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# A single-shot line-scanning spatially dispersed short coherence interferometer using Fourier transform profilometry

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## Abstract

Single-shot inspection at nanoscale resolution is a problematic challenge for providing on-line inspection of manufacturing techniques such as roll-to-roll processes where the measurand is constantly moving. An example of such a measurement challenge is defect detection on vapor barrier films formed by depositing an aluminum oxide layer several tens of nanometres thick on a flexible polymer substrate. Effective detection and characterisation of defects in this layer requires a single-shot approach with nanometre scale vertical resolution.

This paper describes a line-scanning interferometer where a short coherence light source having a 25 nm linewidth source is spatially dispersed across the measurand thus encoding spatial position along a profile by wavelength. Phase shift interferometry (PSI) can be used to decode phase and thus height information, but requires multiple image captures. In order to realise single-shot measurement which is more suitable for online applications, a Fourier transform profilometry (FTP) approach is necessary. This paper explores the implementation of the FTP approach and presents a comparison of the measurement capability of FTP with the previously reported PSI method.

## 1 Introduction

Improvement of online techniques for surface profile measurement will be beneficial in many high/ultra-precision manufacturing applications, enabling their manufacture and reducing costs.

Currently available optical metrology sensors are either bulky, slow in speed and expensive. For manufacturing, the inherent benefits of optical methods for implementing embedded surface topography measurement are the potential for sensors, fast measurement without surface contact. For single-shot interference based measurement, all the required data must be captured at one interferogram pattern recorded [1].

There are several key requirements any measurement method must satisfy to allow for the successful embedding on the manufacturing platform: non-contact, high speed, compact system/probes, insensitivity to environmental noise. In addition for precision applications, the embedded measurement sensor should maintain the same levels of precision as standalone instruments. In this paper, we introduce a system that goes some way to addressing those challenges while operating at a nanometre scale in terms of ability to measure surface height. We call this technique, spatially dispersed short coherence interferometry (SDSCI).

## 2 Principle of Operation

Figure 1 shows the schematic diagram of the SDSCI setup for PSI.

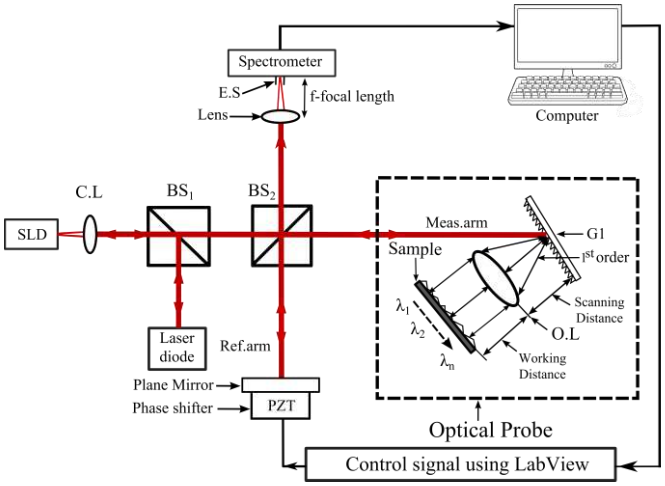


Figure 1: schematic diagram of the SDSCI system

SDSCI is sourced by a super luminescent diode (SLD) operating at a central wavelength of 820 nm and having a linewidth of 25 nm. This short coherence light is spatially dispersed across a surface using a reflective grating and a scan lens. In this way, the phase data pertaining to a surface height at a position along the dispersed line is spectrally encoded. The light reflected from the surface is interfered with a reference beam in a Michelson interferometer configuration after which the resulting spectral interferogram is interrogated by a spectrometer. The reference arm allows for phase shifting because it has a piezo-electric transducer (PZT) holding the mirror. The PZT is controlled using National Instruments Labview software and a data acquisition (DAQ) card with an analogue output (National Instruments USB-6211). The PZT position is incremented to increase the OPD by adjusting the applied voltage using the analogue output on the DAQ card. The measurement arm comprises a dispersive optical probe and the surface under test.

