Surface Topography: Metrology and Properties

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To cite this article before publication: Tong Guo *et al* 2019 *Surf. Topogr.: Metrol. Prop.* in press https://doi.org/10.1088/2051-672X/ab2b20

IOP Publishing Journal Title
Journal **XX** (XXXX) XXXXXX https://doi.org/XXXX/XXXX

Rapid measurement of large step heights using a microscopic white-light spectral interferometer

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Received xxxxxx
Accepted for publication xxxxxx
Published xxxxxx

Abstract

A method for rapid measurement of large step heights is proposed. Owing to elimination of mechanical scanning processes, this method possesses a greatly reduced measurement time. The theory underlying the proposed method is described in detail. The single-shot spectral interferometric signal is recorded using a Linnik microscopic white-light spectral interferometer and phase information is retrieved using a windowed Fourier transform. The proposed method was used to measure a 10.083(±0.022) μm step height standard. The mean measured height and standard deviation obtained from ten measurements were 10.0827 μm and 2.1 nm, respectively, and the experimental results agreed well with the calibrated value.

Keywords: height measurements, spectroscopy, interferometry, Fourier transforms

1. Introduction

Many metrological methods and instruments have been applied to measure step heights. Heterodyne interferometry[1] and monochromatic optical interferometry[2] are well suited for the precise measurement of step heights owing to their high resolution and accuracy, but these techniques suffer from the problem of phase-ambiguity, which limits the maximum measurable range to half of the wavelength. Although white-light interferometry (WLI)[3,4] solves the phase-ambiguity problem and extends the measurement range, this method requires time-consuming mechanical scanning processes that make the measurements more sensitive to environmental disturbances. In our previous work, white-light spectral interferometry (WLSI)[5] both solves the problem of phase-ambiguity and permits the removal of mechanical scanning in vertical direction owing to the spectral characteristics, ultimately resulting in improved measurement efficiency. However, this technique is a point-by-point measurement method and therefore still requires one-dimensional (1D) scanning along the cross section of the step.

With respect to the measurement of large step heights, a variety of techniques have been developed over the last two decades to extend the measurement range and reduce the measurement time[6-8]. However, the systems used in these technologies typically require very expensive components, are complicated and bulky, or involve the use of mechanical scanning.

We report on the construction of a Linnik microscopic white-light spectral interferometer. Based on this system, we propose a method for the rapid measurement of large step heights. The single-shot spectral interferometric signal of the step height was recorded. To obtain the step height, a windowed Fourier transform (WFT) method[9] was used to quickly and accurately retrieve the phase information from the spectral interferometric signal. This technique allowed the step-height measurements to be performed within one second without any time-consuming mechanical scanning processes, thereby reducing the measurement time compared with other methods for the measurement of large step heights. The accuracy of the obtained results was demonstrated to be nanometer or even sub-nanometer.

2. System configuration and measurement principle

2.1 System Configuration

Figure 1 shows a schematic diagram of the Linnik microscopic white-light spectral interferometer used in this work[10]. The light source is a halogen lamp that illuminates the system after collimation. The beam splitter prism divides the incident light into two beams, which then enter the reference and measurement optical paths through two objective lenses. The measuring beam is reflected by the step sample surface and subsequently interferes with the reference beam at the beam splitter prism. A portion of the interference signal is collected by an optical fiber spectrometer via the optical fiber and then the signal is transmitted to a computer after analog-to-digital conversion; the other portion is imaged using a charge-coupled device (CCD) camera.

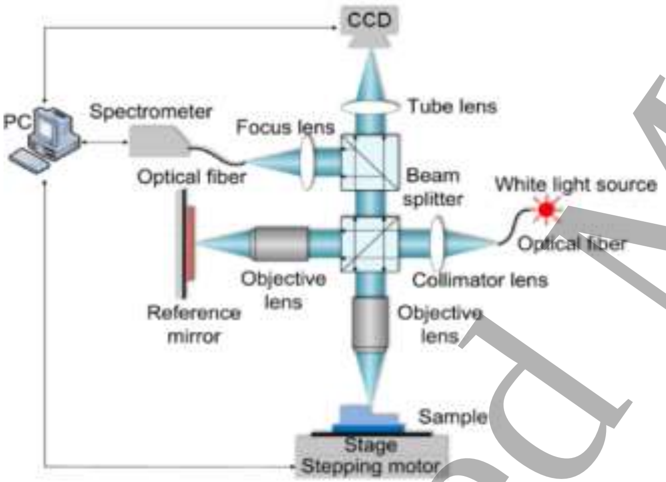


Figure 1. Schematic diagram of the Linnik microscopic white-light spectral interferometer.

