Appl Phys B (2010) 98: 465–469
DOI 10.1007/s00340-009-3643-4

Applied Physics B
Lasers and Optics

Hartmann phase pick-up method for detection and correction of piston aberrations in a multi-beam coherent combination system

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Received: 6 May 2009 / Revised version: 26 June 2009 / Published online: 17 July 2009

Abstract In multi-beam coherent combination laser systems, piston aberration between each sub-beam is often regarded as the dominative factor to deteriorate the combination performance. So as to obtain a favorable combination result, a Hartmann phase pick-up method in combination with a seven-element active segmented mirror is presented to pick up and correct the piston aberrations of a seven-beam coherent combination system. A simulative result indicates that the RMS value of the wavefront can be reduced from 401 nm to 3.7 nm, while the far-field Strehl ratio can be increased from 0.22 to 0.99 after correction.

PACS 02.60.Cb · 42.60.Jf · 42.60.By

1 Introduction

Coherent combination of a great number of fiber or solid-state lasers is usually one of the outstanding techniques for power and brightness scaling. Since, in the coherent combination, electric fields are vectorially summed together, the relative phases among all the beams should keep in phase for obtaining the best coherent performance. However, the phase errors of beams can deteriorate the combination performance greatly. In order to limit the degradation of the Strehl ratio caused by phase errors to above 0.7 (which is usually needed for actual applications), the RMS value must be limited to about $1/10\lambda$. Among phase errors, piston aberration between each beam generally plays the dominant role to decrease the far-field Strehl ratio of light intensity. As a result, we have to measure the piston aberrations before applying corrections to them. However, the piston aberration of two neighboring beams may be measured conveniently by just using a peak-rate (PR) algorithm, which is usually used to pick up the piston aberrations in large segmented telescopes [1], whereas it is difficult to measure the piston aberrations of multi-beam systems in just the same way without any other steps; therefore, we should develop an appropriate method to solve this problem and meet the application demands of many multi-beam coherent combination systems. The adaptive optics (AO) technique is often taken as a useful technique for correcting dynamic and static phase aberrations in many laser systems [2–4]. Recently, it has also been used for detecting and correcting phase noise in many coherent combination systems [5]. Besides the AO technique, the binary (or diffractive) optics technique can also be employed to control multi-beam combining. One of the unique advantages of binary optics is that totally arbitrary surfaces can be constructed [6]. The binary optics technique can be used to implement a series of custom optical sensors for directly measuring the tip/tilt and piston aberration of adaptive mirror segments. In combination with appropriate hierarchical scaling algorithms, a multi-beam system has been controlled in phase successfully by using a binary optics phase comparator [6].

In this paper, we present an AO system to measure and correct the piston aberrations of a seven-beam coher-

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ent combination system. A seven-element active segmented mirror (ASM) rather than a continuous surface deformable mirror (DM) [3, 4] is employed to correct the piston aberrations. A Hartmann phase pick-up method is presented to measure the phase aberration; after the piston aberrations are ascertained, the ASM can adjust the wavefront of each beam to be in phase automatically.

This paper is arranged as follows: we firstly analyze the influence of piston aberrations on the far-field combination pattern, and then pick up the piston aberrations based on the characteristics of the coherent pattern using the Hartmann method; then, a strategy for decoupling piston aberrations in seven beams is presented to dispose of the redundant data and detect the aberrations precisely. Finally, the capability of an ASM for correcting a group of piston aberrations generated randomly is researched by numerical simulations.

2 The far-field characteristics of coherent beams

The far-field diffraction pattern of coherent combination beams can in fact fall into the Fraunhofer diffraction; therefore, it can be formed through a fast Fourier transform (FFT) of a multi-beam system

$$\tilde{E}(x,y)=\frac{c}{f}\exp\left[\mathrm{i}k\left(f+\frac{x^2+y^2}{2f}\right)\right]\iint\limits_{\Sigma}\tilde{E}(x_1,y_1)\times\exp\left[-\mathrm{i}2\pi\left(\frac{x}{\lambda f}x_1+\frac{y}{\lambda f}y_1\right)\right]\mathrm{d}x_1\,\mathrm{d}y_1, \quad (1)$$

