Surface Topography: Metrology and Properties

PAPER

Accuracy improvement of a white-light spectral interferometer using a line-by-line spectral calibration method

Tong Guo1,2 (✉), Guanhua Zhao3, Dawei Tang4, Qianwen Weng1, Feng Gao1, and Xiangqian Jiang3
1 State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin, People’s Republic of China
2 Nanchang Institute for Microtechnology of Tianjin University, Tianjin University, Tianjin, People’s Republic of China
3 Centre for Precision Technologies, University of Huddersfield, Huddersfield, United Kingdom

E-mail: guotong@tju.edu.cn

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Abstract

Smile distortion caused by aberration of the optical system is the key factor that affects the spectral calibration of a white-light spectral interferometer. To improve the accuracy of surface metrology, this paper proposes a novel calibration approach based on a line-by-line method. An acousto-optic tunable filter (AOTF) is adopted for the wavelength scanning process during calibration. By fitting sufficient calibration data, a more accurate relationship between wavelength and pixel position can be obtained. The simulation results show that the accuracy of surface metrology has different sensitivities to the coefficients of the calibration equation, and that the effect of smile distortion becomes more severe as the optical path difference increases. The presence of smile distortion is confirmed in the calibration experiment of a home-built white-light spectral interferometer. Subsequently, a silicon wafer and a standard step of 1.806 ± 0.011 μm are tested using the calibrated metrology system. The measurement results demonstrate that the line-by-line calibration method performs well in correcting spectral distortion and can improve the measurement accuracy of surface profile.

1. Introduction

As an optical technique for surface metrology, white-light spectral interferometry can obtain a surface profile quickly with nanoscale measurement accuracy [1]. In a white-light spectral interferometer, a two-dimensional detector is employed to capture a spectral interferogram [2, 3], one dimension of which represents the spectral vector and the other the spatial vector [4]. A broadband illumination beam is dispersed by a diffraction grating along the chromatic axis of the camera (spectral vector). One of the key aspects of this interferometry technique is spectral calibration, since it is this that establishes the relationship between pixel position and wavelength [5].

Tong et al [6] determined the relationship between pixel position and wavelength by using the change in the number of interference fringe cycles. This calibration method is easy to perform, but high precision is required in the positioning of the piezoceramic actuator. To characterize material dispersion over a wide spectral range, Arosa et al [7, 8] used a prism spectrometer, which was calibrated with an Hg–Ar lamp. However, the spectral lines of a Hg–Ar lamp are not sufficient for accurately determining the relationship between pixel position and wavelength [9]. Kim et al [10] used zero-crossing detection to estimate the sampling indices corresponding to unknown wavelengths based on low-coherence interferometry. However, this calibration method requires a scanning procedure to acquire the interference spectrum, the result of which will be affected by environmental noise. Li and Mou [11] used a manual monochromator to perform spectral calibration. Despite being more precise than the other methods mentioned above, this calibration procedure takes more time to perform and to process data. In this paper, we propose a calibration method based on wavelength scanning [12], which uses an acousto-optic tunable filter (AOTF) [13] to generate a sufficient number of spectral lines. Therefore, high fitting accuracy between pixel position and wavelength can be achieved.

In a white-light spectral interferometer, distortion due to the spectroscopic element and aberration of the
optical system causes the spectral lines to bend, which is known as smile distortion [14]. The degree of distortion varies with the pixel along the spatial direction. This phenomenon causes sampling points with the same height to have different spectral locations. Furthermore, the installation angle of the camera and the aberration problem can introduce what is known as keystone distortion [15], as a result of which the lengths of spectral lines at different wavelengths vary. These two types of distortion are common in dispersive imaging systems. They have been discussed more in the context of hyperspectral imaging systems [16] than in that of white-light spectral interferometers. In the case of hyperspectral imaging systems, the effect of distortion is reduced by choosing an appropriate system configuration and element [17]. In fact, for a white-light spectral interferometer, the distortion will affect phase extraction, leading to an incorrect profile.

