Development of a Surface Profiler Based on Three-Wavelength Phase-Shifting Interferometry

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To overcome the phase ambiguity problem in phase-shifting interferometry, multi-wavelength interferometry has been long investigated. However, its industrial application has been limited because of its complex optical configurations. This paper introduces a surface profiler which uses a low-cost and simple three-wavelength imaging system consisting of a white-light illuminator, a multi-bandpass filter and a color CCD camera. The algorithms used and experimental results are presented.

1. Introduction

The phase shifting method in optical interferometry is widely used in industry as an ultra-high-precision surface profile measurement method, but there is a limitation that the step between adjacent pixels is less than 1/4 of the wavelength. As a solution to this problem, the multi-wavelength phase shifting method has been proposed for a long time, but the method [1] in which the wavelengths are switched sequentially requires a long measurement time, and the method [2] in which three lasers are simultaneously irradiated has no freedom in wavelength selection.

On the other hand, the author has developed a three-wavelength one-shot interferometry method that introduces carrier fringes [3], expanded the measurement range to 4 μm, and developed an automatic film thickness measurement system for inkjet color filter substrates [4,5].

In this report, we report a surface profile measuring system by the three-wavelength phase shifting method using the optical system and the measurement algorithm.

2. Principle of measurement

2.1 Interferometric optics and imaging system

Figure 1 shows the optical system. In the interference microscope, the objective lens is moved in the optical axis direction by the piezo drive mechanism to shift the phase. The three-wavelength imaging system is the same as in the previous report [5] and uses a three-wavelength illuminator that uses a multi-wavelength band-pass filter (MBPF) and a color camera (three-CCD type; 1344 x 1024 pixels).

As shown in Fig. 2, the transmission wavelengths of MBPF are B(470nm), G(560nm), R(600nm), and the half width is about 10nm. Figure 3 shows the spectral sensitivity characteristics of a color camera and three wavelengths. When the captured color image is decomposed into R, G and B, phase-shifted images of 3 wavelengths are obtained.

2.2 Crosstalk compensation

As shown in Fig.3, the spectral sensitivity curves of the camera overlap, but in the case of the three wavelengths used in this report, the crosstalk of B, G, and R signals is very small and can be ignored.

2.3 Phase calculation

The phase ϕ of each wavelength at each point is obtained by least squares fitting of the following model equation to the intensity data $g_i (i = 1,\ldots, n)$ at n points (n>=3).

$$g_i = a + b\cos\{(4\pi\Delta/\lambda)i + \phi\} \qquad (1)$$

where a is the DC component, b is the amplitude, Δ is the piezo movement interval, and λ is the wavelength.

This nonlinear least-squares problem can be converted into a linear problem by the variable transformation of $\xi_c = b\cos\phi$ and $\xi_s = b\sin\phi$, as in the Local Model Fitting method [6, 7]. Solving a simultaneous linear equation, we can obtain a, ξ_c, ξ_s, then the phase

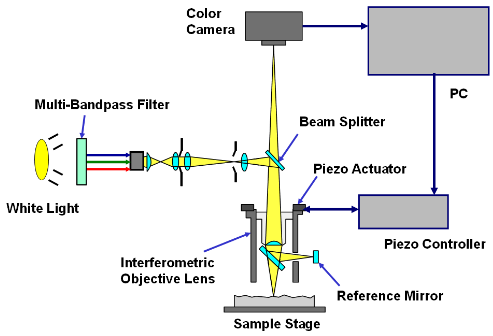

Fig.1　Optics of three-wavelength phase shifting interferometry

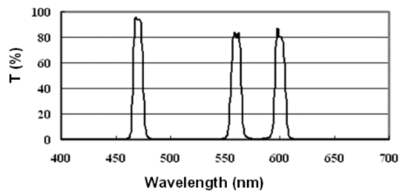

Fig.2　Three-wavelength band-pass filter

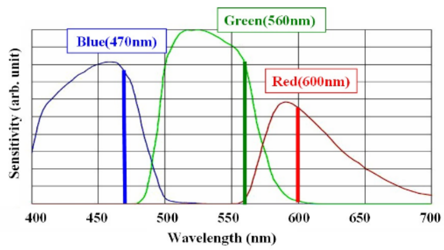

Fig.3　Spectral sensitivity of color camera and three wavelengths

ϕ by the following formula:

$$\phi = \arctan(\xi_s/\xi_c) \qquad (2)$$

2.4 Three wavelength phase unwrapping

Phase unwrapping is achieved by a method of calculating height candidates from the phases obtained at each wavelength and selecting the best matching height candidate within the expected height range (Fig. 4). In other words, the height candidate values $h_j(n)$ are calculated by Eq. 3.

$$h_j(n)=(\phi_j/2\pi)*(\lambda_j/2)+ n*(\lambda_j/2) \qquad (3)$$

where j is the number of wavelength (j=1,…,3),　n is the order, ϕ is the phase, λ is the wavelength.

