Oblique-Incidence Interferometric Measurement of Optical Surface Based on a Liquid-Crystal-on-Silicon Spatial Light Modulator

Zhen Zeng 1,*, Chengzhao Jiang 1, Yuxuan Jia 1, Zhongsheng Zhai 1 and Xiaodong Zhang 2

1 Key Lab of Hubei Province for Modern Manufacturing Quality, Hubei University of Technology, Wuhan 430068, China; jcz@hbut.edu.cn (C.J.); jiayuxuan@hbut.edu.cn (Y.J.); zs.zhai@hbut.edu.cn (Z.Z.)
2 State Key Laboratory of Precision Measuring Technology & Instruments, Laboratory of Micro/Nano Manufacturing Technology, Tianjin University, Tianjin 300072, China; cgzs.zhang@gmail.com

* Correspondence: zengzhen@hbut.edu.cn; Tel.: +86-15822112527

Abstract: An oblique-incidence interferometric measurement method is proposed to measure and adjust optical surfaces with a liquid-crystal-on-silicon spatial light modulator (LCoS-SLM). The optical system only consists of an interferometer and an LCoS-SLM with precision mounts. It could reduce the measuring cost and time consumption due to the programmable function of the LCoS-SLM and offer the ability to align the optical system. The oblique-incidence measurement theory and optical system adjustment method are established based on an off-axis paraboloid model. The ray-tracing program to calculate the compensation phase map in the measurement is proposed with math models. In the optical alignment step, the off-axis paraboloid model is used to apply the LCoS-SLM as a phase compensator to generate a focusing spot or light spot array to adjust the measured optical surface. And in the interferometric measurement step, the calculated compensation phase map from the ray-tracing calculation is loaded on the LCoS-SLM using the same optical setup as the optical alignment step without any mechanical adjustment. Two interference measurement experiments of typical optical surfaces were carried out to verify the accuracy of the measuring system.

Keywords: spatial light modulator; interferometric measurement; optical alignment; oblique incidence

1. Introduction

Interferometry is an effective and high-precision measurement method for optical surfaces [1]. Based on the null interferometric measurement method, the application range of interferometry could be extended to measure optical surfaces from optical planar and spherical surfaces to paraboloid mirrors and secondary surfaces with additional planes and spherical mirrors. However, for more complex optical surfaces [2,3], complex null optical compensators or computer-generated holograms (CGHs) need to be designed and manufactured to compensate for the optical path difference of the measuring optical path, creating null interferometry [4]. For example, Burge applied CGHs in a null test of the optical surfaces of a telescope [5] and Zhang used a CGH to test a cubic-phase plate [6] shaped like a flower.

However, the measurement of different optical surfaces requires the fabrication of different CGHs, and it is still difficult to make a CGH on a plane- or spherical-reference-fused silica substrate [7]. Thus, it is still not so convenient to use CGHs because when testing different optical surfaces, specially designed CGH substrates must be fabricated according to the application’s needs.

As a hot research topic, the interferometric method of optical surfaces based on SLM has attracted the attention of many researchers. In 2005, Cao Z.L. studied the application of a phase diagram in optical detection and tested the front surface of a convex lens with a transmissive spatial light modulator modified from a liquid crystal display [8]. In 2006,
Jacek Kacperski applied the SLM in an active laser interferometer for microelement tests [9]. In 2019, Xue S conducted a full-aperture splicing measurement experiment. He first measured the main part of an optical mirror with a null offset mirror and then measured the rest of the optical mirror with the help of an SLM to find the missing part of the wavefront [10,11]. In 2020, Pushkina introduced a comprehensive model and performance optimization modeling method to estimate the phase-only SLM model parameters with high accuracy [12]. In 2021, Liebmann reported the wavefront compensation for spatial light modulators based on Twyman Green interferometry [13]. In 2022, Xing Z proposed a module-\(\pi\) phase-wrapping method based on the grayscale segmentation method to reduce fly-back zone error in the phase-response measurement of spatial light modulators [14,15].

