Laser Physics

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To cite this article: Jikun Song *et al* 2020 *Laser Phys.* **30** 085102

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Laser Phys. 30 (2020) 085102 (7pp) https://doi.org/10.1088/1555-6611/ab9118

# Numerical and experimental study on coherent beam combining using an improved stochastic parallel gradient descent algorithm

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Received 8 January 2020
Accepted for publication 29 April 2020
Published 26 June 2020

**Abstract**
The adaptive gradient (AdaGrad) method is an optimization algorithm widely used in the field of artificial intelligence. An adaptive gradient stochastic parallel gradient descent (SPGD) algorithm (AdaSPGD algorithm), combining an AdaGrad algorithm with an SPGD algorithm, is innovatively introduced and implemented in coherent beam synthesis. The performance of a coherent beam combination system utilizing the AdaSPGD method is validated by numerical simulation of straightening static phase aberrations. The results of the simulations indicate that the AdaSPGD algorithm not only can effectively solve the trouble of difficulty in selecting the gain coefficient in the actual beam combining system, but also can accelerate the convergence of the phase control algorithm. Furthermore, the effectiveness of the proposed algorithm is demonstrated by means of the experimental investigation on coherent beam synthesis of a two-channel fiber array. The AdaSPGD algorithm is a satisfactory modification of the conventional SPGD algorithm.

Supplementary material for this article is available online

Keywords: coherent beam combining, adaptive gradient, stochastic parallel gradient descent algorithm

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Coherent beam synthesis, a prospective technology for realizing high-power laser beams andsustaining excellent beam quality, is able to effectively overcome the limitations induced by the nonlinear effects of the laser gain medium and the thermal effects of optical elements (Liu *et al* 2013). It can be used in various fields such as industry, medicine, free-space optical communication, and directed energy (Fan 2005, Wang *et al* 2011, Stihler *et al* 2018, Qi *et al* 2019). Coherent beam combinations are mainly divided into two categories, passive phase control and active phase control configurations (Su *et al* 2012, Ma *et al* 2013). The highest-power demonstration of a coherent synthesis system to date has concerned positive phase controlling based on the master oscillator power amplifier (MOPA) framework. Many active phase control methods have been introduced and implemented in the coherent combination system, for instance the multi-dither technique (Ma *et al* 2010), the stochastic parallel gradient descent (SPGD) algorithm technique (Zhou *et al* 2009a, 2009b, Song *et al* 2020), and the heterodyne phase detection technique (Goodno *et al* 2006, Augst *et al* 2007). The SPGD

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algorithm, owing to its advantage of less system complexity, has been widely employed in projects of coherent beam combinations (Vorontsov and Sivokon 1998, Weyrauch *et al* 2011, Vorontsov *et al* 2012). Vorontsov and Kansky have illustrated coherent beam synthesis system using an SPGD algorithm in their earlier paper (Kansky *et al* 2006, Vorontsov *et al* 2009). Coherent beam synthesis of two 10 W fiber amplifiers employing an SPGD algorithm has been realized by Zhou *et al* (2009a). Xi has presented an experimental investigation on a coherent beam synthesis system of a 37-channel tiled fiber array utilizing an SPGD algorithm to achieve phase locking (Xi *et al* 2019). Nevertheless, the SPGD algorithm has the issue of slow convergence speed as the number of beams increases. These disadvantages greatly limit the practical application of coherent beam combination systems utilizing the SPGD algorithm. Duchi has proposed the adaptive gradient (AdaGrad) algorithm and applied it to deep learning at first (Duchi *et al* 2011). Afterwards, the algorithm, which has been demonstrated as efficacious in solving non-convex stochastic optimization, was widely applied in the field of artificial intelligence (Hadgu *et al* 2015, McMahan 2017). To our knowledge, use of the AdaGrad method to realize beam synthesis has not been reported. In this paper, an AdaGrad algorithm and SPGD algorithm are combined into a new algorithm—the AdaSPGD algorithm—and it is employed in a coherent beam combination system. The structure of the article is as follows: the fundamental theory of the AdaSPGD algorithm is briefly introduced in section 2; the effectiveness of coherent beam synthesis utilizing the AdaSPGD algorithm by means of simulation of straightening static phase aberrations is demonstrated in section 3; a laboratory investigation on a coherent synthesis system of two fiber amplifiers is demonstrated in section 4; and finally, the conclusion is given in section 5.