Single-point calibration, in which one position of the spatial vector is chosen to calibrate the chromatic axis, is easy to be carried out but does not take account of distortion. In this paper, after describing the effect of distortion, we propose a method of calibration in which the spectral calibration is repeated line by line. With this method, it is possible to calibrate the correct wavelength position while taking account of distortion and thereby reducing the influence of distortion on surface topography measurements.

To implement the proposed method, we first constructed a Michelson-type white-light spectral interferometer. We analyzed the sensitivity of the calibration coefficients by simulation to provide a theoretical guide. Then, we assessed the effect of smile distortion by both simulation and experiment. The results show that, compared with single-point calibration, line-by-line spectral calibration effectively corrects smile distortion and improves the measurement accuracy of surface profile.

2. System configuration and measurement principle

A home-built white-light spectral interferometer was constructed as shown in figure 1. A 5X Michelson-type interferometric objective is used to observe the tested surface and generate the interference beam. The reflected interference beam is divided into two beams by a beam splitter. One beam is imaged onto a monitoring camera for observing the sample and adjusting the reference mirror. The other beam is focused onto a slit. In this way, only single-line information of the tested sample is selected and then collimated by the achromatic lens. A diffraction grating splits the polychromatic light into monochromatic light with different wavelengths. The groove direction of the grating is parallel to the length direction of the slit, which corresponds to the spatial vector. Finally, the dispersed light is imaged on a camera for acquisition of the spectral interferogram. Each row of the obtained spectral interferogram is registered in the spectral information of the corresponding spatial position.

According to the theory of two-beam interferometry [18], the interference signal can be described as

$$ I(k) = I_m + I_r + 2\sqrt{I_m I_r} \cos \delta, $$

(1)

where $I_m$ and $I_r$ are the intensities of the measurement beam and the reference beam, respectively. $\delta (=2\pi k)$ is the phase difference, and $k$ is the wavenumber. To extract the phase of the spectrum, the five-step phase-shifting method [19] is adopted. From equation (2), the unwrapping phase $\varphi$ has the following linear relationship with the wavenumber $k$:

$$ h = \frac{\Delta \varphi}{2\Delta k} = \frac{\Delta (\varphi + 2m\pi)}{2\Delta k} = \frac{\Delta \varphi}{2\Delta k}, $$

(2)

where $m$ is the interference order, and $h$ is the absolute distance, which is the distance to the position of zero optical path difference (OPD) [20]. The absolute distance, which represents information about surface topography, can be determined by calculating the slope value. For a dispersive interferometry system, the processing of the row signal of the spectral interferogram line by line follows the steps illustrated in figure 2.

3. Simulation analysis of spectral calibration

Spectral calibration, i.e., determination of the relationship between pixel position and wavelength, is important for ensuring accurate measurement of surface topography. Using equation (2), the absolute distance $h$ is calculated from the phase slope with respect to the wavenumber. To reduce conversion errors, wavenumber calibration is used in our system.

3.1. Sensitivity of calibration coefficients for measurement

Commercial spectrometers with a wide waveband usually use a cubic polynomial to fit the relationship between pixel position and wavelength [21]. However, our system has a narrow waveband, and quadratic polynomial fitting has sufficient accuracy for spectral calibration. To evaluate the effect of the calibration coefficients, we use the following original calibration formula obtained by an actual calibration experiment at the central spatial location to generate the simulation signal:

$$ y = 1.5406 \times 10^{-8} x^2 + 1.5324 \times 10^{-4} x + 1.696, $$

(3)

