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Incoherent beam combining based on imperialist competitive algorithm

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ABSTRACT

Incoherent beam combining is an extremely efficient method to achieve high-energy laser output. In this paper, we present the numerical study on the incoherent beam combining using imperialist competitive algorithm (ICA). The feasibility is validated by the simulation of incoherent beam combining system using the ICA under the conditions of free space. The capability of ICA under the different condition of atmosphere turbulence is numerically studied by simulation. It is revealed that ICA is a feasible means for beam combining system even under the condition of strong turbulence. Further, the performance of ICA for incoherent beam combining is compared with a widely used stochastic parallel gradient descent (SPGD) algorithm. The ICA have a small number of iterations and satisfactory correction effect compared with SPGD algorithm. Therefore, the ICA is a promising method for beam combining system.

1. Introduction

Beam combining is an important way for fiber laser to develop toward the higher power. It can effectively solve the limitation of laser medium nonlinear effect and optical element technology [1]. Fiber lasers can be combined by coherent, spectral or incoherent means [2–6]. Incoherent beam combining which is achieved by the individual fiber laser beam overlapping at a target plane, has a number of advantages, such as simple structure and not requiring controlling the beam phase like coherent beam combining (CBC) [7–9]. Therefore, the current, incoherent beam combining is simple and effective way to obtain high power output.

A new optimization algorithm—imperialist competitive algorithm, which originates in a simulation of the social political process of imperialism and imperialistic competition, was proposed by Atashpaz-Gargari and Lucas in 2007 [10]. At present, there are a number of scholars to improve the ICA and to solve the practical problems in various fields, such as solving scheduling problems in industrial production, solving optimization problems in communication systems, and designing controllers for industrial systems [11–13]. In 2014, ICA was used for phase aberration correction in a wavefront sensorless adaptive optical system by Yazdani [14]. The simulation results indicate that ICA has approving correction capability. Nevertheless, there are few articles that report application of the ICA in beam combining.

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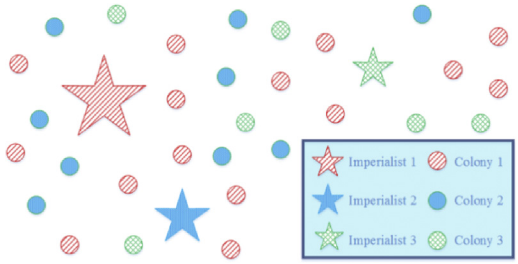

Fig. 1. Creating the initial empires. The imperialist with more colonies has bigger ⋆ mark.

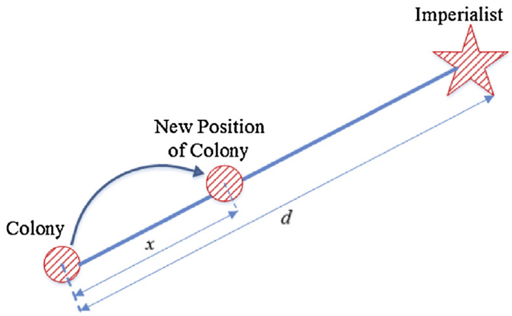

Fig. 2. Assimilation policy. The colony moves toward its imperialist.

In this paper, we present the numerical study on incoherent beam combining using the ICA. This paper is organized as follows: in Section 2, the basic principle of the ICA is described; In Section 3, the system setup and technique details for incoherent beam combining using the ICA are illustrated. Moreover, the performances of incoherent beam combining using the ICA under the conditions of free space and atmospheric turbulence are simulated and analyzed. A comparison is made between the SPGD algorithm and the ICA in Section 4. The summary is given in Section 5.

