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Citation	Upputuri, P. K., Pramanik, M., Nandigana, K. M., & Prasad, M. (2015). White light single-shot interferometry with colour CCD camera for optical inspection of microsystems. Proceedings SPIE 9524, 95240C.
Date	2015
URL	<a href="http://hdl.handle.net/10220/38386">http://hdl.handle.net/10220/38386</a>
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# White light single-shot interferometry with colour CCD camera for optical inspection of microsystems

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## ABSTRACT

White light interferometry is a well-established optical tool for surface metrology of reflective samples. In this work, we discuss a single-shot white light interferometer based on single-chip color CCD camera and Hilbert transformation. The approach makes the measurement dynamic, faster, easier and cost-effective for industrial applications. Here we acquire only one white light interferogram using colour CCD camera and then decompose into its individual components using software. We present a simple Hilbert transformation approach to remove the non-uniform bias associated with the interference signal. The phases at individual wavelengths are calculated using Hilbert transformation. The use of Hilbert transformation introduces phase error which depends on number of fringe cycles. We discuss these errors. Experimental results on reflective micro-scale-samples for surface profiling are presented.

**Keyword:** White light interferometry, Hilbert transformation, Single-shot, Colour CCD, Surface profiling, Microsystems

## 1. INTRODUCTION

Interferometry is widely applied tool for non-destructive, non-contact, whole-filed optical metrology<sup>1-5</sup>. It can handle both reflective<sup>1-5</sup> and speckled surfaces<sup>6-10</sup>. The single wavelength phase shifting Interferometry (PSI) offers excellent vertical resolution and sensitivity. But, it's unambiguous step-height measurement range is limited to half-a-wavelength ( $\lambda/2$ ). The techniques used to extend the measurement range are multiple-wavelength<sup>11-17</sup> and white light interferometry<sup>18-21</sup>. Multiple-wavelength technique requires two or three laser wavelengths for surface profiling, which makes the system bulky and expensive. The coherent laser light could generate unwanted speckle noise which would affect the measurement accuracy. White light interferometry (WLI) is more like an ideal tool for optical metrology of reflective samples. It makes use of the short coherence length of the white light source. High contrast fringe occurs only when the optical path difference (OPD) is close to zero. The 3-D plot of the axial positions of the zero OPD along the optical axis represents the surface of the test object. But, WLI is rather slow compared to single wavelength PSI because it requires large number of frames for analysis. The use of colour CCD in white light interferometry allows faster measurement. White light phase shifting interferometry combined with 3-chip<sup>18</sup> and 1-chip<sup>19,20</sup> colour CCD camera have been successfully demonstrated for large step-height measurement. A 3-chip colour CCD can provide high resolution, but is bulky and expensive. On the other hand a single-chip CCD camera is compact and less-expensive. However, the phase shifting technique requires typically 3 to 8 (depending on the error compensation required) phase shifted frames for phase evaluation<sup>3,16</sup>. Though PSI can provide high resolution phase profile; it is time consuming and cannot be used for dynamic or quasi-dynamic measurements. So, fringe analysis using a single frame obviously is an attractive scheme as it makes the measurement faster and dynamic. Hilbert Transform (HT) method has been successfully applied for single frame analysis<sup>22-27</sup>. In this paper, we discuss white light interferometry combined with single-chip colour CCD camera and Hilbert transformation for fringe analysis. This approach has several advantages: (a) It makes the measurement system compact, faster and less-expensive for industrial applications, (b) measurement is faster as colour CCD makes the data acquisition as simple as single wavelength case, (c) HT is a single frame method hence allows dynamic and quasi-dynamic measurements as well, (d) using multiple-wavelength data enhances

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the unambiguous step-height measurement range of a monochromatic interferometry, and (e) It allows simultaneous measurement of shape and deformation. Simulation study on HT phase error analysis and experimental results on micro-specimens for step-height measurement are presented.