A liquid-crystal-on-silicon spatial light modulator (LCoS-SLM, the type used in the research is Pluto-VIS, HOLOEYE Photonics AG, Berlin, Germany) is an optical device that can be controlled by computer programming [16]. It could be used as an ideal optical compensator instead of a CGH for phase modulation. In 2020, Shanyong C reviewed the trade-off between the accuracy and dynamic range of the measurement of freeform optical surfaces and pointed out that SLM could be used as a reconfigurable interferogram-type CGH in adaptive null interferometry [17]. LCoS-SLM can not only be used to shorten the manufacturing cycle, simplify the system structure and improve the measuring range but also enable the measurement system to be installed in a convenient way.

The special significance is that we focus on the measurement and alignment of astronomical telescopes [18], such as the Giant Magellan Telescope (GMT) [19] and the James Webb Space Telescope (JWST) [20,21], which consist of many sub-mirrors. They use a similar off-axis parabolic mirror as the first mirror, focusing the light beam on the secondary mirror and the subsequent mirrors to get clear images. The wavefront measurement and image quality adjustment process of a single sub-mirror is always time-consuming. There is a low-budget and minimum-complexity demand for novel interferometry measurement and alignment methods. This part of the optical path could be simplified into an interferometric optical path at oblique incidence with an off-axis parabolic (OAP) model [22] to study its wavefront transmission characteristics, which is helpful in reducing the consumption of the tasks. Our previous work also reported an off-axis optical configuration, which used a focused light spot array and its interference fringes to align the LCoS-SLM with the interferometer and align the measured surface with the LCoS-SLM at oblique incidence [23]. The OAP model offers a basic concept for building a measurement system at oblique incidence.

Based on previous studies, the idea of this research is to propose a simple structure of an optical path using an LCoS-SLM at oblique incidence to obtain the wavefront and surface information of optical lenses and find a solution for the phase diagram calculation method for null interferometric testing of optical surfaces.

2. Interferometric Measurement System at Oblique Incidence

The setup of the interferometric system could be more reliable when combined with a commercial interferometer [24] (µPhase 1000, Fisba Optik, TRIOPTICS GmbH, Berlin, Germany, with an accuracy of \(\lambda/20\) PV (peak to valley)) and necessary optical elements. Based on this consideration and some early experiment attempts of normal-incidence interferometric setup, the interferometric measurement system at oblique incidence is built as shown in Figure 1. It only consists of a Twyman–Green interferometer, an LCoS-SLM with a precision rotator and the measured surface with a five-axis precision mount.
It is an off-axis oblique-incidence optical setup. In the proposed optical configuration figure, the LCoS-SLM head is mounted with a precision rotator so the light from the interferometer is tilted incident with an angle $\theta$. So, the primary optical axis rotates with an angle of $2\theta$. An off-axis parabolic model is used to calculate the alignment phase to load onto the LCoS-SLM to generate a light spot array and adjust the measured surface to the proper position. The LCoS-SLM used in the research is a phase-only SLM (Pluto-VIS, HOLOEYE Photonics AG, Berlin, Germany). Its liquid crystal material type [25,26] is parallel nematic liquid crystals. By varying the amplitude of the applied voltage, the phase of incident light is modulated [27].

Before the measurement, the interferometric measurement system should be aligned. This kind of off-axis system alignment method is designed under consideration to align all parts of the optical setup without additional equipment. With the proposed optical setup at oblique incidence, the off-axis system could generate four focus spot arrays, which could be employed to adjust the alignment according to the predesigned positioning marks (Figure 2a) on a flat reference ring near the tested optical surface firstly, as shown in Figure 2b. The position and distance of the focused spot array can be precisely determined by programming the phase diagram, which are shown as four red dash line circle on a large black dash-line circle in Figure 2. It is also possible to make precise angle and distance adjustments by projecting these four focused spots onto a surface and generating four interference pattern arrays. After rotation and translation adjustment (with the rotation angle $\alpha$ and $\beta$ shown in Figure 2a,b), the sample surface can be aligned and positioned precisely. Then, the LCoS-SLM can be used to generate the measurement wavefront and project it to the measured surface to obtain surface data. The oblique incidence and reflected light travelling path are marked with red color.