2. Imperialist competitive algorithm (ICA)

The ICA is a mathematical model that is established by simulating the social political process of imperialism and imperialistic competition. The procedures of the basic ICA are described as follows:

Generating Initial Empires. The initial countries of size N_c are randomly produced. N_{imp} of the most powerful countries are selected as the imperialists, and the rest (N_{col} = N_c - N_{imp}) are the colonies. Colonies distribute among the imperialists depending on their powers. The detailed method of allocation refers to Eqs. (1)–(3).

$$J_n = J_{imp.n} - \min\{J_{col.i}\} \tag{1}$$

$$P_n = \left| \frac{J_n}{\sum_{i=1}^{N_{imp}} J_i} \right| \tag{2}$$

$$NC_n = round\{P_n(N_c - N_{imp})\} \tag{3}$$

Where $J_{imp.n}$ is the cost of the nth imperialist and $J_{col.i}$ is the cost of its ith colony; J_n is the normalized cost; P_n is the normalized power; NC_n is the initial number of colonies of nth empire. Fig. 1 displays that bigger empires have bigger ⋆ mark, while weaker ones have smaller.

Assimilation Policy. Imperialists start to improve their colonies by the assimilation policy, which make their colonies move to them along optimization axes. Fig. 2 shows that the colony moves toward its imperialist by x units.

In order to improve the global searching ability and to prevent the local extremum of the algorithm, a small part of the colonies will undergo reforms. Fig. 3 illustrates the reform for a two-dimensional optimization problem.

Colonies Uprising. Some colonies may reach a position with higher cost than that their empire after assimilation for all colonies and revolution for a percentage of them. In such a case, the positions of the colonies and that their imperialist are exchanged. Fig. 4 describes colony against empire.

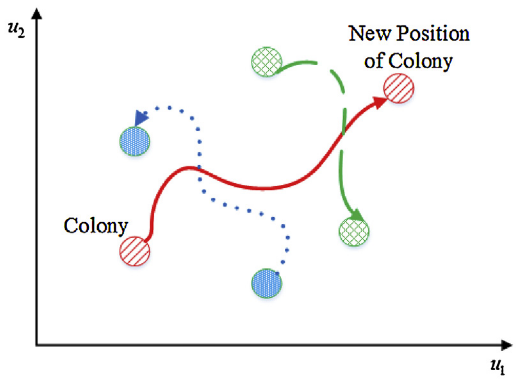

Fig. 3. Revolution. The colony was not assimilated by its imperialist.

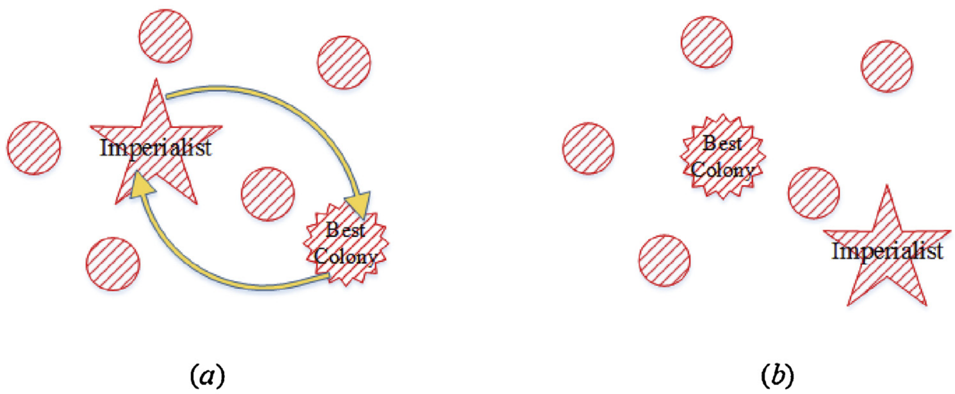

Fig. 4. Colonies uprising. (a) Exchanging positions of the colony and its imperialist. (b) The entire empire after position exchanging.

Imperialistic Competition. Imperialistic competition is the most important process in ICA, which simulates the process that all empires try to take possession of colonies of other empires. The total cost that represents the comprehensive power of the imperialist is calculated as follows:

$$J_{T.C.n} = j_{imp.n} + \gamma(\sum_{i=1}^{NC_n} j_{col.i})/NC_n \tag{4}$$

Where $J_{T.C.n}$ is total cost of the nth imperialist and γ $(0 < \gamma < 1)$ is the influence coefficient of the colonies on their empire.

