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Dynamic phasing of multichannel cw laser radiation by means of a stochastic gradient algorithm

V.A. Volkov, M.V. Volkov, S.G. Garanin, Yu.V. Dolgopolov, A.V. Kopalkin, S.M. Kulikov, F.A. Starikov, S.A. Sukharev, S.V. Tyutin, S.V. Khokhlov, D.A. Chaparin

Abstract. **The phasing of a multichannel laser beam by means of an iterative stochastic parallel gradient (SPG) algorithm has been numerically and experimentally investigated. The operation of the SPG algorithm is simulated, the acceptable range of amplitudes of probe phase shifts is found, and the algorithm parameters at which the desired Strehl number can be obtained with a minimum number of iterations are determined. An experimental bench with phase modulators based on lithium niobate, which are controlled by a multichannel electronic unit with a real-time microcontroller, has been designed. Phasing of 16 cw laser beams at a system response bandwidth of 3.7 kHz and phase thermal distortions in a frequency band of about 10 Hz is experimentally demonstrated. The experimental data are in complete agreement with the calculation results.**

Keywords: *phasing of multichannel cw laser radiation, stochastic parallel gradient algorithm.*

1. Introduction

The possibility of active coherent phasing of radiation of cw (in particular, fiber) lasers attracts attention of many researchers in view of the prospects of developing high-power laser systems with a very small divergence (see, for example, [1–5]). In the case of parallel summation of N_f laser channels and increase in the energy of the system by a factor of N_f (in comparison with the single-channel case), coherent addition of output beams makes it possible to increase the radiant intensity by a factor of N_f^2 due to the mutual phasing of radiation in parallel channels [6]. It was reported in [7–11] about application of an iterative procedure of phasing the radiation of cw single-mode lasers, based on the stochastic parallel gradient descent method [12]. This approach is iterative and its great advantage is that it does not require to determine either the phase or the phase difference for individual laser beams.

In this study we performed phasing of cw multichannel laser radiation using one of the versions of the aforementioned approach: the stochastic parallel gradient (SPG) algorithm, which is also applied in adaptive optics [13, 14]. Our purpose was to demonstrate (both numerically and experimentally) the efficiency of the SPG algorithm for active phasing of a multichannel beam.

V.A. Volkov, M.V. Volkov, S.G. Garanin, Yu.V. Dolgopolov, A.V. Kopalkin, S.M. Kulikov, F.A. Starikov, S.A. Sukharev, S.V. Tyutin, S.V. Khokhlov, D.A. Chaparin Russian Federal Nuclear Center 'All-Russian Research Institute of Experimental Physics', prosp. Mira 37, 607190 Sarov, Nizhni Novgorod region, Russia; e-mail: wolf-87ph@yandex.ru, garanin@otd13.vniief.ru

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2. Scheme of SPG phasing of parallel laser channels

The block diagram of coherent phasing of cw laser radiation using the SPG algorithm in the 'single-channel master oscillator + set of amplifiers' geometry is shown in Fig. 1. The phase modulators are controlled in correspondence with the SPG procedure using a computer and a multichannel control unit. A small fraction of the multichannel beam transmitted through amplifiers (*4*) is split off using a beam-splitter (*6*) and focused by a lens (*7*) onto a photodetector (*8*). The photodetector measures (in the lens focal plane) a certain objective function: axial intensity, power of radiation transmitted through a small paraxial diaphragm, beam size, etc.

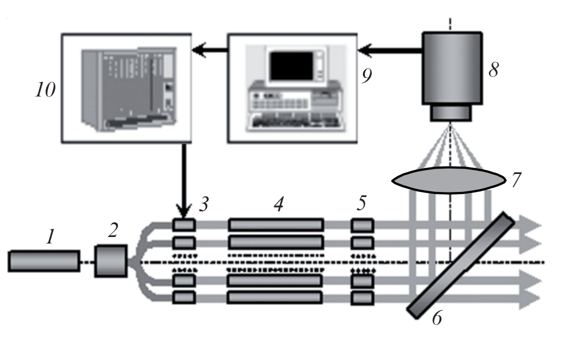


Figure 1. Scheme of coherent active phasing of fiber lasers using the SPG procedure: (*1*) master oscillator, (*2*) beam splitter into N_f beams, (*3*) phase modulators, (*4*) amplifiers, (*5*) optical insulators, (*6*) beam-splitter, (*7*) lens, (*8*) photodetector, (*9*) computer, and (*10*) multichannel unit for controlling phase modulators.

