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K.-N. Joo, H. M. Park, H. B. Jeong, C. E. Guthery, D. Kim, Y. S. Ghim, "Surface figure metrology based on geometric phase components," Proc. SPIE 12137, Optics and Photonics for Advanced Dimensional Metrology II, 121370C (20 May 2022); doi: 10.1117/12.2624872

SPIE.

Event: SPIE Photonics Europe, 2022, Strasbourg, France

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ABSTRACT

A geometric phase component is very attractive in optical metrology because its meta-surface characteristic enables traditional optical systems to be more compact and multi-functional. In this presentation, we introduce two types of geometric phase components, i.e. a geometric phase lens and a polarization grating in surface figure metrology. Their features of polarized beam splitting and phase retardation play a role of wavefront shearing device, and simple shearing interferometers can be designed. We focus on the instrumentation of a radial shearing interferometer using a geometric phase lens and a lateral shearing interferometer based on a polarization grating. With the aid of a polarization pixelated CMOS camera, each interferometer can provide the phase map corresponding to the sheared wavefront as a snapshot measurement. In the experiment, various wavefronts generated by a deformable mirror and shapes of several mirrors were measured and compared with other commercial devices.

Keywords: Geometric phase, surface figure, radial shearing interferometer, lateral shearing interferometer, wavefront

1. INTRODUCTION

Recently, various optical components for wearable optical devices, head-up displays (HUD) and high-end digital cameras including smartphone cameras have been designed and manufactured. Especially, the demand of aspheric and freeform components has significantly increased to overcome the limitations of traditional optical system, and the surface figures of these optical components should be precisely determined by comparing the designed and experimentally measured values in order to confirm their functionality. One of the difficulties to develop them, however, is that there are no standard methods to evaluate the surface figures until now. Typically, a stylus probe is used to reconstruct the surface profile of an optical component, but it takes long time for measurements, and needs much effort to minimize the surface damage because of their point-like contact measurement characteristics.

Optical techniques are attractive to be used in surface figure metrology because of their non-contact and rapid measurement capabilities. Several types of optical techniques such as optical triangulations, fringe projections and Moiré techniques have been reported, and nowadays deflectometry and interferometry are widely used in precise measurements of surface profiles. Generally, optical techniques can be categorized as surface-measuring techniques and slope-measuring techniques. The surface-measuring techniques such as phase shifting interferometry and vertical scanning interferometry can measure the surface profile of a specimen compared to the reference shape in a direct way. However, this surface-measuring approach experiences poor fringe visibility or too dense fringe patterns when it comes to complex shape measurements. In addition, it needs a well-defined reference shape corresponding to that of the specimen.

The slope-measuring techniques offer significant advantages for 3D measurement of complex shape such as freeform optical surfaces since it requires no reference and provides a large dynamic range. For example, deflectometry detects the variation of specific patterns reflected on the surface, is appropriate for measuring specular ones in the large scale. However, it needs a complicated and time-consuming calibration procedure to reconstruct surface shapes based on the geometrical calibration by establishing the relative position of the screen, camera, and test surface [1].

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Optics and Photonics for Advanced Dimensional Metrology II, edited by Peter J. de Groot, Richard K. Leach, Pascal Picart, Proceedings of SPIE Vol. 12137, 121370C
© 2022 SPIE · 0277-786X · doi: 10.1117/12.2624872

On the other hand, shearing interferometers have been adopted to reconstruct the wavefront of light with the advantage of no reference light. A lateral shearing interferometer (LSI) can reconstruct the wavefront using so called, x- and y-sheared interferograms with the aid of zonal and modal reconstruction algorithms [2]. A radial shearing interferometry (RSI) has the advantage of reconstructing the wavefront with a single radial shearing interferogram [3]. However, the traditional shearing interferometers are too bulky to generate the sheared wavefronts and not easy to extract the phase map of the interference fringe. Moreover, the shearing ratio is difficult to change, only adjustable by replacing optical components or using a sophisticated optical system.

Recently, a geometric phase component has been introduced and applied in shearing interferometry [4]. The birefringent, polarizing beam splitting characteristics of the geometric phase component make the optical configuration compact and flexible to adjust the shearing ratio. In this presentation, we introduce two novel types of shearing interferometers (LSI and RSI) based on polarization gratings and geometric phase lenses. In the interferometers, polarization-pixelated cameras are used to extract the phase maps of the interference fringes without sequential measurements. It is noted that this presentation is referred to our two recent publications [5,6], which are related to the analytic and experimental approach for shearing interferometry with the system instrumentation and characterization.