Such an interferometric setup prevents the aliasing of light beams when using beam splitters in a normal-incidence optical setup with LCoS-SLM, which would result in the interference pattern being disturbed. This phenomenon can be reduced by coating technology or manufacturing a back wedge angle on the beam splitters. However, the cost of the coating and special processing of the beam-splitting prism is very high and time-consuming. The interferometric setup at oblique incidence also prevents complex adjustment and alignment processes with a minimum number of optical components. Potential applications include in situ measurement and alignment of surface shapes of the mirror surfaces of off-axis three-mirror anastigmat systems, such as JWST, which uses a similar off-axis oblique-incidence optical setup.
phase needs to be carried out according to the classic equal-optical path principle, the

The sample surface and the positioning marks in the optical alignment step, (Figure 2).

Interference pattern being disturbed. This phenomenon can be reduced by coating tech-

3. Compensation Phase Calculation Model at Oblique Incidence

In null interferometry using CGHs, the equal-phase point is a key element in calculating the compensation phase of the CGH, which is usually selected as the focus point when using a spherical lens with the interferometer. However, it is not easy to define an equal-phase point when using a plane lens with the interferometer. The LCoS-SLM head surface is not an equal-phase surface in the oblique-incidence optical setup as expected. The incident and emergent light equal-phase surfaces are shown in Figure 3 when the plan wavefront is incident on the LCoS-SLM with zero phase loaded. The two equal-phase surface sample positions are marked by blue dashed lines and arrows. The oblique incidence light and reflected light are marked by red color arrows.

In the proposed measuring optical path, the phase calculation of the compensating phase needs to be carried out according to the classic equal-optical path principle, the ray-tracing model, shown in Figure 4. The blue, black and red arrows stand for the light travelling in different optical paths from left to right with number marked from one to three.

Figure 3. The equivalent optical path model and equal-phase surface near the LCoS-SLM head.

Figure 2. The alignment strategy using SLM-generated light spot arrays before measurement. (a) The sample surface and the positioning marks in the optical alignment step, (b) the measured surface in optical surface measurement step.
In the proposed measuring optical path, the phase calculation of the compensating surface needs to be carried out according to the classic equal-optical path principle, the ray-tracing model, shown in Figure 4. The blue, black and red arrows stand for the light traveling order "M-S-R", which is thought to reflect the light as a mirror; and the virtual phase surface (V), which is calculated from the compensation phase map for the LCoS-SLM. The surface order in which light travels in the optical path is “M-S-R”. For the purpose of calculating the phase loaded on the LCoS-SLM, the virtual optical path traveling order is assumed to be “M-T-R” and the virtual phase surface traveling order is “M-T-R”. For the purpose of calculating the phase loaded on the LCoS-SLM, the virtual optical path traveling order is assumed to be “M-T-R” and the total optical path difference (OPD) to obtain the phase map.

There are five types of functional surfaces in the model: the reference surface (R), where the light is also projected from the plane lens of the interferometer; the measured surface (M); the LCoS-SLM’ physical surface (S); the assumed reflecting surface (T), which is thought to reflect the light as a mirror; and the virtual phase surface (V), which is calculated from the compensation phase map for the LCoS-SLM. The surface order in which light travels in the optical path is “M-S-R”. For the purpose of calculating the phase loaded on the LCoS-SLM, the virtual optical path traveling order is assumed to be “M-T-R” and the phase retardation is added at the virtual reflecting surface. In the model, for example, we used the V surface and Vn to express the surface and the point on it. Vn points are defined by the Tn points and the optical path difference (OPD) to obtain the phase map.

