White Light Spectral Interferometry for Real-time Surface Profile Measurement

Feng Gao[1,a], Dawei Tang[1,b], and Xiangqian Jiang[1,d]

[1]Centre for Precision Technologies, University of Huddersfield, Huddersfield, UK, HD1 3DH

[a]f.gao@hud.ac.uk, [b]U1179033@hud.ac.uk, [d]x.jiang@hud.ac.uk

Keywords: White Light Spectral Interferometry, Online Inspection, Surface Measurement

Abstract. This paper presents a high speed surface profile optical measurement technique based on white light spectral interferometry and parallel signal processing using a general purpose graphic processing unit (GPGPU). A white light source is used to acquire the surface profile of the sample instantly in real time through a cylindrical Michelson interferometer. The interference signals are resolved by a diffraction grating and recorded by a high speed CCD camera. The spectrum of the interference signal contains the phase information in just one shot of the CCD camera frame image. By analysing the spectrum of the interference signal, the system can measure a surface profile as the measured surface in a moving state. As the measured surface laterally passes through the measurement arm of the interferometer, a surface map can be constructed by combining each of the measured profiles. Structured surface samples were measured and the results are discussed. This measurement system can be applied for roll-to-roll processed film surface inspection.

Introduction

The rapidly increasing use of nano scale and ultra-precision structured surfaces is widely spread in many application ranges and covers photovoltaic thin film, optics, Si wafers, hard disks, MEMS/NEMS, micro fluidics and micro moulding. These industries all critically rely on ultra precision surfaces. There is however a fundamental limiting factor to the manufacture of such surfaces, namely the ability to measure the product rapidly in the manufacturing environment. It has been reported that currently the quality of fabrication depends largely on the experience of process engineers backed up by an expensive trial-and-error approach [1].

In those industries making high volume large area foil products such as paper and packaging products, and in emerging market sectors such as flexible electronics, the manufacturing processes often involve the deposition and patterning of multi-layer thin films on large area substrates and foils. For these types of product, increased product performance and functionality can come from an increase in the number of layers, or a decrease from micro- to nano-scale in the thickness of individual layers or size of pattern features. To achieve a high yield in the coating and patterning processes, the films must be uniform and largely perfect over most of the area of the foil. However there is an increased risk of defects forming as the number of interfaces increases in the multi-layer films, and the size and nature of those defects changes as the layer thicknesses shrink to the nano-scale [2-3].

Optical profilometry has been widely explored [4-7]. The technique has the advantage of giving non- contact and high accuracy measurements. However, they are either restricted by application to a surface discontinuous height step of less than half of the illuminating wavelength or slow scanning speed. There are three demands for extending its application field to structured surface evaluation in the manufacturing environment, namely high measurement speed, large measurement/resolution ratio, and noise insensitivity.

Dispersive interferometry has been reported by many researchers worldwide in the field of absolute distance, displacement and profile measurement [8-10]. Surface topography measurements are based on phase shifts due to wavelength variations, avoiding any optical path difference scanning and phase shift calibration problems. Absolute optical path difference can be measured without 2pi phase ambiguities.

This paper presents a high speed profile optical measurement technique based on white light spectral interferometry and parallel signal processing using a general purpose graphic processing unit (GPGPU). A white light source is used to acquire the surface profile of the sample instantly in real time through a Michelson interferometer. The interference signals are resolved by a diffraction grating and recorded by a high speed CCD camera. The spectrum of the interference signal contains all the phase information in just one shot of a CCD camera frame image. By analysing the spectrum of the interference signal the system can measure a surface profile as the measured surface in a constantly moving state. As the measured surface laterally passes through the measurement arm of the interferometer, a surface map can be constructed by combining each of the measured profiles. Structured surface samples were measured and the results are discussed. It can be used for surface measurement with discontinuous surface profiles.The system can be used for on-line or in-process measurement on shop floors. Measurement results from step height standard and other samples were presented and nanometre accuracy achieved. These techniques combined have the potential to be used for real-time measurement of high precision surfaces such as those resulting from roll-to-roll (R2R) film processing, lithographic etching processing, doping, CVD/PVD coatings, lapping, and CMP processing on the production line.