where λ is the wavelength, $\sum$ is the space area of the beams, $c=\frac{1}{\mathrm{i}\lambda}$, $k=\frac{2\pi}{\lambda}$, f is the focus length, $\tilde{E}(x_1,y_1)$ is the complex amplitude of the incident wavefront in the x_1–y_1 plane and $\tilde{E}(x,y)$ is the complex amplitude of the incident wavefront in the diffraction plane. The energy of the far-field diffraction pattern can be described as

$$I(x,y)=\left|\tilde{E}(x,y)\right|^2. \quad (2)$$

Equation (1) indicates that $\tilde{E}(x,y)$ is in fact the FFT of $\tilde{E}(x_1,y_1)$ when the phase item is moved; the essence of coherent diffraction imaging of multi-beam systems is to change the complex amplitude of the incident wavefront. Figure 1a shows the configuration of seven beams which are adopted for coherent combination in this paper, while Fig. 1b shows the configuration of a seven-element ASM which is introduced to correct the piston aberrations of the beams.

The complex amplitude of the seven beams is

$$\tilde{E}(x_1,y_1)=\exp\left[\mathrm{i}kw_i(x_1,y_1)\right]\mathrm{circ}(a;\xi,\eta), \quad (3)$$

where $w_i(x_1,y_1)$ is the aberration of the ith $(i=1,2,\ldots,7)$ beam, a is the radius of the sub-beam; $\mathrm{circ}(a;\xi,\eta)$can be described as

$$\mathrm{circ}(a;\xi,\eta)=\begin{cases}1,\ (\xi-\xi_i)^2+(\eta-\eta_i)^2\le a^2\\ \quad (i=1,2,\ldots,7),\\ 0,\ (\xi-\xi_i)^2+(\eta-\eta_i)^2> a^2\\ \quad (i=1,2,\ldots,7),\end{cases} \quad (4)$$

where (ξ_i,η_i) is the coordinate of the ith sub-beam's center of a circle. Without phase aberrations $(w_i(x_1,y_1)=0)$, the coherent combination diffraction pattern is shown in Fig. 2a, whereas Fig. 2b corresponds to the one with a group of piston aberrations added into the beams $(w_i(x_1,y_1)\neq 0)$. Comparing Fig. 2a with Fig. 2b, we can show that the diffraction energy is more centralized when all the beams are in phase, whereas the energy is spread around when the group of random piston aberrations in the beams is not compensated.

3 Measurement and decoupling of piston aberrations on basis of Hartmann method

In a conventional AO system, a Hartmann sensor is usually taken as the detection device to measure the phase aberration of a wavefront. Compared with many other wavefront measurement devices, the Hartmann sensor has many advantages, for example it is very compact and intelligent, and both a pulsed laser beam and a continuous laser beam can be measured in real time without any external reference beam [7]. Utilizing a Hartmann sensor, the RMS value of the

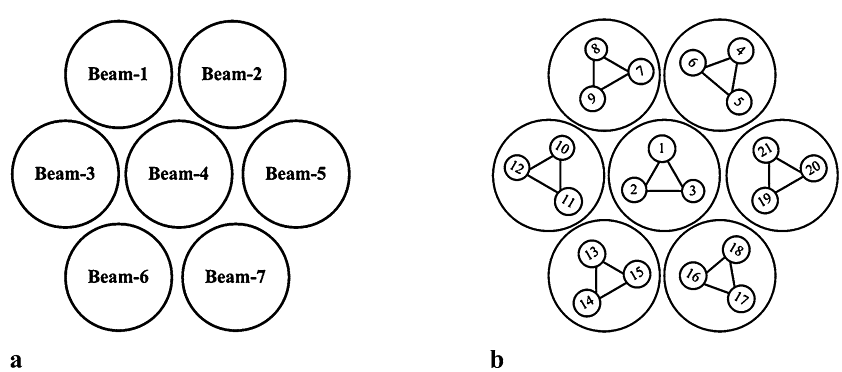

Fig. 1 (**a**) The spatial arrangement of seven beams, (**b**) the configuration of seven-element active segmented mirrors: there are three actuators on the back of each sub-mirror

