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White light interferometer with color CCD for 3D-surface profiling of microsystems

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ABSTRACT

White light interferometry (WLI) is a state-of-the-art technique for high resolution full-field 3-D surface profiling of Microsystems. However, the WLI is rather slow, because the number of frames to be recorded and evaluated is large compared to the single wavelength phase shifting interferometry. In this paper, we combine white light interferometer with a single-chip color CCD camera which makes the measurement faster, simpler, and cost-effective. The red-blue-green (RGB) color interferogram stored in a computer is then decomposed into its individual components and corresponding phase maps for red, green, and blue components are calculated independently. The usefulness of the technique is demonstrated on reflective micro-scale-samples.

Keyword: White light interferometry, Colour CCD, Surface profiling, Microsystems

1. INTRODUCTION

The single wavelength phase shifting interferometry (PSI) offers excellent vertical resolution and sensitivity¹⁻⁴. It requires more than 3 phase shifted frames for phase calculation. But, its unambiguous range is limited to half a wavelength ($\lambda/2$). The approaches adopted to extend the measurement range are based on multiple-wavelength⁵⁻¹⁷ and white light interferometry^{4,18}. Multiple wavelength technique requires typically 2 or 3 laser wavelengths for surface profiling. White light interferometry makes use of the short coherence length of the white light source. High contrast fringe occurs only when the optical path difference is close to zero. The 3-D plot of the axial positions of the zero OPD along the optical axis represents the surface profile of the test object. Compared to single wavelength PSI, the white light interferometry is rather slow, as the number of frames to be recorded and evaluated is large. The spectrally resolved white light interferometry¹⁹, on the other hand gives only a line profile of the object, although the requirement on number of frames is similar to the single wavelength PSI.

Phase shifting white light interferometry combined with 3-chip¹⁶ and single-chip^{17,18} colour CCD camera have been demonstrated. It can make the data acquisition as simple as in single wavelength case. In a 3-chip CCD each chip registers a different primary colour, red (R), green (G), or blue (B). Thus one pixel for chip is used to reproduce image. A 3-chip colour CCD can give high resolution, but is costly. In a single-chip CCD camera, on the other hand, a group of three pixels is required to register all the three colours of the image with the help of colour filters. However, this technique requires typically 5 to 8 phase shifted frames for phase evaluation^{16,17}. Though PSI can provide high resolution phase profile; it is time consuming and cannot be used for 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 analysis²¹⁻²³.

In this paper, we discuss Hilbert transform fringe analysis of a single white light interferogram acquired with a single-chip colour CCD camera for optical inspection of microsystems. First the individual interference data for red, green, blue colors are separated from the color white light interferogram and then processed independently for phase calculation using Hilbert transformation. The present technique does not require phase shifting method, multiple-wavelength laser sources, or 3-chip CCD for surface profiling. Thus, it makes the measurement faster, simpler and less expensive. The single chip-CCD has three separate spectral bands, R, G, B centered at Red ($\lambda_1=620$ nm), Green ($\lambda_2=540$ nm), and Blue ($\lambda_3=460$ nm) wavelengths respectively. Experimental results on micro-specimens are presented.

2. THEORY

The white light interferogram may be considered as the superposition of the interferograms corresponding to the R, G, B wavelengths. In this procedure we separate the R, G, B data and process them separately. The intensity distribution of any one of the interferograms may be expressed as

$$h_0(x, y) = h_b(x, y) + h_b(x, y)\gamma(x, y)\cos\delta(x, y) \quad (1)$$

where $h_b(x, y)$ is the bias intensity, $\gamma(x, y)$ is the visibility, and $\delta(x, y)$ is the phase at any point (x, y) in the interferogram corresponding to the wavelength under consideration.

According to the signal theory, a complex wave function $\psi(x) = p(x) + iq(x)$ may associated, with each real wave function $p(x)$. Here, the real part $p(x)$ is the original signal and imaginary part $q(x)$ is the HT of the original signal which is phase shifted by $\pi/2$ ²¹⁻²³. 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. Prior to the application of Hilbert transformation, the bias must be eliminated from the signal. If the bias is uniform, it can be removed by applying Hilbert transformation. But the phase analysis in this case requires second time application of HT.