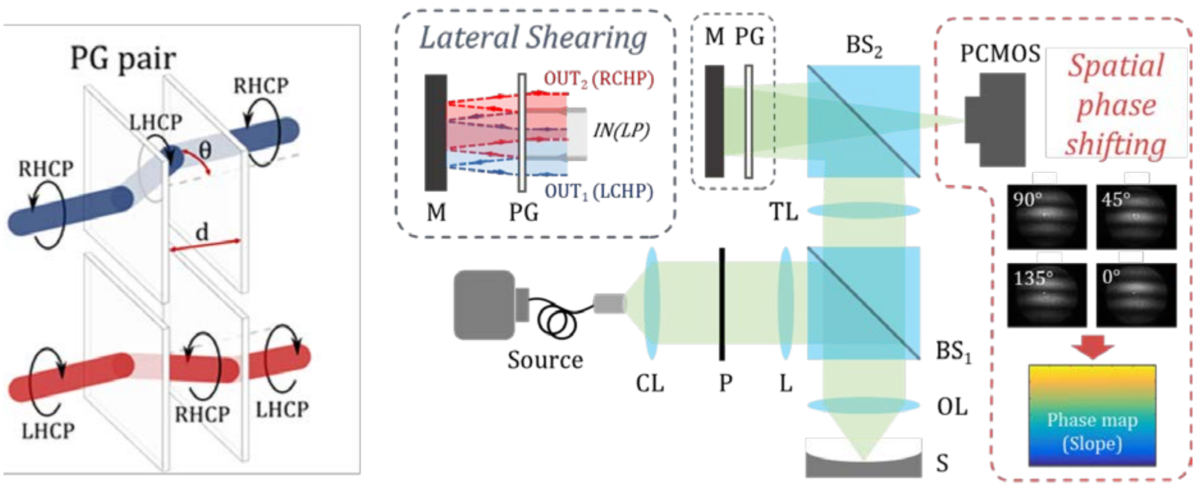
2. LATERAL SHEARING INTERFEROMETER USING A POLARIZATION GRATING

2.1 Polarization grating

A polarization grating (PG) is made by a liquid crystal array with a periodic pattern on a thin glass plate to obtain the functionality of a diffraction grating. An incident beam is angularly separated into two orthogonal polarized beams (± 1st order diffracted beams) through the PG, of which eigenpolarizations are circular. If two PGs are consecutively used as shown in Fig. 1(a), two output beams have the same propagation direction as the incident beam after passing the PG pair because of polarization and diffraction characteristics of the PG. Subsequently, two laterally shifted two beams are generated by this PG pair, and the lateral shear (s) between two beams is determined by the diffraction angle (θ) as

$$s=2d\sin\theta \tag{1}$$

where d is the distance between two PGs. By simply changing d, s can be adjusted in the system as known in Eq. (1).



(a) (b)

Figure 1. (a) Lateral shearing device with two polarization gratings and (b) optical configuration of lateral shearing interferometer using a reflective type of lateral shearing device; RHCP, right-handed circular polarization; LHCP, left-handed circular polarization; CL, collimating lens; P, polarizer; L lens; BS, beam splitter; OL, objective lens; S, specimen; TL, tube lens; PG, polarization grating; M, flat mirror; PCMOS, polarization pixelated camera. The left inset describes a reflective lateral shearing device, and the right inset shows the spatial phase shifting technique using a PCMOS. These figures are originated from Ref. 5.

Instead of using two PGs, a reflective type of the lateral shearing device can be realized with a single PG and a flat mirror as shown in Fig. 1(b). Because the beams pass through the same PG twice in reflective type, the Moiré pattern caused by the slight difference between two PGs does not have to be considered and *s* becomes twice.

2.2 Lateral shearing interferometer using a polarization grating

Figure 1(b) shows the optical configuration of the proposed LSI, which consists of a polarization grating (PG), a mirror (M) and a polarization pixelated CMOS camera (PCMOS). As an optical source, a LED is used, and the reflected beam from the specimen is incident to the lateral shearing device. In the lateral shearing device, the incident beam is split into two beams by the PG, and the returning beams are laterally shifted after reflecting off the flat mirror and passing through the PG again. These two beams are not only laterally shifted, but also their polarization states are orthogonal to each other as circular polarizations. Then, the PCMOS, where a polarizer array with 0°, 45°, 90° and 135° transmission axes is put on the imaging sensor, can obtain four phase-shifted interferograms at once to calculate the phase map based on the spatial phase shifting technique. With a single image obtained by the PCMOS, the proposed LSI can obtain the phase map corresponding to the x-sheared interferogram, and the other phase map can be calculated from another single image obtained by the 90° rotation of the shearing device. These two phase maps indicate the slopes of the wavefront along x- and y-directions. Then, the original wavefront corresponding to the surface figure of the specimen can be reconstructed via the wavefront reconstruction algorithms [5].