## 2. THEORY

White light interferogram can be considered as the superposition of red (R), green (G), blue (B) interferograms. We first separate the R, G, B components and process them separately. The intensity distribution of any one of the interferograms can be expressed as<sup>22-27</sup>

$$H_0(x, y) = H_b(x, y) + V(x, y) \cos \phi(x, y) \quad (1)$$

where,  $H_b(x, y)$  is the uniform or non-uniform bias,  $V(x, y)$  is the visibility, and  $\phi(x, y)$  is the phase at any point  $(x, y)$  in the interferogram. Hereafter, the spatial co-ordinates are ignored for simplicity. A complex wave function  $\omega(x) = \rho(x) + \sigma(x)$  may associated, with each real wave function  $\rho(x)$ . Here, the real part  $\rho(x)$  is the original signal and imaginary part  $\sigma(x)$  is the HT of the original signal which is phase shifted by  $\pi/2$ . In Hilbert transform, only the phases of the spectral components are altered by  $\pi/2$ , positively or negatively according to the sign of  $x$ , but their amplitudes left unchanged<sup>22-27</sup>.

### 2.1. Eliminating the uniform/non-uniform bias

If the signal bias is uniform, it can be eliminated by subtracting its mean from the signal. Usually, white light interference fringes are modulated and associated with non-uniform bias as shown in Fig. 1(a). To remove non-uniform bias, two empirical approaches Min-Max (MM)<sup>26-28</sup>, and Huang-Hilbert transformation (HHT)<sup>29,30</sup> have been used. Here we present a simple approach using Hilbert transformation (HT) to remove a low frequency non-uniform background of an interference signal and to obtain corresponding cosine-signal. The Min-Max (MM) method finds the maxima and minima envelopes of the original signal ( $H_0$ ) by interpolation. The envelopes are indicated by min, max in Fig. 1(b). The mean of the two envelopes  $(\max + \min)/2$ , represents the non-uniform background (BG) of the signal ( $H_0$ ). Eq. (2) can be used to obtain  $\cos\phi$  at any pixel.

$$C1 = \frac{2H_0 - H_{0max} - H_{0min}}{H_{0max} - H_{0min}} = \cos \phi \quad (2)$$

The bias-free signal C1 thus evaluated shows errors near the edges and the MM methods works only on a signal and hence takes relatively long time cannot for image to be processed. The bias estimation is not accurate if there are less number of maxima and minima in the signal. The Huang-Hilbert transformation (HHT) can decompose a signal in to its intrinsic mode functions (IMF). These IMFs can have variable amplitude and frequency unlike simple harmonic components. Detailed description of HHT approach can be found in Ref. 29, and 30. The first three modes ( $m=1, 2, 3$ ) of the original signal ( $H_0$ ) are shown in Fig. 1(c), here C2 is the desired cosine-signal. This approach introduces distortion (identified in profile C2) in the signal. Also, it works on signal-by-signal basis, hence takes relatively long time for processing whole image. The Hilbert transformation (HT) can act as a high-pass filter which can block the uniform and slowly varying (low-frequency) background as well. And hence it can be used as a simple tool to remove non-uniform background associated with white light interference signal. The HT of the original signal  $H_0$  is  $H_1$  and are shown in Fig. 1(d).  $H_1$  can be calculated using Eq. (3). The  $H_1$  is then used in Eq. (4) to obtain the cosine-signal (C3).

$$H_1 = \text{imag}(\text{hilbert}(H_0)) \quad (3)$$

$$C3 = \frac{H_1}{\text{abs}(\text{hilbert}(H_1))} = \cos \phi \quad (4)$$

where, *abs* and *hilbert* are MATLAB functions. The function *abs* results in absolute value, and *Hilbert* generates an analytical function of the input function,  $H_0$ . Eq. (4) is applied on a typical interference signal ( $H_0$ ) and the cosine-signal, C3,

obtained after removing non-uniform bias is shown in Fig. 1(d). The signal C3 looks better than C2, and comparable to C1. This approach is simple and can be applied directly on the image with no closed fringes.

### 2.2. Phase evaluation using Hilbert transformation function

The HT of the signal in Eq. (4) can be obtained as<sup>25,27</sup>

$$S = \text{Img}(\text{hilbert}(C3)) = \sin\phi \quad (5)$$

where, *Img* MATLAB function results in an imaginary part. Now, the phase can be calculated using Eq. (4) and Eq. (5)

$$\phi = \arctan\left(\frac{S}{C3}\right) \quad (6)$$

The phase  $\phi$  thus obtained is wrapped between  $-\pi$  to  $+\pi$  due to *arctan* function.