However, typical white light interference fringes are modulated and associated with non-uniform bias. Such a fringe system can be effectively processed using a min-max method^{25, 26}. Eq.(1) represents a typical signal in the colour channels. Eq(1) can be used to obtain $\cos\delta$ at any pixel using the relation :

$$\cos(\delta) = \frac{2h_0 - h_{0\max} - h_{0\min}}{h_{0\max} - h_{0\min}} = C \quad (2)$$

Eq.(2) represents a cosine signal (C). The HT of the signal in Eq.(2) can be obtained as

$$S = \text{Im}[\text{hilbert}\{C\}] = \sin(\delta) \quad (3)$$

Now, the desired phase can be calculated using Eq.(2) and Eq.(3)

$$\delta = \arctan\left(\frac{S}{C}\right) \quad (4)$$

However, the phase δ determined using Eq.(4) differs from the correct argument δ of the cosine function in Eq.(1) because of finite extent of the original signal. Hence the calculated phase using Eq.(4) may be represented as δ' , where δ' may be written as

$$\delta' = \delta + \xi \quad (5)$$

where ξ is the error. The error ξ can be calculated for any value of δ to create a look-up table which can be used to correct the calculated phase^{22,23}.

3. FRINGE ORDER METHOD

The phase δ is related to the surface profile 'z' by the following equation:

$$\delta_i = 4\pi k_i z \quad (6)$$

where, i represents the wavelengths in the RGB channels, z is the height or depth of the surface, $k_i = 1/\lambda_i$ is the wavenumber. The individual phase maps thus evaluated can be used to remove half wavelength ambiguity which appears at single wavelength in two ways: (a) Phase subtraction method⁵⁻¹², and (b) Fringe order method^{16,17}. In this paper, we use fringe order method to achieve ambiguity-free high resolution surface profile phase.

The variation of δ_i with k_i is linear as shown in Eq. (6). Using the phases at three wavelengths, it is possible to adjust the wrapped phase data at any pixel such that they lie on a best fit line by addition or subtraction of multiples of 2π . The slope of this line gives the absolute height at the pixel as

$$z_a = \frac{1}{4\pi} \left(\frac{\Delta\delta}{\Delta k} \right) \quad (7)$$

where $(\Delta\delta/\Delta k)$ is the slope of the line obtained by plotting the individual phases (δ_i) with respect to the corresponding wavenumbers (k_i). The value of z_a obtained from Eq.(7) is less precise but it is quite close to the actual value. The absolute height z_a thus measured can be used to estimate the fringe order (n) using the relation

$$n_i = \text{round} \left(\frac{\delta_i - 4\pi k_i z_a}{2\pi} \right) \quad (8)$$

The function round () gives the nearest integer. Using the fringe order number (n), the total phase (Φ) with single wavelength resolution can be obtained as

$$\Phi = \delta_i - 2\pi n_i \quad (9)$$

Thus the fringe order method allows measurement of large discontinuities and retains the single wavelength resolution of the surface profile.

4. EXPERIMENTAL RESULTS

Experiments were carried out using a conventional white light interferometer with single-chip RGB CCD. The test specimen is an etched silicon sample with discontinuities beyond the range of a single wavelength measurement. Fig.1(a) shows the colour image of white light tilt fringes generated on the surface of the test specimen. The dimensions of the raw colour image acquired using the single-chip CCD are 2456 X 2058 X 3 pixels. The colour image is then separated into its individual R, G, and B components of dimensions 2456 (H) X 2058 (V). The decomposed components correspond to Red ($\lambda_1 = 620$ nm), Green ($\lambda_2 = 540$ nm) and Blue ($\lambda_3 = 460$ nm). The signals from the R G B channels are associated with non-uniform bias and are modulated. So, these individual interferograms are processed using min-max method as discussed in Section-2. The interference pattern at λ_1 is shown in Fig.1(b). The corresponding phase calculated using Eq.(4) is shown in Fig.1(c). Similarly, the phases at individual wavelengths are calculated using Eq.(4).