## 2. AdaSPGD algorithm

SPGD majorization is one of the simplest means of finding the extrema of a function. The metric factor $J = J(\boldsymbol{u})$, which is received or computed according to the probed signal by the photodetector, is a function of the phase controlling voltages $\boldsymbol{u} = u_1, u_2, \ldots u_N$, which are employed in the phase modulators. Slight perturbations $\delta\boldsymbol{u} = \delta u_1, \delta u_2, \ldots \delta u_N$ are used simultaneously in the phase control voltages $\boldsymbol{u} = u_1, u_2, \ldots u_N$. The slight disturbances are usually selected as statistically independent variables that meet equal variance and zero mean. The change of the system evaluation function under the corresponding disturbance is as follows:

$$\delta J = J(u+\delta u) - J(u). \tag{1}$$

Equation (1) for Taylor series expansion can be expressed as:

$$\delta J = \sum_{j=1}^{N} \frac{\partial J}{\partial u_j}\delta u_j + \frac{1}{2}\sum_{j,k=1}^{N}\frac{\partial^2 J}{\partial u_j \partial u_k}\delta u_j \delta u_k + \ldots \tag{2}$$

For the expectation $<\delta J \delta u_i>$ we have

$$\begin{aligned}\langle \delta J \delta u_i\rangle &= \sum_{j}^{N}\frac{\partial J}{\partial u_j}\langle \delta u_j \delta u_i\rangle \\ &+\frac{1}{2}\sum_{j,k}^{N}\frac{\partial J}{\partial u_j \partial u_k}\langle \delta u_j \delta u_k \delta u_i\rangle + \ldots\end{aligned} \tag{3}$$

For the gradient descent algorithm, the disturbances are generally described by $<\delta u_j \delta u_i> \geqslant \sigma^2 \delta_{ji}$, where $\delta_{ji}$ is the Kronecker symbol ($\delta_{ji} = 1$ for $j = i$ and 0 otherwise). The probability densities $p(\delta u_j)$ are symmetrical about their mean values. For statistically independent random variables, $<\delta u_j \delta u_k \delta u_i> \geqslant 0$ for all $j$, $k$, and $i$. Hence expression (3) can be represented as

$$\frac{\langle \delta J \delta u_i\rangle}{\sigma^2} = \frac{\partial J}{\partial u_i} + o\left(\sigma^2\right). \tag{4}$$

In the standard gradient descent method, the update rule of control parameters $u_i$ ($i = 1, 2,\ldots, N$) is:

$$u_i{}^{(k+1)} = u_i{}^{(k)} - \lambda \frac{\partial J}{\partial u_i{}^{(k)}}. \tag{5}$$

Similar to the gradient descent algorithm, the iterative process of the traditional SPGD algorithm can be written as:

$$\mathbf{u}^{(k+1)} = \mathbf{u}^{(k)} + \gamma \delta J^{(k)} \delta \mathbf{u}^{(k)} \tag{6}$$

where the superscript $k$ ($k = 1, 2, \ldots$) indicates the $k$th iteration. $\gamma$ is the iterative step, and $\gamma < 0$ corresponds to the update of minimization; $\gamma > 0$ corresponds to the update of maximization.

The SPGD algorithm has an essential control parameter that is required to be optimized: the gain coefficient $\gamma$. If the gain coefficient is too small, the convergence speed of the algorithm is slowed down, which does not satisfy the requirements of the real-time coherent beam combining system. If the gain coefficient is too large, the performance evaluation function of the system oscillates around the extreme value, which reduces the stability of the coherent beam combination system.

