Single Shot Dual Wavelength Polarised Interferometer

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***Abstract*— In this paper we present a single-shot Dual-wavelength Polarised Interferometer (DPI) for measuring micro/nano-scale structured surfaces. The two wavelength interferometer is combined with a polarisation phase shift method to extend the 2π ambiguity range without any mechanical movement, enabling a single-shot approach to freeze any unwanted environmental disturbances. The measurement results of using cross grating of 200 nm, 500 nm, and 1200 nm depth is presented. A measurement of 40 nm step height also is presented. The system has the potential to be used for measuring moving surfaces with the measuring range being limited by synthetic wavelength.**

***Keywords*— polarised interferometry, two-wavelength, single-shot**

I. INTRODUCTION

Optical interferometry has been widely studied and developed for surface measurement because of the advantages of non-contact and high accuracy interrogation. The interferometry techniques can be classified according to phase shift mechanisms. For example, a Phase Shift Interferometer (PSI) usually shifts the optical phase over several equal steps mechanically to measure a limited height range but with a high level of accuracy. The wavelength scanning interferometer (WSI)[1] shifts the optical phase over many steps by tuning the wavelength to measure absolute heights greater than PSI methods. Coherence scanning interferometer (CSI) scans envelope the coherence of a broadband light source with respect to interferometer head movement, achieving accurate height measurements over a large vertical range.

Areal measurement of precision surfaces is usually achieved optically by capturing multiple frames to cover a large vertical measurement range. The scanning time for methods such as CSI and WSI is considered a limiting factor for using such interferometry systems for dynamic on-line measurement of surfaces produced in a roll-to-roll process (R2R) process. A single-shot Phase Shift Interferometry (PSI) system called "FlexCam" developed by 4D Technology is currently being used to detect defects for PV barrier films manufactured through R2R technology [2]. This interferometer can provide areal measurements in milliseconds with 2 nm vertical resolution; however, the short measurement range of conventional PSI may pose a problem when identifying and classifying large vertical defects.

All techniques of single wavelength phase shift interferometers have the limitation that the maximum difference between two adjacent pixels of the surface height must be less that $\lambda/4$, where λ is the wavelength of the light source. A common method to extend the measurement range of surface height is to use two wavelengths to produce a large synthetic wavelength, enabling a 2π phase ambiguity extension. By processing the phase profile of the first wavelength and second one, a synthesised phase profile can be obtained [3, 4] in order to have an unambiguous range larger than the result from a single wavelength.

The data acquisition of the synthesised phase is usually obtained by capturing interferograms instantaneously by using a Bayer filter in front of the camera. A multi wavelength with phase-shifting technique was employed for surface measurement using a holography configuration[5]. The height of each point can be calculated without depending on neighboring pixels. A monochromatic camera with a micro-polariser array was used to obtain four phase shifts for the two wavelengths (Green-Blue). A measurement of 1.9 µm step height was successfully demonstrated but without describing the measurement noise level.

The instantaneous, or single shot, method is preferred for fast measurement, but it may depend on a tilted surface as a phase shift mechanism. A titled surface interferometry configuration with a spatial fringe analysis method was successfully used to measure areal surface with single camera [6]. The experimental results showed that the system can measure 357 nm using two wavelengths. In addition to the single shot capability, the lowcost and simplicity of the configuration setup are the main advantages.

This paper presents a single shot Dual wavelength Polarised Interferometer (DPI), which is independent of the surface inclination. The phase shift is achieved by a polarisation technique to avoid any scanning or tilting mechanisms.

Red and green colors are used as an illumination source for Michelson interferometers where the detection unit is a two-dimensional colour camera. The measurement principle is described in Fig (1).

The operation principle is based on interfering two wave fronts (test and reference wave fronts) which are orthogonal linearly polarised. The wave plates and polarizers introduce the phase delay between the test wave front and reference wave front.