where $y$ and $x$ are the wavenumber and the pixel, respectively.
In the calibration formula, the three coefficients have different levels of influence on measurement accuracy. The three coefficients are changed in the range of 0%–1%, and the amended calibration formula is used to process the interference signal at an OPD of $40 \, \mu\text{m}$. The measurement errors due to changes in the three coefficients are shown in figure 3. The coefficient of the $x$ term has the greatest impact. As it deviates gradually from its original value, the maximum error that is thereby introduced reaches $0.176 \, \mu\text{m}$. The second-largest error is introduced by the coefficient of the $x^2$ term. Although this coefficient is smaller than the others, it nevertheless introduces an error of $0.023 \, \mu\text{m}$ when its value is changed by the maximum amount. According to equation (2), the absolute distance is calculated from the slope, which is determined by phase variation ($\Delta \varphi$) and wavenumber variation ($\Delta k$). Therefore, it will not be affected by changes in the constant term in equation (3). However, it is worth noting that changing the constant term will shift the operating bandwidth toward either shorter or longer wavelength. Any other analysis results involving the wavelength information will be unreliable.

The simulation results show that the calibration coefficients are of great significance for surface topography measurement. In practice, these coefficients are easily influenced by spectral distortion, and so, to improve measurement accuracy, it is necessary to perform line-by-line calibration to minimize spectral distortion.

### 3.2. Smile distortion analysis of spectral interferogram

For the interferometric system shown in figure 1, the keystone distortion is not obvious, because a plane grating is used to separate the spectrum [22]. Therefore, we discuss only the smile distortion, which can be modeled by changing the calibration formula line by line to generate a distorted spectral interferogram (figure 4(a)).

#### 3.2.1. Analysis of degree of smile distortion

When there is no smile distortion, the imaged spectral line for a specific wavelength is straight. This means that the light intensity of any column in the plane’s spectral interferogram is the same. As the smile distortion becomes more severe, the spectral lines bend more and increase the difference in light intensity in each column. We define the ratio of the peak-to-peak value of light intensity to the corresponding position difference, $\Delta I / \Delta P$, as the degree of smile distortion (figure 4(b)).

![Figure 1. Schematic of Michelson-type white-light spectral interferometer.](image)
To show the influence of the OPD on smile distortion, the smile distortions at OPDs of 20 μm, 60 μm, and 100 μm were simulated. As shown in figure 5, the degree of distortion of each column in the spectral interferogram at a given OPD is periodic because of the interference modulation. The distortion increases with increasing OPD.

Next, we will discuss the effects of smile distortion on surface topography measurement for a plane and a step height.

3.2.2. Effect of smile distortion on measurement of a plane profile

The distorted spectral interferogram of a plane at an OPD of 60 μm (absolute distance 30 μm) was analyzed using wavenumber registration data obtained both by single-point calibration and by line-by-line calibration. As shown in figure 6(a), the surface profile calculated using line-by-line calibration accurately reflects the topography of the plane, while the profile calculated using single-point calibration is curved.

Figure 2. Processing procedure for obtaining a surface profile: (a) acquiring the interference spectrum of a single point; (b) extracting the phase using the five-step phase-shifting method; (c) unwrapping the extracted phase; (d) obtaining the surface profile of the tested sample.

Figure 3. Measurement errors due to variations in the calibration coefficients.
owing to the lack of correction of smile distortion. The error introduced by single-point calibration is up to 1.330 μm in the 512th spatial position. From equation (2), the calculation of absolute distance involves the unwrapping phase and wavenumber, so the phase of the 512th spatial position was extracted for discussion as shown in figure 6(b). Compared with the phase difference of 83.4 rad without distortion, the phase difference with distortion is 87.1 rad. This result indicates that distortion will affect the extracted phase. If the wavenumber is not adjusted to take account of distortion, then the phase is not correctly assigned to the wavenumber, resulting in a reduced accuracy in the calculation of the absolute distance. However, if each row of the distorted spectral interferogram has its own calibration formula based on the actual situation, the wavenumber position will correspond accurately to the phase with distortion, thereby greatly reducing the effect of smile distortion.