Unlike the SPGD algorithm, the AdaSPGD algorithm has an adaptive factor that can adjust the size of the gain coefficient $\gamma$ in real time. In the AdaSPGD algorithm, the phase controlling parameters are produced pursuant to the regulation:

$$\mathbf{u}^{(k+1)} = \mathbf{u}^{(k)} + \frac{\gamma}{\sqrt{\mathbf{g}^{(k)} + \varepsilon}}\delta J^{(k)}\delta \mathbf{u}^{(k)} \tag{7}$$

$$\mathbf{g}^{(k)} = \eta \mathbf{g}^{(k-1)} + (\delta J^{(k)}\delta \mathbf{u}^{(k)})^2 \tag{8}$$

where $\boldsymbol{g}^{(k)}$ is the $k$th cumulative gradient squared value, $\varepsilon$ is a very small amount to prevent the denominator from being zero, and $\eta$ is a regulatory factor.

AdaSPGD is an adaptive gradient optimization algorithm. At the initial stage of the correction process, the value of the system performance function may deviate farther from the extreme point, so the iteration step size will be increased to accelerate the algorithm. The system performance evaluation function value may be near the extreme point at the later stage of the correction process, so the iterative step size will be reduced appropriately to decrease the evaluation value shock near the extreme point. Furthermore, the adaptive factor that is a function of historical gradients can change with each iteration, so the AdaSPGD algorithm does not require artificial tiny adjusting parameters such as the step size schedule. Nevertheless, the AdaSPGD algorithm has the issue that the adaptive factor eventually becomes infinitely small as the historical gradient accumulates, which can cause the performance of the coherent synthesis system to deteriorate under dynamic phase disturbance conditions. In order to solve this problem, a regulatory factor $\eta$ is cleverly used in the process of the AdaSPGD algorithm to initialize $\boldsymbol{g}^{(k)}$:

$$\begin{aligned} &if \quad \left(J^{k}+J^{k-1}\right)/\left(J^{k-2}+J^{k-3}\right)<0.8 \\ &\qquad \eta=0.5 \\ &else \\ &\qquad \eta=1. \end{aligned} \tag{9}$$

During the algorithm iteration process, if the sum of the $k$th and ($k$ – 1)th evaluation indexes is less than 80% of the sum of the ($k$ – 3)th and ($k$ – 2)th evaluation indexes, the regulatory factor $\eta$ is 0.5. Otherwise, $\eta$ is 1.

Figure 1 illustrates the conceptual schematic of the coherent beam combination program. The laser beam from the main oscillation laser is divided into $N$ channels. Each beam laser is then sent to the phase modulator (PM) and the fiber amplifier (FA). The laser beam from the fiber amplifier (FA) is transmitted to free space through the collimator. The straightened beams are irradiated at a beam splitter that has a low reflectivity. The reflected beams irradiate a photodetector. The probed signal is considered as the evaluation factor $J$. The evaluation factor $J$ is then transmitted to the system algorithm controller. The control voltages are generated by the control system according to the probed signal from the photodetector that involves the status of phase undulation of each laser beam. The phase modulator has a control voltage applied, so the entire system is in a closed-loop state. The AdaSPGD algorithm constantly updates the control voltages using the variation of the metric index $\delta J$ and the perturbation of the control voltages $\delta\boldsymbol{u}$, and finally realizes the maximization of the evaluation index. Coherent beam synthesis utilizing the AdaSPGD algorithm is realized in the following manner.

(1) Set initial aggregate gradient $g^{(0)}$ and phase controlling voltages $\boldsymbol{u}^{(0)}$;
(2) Set small perturbations that meet the Bernoulli probability distribution with equal variance and zero mean;
(3) Employ $\delta\boldsymbol{u}$ in the phase controlling parameters to obtain the evaluation values $J(\boldsymbol{u}^{(k-1)}+\delta\boldsymbol{u})$ and $J(\boldsymbol{u}^{(k-1)}-\delta\boldsymbol{u})$;
(4) Assess the gradient using equation (2);
(5) Renovate the aggregate gradient $g^{(k)}$ and the phase controlling voltages $\boldsymbol{u}^{(k)}$ using equation (4);
(6) Get the evaluation factor $J(\boldsymbol{u}^{(k)})$ and judge whether it is necessary to initialize the adaptive factor;