Eliminating the Powerless Empires. Imperialistic competition gradually weakens the power of the weak empire and strengthens the force of the powerful ones. Finally, the empire that loses all of its colonies is considered as a colony and assigned to the strongest empire. The main steps in the ICA were illustrated in Fig. 5.

3. Incoherent beam combining using the ICA

3.1. Model for the incoherent beam combining

The incoherent beam combining system consists of three parts: the light source subsystem, the beam pointing control subsystem and the beam combining control subsystem. Fig. 6 illustrates the notional schematic of the incoherent beam combining. The light source subsystem consists of six fiber lasers that are arranged in a rectangle. Each beam of fiber laser is collimated through collimator lens. The beam pointing control subsystem mainly controls the output beam pointing by fast steering mirrors (FSMs). The beam combining control subsystem uses CCD to receive the spot image in the target plane, then calculates the spot information by control unit and generates voltages transmitted to the beam pointing control subsystem (the FSMs).

Fast steering mirror has many advantages, such as big resonance frequency and rapid response speed which are well suitable in real time pointing correction for the beam pointing control system. This paper assumes the FSMs are rigid. Each

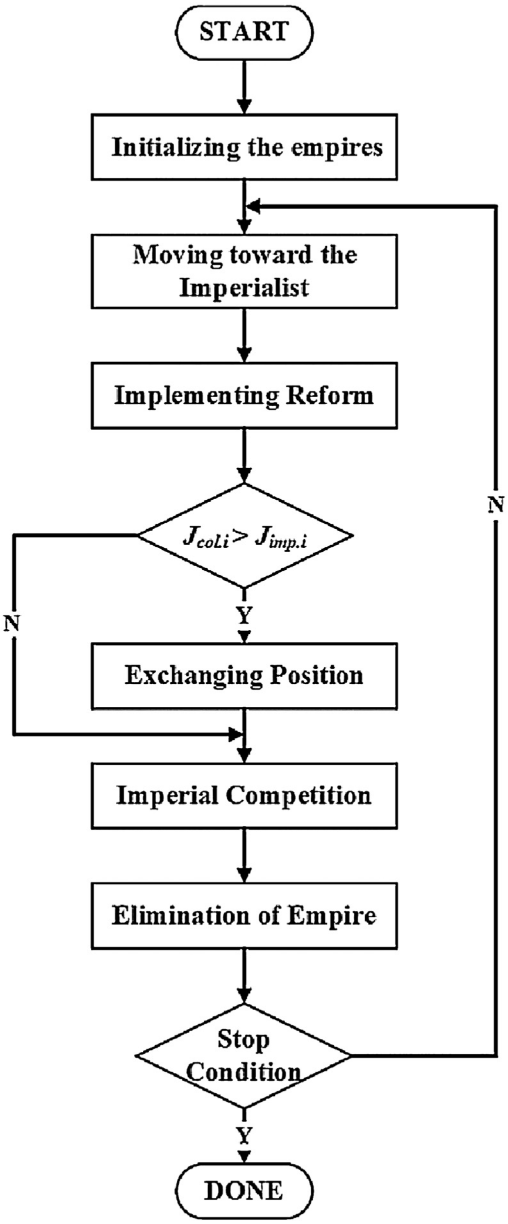

Fig. 5. The flowchart of the ICA.

FSM can be driven using two voltages V_x and V_y. The relationship between the reflect wavefront and the driving voltages (V_x, V_y) was deduced [15]. This is showed as follows:

$$U = U_0 \exp[ik(x\cos(\frac{\pi}{2} + 2\theta_x) + y\cos(\frac{\pi}{4} + \sqrt{2}\theta_y) + z\cos(\frac{\pi}{4}))] \tag{5}$$

$$U_0 = a_0 \exp[\frac{-(x^2 + y^2)}{2w_0}] \tag{6}$$

Where a_o and w_o are the amplitude and beam waist of the incident Gauss beam separately; θ_x and θ_y are the tilt angles of the fast steering mirror under the driving voltages V_x and V_y. The relationship between the tilt angles (θ_x, θ_y) and the driving voltages (V_x, V_y)can be deduced as follows:

$$\cos(\theta_x) = \frac{s_0}{\sqrt{(0.464r)^2 + s_0^2(V_x + V_y)}} \left|V_x\right| \tag{7}$$

