Phase retrieval algorithm for line-scan dispersive interferometry

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ABSTRACT

The line-scan dispersive interferometry (LSDI) benefits from single-shot measurement in nature and has potential to perform in-line surface metrology. In this technique, the interference beam produced by the two arms of the interferometer is spatially dispersed by a diffraction grating along the rows (or columns) of the CCD pixels. In which case, a two-dimensional spectral interferogram is generated. In this paper, fringe order determination is carried out to retrieve the more accurate phase information along the chromaticity axis of the interferogram and then the height map of the tested profile can be calculated with high resolution. Two standard artefacts have been evaluated using the developed LSDI and the experimental results are compared with that of phase slope method as well as the commercial instrument (Talysurf CCI 3000), which shows that better performance in measurement noise is achieved. Additionally, the measurement repeatability is significantly improved and demonstrated within sub-nanometer range.

Keywords: Dispersive interferometry, surface metrology, spectral interferogram, phase retrieval.

1. INTRODUCTION

In recent times, significant development in electronics, software and high performance computer has made optical interferometry a popular technique for metrological applications. According to the light source used in the interferometer, interferometric techniques can be generally divided into two main categories, namely monochromatic interferometry (including single wavelength and multi-wavelength interferometry) and white light interferometry. Monochromatic interferometry can achieve surface measurement with low noise and a high resolution of the level of angstrom. Nevertheless, it is limited to the measurement of relatively smooth surfaces due to the well-known 2π phase ambiguity problem [1-2]. Line-scan dispersive interferometry (LSDI) [3-4] has been considerable interest due to an advantage of single-shot measurement without 2π phase ambiguity and could be potentially applied to in-line surface inspection. By spatially dispersing the interference beam produced by an interferometric objective, a spectral interferogram is obtained with the incoherent superposition of numerous monochromatic interferograms. The phase information is encoded as a function of wavenumber along the chromaticity axis of the camera [5]. Therefore, the depth information of the measured profile can be obtained by interpreting a single two-dimensional frame.

Several analysis techniques have been proposed to analyze the spectral inteferogram, including phase shifting (temporal and spatial) [5], Fourier transform [6], Hilbert transform [7], and convolution [8]. The temporal phase shifting technique is independent on the neighbor pixels and provides accurate results, however, several frames are required to calculate the phase. The spatial phase shifting method only needs single frame to obtain the phase-shifted intensity data. It was however demonstrated to be prone to errors because the intensity variation is not only following the interference equation but also affected by the spectral distribution of light source and spectral response of the camera. A comparison of several single frame methods for phase retrieval was made by Sanjit, et al [9]. In our previous work [10], we applied fast Fourier transform to interpret the fringe pattern in spectral domain, and calculated the phase slope to acquire the absolute height profile. In this paper, firstly, a bench-top LSDI using a 4X Michelson interferometric objective was built. For the fringe analysis, we discuss here the determination of fringe order from the interference signal to improve the measurement resolution, which gives repeatability comparable to phase shifting technique.

2. PHASE RETRIEVAL FOR LSDI

2.1 Interferometry principle

Interferometry makes use of the interference principle of two beams originating from the same source but travelling on different paths in the interferometric objective, and provides nanoscale vertical resolution for precise surface metrology by analyzing the captured interferogram. As for the LSDI, the spectral intensity recorded at the output of interferometer can be mathematically described as formula [11]

$$I(z,k) = S(k)[I_R + I_M + 2\sqrt{I_R I_M}\cos(\varphi(z,k) + \varphi_0)] \tag{1}$$

Where $S(k)$ is the power spectral density of the light source, and I_R, I_M represent the intensities of the reference arm and measurement arm, respectively. $\varphi(z,k)$ is the phase term related to the optical path difference (OPD) as well as the wavenumber k, and φ_0 is the initial phase due to reflection. More specifically, the round-trip OPD equals to $2z$ and the phase is determined by

$$\varphi(z,k) = 4\pi k z \tag{2}$$

2.2 Phase retrieval

Interpreting the fringe pattern generated by a white light source is performed to retrieve the phase information and subsequently calculate the height profile of the tested surface. The equation (1) can be written in another form as

$$I(z,k) = a(k) + b(k) + b^*(k) \tag{3}$$

With

$$b(k) = \exp[i\varphi(z,k)] \tag{4}$$

Where $a(k)$ is the background intensity and $b(k)$ is the fringe visibility, and $*$ denotes a complex conjugate. By applying a fast Fourier transform to equation (4), the original spatial signal is described in the frequency domain. Therefore, the unwanted background variation can be removed with a filtration window. Finally, the frequency peak with phase information is performed with inverse fast Fourier transform (IFFT). Taking the natural logarithm of the IFFT formula and then the phase information corresponding to each geometric surface point is obtained by the imaginary part of ***ln*** $exp[i\varphi(z,k)]$.