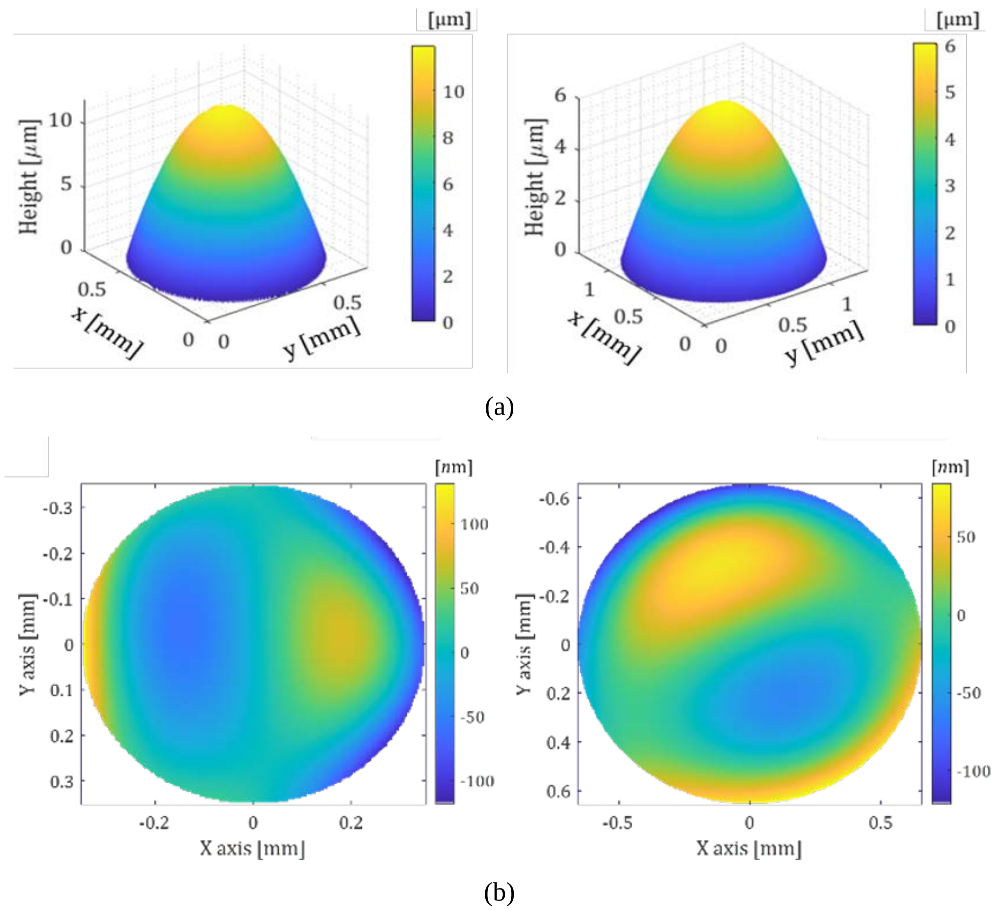
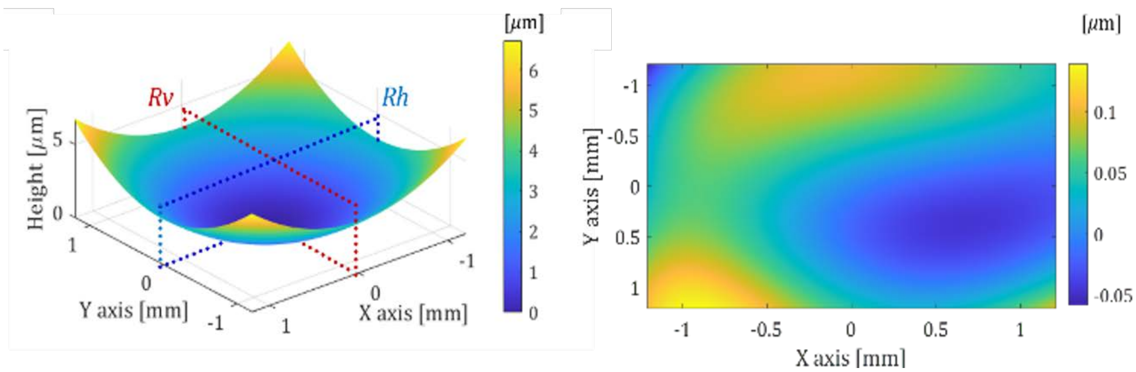


Figure 2. (a) Reconstructed surfaces of aspheric lenses, and (b) their corresponding residual error maps deviated from each best-fit aspheric surface. These figures are originated from Ref. 5.

