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Dynamic wavefront sensor by radial shearing int erferometry using geometric phase lenses

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In this investigation, we propose a compact wavefront sensor, which consists of a geometric phase lens (GPL) pair to generate two radially-sheared wavefronts and a polarization pixelated camera (PCMOS) to simultaneously obtain four phase-shifted interferograms from a single image. An arbitrary wavefront is incident to the GPL pair, and two radially-sheared wavefronts are generated, and they are combined by the polarization array inside of the PCMOS, which can generate four phase-shifted interferograms at once. By using the spatial phase shifting technique, the phase map is simply calculated from the interferograms, and finally the original wavefront can be obtained by the wavefront reconstruction algorithm. Furthermore, the radial shearing ratio can be easily adjusted by changing the distance between two GPLs. In the experiments, the wavefront corresponding to the specific surface shape of a deformable mirror was measured, and the measurement result was compared with the counterpart of a commercial Shack-Hartmann wavefront sensor to verify the performance of the proposed sensor. As the result, the reconstructed wavefronts was the same as those of the Shack-Hartmann wavefront sensor, and even it was confirmed that the proposed sensor can reconstruct a wavefront with the higher resolution than the typical Shack-Hartmann wavefront sensor.

1. Introduction

The importance of wavefront sensing has been significantly increased in adaptive optics for astronomical applications and EUV lithography [1]. Moreover, wavefront sensors are widely used for optical testing of optical devices for virtual reality (VR) and augmented reality (AR) and smartphone cameras. The conventional ways for measuring wavefronts are the use of the Shack-Hartmann sensors [2] and pyramid techniques [3], which have the high sensitivity and robustness, but these have the limitation of lateral resolution. As the alternative for the wavefront metrology, an optical interferometer can be used to improve the higher lateral resolution, and several kinds of interferometric principles have been proposed and experimentally verified. Among them, a radial shearing interferometer (RSI) has the benefit to reconstruct the wavefront with a single radially-sheared interferogram. Especially, a cyclic radial shearing interferometer (CRSI) has the advantages of common paths between two sheared beams, the immunity of vibrations and high system stability [4].

However, RSI has the to be applied for measuring various wavefronts because the optical configuration is quite bulky and complicated. As a wavefront sensor, it should be compact and convenient to be installed. Furthermore, the snapshot wavefront measurement is needed to observe the wavefront variations in real time.

In this investigation, we propose a simple radial shearing wavefront sensor using a geometric phase lens (GPL) pair [5]. We focus on the analytic approach for wavefront sensing based on the properties of the GPL, and the system instrumentation and characterization with theoretical and experimental concerns.

2. Principle of dynamic wavefront sensor

The wavefront sensor in this investigation is consists of a GPL pair to generate two radially-sheared wavefronts and a polarization pixelated camera (PCMOS) to simultaneously obtain four phase-shifted interferograms from a single image as shown in Fig. 1. An arbitrary wavefront is incident to the radial shearing part, which consists of a GPL pair, and two radially-sheared wavefronts are generated. Typically, a collimated *RHP* beam is focused by a single GPL, and its polarization status is converted into *LHP* while it is vice versa for an *LHP* beam. When a collimated linearly polarized (LP) beam is incident to the GPL, therefore, it can be divided into two beams; a focused beam and its conjugated diverging beam. If another GPL is used again, furthermore, both of the focused and the diverging beams can be converted into semi-collimated beams, which are radially sheared. In addition, the polarization states of two beams become the same as those of the incident beams, respectively. Based on this polarization characteristics of a GPL, the polarization states of two wavefronts are orthogonal with each other, e.g. one has the right-handed circular polarization (*RHP*) and the other has the left-handed circular polarization (*LHP*).

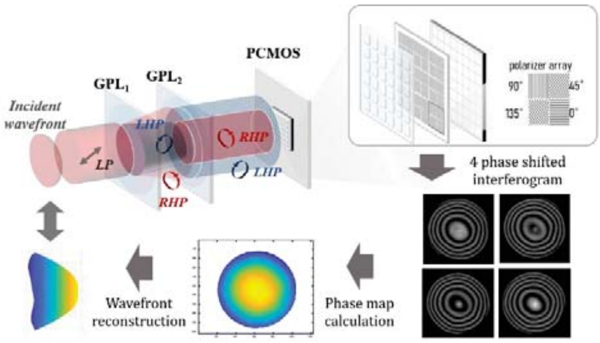

Fig. 1 Dynamic wavefront sensor based on a geometric phase lens pair; GPL, geometric phase lens; PCMOS, polarization pixelated camera; LP, linear polarization; LHP, left-handed circular polarized; RHP, right-handed circular polarized. The inset describes an inner polarizer array of the PCMOS.