Because the extracted phase produces a phase modulo 2π as a function of wavenumber k, the phase unwrapping is required to obtain the continuous phase variation with respect to k, which is illustrated in detail by Takeda et. al. in 1982 [12]. According to equation (2), the absolute height value can be determined by the unwrapped phase slope $\mathcal{S}$, as shown in formula

$$z = \Delta\varphi(z,k)/4\pi\Delta k = \mathcal{S}/4\pi \tag{5}$$

2.3 Fringe order determination

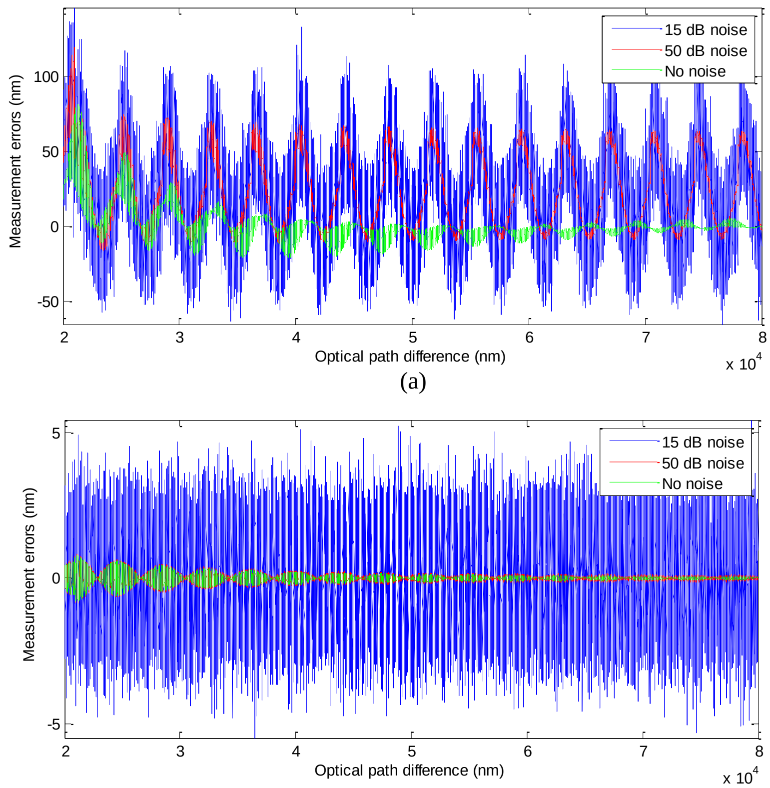
The height z obtained by phase slope method is close to the actual value and it can be further improved. This z value is used to estimate the fringe order $\mathcal{F}_N$ of the spectrally resolved interference signal, which is described by formula [13]

$$\mathcal{F}_N(i) = Round((\varphi_i - 4\pi k_i z)/2\pi) \tag{6}$$

The function Round ( ) generates the nearest integer value of $\mathcal{F}_N$. Therefore, the improved height value using fringe order method has a single wavelength resolution and is expressed as

$$z_f = (\varphi_i - 2\pi\mathcal{F}_N(i))/4\pi k_i \tag{7}$$

To demonstrate the enhancement, simulated interference patterns I_s with different absolute distances and linear wavenumber across the sampling axis were processed using both phase slope method and fringe order method to make a comparison. Different levels of white noises (none, 50dB and 15 dB) were added to I_s with consideration of the actual interference signals. The OPD in this simulation is given between 20 µm to 80 µm and Figure 1 shows the simulation results. It is found that fringe order technique greatly improves the measurement resolution to nanometer scale, comparing to that of tens of nanometers for phase slope method. It offers stable measurement accuracy even with 15dB noise.



(b)

Figure 1. Simulation results. (a) phase slope method; (b) fringe order method

3. EXPERIMENTS AND RESULTS

3.1 LSDI experimental setup

The basic configuration of the LSDI system is illustrated in Figure 2. A halogen bulb with broadband spectrum provides the white light illumination for the system. A 4X Michelson interferometric objective is employed to resolve the features on the tested surface. Interference occurs when the two light beams reflected from the reference arm and measurement arm are brought together. Then this interference beam is focused by a spherical tube lens and split into two parts by a beamsplitter. A CCD camera is set at the reflected optical branch to provide real-time images of the tested surface. The other optical branch is brought to a spectrometer to produce spectral interferogram for surface profile measurement. The slit is used to block the light redundant for measurement and is set to be parallel to the columns of camera pixels in the optical arrangement, therefore the dispersion axis is along the rows of the pixels.