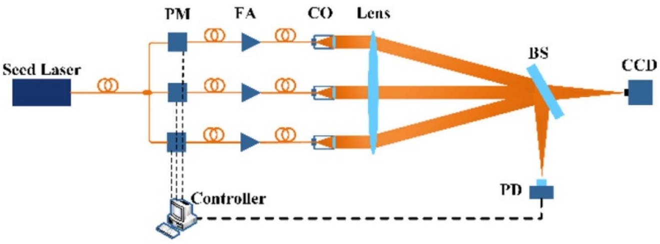


**Figure 1.** Conceptual schematic of coherent beam combination system. PM: phase modulator; FA: fiber amplifiers; CO: collimator; BS: beam splitter; PD: photodetector.

**Table 1.** System parameter settings in the simulation.

| Parameters | Values |
|---|---|
| Distance: $L$ | 2 m |
| Wavelength: $\lambda$ | $1064 \times 10^{-9}$ m |
| Beam waist: $w_0$ | $5 \times 10^{-3}$ m |
| Sampling number: $N$ | 256 |

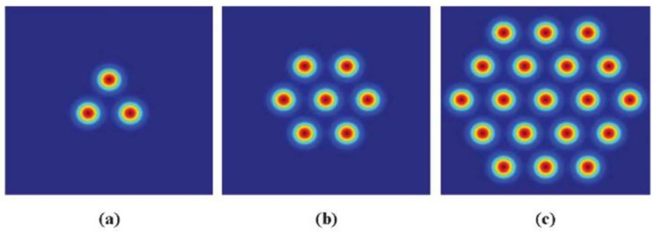


**Figure 2.** Near-field beam distribution with different numbers of lasers. (a) 3-channel laser array; (b) 7-channel laser array; (c) 19-channel laser array.

(7) Repeat step 2 to step 7 until the control parameters satisfy the requirement.

## 3. Simulation and analysis

In this section, the capabilities of the AdaSPGD algorithm are studied by the means of simulation of correcting phase distortions. Generally, three types of laser array (3-laser array, 7-laser array, 19-laser array) are implemented by numerical simulation in coherent beam combination. The numerical simulation was demonstrated according to the notional schematic (figure 1).

The parameters of the coherent beam combination system are shown in table 1. It is assumed that each laser beam is a fundamental-mode Gaussian beam. The center distance of the nearest neighbor laser unit is 20 mm. The ideal near-field laser patterns with different numbers of lasers are demonstrated in figure 2. In real applications, because of the nonlinearity of the laser medium and the effects of external environmental disturbances, the phase of each laser beam is not consistent. The root mean square (RMS) of the beam phase deviation for the laser array is assumed to be $3\pi$ in the numerical simulation.

The evaluation curves of systems against iteration number are illustrated in figure 3. It is evidently expressed that

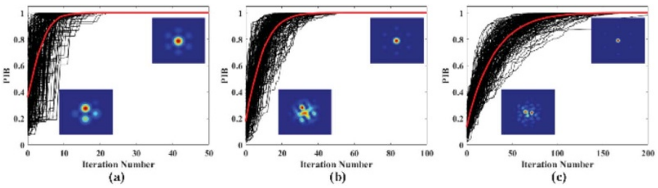


**Figure 3.** Evaluation curves of systems against iteration number (random 200 times; the solid red line represents the average of 200 times of simulation). (a) 3-channel laser array; (b) 7-channel laser array; (c) 19-channel laser array.

the AdaSPGD algorithm is able to converge to the extremum of the evaluation for all three laser arrays and realize the phase lock output of the coherent beam summation system. Therefore, the scheme of coherent beam synthesis utilizing the AdaSPGD algorithm is practicable.

The SPGD algorithm has been employed in coherent beam summation fields for years. In this paper, with the same laser array and stochastic disturbances, the capability of the AdaSPGD method for a coherent beam combination system is compared with the traditional SPGD algorithm in terms of convergence speed.

