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Spectral Domain Low- Coherence Interferometry for On-line Surface Inspection

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ABSTRACT

We present an on-line surface measurement technique based on spectral domain low-coherence interferometry (SD-LCI), which can obtain a one dimensional surface profile with just one shot. This technique has an advantage over existing spectral interferometry in the large scale measurement up to 10 mm in length along the tested surface by using a cylindrical lenses based interferometic objective. In this SD-LCI system, the white light interferogram is spectrally decomposed by a spectrometer to determine the phase, which is encoded as a function of wavenumber along the chromaticity axis. After the phase of the channelled spectral signals is calculated at all wavelengths simultaneously, the optical path difference (OPD) is determined as the slope of the phase versus wavenumber. By adding a lateral scanning or rotating the cylindrical lenses, large-scale areal measurement is achieved as well. The experimental details of measurements on two surface samples are presented and discussed in this paper.

Keywords Spectral Domain Low- Coherence Interferometry, Channelled Spectral Signals, Cylindrical Lenses

1. INTRODUCTION

Optical interferometry provides a non-contact method for precise surface metrology in the rapidly developing fields of Micro-Electro Mechanical System (MEMS) and micro optics [1-3]. However, it is still limited in on-line surface metrology to some degree. Therefore, the ability to measure the products quickly and easily within the manufacturing environment provides many research opportunities.

White light interferometry, using broadband illumination like super-luminescent diode and halogen lamp, has been widely used for determining the absolute distance between the testing surface and the reference surface without 2pi phase ambiguity problem [4-6]. In general, it can be classified into three types, namely Vertical Scanning Interferometry (VSI), Wavelength Scanning Interferometry (WSI) and Spectral Domain Low- Coherence Interferometry (SD-LCI), also called Spectrally Resolved White Light Interferometry (SRWLI) in other literatures.

VSI has a disadvantage of utilizing mechanical scanning in the depth direction to localize the fringes in the vicinity of zero optical path difference, which is time consuming and permits measurement only for stationary object [7, 8]. As for the WLI and SD-LCI, they belong to spectral interferometry taking advantage of spectral interference fringes for a wide range of wavelength without any mechanical scanning. What is more, SD-LCI system has the potential to be used in performing on-line measurement with just one shot. There has been considerable interest in Spectral Domain Low-Coherence Interferometry since it was first proposed by Schwider and Zhou [9], for the purpose of retaining the unambiguous measurement advantage while eliminating the mechanical scanning. The development of computers and spectrometers has allowed for the SD-LCI for many applications like measuring the differential index of refraction, distance and displacement measurement, thickness of the thin-film and for profile measurement [10-13].

In this paper, a new Spectral Domain Low- coherence Interferometric technique for fast surface profile measurement is presented. Cylindrical lenses are introduced into the Michelson interferometic objective instead of microscopes used in currently spectral interferometers [4]. The measurement range can, therefore, be achieved up to 10mm, which actually is dependent on the NA of the system, diameter of the cylindrical lenses and the requirement of lateral resolution. The white-light interferogram of the tested surface is imaged on the entrance slit of a spectrometer and eventually recorded by the CCD camera with the phase information encoded as a function of wavenumber along the chromaticity axis [14]. For every given point from the object, the phase of the channelled spectral signals is determined at all wavelengths simultaneously and the OPD can be obtained as the slope of the phase versus wave number [15]. With a lateral scanning of the testing surface by using precision displacement stage, a surface map can be constructed by combining each of the measured profiles. Two surface samples have been measured with our setup and the results are discussed. These results show that cylindrical lenses based SD-LCI has the potential to be used for on-line surface measurement, like surface metrology for roll-to-roll film processing, Micro/Nano structured surfaces, Lithographic etching processing, doping, CVD/PVD coating, lapping, and CMP processing.