For the feasibility test, a commercial PG with 125 lines/mm and a LED with 550 nm center wavelength as same as the designed wavelength of the PG is used with a 10 nm band-pass filter. A flat mirror was nearly contact to the PG for reflective type of the lateral shearing device, of which the lateral shear was 69 μm detected by a specific spot of the obtained image. An infinity corrected microscope with a 2x objective and a PCMOS with 3.45 μm pixel size and (2048x2448) resolutions were used to image the four phase-shifted interferograms. As aspheric surfaces, aspheric lenses were used, and each convex surface was reconstructed shown in Fig. 2(a) with the corresponding residual error map obtained by subtracting the best-fit aspheric surface as shown in Fig. 2(b). The standard deviations between the reconstructed and the best-fitted surfaces were calculated as 38.0 nm and 36.9 nm, respectively, which indicates the proposed LSI can successfully reconstruct the surface figures of aspheric surfaces.

Furthermore, the shape of a toroidal mirror, where the curvatures of orthogonal two axes are different from each other, was also measured as shown in Fig. 3(a), and its corresponding residual error map is shown in Fig. 3(b). As the result, the radii of curvatures were 231.77 mm and 210.67 mm along horizontal (Rh) and vertical (Rv) directions, respectively, similar to the measurement results by the stylus probe. The deviations of each line profile between two methods were less than 42.0 nm.



(a) (b)

Figure 3. (a) Reconstructed surface of toroidal mirror, (b) residual error map deviated from a best-fit surface. These figures are originated from Ref. 5.

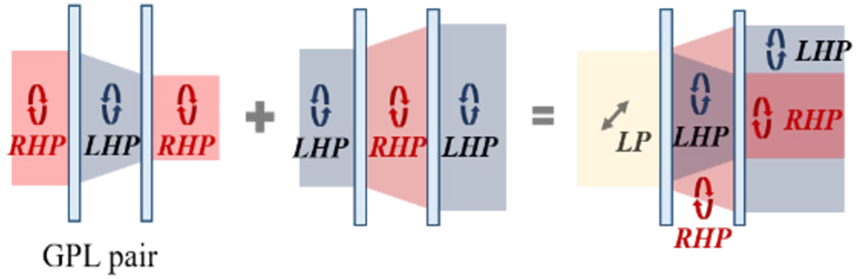
3. RADIAL SHEARING INTERFEROMETER USING A GEOMETRIC PHASE LENS PAIR

3.1 Geometric phase lens

In a geometric phase lens, an incident beam collimated and right-handed circular polarized (RHP) converges after a single GPL and converts into left-handed circular polarized (LHP). On the other hand, a collimated LHP beam diverges and converts to RHP light. When the incident collimated beam is linearly polarized (LP), therefore, it is divided into two beams; a focused LHP and a diverging RHP beams. If another GPL is used in serial as shown in Fig. 4(a), both the focused and the diverging beams are converted into semi-collimated beams, which are radially sheared. 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 beams are orthogonal with each other.

3.2 Radial shearing interferometer using a geometric phase lens pair

Figure 4(b) shows the optical configuration of the RSI in this investigation with a GPL pair to generate two radially-sheared wavefronts and a polarization pixelated camera (PCMOS) to obtain four phase-shifted interferograms from a single image. When a linearly polarized wavefront is incident to the GPL pair, two radially-sheared wavefronts are generated with the two orthogonal circular polarizations. Then, two circularly polarized wavefronts are combined by the polarization array inside of the PCMOS, which can generate four phase-shifted interferograms [6]. Then, the phase map is instantaneously calculated, and the original wavefront is obtained by the reconstruction algorithm.