This apparatus allows the investigating of both PSI for phase interrogation using the adjustable reference arm as well as a Fourier transform profilometry (FTP). The latter method requires the recording of a single interferogram without the need for any mechanical movement using the PZT. Single-shot acquisition is one of the key requirements for embedded metrology in dynamic processes. One could benefit from using single-shot measurement to assess those systems based on, for instance, roll-to-roll (R2R) where the manufacturing process is continuous. This paper focuses on the comparison between PSI and FTP methods applied to acquiring surface profiles using SDSCI.

## 2.1 Phase Shift Interferometry

PSI is widely used for retrieving phase information encoded in interferograms across a number of applications. This technique has is commonly employed to extract the surface profile of a sample under test such as a highly polished sample where the surface profile varies in such a way that fringe order may be tracked continuously [2]. The first measurement method considered for SDSCI is a method of phase shift interferometry (PSI) based on the Carré algorithm. In all phase shift interferometry a phase shift is introduced but an advantage of the Carré algorithm is that the four phase shifts applied to the interferometer reference need not be of known phase so long as they are all equal [3]. This is useful for SCSDI because a physical length is changed using the PZT, and because we are using broadband light, each of the constituent wavelengths will experience a slightly different phase shift. The spectrometer output is recorded as the path length in the reference arm is changed incrementally. Each wavelength, $\lambda$ as analysed by the spectrometer is mapped to a single position, x along a line upon of the sample through the action of the dispersive optical probe. The phase of the interferogram pattern at any specific wavelength is a function of the optical path difference (OPD) and thus the surface height, h, at the respective surface position, x

$$I(x,\lambda) = I_r(\lambda) + I_m(x_\lambda) + 2\sqrt{I_r(\lambda) I_m(x_\lambda)}\cos\phi(x,\lambda) \qquad (1)$$

Where $I_r(\lambda)$ and $I_m(x_\lambda)$ are the intensities of the light returning from the reference mirror and the surface under test respectively. $\phi$ is the phase difference and is related directly to the surface height as follows,

$$\phi(x,\lambda) = \frac{4\pi}{\lambda} h_x \qquad (2)$$

## 2.2 Fourier Transform Profilometry FTP

FTP can be applied to extract phase from the SDSCI system and has the distinct benefit over PSI in that it can capture the required phase information in a single shot. The FTP technique initially requires a calibration routine in which background intensity is recorded by blocking the measurement arm. After this a single spectral interferogram is captured using the spectrometer interrogation. An FFT algorithm is employed to determine the phase as follows,

$$\mathrm{I}\left(x,\lambda\right)=\mathrm{I}_{r}\left(\lambda\right)+\frac{1}{2}\mathrm{I}_{m}\left(x_{\lambda}\right)\exp\left[i\phi(x_{\lambda})\right]+\frac{1}{2}\mathrm{I}_{m}\left(x_{\lambda}\right)\exp\left[-i\phi(x_{\lambda})\right] \qquad (3)$$

The middle term of equation (3) can be represented by:

$$c\left(x,\lambda\right)=\frac{1}{2}\mathrm{I}_{m}\left(x_{\lambda}\right)\exp\left[i\phi(x_{\lambda})\right] \qquad (4)$$

By applying a discrete Fourier transform (DFT) to equation (4), the new equation can be written as:

$$\mathrm{I}\left(x,\lambda\right)=\mathrm{A}\left(\lambda\right)+\mathrm{C}\left(x_{\lambda}\right)+\mathrm{C}^{*}\left(x_{\lambda}\right) \qquad (5)$$

