Piston measurement by quadriwave lateral shearing interferometry

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We present what is to our knowledge a new method for measuring the relative piston between two independent beams separated by a physical gap, typical of petawatt facilities. The feasibility of this measurement, based on quadriwave lateral shearing interferometry, has been demonstrated experimentally: piston has been measured with accuracy and sensitivity better than 50 nm. © 2006 Optical Society of America

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The damage threshold of diffraction gratings is one of the main constraints of compressors used in chirped pulse amplification (CPA) high-power lasers. To reach a multikilojoule energy level, the grating incident angle should be high to limit the fluence on the surface. For kilojoule–petawatt class lasers,[1] meter-size gratings should be used to stay below the damage threshold. Nevertheless, since the fabrication process limits the maximum size of a monolithic grating to less than 1 m, tiled optics have been studied. To keep the same effective aperture it is important to keep the tiled optic wave fronts in phase. Otherwise, destructive interference may decrease the intensity in the far field. Considering that tiling is mandatory for multipetawatt scale laser chains, two alternative schemes have been studied for a tiled grating compressor. The first alternative is similar to the one deployed by the astronomy community to construct very large telescopes using arrays of mirrors.[2,3] The compressor consists of tiled grating assemblies, where each assembly contains several subaperture diffraction gratings. A second alternative consists of phasing small independent compressors.[4] Since alignment techniques for monolithic grating compressors are now completely mastered, the groove orientation and position management are removed from the "phasing" process, which greatly relaxes the alignment constraints. In any case, the beam is subdivided into several independent subbeams. To optimize the optical performance of the compressor, these subbeams have to be phased to act as a monolithic beam.[5] The easiest way to estimate a phase difference is to use interferometry. However, in the case of phasing of independent compressed subbeams, a piston difference measurement, by self-referenced interferometry, can be affected by the physical gap between the independent subbeams.

In this Letter, we experimentally demonstrate the feasibility of a piston difference measurement for two independent subbeams using a quadriwave lateral shearing interferometer (QWLSI). This measurement is self-referenced, which makes it very easy to implement. This method adapts the well-known multiwave lateral shearing interferometry used for wavefront sensing to phase difference evaluation by extending the shearing distance so that the edge of one subbeam overlaps the edge of another subbeam. Analyzing the interference pattern in this overlapping region leads to the phase difference between the two subbeams. Before showing experiments, we will explain how we can deduce this phase difference from a 4-wave interference pattern.

Let us consider two beams with complex amplitude $A(B)=\sqrt{I_{A(B)}}\exp[j\varphi_{A(B)}]$. If they can be partially overlapped, their amplitudes are summed. The analysis of the interference pattern should give their phase difference:

$$I_{A+B}=I_A+I_B+\sqrt{I_AI_B}\exp[j(\varphi_A-\varphi_B)]+\mathrm{c.c.} \quad (1)$$

However, in the case of the compressed independent subbeams, there is no overlapping. Thus the mind experiment would be to take A and B and tilt them a little bit, so that after propagation they start to overlap. In the region where they overlap, we should get the information we are looking for. This mind experiment is actually naturally implemented if you send the two beams to a multiwave lateral shearing interferometer.[6] In lateral shearing interferometry, an incident beam A is split in two tilted replicas A_1 and A_2, by either a refractive (prism) or a diffractive optics (linear grating). A_1 propagates along k_1 and A_2 along k_2. Because of this tilt, they separate by an amount called the shearing distance S, proportional

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to the propagation distance. At a distance z from the replication plane and if diffraction is neglected, their amplitude can be expressed as

$$A_m(\mathbf{r},z) = A_m(\mathbf{r})\exp\left(j\mathbf{k}_{\mathrm{Tm}} \cdot \mathbf{r} + j\frac{2\pi}{\lambda}z\right), \qquad (2)$$

where $\mathbf{r}$ and $\mathbf{k}_{Tm}$ are the projections of the position vector and of the wave vector respectively, in the transverse plane, $\mathbf{u}_m = \mathbf{k}_{Tm}\lambda/2\pi$ and $A(\mathbf{r}) = A(\mathbf{r} - S\mathbf{u}_m)$. The intensity at a distance z arises from the sum of the two beamlets, so that

$$I(\mathbf{r},z) = \sum_m I_A(\mathbf{r} - S\mathbf{u}_m) + \sqrt{\prod_m I_A(\mathbf{r} - S\mathbf{u}_m)} \times \exp\{j[\varphi(\mathbf{r} - S\mathbf{u}_1) - \varphi(\mathbf{r} - S\mathbf{u}_2)] + j(\mathbf{k}_{T1} - \mathbf{k}_{T2})\mathbf{r}\} + \mathrm{c.c.} \qquad (3)$$