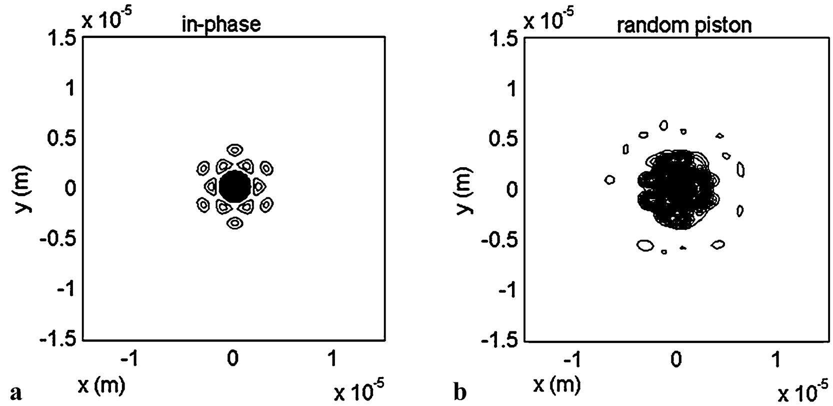

Fig. 2 The far-field diffraction pattern of seven beams: (**a**) the beams are in phase, (**b**) piston aberrations are not compensated

wavefront error, the peak-to-valley (PV) value of the wavefront error and the beam Strehl ratio, even M^2, along with other beam parameters, can be determined in a single measurement. The principle and configuration of the Hartmann sensor are described in detail in many papers [7–9]; however, in traditional systems, it is always taken to detect a single beam rather than to measure a multi-beam system, since for a single beam the piston aberration will not deteriorate the beam quality, so it is not necessary to ascertain it. However, when dealing with a multi-beam coherent combination, piston aberration is the principal one to reduce coherent performance and must be figured out and compensated. Thus, there is a large difference between single-beam and multi-beam measurement when using the Hartmann detection method. We will introduce how to employ it for detecting the piston aberrations of a multi-beam combination system in the following paragraphs.

For detecting the piston aberrations of a seven-beam coherent combination system on the basis of the Hartmann method, the configuration of seven beams and the micro array lenses of the Hartmann sensor are arranged in Fig. 3.

The seven dashed circles stand for seven beams while the solid line circles represent the 19 micro lenses. In the actual application, the seven beams will firstly be reflected by the seven-element ASM before incidence on the Hartmann sensor; the ASM is employed to compensate the piston aberrations and keep the wavefronts of the seven beams in phase. The diameter of a sub-micro lens is half of that of the beam. There is a sub-micro lens (labeled p1 to p12) between each two beams for measuring the piston aberration, while the sub-micro lenses labeled T1 to T7 are used for detecting the tilt aberrations of the seven beams. Since the tilt aberrations can be easily measured using a centroid calibration which is often used in traditional AO systems [7–9], in this paper we just pay attention to the piston aberration detection. It can seen from Fig. 3 that there are 12 sub-micro lenses bestriding each two neighboring beams, which means that 12 items of data should be calculated when adopting the PR algorithm to measure the piston aberrations. Nevertheless, there are only seven beams that should be detected actually;

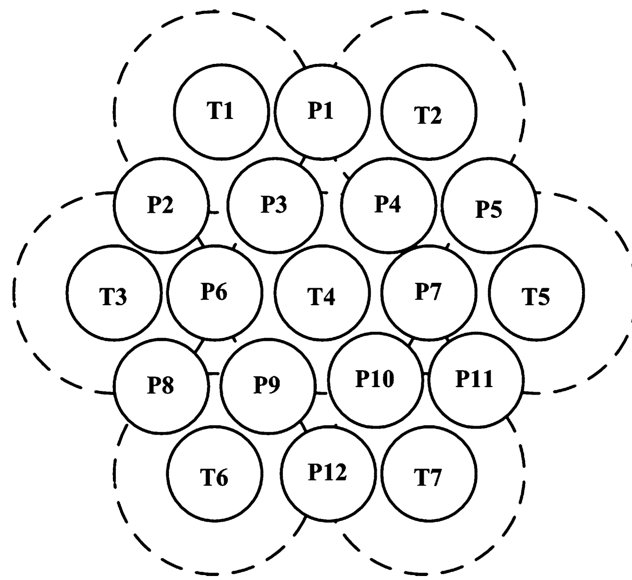

Fig. 3 The configuration of beams and the micro array lenses of Hartmann sensor

thereby, we take the first beam as the reference beam, then the remaining six beams' piston aberrations are defined as the piston values in relation to the reference beam. Finally, we employ the least-square method (LSM) [10] to decouple the 12 data items into six effective data items which will be applied to the ASM for piston aberration correction. The piston aberrations can be ascertained in the following steps.