2.2 Measurement Principle

2.2.1 Phase extraction

The white-light spectral interferometric signal can be expressed as:

$$f(x) = a(x) + b(x)\cos[\varphi(x)] \quad (1)$$

where $f(x)$, $a(x)$ and $b(x)$ are the recorded intensity, background intensity, and fringe amplitude, respectively, and $\varphi(x)$ is the wrapped phase.

The phase φ can then be unwrapped using phase unwrapping algorithms:

$$\varphi = 4\pi dk = \phi + 2m\pi \quad (2)$$

where d is the optical path difference (OPD) between the reference beam and the measuring beam, $k = 1/\lambda$ is the wavenumber, ϕ is the unwrapped phase, and m is the interference order.

According to Eq. (2), d can be solved as:

$$d = \frac{1}{4\pi}\frac{\Delta\varphi}{\Delta k} = \frac{1}{4\pi}\frac{\Delta(\phi+2m\pi)}{\Delta k} = \frac{1}{4\pi}\frac{\Delta\phi}{\Delta k} \quad (3)$$

The unwrapped phase ϕ and the wavenumber k are fitted to a linear function by using the least squares method. Then the parameter d can be obtained by the slope of the linear function. Therefore, it is not sensitive to random noise and has high accuracy[5,11].

2.2.2 Step height measurement

For the step height measurement shown in figure 2, the measurement beam illuminates a region on the step. The OPDs of the upper and lower surfaces of the step, d_1 and d_2, are different, thus, two different spectral interferometric signals form a superimposed signal that is collected by the spectrometer.

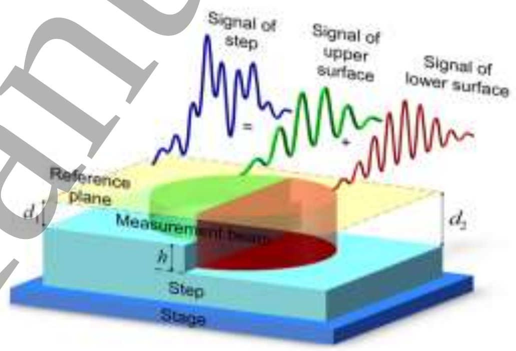


Figure 2. Structure of a step sample. The reference plane is drawn with a dotted line to highlight the difference in the OPD.

The simulated spectral interferometric signals of the steps with different heights are shown in figure 3. And larger step heights will lead to a faster beat frequency of the signal.

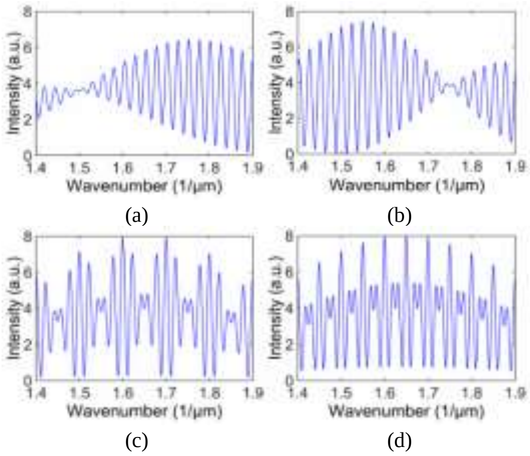


Figure 3. Simulated spectral interferometric signals of steps with (a) h = 0.5 μm, (b) h = 1 μm, (c) h = 4 μm, and (d) h = 10 μm.

To retrieve the phase information from the spectral interferometric signal, a WFT is used. The WFT can be written as

$$F(\mu,\xi)=\int_{-\infty}^{+\infty} f(x)h(x-\mu)\,exp(-j\xi x)\,dx \qquad (4)$$

where $h(x-\mu)$ is the window function. There are two Fourier peaks in the frequency domain of the superimposed signal, which come from the upper and lower surfaces of the step respectively, as shown in figure 4. After extracting the Fourier peaks separately, an inverse fast Fourier transform (IFFT) is performed to obtain the wrapped phase. Then, the OPDs can be obtained after the phase unwrapping according to Eq. (2) and (3). The step height can be calculated using the following equation:

$$h=|d_1-d_2| \qquad (5)$$

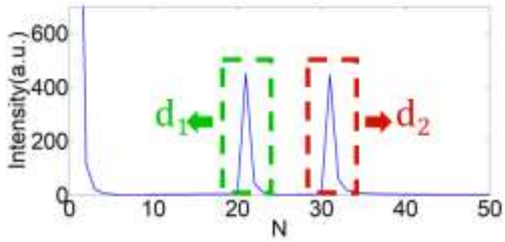


Figure 4. Two Fourier peaks in the frequency domain.