The SPG algorithm is implemented in the predictor–corrector scheme; i.e., each iteration consists of two stages [13, 14]. In the first stage, phase modulators (*10*) induce simultaneously (with the aid of a control unit) relatively small probe random phase shifts in channels, after which the change in the chosen objective function is analysed. Based on the analysis results, additional correction phase shifts are induced in the channels in the second stage, as a result of which the objective function increases in comparison with the initial one. After the correction, a new value of the objective function is recorded, a current iteration is performed, etc., until the objective function reaches (according to some criterion) the limiting value.

3. Optimisation of the SPG algorithm

When performing calculations, it was assumed for definiteness that the set of parallel amplifiers is enclosed in a square packing, and the phase and intensity distributions at the output of each amplifier are uniform. It was also assumed that the multichannel beam at the output is characterised by a random spread of phases over channels with a uniform phase distribution in the range $[-\pi, +\pi)$, because the phase delay on the path from the splitter to the amplifier output in different channels is different, and amplifiers are differently heated during operation. The phases at the amplifier outputs can be equalised by inducing certain phase shifts in the channels with the aid of phase modulators.

Suppose we have a set of phases $\varphi_n^{(m)}$ (which is unknown) and an objective function $Q_m = Q(\boldsymbol{\varphi}^{(m)})$ (which is known) at the output after the mth iteration of SPG algorithm. Random and relatively small phase shifts $\tilde{\varphi}_n^{(m+1)} = \varphi_n^{(m)} + \delta\varphi_n^{(m)}$ (n = 1, 2,..., and N_f is the laser channel number) are induced in channels in the first stage of the (m + 1)th iteration. It is assumed in the calculations that $\delta\varphi_n^{(m)}$ take values α, identical in modulus but random in sign. After the first stage the objective function takes the value $\tilde{Q}_m$. In the second stage of the (m + 1)th iteration, phases are corrected: $\varphi_n^{(m+1)} = \varphi_n^{(m)} + \gamma\beta(Q_m, \tilde{Q}_m)\delta\varphi_n^{(m)}$, where γ = const and β depends on the objective function values [15]. It was shown in [15] that, at $\delta\varphi_n^{(m)} < 1$ and $\Delta\varphi_n^{(m)} = \gamma\beta\delta\varphi_n^{(m)} < 1$, each iteration step increases the objective function. The $\delta\varphi_n^{(m)}$ and $\Delta\varphi_n^{(m)}$ values determine the parameters α and γ, respectively; it is important to choose them correctly to ensure convergence of the SPG algorithm. For example, when the α value is fixed, there is an optimal γ value, at which the number of iterations necessary to obtain a specified Strehl number is reduced to minimum.

The optimal value of the parameter γ was determined for 4-, 9-, and 16-channel laser beams [15]. The axial total radiant intensity was considered as the objective function. The optimal γ value was determined after averaging the dependence of the axial radiant intensity on the number of iterations over the set of realisations (1000) of initial phase distributions in the channels at the amplifier output. Figures 2a and 2b show the calculated dependences of the optimal γ value on α and the mean number of iterations $\langle N \rangle$ at the optimal γ value that must be done to obtain Strehl numbers of 0.8 and 0.9 for a 9-channel beam. The Strehl number is defined by the formula St = $Q_n/Q_{\max}$, where Q_n is the total axial radiant intensity at the nth iteration and $Q_{\max}$ is the axial phase-matched radiant intensity. Similar results for the 16-channel case are shown in Figs 2c and 2d.

