

Fast aberration-correcting algorithm for an SLM-based optical switch

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Abstract: We propose a novel method to efficiently correct the aberration in a free-space optical switch, where a spatial light modulator (SLM) is used to control wavefronts. A particle swarm optimization (PSO) method is applied to finding the optimum set of Zernike modes to compensate the aberration. We find out that the obtained coefficients of the lower-order modes and those of the higher-order ones exhibit a linear relationship when the optimization flow is interrupted by the local optima. We can drastically reduce the time for the calibration by using this relationship among the Zernike coefficients.

Keywords: spatial light modulator, optical switch, aberration correction, particle swarm optimization

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

A large-scale optical switch is necessary for a future optical network node in order to meet the increasing demand of the Internet traffic. A free-space optical switch composed of a fiber array, lenses, and a spatial light modulator (SLM) [1] is suitable for a node with a large port count because I/O ports can be arranged in a two-dimensional array. Moreover, it can be assembled with a low-cost singlet spherical lens because the SLM can compensate the distorted wavefront. The aberration correction is useful for reducing the insertion loss. The interference method [2] and the Shack-Hartmann method [3] are commonly used for directly measuring the aberration to obtain the phase pattern for the SLM to compensate it. However, both methods generally require additional optics such as a beam splitter. This makes the alignment difficult in the case of optics with small lenses. On the other hand, the algorithmic optimization method [4] is advantageous because in this method, we can measure and correct the aberration without any additional optics. The optimum phase pattern for the SLM that reduces the coupling loss of the fibers is calculated with an iterative trial-and-error procedure. However, it takes a considerable amount of time to obtain the true aberration correcting pattern with the conventional algorithm because the calculated aberration pattern is likely to be trapped around the local optima.

In this paper, we propose an aberration correcting algorithm that utilizes regularity among the Zernike coefficients found near the local optima. The drastic speed-up of the calibration is demonstrated.

2 Experimental setup and algorithm

2.1 Experimental setup

Fig. 1 shows the experimental setup for the aberration correction of the fiber coupling using an SLM. The facet of the I/O fiber array and the SLM were placed on the mutual Fourier plane of the plano-convex singlet spherical lens. By tilting the wavefront of the incident collimated light with the SLM, we could steer the focal position of the reflected light so that the light could be coupled to a certain output fiber. The focal length, radius, and center thickness of the lens were 30 mm, 15.5 mm, and 6 mm, respectively. The SLM was the liquid crystal on silicon (LCOS), which had 512×512 pixels in the active area, and its pixel size was $15 \mu\text{m} \times 15 \mu\text{m}$. The fibers were single-mode, and their mode field diameters were $10 \mu\text{m}$. The beam profile on the SLM could be approximated to a Gaussian shape, and its $1/e^2$ diameter,

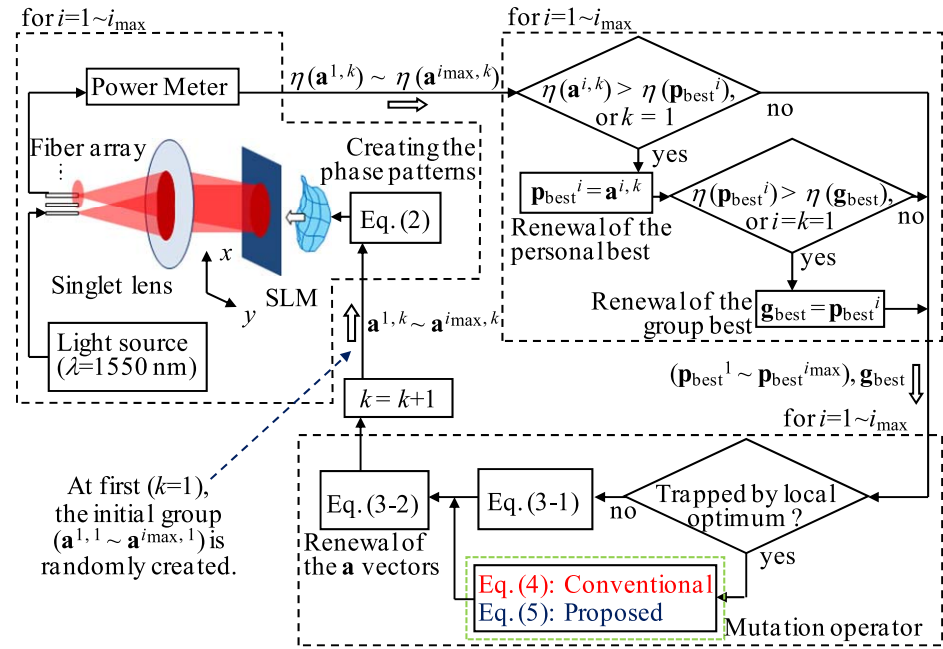


Fig. 1. Experimental setup and algorithm for aberration-correction.