Measurement results from cross grating standard samples of depth 200 nm, 500 nm and 1200 nm and a step height standard of 40 nm are presented. The proposed interferometer provides a nanometer vertical resolution and diffraction limited lateral resolution. The proposed measurement vertical range is extended to a quarter of the synthetic wavelength.

II. Experimental setup.

The experimental setup shown in Fig. 1 consists of a RGB light source filtered by an acousto-optics tunable filter (AOTF) to produce two wavelength (λ_1=630nm, λ_2=560nm) with 2nm narrow line-widths, a polarised Michelson interferometer and four polarised detection arms.

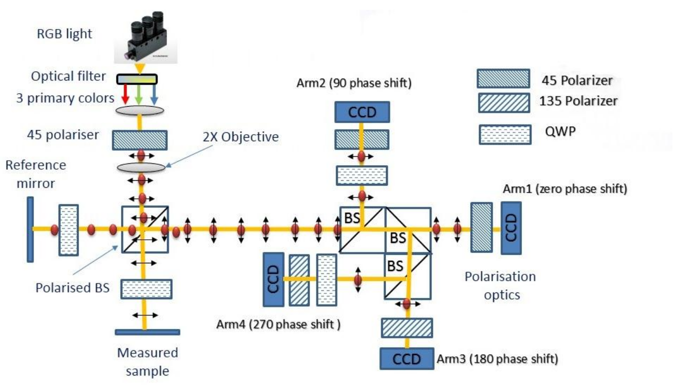


Fig. 1. DPI configuration.

The polarisation condition of the filtered light emerged from the AOTF is a vertical P-state. It is converted to a P-state at +45° by placing a linear polariser at 45° in order to construct P and S states subsequently by the interferometer.

The polarised filtered light is passed through a 2X microscope objective to the interferometer. The interferometer consists of two balanced optical path arms split by a polarised beam splitter (P.B.S). The two arms are demarcated as a reference arm which ends with a reference mirror and a measurement arm which ends with a measurement sample; they are linearly polarised along orthogonal axes.

Quarter-wave plates have been used to convert the polarisation states of reference and test beams in order to pass through P.B.S to the detection arms. The two orthogonal beams are focused using a doublet imaging lens of 100 mm focal length. The focused beam is made to travel through the three no polarisation beam splitters pasted together, and this forms the four arms of the phase-shifting arrangement. In general, phase shift interferometers often have an optical element that introduces three or more phase shift in the reference wave front. The phase shifting is proposed, here to be instantaneous. Using this technique, the required phase shift is achieved by polarisers and quarter-wave plates, as shown in Fig- 1, in the same manner as reference [7]. The combination of quarter-wave plates and polarisers which have been used in this set-up is shown in Table I.

The interference fringes are focused onto a two dimensional colour CMOS Camera. The cameras with sensor model Sony IMX174 are triggered at once using single exposure time. The captured four images are transferred to the CPU memory for fringe analysis.

TABLE I. Polarizers arrnagement for incremental phase shift of 90° .

	Polarisers (deg)	Quarter-Wave Plate (deg)	Phase Shift Achieved (deg)
Arm1	45	none	0
Arm2	45	fast axis at zero	90
Arm3	135	none	180
Arm4	135	fast axis at zero	270

III. Fringe analysis and algorithm.

Fringes obtained from DPI can basically be analysed by using one of the PSI algorithms that require four shifted intensity values to calculate the phase. The red and green components of each interferograms obtained from the cameras are extracted using the Matlab function, resulting in four red interferograms and four green interferograms. The phase shift between every interferograms is 90° for each colour due to the polarisation arrangement. The mathematical description of the interference given in Equation (1) can be re-written as [8]:

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

where b and a are interference bias and amplitude of the fringe contrast respectively, r and g are symbols for red and green colours respectively, $\Delta\varphi$ is the amount of phase shift by polarisation. As such, each pixel on the sample has four intensity values at each colour, as described in Table II. The four intensity values were calibrated in order to equalise the (bias) and **b** (visibility) between all cameras.

TABLE II. INTENSITY VALUE FOR EACH COLOR RECORDED BY THE FOUR CAMERAS.