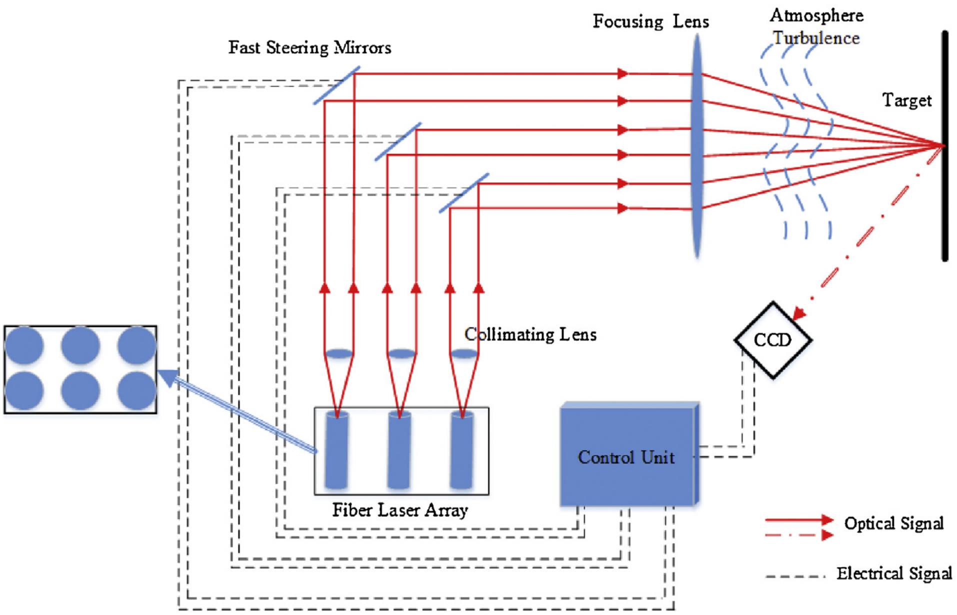

Fig. 6. The notional schematic of the incoherent beam combining. The signal captured by the camera will be sent to the control unit where it would be analyzed and produce a series of control voltages applied to the FSMs.

Table 1
The system parameters in the simulation.

Parameters	Values
Distance : L	200 m
Wavelength : λ	532×10^{-9} m
Beam waist : w_0	5×10^{-3} m
Diameter of the FSM : R	30×10^{-3} m
Sampling number : N	256

$$\cos(\theta_y) = \frac{s_0}{\sqrt{(0.464r)^2 + s_0^2(V_x + V_y)}} \left| V_y \right| \tag{8}$$

Where s_0 is the displacement of the FSM under a unit voltage; r is the radius of the fast steering mirror.

3.2. The ICA of incoherent beam combining

An incoherent beam combining system for six fiber lasers is simulated. The country (Colony or Empire) can be defined as follows:

$$country = Loc = [V_{x1}, V_{x2}, V_{x3}, \ldots, V_{x6}, V_{y1}, V_{y2}, V_{y3}, \ldots, V_{y6}] \tag{9}$$

Where V_{xi}, V_{yi} are the driving voltages of the ith FSM.

The power in the bucket (PIB) index which is an extremely important parameter in high energy laser application is chosen as the cost function [15]. The PIB is defined as follows:

$$J = I_R/I \tag{10}$$

Where I_R is total power inside a circle with radius of R and I is total power of the six fiber lasers.

3.3. Simulations using ICA

In order to prove the effectiveness of the ICA in incoherent beam combining application, the simulations are carried out both in the free space and atmospheric turbulence. The system parameters are illustrated in Table 1.

3.3.1. Simulation with free space

The intensity distribution at the target plane in the free space before correction is showed in Fig. 7(a).