In this way, any phase shift between two initially separated points in the incident beam will result in a modulation of an interference pattern in which the spatial frequency is $\mathbf{k}_{T2} - \mathbf{k}_{T1}$. If the shearing distance S is small compared with the typical phase variations, the phase difference is identified to the phase gradient in the $\mathbf{k}_{T2} - \mathbf{k}_{T1}$ direction. It is numerically recovered from a Fourier deconvolution around the interferogram fundamental spatial frequency $\mathbf{k}_{T2} - \mathbf{k}_{T1}$. Multiwave lateral shearing interferometry is a natural evolution of lateral shearing interferometry. A specific diffractive optic is used to create more than two replicas of the incident beam. Therefore from one measurement more than one gradient is recovered from the interferogram analysis. Since two gradients are necessary to fully describe a 2D function, the beam aberrations can be measured.

The same formalism is used for a segmented beam $A+B$, with a physical gap whose thickness is T. For simplicity, the 2-wave shearing interferometer is first detailed and extended to the 4-wave interferometer, used for our experiments. After the replication diffractive optics, A and B are transformed into A_1, A_2, B_1, and B_2 (top of Fig. 1). If the shearing distance S is larger than half the dead zone thickness T, A_1 and B_2 will interfere. At the left and right of this overlapping region (OR), there is a zone with no interference pattern since only one wave exists. Then the usual 2-wave interference pattern is observed. The spatial frequency is the difference between the two wave vectors. In the OR, whose width is $W = 2S - T$, the intensity is

$$I(\mathbf{r},z) = I_{A_1} + I_{B_2} + \{A_1 B_2^* \exp[j(\mathbf{k}_{T1} - \mathbf{k}_{T2}) \cdot \mathbf{r}] + \mathrm{c.c.}\}. \qquad (4)$$

The deconvolution gives a signal equal to $A_1 B_2^*$, whose argument is $\varphi_{A_1} - \varphi_{B_2}$, where $\varphi_{A_m} = \varphi(\mathbf{r} - S\mathbf{u}_m)$. A complete wavefront measurement would also require phase gradient information in more than one direction. This can be done using QWLSI.

This approach is extended to 4-wave interferometry. In the case of independent subbeams, and to obtain the simplest beamlet combination, it is necessary to align the physical gap direction between the subbeams with the interferometer replication grating axis y. In this case, we obtain a situation similar to the 2-wave case, as seen in Fig. 1. In OR, we observe 4-wave interferences, with two 2-wave interference zones at its left and right. The 4-wave interference zone OR is illuminated by four replicas, A_1, A_3, B_2, and B_4. In the OR, the pattern results from the amplitude double product $(A_1 B_2^* + A_3 B_4^*)$. The argument of this sum leads to a phase difference that is equal to $[(\varphi_{A1} + \varphi_{A3}) - (\varphi_{B2} + \varphi_{B4})]/2 \approx \varphi_A - \varphi_B$. In the left (right) zone, the pattern results from the interference of replicas from the same initial beam A (B). The argument of the corresponding amplitude sum leads to the A (B) beam phase gradient. Considering an unaberrated beam, this phase gradient should be equal to zero or to a constant if the wavefront is tilted. In the case of unaberrated beams a graph of the total amplitude argument versus x may present a top hat shape where its amplitude, $P(x)$, represents the phase difference between the two independent subbeams A and B. Furthermore, in the case of angularly phased subbeams, its amplitude would be equal to the piston difference between them.

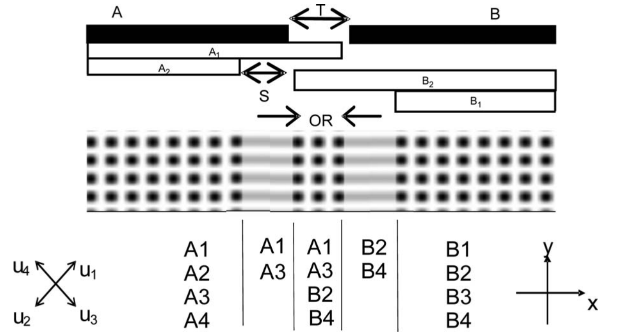

Fig. 1. Replication of independent beams A and B, separated by a physical gap whose thickness is T; on the top by a 2-wave shearing interferometer, on the bottom schematic interference pattern of 4-wave replicas.

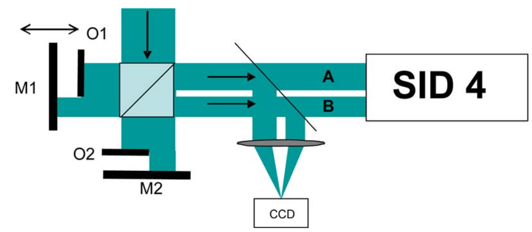

Fig. 2. (Color online) Mirrors M1 and M2, and beam blocks O1 and O2 deliver two independent subbeams A and B separated by a physical gap; their relative piston misalignment is analyzed by a far-field sensor and a QWLSI.