2. MEASUREMENT PRINCIPLE

A. Channelled spectral signals

The chromatic axis of SD-LCI is along one of the axes (supposing row direction) of CCD camera, which is perpendicular to the slit of spectrometer. The row of CCD pixels registers a channelled spectral signal representing the absolute distance of a single object's point from the corresponding reference point. This spectral intensity $I\ (\sigma, h)$ recorded at the output of the interferometer can be expressed as [7, 14]:

$$I\ (h,\sigma)\ = I_r + I_o + 2\sqrt{I_r I_o}\, cos(\varphi(h,\sigma)) \tag{1}$$

Where I_r, I_o are the intensities of the spectrums reflected by the reference and tested surface, respectively, and σ denotes the wavenumber $(1/\lambda)$. The phase $\varphi(h,\sigma)$ varies linearly with the wave number.

B. Spectrometer system

The spectrometer composed of slit, grating, optical bench and detector plays an important role in resolving the channelled spectral signal of SD-LCI. For a diffraction grating with spacing $d,$ if a plane wave is incident with an angle $\theta_i,$ the diffraction angle is θ_m at the order m , then with respect to a beam with wavelength λ, the following equation should be satisfied:

$$m\lambda = d(sin\,\theta_i + sin\,\theta_m) \tag{2}$$

From the equation above, by selecting a proper grating spacing, the distance and the angle between the grating and CCD camera, the CCD is able to capture a desired band of light in a linear way with respect to the CCD pixels and the spectral wavelength.

C. Signals processing

Fig. 1 shows the fringes pattern of the step object obtained by the spectrally resolved interferometry. The phase along the chromaticity axis with respect to the wavenumber σ needs to be extracted to determine the OPD of corresponding point. The height map of a one dimensional profile on the tested surface can be acquired after analysis of a series of row signals.

There are many algorithms to analyse the interferograms with white light illumination [16], such as Fourier transform [17, 18], convolution [18], temporal phase shifting [14, 19], Hilbert transform [20] and wavelet transform [21]. In this paper, we use fast Fourier transform (FFT) algorithm to extract the point elevation from the intensity distribution. Firstly, FFT is applied to each horizontal signal $I\ (h,\sigma)$ and the unwanted background variation can be filtered out in frequency domain. Then the inverse FFT of the remaining signal is computed to give a smooth signal $I_s(h,\sigma)$ without unwanted. At last after phase unwrapping process the phase variation $\Delta\varphi$ of each point is extracted as:

$$\Delta\varphi = Imag\ [\log(I_s(h,\sigma))] \tag{3}$$

Where Imag denotes the imaginary part of corresponding function. The point elevation finally can be expressed as:

$$h = \frac{\Delta\varphi}{4\pi(\frac{1}{\lambda_m} - \frac{1}{\lambda_n})} \tag{4}$$

Where λ_m, λ_n are the wavelengths corresponding to the phase difference $\Delta\varphi$.

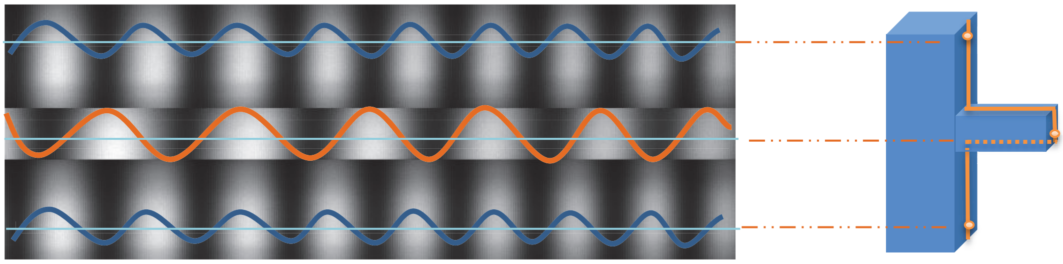


Fig. 1: Fringes pattern for the step object as obtained spectrally resolved interferometry

D. Wavelength calibration

To calibrate the wavelength with respect to the CCD pixels number, a light source with the acoustic-optical tunable filters (AOTF) and a commercial spectrometer with resolution of 0.5nm are used.