The wrapped phase maps thus evaluated at three wavelengths λ_1 , λ_2 , λ_3 are used to increase the unambiguous range using fringe order method as explained in Section-3. 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 line gives the absolute value of z at the pixel. Fig. 2(a) shows the ambiguity removed 3-D surface profile using the fringe order method for $\lambda_1 = 620$ nm. The surface profile measured along central y-axis is shown in Fig. 2(b) and as expected it has the usual smoothness of single wavelength phase shifting interferometer. 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. From the analysis, the step height value measured is 645 nm.

We have also carried out surface profiling on micro-lens array as shown in Fig.3. The application of HT is straight forward for open fringe system (such as tilt fringes). For objects which generate closed fringes, the application of HT is not straight forward. This results in an additional ambiguity in the wrapped phase map. To solve this problem, procedures described in the references²²⁻²⁴ can be followed. Fig.4. shows the surface profile analysis on a reflective sample with micro-grooves.

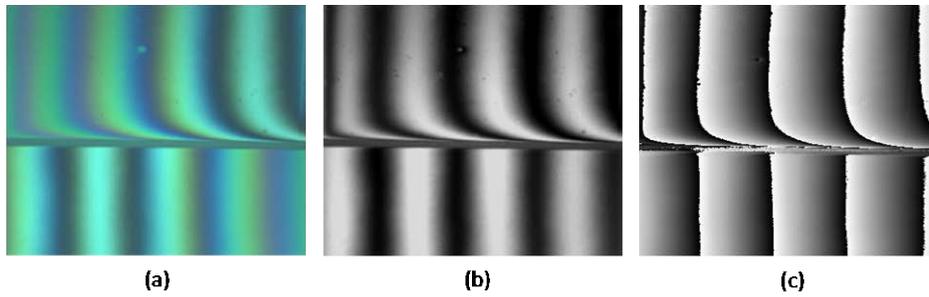


Fig.1. Fringe analysis using Hilbert transformation: (a) white light interferogram, (b) interferogram at λ_1 , and (c) wrapped phase calculated.

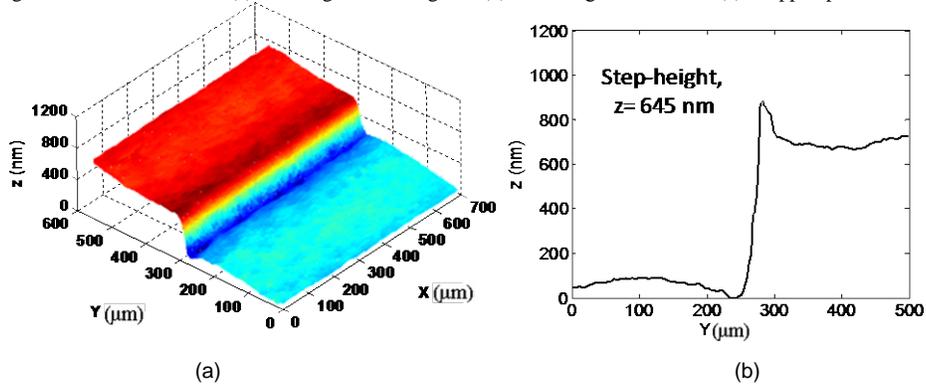


Fig.2. Surface profile analysis using the fringe order method: (a) 2π ambiguity corrected single wavelength 3-D surface profile of an etched silicon sample using the phase at λ_2 , and (b) line scan profile showing the step height 645 nm.