Firstly, labeling the beams and the sub-micro lenses from top to bottom and from left to right of the configuration in Fig. 3, supposing that the piston aberration of the ith ($i = 1, 2, \ldots, 7$) beam is $Piston_i$ and the piston aberration between the ith and jth ($j = 1, 2, \ldots, 7$) beams is PS_k ($k = 1, 2, \ldots, 12$), then

$$Piston_i - Piston_j = PS_k. \tag{5}$$

It should be noted that i, j are tangent with each other.

The PS_k ($k = 1, 2, \ldots, 12$) can be calculated by use of the PR algorithm: it is known that when two beams are in phase (with no piston aberration between them), the two lobes on the right and left of the largest peak of the far-field interference pattern are equal. Therefore, we can make use of this characteristic to pick up the piston aberrations.

Figure 4 shows the schematic of the interference pattern of two beams with piston aberrations. The first step is to sum the intensity of the far-field interference pattern along the Y-axis, then search for the largest peak of the light stripes. (ii) Secondly, search for two local maximum peaks (p_l and p_r) at the left and right of the largest peak light stripes along the X-axis, then compare p_l and p_r; if $p_l < p_r$, then let $\mathrm{PR} = p_r/p_{\max}$, else let $\mathrm{PR} = p_{\max}/p_l$. (iii) Thirdly, we can calculate the PR value of the diffraction pattern of two beams under different piston aberrations, and then draw a relative curve between the PR value and piston aberrations; finally, once a PR value is obtained, the amplitude of the corresponding piston aberration can be ascertained from the curve.

Additionally, for lessening the stroke range of an active segmented mirror, a restriction term is added to make the summation of the seven piston aberrations equal to zero:

$$\sum_{i=1}^{7} Piston_i = 0. \tag{6}$$

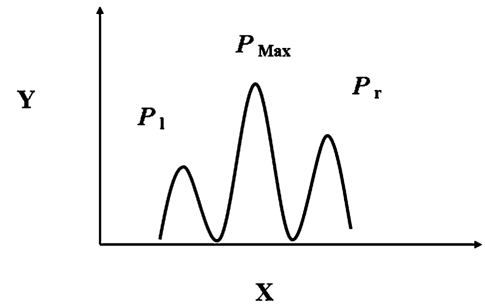

Fig. 4 The schematic of the interference pattern of two beams with piston aberration

Equations (5) and (6) form a group of 13 linear equations which have seven unknown variables ($Piston_1$ to $Piston_7$) and 12 known numbers (PS_1 to PS_{12}) obtained through the combination of the PR algorithm and the Hartmann sensor. This group of equations can be described in matrix form

$$\mathbf{A} \cdot \mathbf{P} = \mathbf{PS}, \tag{7}$$

where

$$\mathbf{A} = \begin{pmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & -1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & -1 & 0 & -1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 & -1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & 1 \end{pmatrix}^T,$$

$$\mathbf{P} = [Piston_1 \quad Piston_2 \quad Piston_3 \quad Piston_4 \quad Piston_5 \quad Piston_6 \quad Piston_7]^T,$$

$$\mathbf{PS} = [PS_1 \quad PS_2 \quad PS_3 \quad PS_4 \quad PS_5 \quad PS_6 \quad PS_7 \quad PS_8 \quad PS_9 \quad PS_{10} \quad PS_{11} \quad PS_{12} 0]^T.$$

A is a constant matrix and determined by the label rule of beams and sub-micro lenses (described in the above paragraphs). When **A** and **PS** are obtained, the piston aberration matrix **P** can be calculated through obtaining the generalized inverse matrix of **A**:

$$\mathbf{P} = \mathbf{A}^+ \cdot \mathbf{PS}. \tag{8}$$

4 The simulative results

The above sections describe the process to detect the piston aberrations; this section will introduce the simulation of the detection and correction of these aberrations.

For demonstrating the detection and correction performance of the Hartmann method, a group of piston aberrations is generated: let the piston aberrations in seven beams be P1 = [0.95, 0.23, 0.61, 0.49, 0.89, 0.76, 0.46] and the unit of piston aberrations be wavelength (wavelength = 0.63 μm); then, we use the Hartmann method to detect these aberrations through (5) to (8). The simulative result shows that the measured piston aberrations is P2 = [0.94, 0.27, 0.62, 0.50, 0.86, 0.79, 0.43], which is very close to P1 and indicates that this method can pick up the piston aberrations precisely.