Measurement principle

The basic configuration of the instant surface profile measurement system is illustrated in Fig. 1. The measurement system is employed a cylindrical Michelson interferometer. A white light source is used to acquire the surface profile of the sample instantly in real time. The light beams from the white light are coupled into an optical fibre patch cable and then collimated by Collimator 2. The collimated beam is then passed through a cylindrical objective lens and split into two beams by a beam splitter. One beam is incident into a reference mirror and the other beam is incident into a measured sample. The two beams of light are than brought together through a cylindrical lens and an image lens. A slit is used to block the lights that are redundant for measurement. Only a narrow line of light which represents an interference signal of a profile of the measured surface is passed through the slit. After this, the light is incident onto a reflective diffraction grating. The spectrum of the interference signal is separated by the diffraction grating. For a diffraction grating with spacing d, if a plane wave is incident at an angle θ_i, the light of wavelength λ appears at angle θ_m and the diffraction order m satisfies the following relation:

$$m\lambda = d(\sin\theta_m + \sin\theta_i), \tag{1}$$

Consider only the first order with normal incident light, the above equation becomes:

$$\lambda = d\sin\theta_m \tag{2}$$

By selecting a proper grating space, the distance between the grating and CCD camera and the angle between the CCD camera and the diffraction grating, the CCD is able to capture a band of light between 500 nm and 600 nm in a linear way with respect to the CCD pixels and the spectral wavelength.

The interference fringe intensities detected by a row of pixels lie parallel to the slit of the spectrometer and have the same mean wavelength λ. For a pixel (x) on a row of the CCD camera that corresponds to a point (x') on the profile of the test surface, the intensity of the fringes can be expressed by:

$$I(x,k) = A(x,k) + B(x,k)\cos(kh(x)) \tag{3}$$

where $A(x,k)$ and $B(x,k)$ are the DC component and fringe visibility respectively, k is the angular wave number $2\pi/\lambda$, and $h(x)$ is the absolute optical path difference of the interferometer.

The phase of the interference signal, $\varphi(x,k)$ is given by:

$$\varphi(x,k) = kh(x) \tag{4}$$

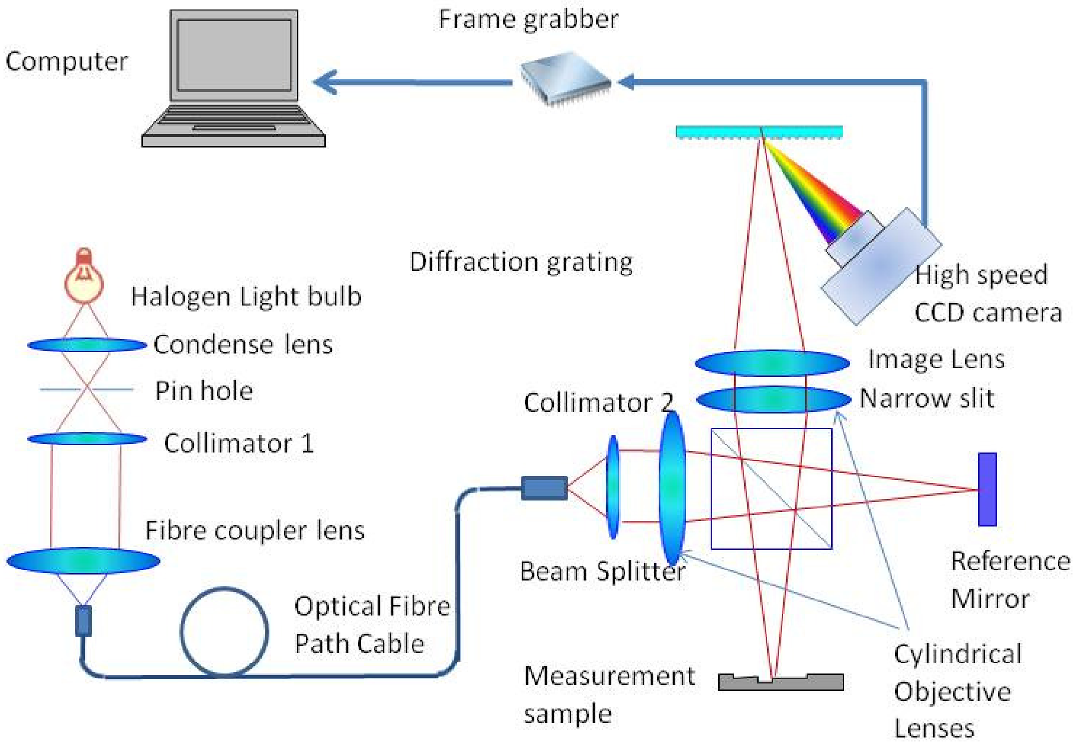


Figure 1. System configuration

The phase shift of the interference signal owing to the angular wave number shift is given by:

$$\Delta\varphi(x,\Delta k) = \Delta k h(x) \tag{5}$$

The phase change of the interference signal is proportional to the wave vector k change. Then the optical path difference $h(x)$ is given by:

$$h(x) = \frac{\Delta\varphi(x,\Delta k)}{\Delta k} \tag{6}$$

Since a phase change of π can be easily detected by using a zero cross algorithm of the interference signal, and the change of k can be calibrated first by using several single wavelength lasers, surface height distribution can be calculated by Eq. (5). A height map of the measured profile is available by processing the images of a series of rows pixels of the CCD camera which represent the interference fringes from a sequence of wavelengths.