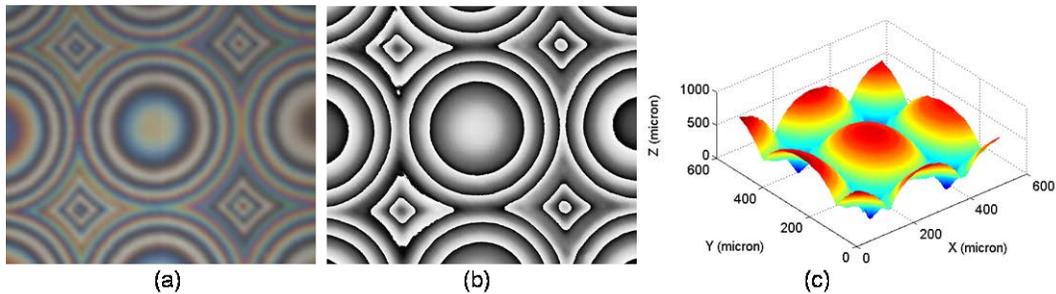


Fig.3. Surface profiling on micro-lens array: (a) white light interferogram, (b) wrapped phase calculated at λ_1 , and (c) 3-D view of the micro-lens array.

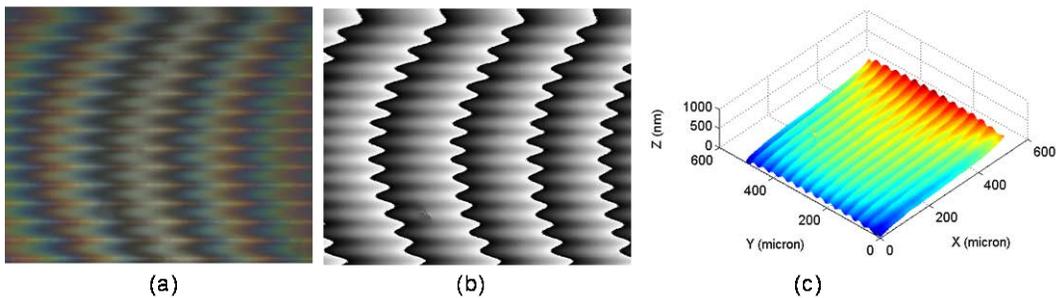


Fig.4. Surface profiling on micro-grooves: (a) white light interferogram, (b) wrapped phase calculated at λ_1 , and (c) 3-D view of the micro-grooves.

5. CONCLUSIONS

We have demonstrated a single frame white light interferometer using a single-chip colour CCD camera for surface profiling of both continuous and discontinuous surfaces. Hilbert Transformation is used to generate the phase shifted frame; hence it does not require any phase shifting hardware. The proposed method is simpler, faster, and cost-effective. As it requires only one frame, it allows dynamic measurements as well. The system will find applications in industry for optical inspection of microsystems.

