PROFILOMETRY BY POLARIZING PHASE-SHIFTING INTERFEROMETER

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Abstract: A polarizing phase-shifting interferometer is introduced and its application to non-contact profilometry described. Given the nature of the polarizing phase-shifter, it is shown that phase steps are applied without a change in the optical path difference (and translation of the mirror) by manipulation of the geometric (Pancharatnam) phase. Compared with a commercial optical non-contact profilometer (working by white light interferometry principle) the experimental setup gives similar results, when measuring the profile of a thin film sample.

Key words: interferometry, phase-shifting, polarization, profilometry, geometric phase

1. INTRODUCTION

Phase shifting interferometry (PSI) [1–6] is a practical and accurate approach to phase measurement [7, 8] for surface profile characterization. Usually, the method incorporates optical phase shifters that are controlled mechanically or electrically via translation stages or using a piezoelectric transducer (PZT) [9, 10], in order to precisely move one of the interferometer mirrors. Thus, a phase difference between the two interfering waves is achieved in steps, while their amplitudes are kept with no changes such that a constant visibility is retained during the process [11]. Polarizing PSI works in the same way but makes use of polarizing optical components and phase shifter to introduce these phase steps. It acts on the geometric (i.e. Pancharatnam) phase [12–16] and not the dynamic phase [13, 17], resulting in no motion of the mirror. Therefore, the optical path difference (OPD) remains constant (ideally, when the interferometer is perfectly aligned it is zero) and the only contribution to the phase difference comes from the geometric term.

In the present work, the design, working principle and calibration of a polarizing PSI are presented. A polarizing phase shifter encompassing two birefringent wave plates (quarter- and half-wave retarders), is also presented. The phase-stepping is achieved by rotating the half-wave plate (HWP) while keeping the quarter-wave plate (QWP) fixed. This setup is used to measure the profile of a thin film sample and compared with a commercial non-contact optical profilometer.

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2. POLARIZING PHASE-SHIFTING INTERFEROMETER

2.1. THEORETICAL CONSIDERATIONS

Using monochromatic radiation, the optical path difference (OPD) acquired by translating one of the mirrors in a Michelson interferometer is given by the number of interfering fringes counted on the detector. When one dark (or bright) fringe takes the place of a similar adjacent one the traveled distance is equal with the wavelength of the radiation circulating in the interferometer. Therefore, we may express the OPD as:

\[ \text{OPD} = N \lambda, \]  

(1)

where \( N \) is the number of interference fringes of the same kind (bright or dark) counted on the detector during displacement and \( \lambda \) is the wavelength of the radiation. Thus, the phase difference between the interfering waves is:

\[ \phi = \frac{2\pi}{\lambda} \text{OPD}. \]  

(2)

In the polarizing PSI we have a rotating phase-shifter that alters the phase difference, but with no displacement of the mirror. The OPD-dependent phase is also called dynamic phase and is exclusively due to the difference in optical paths travelled by the two waves in the interferometer. By using a polarizing phase shifter, another term called the geometric (Pancharatnam) phase is also contributing to the total phase difference. This phase term depends on the anisotropy of the material the polarizing phase shifter is made of. The total phase difference, in this case, may be written as:

\[ \phi = \frac{2\pi}{\lambda} \text{OPD} + \alpha, \]  

(3)

where \( \alpha \) is the geometric phase term. So, by keeping the OPD constant and varying the azimuth angle of the HWP we are able to control the geometric phase and the total phase difference, respectively.

For simplicity, we consider a perfectly aligned interferometer, in which case it is said to be at zero path difference (ZPD). In this case, the OPD is zero and the total phase difference depends only on the geometric phase. Let \( \phi \) be the HWP’s rotation angle required to translate the interference pattern on the detector with one fringe. Therefore, a similar expression for the fringe displacement may be written as:
\[ \Delta_{\text{rot}} = N\phi, \]  

(4)

with \( \Delta_{\text{rot}} \) the angular displacement achieved by rotation of the HWP. From equations (1) and (4) it follows that

\[ \Delta_{\text{rot}} = \frac{\text{OPD}}{\lambda} \phi. \]  

(5)

The increment of displacement in a mirror-translation interferometer is just:

\[ \delta x = \frac{\text{OPD}}{N_{\text{pts}}}, \]  

(6)

where \( N_{\text{pts}} \) is the number of points in the measurement. Similarly, the increment of rotation of the HWP’s fast axis would be:

\[ \delta_{\text{rot}} = \frac{\Delta_{\text{rot}}}{N_{\text{pts}}}, \]  

(7)

and considering equation (4), we get:

\[ \delta_{\text{rot}} = \frac{N}{N_{\text{pts}}} \phi. \]  

(8)