The distance between the center of the reference plane (R surface) and the center of the LCoS-SLM surface is \( d_1 \), and the distance between the center of the LCoS-SLM surface and the measured surface is \( d_2 \). The equations can be set up to simulate the model. The total optical path can be expressed as

\[
OP = d_1 + d_2 \pm L \tag{1}
\]

in which \( L \) is the length of the S point to the T point,

\[
L = [l + \cos(2\theta)] \Delta l \tag{2}
\]

and \( \Delta l \) is the distance between the Tn point and the (0, 0, 0) point at surface S. In ray tracing, the relationship between the Mn points \((x_M, y_M, z_M)\), Tn points \((x, y, z)\) and Rn points \((x_R, y_R, z_R)\) and the direction vectors \((a, b, c)\) of the Mn point on the measured surface and vectors \((\alpha, \beta, \gamma)\) of the Rn point on the reference surface could be expressed as the parametric equations in Equation (3) and Equation (4), according to the point-vector method of analytic geometry. And the total optical length must meet the requirements of Equations (1) and (2), shown in Equations (5) and (6). The symbol in Equation (6) depends on the concave/convex shape of the surface being measured.

\[
\begin{align*}
[x] & = [x_M] + \left[ \begin{array}{c} \cos a \\ \cos b \\ \cos c \\ \end{array} \right] t \\
[y] & = [y_M] + \left[ \begin{array}{c} \cos a \\ \cos b \\ \cos c \\ \end{array} \right] t \\
[z] & = [z_M] + \left[ \begin{array}{c} \cos a \\ \cos b \\ \cos c \\ \end{array} \right] t \\
\end{align*} \tag{3}
\]

\[
\begin{align*}
[x] & = [x_R] + \left[ \begin{array}{c} \cos \alpha \\ \cos \beta \\ \cos \gamma \\ \end{array} \right] t' \\
[y] & = [y_R] + \left[ \begin{array}{c} \cos \alpha \\ \cos \beta \\ \cos \gamma \\ \end{array} \right] t' \\
[z] & = [z_R] + \left[ \begin{array}{c} \cos \alpha \\ \cos \beta \\ \cos \gamma \\ \end{array} \right] t' \\
\end{align*} \tag{4}
\]

\[
x \cos \alpha + y \cos \beta + z \cos \gamma = d_1 \tag{5}
\]

\[
\sqrt{(x - x_M)^2 + (y - y_M)^2 + (z - z_M)^2} + \sqrt{(x - x_R)^2 + (y - y_R)^2 + (z - z_R)^2} = d_1 + d_2 \pm (1 + \cos(2\theta))\Delta l \tag{6}
\]
In this case, the calculation of the point coordinates of \( T_n \) becomes a multivariate equation-solving problem. The solved points are located on the virtual reflecting surface within the LCoS-SLM aperture.

In the proposed ray-tracing model (Figure 5a), the compensated optical path difference within the LCoS-SLM aperture is calculated, shown in Figure 5b and turned into a phase value. Figure 5a is plotted in the MATLAB program according to the ray-tracing model shown in Figure 4. The light between the reference and the SLM is marked in green. The light between the SLM and the measured surface is marked in yellow. In order to obtain a continuous phase, the points of the phase data are resampled and output to a hologram map, shown in Figure 5c. The accuracy of the ray tracing can be evaluated by comparing the error of the virtual reflecting surface and the off-axis paraboloid designed according to prior knowledge about OAPs. The calculated surface error is shown in Figure 5d, which is within 121.36 nm.

![Figure 5](image_url)

**Figure 5.** The ray-tracing result of the interferometric system at oblique incidence. (a) The ray-tracing model (b) Calculated phase value on the SLM (c) Hologram map (d) Calculated surface error.

4. Experiments and Results

Two experiments were carried out to verify the accuracy of the proposed interferometric system at oblique incidence.