System calibrations have been done in terms of wavelength registration and measurement ranges [10]. The result shows that the system covers a range of 1.50 μm^{-1} to 1.65 μm^{-1} for wavenumber k, corresponding to wavelength span of 605.07 nm to 657.21 nm. Lateral sampling resolution was calculated as 1.826 μm using a microscope slide (R1L3S1P, Thorlabs), and the measurable profile length is obtained as 876.712 μm.

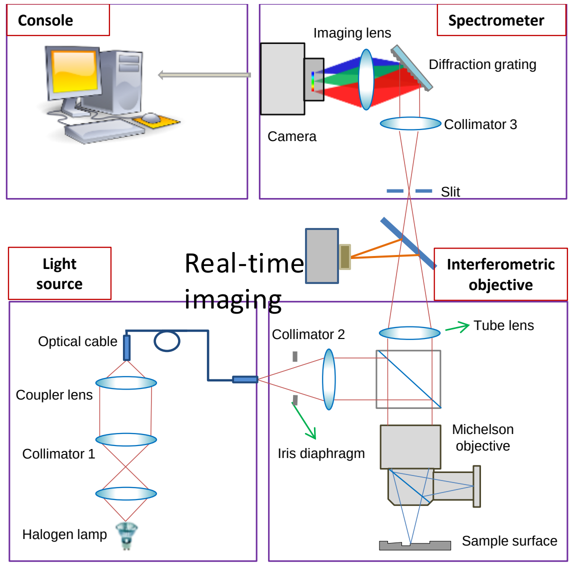


Figure 2. Schmatic diagram of LSDI system

3.2 Experimental results and discussion

An optical flat was measured 100 times at the same position and a subtraction technique is adopted for estimating the measurement noise [14]. It is found that the developed LSDI has an average measurement noise of 0.6 nm with an associated standard deviation (STD) of 0.02 nm using fringe order method. Whist the phase slope method is applied, the measurement noise is 9.7nm with a STD of 0.3nm. The results are shown in figure 3 as a function of the number of measurements recorded. To make a better visualisation, the mean values have been subtracted from the estimated noises. In conclusion, the performance has been achieved by a factor of fifteen.

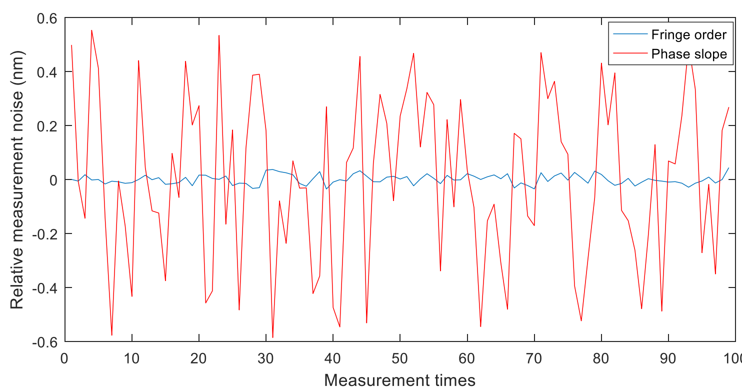


Figure 3. Evaluation of measurement noise (LSDI)

To verify the measurement accuracy and repeatability of LSDI, a standard step artefact (from VLSI, USA) was evaluated. It was calibrated with a nominal height of 178.5 $\pm$ 2.0 nm. Figure 4 are the measurement results using a commercial instrument (Talysurf CCI 3000), which gives a mean height value of 181.9 nm. In Figure 5 the measurement results by LSDI are depicted using two analysis methods for a comparison. The obtained mean height values are 192.7nm and 179.2nm corresponding to phase slope and fringe order method, respectively. It is apparent that the fringe order result is in good agreement with the nominal value provided the manufacturer. Furthermore, the improvement is clearly noticeable as well when comparing the profiles by two techniques (as well as Talysurf CCI results). The amplitude of the ripples on the measured profile is reduced from the order of tens of nanometers to nanometer scale when the fringe order technique is applied.

Likewise, by measuring the surface profile on the step artefact 100 times, the measurement repeatability can be assessed and shown in Table 1. The analysis result using fringe order method is depicted in Figure 6 as well with respect to the measurement times. It is found that the measurement repeatability is improved to sub-nanometer range.