The convergence curves of the combination system control algorithm against iteration number with different gain conditions (running 200 times average) are shown in figure 4. The numerical results show that the convergence speed of the traditional SPGD algorithm is greatly affected by the gain coefficient under the condition of the same number of control units and disturbance amplitude. An example is the combining system of the 7-laser array. More iteration steps will be required for the traditional SPGD algorithm to converge to the extremum of the evaluation values when the gain factor ($\gamma = 0.2$) is too small, which means that the coherent beam combining system has bad real-time performance. The performance evaluation function of the system will oscillate around the extreme value when the gain coefficient ($\gamma = 0.8$) is too large, which will reduce the stability of the synthesis system. The convergence speed of the AdaSPGD algorithm is much less affected by the gain coefficient than the traditional SPGD algorithm. Obviously, the optimal interval (0.6–0.8) of the gain coefficients of the AdaSPGD algorithm for different control units is almost constant. However, the optimal interval of the gain coefficient of the traditional SPGD algorithm varies with the number of control units (3-laser array, 0.6–0.8; 7-laser array, 0.4–0.6; 19-laser array, 0.2–0.4). The adaptive factor in the AdaSPGD algorithm is so small that the gain coefficient can be a larger value at the beginning of the correction process, which can effectively improve the convergence speed of the algorithm. Then, the adaptive factor causes the gain factor to decrease as the gradient is accumulated, which can increase the stability of the coherent beam synthesis system. Consequently, the AdaSPGD algorithm can effectively solve the problem of difficulty in selecting the gain coefficient in the actual beam combining system, and greatly improves the applicability of the beam combining system.

As the number of control units increases, the number of iterations required for the algorithm to converge significantly increases under the condition of the same disturbance amplitude. This paper stipulates that the control algorithm shows convergence when the power-in-the-bucket (PIB) energy ratio exceeds 0.90, which is the phase-locked output state of the coherent beam combining system. Figure 5 shows the relationship between the number of iterations required for system convergence and the number of control units. It can be seen from figure 5 that the number of iterations required for the convergence has a roughly linear relation with the number of control units, but the slope of the AdaSPGD algorithm is significantly smaller than the slope of the traditional SPGD algorithm. It can be judged that the iteration number of the AdaSPGD algorithm is significantly less than that of the traditional SPGD algorithm. Further, table 2 intuitively reveals the percentage improvement of the AdaSPGD algorithm relative to the traditional SPGD algorithm. The results indicate that the convergence speed of the AdaSPGD algorithm for the 3-laser array, 7-laser array, and 19-laser array combining systems is improved respectively by 33.33%, 66.66%, and 83.60% compared with the traditional SPGD method. The numerical results strongly demonstrate that the AdaSPGD algorithm can better meet the real-time requirements of the combining system, and can be extended to more laser coherent combining.

**Table 2.** Relation between n90% and number of control units.

| *N* | SPGD | AdaSPGD | Rate |
|---|---|---|---|
| **3** | 8 | 6 | 33.33% |
| **7** | 30 | 18 | 66.66% |
| **19** | 112 | 61 | 83.60% |

Vorontsov once proposed an adaptive gain coefficient method (herein referred to as JSPGD) (Vorontsov *et al* 2009). This method uses the current metric value $J^{(k)}$ to adjust the gain coefficient. A comparison is made between the AdaSPGD algorithm and JSPGD algorithm. As an example of a 7-laser array system, the convergence curves of different algorithms with iteration number are shown in figure 6. Both of the proposed adaptive gain methods can improve the convergence speed of the coherent synthesis systems. Furthermore, the AdaSPGD algorithm has a faster convergence speed compared with the JSPGD algorithm.