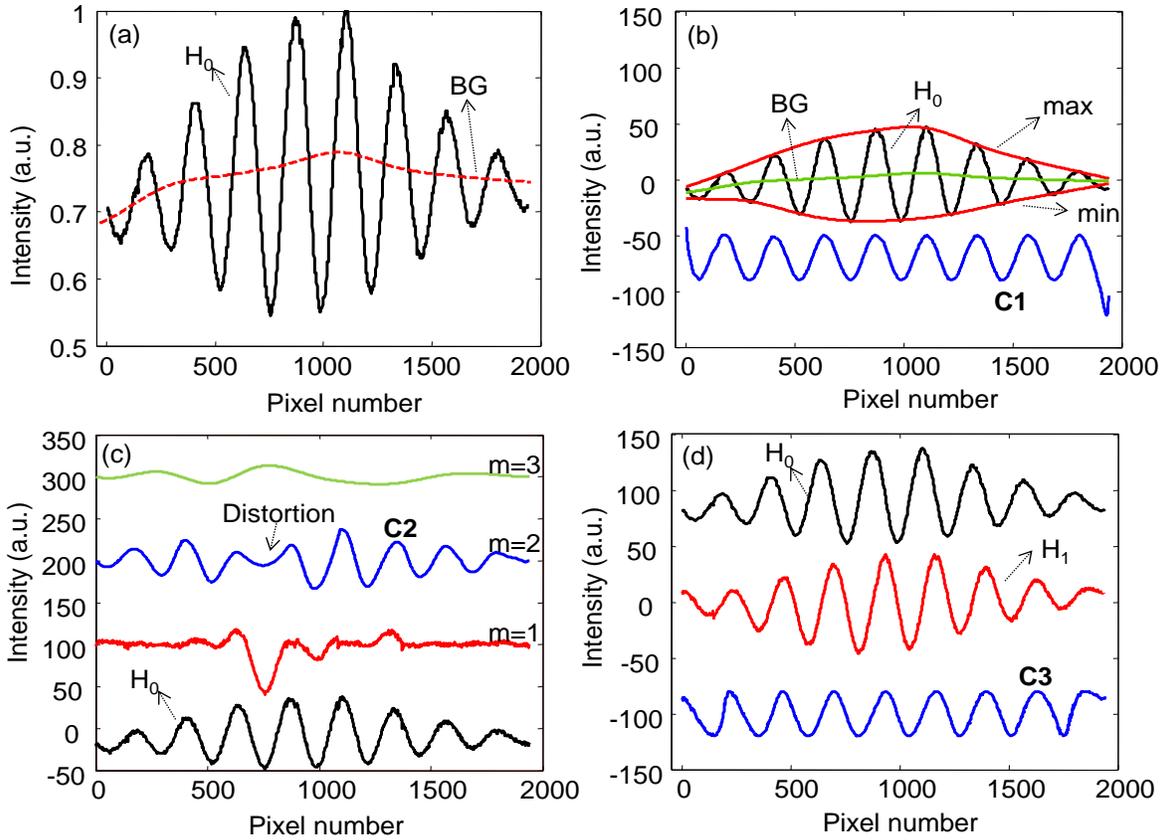


Fig. 1. Interference signal with a non-uniform bias (a), Eliminating bias by using Min-Max method (b), Huang-Hilbert transformation method (c), and Hilbert transformation method (d). Here BG is the background,  $H_0$  is the original signal,  $H_1$  is the Hilbert transformed signal, C1, C2, C3 are cosine-signals obtained from MM, HHT, and HT methods, respectively.

### 2.3. Phase error analysis

However, the phase  $\emptyset$  determined using Eq. (6) differs from the correct argument  $\emptyset$  of the cosine function in Eq. (1). Hence the calculated phase using Eq. (6) may be represented as  $\emptyset'$ , where,  $\emptyset'$  may be written as<sup>23,25</sup>

$$\emptyset' = \emptyset + \varepsilon \quad (7)$$

where,  $\varepsilon$  is the phase error. We have investigated the phase error due to HT. We found that it depends on the number of fringe cycles (N). Fig. 2(a) shows simulated cosine-signal (C) with 5-cycles (N = 5) and its HT signal (S). Here, the Hilbert transformed signal S has no significant amplitude variations compared to C, hence the phase calculated using these two signals shows small errors as shown in Fig. 2(b). Fig.2(c) shows simulated cosine-signal (C) with 5.25-cycles (N = 5.25) and its HT signal (S). Here, the Hilbert transformed signal S has significant amplitude variations compared to C especially near the edges, hence results in large errors as shown in Fig. 2(d). We have calculated the maximum error for complete cycle, starting from 0.01-cycle to 1-cycle (full-cycle). Similarly, we repeated the calculation for first 5-cycles and plotted the error (e) as function of N in Fig. 3(a). The calculated average errors for full-cycle, half-cycle, and quarter-cycle are as follows :