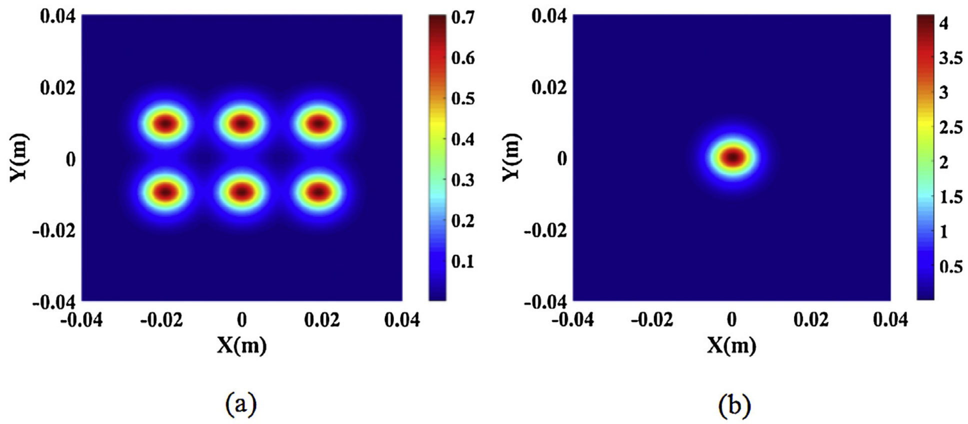

Fig. 7. (a) The intensity distribution at the target plane before correction under the free space; (b) The result of beam combining after correction in the free space.

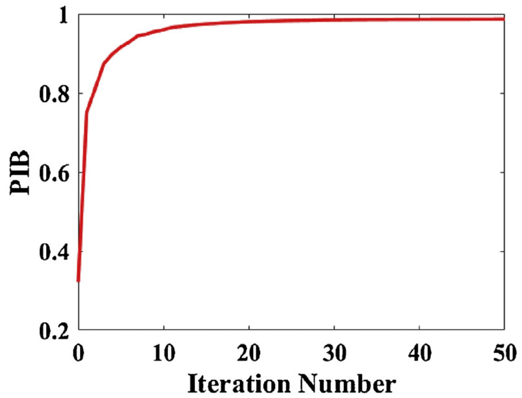

Fig. 8. The curve of PIB value against iteration number during the correction in the free space.

Fig. 7(b) displays the distribution of light spot after correction in the free space. The conclusion that the power of light spot after correction is about six times stronger than the one before correction can be drawn from the comparison of Fig. 7(a) and (b). The curve of PIB values (the mean of 20 times simulation, the same below) against iteration number in the course of the correction are illustrated in Fig. 8. The curve reveals that the PIB value increase rapidly when the iteration number is below 20. The PIB value is about 0.98 when stabilized. The light spot after correction and the PIB values illustrate that ICA is able to achieve a good correction result in the free space. Besides, the light spot after correction can maintain the near-diffraction limit beam quality.

3.3.2. Simulation with turbulence

The fluctuation of the atmospheric refractive index caused by turbulence can lead to wavefront distortion [16]. Therefore, the atmospheric turbulence is an exceedingly serious trouble for far-field beam combining. This paper simulates the turbulence by using the split-step beam propagation method in which the phase screens are generated through power spectrum method based on fast Fourier transform (FFT).

The intensity distribution at the target plane under different coherent lengths (0.08 m, 0.1 m, 0.12 m) before correction are respectively indicated in Fig. 9(a), (b), (c). Compared to Fig. 7(a), the light spot distribution in the target plane before correction becomes more and more irregular as the coherent length decreases. Smaller coherent length denotes stronger turbulence which can more easily cause random drift of the laser beam and the change (distortion, broadening, crushing) of spot shape. Fig. 9(d), (e), (f) respectively illustrate the result of beam combining after correction of Fig. 9(a), (b), (c). It can be inferred from the figure that ICA can still achieve a satisfactory result under the different condition of atmosphere turbulence.

