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An Investigation of a Single Shot Dual Wavelength Polarised Interferometer which uses Carre and Four Step Phase Shift Algorithms

Saif Al-Bashir[1], Hussam Muhamedsalih [1], Feng Gao[1], Xiangqian Jiang [1]

[1]*EPSRC Future Metrology Hub, University of Huddersfield*

h.muhamedsalih@hud.ac.uk

Abstract

In this paper, we present a single-shot Dual-wavelength Polarized Interferometer (DPI) for measuring micro/nano-scale structured surfaces. This two-wavelength interferometer is combined with a polarization phase shift method to extend the 2π ambiguity range without any mechanical movement, enabling a single-shot approach to 'freeze' any unwanted environmental disturbances. Two fringe analysis algorithms, for the evaluation of surface topography, are presented. Three standard step height samples are measured in order to investigate the performance of the DPI. The system has the potential to be used for measuring moving surfaces, and the measuring range is limited by synthetic wavelength.

Polarised interferometry, two-wavelength, single-shot, Carre and Four Step algorithms

1. Introduction

Optical interferometry has been widely used for surface measurements because of its inherent advantages: non-contact, high accuracy interrogation and high measurement speed. However, the requirement for the use of multiple frames to cover a large vertical measurement range is still considered a limiting factor in relation to using such interferometry systems for dynamic on-line measurement of surfaces produced by roll-to-roll (R2R). The solution for any optical system measuring moving objects should be realized using a single frame capturing approach. Most single shot interferometers are operated at a single wavelength; thus, the maximum different between two adjacent pixels, representing the surface height, will be less that λ/4, where λ is the wavelength of the light source. A common method for extending the measurement range for surface height is to use two wavelength to produce a larger synthetic wavelength, enabling a 2π phase ambiguity extension [1, 2, 3]. This paper presents a single shot Dual wavelength Polarized Interferometer (DPI) which can operate independently of the surface inclination. The phase shift is achieved by polarization techniques – so as to avoid any scanning or tilting mechanisms. The measurement principle is described in figure-1.

2. Experimental setup

The experimental setup shown in figure (1) consists of a red and green light source filtered by an acousto-optics tunable filter (AOTF) to produce two wavelengths (λ1=630nm, λ2=560nm) with 2nm narrow line-widths, plus a polarized Michelson interferometer and four polarized detection arms.

The required phase shift is achieved by polarizers and quarter-wave plates as shown in figure-1 in the same manner as described in reference [4]. The interference fringe is focused onto four-colour CMOS Cameras; all can be triggered at once using a single exposure time. The captured colour images are decomposed into their primary colours to obtain four shifted interferograms at each wavelength.

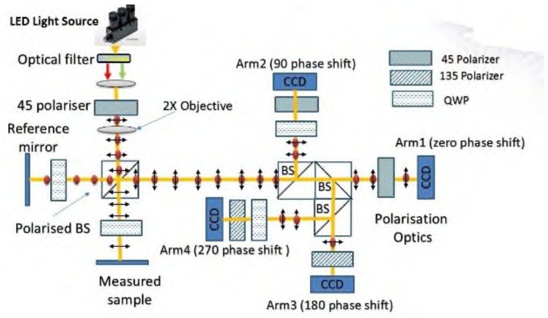


Figure .1 DPI configuration.

3. Fringe analysis: Carre and Four Step algorithms

The resolution and accuracy of the measurements when using DPI depend on the robustness of the algorithm utilised. There are two PSI algorithms by which interferograms obtained via a DPI can be analysed. Both of these require four shifted intensity values in order to calculate the phase. The red and green components of each of the interferograms obtained from the cameras are extracted using a Matlab function, resulting in four red interferograms and four green interferograms. The phase shift between each interferograms is 90^{o} for each color due to the polarization arrangement. The mathematical description of the interference is given in Equation (1) [5]:

$$I(r,g) = a(r,g) + b(r,g)\cos(\varphi xy(r,g) + \Delta\varphi) \qquad (1)$$

where **a** and **b** are the interference bias and amplitude of the fringe contrast respectively, r and g are symbols for the red and green colours respectively and $\Delta\varphi$ = (0^{o}, 90^{o}, 180^{o}, 270^{o}) – the amount of phase shift obtained by polarization. Hence, each pixel on the sample has four intensity values at each colour.
The Four Step algorithm [6] is used to calculate the phase valueφ, and hence the phase map for the entire surface. The wrapped phase for each color is calculated using Equation (2) as the phase shift between intensity values is 90^{o}.