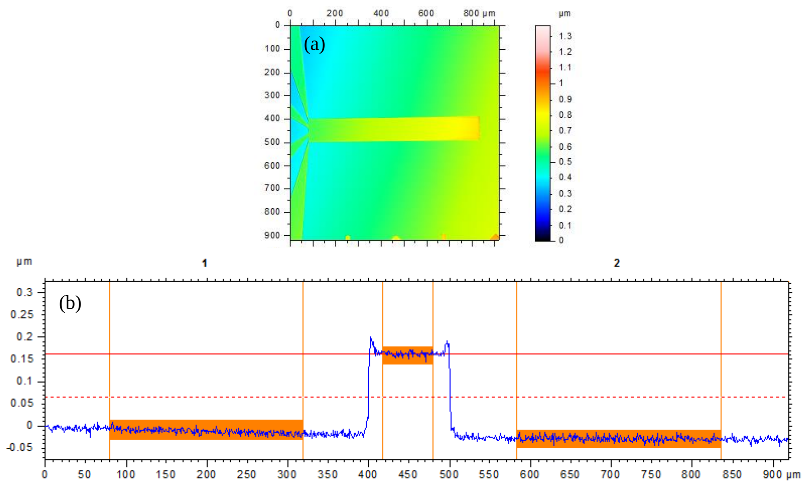


Figure 4. Measurement results using Talysurf CCI 3000. (a) 3D surface map; (b) 2D profile

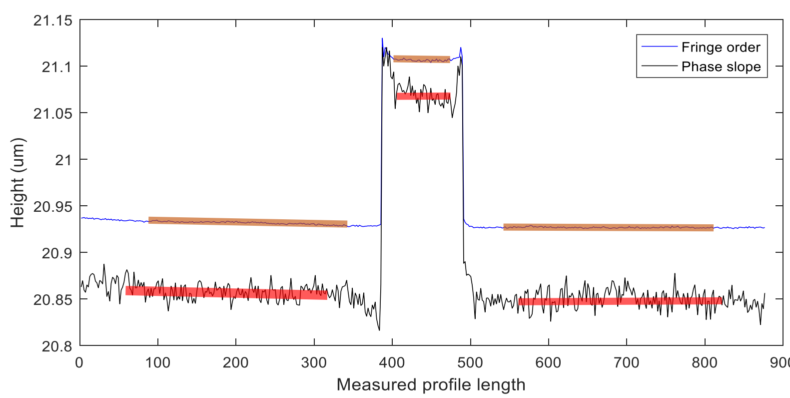


Figure 5. Measurement results of 178.5nm step artefact (LSDI)

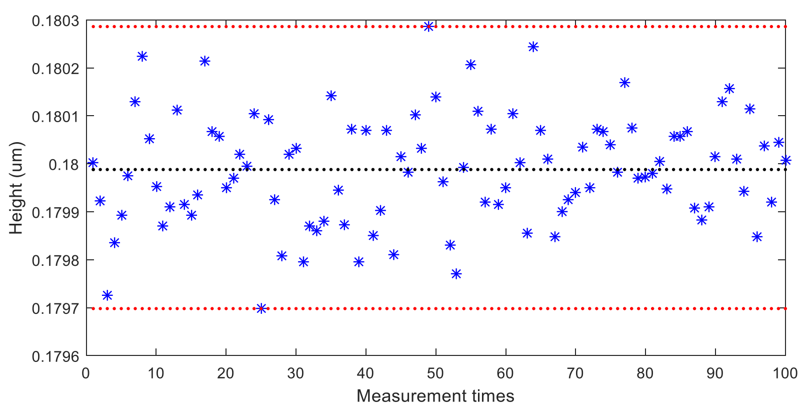


Figure 6. Evaluation of measurement repeatability using fringe order (LSDI). Black broken line is the mean value of the measurements; red broken lines represent one standard deviation from the Mean line.

Table 1. Comparison of the measurement repeatability

Methods	Mean height value (nm)	Standard deviation (nm)	Peak-to-valley (nm)
Phase slope	193.9	1.9	10.8
Fringe order	180.0	0.1	0.6

4. CONCLUSION

In this paper, implementing the fringe order determination in phase retrieval of the spectral interferogram is reported. Comparisons have been made with the phase slope method to demonstrate the improvement using both theoretical simulation and practical measurements. Two standard artefacts were evaluated by the developed LSDI system as well as a commercial optical instrument. The experiment results show that the algorithm effectively enhances the measurement resolution to a comparable level with phase shifting interferometry. The extended dynamic range also expands the scope of potential applications of the LSDI system in nanoscale surface metrology.

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