

Two-Wavelength Single-Shot Interferometry

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Abstract: A new surface profiling technique is proposed, which enables us to measure a surface profile without a rounding effect and with extended phase measurement range. It is accomplished by a newly developed two-wavelength imaging system and the local model fitting (LMF) algorithm for carrier pattern analysis. The experimental results demonstrated that the proposed method can measure steep steps fast and accurately with an extended measurement range, while the robustness against vibration of the conventional single-shot methods is maintained.

Keywords: Interferometry, surface profiler, two-wavelength, single-shot.

1. INTRODUCTION

The technique of surface profile measurement utilizing optical interference is widely used in the industry as a non-contact and non-destructive method to quickly and accurately measure the profile of microscopic surfaces. However, it involves a shortcoming of being susceptible to vibration. This is because the measurement needs multiple images with different reference positions. For example, at least three images are required in the phase-shift interferometry to calculate the optical phase of each point.

To overcome this problem, several methods that can measure the surface profile only from a single image have been proposed. These methods are generally called *single-shot interferometry*. A typical example is spatial carrier interferometry, in which the carrier fringes are introduced by tilting the reference mirror (Fig. 1). From a single interferogram with carrier fringes (Fig. 2), the phase distribution can be calculated by the Fourier-transform method [1] or the spatial synchronous method [2-3].

However, both methods use integral transforms, which filter out the high-frequency components resulting in edge- rounding effects and low spatial resolution.

Recently, a new single-shot algorithm has been proposed [4] which can solve the above problem.

However, all methods developed so far have a common limitation that the maximum difference of the surface height between two adjacent pixels should be less than $\lambda/4$, where λ is the wavelength of the light source.

A common approach to alleviating this problem is to use two-wavelength interferometry [5-6]. To employ this technique in the single-shot interferometry, ordinary imaging systems are not satisfactory since they capture two images at certain time interval.

In this paper, we propose a new optics for two-wavelength interferometry, which allows us to simultaneously capture two images at two different wavelengths.

Thus our new system can achieve a wider measurement range while the robustness against vibration is maintained.

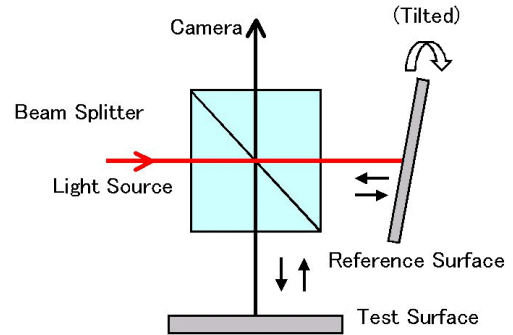


Fig. 1 Optics of spatial carrier interferometry.



Fig. 2 Interferogram with carrier fringes.

2. LOCAL MODEL FITTING ALGORITHM

In this section, we give a short review of the *local model fitting (LMF)* method proposed in Ref. 4.

When we tilt the reference mirror, the observed signal is given by

$$g(x, y) = a(x, y) + b(x, y) \cos(\phi(x, y) + 2\pi f_x x + 2\pi f_y y), \quad (1)$$

where $a(x, y)$ and $b(x, y)$ are the bias and the amplitude. The function $\phi(x, y)$ contains the information on the surface profile, which we would like to extract.

Notations f_x and f_y stand for the spatial carrier frequencies along x - and y -axes, respectively.

Here we make the following assumption: $a(x, y)$, $b(x, y)$, and $\phi(x, y)$ are constant in the vicinity of (x_0, y_0) , i.e., our local model is

$$g(x, y) = a + b \cos(\phi + 2\pi f_x x + 2\pi f_y y). \quad (2)$$

Suppose we have reasonable estimates of the spatial carrier frequencies f_x and f_y , denoted by \hat{f}_x and \hat{f}_y , respectively. Such estimates can be obtained from image data of a flat area. Note that the spatial carrier frequencies f_x and f_y are global quantities which do not depend on the target object and are determined by the relative tilting angle of the reference mirror.