Then we find the height that minimizes the range (difference between the maximum and minimum values) of the combination of height candidates that are closest to each other.

3. Experimental results and discussion

For verification experiments of the proposed method, the

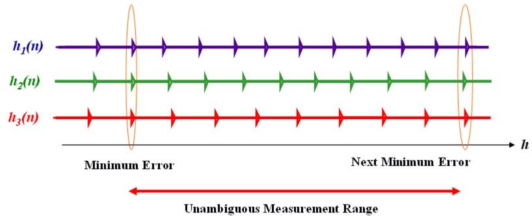

Fig.4 Principle of coincidence method

Fig.5 Optical profiler used for experiment.

illumination/imaging system of Toray Engineering Co., Ltd. SP-500 (Fig.5) [8] was replaced with a three-wavelength imaging system, and the proposed algorithm was installed. The standard step sample of about 1130 nm was used as the measurement target.

(1) Phase shift image capture: The piezo was driven at a pitch of 75 nm and 7 color images were captured (Fig. 6).

(2) Phase calculation: The phases at each point and each wavelength were obtained. Figure 7 shows the phase profiles of the y=512 line.

(3) Height calculation: The height was calculated from the phase data using the coincidence method. The height profile of the y=512 line and the coincidence error are shown in Fig. 8, and the three-dimensional height of the entire surface is shown in Fig. 9. The step height of 1130 nm was measured correctly. In the case of the three wavelengths used in this experiment, the relationship between the coincidence error and the coincidence cycle is already obtained [4], and if the error is 33 nm or less, the cycle is 4.2 µm. Therefore, it is expected that the 1 µm step, which is the measurement target of this experiment, can be measured stably.

The measurement time was about 1.8 s for imaging and about 2.0 s for calculation (1344 x 1024 pixels) using a PC (Intel Core2 Duo, 3 GHz). Regarding the measurement reproducibility, the average deviation of the two measurements was less than 1 nm (rms), except for the step edge.

4. Summary

In this report, we developed a surface profiler by the three-wavelength phase shifting method by using the optical system and the calculation algorithm already developed for the three-wavelength single-shot method, and obtained the following findings.

(1) An inexpensive and compact three-wavelength simultaneous imaging system can be constructed by illumination with a multi-wavelength band-pass filter and a color camera.

(2) The combination of wavelength and camera used in this experiment does not require crosstalk compensation.

(3) From three or more phase-shifted color images, the phases of the BGR wavelength can be obtained by the least-squares method, and the three-dimensional profile can be obtained by the phase unwrapping by the coincidence method.

(4) It was confirmed that the actual sample surface profile with a steep step exceeding 1 µm could be measured correctly.

(5) Compared with the conventional phase shifting method, it has

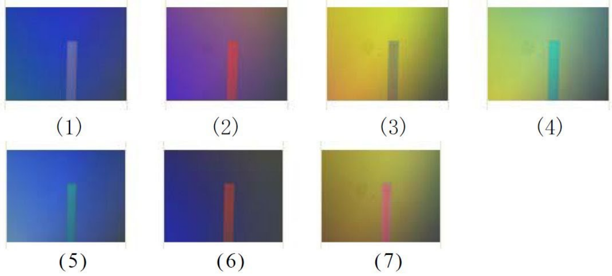

Fig.6 Captured color images with phase shifting.

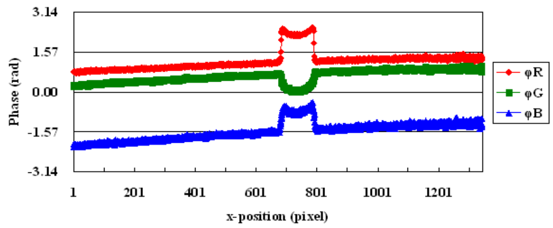

Fig.7 Phase profiles (y=512).

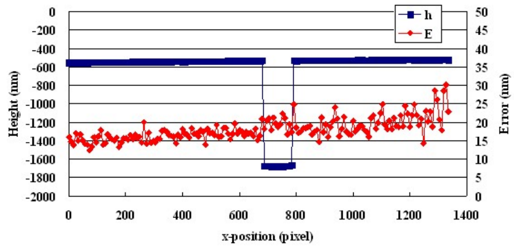

Fig.8 Height and coincidence error profiles (y=512).

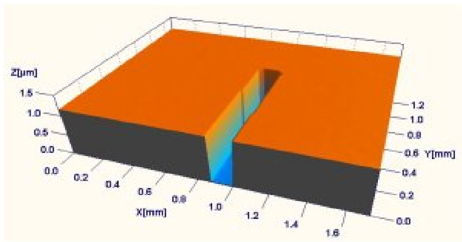

Fig.9 Measured height (3D view).

a wider measurement range, and has a higher horizontal resolution and measurement accuracy than the single-shot method.

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