The curves of PIB values against iteration number during the correction under the different coherent lengths of atmosphere r_0 and the free space are illustrated in Fig. 10. It can be seen from the curves that the PIB values are able to apace reach 0.8 or more when the iteration number is about 20 and the ICA is still feasible even under turbulence. Additionally, comparing the convergence rate and the maximum PIB values under different condition of atmosphere turbulence, it is can be inferred that the correction result under the longer coherence length (weak turbulence) is much better than the result under short

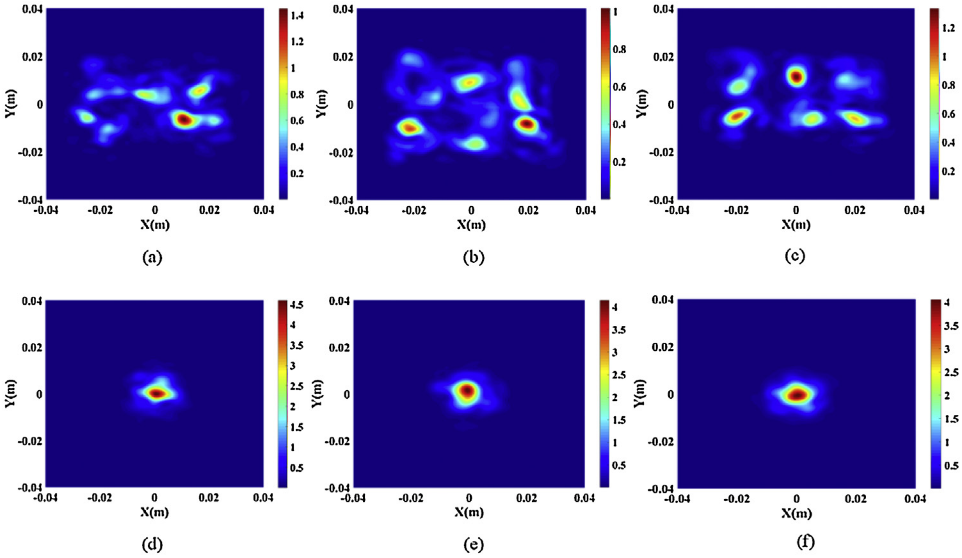

Fig. 9. (a), (b), (c): The intensity distribution at the target plane under different coherent lengths (0.08 m, 0.1 m, 0.12 m) before correction. (d), (e), (f): The result of beam combining after correction of (a), (b), (c).

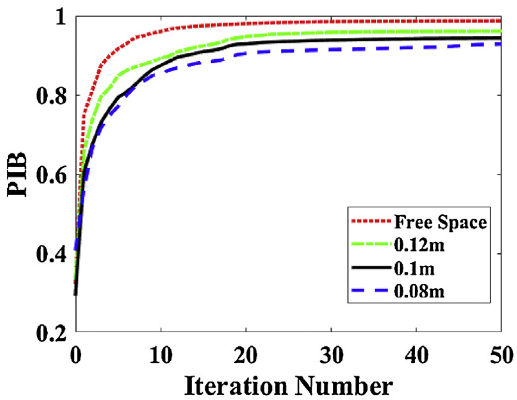

Fig. 10. The curve of PIB value against iteration number during the correction under different coherent lengths (0.08 m, 0.1 m, 0.12 m) and free space.

coherent length (strong turbulence). The reason for that is the turbulence can decrease the beam energy concentration. Therefore, the simulation results clearly demonstrate that the ICA is a promising method for beam combining system even under the condition of strong turbulence.

4. Comparison of ICA with SPGD algorithm

SPGD algorithm has been the most widely used stochastic optimization algorithm that has been applied to beam combining system [9,17]. In the section, a comparison is made between SPGD algorithm and ICA from iteration number and correction effect.

4.1. Iteration number

To some extent, the iteration number can reflect the convergence speed of the algorithm. So the size of the iteration number has an important guiding significance for the application of the incoherent beam combining system. Fig. 11 displays the curve of PIB value which are obtained using ICA and SPGD algorithm against iteration number. It can be seen that, when the PIB values are same, the iteration number using ICA is significantly less than that using SPGD algorithm, whether in free space or atmospheric turbulence. This is because, unlike SPGD's random optimization, the ICA approaches the optimal solution at each iteration. Nevertheless, it can be understood by analyzing the implementation of algorithms, that the ICA needs N_c (the number of countries) performance metrics for per iteration, but SPGD only needs one. Therefore, reducing the number of the ICA required performance metrics and the ICA-SPGD fusion algorithm will be the research direction later.