(a)

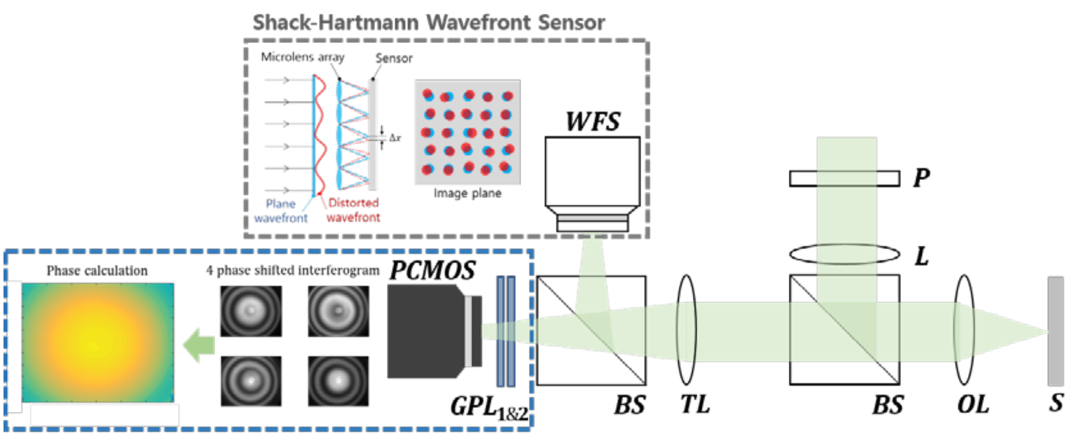


Figure 4. (a) radial shearing by the geometric phase lens pair; GPL, geometric phase lens and (b) optical configuration of radial shearing interferometer using a GPL pair; RHP, right-handed circular polarization; LHP, left-handed circular polarization; P, polarizer; L lens; BS, beam splitter; OL, objective lens; S, specimen; TL, tube lens; GPL, geometric phase lens; PCMOS, polarization pixelated camera; WFS, Shack Hartmann wavefront sensor. The inset shows the spatial phase shifting technique using a PCMOS. These figures are originated from Ref. 6.

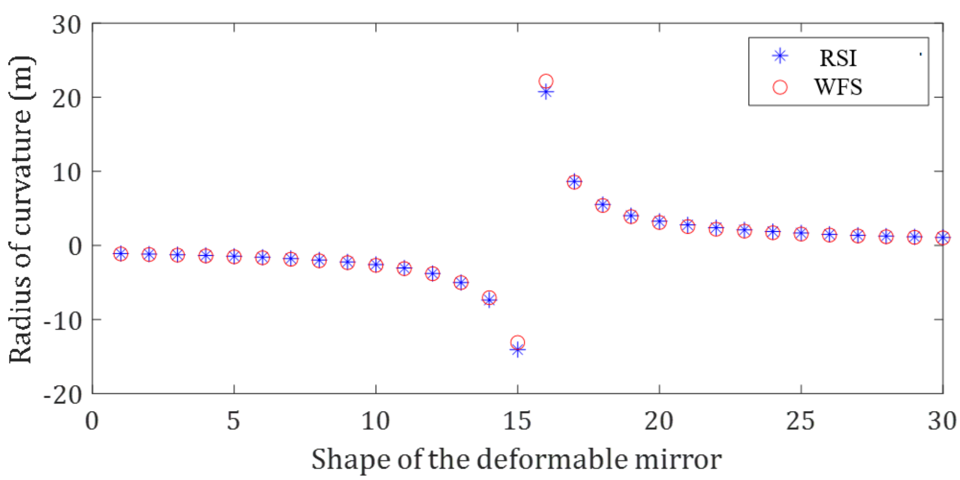


Figure 5. Radius of curvature estimation compared between the RSI and the WFS. These figures are originated from Ref. 6.

To verify the proposed RSI, a deformable mirror (DM) was operated to generate various wavefronts, and they were measured by the RSI. For the measurement result comparison, a commercial Shack-Hartmann wavefront sensor (WFS) was used. While the DM was operated to induce the defocus by gradually changing the surface of the DM from concave to convex shapes, the PCMOS captured the instantaneous interferograms, and each phase map was recorded. After the systematic error compensation, each wavefront was reconstructed with the modal method based on the optimization of Zernike polynomials. As the result, the reconstructed wavefronts gradually varied from concave to convex shapes and the radii of curvatures were close to those of WFS within 1.5% as shown in Fig. 5.

To further monitor the dynamic motion, the DM was continuously switched between applying several different Zernike aberrations as shown in Fig. 6. For this test the RSI measured each wavefront within a 0.1s time interval. The measurement speed is determined solely by the frame rate of the PCMOS, as no additional temporal procedures are needed to complete reconstruction.

