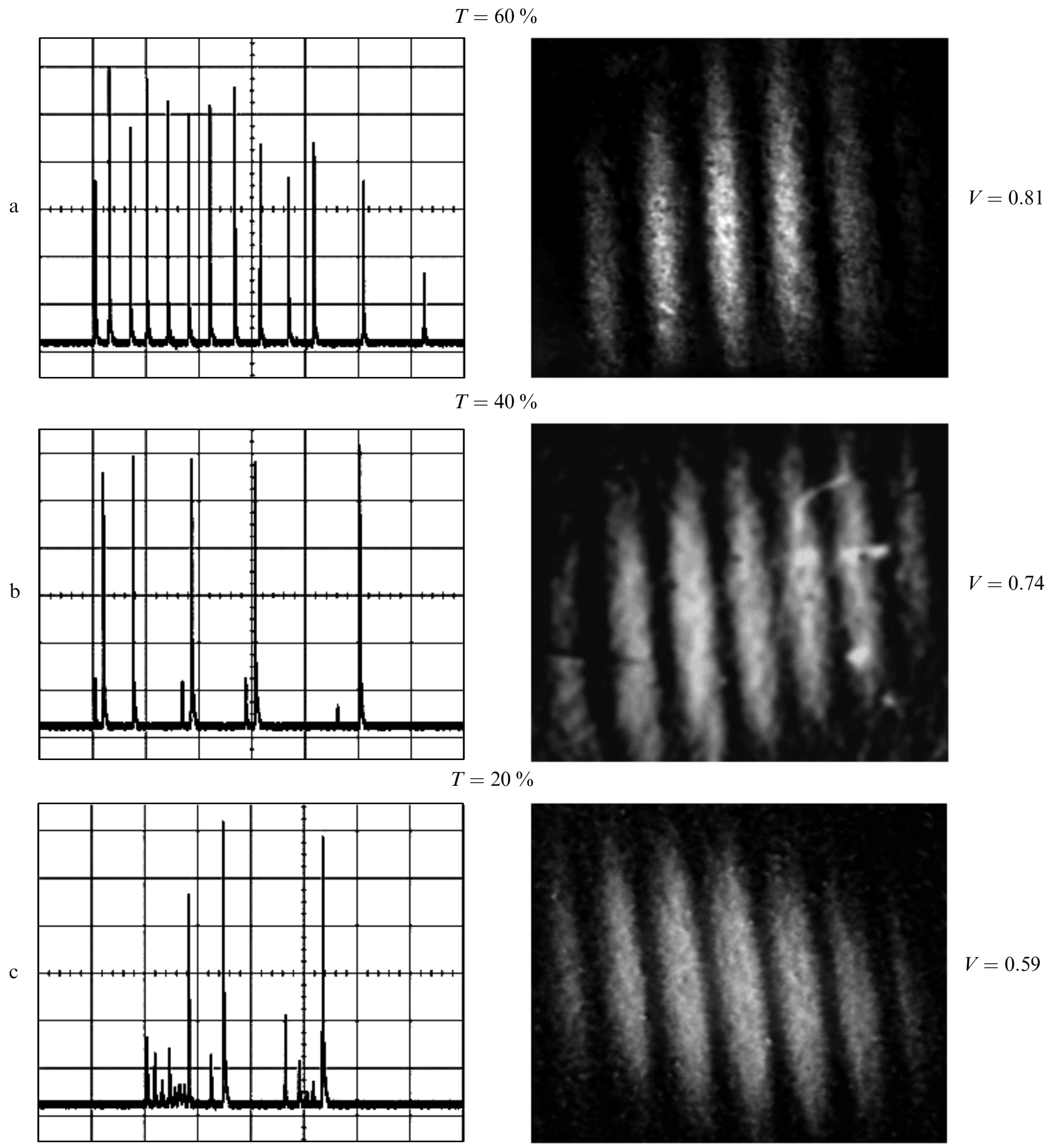

Figure 3. Experimental oscillograms (left column) and interferograms of the second and third laser channels (right column) at $T_0 = 60\,\%$ (a), 40 % (b), and 20 % (c).

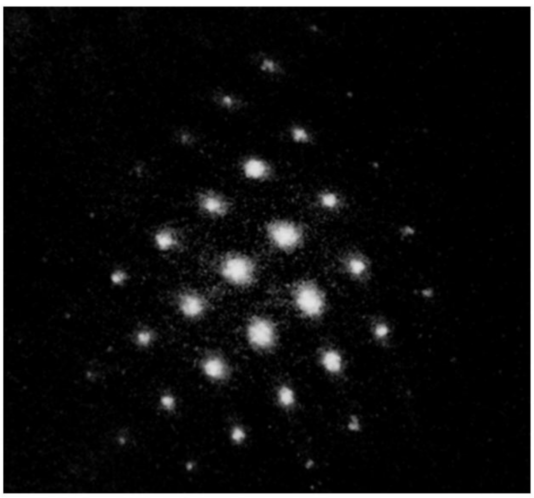

Figure 4. Typical interference pattern of all the three output laser beams at $T_0 = 60\,\%$ with an interference contrast higher than 0.8.

40 % each. The lower energy of the first laser channel is explained by losses in the optically dense PQS.

Thus, our experimental results confirm the conclusion that, to obtain phase-locked and stable operation with a high interference pattern contrast of the laser beams at a lower initial transmittance of the PQS, it is necessary to compensate the losses in the PQS by increasing the gain of the first channel with respect to the laser channels without PQS. The use of a gradient coloured PQS [4] will allow one to continuously control the phase-locked lasing by changing the PQS initial transmittance and the pump energy of the first laser channel.

4. Conclusions

Thus, we studied the possibility of controlling the phase locking of radiation in a holographic three-channel Nd:YAG laser system by introducing a PQS in one of the laser channels in order to ensure a synchronous start of the entire multichannel laser system.

By mathematical simulation, we determined the ranges of stable laser operation, which well agree with the experimental results. It is found that the stable and phase-locked regime of diffraction-coupled lasing occurs if the gain of the AE of the first channel (with a PQS) exceeds the gain of the active elements in the other channels (without PQS) by a value that compensates the initial losses in the PQS.

The phase-locked single-mode operation of a three-channel diffraction-coupled Nd : YAG laser system based on gain gratings with a $LiF:F_2^-$ passive *Q*-switch with different initial transmittances is experimentally realised for the first time and demonstrated identical space-time patterns of the 1.064-μm emission of trains of nanosecond pulses both in the channel with a PQS and in the channels without PQS with their interference contrast up to 0.81 and the total output energy of the single-mode laser radiation up to 0.5 J.

Acknowledgements. This work was partly supported by the Analytical Departmental Targeted Program 'Development of Scientific Potential of Higher School' (Grant No. RNP.2.1.1/3838) and by the Russian Foundation for Basic Research (Grant No. 09-02-99023).

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