W , was 6 mm.

Since the lens had a large aberration due to its spherical surface and finite thickness, the focused beam profile on the output fiber facet was distorted without the wavefront control with the SLM. The coupling efficiency, η , was calculated as

$$\eta = \left| \frac{8}{\pi W^2} \iint \text{Amp}^2(x, y) \exp [j \{ \phi_{\text{in}}(x, y) + \phi_{\text{out}}(x, y) - \phi_{\text{SLM}}(x, y) \}] dx dy \right|^2, \quad (1)$$

$$\text{Amp}(x, y) = \exp \left[-4 \left(\frac{\sqrt{x^2 + y^2}}{W} \right)^2 \right],$$

where ϕ_{in} and ϕ_{out} are the phase terms of the light on the SLM launched from the input fiber and the output fiber, respectively. ϕ_{SLM} is the phase shift with the SLM. When ϕ_{SLM} was set to zero, the excess coupling loss was 2.7 dB. To maximize the efficiency, ϕ_{SLM} should be equal to $(\phi_{\text{in}} + \phi_{\text{out}})$, which were unknown values. Therefore, we should find the optimum ϕ_{SLM} , that is, the optimum set of aberration coefficients ($\mathbf{a} = [a_1, a_2, \dots, a_{n_{\text{max}}}]$). ϕ_{SLM} is expressed by a combination of Zernike orthogonal polynomials [7]:

$$\phi_{\text{SLM}}(r, \theta) = 2\pi \sum_{n=1}^{n_{\text{max}}} a_n Z_n(r, \theta), \quad (2)$$

$$\begin{pmatrix} Z_1(r, \theta) = r \cos \theta, & Z_2(r, \theta) = r \sin \theta, \\ Z_3(r, \theta) = 2r^2 - 1, & Z_4(r, \theta) = r^2 \cos(2\theta), \\ Z_5(r, \theta) = r^2 \sin(2\theta), & Z_6(r, \theta) = (3r^3 - 2r) \cos \theta, \\ Z_7(r, \theta) = (3r^3 - 2r) \sin \theta, & Z_8(r, \theta) = (6r^4 - 6r^2) + 1, \end{pmatrix}$$

where r and θ were the normalized radial metric and the argument in the polar coordinate on the surface of the SLM, respectively. r was defined

as $(x^2 + y^2)^{1/2}/0.875W$ in this measurement. It was clarified by the ray-tracing-based simulation that n_{\max} value of 8 was sufficient for the aberration correction.

2.2 PSO Algorithm

Particle swarm optimization (PSO) [5, 6] is one of the popular methods used for solving the optimization problem in a multivariate function. The flowchart of the PSO for the experiment is shown in Fig. 1. First ($k = 1$), an initial group, which consists of an arbitrary number ($i = 1 \sim i_{\max}$) of individuals $\mathbf{a}^{i,1}$, is randomly created. Each $\mathbf{a}^{i,1}$ indicates the Zernike coefficients ($[a_1^{i,1}, a_2^{i,1}, \dots, a_8^{i,1}]$). They determine ϕ_{SLM} according to Eq. (2). The corresponding output powers and coupling efficiencies, $\eta(\mathbf{a}^{i,k})$, are obtained by the measurement. Then, each individual changes its position in the vector space over the iteration using the following recurrence equations:

$$\mathbf{v}^{i,k+1} = c_0 \mathbf{v}^{i,k} + c_1 \gamma_1(i, k) (\mathbf{p}_{\text{best}}^i - \mathbf{a}^{i,k}) + c_2 \gamma_2(i, k) (\mathbf{g}_{\text{best}} - \mathbf{a}^{i,k}), \quad (3-1)$$

$$\mathbf{a}^{i,k+1} = \mathbf{a}^{i,k} + \mathbf{v}^{i,k+1}, \quad (3-2)$$

$$\mathbf{v}^{i,1} = \mathbf{0}, \quad (3-3)$$

where c_0 , c_1 , and c_2 are the positive constants; $\gamma_1(i, k)$ and $\gamma_2(i, k)$ are the random numbers varying from 0 to 1; and the vector $\mathbf{a}^{i,k}$ represents the set of Zernike coefficients of the i^{th} individual at the k^{th} iteration. $\mathbf{p}_{\text{best}}^i$ is the \mathbf{a} vector that exhibited the maximum coupling efficiency among the previous iterations of the i^{th} individual (personal best value), and \mathbf{g}_{best} is the \mathbf{a} vector that exhibited the maximum personal best value among the group (group best value). Further, a mutation operator [6] is generally introduced into the system in order to avoid the conversion to the local optima. In this case, the following equation is used instead of Eq. (3-1) when the evolution is judged to be stagnant:

$$v_n^{i,k+1} = \gamma(i, k, n) \quad (n = 1, 2, 3, \dots, 8), \quad (4)$$

where $\gamma(i, k, n)$ is a random number. With the above rules, the group best value evolves over the iterations.