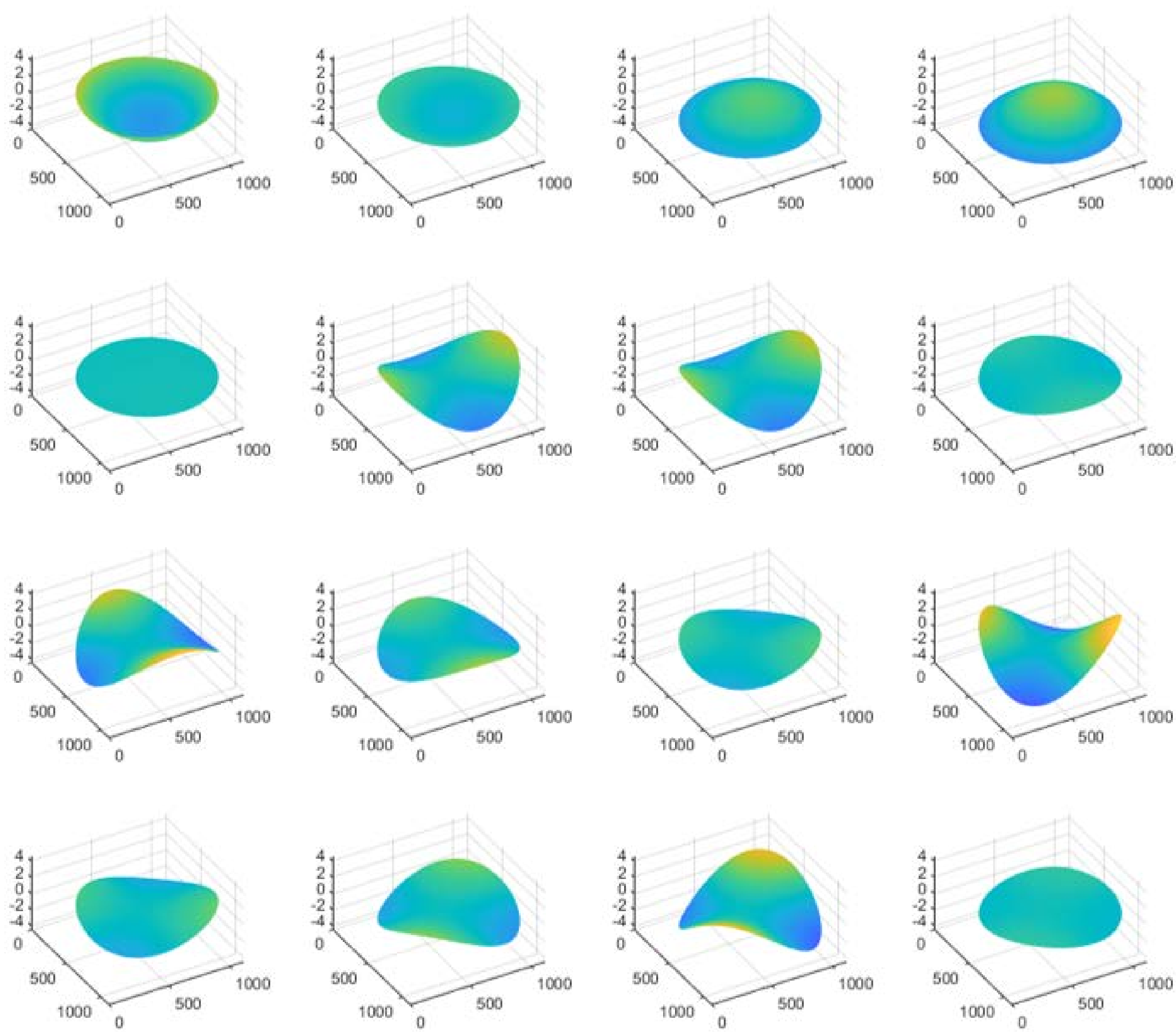


Figure 6. Various surface figure measurement results by the proposed RSI. These figures are originated from Ref. 6.

4. CONCLUSION

To summarize, we proposed and experimentally verified shearing interferometers based on geometric phase components in this investigation. By the polarization nature of the geometric phase components, a polarization pixelated camera can directly obtain the phase map with two orthogonally polarized wavefronts. In the experiments, various shapes of mirrors were measured to experimentally verify the proposed interferometer.

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