## 4. Experimental results

In this section, the effectiveness of the proposed algorithm is demonstrated by means of the experimental investigation on coherent beam synthesis. The experimental system is illustrated in figure 7. The seed laser is a fiber laser, and its wavelength is 1064 nm. The linewidth of the seed laser is less than 20 kHz. The seed laser beam is divided into two channels. Then, each laser beam from the LiNbO3 phase modulator is delivered to the fiber amplifier which can be tuned to be more than 10×. The collimated beams (beam radius about 1.2 mm) are spliced by using a reflecting mirror and a beam splitter to make the distance smaller (about 8 mm). The stitched beams irradiate a beam splitter at 2 m (in order to facilitate the display, the distance is reduced in the experimental diagram). The

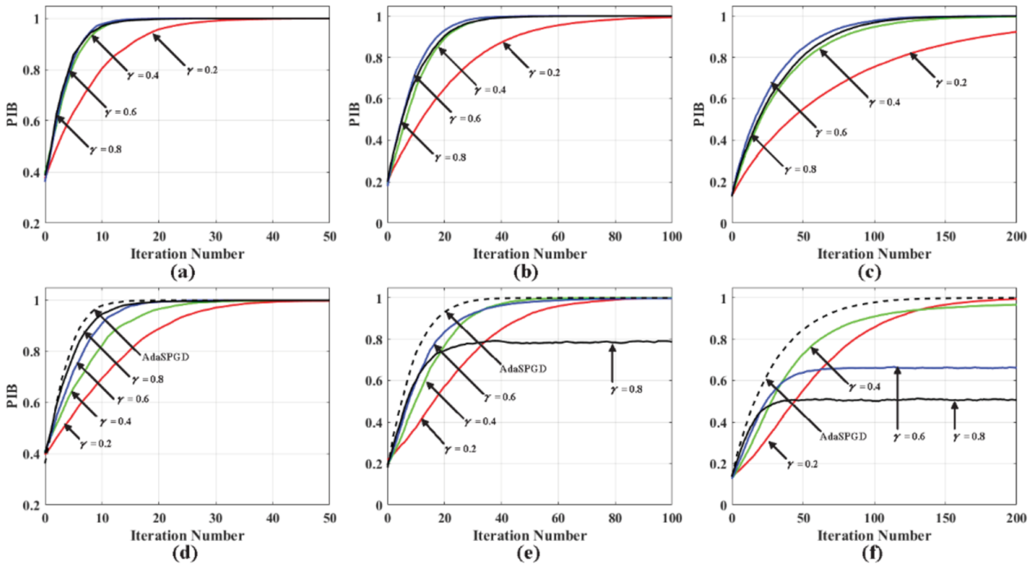


**Figure 4.** Evaluation curves of systems against iteration number with the same disturbance amplitude and different gain coefficients. (a) 3-laser array using the AdaSPGD algorithm; (b) 7-laser array using the AdaSPGD algorithm; (c) 19-laser array using the AdaSPGD algorithm; (d) 3-laser array using the traditional SPGD algorithm; (e) 7-laser array using the traditional SPGD algorithm; (f) 19-laser array using the traditional SPGD algorithm.

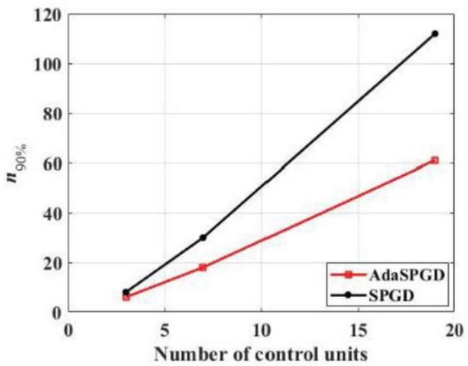


**Figure 5.** Relation between n90% and number of control units. n90% represents the number of iterations required to control the algorithm when the PIB exceeds 90%.