3. EXPERIMENTAL SETUP AND RESULTS

The basic experimental setup of cylindrical lenses based SD-LCI is shown in Figure 2. The whole system mainly comprises of four parts, namely a white light source, cylindrical lenses based interferometric objective, spectrometer and data processing unit. Two cylindrical lenses are used for the purpose of line sampling and reconstruction of beam shape, respectively. With an iris diaphragm before collimator 2, we can change the length of the tested profile. Additionally, if necessary, a compressor or expander can be used before the superposition beams come into the spectrometer, in which way we can adjust the system's spatial resolution along with the iris diaphragm. The spectral interferogram is selected by a slit and resolved by a diffraction grating, eventually received by an imaging lens and CCD camera (ICL-B0620). To achieve areal measurement, the tested object is fixed on a precision displacement stage offering the lateral scanning.

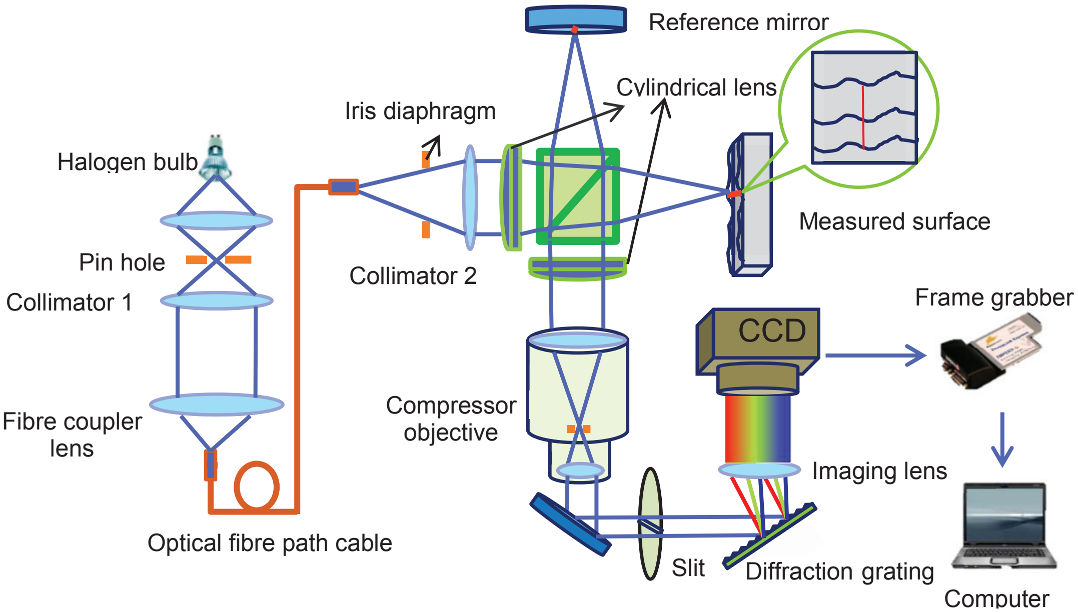


Fig. 2: Optical setup of the cylindrical lenses based spectral domain low-coherence

Two samples have been measured with this SD-LCI setup, including a mirror and a step samples. Our setup covers a range of 1.63 μm^{-1} 1.91 μm^{-1} for σ corresponding to the wavelength range of 612.336 nm to 524.082 nm. The mirror measured here is from Thorlabs with flatness of $\lambda/10$. One of the spectral interference signals along the chromaticity axis, captured by CCD and with background removed, is shown in Figure 3. Figure 4 (a) shows the wrapped phase extracted from series of channelled spectral signs through Fourier transform, and Figure 4 (b) shows the corresponding unwrapped phase. By giving a lateral scanning with a speed of 0.5 mm/s, the mirror sample is measured in motion. The measurement data of 600 sampled profiles were captured and then a 3D surface map was constructed by combining each of the measured profiles, as shown in Figure 5. We can see the PV value is within the range of flatness.

