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ABSTRACT

Interferometry has been widely used for surface metrology because of their precision, reliability, and versatility. Although monochromatic-light interferometery can provide high sensitivity and resolution, but it fails to quantify large-discontinuities. Multiple-wavelength techniques have been successfully used to extend the unambiguous step height measurement rage of single wavelength interferometer. The use of RGB CCD camera allows simultaneous acquisition of fringes generated at different wavelengths. In this work, we discuss details about the fringe analysis of white light interferograms acquired using colour CCD camera. The colour image acquired using RGB camera is decomposed in to red, green, blue components and corresponding interference phase is measured using phase evaluation algorithms. The approach makes the 3D surface measurements faster, cost-effective for industrial applications.

Keyword: Multiple-wavelength interferometry, fringe analysis, surface profiling, step-height

1. INTRODUCTION

Profilometers are used in many situations where micro-measurement of surface variations is essential [1-3]. Industries such as optics and data storage use highly polished surfaces. Surface profiling can be done in two ways: contact and non-contact methods. Stylus profiling involves dragging a stylus across the surface. It is a contact, and slow approach for profiling. Non-contact methods include: interferometry, digital holography, confocal microscopy, etc. [4-8]. Interference profiling, an optical method, is a well-established method of obtaining accurate surface measurements. It has been widely used in research and development (R&D), and industrial applications because of its precision, reliability, and versatility. Interferometric techniques can be used to inspect both reflecting (smooth) and scattering (diffusive) surfaces in wide range of sizes [9-12]. The inspection can be done under static, quasi-static or dynamic conditions [13-17]. Conventional interferometry can only handle smooth or mirror like samples. If the test surface is diffusive, the interference between reference and test beam results in no-visible fringe pattern. So, conventional interferometry fails to characterize samples with diffusive (speckled) surface. The interferometry that can study rough or scattering surfaces is known as Electronic / Digital speckle pattern interferometry (ESPI/DSPI) or TV holography (TVH). In interferometry, the surface profile information is encoded in the fringe pattern. The phase information can be obtained from single interferogram such as Fast Fourier Transform (FFT), Huang-Hilbert transformation (HHT), Hilbert Transform (HT), Pixelated-polarization phase shifting (PPPS) [3, 18-21] or multiple interferograms [9, 22, 23]. Phase shifting method, a multiple-frame method, is an accurate approach for phase measurement [24, 25]. Various interferometric profilers such as 1λ, 2λ or 3λ- interferometry [5, 10, 26, 27], scanning white light interferometry [28, 29], spectrally resolved white light interferometry [30, 31], and white light interferometry with colour CCD [32, 33]. Phase shifting white light interferometry (PS-WLI) with colour CCD is a low-cost, high-speed technique for surface profiling of smooth surfaces with high accuracy. WLI 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. Due to the presence of multiple wavelengths in white light (from violet to red), each wavelength will generate its own interference pattern. The acquisition of frames can be done in two ways: (i) sequential illumination mode [5, 34] in which interferograms are recorded with different wavelength one after another sequentially using a monochrome CCD. This is a time consuming process and (ii) simultaneous illumination mode [35-37] in which all the interferograms are recorded in one go by using a colour CCD camera. This approach makes the fringe acquisition as simple as in single-wavelength case. 1-CCD sensor [38], 3-CCD sensor [36], and Foveon X3 sensor [39], were used to acquire colour interference pattern. A comparative study of the three sensors has been done in digital 3λ holographic interferometry [39]. The Bayer filter 1-CCD RGB camera was successfully demonstrated for many applications including: surface profiling of large discontinuities [37], simultaneous measurement of shape and deformation [35, 40], non-destructive testing (NDT) of large defects [41], simultaneous acquisition of blood flow, blood

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volume, and oxygenation on human fingers using dual-wavelength laser imaging [42] etc. Recently, white light illumination combined with single-chip CCD RGB camera was successfully demonstrated for surface profiling of micro-lens array and large-discontinuities [43], refractive index profiling of biological cells (RBCs) [44], etc. This approach was further simplified by using single-frame methods instead of multiple-frame methods for phase measurements [40]. In this work, we will discuss the details of acquiring and processing colour fringes grabbed with RGB 1-chip CCD camera for surface profiling of micro-sample with groove structure. With all these advantages of simplicity, high-speed, low-cost, and accurate imaging ability, the white light colour CCD system will find new applications in optical metrology and imaging applications.