Then the unknowns in the simplified model (2) are only a , b , and ϕ . They can be determined by solving the following least-squares problem:

$$(a, \hat{b}, \phi) = \underset{(a, b, \phi)}{\operatorname{argmin}} \sum_{i=1}^n [g(x_i, y_i) - a - b \cos(\phi + 2\pi \hat{f}_x x_i + 2\pi \hat{f}_y y_i)]^2. \quad (3)$$

Since Eq. (3) is non-linear with respect to ϕ , it is cumbersome to be solved. To ease the problem, we employ the following reparameterization:

$$\xi_c = b \cos \phi, \quad (4)$$

$$\xi_s = b \sin \phi, \quad (5)$$

$$\varphi_c(x, y) = \cos(2\pi \hat{f}_x x + 2\pi \hat{f}_y y), \quad (6)$$

$$\varphi_s(x, y) = -\sin(2\pi \hat{f}_x x + 2\pi \hat{f}_y y). \quad (7)$$

Now we solve the following least-squares problem instead:

$$(a, \xi_c, \xi_s) = \underset{(a, \xi_c, \xi_s)}{\operatorname{argmin}} \sum_{i=1}^n [g(x_i, y_i) - a - \xi_c \varphi_c(x_i, y_i) - \xi_s \varphi_s(x_i, y_i)]^2. \quad (8)$$

Since the above model is linear with respect to a , ξ_c , and ξ_s , we can obtain the closed-form solutions \hat{a} , $\hat{\xi}_c$, and $\hat{\xi}_s$ by solving the following system of linear equations in three variables.

$$A \begin{pmatrix} \hat{a} \\ \hat{\xi}_c \\ \hat{\xi}_s \end{pmatrix} = g, \quad (9)$$

where

$$A = \begin{pmatrix} n & \sum \varphi_c(x_i, y_i) & \sum \varphi_s(x_i, y_i) \\ \sum \varphi_c(x_i, y_i) & \sum \varphi_c(x_i, y_i)^2 & \sum \varphi_s(x_i, y_i) \varphi_c(x_i, y_i) \\ \sum \varphi_s(x_i, y_i) & \sum \varphi_s(x_i, y_i) \varphi_c(x_i, y_i) & \sum \varphi_s(x_i, y_i)^2 \end{pmatrix}, \quad (10)$$

$$g = \begin{pmatrix} \sum g(x_i, y_i) \\ \sum g(x_i, y_i) \varphi_c(x_i, y_i) \\ \sum g(x_i, y_i) \varphi_s(x_i, y_i) \end{pmatrix}. \quad (11)$$

Given $\hat{\xi}_c$ and $\hat{\xi}_s$, we can obtain an estimate ϕ of the surface profile at (x_0, y_0) by

$$\phi(x_0, y_0) = \arctan(\hat{\xi}_s / \hat{\xi}_c) + 2m\pi, \quad (12)$$

where m is an unknown integer, and can be determined by a phase-unwrapping algorithm if the surface is smooth enough so that the phase difference between two adjacent pixels is less than π .

3. TWO-WAVELENGTH SINGLE-SHOT METHOD

3.1 Algorithm

As mentioned above, the spatial carrier method cannot measure a steep step correctly when the phase difference between two adjacent pixels is larger than π . This problem also occurs in the phase-shifting interferometry, and two-wavelength interferometry is a well-known technique to resolve this problem [5-6]. The surface under test is measured using two wavelengths, λ_1 and λ_2 , and the two phases are obtained as ϕ_1 and ϕ_2 . The simplest method to obtain the height from these data is "the equivalent wavelength method", where the height H is given by the following equation;

$$H = (\Phi/2\pi + N) * (\lambda_{eq}/2), \quad (13)$$

where N is an unknown integer,

$$\Phi = \phi_1 - \phi_2, \quad (14)$$

$$\lambda_{eq} = \lambda_1 \lambda_2 / (\lambda_2 - \lambda_1). \quad (15)$$

This means that if we subtract two phases measured at two wavelengths, we obtain a new equivalent phase Φ corresponding to a longer equivalent wavelength λ_{eq} .

Thus, the height-step condition for a correct phase-unwrapping is expanded from $\lambda_1/4$ to $\lambda_{eq}/4$.