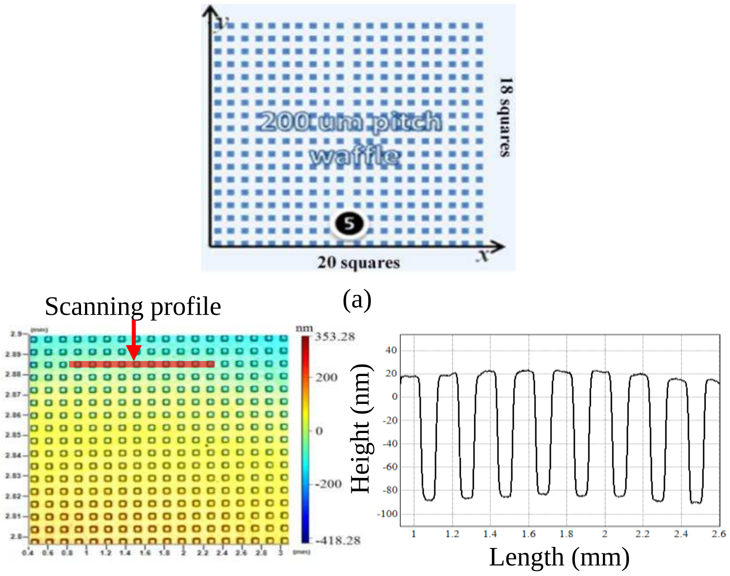
Where the term $\mathrm{C}^{*}\left(x_{\lambda}\right)$ represents the complex conjugate of $C$. After applying an inverse DFT to the conjugated term as in equation (5) it is possible to retrieve the phase by taking the complex logarithm.

$$\log\left\{\frac{1}{2}\mathrm{I}_{m}\left(x_{\lambda}\right)\exp\left[i\,\phi\left(x_{\lambda}\right)\right]\right\}=\log\left[\frac{1}{2}\mathrm{I}_{m}\left(x_{\lambda}\right)\right]+i\,\phi\left(x_{\lambda}\right) \qquad (6)$$

The phase is now isolated in the imaginary part which may be unwrapped if necessary using a suitable algorithm [4, 5].

## 3 Experimental Results

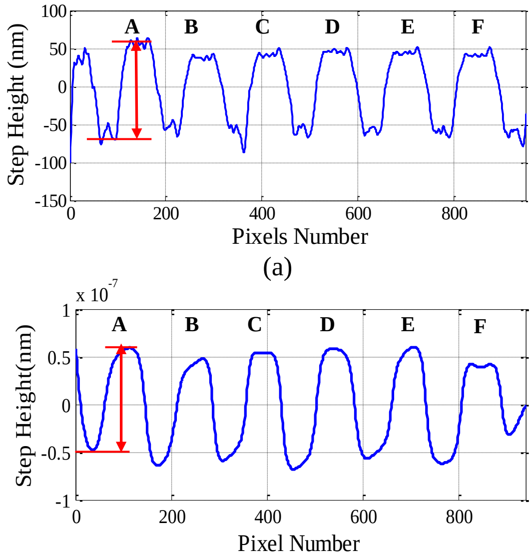
To compare the measurement capability of PSI and FTP a sample artefact having a grid pattern of raised square areas with a height of 100 nm and a 200 µm pitch. This type of structured surface is commonly known as a waffle plate [6]. **Error! Reference source not found.** (a) shows the ideal sample structure, while (b) and (c) show the measurement acquired from a Taylor Hobson CCI white light interferometer using a 5X objective lens. The SDSCI system successfully resolves sample profile using both PSI and FTP techniques. An important observation is that the sample profile can be extracted using both techniques as shown in figures 3 (a) and (b) were the height of the sample identified by the letters A to F by using PSI and FTP methods respectively.



(a)

(b) (c)

Figure 2 (a) Waffle plate sample; (b) areal measurement using the Taylor Hobson CCI; (c) an extracted profile from the CCI measurement result.



(a)

(b)

Figure 3 A measured surface profile on the waffle plate using SDSCI system using (a) PSI; (b) FTP.

## 4 Discussion and conclusions

This paper reports on a comparison study comparing PSI and FTP methods for extracting surface height information from an SDSCI apparatus. FTP is a potentially beneficial method due to the fact it requires only a single-shot acquisition. While PSI method is generally a more precise method to extract the surface profile information it requires the generation of several phase shifted interferograms. Where single-shot inspection is required in dynamic systems (such as roll-to-roll manufacture) FTP analysis can provide an answer. In addition such a system is cheaper and as there is no need for the PZT and associated electronics. There are however several caveats to the successful application of FTP. Generally speaking the results will be less precise than an equivalent measurement using PSI. Furthermore the method is more limited in the ability to resolve surface profiles having high frequency content in the lateral dimension because this leads to an inability to separate the imposed carrier fringes required for FTP analysis. None the less FTP a potentially useful tool for allowing single-shot measurement using SDSCI thus allowing applications where there are dynamic processes or problematic levels of environmental noise.

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