However, the above phase calculation algorithm is not accurate in practice since not all the rows of a CCD frame are utilised. The height resolution is limited to several tens of nanometers. Some researchers have proposed several phase calculation algorithms to realise nano resolution measurement based on a least-square fitting approach or a seven-point method similar to conventional phase shifting interferometry [11, 12]. Both of them take advantage of the full CCD frames.

In the production line, such as roll-to-roll film processing, the measured sample moves at a constant speed v in the y direction, which is perpendicular to the measured profiles. If the frame rate of the CCD camera is f fps, it is possible to build a 3D surface profile with a sample spacing at:

$$\Delta y = \frac{\upsilon}{f} \tag{7}$$

Measurement results and discussion

The experimental setup is shown in Fig 2. Two interferometer configurations; a cylindrical lens interferometer and a microscope objectives Michelson interferometer setup respectively; are included in the system. The cylindrical lens system projects a narrow line onto the measured sample and the reference surfaces and reflected signals are combined through a cylindrical lens and an image lens. The samples are fixed on a mirror holder with a post mounted on a linear stage. As the linear stage moves, the CCD camera captures the spectral resolved interference images. The spectrometer was calibrated by using the light passing through an acousto-optical tunable filter.

A measured profile of a mirror surface and the phase signals processing sequences of one single row of CCD pixels are shown in Fig. 3. The spectral resolved interference signal captured by the CCD camera is shown in the top left image. It contains the interference signal and the background of the light source. By calibrating the light source, the background can be removed from the captured signals. The top middle image shows the spectral background of the light source. The top right image shows the interference signal after the background signal has been removed. The wrapped phase signals are shown in the middle left image and the unwrapped phase signals are shown in the middle right image. The optical path difference (OPD) can be calculated from the unwrapped phase signal. By combining all the OPD values of the whole row of the CCD pixels, the measured profile can be generated as shown in the bottom image. The tested surface is a mirror with λ/10 flatness. The measurement result shows that the peak-peak value of the measured profile is less than 40 nm, which is within the flatness specifications of the mirror.