3. Simulation and analysis

3.1 Maximum measurable step height

The measurement range of the absolute distance, that is, the OPD, by the WLSI can be described by the following equation [12-14]:

$$\begin{cases} z_{min}=\dfrac{{\lambda_0}^2}{\Delta\lambda} \\ z_{max}=\dfrac{{\lambda_0}^2}{2\delta\lambda} \end{cases} \qquad (6)$$

where λ_0 is the center wavelength, $\Delta\lambda$ is the bandwidth of light source, and $\delta\lambda$ is the full width at half-maximum of the spectrometer. In this study, we used a white-light source with $\lambda_0 = 608$ nm and $\Delta\lambda = 300$ nm, and $\delta\lambda$ was 1.5 nm. Therefore, for our WLSI system, the theoretical minimum measurable distance z_{min} was 1.2 μm, and the theoretical maximum measurable distance z_{max} was 123.2 μm. Thus, the maximum step height that can be measured by the proposed method was obtained, that is, $z_{max}-z_{min}$ =122.0 μm.

It should be noted that because the OPD retrieved by WFT cannot determine the distance sign (positive or negative), it is necessary to ensure that the upper and lower surface of the step are on the same side of the plane of the zero OPD. Because if not, the measured step height is erroneous. As shown in figure 5, assuming that the two Fourier peaks can be separated, the correct step height should be $|d_1|+|d_2|$, but the measured step height is $|d_1|-|d_2|$.

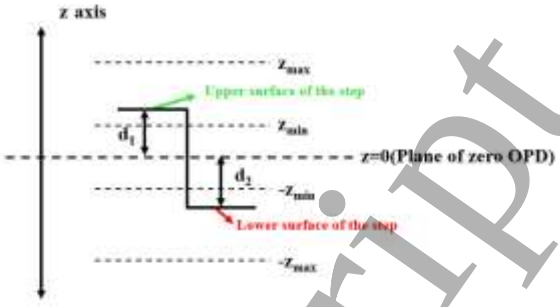
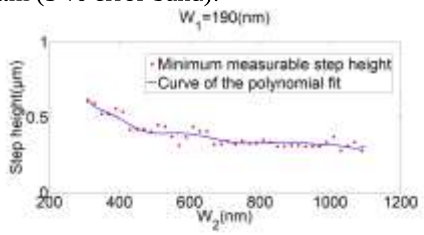


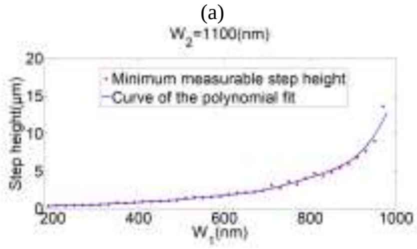
Figure 5. Schematic diagram of the position of the step.

3.2 Minimum measurable step height

The minimum measurable step height of our proposed method is related to the used wavelength bandwidth: w_1-w_2, and we simulated two cases to illustrate their influences. In the first case, we fixed w_1=190 nm, gradually increased w_2 from 310 nm to 1100 nm, In other words, we got a series of different bandwidths with the same w_1 . Then we calculated the minimum measurable step height in each bandwidth, and the result is shown in figure 6(a). In the second case, we fixed w_2=1100 nm, gradually increased w_1 from 190 nm to 980 nm. Similarly, we got a series of different bandwidths with the same w_2 and calculated the minimum measurable step height. The result is shown in figure 6(b). So it can be seen that the short-wavelength has a greater impact on the minimum measurable step height of our proposed method. Increasing the spectral interferometric signals of short-wavelength allows the measurement of smaller step heights, such as the step height of hundreds of nanometers. The opposite is that the influence of the long-wavelength on the measurement range and accuracy of the proposed method is not significant. The applied bandwidth of our measuring system was 526 nm-714 nm, and the theoretical minimum measurable step height was around 1.8 μm (5 % error band).