3 Analysis of local optima

We corrected the aberration in the setup shown in Fig. 1 using the conventional PSO. It was time consuming to get out from the local optima. This was because the number of variables in this system was considerably large.

Meanwhile, we found out that the Zernike coefficients of the lower-order modes and those of the higher-order ones exhibited linear relationships near the local optima. Figs. 2(a), 2(c), and 2(e) show the relationship among the Zernike coefficients. \mathbf{a} vectors of the different local optima were sampled over 16 statistical trials, and (a_1, a_6) , (a_2, a_7) , and (a_3, a_8) were plotted. The data points were around the straight line in each case. The measured slopes of the lines, da_6/da_1 , da_7/da_2 , and da_8/da_3 were 0.566, 0.566, and 0.368,

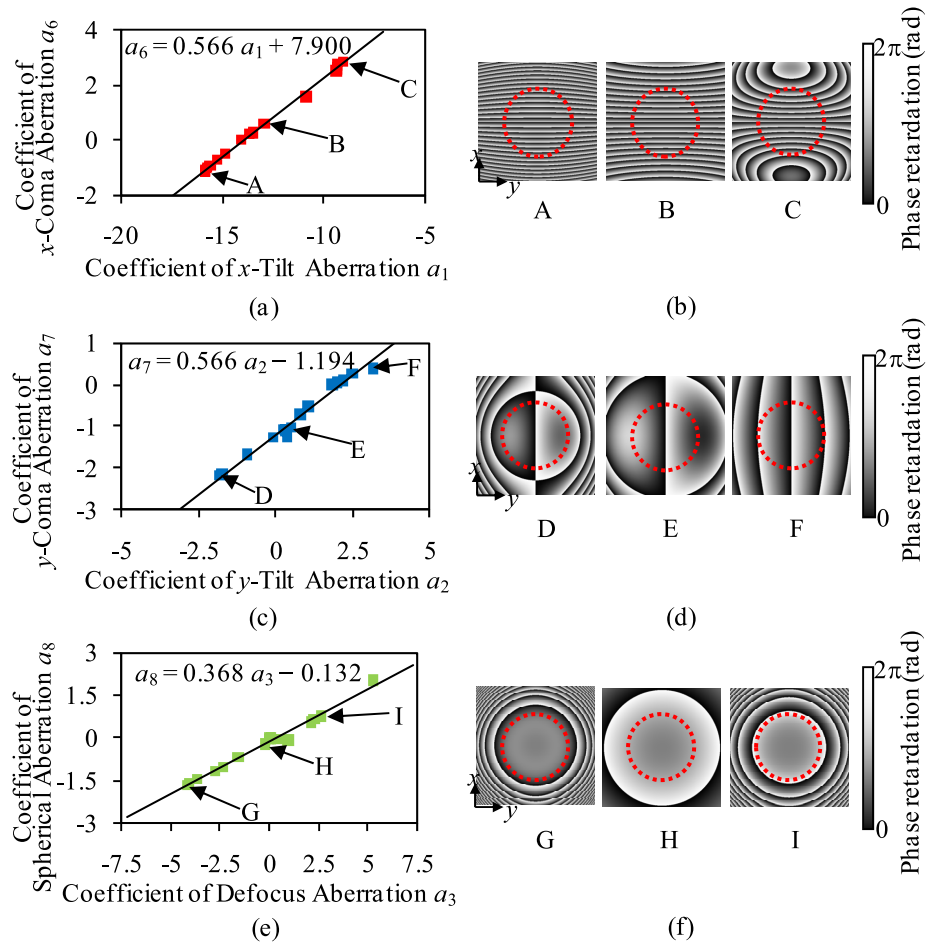


Fig. 2. Measured aberration characteristics near local optima. Relationship among Zernike coefficients: (a) a_1 and a_6 ; (c) a_2 and a_7 ; and (e) a_3 and a_8 . Corresponding phase patterns of the combined mode at different sampling points: (b) A, B, and C; (d) D, E, and F; and (f) G, H, and I. Each mode is folded at 2π ; hence, it indicates the phase pattern on the SLM.