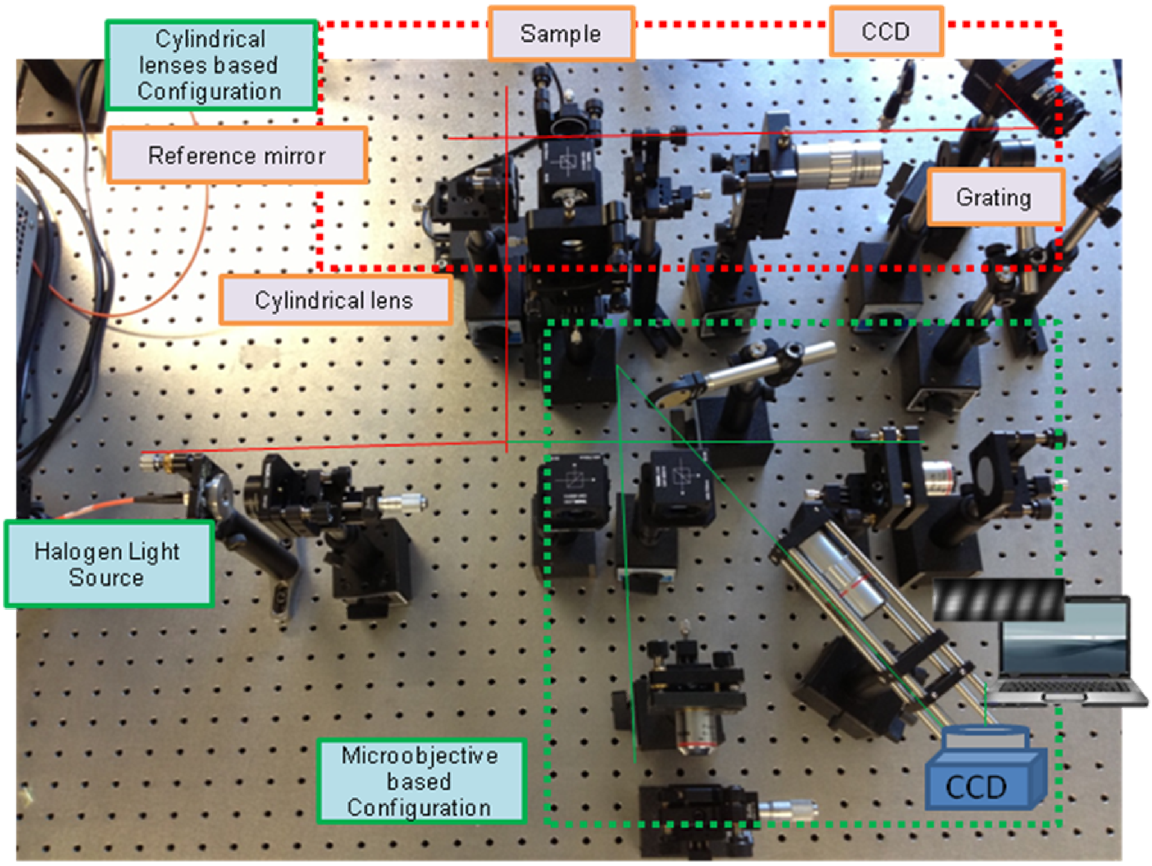


Figure 2. Experimental setup of the white light spectral interferometry

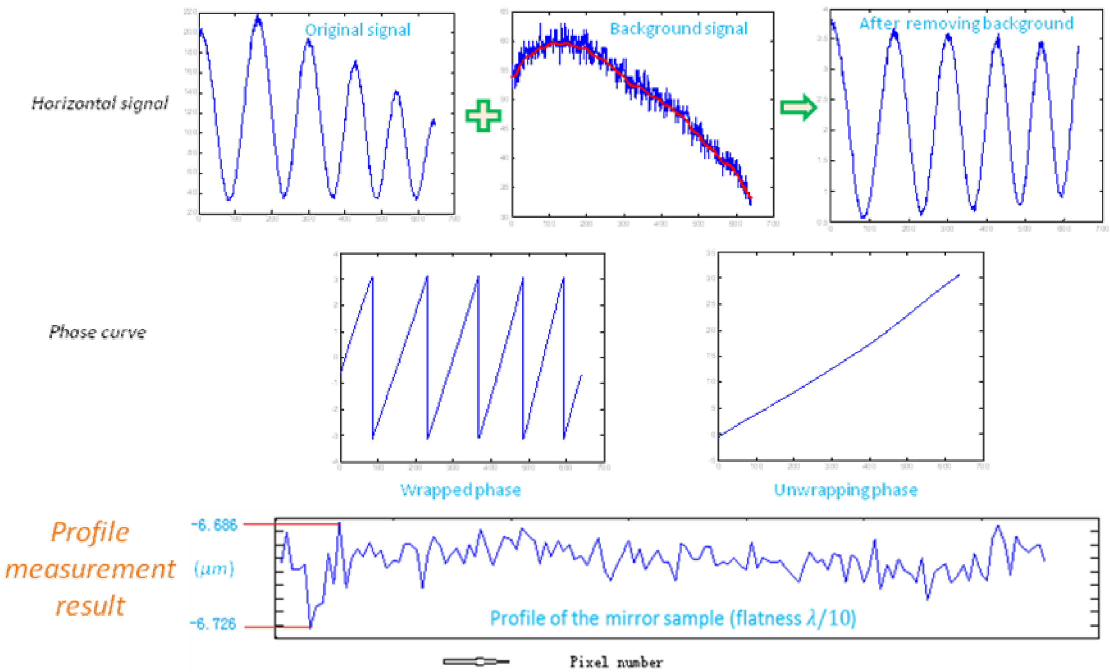
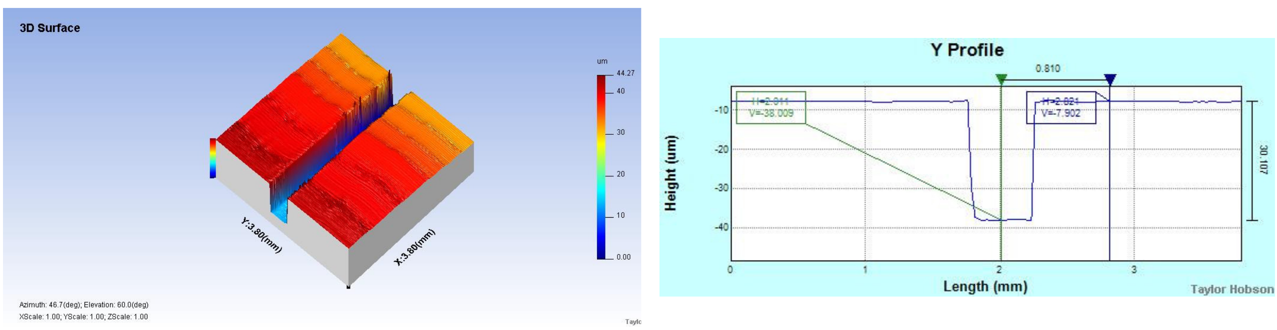