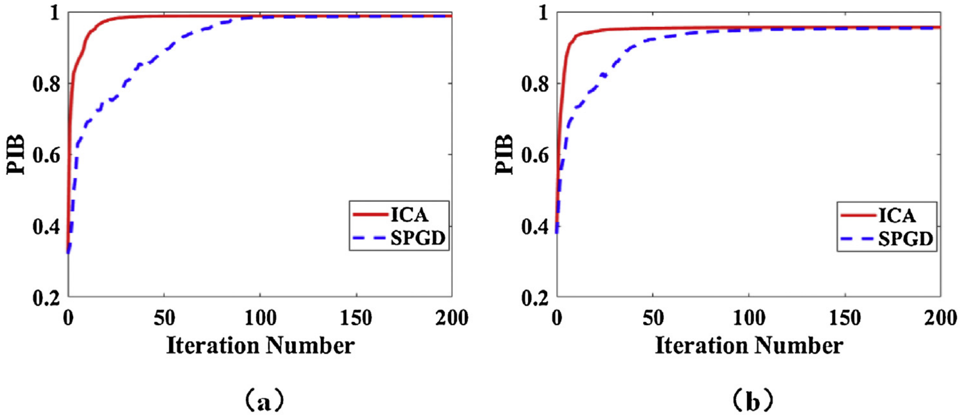

Fig. 11. The curve of PIB value against iteration number. (a) free space; (b) atmospheric turbulence.

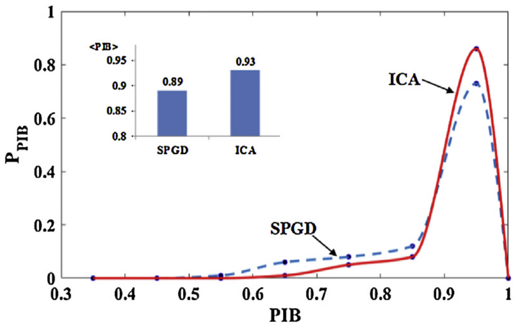

Fig. 12. Probabilistic distribution curves of PIB values for using ICA and SPGD algorithm respectively. The black dots represent the probability of each PIB cell (cell length = 0.1.

4.2. Correction effect

The incoherent beam combining system of using ICA and SPGD algorithm are randomly simulated 100 times respectively and the iteration number is 200. Fig. 12 shows the probabilistic distribution curves of PIB values for using ICA and SPGD algorithm respectively. Firstly, the probability of the PIB value greater than 0.9 using ICA is obviously higher than using SPGD algorithm and the local extremum (the PIB values <0.8) probability using ICA is less than that using SPGD algorithm. It can be concluded that the calibration stability of ICA is better than SPGD algorithm. Secondly, the <PIB> (the mean of PIB values) of using ICA is 0.93, but the <PIB> of using SPGD algorithm is 0.89. This shows that the ICA has good correction effect compared with SPGD algorithm. The reason is that, easy to fall into local extremum is an inherent characteristic of the SPGD algorithm [17], as well as this paper improves the original ICA and adds some measures such as “Colonies Uprising” and “Colonial Reform” to prevent the algorithm form getting into local extremum in solving.

5. Conclusion

In summary, we propose and demonstrate the ICA applied for incoherent beam combining to substitute for the traditional algorithms. Firstly, the six fiber lasers incoherent beam combining system that the ICA is applied to search the optimum driving voltages of the fast steering mirrors (FSMs), is simulated both in the free space and turbulence. According to the results of the simulation, it can be concluded that the ICA is feasible and effective for incoherent beam combining. Secondly, a comparison is made between SPGD algorithm and ICA from iteration number and correction effect. The results are reveal that the ICA have a small number of iterations and satisfactory correction effect compared with SPGD algorithm. Consequently, the ICA is a promising way for beam combining system, and the simulation study can be helpful for analyzing and designing practical system for incoherent beam combining using the ICA.

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