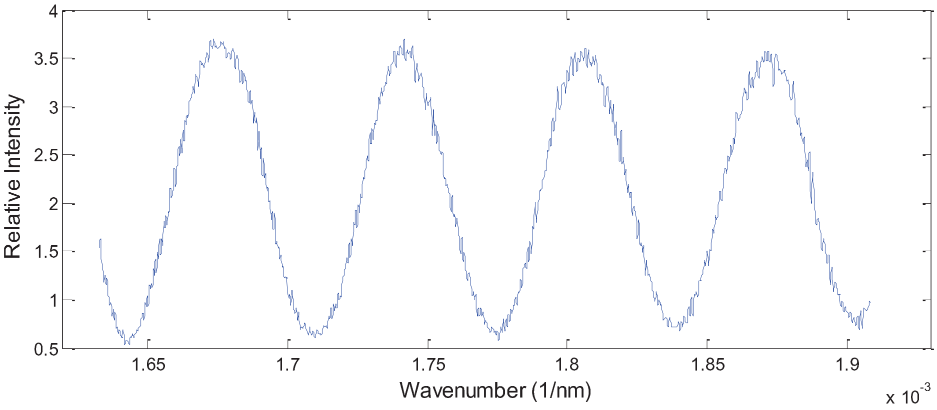


Fig. 3: the spectral interference signals along the chromaticity axis

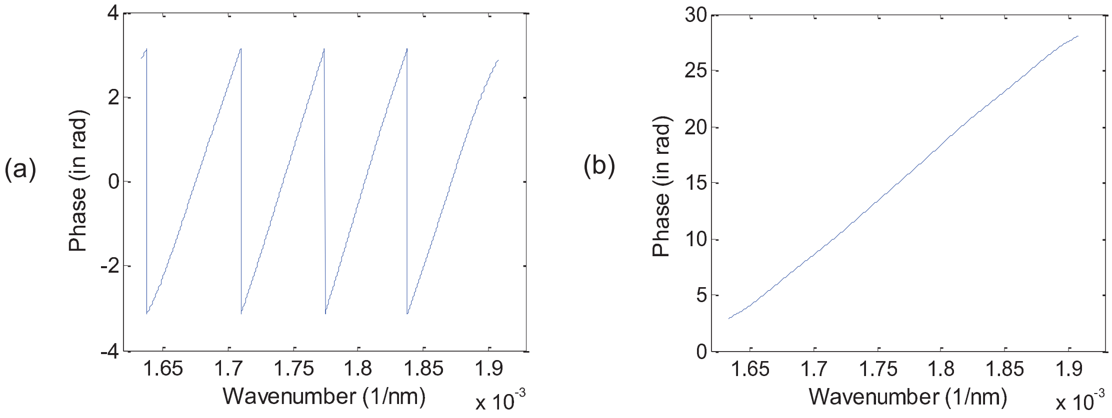
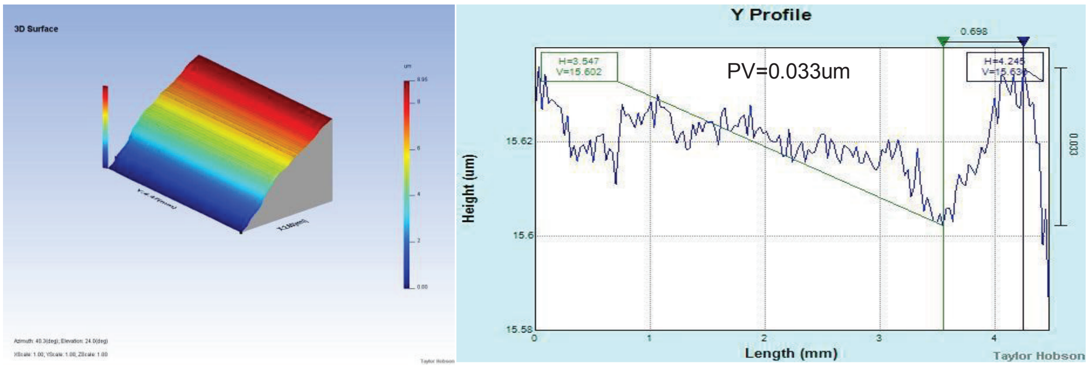