(a)



(b)

Figure 6. Influence of wavelength bandwidth on the minimum measurable step height (a) long -wavelength, and (b) short -wavelength.

3.3 Appropriate window function

Our proposed method for the step-height measurement need to minimize the overlap of the two Fourier peaks in the frequency domain, so the appropriate window function should be chosen when using WFT. We simulated the spectral interferometric signals of the steps with different heights using the wavelength bandwidth of 526 nm-714 nm, then used the rectangular window and the Hamming window to perform the WFT respectively. The frequency domain analysis for representative step heights, 2 µm and 5 µm, were presented in this paper. Figure 7 shows that when the step height is 2 µm, the overlap of the two Fourier peaks of the rectangular window is smaller than that of the Hamming window because the width of the main lobe of the rectangular window is narrower. Therefore, the calculated step height of rectangular window is more accurate, respectively 1.9970 µm and 2.3980 µm. But when the step height is 5 µm as shown in figure 8, the two Fourier peaks using the Hamming window have been almost completely separated, but the two Fourier peaks using the rectangular window have partial overlap due to the side lobes. So, the calculated step height of the Hamming window is slightly more accurate, respectively 5.0009µm and 5.0020 µm.

Therefore, it can be seen that there is a theoretical height threshold. When the step height is smaller than the threshold, the window function with narrower main lobe width should be chosen. When the step height is larger than the threshold, it is more inclined to choose the window function with wider main lobe width to reduce side lobes. The theoretical height threshold for the wavelength bandwidth of 526 nm-714 nm was approximately 4.0 µm.

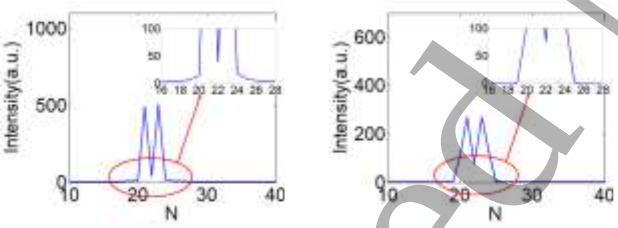


Figure 7. Frequency domain analysis for 2 µm step height of (a) rectangular window, and (b) Hamming window.

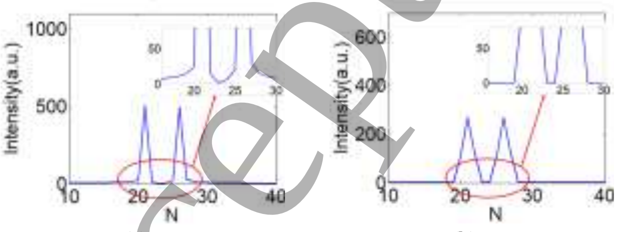


Figure 8. Frequency domain analysis for 5 µm step height of (a) rectangular window, and (b) Hamming window.

3.4 Simulation of various step heights

We simulated the spectral interferometric signals for the steps with different heights with the wavelength bandwidth of 526 nm-714 nm and chose the appropriate window function for the calculation as described in section 3.3. The results are shown in table 1. For simulated step heights greater than 2 µm, the deviation was found to be very small and the calculated step heights demonstrated nanometer or even sub-nanometer level accuracy. For simulated step heights under 2 µm, the deviation increased as the accuracy gradually decreased. These observations can be attributed to the fact that the two Fourier peaks began to partially overlap and became indistinguishable at the step height of 1.5 µm, as shown in figure 9. This overlap interfered with extraction of the phase information.

Table 1. Simulation results for various step heights.

Simulated step height (µm)	Calculated step height (µm)	Deviation (µm)
1.5	1.1207	0.3793
1.8	1.7065	0.0935
2	1.9970	0.0030
4	4.0006	0.0006
5	5.0009	0.0009
10	10.0004	0.0004
25	25.0002	0.0002
50	50.0002	0.0002
100	100.0003	0.0003

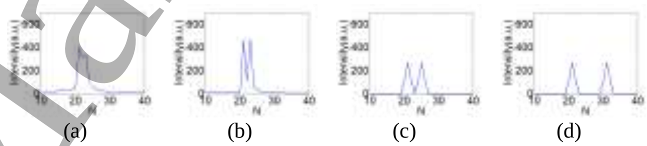


Figure 9. Plots showing the overlap of the two Fourier peaks for (a) h = 1.5 µm, (b) h = 1.8 µm, (c) h = 4.0 µm, and (d) h = 10.0 µm.