Intensity at red (λ1=630nm)	**Intensity at green (λ2=560nm)**
I1(r) $= a(r) + b(r)\cos(\varphi + 0)$	I1(g) $= a(g) + b(g)\cos(\varphi + 0)$
I2(r) $= a(r) + b(r)\,cos(\varphi + \pi/2)$	I2(g) $= a(g) + b(g)\,cos(\varphi + \pi/2)$
I3(r) $= a(r) + b(r)\cos(\varphi + \pi)$	I3(g) $= a(g) + b(g)\cos(\varphi + \pi)$
I4(r) $= a(r) + b(r)\cos(\varphi + 3\pi/2)$	I4(g) $= a(g) + b(g)\cos(\varphi + 3\pi/2)$

A four Step algorithm [9] is used to calculate the phase value φ, hence the phase map for the entire surface. The wrapped phase for each colour is calculated using Equation (2) as the phase shift between intensity values is 90°.

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

The synthetic wrapped phase $\boldsymbol{\varphi syn}$ with a longer 2π interval is determined by subtracting the phase of the shorter wavelength (green) from the longer wavelength (red), as shown in Equation (3). As a result of this subtraction, phase jumps may appear due to a wrapping spatial mismatch between both wrapped phase maps; these are resolved by adding 2π when the difference is negative. The surface height $\boldsymbol{h}$ is then calculated using Equation (4).

$$\varphi syn = \varphi red - \varphi green \quad (3)$$

$$h = \frac{1}{2}\left[\frac{\varphi syn\ \lambda syn}{2\pi}\right] \quad (4)$$

The synthetic wavelength is given by

$$\lambda syn = \frac{\lambda 1 \lambda 2}{[\lambda 1 - \lambda 2]} \quad (5)$$

Which is equal to 5.04 µm, extending the measurement range to approximately 1.26 µm.

Based on the camera spectral response shown in Fig-2, it can be predicted that intensity cross talk between the Red and Green channel is higher than the Green and Blue channel for a single shot frame capture. This can increase the phase noise in Red and Green interferograms, leading to measurement error. An investigation has been carried to provide quantitative information about the cross-talk in DPI.

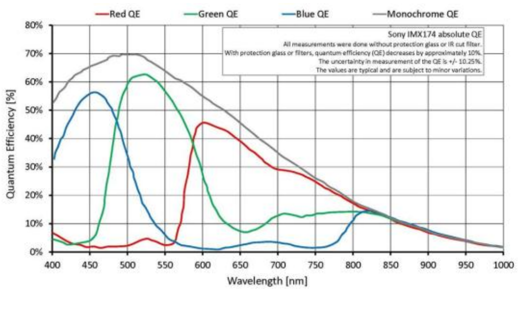


Fig. 2. Camera Spectral Response.

The system has been illuminated by only red light and then by only green light at the aforementioned wavelength and line-width values. A single frame has been captured at each colour. The red and green values were registered as references. Later, the green cross-talk component has been extracted from the red frame, similarly the red cross-talk component from the green frame. The green and red cross-talk components were registered as cross-talk value. The percentage of the cross-talk is calculated using Equation (6).

$$cross\ talk\ \% = \frac{Rcross\ talk\ value}{Reference\ Value} * 100 \quad (6)$$

It has been found that the cross-talk of red is 30.8% in the green filter and the cross-talk of green is 15.5% in the red filter. The cross-talk has also been studied for the Green-Blue channel. The same above procedure has been repeated but for green and blue lights only. The cross-talk of green in the blue filter is 23.1% and the cross-talk of blue in the green filter is 18.7%.