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REFERENCES

1. J. E. Greivenkamp, J. H. Bruning, Phase shifting interferometry, D. Malacara Ed., Optical Shop Testing, Second edition, pp.501-598, John Wiley & Sons Inc, New York, 1992.
2. K. Creath, "Phase-measurement interferometry techniques" Progress in Optics, E. Wolf, Ed., XXVI, pp. 349-393, Elsevier, Amsterdam, 1988.
3. J.C.Wyant and K. Creath, "Advances in interferometric optical profiling," *Int. J. Mach. Tools Manufact*, **32**, 5-10(1992).
4. W. Osten, *Optical inspection of Microsystems* (Florida,CRC Press, 2007).
5. C. Polhemus, "Two wavelength interferometry," *Appl. Opt.* **12**, 2071-2073(1973).
6. J. Schmit, and P. Hariharan, "Two-wavelength interferometry profilometry with a phase-step error - compensating algorithm," *Opt. Eng.* **45**,115602-1-115602-3(2006).
7. K. Creath, "Step height measurement using two-wavelength phase-shifting interferometry," *Appl. Opt.* **26**, 2810-2816(1987).
8. U. Paul Kumar, B. Bhaduri, N. Krishna Mohan, and M. P. Kothiyal, "Two wavelength interferometry for 3-D surface profiling," *Opt. Lasers Eng.* **47**, 223-229(2009).
9. Y.Y. Cheng, and J.C. Wyant, "Multiple-wavelength phase-shifting interferometry," *Appl. Opt.* **24**, 804-807(1985).
10. U. Paul Kumar, N. Krishna Mohan, and M. P. Kothiyal, "Measurement of discontinuous surfaces using multiple-wavelength interferometry," *Opt. Eng.* **48**, 073603-1-073603-8(2009).
11. U. Paul Kumar, N. Krishna Mohan, and M. P. Kothiyal, "Multiple wavelength interferometry for surface profiling," *Proc. SPIE*, **7063**, 70630W-70630W-10 (2008).
12. U. Paul Kumar, N. Krishna Mohan, and M. P. Kothiyal, "Measurement of static and vibrating microsystems using microscopic TV holography" *Optik*, **122**, 49-54(2011).
13. U. Paul Kumar, N. Krishna Mohan, and M. P. Kothiyal, "Microscopic TV sherography for microsystems characterization," *Opt. Lett.* **34**, 1612-1614(2009).
14. U. Paul Kumar, Y. Kalyani, N. Krishna Mohan, and M. P. Kothiyal, "Time-average TV holography for vibration fringe analysis," *Appl. Opt.* **48**, 3094-3101(2009).
15. U. Paul Kumar, N. Krishna Mohan, M. P. Kothiyal, and A.K. Asundi "Deformation and shape measurement using multiple-wavelength microscopic TV holography" *Opt. Eng.* **48**, 023601-1-023601-10(2009).
16. A. Pfortner, and J. Schwider, "Red-green-blue interferometer for the metrology of discontinuous structures," *Appl. Opt.* **42**, 667-673(2003).
17. U. Paul Kumar, W. Haifeng, N. Krishna Mohan, and M. P. Kothiyal, "White light Interferometry for surface profiling with colour CCD," *Opt. Lasers Eng.* **50**, 1084-1088(2012).
18. U. Paul Kumar, Li Gong, W. Haifeng, Manojit Pramanik, N. Krishna Mohan, and M.P. Kothiyal, "Measurement of large discontinuities using single white light inteferogram," *Opt. Exp.*, accepted(2014).
19. P. de Groot, and L. Deck, "Surface profiling by analysis of white-light interferograms in the spatial frequency domain," *J. Mod. Opt.* **42**, 389-401(1995).
20. S. K. Debnath, and M. P. Kothiyal, "Experimental study of the phase-shift miscalibration error in phase shifting interferometry: use of a spectrally resolved white-light interferometer," *Appl. Opt.* **46**,5103-5109(2006).
21. V. D. Madjarova and H. Kadono, "Dynamic electronic speckle pattern interferometry (DESPI) phase analyses with temporal Hilbert transform," *Opt. Exp.* **11**, 617-623 (2003).

22. U. Paul Kumar, N. Krishna Mohan, and M. P. Kothiyal, "Time average vibration fringe analysis using Hilbert transformation," *Appl. Opt.* **49**, 5777-5786(2010).
23. U. Paul Kumar, N. Krishna Mohan, and M. P. Kothiyal, "Characterization of micro-lenses based on single interferogram analysis using Hilbert transformation," *Opt. Commun.* **284**, 5084-5092(2011).
24. K. G. Larkin, D. J. Bone, and M. A. Oldfield, "Natural demodulation of two-dimensional fringe patterns. I. General background of the spiral phase quadrature transform," *J. Opt. Soc. Am. A* **18**, 1862-1870 (2001).
25. J. T. Mercado and A. V. Khomenko, "Precision and sensitivity optimization for white light interferometric fiber-optic sensors," *J. Lightwave Technol.* **19**, 70-74 (2001).
26. S. K. Debnath, M. P. Kothiyal, and S. W. Kim, "Evaluation of spectral phase in spectrally resolved white-light interferometry: Comparative study of single-frame techniques," *Opt. Lasers Eng.* **47**, 1125-1130 (2009).