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Multi-wavelength phase-shifting interferometry for micro-structures measurement based on color image processing in white light interference

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ABSTRACT

Conventional multi-wavelength phase-shifting interferometry utilizes two or three monochromatic light sources, such as lasers, to realize the measurement of the surface topography with large discontinuity. In this paper, the white light source, with a single-chip CCD color camera, is used to accomplish multi-wavelength phase-shifting interferometry. In addition, we propose an algorithm which combines white light phase-shifting algorithm, equivalent wavelength method and fringe order method to achieve measuring and calibrating the micro-structures ranging from nanometer scale to micrometer scale. Finally, the proposed method is validated by a traceable step height standard.

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1. Introduction

High precision and reliable surface topography and micro-structure measurement plays an important role in some scientific and industrial applications [1–4], such as ophthalmologic investigations of the health of cornea and retina, quality control in micro-electro-mechanical systems (MEMS) fabrication and ultra-precision manufacture.

Optical interferometry, as a non-contact method, is widely used in measuring and calibrating micro-structures ranging from nanometer scale to micrometer scale. Phase shifting interferometry (PSI) is a conventional technique in the field of optical measurement. Monochromatic light, with a narrow band of optical wavelengths, is utilized and the problem of phase ambiguity occurs during the calculation in PSI. In the process of phase unwrapping, the phase difference between two adjacent measured points must be less than π, which limits the measuring range of this method.

To overcome the phase ambiguity and achieve measuring the surface profile with large discontinuous structures, several methods have been proposed, including dual-wavelength [5–10] or multi-wavelength interferometry [11–14], white light interferometry (WLI) [15–20]. In dual-wavelength or multi-wavelength interferometry, unambiguous range is extended via synthetic wavelengths and synthetic phases; however, two or three lasers are utilized and the same optical path for all lasers is required [9,10,12], which makes the interferometric system expensive and complicated. In WLI, the white light source has a short coherence length and zero fringe order can be determined by detecting maximum fringe contrast, but more interferograms have to be recorded over time, which makes WLI more vulnerable to time-dependent phenomena, such as environmental vibrations.

That is to say, it is by using more than one wavelength that measuring unambiguity could be enlarged. For each wavelength a certain interference fringe is formed, and the sum of all of the fringes can generate color interferograms as a result. As to the traditional interferometry [6–8,15,16], a monochromatic CCD camera is normally utilized to record color interferograms as grayscale images, which loses a wealth of information contained in color fringe patterns. Therefore, there has been considerable interest in the study of making full use of color information of interferograms via a color CCD camera [17–20]. The recorded color image (RGB image) can be decomposed into red (R), green (G), blue (B) channels corresponding to different color wavelength components. Then for each channel the phase-shifting algorithm is applied to obtaining the phase related to a certain wavelength component. Combined with all of phases in RGB channels, surface topography measurement could be ultimately achieved by the means of equivalent wavelength method or fringe order method.

The white light source, compared with the laser, is not only a broadband light source that is composed of a range of wavelengths, but also low cost and undamaged to living organisms in

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biological research [19]. When the white light source, such as a halogen lamp or a tungsten lamp, is utilized for illumination, we should pay attention that conventional phase-shifting algorithms are not appropriate to calculate the phase of each channel, for the interference intensity is affected by not only the phase variation, but also the coherence envelope in the interferograms. Relevant research [1,18,19]; however, ignores the effect of the coherence envelope and regards the fringe contrast as a constant in the analysis of color fringe patterns, which could not acquire the accurate result of surface topography consequently.

In addition, the noise would be scaled by the wavelength as to equivalent wavelength method [6,11], which is not suitable for measuring micro-structures with high accuracy. Fringe order method needs a priori knowledge of measuring range of surface topography so as to define the fringe order, but it is usually difficult to realize the correct pre-determination of measuring range, especially for micro-structures [12].

In this paper, multi-wavelength phase-shifting interferometry is performed by processing color images of white light interference fringes, which could achieve measuring surface topography of micro-structures with high accuracy. The proposed method has several features as follows. Calculating phases of RGB channels is based on white light phase-shifting algorithm [21–23], which takes into account the influence of the coherence envelope in the interferograms. Besides, continuous wavelet transform (CWT) is applied to extract the mean wavelengths of the RGB channels, which can obtain the mean wavelengths very accurately and avoid the influence of the crosstalk of the color CCD camera. This method makes micro-devices with large discontinuities measurement convenient and efficient. Finally, the proposed method was validated by measuring a step height standard from VLSI which is traceable to NIST.