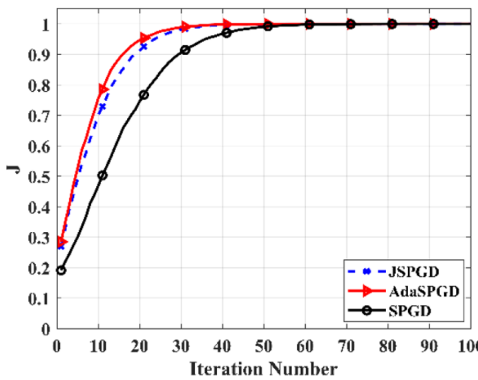


**Figure 6.** Convergence curves of different algorithms under static disturbance.

reflected laser irradiates a photodetector with 0.1 mm effective detection radius. The optical energy detected is treated as the

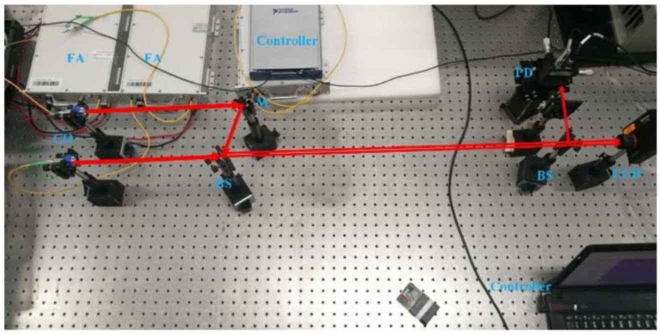


**Figure 7.** Schematic diagram of experimental steps of two-channel coherent synthesis.

evaluation factor *J*. The evaluation factor *J* is then sent to the system controller that is built based on the software platform LabVIEW and acquisition cards NI.

The dependence of the metric function on iteration number in a closed loop and open loop is demonstrated in figure 8. Initially, the system control unit is not running. The beam combination system enters an open loop. Due to the external environmental disturbance and the effect of the fiber amplifier, the uncontrolled beam phase of each laser unit fluctuates randomly, which causes random changes in the target surface intensity pattern. The evaluation index detected by the photodetector fluctuates randomly between 0.5 V and 0.7 V, with an average value of about 0.57 V. The long-term exposure (30 s) of the target surface intensity pattern is illustrated in figure 9(a). The fringe contrast is about 49.51%. The fringe contrast is defined by the formula $(I_{max} - I_{min})/(I_{max} + I_{min})$, where $I_{max}$ and $I_{min}$ are the maximum and the adjacent minimum of the brightness pattern respectively. When the phase controller is performed, the phase controlling voltages are produced by

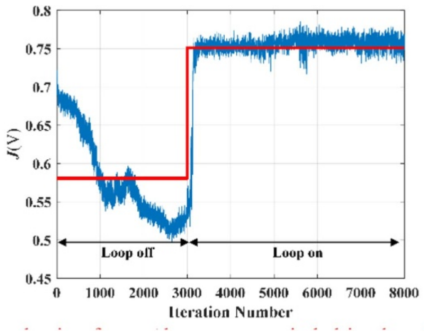


**Figure 8.** Evaluation factor (the energy encircled in the photodetector) with iteration number in an open loop and closed loop.

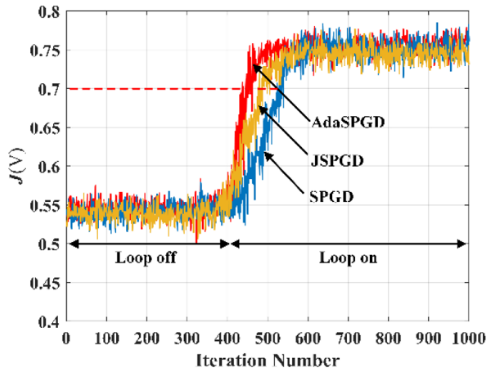


**Figure 10.** Metric functions with iteration number during the correction process in the experiment.

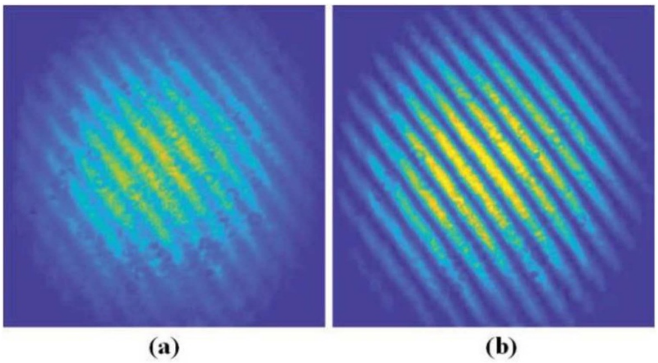


**Figure 9.** Target surface intensity pattern of the coherent beam combining system under long-term exposure: (a) loop off, (b) loop on with the AdaSPGD algorithm.