From the discussion in section 3.2.1, the degree of smile distortion grows with increasing OPD. At a specified OPD, one surface profile of the plane is obtained, and we use the mean error and the standard deviation of the measured profile values to describe how the distortion affects the measurement. The OPD was changed from zero to 100 μm, and then the mean error and the standard deviation at different OPDs were calculated. From figure 7(a), the
difference between the mean calculated result and the theoretical result grows with increasing OPD, with the largest error being $1.412 \mu m$. The standard deviation obeys the same rule, as shown in figure 7(b). In other words, for a plane surface, smile distortion causes a measurement error that increases with increasing OPD.

3.2.3. Effect of smile distortion on measurement of step heights

A step height can be regarded as a combination of two planes. When calculating the value of a step height, the difference between the absolute distances of the two planes may reduce the smile distortion error. We discuss the following two situations: (i) the same step height at different OPDs and (ii) different step heights at the same OPD.

Figure 6 shows the comparison results of two calibration methods and distortion analysis: (a) calibration comparison results; (b) extracted phase with and without distortion.

Figure 7 shows the effect of smile distortion on the measurement of a plane at different OPDs: (a) mean error of results; (b) standard deviation of results.

Figure 8 shows the simulation results for a 10 $\mu m$ step at OPDs of 0–100 $\mu m$. The calculated step height errors increase with increasing OPD, which is similar to the measurement of a plane surface. Different step heights from 0.5 $\mu m$ to 10 $\mu m$ at an OPD of 20 $\mu m$ were simulated as well. The relative error was used to assess how smile distortion affects the measurements. As shown in figure 8(b), the smaller the step height, the greater is the effect of distortion. For a given degree of distortion, the relative error reaches 7.8% for a step of 0.5 $\mu m$. 
4. Experimental results and discussion

4.1. Spectral calibration experiments

The wavelength scanning method in the calibration procedure is based on the acoustic–optical effect [23]. When an electrical signal of a certain frequency is applied to a crystal, the refractive index of the crystal changes. The incident beam will be diffracted and reproduced with a specified wavelength when passing through the crystal:

\[ \lambda = \Delta n \alpha \nu_a (f_a)^{-1}, \]  

where \( \Delta n \) is the birefringence of the crystal, \( \alpha \) is a design parameter of the AOTF, \( \nu_a \) is the speed of the acoustic wave, and \( f_a \) is its frequency.

When a white light beam passes through the AOTF, the corresponding spectral line determined by equation (4) is emitted and then imaged onto the spectral camera. Owing to the finite bandwidth of the filtered light and the slit width, the spectral line will take up several pixels on the chromatic axis. The centroid pixel position of the spectral line is taken to be the pixel corresponding to the wavenumber. Furthermore, by knowing the wavenumber and its assigned pixel for each filtered spectral line, the calibration formula can be obtained using quadratic polynomial fitting, whereupon the relationship between light intensity and wavenumber is obtained.

Figure 9 shows a spectral interferogram with eight spectral lines obtained by blocking the measurement arm of the interferometer. The numbers in the image are the corresponding illumination wavelengths, and the wavelength decreases with pixel position owing to the grating direction in the system set-up. The centroid line of the 528.28 nm spectral line is also plotted in figure 9. As can be seen, the centroid line is not straight, which indicates the existence of smile distortion.

To calculate the degree of smile distortion at different pixel positions, 31 spectral lines from the wavelength range 527–589 nm were chosen, and the results are shown in figure 10. The degree of distortion of different wavelengths ranges from 0.72% to 1.56%. This result shows that the degree of distortion varies with wavelength, which is a consequence of the aberration of the optical system.

In sections 4.2 and 4.3, the results of measurements obtained using line-by-line calibration are compared with those obtained using single-point calibration, which shows that line-by-line calibration can reduce the effect of distortion and improve measurement accuracy.

4.2. Experiments with a silicon wafer profile

From section 3.2, we know that smile distortion is inevitable in any dispersive imaging system. We tested a silicon wafer, and a spectral interferogram at an OPD of 30 \( \mu \)m is shown in figure 11. In the vertical direction, the interference fringes are bent. The light intensity curve of the 500th column is plotted and can be seen to be curved, which indicates the presence of smile distortion.