IV. Results and Discussion.

In order to confirm the performance of the DPI described in previous sections, three cross grating National Physical Laboratory (NPL) standards, having depth values of 1264_nm ± 4 nm, 502 nm ± 4 nm and 185 nm ± 2 nm have been used. The samples have been measured and evaluated according to ISO 5436. The measurement results are shown in Fig. 3, Fig. 4 and Fig. 5 respectively. The same samples were measured using a commercial Coherence Scanning Interferometer (CCI) manufactured by Taylor Hobson Ltd using a 5X objective lens. The DPI results, the CCI results and the samples' NPL conformity certificate values are compared in Table III. The results demonstrate that the DPI can measure structured surfaces with an average absolute error of 71.1 nm. The error is sustained for different height values. The degradation in signal-to-noise ratio, due to cross-talk between colours, camera sensitivity and fringe contrast of the synthetic wavelength, can contribute to the error in the measurement.

To reduce the average error due to cross talk, an alternative wavelength combination compatible with the cameras' Bayer filters has been investigated.

It is possible to change the combination of wavelengths in DPI because the wavelength filtration mechanism is dynamic and achieved by the AOTF. Green and blue colors are filtered at λ1=560 nm and λ2=450 nm with 2 nm line-width. This wavelength combination produces less cross-talk between colours and a shorter synthetic wavelength (2.29 µm), enhancing the synthetic fringe contrast. However the 2π ambiguity interval is shortened by over 0.57 µm. Resultantly, only the 185.9 nm and 502.0 nm step height standards have been re-measured. The measurement results using DPI were found to be 217.3 nm and 475.4 nm. The average error has been reduced from 31.1 nm to 27 nm, as shown in Table III.

In order to investigate the performance of the polarisation for phase shifting, a VLSI Standards Inc. (VLSI) standard having 43.7 nm ± 1.4 step height has been measured and evaluated according to ISO 5436 using a single wavelength λ=630nm. .The areal measurement result with the cross-section profile is shown in Fig. 6. The measured step height was found to be 39.25 nm, giving an error equal to 4.4 nm as shown in Table IV. The same step measurement is equal to 42.55 nm when measured by CCI. The small error (less than 5 nm) in measurement when using the single wavelength proves that the polarisation phase shift technique works sufficiently.

In order to confirm the ≃70 nm measurement error obtained when using the red and green combination in previous experiments, the VLSI step height was evaluated and measured by DPI using the red and green illumination combination. The areal measurement result with the cross-section profile is shown in Fig.7. As expected, the system failed to evaluate the step height accurately since the error value is greater than the step value.

TABLE III. MEASURMETN RESULT (RED-GREEN ANE GREEN-BLUE) COMPARISON BETWEEN DPI AND CCI.

ST	DPI-RG	DPI - GB	CCI (nm)	ABS-RG	ABS-GB	ABS DPI–NPL GB	ABS DPI–NPL RG
185.9 ±2.3nm	257.0	217.3	192.1	65	25	31.1 ±2.3 nm	71.1 ±2.3 nm
502.0 ±4.1nm	588.3	475.4	516.4	72	41	27 ± 4.1 nm	86.3 ± 4.1 nm
1264 ±4nm	1213.2	Faild	1268	55	Faild		50.8 ± 4.1 nm

ST: Step height value (nm) ±0expanded uncertainty.

DPI-RG: DPI (nm) Red-Green.

DPI-GB: DPI (nm) Green –Blue.

ABS-RG: Abs error |DPI –CCI| Red-Green (nm).

ABS-GB: Abs error |DPI –CCI| Green-Blue (nm).

ABS DPI–NPL GB: Abs error |DPI–NPL values| Green-Blue (nm).

ABS DPI–NPL RG: Abs error |DPI–NPL values| Red Green (nm).

TABLE IV. MEASURMETN RESULT COMPARISON BETWEEN DPI AND CCI FOR RED (R) AND RED-GREEN (RG) .

ST	DPI -R	DPI-RG	CCI (nm)	ABS-R	ABS-RG	ABS-VLR	ABS-VLGR
43.7 ±1.4 nm	39.259	Faild	42.551	-3.292	Faild	- 4.441± 1.4nm	Faild

ST: Step height values (nm) ±0expanded uncertainty.

DPI-R: DPI (nm) Red.

DPI-RG: DPI (nm) Red-Green.

ABS-R: Abs error |DPI –CCI| Red (nm).