The first one is to measure a reference sphere with a known surface error of less than 50 nm (approximately \( \lambda/12, \lambda = 632.8 \text{ nm} \)). An off-axis parabolic phase is preloaded by the LCoS-SLM, and the parallel light emitted by the interferometer is modulated by the LCoS-SLM to form a focused beam projected onto the measured reference sphere. The simplified interference fringe is obtained after precise alignment by the five-axis displacement table, and the spherical wavefront measurement results of 0.117\( \lambda \) (\( \lambda = 632.8 \text{ nm} \)) are obtained (shown in Figure 6b), which are consistent with the reference sphere wavefront error (twice its shape error, approximately \( \lambda/6, \lambda = 632.8 \text{ nm} \)). The measurement setup is shown in Figure 6a. The oblique incidence measuring light is marked in yellow color and the interference pattern is magnified and shown in a red line box.
In the next measurement experiment, the measurement object is a concave sphere, as shown in Figure 7. The diameter of the measured object is 30 mm. Its concave spherical part is machined in the center and a reference plane ring with a width of 10 mm is turned around, so the measured wavefront is shaped like an upside-down hat. The sag value of the concave sphere part is 2.25 µm with a sphere radius of 50,000 mm, so this gentle concave sphere surface could be measured directly by the interferometer with a planar objective lens to obtain the reference value for comparison with the proposed optical setup at oblique incidence. The distance between the measured parts and the modulator is set as 550 mm, and the off-axis angle of oblique incidence is set as 6°. Through the alignment method mentioned, the concave sphere can be measured when placed at the designed measurement position. The oblique incidence measuring light is marked by red color and the light reflected by the measured surface back to the interferometer is marked by yellow. The measured surface and its wavefront result are shown on the left blue dash-line box.

Figure 7. Oblique-incidence interferometric system of concave sphere surface.

Figure 8 shows the measurement result of the concave sphere. Within the aperture range of the LCoS-SLM, the wavefront measured by the interferometric system at oblique incidence is shown in Figure 8b, and the wavefront measured directly by the interferometer is shown in Figure 8a. The PV (peak-to-valley) value of the wavefront measured by the oblique-incidence interferometry system is 1.459λ (λ = 632.8 nm), which is very close to the direct value of 1.470λ measured by the interferometer. And after the compensation phase is loaded on the LCoS-SLM, uniform zero-order interference fringes can be obtained within the measurement aperture range. The wavefront residual error of the concave sphere measured by the interferometric system at oblique incidence is 0.250λ, and RMS 0.031λ (Figure 8d), which is close to the wavefront residual error (PV0.258λ and RMS0.028λ), is measured by the interferometer directly (Figure 8c).
In this research, two typical optical surfaces are measured using the oblique-incidence interferometric measurement method. It is proven that LCoS-SLMs can be used for optical surface interferometric measurements as a phase compensation. The experimental results show that the surface error results are in good agreement with those measured by a commercial Twyman–Green interferometer. The measurement configuration could offer a solution for a lack of space or an inability to introduce additional auxiliary measuring equipment in the measurement and calibration process of an off-axis three-mirror anastigmat system.

Author Contributions: Conceptualization, Z.Z. (Zhen Zeng) and X.Z.; methodology, Z.Z. (Zhen Zeng); software, Z.Z. (Zhen Zeng) and X.Z.; validation, Y.J., and Z.Z. (Zhen Zeng); formal analysis, Z.Z. (Zhongsheng Zhai) and C.J.; investigation, Y.J.; resources, X.Z.; data curation, Z.Z. (Zhen Zeng); writing—original draft preparation, Z.Z. (Zhen Zeng); writing—review and editing, Z.Z. (Zhen Zeng) and C.J.; visualization, Z.Z. (Zhen Zeng); supervision, X.Z.; project administration, X.Z.; funding acquisition, Z.Z. (Zhongsheng Zhai) and X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant numbers 32071457 and 61635008, and the Hubei Natural Science Foundation, grant number 2022CFA006.
Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data can be obtained from the corresponding author upon request.

Acknowledgments: The authors thank the support of the Laboratory of Micro/Nano Manufacturing Technology (MNMT) of Tianjin University.

Conflicts of Interest: The authors declare no conflicts of interest.

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