As can be seen in Figs 2a and 2b, the dependence of the optimal γ value on the probe phase shift α changes only slightly with a change in the number of channels. According to Figs 2b and 2d, the mean number of iterations $\langle N \rangle$ is minimum at small α and depends weakly on this parameter. With an increase in α the $\langle N \rangle$ value rises, and the SPG algorithm becomes less efficient. The dependences of the mean number of iterations that must be done to obtain a Strehl number of 0.8 on the number of channels at different α are shown in Fig. 3. At $\alpha = 0.05\pi$ and 0.03π, the optimal γ values are, respectively, 10 and 30.

It follows from the aforesaid that the optimal parameter for phasing multichannel laser radiation using the SPG algorithm is the range of amplitudes of the probe phase shift α from 0.01π to 0.04π. In this case, the convergence rate for obtaining a desired Strehl number is maximum, and the number of iterations linearly increases with an increase in the number of phased laser channels. The choice of α below 0.01π

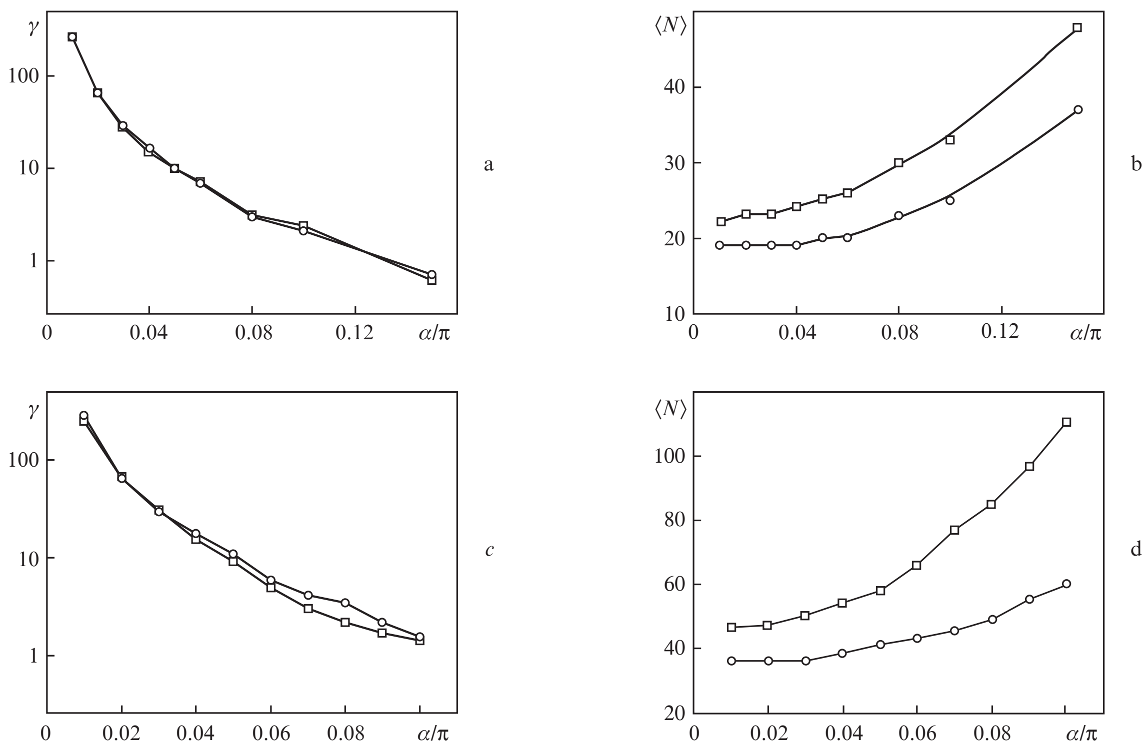


Figure 2. Averaged dependences of the (a, c) optimal γ value and (b, d) mean number of iterations $\langle N \rangle$ that must be done to obtain specified Strehl numbers, (□) 0.9 and (○) 0.8, on the phase shift α for (a, b) 9-channel and (c, d) 16-channel laser beams.