Then, two circularly polarized beams are combined by the polarization array inside of the PCMOS, which can generate four phase-shifted interferograms at once. By using the spatial phase shifting technique, the phase map is simply calculated from the interferograms, and finally the original wavefront can be obtained by the wavefront reconstruction algorithm.

3. Experimental results

As a deformable mirror (DM) was operated to induce the defocus by gradually changing the surface of the DM from concave to convex shapes, the PCMOS obtained the interferograms to calculate the phase maps. The phase map of the plane mirror was subtracted from each measured phase map for systematic error compensation, and each wavefront was reconstructed with the modal method based on the optimization of Zernike polynomials [5] shown in Fig. 2(a) after the tilts of the wavefronts were eliminated. Because the original wavefront can be expressed as the Zernike polynomials, its radial shearing phase is also a function of Zernike polynomials, and their coefficients can be extracted by the regression technique. In this investigation, we use the Zernike polynomials up to Z_4^4 as the same order of operating modes of the DM and SHWS. As expected, the reconstructed wavefront gradually varied from concave to convex shapes. For the comparison of the measured results, the wavefronts were also obtained by the SHWS after the same procedure of the systematic error compensation, and it was confirmed that both of the measurement results were very close to each other. To quantitatively estimate the differences between them, each radius of curvature (ROC) was calculated by the sphere fitting technique as shown in Fig. 2(b), and the differences were smaller than 1.5%.

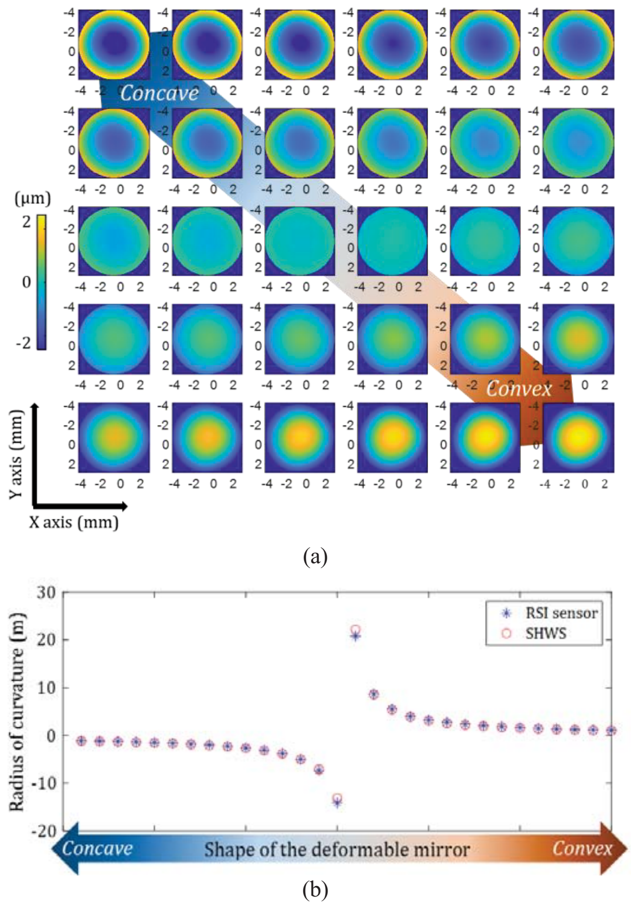

Fig. 2 (a) Reconstructed wavefronts according to the change of DM surfaces from concave to convex shapes and (b) radii of curvature comparison between the radial shearing wavefront sensor and the Shack-Hartmann wavefront sensor.

4. Conclusion

we proposed a radial shearing wavefront sensor based on a geometric phase lens pair in this investigation. By the polarization nature of the geometric phase lens, a polarization pixelated camera can directly obtain the phase map with two orthogonally polarized wavefronts, which are radially sheared. In the experiments, the measured results were compared with those of a Shack-Hartmann wavefront sensor, and the proposed sensor was experimentally verified. In order to non-planar wavefronts, the variation of the radial shearing ratio and quadrature phase were also discussed.

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