Although this technique is simple to understand, it magnifies any phase error by a factor of λ_{eq}/λ_1 . One of the techniques to avoid this problem is "the fringe order determination method", where the fringe order N_1 of the first wavelength is determined by the height obtained by the equivalent wavelength method [6]. Then the height H is calculated by the following equation;

$$H = (\phi_1/2\pi + N_1) * (\lambda_1/2). \quad (16)$$

The fringe order N_1 can be expressed by the following equation:

$$N_1 = \operatorname{Round}[(\lambda_1 \phi_1 - \lambda_2 \phi_2) / 2\pi(\lambda_2 - \lambda_1)], \quad (17)$$

where 'Round' means to round off to the nearest integer.

These two methods were used in our experiments and the comparison results will be shown in Section 3.3.

3.2 Two-Wavelength Imaging System

In order to apply the idea of the two-wavelength method to the single-shot interferometry, it is necessary to capture two interference fringe patterns using two different wavelengths simultaneously. So far, no inexpensive and compact imaging system is available. We propose a sophisticated two-wavelength imaging system for the single-shot interferometry. It is easily and economically constructed by using a commercially available RGB LED illuminator and a color camera.

Fig. 3 shows the picture of the illuminator (CCS: HLV-3M-RGB-3W) we used. Its optical specifications are shown in Table 1.



Fig. 3 RGB LED illuminator

Table 1. Specifications of the illuminator

Color	Wavelength (nm)	Bandwidth (nm)
R	627	20
G	530	35
B	470	25

Fig. 4 shows the spectral sensitivity of the color CCD camera we used, with the spectral peaks of two LEDs (B at 470 nm and R at 627nm). It is noted that when only the red and blue LEDs are turned on and the color camera captures a fringe image, we can simultaneously obtain the 470nm image from B-frame and 627nm image from R-frame. In this case, the equivalent wavelength is calculated to be 1877 nm according to Eq. (15). This means that the height gap between adjacent data points can be as large as 469nm without any ambiguities.

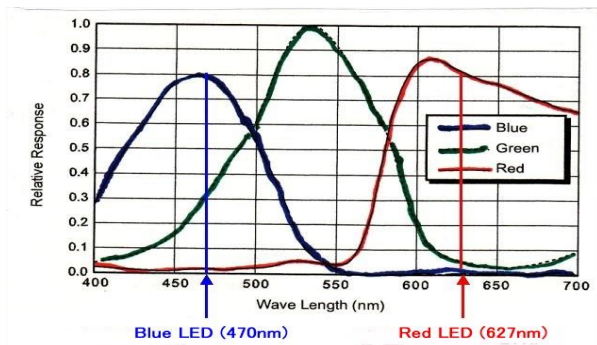


Fig. 4 Spectral curves of LEDs and color camera.

3.3 Experiments

In order to show the validity of the proposed method, we performed an interferometric test using a Toray Engineering SP-500 surface profiler [7], shown in Fig. 5, which incorporates a Michelson interferometric microscope as shown in Fig. 1.



Fig. 5 Toray Engineering SP-500 surface profiler.

As the test sample, we chose a patterned quartz plate with a nominal step height of 350 nm. Its surface profile was measured as shown in Fig. 6 by conventional white-light interferometry.

Fig. 7 shows the captured color image by the two-wavelength single-shot interferometry system. Figs. 8 and 9 show the extracted B and R components.

We first present the results of line-wise measurements along the horizontal line indicated in Fig. 7. The intensity profiles of the B and R images are shown in Fig. 10. By applying the LMF algorithm to these data, we obtained two phase profiles (Fig. 11). The parameters for phase calculations were set as follows:

- 1) Sample data size: 25(horizontal pixel).
- 2) Estimated spatial carrier frequencies: \hat{f}_x was calculated for each wavelength from the horizontal fringe counts, and \hat{f}_y was set to zero.

First we calculated the surface height by using only R color phase data. The result is shown in Fig. 12. The measured step height of 44nm is reasonable enough because the nominal step height of 350nm is 36 nm higher than half the wavelength of 627nm.

Next we tested the two-wavelength method. From the two unwrapped phase data, we obtained two surface profiles by using two algorithms mentioned in Section 3.1, namely Eqs. (13) and (16). Fig. 13 shows profiles H(Eq) and H(Order) obtained by the equivalent wavelength method and the fringe order determination method, respectively. It is noted that the latter method gives better and satisfactory results.

Table 2 compares the measured average step heights by three methods. It is clearly shown that the proposed two-wavelength single-shot method expands the measurable vertical range.