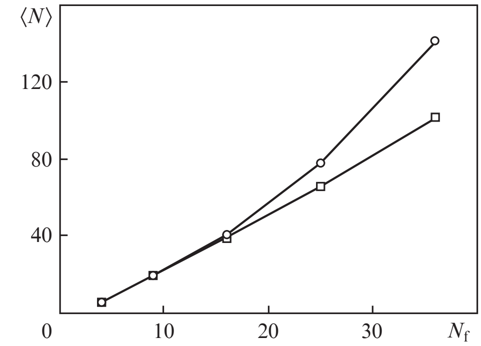


Figure 3. Dependence of the mean number of iterations $\langle N \rangle$ that must be done to obtain a Strehl number of 0.8 on the number of phased channels N_f at α = (○) 0.05π and (□) 0.03π.

in an experiment is doubtful, because in this case the change in the objective function in the first iteration stage may be below the noise level.

4. Experimental phasing of 16 laser beams

The application of the SPG algorithm in the presence of time-dependent optical distortions was experimentally demonstrated for a 16-channel laser beam [16]. The phase delay in a channel was varied by applying a voltage from a multichannel control unit to each phase modulator. The experimental random voltage shifts applied to the phase modulators in the first iteration stage were $\pm\Delta U$ (identical in modulus but with random signs). A schematic of the experiment on phasing 16 cw laser beams is shown in Fig. 4.

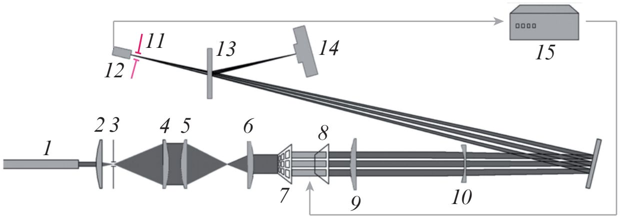


Figure 4. Schematic of the experiment on phasing 16 cw laser beams: (*1*) cw laser, (*2*, *4*, *5*, *6*) lenses, (*3*) diaphragm, (*7*) opaque screen forming a multichannel beam, (*8*) assembly of phase modulators, (*9*, *10*) two-lens focusing system, (*11*) diaphragm, (*12*) photodiode, (*13*) beam-splitter, (*14*) CCD camera, and (*15*) control unit.

The radiation of the cw laser (*1*) (λ = 532 nm, power P = 200 mW, linewidth $\delta\lambda$ = 0.0057 nm, coherence length ~5 mm) passes (after divergence and collimation) through an opaque screen (*7*) (2 × 2 mm in size) with 16 holes, enclosed in a square packing, with a gap of 0.4 mm between neighbouring holes (Fig. 5a); as a result, a 16-channel beam is formed. Then the multichannel beam arrives at an assembly (*8*) composed of 16 phase modulators based on $LiNbO_3$ crystal. The modulator size is 2 × 2 × 20 mm, and the geometry of the modulator assembly corresponds to the arrangement of holes in the screen (Fig. 5b).

Lenses (*9*) and (*10*) (with focal lengths f_1 = 750 mm and f_2 = –120.2 mm, respectively) formed a two-lens system with an equivalent focal length $F_{eqv} = f_1 f_2/(f_1 + f_2 - d)$ = 20 m and a length d = 635 mm between the lenses. To visualise the process under study, a beam-splitter (*13*) split off part of radiation to the matrix of the CCD camera (*14*). Initially, individual beams were phase-mismatched, and the total-beam intensity distribution in the far-field zone was random.