Figure 3. Surface profile measurement of a mirror surface and the signal processing

When a measurement sample moves in a perpendicular direction to the measurement beam as the linear stage driven at a constant speed, a 3D surface measurement can be achieved. A step height sample made by Rubert & Co. Ltd. with 30 μm depth and 0.5 mm width has been measured. The measurement data contains 600 sampled profiles as the linear stage moved at 10 mm/s. The areal surface measured by the cylindrical lens white light spectral interferometer is shown in Fig. 4(a). A profile plot is shown in Fig 4(b). The same sample was measured by a Taylor-Hobson CCI instrument. The profile measurement result is close to the result of the CCI. The areal surface map appears to be rough and the measured profiles' vertical position varies in several micrometre ranges along the lateral scanning direction. This is because the sample was mounted on a 100mm post, which is connected to the linear stage, so any of the tilt, yaw and pitch errors of the linear stage were magnified through the long post. In the measurement surface map it appears as the variation in the vertical position of the profiles. By reducing the length of the post, these variations can be reduced. In the R2R surface inspection, only defects on the film surface are the concern of the quality control. It will be detected by a profile measurement. The variation of the vertical position of the measured profile will not affect the inspection result.



(a) (b)

Figure 4. Measurement by the cylindrical lens white light spectral interferometer on a 30 μm step height sample: (a) areal surface map; (b) a profile plot

Conclusion

This paper presents a high speed surface profile optical measurement technique based on white light spectral interferometry and parallel signal processing using GPGPU. Nanometer accuracy surface measurement results have been obtained for a 30 µm step height sample and a mirror surface. There is no need for optical path scanning as found in conventional white-light vertical scanning interferometry. For a CCD camera with 200 fps rate, capturing a full frame image only takes 5 ms time. By combining a high speed CCD camera and a GPGPU, the system is able to perform fast profile on-line surface inspection.

Acknowledgments

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding of the First Grant (Grant Ref: EP/K007068/1) and the funding of EPSRC Centre for Innovative Manufacturing in Advanced Metrology (Grant Ref: EP/I033424/1).

References

[1] Singleton L, Leach R, Lewis A and Cui Z, "Report on the analysis of the MEMSTAND survey on Standardisation of MicroSystems Technology" MEMSTAND Project IST-2001-37682, (2002)

[2] B. Parida, S. Iniyan and R. Goic., A review of solar photovolataic technologies, Renewable and sustainable Energy Reviews 15 (2011) 1625–1636

[3] F. C. Krebs, Fabrication and processing of polymer solar cells: A review of printing and coating techniques, Solar Energy Materials & Solar Cells 93 (2009) 394–412

[4] Wang, K, Martin, H. and Jiang, X., Actively stabilized optical fiber interferometry technique for online/in-process surface measurement. Review of scientific instruments, 79 (2), (2008), ISSN 0034-6748

[5] Yang S, Jiang X, Maxwell G. and Wang K., An integrated optical coupler used in a fibre interferometry system for on-line surface measurements. Optics Communications, 281 (5), (2008) pp. 1099-1107.

[6] Martin H and Jiang X., Rapid phase shifting fiber interferometer with optical stylus. Optical Letters, 35 (5), (2010) pp. 655-657.

[7] Massie N., Real-time digital heterodyne interferometry system, Appl. Optics 19 (1): (1980) 154-160

[8] Schwider J., Zhou l., Dispersive interferometric profilometer, Opt. Lett. 19 (13), (1994) 995-997

[9] Sandoz P, Tribillon G, Perrin H., High-resolution profilometry by using phase calculation algorithms for spectroscopic analysis of white-light interferograms, J. Modern Opt. 43 (4): (1996) 701-708

[10] Schnell U., Dandliker R., Gray S., Dispersive white-light interferometry for absolute distance measurement with dielectric multilayer systems on the target, Opt. Lett. 21 (7), (1996) 528-530

[11] Bowe B. and Toal V., White light interferometric surface profiler, Opt. Eng. 37, (1998) 1796-1799.

[12] Hirai A., Seta K., Matsumoto H., White-light interferometry using pseudo random-modulation for high-sensitivity and high-selectivity measurements , Opt. Commun. 162, (1999)11-15.