respectively. These results came from the correlations between the phase patterns of the lower-order modes (Z_1 , Z_2 , and Z_3) and those of the higher-order ones (Z_6 , Z_7 , and Z_8). The combinations of the lower- and higher-order modes, $a_1 Z_1 + a_6 Z_6$, $a_2 Z_2 + a_7 Z_7$, and $a_3 Z_3 + a_8 Z_8$, are shown in Figs. 2 (b), 2 (d), and 2 (f), respectively. Each phase pattern resembles the other closely in the center of the coordinate plane. Most of the optical power was focused on the center circle; therefore, the coupling efficiency was not sensitive to the pattern differences. Hence, the conventional PSO program could hardly identify the global optimum from the local ones.

4 Fast aberration correction with improved PSO

Since the global optimum was on the straight lines in Fig. 2, it was efficient to limit the searching area to only around the lines. We replaced Eq. (4)

with the following mutation operator:

$$\begin{aligned} v_n^{i,k+1} &= \gamma(i, k, n) & (n = 1, 2, 3, 4, 5), \\ v_n^{i,k+1} &= \frac{da_n}{da_{n-5}} v_{n-5}^{i,k+1} & (n = 6, 7, 8). \end{aligned} \quad (5)$$

The coefficients of the higher-order modes ($n = 6, 7, 8$) could be determined by using the lower-order ones ($n = 1, 2, 3$). Therefore, this procedure reduced the number of variables of the system from 8 to 5 after the first contact with the local optimum.

Fig. 3 shows an example of the optimization curve. Two PSOs were compared under the same initial condition—one was based on the conventional mutation operator (Eq. (4)) and the other was based on the proposed operator (Eq. (5)). The total number of the individuals, i_{\max} , was 20. The output power was normalized, and the theoretical global optimum power was 0 dB. The oscillation after the first local optimum was derived from the mutation operator. The envelope of each curve indicates the evolution of the group best value. It was obvious that we could reach the global optimum with the proposed PSO; this was difficult to achieve with the conventional PSO. The excess loss after the 100th iteration was less than 0.12 dB, which means that the aberrations in the singlet lens were almost completely compensated. This result was reproducible against the different initial conditions. The average time for the calibration was less than half of that of the conventional PSO.

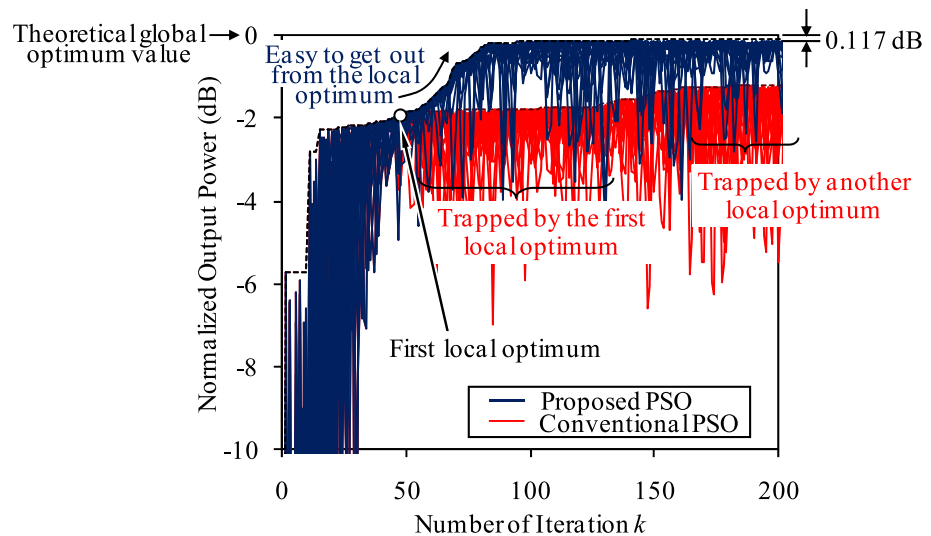


Fig. 3. Comparison of optimization curves between two PSOs. The broken lines indicate the evolutions of the group best values.

5 Conclusion

We proposed a novel algorithm that is useful for correcting the aberration in an SLM-based optical switch. The PSO-based algorithm was used to find the optimum set of Zernike modes in order to compensate the aberration of the

singlet lens. We found the linear relationships among the Zernike coefficients in the local optimum by statistical experiments. The mutation operator utilizing the above relationships effectively worked, and the time required for the calibration was less than half of that required by the conventional PSO.

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