4. Experiments and analysis

4.1 Measurement of steps at different heights

To evaluate the use of the method described here for the rapid measurement of large step heights, we used a 10× double-objective lens with a numerical aperture (N.A.) of 0.28 to measure two standard steps, namely, a standard step calibrated by the National Institute of Standards and Technology (NIST) as 1.806(±0.011) µm and a standard step calibrated by the Physikalisch-Technische Bundesanstalt (PTB) as 10.083(±0.022) µm. The spectral interferometric signals for the two steps are shown in figure 10. To retrieve the phase information from the spectral interferometric signal, the WFT is used. Then we get two Fourier peaks in the frequency domain, which come from the upper and lower surfaces of the step respectively. And after extracting the Fourier peaks separately, the IFFT and phase unwrapping algorithms are used to obtain the unwrapped phase. The process of extracting the OPD is shown by the measurement data of 10.083(±0.022) µm step in figure 11. The unwrapped phase ϕ and the wavenumber k are fitted to a linear function by using the least squares method. The equations of the fittted linear functions are as follows:

$$\phi_1 = -272.9622 * k + 509.7221 \quad (7)$$

$$\phi_2 = -399.6517 * k + 742.5677 \quad (8)$$

Finally, according to Eq. (3), the OPDs can be obtained by the slope of the fitted linear function to calculate the step height, that is, h = 10.0816 μm in figure 11. The measurements were repeated ten times and the results are shown in table 2.

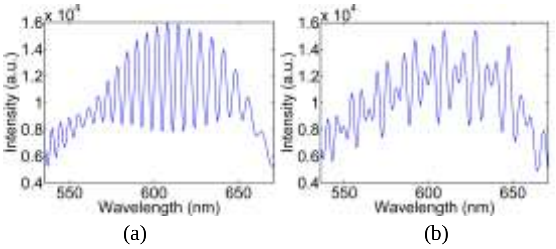


Figure 10. Spectral interferometric signals for two standard steps with heights of (a) 1.806(±0.011) μm, and (b) 10.083(±0.022) μm.

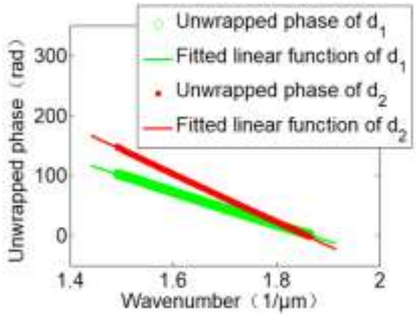


Figure 11. Unwrapped phase and fitted linear functions.
(d_1 represents the OPD of left Fourier peak, and d_2 represents the OPD of right Fourier peak as shown in figure 4)

Table 2. Summary of measured heights for two standard steps using a 10× double-objective lens.

Step (μm)	Mean height (μm)	Standard deviation (μm)	Mean time (s)
1.806(±0.011)	1.7150	0.0276	0.135
10.083(±0.022)	10.0827	0.0021	0.133

The mean measured height for the 1.806(±0.011) μm step was found to be relatively inaccurate and was not within the calibration range. This is consistent with the previous simulation results. When the step height is close to the minimum measurable step height, the phase information is incomplete owing to the overlap of the two Fourier peaks in the frequency domain, thus resulting in large errors in the measurement. In contrast, the mean measured height for the 10.083(±0.022) μm step was found to be very accurate and was within the calibration range, with a standard deviation of 2.1 nm, demonstrating that the proposed method and system exhibit good repeatability and stability.

4.2 The influence of the position of the step in the field of view

The position of the step in the field of view also affects the shape of the spectral interferometric signal. The 10.083(±0.022) μm standard step was driven horizontally to the left using the stepping motor. The spectral interferometric signals and the frequency domain analysis for several representative measurement positions are shown in figure 12. The upper area on the left side of the step in the field of view is defined as s_1, and the lower area on the right side of the step in the field of view is defined as s_2. The OPD and the positions of the two Fourier peaks corresponding to the left and right planes remained unchanged during the measurement. When s_1 decreased, the corresponding Fourier peak intensity decreased, whereas s_2 and the corresponding Fourier peak intensity increased. The Fourier peak intensity corresponds to the area of the step plane in the field of view. When $s_1 = s_2$, the step is in the center of the field of view, and the intensities of the two Fourier peaks were equal.