For the spectral interferogram at an OPD of 30 \( \mu \)m, single-point calibration and line-by-line calibration were used separately. The obtained profiles of the silicon wafer are shown in figure 12. The result with line-by-line calibration has a much better linear relationship with the pixel position along the spatial direction than the result with single-point calibration. In the experiment, the tilt angle of the sample stage causes the obtained profile to be inclined, so it is necessary to perform a leveling operation. From the discussion...
Figure 9. Spectral lines (the numerical value is the corresponding wavelength).

Figure 10. Degree of smile distortion for different wavelengths.

Figure 11. Distorted spectral interferogram of a silicon wafer.
in section 3.2.2, it is known that smile distortion will introduce an error in the calculation of the absolute distance and thus make the profile partly nonlinear. This explains why the profile obtained with single-point calibration is curved. Furthermore, the nonlinearity acts in opposition to the leveling operation and lowers the measurement accuracy. However, the line-by-line calibration reduces the effect of smile distortion and thereby weakens the nonlinearity of the profile. This means that it has great significance for achieving high accuracy in measurements of surface topography.

4.3. Experiments with a standard step height

A standard step of $1.806 \pm 0.011 \, \mu m$ was measured, and the spectral interferogram is shown in figure 13 with the light intensity of the 400th column. Theoretically, the two lower surfaces of the step are at the same level, which means that their light intensities should be the same. However, the extracted light intensities of the lower surfaces are not in a straight line. The overall light-intensity curve is shaped like a smile.

Owing to the nonuniformity of the step heights across the sample, we scanned the step using a one-dimensional automatic scanning platform and then acquired its surface topography. We chose 12 sampling lines to calculate the step height. Single-point and line-by-line calibration were used separately to obtain the relationship between pixel position and wavenumber. The spectral interferograms were processed by the five-step phase-shifting method, and the height results from the two calibration methods are given in table 1. The results from single-point calibration are all beyond the tolerance range provided by the manufacturer, with an average height of 1.821 $\mu m$. For the same spectral interferograms, the results of line-by-line calibration
are closely aligned with the theoretical values, with an average of 1.807 $\mu$m. The experimental results for the step height measurement show that line-by-line calibration can reduce the effect of smile distortion and improve measurement accuracy.

5. Conclusions

This paper has proposed a line-by-line spectral calibration method for a home-built Michelson-type white-light spectral interferometer. The sensitivity of the calibration coefficients for surface topography measurement has been analyzed using simulation data. The simulation results show that the coefficients have a great influence on the retrieval of absolute distance, which indicates that the calibration procedure needs to be done repeatedly (if possible) to ensure the accuracy of the obtained coefficients, especially those for high-order terms.

According to the analysis, the degree of smile distortion grows with increasing OPD. In practical measurements, smile distortion bends the fringes and thereby affects phase extraction, which lowers the accuracy of calculations of absolute distance. The simulation results for a plane and for step heights show that the measurement error increases with increasing OPD owing to the effect of smile distortion. In a spectral calibration experiment based on an AOTF, the spectral lines at different pixel positions had various degrees of bending, which demonstrated the presence of smile distortion. Finally, single-point calibration was compared with line-by-line calibration in the measurement of a silicon wafer surface profile and a standard step height. It was demonstrated that smile distortion can be effectively corrected and measurement accuracy thereby improved by using line-by-line spectral calibration in a white-light spectral interferometer.