$$\varepsilon \sim \begin{cases} \frac{\pi}{1570} & \text{for quarter - cycle} \\ \frac{\pi}{2.5} & \text{for half - cycle} \\ \pi & \text{for full - cycle} \end{cases} \quad (8)$$

$\varepsilon$  is minimum if the signal has full cycles, and  $\varepsilon$  is maximum if the signal has a quarter-cycle. We have calculated the error for 0.25-cycle to 1000.25-cycle. The maximum error and average error as a function of N are plotted in Fig. 3(b). The maximum phase error is almost the same and average error reduced with increase in N as expected. In some experiments it is possible to control the number of fringe cycles to be generated on the surface of the test sample. In such cases the error  $\varepsilon$  due to HT can be experimentally eliminated by generating full-cycles and hence look-up table may not be necessary. In general, look-up table can be generated for any value of  $\emptyset$  which than can be used to correct the phase error  $\varepsilon$ .

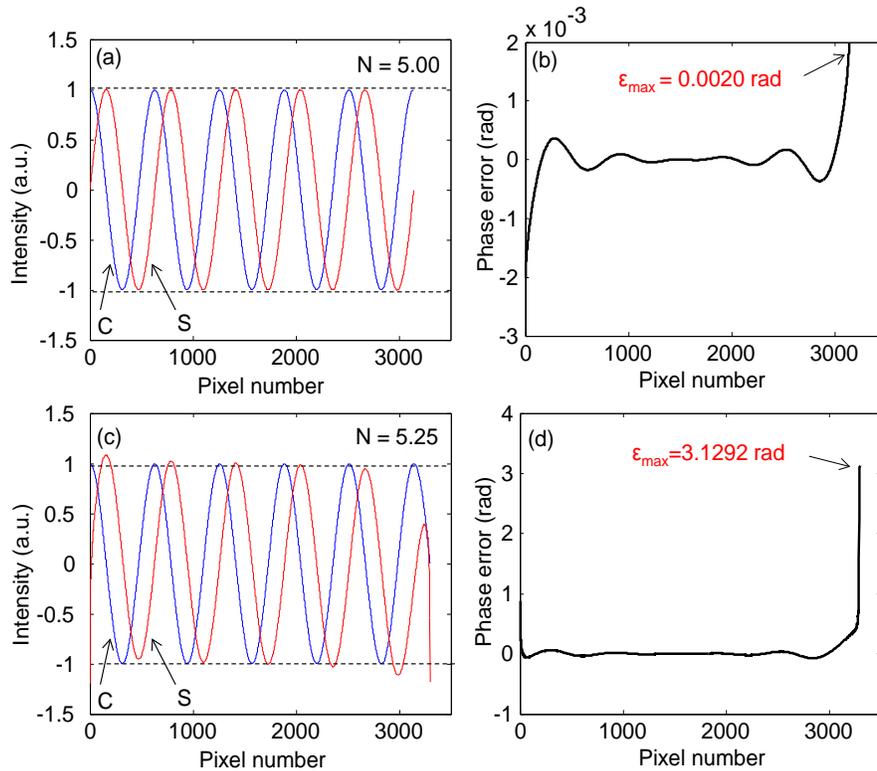


Fig. 2. Phase error calculation: (a) original signal-C with 5-full cycles and its Hilbert transformed signal-S, (b) phase error plot for 5 full-cycles, (c) original signal-C with 5.25- cycles and its Hilbert transformed signal-S, (b) phase error plot for 5.25-cycles.