2. OPTICAL INSTRUMENTATION

Mirau white light interferometer with a single-chip RGB CCD camera was used for surface profiling of micro-groove surface. The measurement system was discussed in detail in Ref. [38]. The interference system equipped with a colour camera (1-CCD JAI BB-500GE 2/300 GigE vision camera) and piezoelectric transducer (PZT) for introducing phase shift between the reference and object beams. The collimated visible light illuminates the sample under test via the beam splitter and the Mirau interferometric objective (MIO). The system has several MIOs with different magnifications to inspect different surface profiles. The white light interference pattern generated by the MIO was acquired using the RGB 1-chip CCD. The colour CCD is interfaced to the computer with a national instruments frame grabber card. The PZT attached to the MIO was calibrated to introduce $\pi/2$ phase shift at green wavelength, 540 nm. The PZT was driven by the PC with a Data acquisition card (DAQ) card. LABVIEW based program was used to visualize fringes in real-time, storing phase shifted frames, and MATLAB based program was used for quantitative fringe analysis. If only single wavelength is used, a simple monochrome CCD would be sufficient. But if multiple-wavelengths are used, each wavelength generates its own interferogram. By adopting RGB colour CCD, one can acquire the interferograms at R, G, and B wavelengths in single-shot. Fig. 1 illustrates the simultaneous recording of three-colours using a Bayer filter 1-CCD sensor. In a 1-CCD colour camera, a mosaic color filter array (CFA) is used on a single image sensor. Different primary filters are distributed over the pixels of the sensor. Each filter has a specific transmission band. Commonly used CFA in digital cameras is Bayer RGB CFA as shown in Fig. 1. The Bayer filter pattern is 50% green, 25% red and 25% blue. The raw output from CCD is an incomplete RGB image which is then CFA interpolated to obtain a full RGB image at resolution reduced by ~25%.

3. EXPERIMENTAL RESULTS

White light or broad band source is ideal for quality testing reflective surfaces. If highly coherent sources like lasers are used for testing, the long coherence length results in speckle noise, which could introduce errors in the measured profiles. In today's world, microsystems technology is advancing to produce miniaturized structures. Measurement of overall shape, surface quality, and uniformity of the microstructures across the wafer is crucial for more demanding applications. A micro-sample with groove like structure was used for demonstration. The object and the reference mirror were illuminated with a white light source and interferogram was collected using the RGB camera. The R, G, and B wavelengths corresponding to the three interferograms were determined by the spectral bands of the colour CCD used. The CCD has three separate spectral bands peaked at 620 nm, 540 nm, and 460 nm wavelengths. The PZT was calibrated at 540 nm for phase shift $\pi/2$. Same phase shift can introduce error at other wavelengths. For example, if a PZT is calibrated at $\lambda2$ = 540 nm for phase shift $\alpha2 = 90^o$. Then, the phase shift values become $\alpha1 = (\lambda2/\lambda1)\ \pi/2 = 78.4^o$ for $\lambda1$ = 620 nm and $\alpha3 = (\lambda2/\lambda3)\ \pi/2 = 105.7^o$ for $\lambda3$ = 460 nm. In such cases, the phase shift algorithm can be chosen based on the amount of phase shift error expected during phase shifting from the nominal value of $\pi/2$. So the maximum phase shift error at 620 nm and 460 nm would be ~16^o, which can be completely removed by using eight step algorithm. Phase shift errors as large as 20^o can be compensated using 8-step algorithm. Hence eight phase shifted frames were acquired and decomposed each frame in to its individual components and the corresponding phases at R, G, B were calculated using 8-step algorithm as shown in Fig. 2. The white light colour interferogram obtained on the grooves is shown in Fig. 2(a). Fig. 2(b) shows the individual interferograms decomposed from interferogram in Fig. 2(a). The corresponding wrapped phase maps are shown in Fig. 2(c).