2.2. EXPERIMENTAL SETUP

The phase-shifting interferometer setup is based on the Twyman-Green interferometer (a variant of the Michelson interferometer), as depicted in Fig. 1. It incorporates polarizing optical components and a phase shifter. The latter is composed of two birefringent retarders, namely a HWP and a QWP respectively, positioned at the input of the interferometer. The QWP has its fast axis fixed at 45° with respect to \( z \)-axis (i.e. perpendicular to optical table plane), which has the effect of changing any plane polarized incident radiation to elliptical or circular polarized one; depending on the incident linear polarization. The HWP is placed on a motorized rotating stage, allowing for precise rotation of its azimuth angle. It is this component that we control in order to change the phase difference between the two interfering waves, given the two mirrors, \( M_{\text{ref}} \) and \( M_{\text{obj}} \), are set to ZPD. Radiation from a HeNe laser is expanded with a spatial filter and collimated (at lens L1) before it is vertically polarized by linear polarizer P90°.
The polarizing beam splitter cube (PBSC) split the incoming circular or elliptical light into two orthogonally polarized parts. Thus, \( p \)-polarized light is transmitted towards the \( M_{\text{obj}} \) mirror and \( s \)-polarized light is reflected towards the \( M_{\text{ref}} \) mirror. Due to the PBSC working principle, the outgoing beams are extracted using a non-polarizing beam splitter (BSC) that redirects them at 90° towards a detector. Because the two waves are orthogonally polarized an analyzer, P45°, is used (with the azimuth angle set to 45°) to bring them at the same polarization state and, hence, make them interfere. The two lenses L2 and L3 are used as relay optics to adjust dimension of the interference pattern on the CCD detector.

2.3. CALIBRATION OF THE INTERFEROMETER

Because the phase difference between the two interfering waves changes with the azimuth angle of the HWP a calibration of the rotation angle with respect to fringe displacement at the CCD and virtual OPD is needed.
We recorded the interferogram produced by a stabilized HeNe laser (with 632.8 nm wavelength) while the HWP rotated 360° (with angle steps $\delta_{\text{rot}} = 0.5^\circ$). The obtained interference pattern (Fig. 2) was fitted with the following theoretical model:

$$A + B \cos \left(2\pi \frac{x}{\lambda_{\text{HeNe}}} + C \pi \right),$$

where $A$, $B$ and $C$, are some parameters and $\lambda_{\text{HeNe}}$ is the wavelength of the HeNe laser. Parameter $A$ adjusts the vertical position (offset) of the sinusoid, $B$ is the amplitude of the wave and $C$ is a phase parameter to account for the initial phase. In this case, the angular displacement, $\Delta_{\text{rots}}$, corresponds to a full rotation of 360° and a number of 720 points, given the angle step. From the theoretical model it follows that a number of four fringes is counted during the measurement. Thus, according to eq. (8), the rotation angle $\hat{\phi}$ corresponding to the displacement of one wave (fringe) is $90^\circ$. Also, according to eq. (5) the corresponding OPD is $2.5 \, \mu\text{m}$ and $\delta x$ is 3.5 nm (see eq. (6)). The values of the fit parameters are: $A = 0.29771$, $B = 0.474301$ and $C = 0.685965$. 

Fig. 2 – (Color online) Calibration of the polarizing PSI showing the corresponding translation OPD and the angular displacement of the HWP azimuth angle, $\varphi$. The 632.8 nm wavelength of a HeNe stabilized laser was used as reference. The blue dotted curve shows the experimentally measured points and the red curve is the theoretical fit model, as described in eq. 9.
2.4. PHASE-SHIFTING PROCEDURE

In PSI the fringe patterns due to interference of the two waves is modulated by:

\[
I(x, y) = I_s(x, y) + I_p(x, y) + \sqrt{I_s I_p} \cos \left[ \phi(x, y) + \delta_n \right],
\]

where \(I_s\) and \(I_p\) are the intensities of the fields in the two arms of the polarizing interferometer, \(\phi\) is the object phase and \(\delta_n\) is the phase step generated to obtain the phase-shifted interferograms (with \(n = 0, 1, ..., M-1\) for \(M\) interferograms). Note that \(I_s(x, y)\) and \(I_p(x, y)\) and \(\phi(x, y)\) are unknown and must remain unchanged during phase-shifting process. Therefore, at least three phase-shifted interferograms are needed in order to find a solution for the object phase [17].

The phase reconstruction was performed using the four-step phase-shifting algorithm [5, 8, 18, 19] where the modulation phase, \(\delta_n\), was made to assume values \(0, \pi/2, \pi,\) and \(3\pi/2\) sequentially (Fig. 3). Consequently, four fringe patterns are achieved with the following intensities:

\[
\begin{align*}
I_0(x, y) &= I_s(x, y) + I_p(x, y) + \sqrt{I_s I_p} \cos \left[ \phi(x, y) \right], \\
I_1(x, y) &= I_s(x, y) + I_p(x, y) - \sqrt{I_s I_p} \sin \left[ \phi(x, y) \right], \\
I_2(x, y) &= I_s(x, y) + I_p(x, y) - \sqrt{I_s I_p} \cos \left[ \phi(x, y) \right], \\
I_3(x, y) &= I_s(x, y) + I_p(x, y) + \sqrt{I_s I_p} \sin \left[ \phi(x, y) \right].
\end{align*}
\]

The phase recovery algorithm is then implemented by computing

Fig. 3 – Typical interferograms with \(\pi/2\) phase shift, recorded during implementation of the four-step phase-shifting algorithm.
\[\phi(x, y) = \tan^{-1} \left[ \frac{I_1(x, y) + I_3(x, y)}{I_0(x, y) + I_2(x, y)} \right],\]  \hspace{1cm} (12)

and the OPD can be reconstructed as:

\[\text{OPD}(x, y) = \frac{\lambda}{2\pi} \phi(x, y).\]  \hspace{1cm} (13)

Take into account that phase is defined modulo \(2\pi\) and when the actual phase extends over this interval unwrapping algorithms [19] need to be applied.