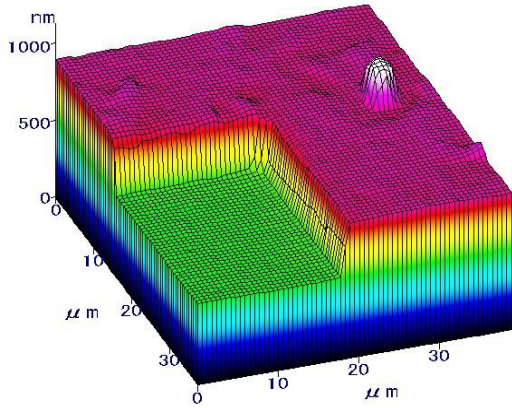


Fig. 6 Surface profile by white-light interferometry.

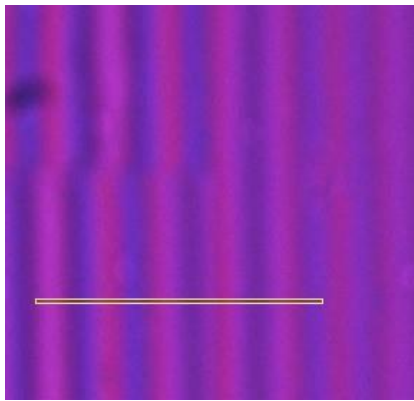


Fig. 7 Captured color image with the profile-analyzed line.

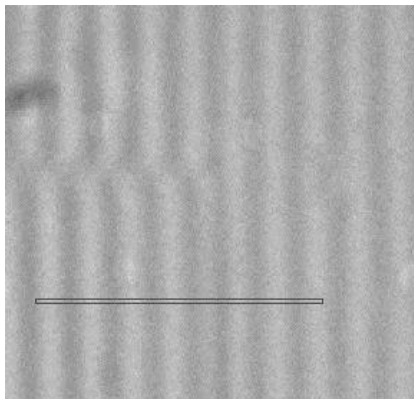


Fig. 8 Extracted image of B component.

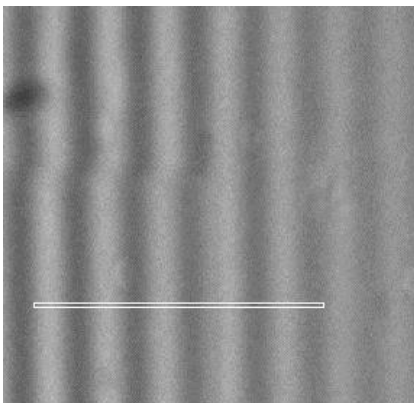


Fig. 9 Extracted image of R component.

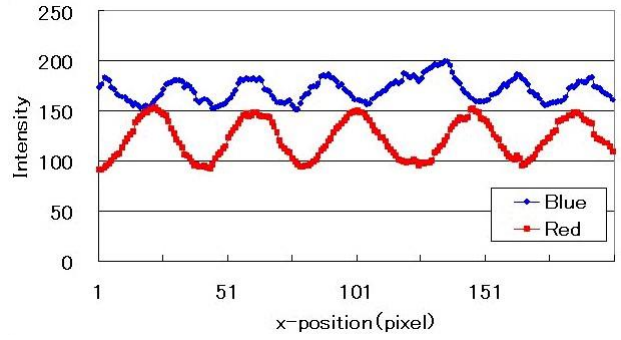


Fig.10 Intensity profiles of the B and R fringes along the horizontal line indicated in Fig. 7.

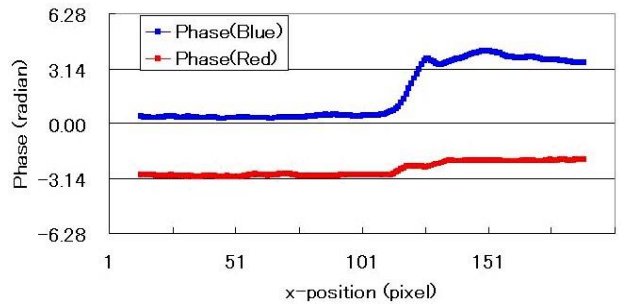


Fig.11 Phase profiles of the B and R fringes.