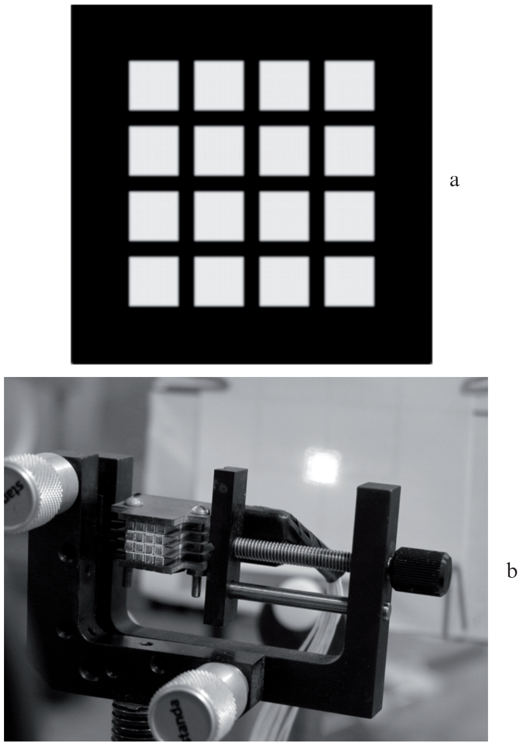
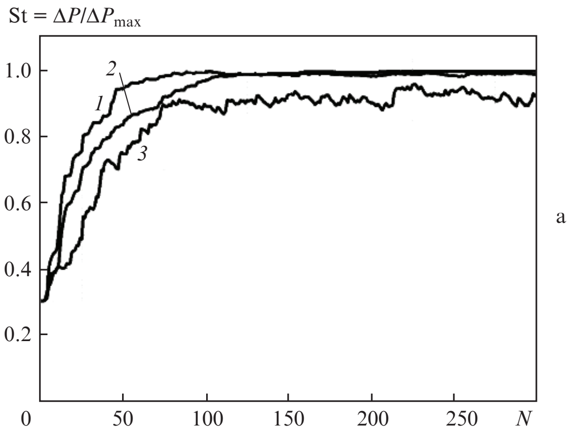


Figure 5. (a) Screen and (b) 16-channel assembly of phase modulators.

The total-beam power distribution in the far-field zone was recorded by the CCD camera, and the total beam power was recorded by a photodiode (*12*), which was located behind the diaphragm (*11*) with a diameter of 1 mm, installed in the focal plane of the focusing system formed by the lenses (*9*) and (*10*). Under these conditions, the photodiode recorded the radiation power in an angle of 3.85×10^{-5} rad at a diffraction divergence of the phase-matched beam of 1.13×10^{-4} rad; the latter parameter was chosen to be the objective function. This choice of the objective function is more reasonable in experiments, because, being an integral value, it is less noisy in comparison with the axial radiant intensity (local beam characteristic). The photodiode signal was displayed on the oscilloscope to visualise phasing and fed to the input of the microcontroller, which generated commands for the control unit to feed voltage to each phase modulator. Thus, the system was closed.

A warm air flow from a fan heater was directed to the wide-aperture (100 × 100 mm) part of the parallel beam in the region between lenses (*4*) and (*5*) to form turbulent atmospheric distortions in it. Applying voltage to phase modulators in correspondence with the SPG procedure, one can completely compensate for distortions. Note that, if the SPG algorithm led to an excess of the limiting voltage (±300 V) across some modulator in the experiment, the voltage across this modulator was automatically stepwise changed in the opposite direction (thus changing the phase by 2π) in order to remain within the dynamic range. In this case, there was no phase shift in the channel that would affect the algorithm run, while the required change in voltage remained in the range available for a given control unit and could further be either increased or decreased.