3. MEASUREMENTS

The sample used in these experiments was a profile etalon with the nominal height of 1000 nm. This is a fine silicon reflective surface with several profiles precisely etched on its surface. First, it was placed in the polarizing PSI as the object mirror, \(M_{\text{obj}}\), and four interferograms were recorded, while \(\delta_n\) took the values 0, \(\pi/2\), \(\pi\), and 3\(\pi/2\) by rotating the HWP; that is, the phase was shifted in steps of \(\pi/2\). To achieve that, the HWP had to be rotated with an amount of degrees of arc after each measurement. From equation (8) and knowing that we need four interferograms to be recorded during one fringe displacement (rotation), it follows that our phase shifter must rotate an angle of 22.5\(^\circ\) after each acquisition, in order to achieve the phase stepping.

The second experimental approach was to measure the profile for the same sample, but with the \textit{white light interferometry} (WLI) technique and using a commercial non-contact optical profilometer. This device uses PSI technique for the \textit{smooth} measuring mode and vertical scanning (or coherence probe) interferometry for the \textit{texture} mode. Choosing one mode or the other depends on the sample that needs to be tested. For a finer or thinner sample, the first mode needs to be employed while for a coarser or steeper profile sample the second will be more appropriate. The profilometer combines these interferometric techniques with an optical microscope and the phase stepping is accomplished by a piezoelectric actuator. \textit{Texture} mode was used for all measurements in this work.

4. RESULTS AND DISCUSSION

Following the measurements in previous section, we computed the wrapped phase (modulo \(2\pi\)) by applying the four-step phase-shifting algorithm described in Section 2. Usually, a set of interference fringes should be visible over the object with such measurements (see Fig. 3).
This is because the mirrors of the interferometer are tilted with respect to each other along the vertical axis, allowing more fringes to be obtained and offering better sensitivity to more complicated objects. Increasing the number of fringes would result in a tilted reconstructed phase and OPD, respectively. This tilt can be eliminated by software processing and is part of every commercial profilometer.

However, because the studied object was a smooth step profile, we opted to work with one interference fringe in the polarizing PSI setup, maintaining the mirrors parallel to each other. The reconstructed wrapped phase and OPD are shown in Fig. 4a and b, respectively. Several stripes are visible over the image, and are due to imperfections in the unwrapping algorithm. This is a subject of many papers and will not be treated here. A profile along the vertical direction was selected from Fig. 4b and its height was measured. The value of the height profile was found to be 949.2 nm, as shown in Fig. 5.

The OPD as measured with the WLI is shown in Fig. 6, where white lines give the direction for the specific profile measurement while the “target” signs show its extent. With this method, we took ten measurements along the edge of the profile and computed an average value of the measured height. The average value for the step-height profile obtained with the WLI was $\Delta z = 965$ nm. This small difference from the nominal height of the sample is due to the tilt compensation procedure, as described above. Figure 7 depicts the profiles and Table 1 shows the quantitative results.
Fig. 5 – (Color online) Profile extracted from the 2D OPD in Fig. 4b. The height of the profile is indicated with red lines.

Fig. 6 – (Color online) OPD obtained with the WLI.
Table 1
Profile measurements with WLI for positions on the sample indicated in Fig. 6

<table>
<thead>
<tr>
<th>No.</th>
<th>Nominal height (nm)</th>
<th>$\Delta z$ (nm)</th>
<th>$\bar{\Delta z}$ (nm)</th>
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<tr>
<td>1</td>
<td>1000</td>
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<td>965</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>981.4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>950.1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>954.9</td>
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5. CONCLUSIONS

A polarizing PSI capable of measuring thin film profiles was presented. It was demonstrated that precise phase shifts, necessary for the measuring technique, can be achieved by a special phase shifter placed at the input of the interferometer. Because it makes use of the geometric phase (and not the dynamic phase), no actual translation motion of the interferometer mirror is necessary. The design, theory and calibration of the polarizing PSI are presented, together with the four-step phase-shifting interferometry algorithm. They are used to measure the step-height profile
of a profile etalon with nominal height of 1000 nm. Because polarized light is used, errors due to mechanical translation are eliminated and a device with virtually no moving parts is achieved.

To fairly assess such a device, a non-contact optical profilometer was also used to measure the profile of the sample.

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REFERENCES