ABS-RG: Abs error |DPI –CCI| Red-Green (nm).

ABS-VLR: Abs error |DPI–VLSI| values Red.

ABS-VLGR: Abs error |DPI–VLSI| values Red _Green.

The measurement noise of MPI has been determined to find its impact on the error. In general there are two methods for evaluating the measurement noise and separating the noise from the surface roughness[10]. The first method measures a high surface finish quality and compares the measurement with the certified value. The second method which is used in this paper subtracts measurement sets to extract the noise from the surface roughness. A standard flat surface was measured three times at the same position. The subtraction of the first measurement from the second and the second measurement from the third has generated two noise measurement maps. The root mean square surface height (Sq) of the maps was calculated using a commercial software package SurfStand. The measurement noise can be obtained by using Equation (7). The calculation, see Table V, shows that the DPI has an average measurement noise of 42.175 nm when using Red-Green. As such, the main impact to the error is found to be the measurement noise.

$$M_{noise}(\text{Red-Green})=\frac{Sq}{\sqrt{2}} \quad (7)$$

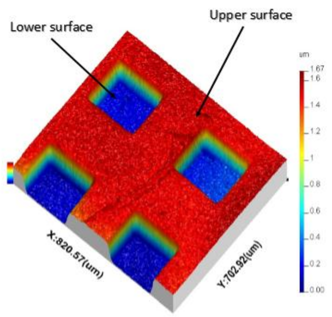
To investigate the impact of synthetic approach including the cross talk on the noise measurement, the aforementioned procedure has been repeated but for single wavelength λ=630 nm. The measurement noise is found to be equal to 0.7113 nm, see Table VI. As such, the measurement noise caused by the instantaneous phase shift mechanism can be neglected for DPI.

TABLE V. MEASUREMENT NOISE ESTIMATION OF DPI USING RED-GREEN COMPINATION.

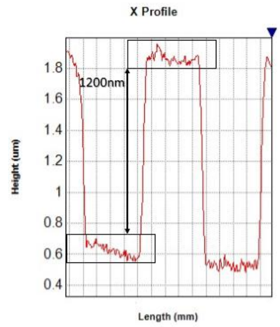
M_{noise} (nm) (Red-Green)		Average M_{noise} (nm) (Red-Green)
49	35.35	42.175

TABLE VI. MEASUREMENT NOISE ESTIMATION OF DPI USING SINGEL WAVELENGTH .

M_{noise} (nm) (Red)		Average M_{noise} (nm) (Red)
0.7113	0.7113	0.7113

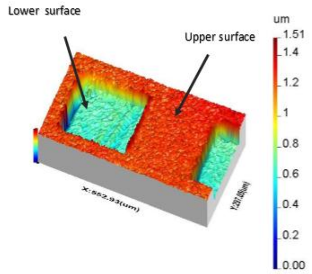


(a)

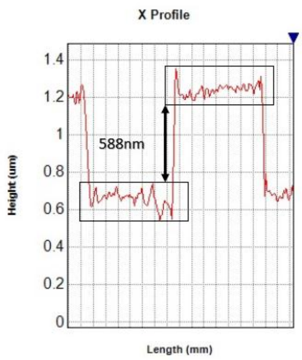


(b)

Fig. 3. (a). Measured result for cross grating depth 1200_nm standard sample, illuminated by red and green sources.(b) Cross-sectional profile.

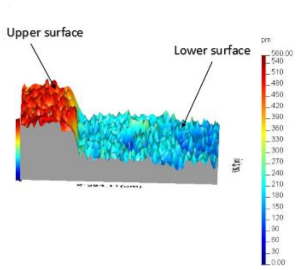


(a)

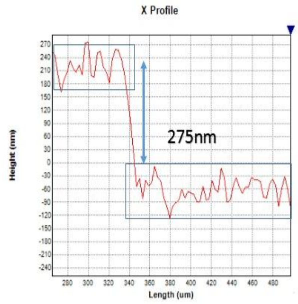


(b)

Fig. 4. Measured result for cross grating depth 500_nm standard sample, illuminatied by red and green sources.(b) Cross-sectional profile.