When the matrix **P** is obtained, the seven-element ASM described in Fig. 1b is employed to compensate the seven

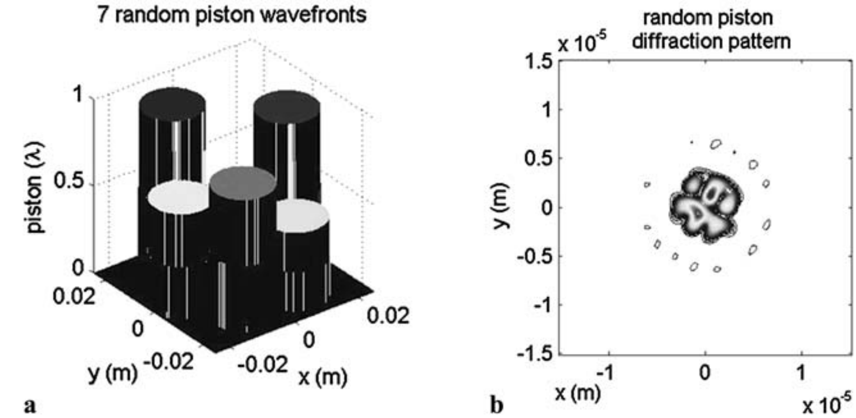

Fig. 5 Before correction: (**a**) three-dimensional description of piston aberrations, (**b**) far-field diffraction pattern

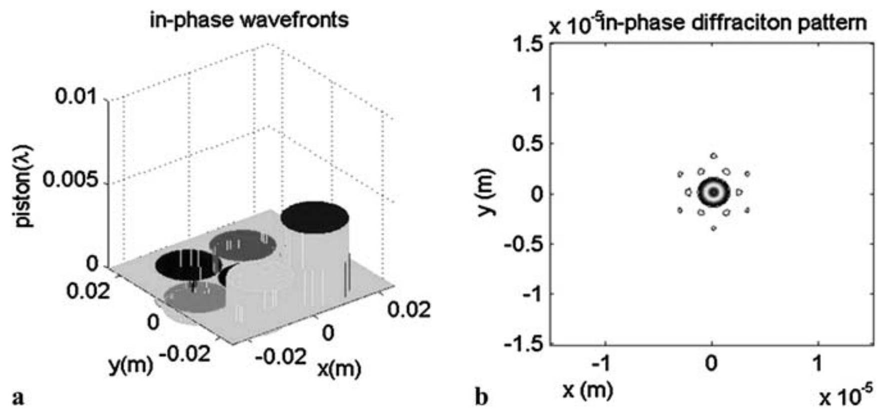

Fig. 6 After correction: (**a**) three-dimensional description of piston aberrations, (**b**) far-field diffraction pattern

piston aberrations. The surface of each sub-mirror of the ASM can generate a piston aberration to counteract the aberrations in the beams under the action of the three actuators on its back. Figure 5 depicts the results for seven beams with piston aberrations described by P1, of which Fig. 5a represents the three-dimensional description of P1 while Fig. 5b represents the far-field diffraction pattern. Figure 6 shows the piston aberration correction results, of which Fig. 6a stands for a three-dimensional description of the residual piston aberrations while Fig. 6b demonstrates the far-field diffraction pattern. After correction, the RMS value of the wavefront can be reduced from 401 nm to 3.7 nm, while the far-field Strehl ratio can be improved from 0.22 to 0.99.

5 Conclusions

A way of detecting and correcting the piston aberrations in a multi-beam system is presented and analyzed. A Hartmann method and an ASM are introduced to measure and correct the piston aberrations. Simulative results indicate that this method can be well used for ascertaining and compensating the piston aberrations. By the way, this method can also detect and correct the tilt aberration of each beam conveniently just through executing a centroid calculation (which is a very common technique in most AO systems with a Hartmann sensor). We will be using this method to detect and control the phase noise of seven 10 W level fiber amplifiers in the near future.

Acknowledgement This work was supported by the 'Western light' talent cultivation program of the Chinese Academy of Sciences.

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