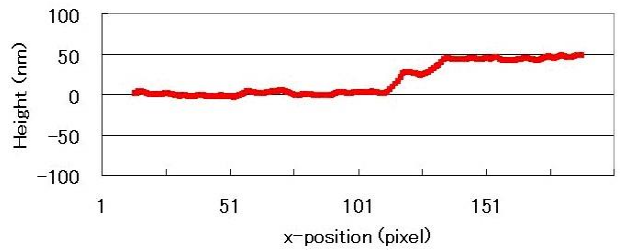


Fig. 12 Surface profile by one-wavelength single-shot method

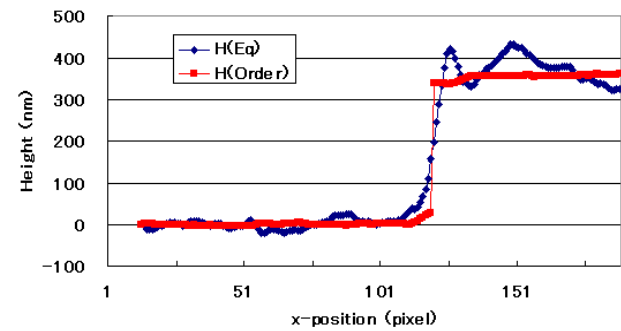


Fig. 13 Surface profiles by two-wavelength single-shot method.

Table 2. Comparison of measured step heights

Method	Step-height(nm)
White-light interferometry	371
Single-wavelength single-shot interferometry	44
Two-wavelength single-shot interferometry	357

Finally we present the 3D measurement results in Fig. 14. The number of vicinity data points in the LMF calculation was 25 (horizontal) \times 5 (vertical). The results agree well with those of a conventional method shown in Fig. 6.

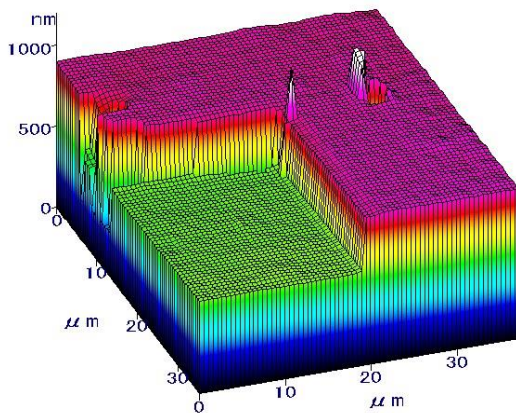


Fig. 14 3D surface profiles by two-wavelength single-shot method.

4. CONCLUSION

We have proposed a new surface profiling technique: Two-Wavelength Single-Shot method, which enables us to measure a surface profile without a rounding effect and with extended phase measurement range. It is accomplished by a newly developed two-wavelength imaging system and the LMF algorithm for carrier pattern analysis.

The experimental results demonstrated that the proposed method can measure steep steps fast and accurately with an extended measurement range, while the robustness against vibration of the conventional single-shot methods is maintained.

REFERENCES

- [1] M. Takeda, H. Ina, and S. Kobayashi, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry", *J. Opt. Soc. Am.*, Vol. 72, No. 1, pp. 156-160, 1982.
- [2] S. Toyooka and M. Tominaga, "Spatial fringe scanning for optical phase measurement", *Opt. Commun.*, Vol. 51, No. 2, pp. 68-70, 1984.
- [3] K. H. Womack, "Interferometric phase measurement using spatial synchronous detection", *Opt. Eng.* Vol. 23, pp. 391-395, 1984.
- [4] M. Sugiyama, H. Ogawa, K. Kitagawa, and K. Suzuki, "Single-shot surface profiling by local model fitting", *Appl. Opt.*, Vol. 45, No. 31, pp. 7999-8005, 2006.
- [5] K. Creath, "Step height measurement using two-wavelength phase-shifting interferometry", *Appl. Opt.*, Vol. 26, pp. 2810-2816, 1987
- [6] Y.Y. Cheng and J.C. Wyant, "Two-wavelength phase-shifting interferometry", *Appl. Opt.*, Vol. 23, pp. 4539-4543, 1984
- [7] Toray Inspection Equipment Home Page, (Toray Engineering Co., 2007), <http://www.scn.tv/user/torayins/>

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