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ORCID iDs

Tong Guo https://orcid.org/0000-0001-9517-6006
Dawei Tang https://orcid.org/0000-0002-8914-7038

References

[1] Vo Q, Fang F, Zhang X and Gao H 2017 Surface recovery algorithm in white light interferometry based on combined white light phase shifting and fast Fourier transform algorithms Appl. Opt. 56 8174–85
[2] Debnath S K, Kothiyal M P and Kim S W 2009 Evaluation of spectral phase in spectrally resolved white-light interferometry: comparative study of single-frame techniques Opt. Lasers Eng. 47 1125–30
[3] Tang D, Gao F and Jiang X 2014 On-line surface inspection using cylindrical lens-based spectral domain low-coherence interferometry Appl. Opt. 53 5510–6
[4] Debnath S K, Kothiyal M P, Schmit J and Hariharan P 2006 Spectrally resolved white-light phase-shifting interference microscopy for thickness-profile measurements of transparent thin film layers on patterned substrates Opt. Express 14 4662–7
[5] Martínez-Matos O, Rickenstorff C, Zamora S, Izquierdo J G and Vaveliuk P 2017 Characterization of digital dispersive spectrometers by low coherence interferometry Opt. Express 25 3222–33
[6] Tong J, Zhong S, Zhang Q, Lin J and Fu X 2017 Spectral calibration of spectrometer based on interference fringes J. Mech. Elec. Eng. 34 856–9
[7] Zhen J, López-Lago E, Varela L M and Fuente R 2016 Spectrally resolved white light interferometer to measure material dispersion over a wide spectral band in a single acquisition Opt. Express 24 17303–12
[8] Arosa Y, López-Lago E and Fuente R 2018 Spectrally resolved white light interferometer for measuring dispersion in the visible and near infrared range Measurement 122 6–13
[9] Zhou J, Chen X, Ji Y, Chen Y and Shen W 2013 Spectral calibration for convex grating imaging spectrometer Proc. SPIE 9045 90451U
[10] Kim JK, Han JH and Jeong J 2015 Accurate wavelength calibration method for spectrometer using low coherence interferometry J. Lightwave Technol. 33 3413–8
[11] Li L and Mou Y 2008 Wavelength correction for fiber spectrometer Opt. Instrum. 30 51–4
[12] Jiang X, Wang K and Gao F 2010 Accelerated surface measurement using wavelength scanning interferometer with compensation of environmental noise Appl. Opt. 49 2903–9
[13] Wang Y and Chen Y 2018 Acousto-optic tunable filter chromatic aberration analysis and reduction with auto-focus system J. Mod. Opt. 65 1450–8
[14] Zhang X, Yu K and Zhang J 2017 Study on imaging spectrometer with smile and keystone eliminated Opt. Commun. 387 243–51
[15] Zheng Y 2005 Design of compact Offner spectral imaging system Opt. Precis. Eng. 13 650–7
[16] Ghamisi P, Yokoya N, Li J and Liao W 2017 Advances in hyperspectral image and signal processing: a comprehensive
overview of the state of the art IEEE Geosci. Remote Sens. Mag. 5 37–78

[17] Zhao M, Li W, Shi B and Lv Q 2017 Aberration correction technique of Offner imaging spectrometer Opt. Precis. Eng. 25 3001–11

[18] Zheng Q, Chen L, Han Z, Ma Y and Yu D 2018 A non-contact distance sensor with spectrally–spatially resolved white light interferometry Opt. Commun. 424 145–53

[19] Gao H, Jiang Y and Zhang L 2018 Five-step phase-shifting white-light interferometry for the measurement of fiber optic extrinsic Fabry–Perot interferometers Appl. Opt. 57 1168–73

[20] Bai C, Li J, Xu Y and Liu J 2018 Compact birefringent interferometer for Fourier transform hyperspectral imaging Opt. Express 26 1703–25

[21] Ocean Optics Inc. Calibrating the wavelength of the spectrometer (www.oceanoptics.cn/system/files/documents/calibrating_wavelength_of_spectrometer.pdf)

[22] Kita T and Harada T 1983 Use of aberration-corrected concave gratings in optical demultiplexers Appl. Opt. 22 819

[23] Zhao H, Shi S, Jiang H, Zhang Y and Xu Z 2017 Calibration of AOTF-based 3D measurement system using multiplane model based on phase fringe and BP neural network Opt. Express 25 10413–33