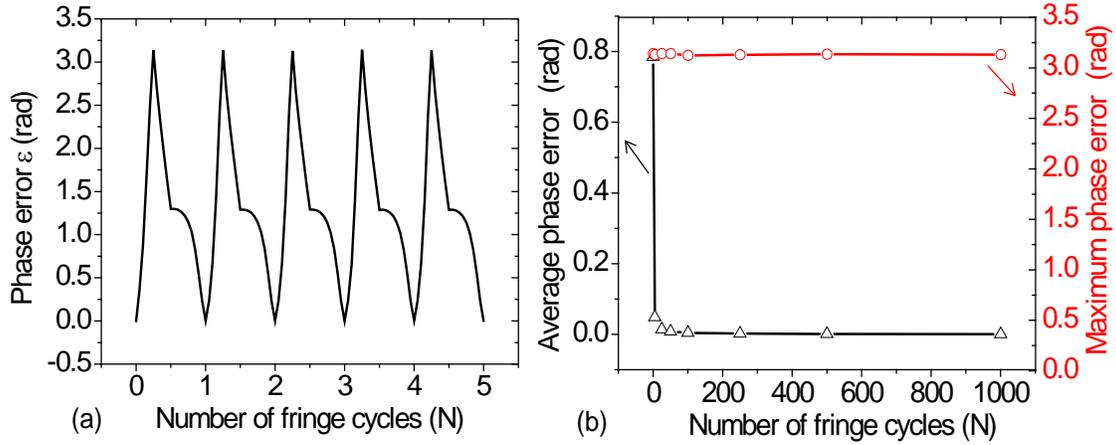


Fig. 3. (a) Phase error  $\epsilon$  as function of number of fringe cycles ( $N$ ) for the first 5-cycles, and (b) maximum and average phase errors as function of  $N$  for the first 1000 cycles.

### 3. EXPERIMENTAL RESULTS

Experiments were carried out using a conventional white light interferometer with single-chip RGB CCD<sup>27</sup> without phase shifter. The use of HT allows single fringe analysis and hence no phase shifter (PZT) is required. Fig. 4(a) shows the white light tilt fringes generated on a reflective surface acquired with a colour CCD. The dimensions of the stored RGB image are 2456 (H) X 2058 (V) X 3. Each pixel contains the information regarding the red, green, blue wavelengths. It is then separated into its monochrome R, G, and B components which have dimensions 2456X2058. The decomposed components at Red ( $\lambda_1 = 620$  nm), Green ( $\lambda_2 = 540$  nm), and Blue ( $\lambda_3 = 460$  nm) are shown in Fig. 4(b). The interferograms are processed independently for phase evaluation. Fig. 4(c) shows the wrapped phase maps generated for each wavelength using Hilbert transformation as discussed in Section-2.

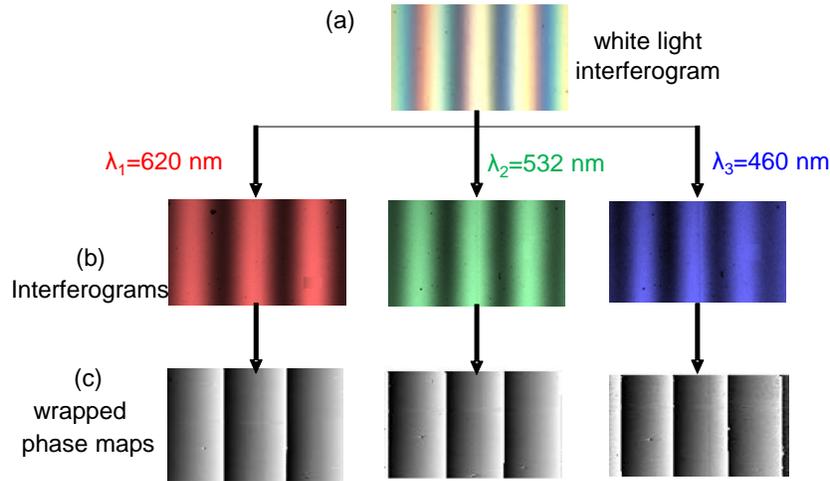


Fig. 4. (a) White light interferogram acquired using single-chip colour CCD camera, (b) Individual interference patterns after decomposition, and (c) wrapped phase maps at individual wavelength calculated using HT.