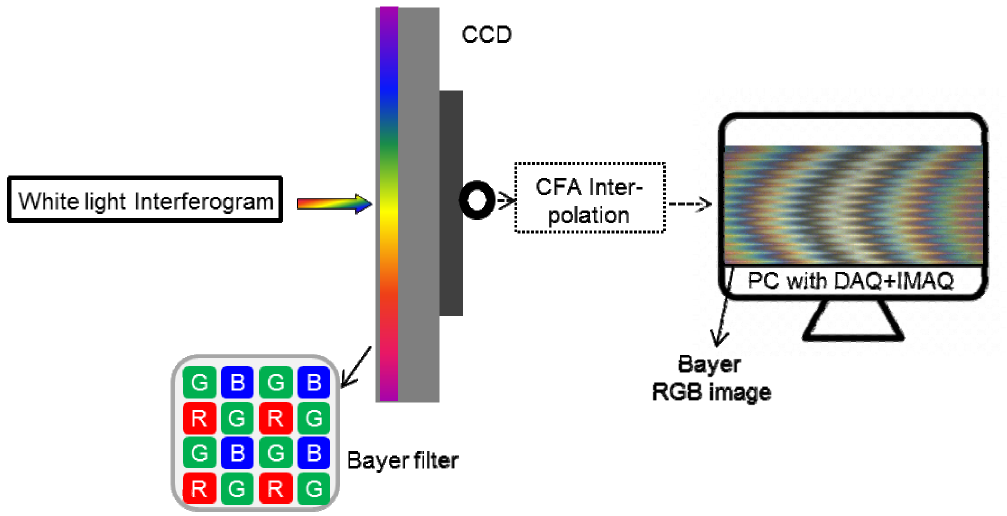

Fig. 1. Schematic drawing of simultaneous recording of red, green, and blue interferograms using Bayer filter 1-CCD sensor. CCD- charged-couple device, CFA- Colour filter array, DAQ-Data acquisition card, IMAQ- Image acquisition card.

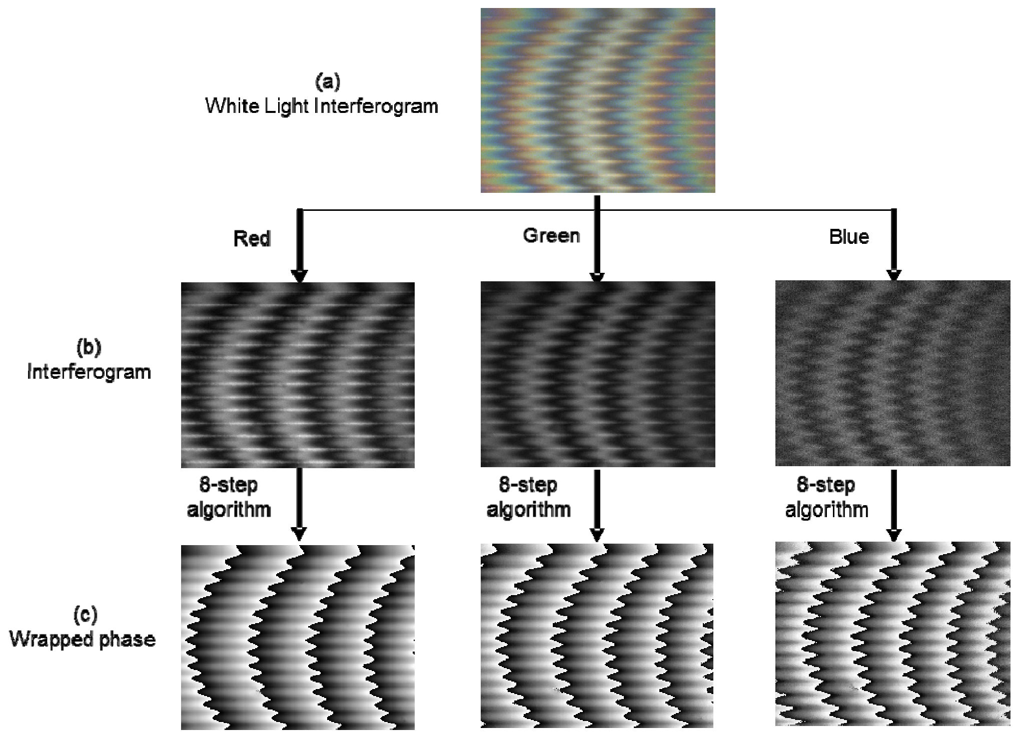

Fig. 2. Flow chart for phase evaluation from RGB colour fringes: (a) typical white light interferogram of a micro-sample with groove structure, (b) decomposed interferograms at red, green, blue wavelengths, and (c) corresponding wrapped phase maps obtained using 8-step algorithm. The phase is wrapped between $-\pi$ to π due to arctan function.