$$\varphi=\tan^{-1}\frac{(I2-I4)}{(I3+I1)} \qquad (2)$$

The Carre Algorithm [6] also used to calculate the phase value φ, since it is required that there be four equal-value phase shift changes. The wrapped phase for each color is calculated using equation (3)

$$\varphi=tan\text{-}1\{\frac{\{[3(I2-I3)-(I1-I4\ )][(I1-I4)+(I2-I3)+(I2-I3)\}\text{^}1/2\ )]}{(I2+I3)-(I1+I4)}\ \} \qquad (3)$$

The synthetic wrapped phase, $\boldsymbol{\varphi syn}$**,** with the longer 2π interval, is determined by subtracting the phase of the shorter wavelength (green) from the longer wavelength (red) as shown in Equation (4). As a result of this subtraction, phase jumps may appear due to a wrapping spatial mismatch between the two wrapped phase maps; these are resolved by adding 2π when the different is negative. The surface height h, is then calculated using Equation (5).

$$\varphi syn = \varphi red - \varphi green \qquad (4)$$

$$h = \frac{1}{2}\left[\frac{\varphi syn\ \lambda syn}{2\pi}\right] \qquad (5$$

The synthetic wavelength is given by (6)

$$\lambda\text{syn} = \frac{\lambda1\lambda2}{[\lambda1-\lambda2]} \qquad (6)$$

Which is equal to 5.04 µm; thus, this extends the measurement range to approximately 1.26 µm.

4. Results and discussion.

In order to confirm the performance of the DPI and the performance of the algorithms described in the previous sections, three standard National Physical Laboratory (NPL) cross gratings, having depth values of 1264 nm ± 4 nm, 502 nm ± 4 nm and 185 nm ± 2 nm were used. The samples were measured and evaluated according to ISO 5436 using the Four Step and then the Carre algorithms. In order to investigate the performance of the DPI, the same spots on all three samples were also measured using a commercial Coherence Scanning Interferometer (CSI) manufactured by Taylor Hobson Ltd using a 5X objective lens. The DPI results, the CSI results and the samples' NPL conformity certificate values are compared in Table 1. The results demonstrate that the DPI can measure structured surfaces with an average absolute error of 67.7 nm, using the Four Step algorithm, and 75.9 nm using the Carre algorithm. The Carre results also show spike errors across the surface as shown in Figure 2. The general degradation in signal-to-noise ratio, due to cross-talk between colours and camera sensitivity, can contribute to the overall error of the measurements. According to the camera spectrum response for Sony IMX174 sensor used in this experiment, the potential of cross-talk between red and green colours is the highest compared to other combinations of channels (green-blue, red-blue). However, the red and green combination is chosen to give the longest synthetic wavelength in order to increase the measurement range in spite of fringe contrast degradation. The error difference between the Four Step and the Carre algorithms could be caused by the 90° phase step not being the optimum step for the Carre algorithm with random intensity noises – which is in accordance with reference [7].

Table 1 Measurment Result (Red-Green and Green-Blue) Component Between DPI and CCI.

ST	DPI-Four	DPI -Carre	CCI (nm)	ABS-Four	ABS-Carre
185.9 ±2.3nm	259.7	268	192.1	67.7	75.9
502.0 ±4.1nm	557	645	516.4	40.6	128.6
1264 ±4nm	1213	1116	1268	55	152

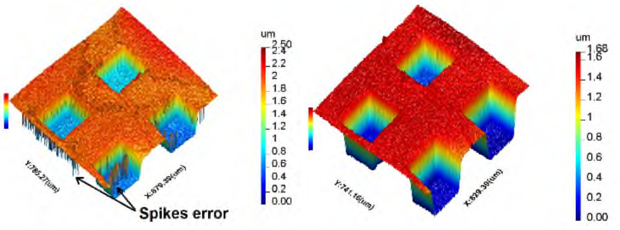
ST: Step height value (nm) ± expanded uncertainty.

DPI- Four: DPI (nm) using Four step Algorithm.

DPI-Carre: DPI (nm) using Carre Algorithm.

ABS-Four: Abs error |DPI –CCI| using Four step algorithm.

ABS-Carre: Abs error |DPI –CCI| using Carre Algorithm.



(a) (b)

Figure 2. Measurement result for cross grating depth, 1200_nm, standard sample, illuminated by red and green sources: (a) Carre algorithm (b) Four step.

4. Conclusions

Here, we have introduced a single-shot Dual-wavelength Polarized Interferometer (DPI) alongside two fringe analysis algorithms. The DPI can extend the vertical range of measurements relative to those obtained by a conventional Phase Shift Interferometer by using a synthesized wavelength and by accelerating the measurement speed via the use of a polarization phase shift arrangement. The synthetic wavelength red-green is chosen to be 5.04 µm. The average error when measuring step height standards of less than 1.2 µm is 67.7 nm using the Four step algorithm and 76 nm using the Carre algorithm. The 90° phase step is more appropriate for use with the Four Step than with the Carre algorithm.

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