2. System set-up

The experimental set-up of the white light microscopic interferometry system is shown in Fig. 1. The collimated light source (halogen lamp) passes through a beam-splitter prism and a Michelson interference objective (Magnification is 5×, and numerical aperture (NA) is 0.13) to generate fringes of white light interference. The single-CCD color camera with a Bayer filter, with an image acquisition card, is utilized to record color images of white light interferograms. A piezo-electric transducer (PZT) is attached to Michelson interference objective, and driven by a PZT controller to realize the phase shift. A halogen lamp, with a Gaussian spectrum, is used as the illumination system, while its spectral energy is deficient in channel B (blue). In order to solve this problem, a light balancing filter could be utilized to make the level of the spectral energy in RGB channels approximately equal by suppressing everything but blue light, as shown in Fig. 2. As a result, we could make full use of the color information contained in color images via increasing the signal to noise ratio (SNR) in channel B.

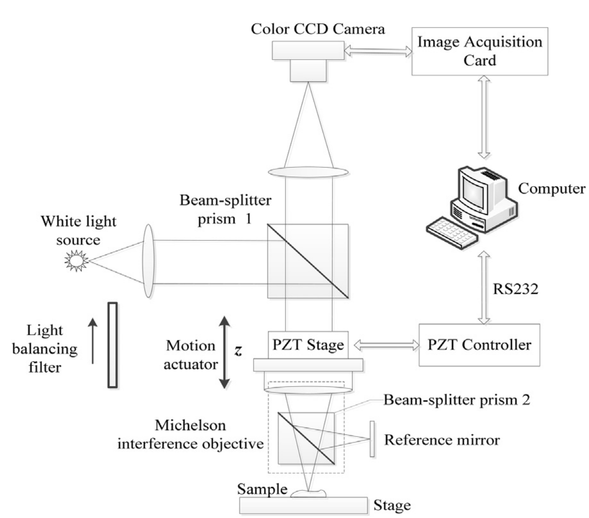

Fig. 1. Schematic of the experimental system.

3. Measuring principle

As to an arbitrary point, the recorded interference intensity distribution of a certain channel in color images can be written as [22]

$$I_{mj} = I_{0m} + \gamma_m I_{0m} g_m\left(\varphi_{mj}\right) \cos\ \varphi_{mj} \quad (1)$$

where j is the sampling number, m represents corresponding channel of R, G and B. I_{0m} is the background intensity, γ_m is the fringe contrast, and $g_m(\varphi_{mj})$ indicates the coherence envelope that depends on the spectrum of the light source in the certain channel. When the light source with a Gaussian spectrum is utilized, $g_m(\varphi_{mj})$ can be written as

$$g_m\left(\varphi_{mj}\right) = \exp\left[-\left(\frac{\varphi_{mj}\lambda_{cm}}{2\pi l_{cm}}\right)^2\right] \quad (2)$$

λ_{cm} and l_{cm} are the mean wavelength and the coherence length of the light source in the corresponding channel respectively. φ_{mj} is the phase that can be given as

$$\varphi_{mj} = \phi_m + \delta\varphi_m \cdot j \quad (3)$$

ϕ_m is the unknown phase to be calculated, and $\delta\varphi_m$ is the phase shift between adjacent sampling numbers.

If the coherence envelope is regarded as locally linear, and the phase shift $\delta\varphi_m$ equals 0.5π which corresponds to a certain wavelength in the channel, ϕ_m can be given as [21–23]

$$\phi_m = \arctan\left(\frac{I_1 - 3I_3 + 3I_5 - I_7}{2(I_2 - 2I_4 + I_6)}\right) \quad (4)$$

Color information of interferograms in RGB channels are recorded by a color CCD camera simultaneously. If the phase shift 0.5π corresponds to the mean wavelength in channel *G*, the phase shift at the mean wavelength in channel *R* or channel *B* can be calculated as [12]

$$\delta\varphi_R = \frac{\lambda_R}{\lambda_G} \cdot \frac{\pi}{2} \quad (5)$$

$$\delta\varphi_B = \frac{\lambda_B}{\lambda_G} \cdot \frac{\pi}{2} \quad (6)$$

Besides, several factors could also affect the phase shift, such as inaccurate calibration of the phase shifter, the numerical aperture effect of the objective. Therefore, it is essential to make sure that the deviation of the phase shift from 0.5π, to a certain extent, has a limit effect on the accuracy of ϕ_m that is calculated by the Eq. (4). For the simulation parameters, I_0 is 120, γ is 0.8, λ is 600 nm and l_c is 2000 nm. The simulation results of the phase errors using seven-step algorithm are given in Fig. 3. Phase errors are evaluated by subtraction the authentic phases from the unwrapped phases based on the Eq. (4). As the phase shift ranges from 0.4π to 0.6π, the maximum phase errors in the range [−4π, 4π] are less than 0.8%. When the phase shift is 0.5π, the phase error is the minimum, so 0.5π is chosen as the phase shift configuration in our measuring system.

The simulation results of phase errors using the other two common used phase-shifting algorithms (Hariharan five-step algorithm and eight-step algorithm [18]) are given in Fig. 4. From Fig. 4, it is shown that the maximum phase errors in the range [−4π, 4π] of these two algorithms are about 6% and 3%

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