The feasibility of an accurate piston measurement has been demonstrated experimentally (Fig. 2). A cw source generates a monochromatic beam (633 nm) of good wavefront quality ($\lambda/15$). This monolithic beam is split into two independent beams A and B using a Michelson-type setup. Two beam blocks, O1 and O2, select the right and left beam part. They are adjusted to create the physical gap between A and B. Mirrors M1 and M2 are adjusted to phase A and B angularly. To induce piston variations, M1 is adjustable through a remotely controlled piezotype actuator, while M2 is held steady. The M1 piezoactuator is used in closed loop to ensure an accurate M1 displacement. After beam reduction, the piston difference between A and B is analyzed by a QWLSI and a far-field sensor. Theoretical simulations show the dependence of the far-field irradiance with the relative piston distance between two independent beams.[3] Comparing the measured far field with a predicted one from the wavefront measurement validates the method. As a first step, M1 is translated to observe a single focal spot, corresponding to a piston difference equal to zero. Then, M1 is translated, step by step, to induce a relative piston variation from 0 to 2π between the A and B wavefronts. For each M1 position, the fringe pattern [leading to $P(x)$] and the focal spot are recorded. Figures 3 and 4 present the focal spots and $P(x)$ for two positions of M1, corresponding to 0 and $\lambda/2$ relative piston. The focal spot evolution shows the coherence of the experimental protocol.

$P(x)$ is a top hat function in which the amplitude is equal to the relative piston between A and B. Indeed, for the case of a $\lambda/2$ piston (316 nm) as seen in Fig. 4(b), its amplitude is estimated by the interferogram deconvolution to 3.5 rad (353 nm). It is equal to the expected piston with an error of 37 nm. In Fig. 4, the piston is not completely flat, which we attribute to a residual angular misalignment of the two mirrors. Figure 5 presents, for each M1 position, the $P(x)$ amplitude as a function of the expected piston (controlled by M1 actuator): the $P(x)$ amplitude is equal to the piston distance with an average accuracy of 40 nm and a sensitivity of 40 nm.

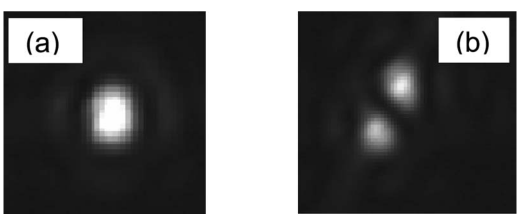

Fig. 3. (a) A single focal spot is observed for a piston value of 0 while (b) a symmetrically split spot is observed for a piston value of π.

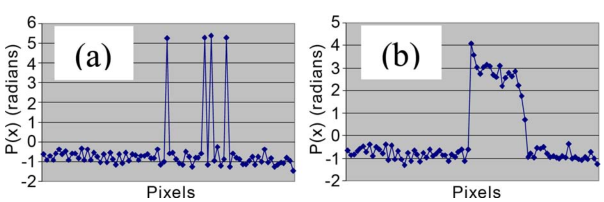

Fig. 4. (Color online) $P(x)$ is a top hat function, whose amplitude is equal to the piston. (a) For a piston equal to zero, $P(x)$ beats between 0 and 2π (optically equivalent). (b) Example for a piston close to 2π.

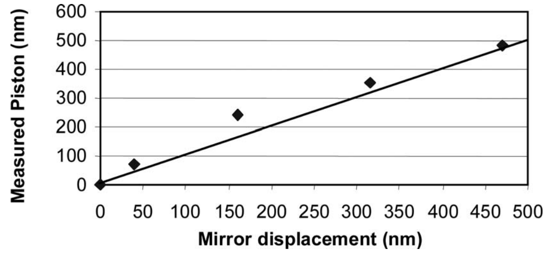

Fig. 5. Amplitude of $P(x)$ is equal to the piston with an average error and a sensitivity of 40 nm.

In conclusion, we showed an experimental demonstration of the feasibility of an accurate absolute piston measurement using QWSLI. However, we have considered unaberrated or slightly aberrated independent beams. In the case of a petawatt facility, careful consideration of the edge effects will be necessary. This may require a full recovery of the absolute phase on the complete segmented beam $A+B$. A deeper theoretical study, beyond the scope of this paper, shows that a deconvoluted signal in the overlapping zone allows characterization of not only the piston but also tilt and higher-order aberrations. Moreover, because the presented measurement is made with monochromatic light, the piston is known only within 2π. Polychromatic measurement could be a solution to extend this measure range and will be explored in a future paper.

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