the system controller in accordance with the electrical signal from the single-point photodetector that reflects the phase variation of each laser channel. The phase controlling voltages are employed in the phase modulator. The metric factor received by the photoelectric detector can be locked steadily with an average value of about 0.75 V, which is 1.3 times that when the coherent beam combination system enters an open-loop state. The long-term exposure intensity pattern on the far-field target plane is clear and stable (illustrated in figure 9 (b)). The streak contrast is about 85.14%, which is far more than that of the open loop. The experimental results show that the AdaSPGD algorithm can effectively control measurement fluctuations. It should be noted that the convergence curve of the algorithm cannot be stabilized at a certain value. There are four main reasons for the unstable convergence curve of the algorithm: the first is the unstable laser power, the second is the noise of the detector, the third is that the control voltage exceeds the specified range and the control voltage is initialized, and the fourth is the mediation factor initialization.

An important criterion of the algorithm being employed in real-time coherent beam combination systems is the convergence speed. The metric functions with iteration number during the correction process are displayed in figure 10. The updating rates of the control signal generated by the AdaSPGD algorithm controller, JSPGD algorithm and SPGD algorithm controller are pretested to be about 330 times, 350 times and 350 times per second respectively. It should be noted that, during the iteration process, the AdaSPGD algorithm needs to judge whether the initialization condition of the regulatory factor $\eta$ is met and accumulate historical gradients. Therefore, the time required for one iteration of the AdaSPGD algorithm is slightly longer than that for the SPGD algorithm. The JSPGD algorithm just employs the current metric value to adjust the gain coefficient, and the time required for one iteration of the the algorithm is almost the same as that for the SPGD algorithm. When the metric value of the system reaches above 0.7 V, the time required for the AdaSPGD algorithm, JSPGD algorithm and SPGD algorithm are $51 \times 1/320 = 0.159$ s, $83 \times 1/350 = 0.237$ s and $112 \times 1/350 = 0.32$ s, respectively. It can be obtained that the AdaSPGD method can effectively accelerate the convergence speed of the coherent combination program compared with the JSPGD algorithm and the conventional SPGD algorithm. The proposed algorithm can better meet the real-time requirements of the combining system.

## 5. Conclusions

In the paper, the AdaSPGD algorithm is creatively proposed and employed in coherent beam synthesis to replace the conventional SPGD algorithm. Firstly, the concept of coherent beam combining using the AdaSPGD algorithm has been introduced in detail. Secondly, the coherent beam synthesis systems (3-laser array, 7-laser array, 19-laser array) using the AdaSPGD algorithm have been implemented by numerical simulation to correct static phase distortions. The numerical results evidence that the AdaSPGD algorithm is satisfactory for a coherent beam synthesis system. Additionally, the performance of the AdaSPGD algorithm for coherent beam combining is compared with the JSPGD and the traditional SPGD algorithm in terms of convergence speed. It can be concluded from the numerical results that the AdaSPGD algorithm can effectively solve the problem of difficulty in selecting the gain coefficient in the actual beam combining system, and can speed up the correction procedure of a coherent beam combination system. Finally, an experimental investigation on a coherent beam synthesis system of two fiber amplifiers is demonstrated. The experimental results illustrate that the fluctuations of the metric function can be successfully suppressed using the proposed algorithm and the AdaSPGD algorithm can improve the convergence rate of the system.

## Acknowledgments

This work was supported by the National Natural Science Foundation of China, (Grant No. 61805234), the Key Research Program of Frontier Sciences, CAS (Grant No. QYZDB-SSW-SLH014) and the Fund of the State Key Laboratory of Laser Interaction with Matter, China, (Grant No. SKLLIM1704).

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