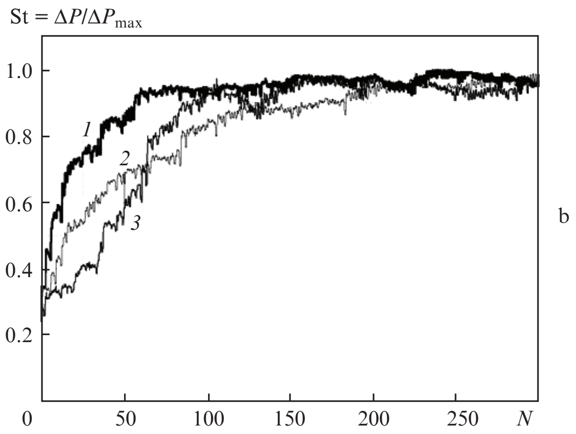
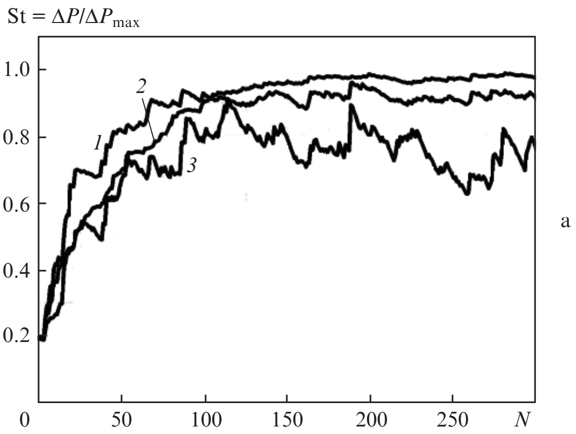


Figure 6. (a) Calculated and (b) experimental dependences of the Strehl number on the number of iterations at a voltage step $\Delta U = 4$ V (phase shift $\alpha = 0.027\pi$) and γ = (*1*) 25, (*2*) 15, and (*3*) 35.



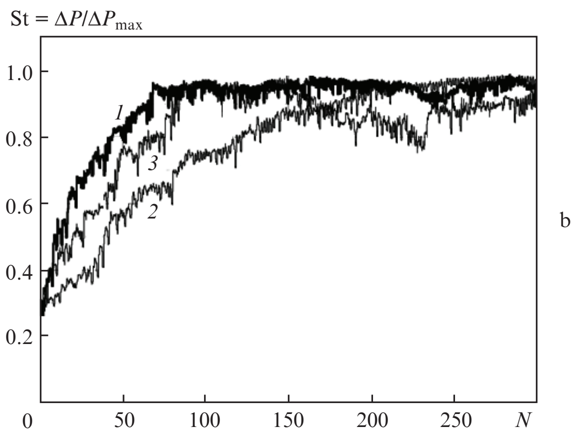


Figure 7. (a) Calculated and (b) experimental dependences of the Strehl number on the number of iterations at a voltage step $\Delta U = 8$ V (phase shift $\alpha = 0.053\pi$) and γ = (*1*) 9, (*2*) 4, and (*3*) 14.

The experimental and calculated data for a 16-channel laser beam, obtained with a voltage step $\Delta U = 4$ V in the first stage of each iteration, which corresponds to the phase shift $\alpha = 0.027\pi$ for $\lambda = 0.532$ μm, are shown in Fig. 6. Different values of the parameter γ were taken near the optimal value $\gamma = 25$ for a shift $\alpha = 0.027\pi$ (see Fig. 2c). Here, the Strehl number $\mathrm{St} = \Delta P_n/\Delta P_{\max}$, where ΔP_n is the total radiation power transmitted through the diaphragm in the nth iteration and $\Delta P_{\max}$ is the power of phase-matched radiation.

Figure 6 shows good agreement between the calculation and experiment. For the given configuration the time per iteration is 0.28 ms. To obtain a Strehl number St = 0.8 at $\alpha = 0.027\pi$, one must perform 37 iterations; their total time amounts to about 10 ms. It can be seen that the number of iterations necessary to ensure SPG algorithm convergence increases when the parameter γ deviates from the optimal value $\gamma = 25$.

Figure 7 presents the calculated and experimental dependences of the Strehl number at a voltage step $\Delta U = 8$ V, which corresponds to the phase shift $\alpha = 0.053\pi$. It can be seen that, in accordance with the calculation, an increase in the phase shift in the first iteration stage increases the phasing time to 12 ms, a value corresponding to 44 iterations.