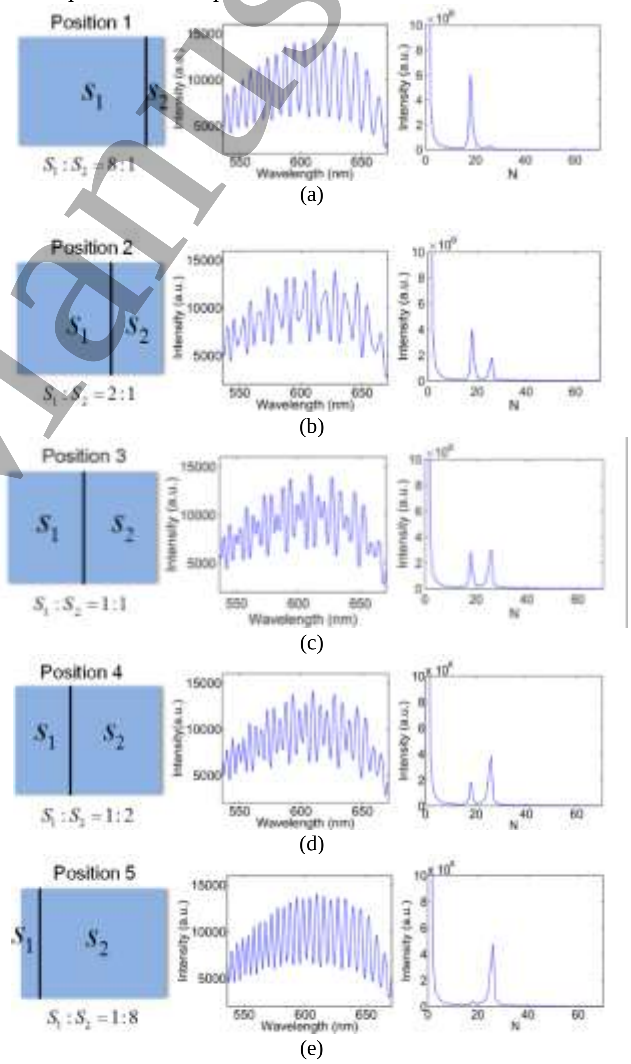


Figure 12. Spectral interferometric signals and frequency domain analysis for several representative measurement positions.

Although the calculated step heights were all within the calibration range, as shown in table 3, the intensities of Fourier peaks of the s_2 at position 1 and the s_1 at position 5 were very weak. Therefore, to obtain the highest accuracy, the step being measured should be placed as close as possible to the center of the field of view.

Table 3. Measured step heights for several representative measurement positions.

Position	$s_1 : s_2$	Calculated step height (μm)
1	8:1	10.0734
2	2:1	10.0808
3	1:1	10.0821
4	1:2	10.0852
5	1:8	10.0772

4.3 Comparison with other measurement methods

Owing to the absence of any mechanical scanning processes and the collection of a single-shot spectral interferometric signal in the proposed method, the small amount of obtained data significantly reduces the data acquisition time and calculation time. We compared the proposed method with white-light interferometry and 1D scanning white-light spectral interferometry, two commonly used methods for step-height measurement. Comparison of the calculation time for various methods is shown in table 4 (3.40 GHz CPU, 4.00 GB RAM, MATLAB R2014a). The data acquisition time is not recorded, because the hardware parameters and performance of each measurement system are different.

Table 4. Comparison of the calculation time for various methods.

Method	Proposed method	WLI	1D scanning WLSI
Calculation time	0.13 s	7 min 55 s	1 min 4 s

5. Conclusion

In this work, we have presented a method for the rapid measurement of large step heights using a Linnik microscopic white-light spectral interferometer. The spectral characteristics and the use of WFT allowed mechanical scanning processes to be eliminated and reduced the measurement time from tens of seconds to less than one second. The performance of the proposed method was successfully verified for a standard step with a step height of 10.083(± 0.022) μm using a 10× double-objective lens. The standard deviation was found to be 2.1 nm and the experimental results agreed well with the calibrated values. The influences of the measurement position were determined. The proposed method has the advantages of a short measurement time and high accuracy and compares favorably with typical methods.

Acknowledgements

The authors acknowledge the support of the National Key Research and Development Program of China (2017YFF0107001) and the 111 Project Fund (B07014).

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