Experiments were carried on an etched silicon sample with large discontinuity beyond the range of a single wavelength measurement. White light interferogram was acquired in a single shot and processed as shown in Fig. 4. The wrapped phase maps at three wavelengths  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$  can be used to increase the unambiguous range using two different approaches : (i) phase subtraction method<sup>3,13,16</sup> and (ii) fringe order method<sup>3,18,19,27</sup>. In phase subtraction method, phase maps at two different wavelengths ( $\lambda$ ) are subtracted to generate an effective wavelength ( $\Lambda$ ) phase map. If phase maps at  $\lambda_1 = 620$  nm and  $\lambda_2 = 540$  nm are subtracted, a phase map at  $\Lambda \sim 4.2$   $\mu$ m can be effectively generated. Again the unambiguous range is limited to  $\Lambda/2$ . The profiles measured at effective wavelengths are noisy due to the fact that the signal-to-noise ratio (SNR) increases with the wavelength used for measurement. The SNR of the profile measured at effective wavelength is reduced by  $(\lambda/\Lambda)$  time compared to that measured at single wavelength. During the subtraction of two phases, the noise gets added up, hence the SNR of the profile measured at  $\Lambda$  is affected<sup>3,13,16,19</sup>.

Whereas the fringe order method can provide surface profile with the resolution of single wavelength and it can extend the measurement range of the interferometer<sup>3,16,19,27</sup>. It requires at least 3 wavelength phase maps. The wrapped phase values at a pixel are adjusted by addition of integers so that the adjusted values lie on a line. The slope of the linear fitted line gives the absolute value of height ( $z$ ) at that particular pixel. Fig. 5(a-c) show the colour white light interferogram, interference pattern at  $\lambda_1$ , and wrapped phase map at  $\lambda_1$ . Fig. 5(d) shows the ambiguity removed 3-D surface profile using the fringe order method for  $\lambda_1 = 620$  nm. As expected the surface profile has the usual smoothness of single wavelength phase shifting interferometer. The profile along central y-axis was measured and the height of the step has been determined by linear least square fitting across the top and bottom of the profile and determining the height difference at the location of the step and the step height value measured is  $\sim 770$  nm.

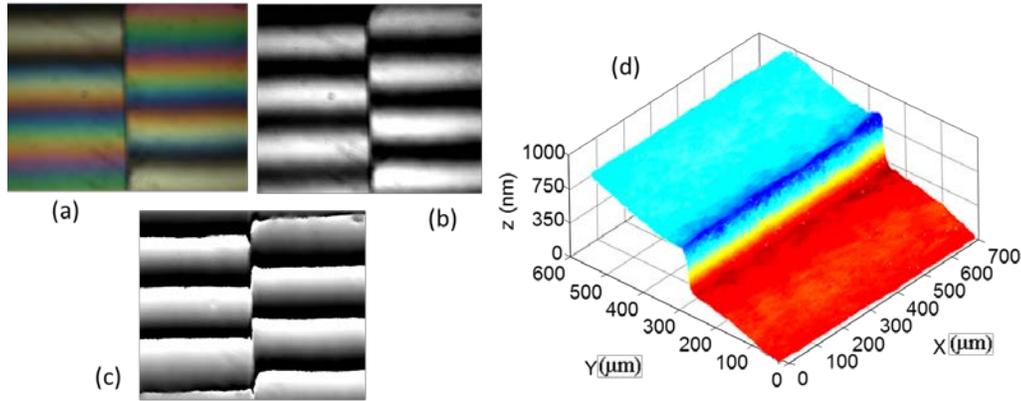


Fig. 5. Large step-height analysis using the fringe order method: (a) white light interferogram, (b) interferogram at  $\lambda_1$ , and (c) wrapped phase at  $\lambda_1$  calculated using Hilbert transformation, and (d) Total 3-D surface profile, of an etched silicon sample showing a step of height  $\sim 770$  nm.

#### 4. CONCLUSIONS

In this work, we discussed single-shot white light interferometry using a single-chip colour CCD camera and Hilbert transformation for fringe analysis. The white light interferogram is acquired in single-shot using colour CCD. A simple approach based on HT is presented to remove the non-uniform bias of the signal and the outcome of this approach is compared that of HHT, MM methods. The Hilbert Transformation is used to extract the phase from a single interferogram and hence the system does not require any phase shifter. The phase error due to HT and its dependence on number of fringe cycles are discussed. The approach makes the measurement simpler, faster, dynamic and cost-effective. The system will find applications in industry for optical inspection of micro systems.

## ACKNOWLEDGMENT

The authors would like to acknowledge the financial support from the Start-up Grant by Nanyang Technological University (SUG: M408120000) and Tier 1 grant funded by the Ministry of Education in Singapore (RG31/14: M401120000).

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