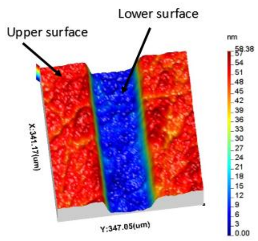


(a)



(b)

Fig. 5. (a). Measured result for cross grating depth 200 nm standard sample, illuminatied by red and green sources.(b) Cross-sectional profile.



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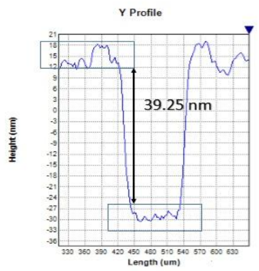
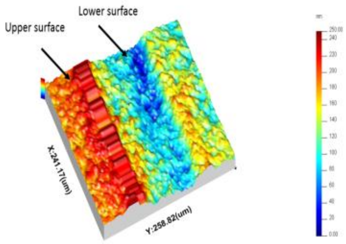
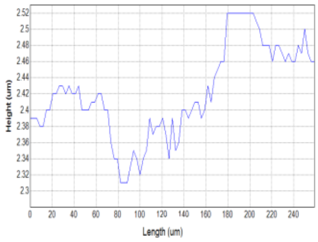


(b)

Fig. 6. (a). Measured result for step height depth 40 nm standard sample, illuminatied by single wave length(Red).(b) Cross-sectional profile.



(a)



(b)

Fig. 7. Measured result for step height depth 40 nm standard sample, illuminatied by red and green sources.(b) Cross-sectional profile.

V. Conclusions

Fast manufacturing requires a dynamic measurement approach for surface inspection. We have introduced a single-shot Dual-wavelength Polarised Interferometer (DPI).

The DPI can extend the measurement vertical range of the conventional Phase Shift Interferometer by using a synthetic wavelength and accelerate the measurement speed by using a polarisation phase shift arrangement. We presented a polarisation-based Michelson interferometer layout for measuring micro/nano-scale surface topographies without compensating for lab vibration disturbances. An incremental phase-shift of 90^{o} has been achieved using linear and quarter wave plate polarisers. The absence of mechanical scanning in this research can advance the DPI not only for single shot capability but also eliminate regular calibration procedures, hence improving the system repeatability.

The four phase shift algorithm is successfully used to obtain wrapped phase maps. The synthetic phase map generated by subtracting the wrapped phase maps is used to extend the measurement range in the height direction.

The average error of measuring step height standards 1.2 µm is 71.1 nm. The average error when measuring a 40 nm VLSI step height using single wavelength was found to be 3.292 nm, suggesting that the polarisation technique shifts the phase at 90^{o} precisely.

The combination of dual wavelengths can be re-configured in this setup to increase the measurement accuracy using the AOTF capabilities. The synthetic wavelength of red-green is chosen to be 5.04 µm and green-blue is 2.29 µm. The cross-talk between colours was found to be significant for this application. The cross-talk of red in the green filter, green in the red filter, green in the blue filter and blue in the green filter is 30.8%, 15.5%, 23.1% and 18.7% respectively. Therefore, the cross-talk can be the main contributor to the error. However, the cross-talk can also potentially be greatly reduced if not completely removed by using three separate monochrome sensors on a single camera that simultaneously splits the incoming light into three separate optical paths. The size of the camera and the low frame rate are the only disadvantage of this kind of equipment.

The measurement noise was found to be significant and approximately 42.1 nm when using Red-Green combination due to the synthetic calculation approach and the cross talk. However, the measurement noise was found insignificant (approximately equal to 0.7 nm) for single wavelength, ensuing the precision of the phase shifting mechanism. Therefore, the measurement noise of the DPI has considered the main contributor to the average error.

Finally, the robustness of the PDI against environmental disturbances and the extended measurement range provides the opportunity for the system to be used as a surface inspection tool on a shop-floor.

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