After the experimental optimisation of the SPG algorithm with respect to the parameters γ and α, we performed dynamic compensation for thermal phase distortions, the characteristic frequency of which did not exceed 10 Hz. The control system bandwidth was 3.7 kHz. The compensation process is illustrated in Fig. 8 (the beam power distribution in the far-field zone on the CCD camera) and Fig. 9 (the dynamics of change in the objective function, i.e., the beam power fraction within a small angle in the far-field zone, observed for 50 s).

When the control system is switched off, a constantly varying pattern, characteristic of dephased beam, is observed

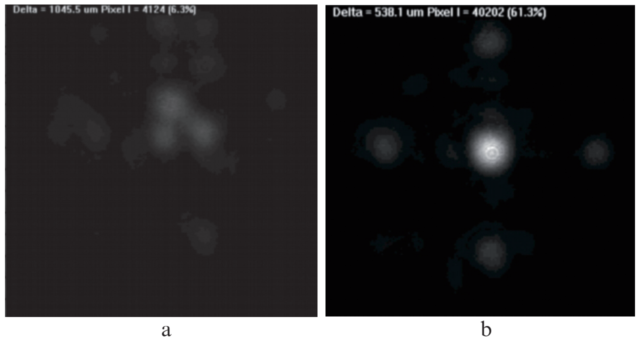


Figure 8. Instantaneous pattern of a multichannel laser beam in the far-field zone (a) without and (b) with compensation for thermal phase distortions.

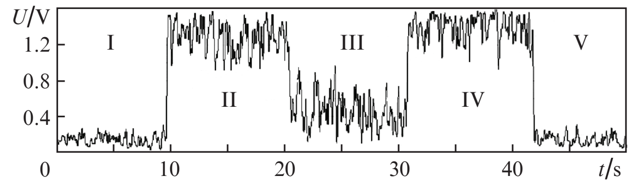


Figure 9. Oscillogram of photodiode signal in different SPG algorithm modes: the feedback is (I, V) switched off, (II, IV) switched on, and (III) paused.

in the far-field zone (see Fig. 8a); therefore, the level of the signal recorded in the far-field zone of the photodiode is minimum (Fig. 9). When the SPG algorithm (i.e., the feedback) is switched on, the axial radiation power increases by almost an order of magnitude, and the multichannel laser beam undergoes phasing (Figs 8b and 9). In the pause mode, when the control voltages across the modulators are fixed at a certain instant and stop changing, the static dephasing of channels is eliminated, while its dynamic component continues to distort the beam pattern. Subsequent switching on the SPG algorithm increases the intensity to the maximum value.

5. Conclusions

We applied the two-stage iterative SPG algorithm to perform numerical and experimental study of phasing a multichannel laser beam in the presence of dynamic phase distortions in channels. In the first stage of each iteration, probe phase shifts were simultaneously induced in channels, and the corresponding value of the objective function (axial power of multichannel beam or a fraction of its power in a specified small angle) was measured. In the second stage, parallel correction of phase shifts was performed on the basis of the measured value of objective function. The optimal range of the amplitudes of probe phase shifts and the corresponding (independent of the number of channels) optimal SPG parameters, at which the convergence rate reaches a maximum, was calculated. An experimental bench, equipped with phase modulators based on lithium niobate and an electronic control unit with a microcontroller, was developed for phasing a 16-channel cw laser beam ($\lambda = 532$ nm). Phasing of this beam with turbulent phase distortions in channels in a frequency band of about 10 Hz at a control-system response bandwidth of 3.7 kHz was demonstrated. It was shown experimentally that the optimal parameters of the SPG algorithm provide a maximum convergence rate. The experimental data were found to be in good agreement with the calculation results.

The results of our study confirmed good prospects of SPG phasing gain channels for the development of high-power cw lasers in the 'single-channel master oscillator + set of amplifiers' geometry. Note that the above-described approach can also be used to correct radiation of cw lasers of many types.

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