Fig. 4: Phase profile of the white light interferogram: (a) Wrapped phase. (b) Unwrapped phase

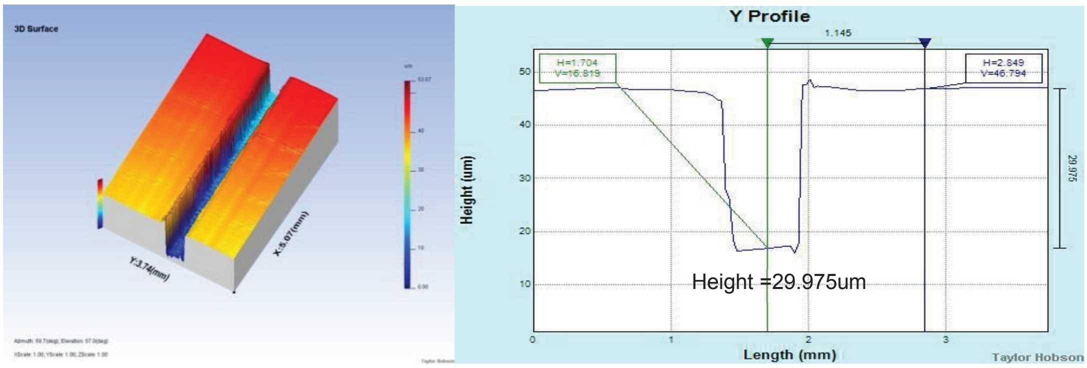
Figure 6 show the 3D surface map of a step height sample made by Rubert & Co. Ltd. with 30 µm depth and 0.5 mm. The profile measurement results are close to the measured result by a Taylor-Hobson CCI instrument.

As for the areal measurements, tilt surfaces are obtained with the measured profiles’ vertical position varying in several micrometre ranges along the lateral scanning direction. This is because the scanning direction cannot be aligned well perpendicular to the optical axis in experimental conditions. In addition, the measured tilt surface show unfairness or roughness as well, which we can tell from the non-uniform colour gradient representing the height variation. There are two error sources may be considered if we trace back to our experiment setup. The first error source comes from the linear stage due to the vibration itself and non-constant moving speed. Imperfection of algorithm can be the second error source. Other powerful algorithms with phase fitting process will be developed and then reconstruct the areal surface more truly. Even so, the tilt unfairness surfaces will not affect the every single profile at all. Therefore, the proposed SD-LCI has the potential to be used in the applications like the R2R surface inspection, where only defects on the film surface are concerned in terms of the quality control.



(a) (b)

Fig. 5: Measured results of the mirror sample: (a) 3D surface map. (b) Profile plot



(a) (b)

Fig. 5: Measured results of the step sample: (a) 3D surface map. (b) Profile plot

4. CONCLUSIONS

We have proposed a new Spectral Domain Low-Coherence Interferometric technique for fast surface profile measurement. Cylindrical lenses are introduced into the Michelson interferometic objective in place of microscopes used in currently spectral interferometers, which greatly enhances the measurement range due to the long focused line of the beam onto the sample surface. Additionally, large scale areal measurement has been achieved as well by adding a lateral scanning with a precision displacement stage. The advantage of obtaining a one dimensional surface profile with just one shot makes this setup minimise the effect of external perturbations and environmental noise and consequently have the great potential to be used for on-line surface inspection. The performance of the SD-LCI was evaluated by measuring the surfaces of a mirror and a step sample. Further Fast Fourier transform technique was implemented to analyse the interferograms recorded by the computer. The measurement results of the samples obtained experimentally show highly agreement with the manufacturer specifications.

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