Here the number of fringes generated on the surface is less, *i.e.,* small surface variation, hence any one of the phase map can be used to reconstruct the surface profile of micro-grooves. If the surface variation or curvature is large, *i.e.,* more number of fringes is expected. If single wavelength fails to quantify the data, then one can use effective phase evaluation method in such case. In this method, the phase at one wavelength is subtracted from that of the other to generate phase at an effective wavelength $\Lambda_{12}(=\lambda_1\lambda_2/|\lambda_1-\lambda_2|)$. This approach will enhance the measurement rage of the interferometer by desensitizing it. The wrapped phase map at 620 nm show in Fig. 2(c) was unwrapped using 2D unwrapping algorithm, and then quantified using the out-of-plane relation $z = (\lambda/4\pi)\Delta\Phi$, where λ-wavelength, $\Delta\Phi$-unwrapped phase, and z- surface profile height. The unwrapped phase map, 3D view of the groove surface, and line san profile cross the groove structure are shown in Fig. 3. The groove depth is about 150 nm, and is uniform across the measured area. To make this measurement simpler and dynamic, single frame methods such as Hilbert transformation can be applied for surface profiling [43].

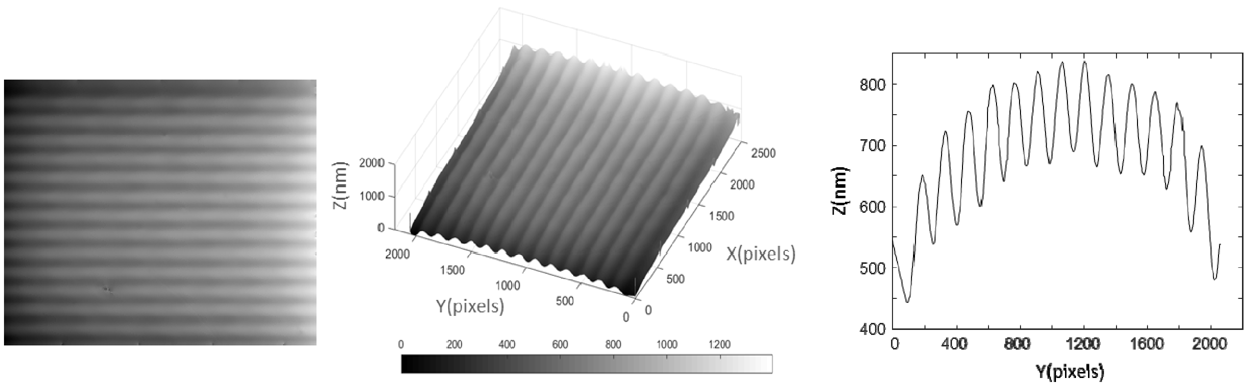

Fig. 3. 3-D Surface profile analysis of a micro-sample with grooves: continuous phase map of the sample (left), 3-D profile showing groove structure (middle), line scan profile across the groove pattern showing 150 nm depth variations (right).

4. CONCLUSIONS

In this article, we presented fringe analysis of white light interferogram acquired with single-chip colour CCD. Typical fringe pattern obtained on a micro-groove structure was demonstrated for surface profiling. To implement eight step methods, eight phase shifted frames were stored. And each colour interferogram was first separated in to individual components, and corresponding phase was evaluated using eight step algorithm to compensate for phase shift error. Finally the 3D surface profile of the test sample was reconstructed. The white light interferometer plus colour CCD system has following advantages: (a) both small and large surface discontinuities can be measured, (ii) spectroscopic imaging of biological cells such as red-blood-cells (RBCs) is possible, (iii) by using single fringe method, it can even measure surface profile under dynamic condition, (iv) the use of colour CCD allows the image acquisition as simple as single wavelength case. Overall the system described could be a promising tool that can provide simpler, cheaper, and faster quantitative measurements for optical metrology and imaging applications.

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