Design of a dispersive lateral scanning surface profilometer

P. Kumar[1], H. Martin[1], G. Maxwell[2], X. Jiang[1]
[1]University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK
[2]Centre for Integrated Photonics, Adastral Park, Martlesham Heath, Ipswich, IP5 3RE

ABSTRACT

Non-destructive testing and online measurement of surface features are pressing demands in manufacturing. Thus optical techniques are gaining importance for characterization of complex engineering surfaces. Profilometers based on the laser scanning confocal microscopy can provide non-contact, fast measurement with high lateral and axial resolution. In this work we present the optical design of a lateral scanning probe using a broadly tuneable laser (1500-1600 nm) source in the IR region using Zemax optical design software. The optical probe being one of the main constituents of integrated optic measurement system critically determines the performance of the original metrology sensor system. Various approaches of reduced device dimension have been investigated without compromising the optical performance enabling the probe system suitable for embedded metrology application. The optimization and analysis revealed that the diffraction limited imaging resolution can be achieved using simple achromatic relay lenses and the objective over the entire field of view.

Keywords: Non-destructive, online measurement, lateral scanning probe, Tuneable laser, embedded metrology.

1 INTRODUCTION

In modern manufacturing a high degree of precision is required for structured surfaces designed to provide certain functionality or enhance material processing for high added value products. Thus there is need for miniaturised high resolution embedded measuring technology delivering a high level of measuring accuracy. Providing closer integration of metrology upon the manufacturing platform can lead to the better control and increased throughput. A hybrid integration approach offers integration of individual optoelectronic components onto a silicon daughterboard which is then incorporated on a silica motherboard to produce the final miniaturised single chip hybrid structure. This provides the device a compact and stable configuration. Further optical methods of surface characterization are gaining importance in non-destructive and online measurement of surface roughness during manufacturing [1]. There are various optical techniques which have been employed to measure surface roughness measurement both on-line and off-line [2]. In recent years the measurement technique based on laser scanning microscopy has emerged as a potential tool for precision surface measurement [3]. While designing the probe based on laser scanning microscope a number of considerations needs to be taken into account. Illumination methods, detection methods, beam scanning approach etc. severely impact the performance of the device. Another issue which needed to be addressed is its limiting single point measurement of the specimen at a time. Large area specimen measurement could be performed by scanning the objective across the specimen or vice versa. Investigations by Minsky have demonstrated that it would be more proper and convenient to scan the weightless beam by some mechanism rather than moving the objective or the specimen [4]. A number of approaches such as perforated discs [5], scanning galvo-mirrors [6] and fast rotating polygon mirrors [7] have been devised and implemented to scan the beam in orthogonal directions onto the object plane. In our design a diffraction grating is used to deflect the beam to provide the beam scanning onto the test surface as shown in figure 2. The use of grating alleviates the need of any mechanical scanners, which significantly simplifies the probe design and construction. Also in terms of scan speed and durability, the performance of diffraction a grating based scanner is naturally much higher compared to mechanical ones

2 THE METROLOGY SENSOR SYSTEM

The metrology sensor system is developed using a hybrid integration approach [8]. In this approach silica based planar light wave circuitry (PLC) is used which enables the construction of highly functional components by combining the passive function of a PLC with the active function of various photonics components assembled on silicon mother boards. The metrology tool (figure 1) is based on the wavelength scanning technique and incorporates a hybrid tuneable laser, a directional coupler, and a photo-detector producing a single optical chip to form a miniaturised and robust online surface measurement system. The basic principle of operation of the proposed metrology tool is based on two interferometry techniques; wavelength scanning and phase shifting. The optical probe being one of the main constituent of the integrated optic measurement system, critically determines the performance of the metrology tool. The optical probe determines the lateral resolution of the system. In addition to the surface profile measurements, this metrology tool can also be employed for absolute distance measurements.

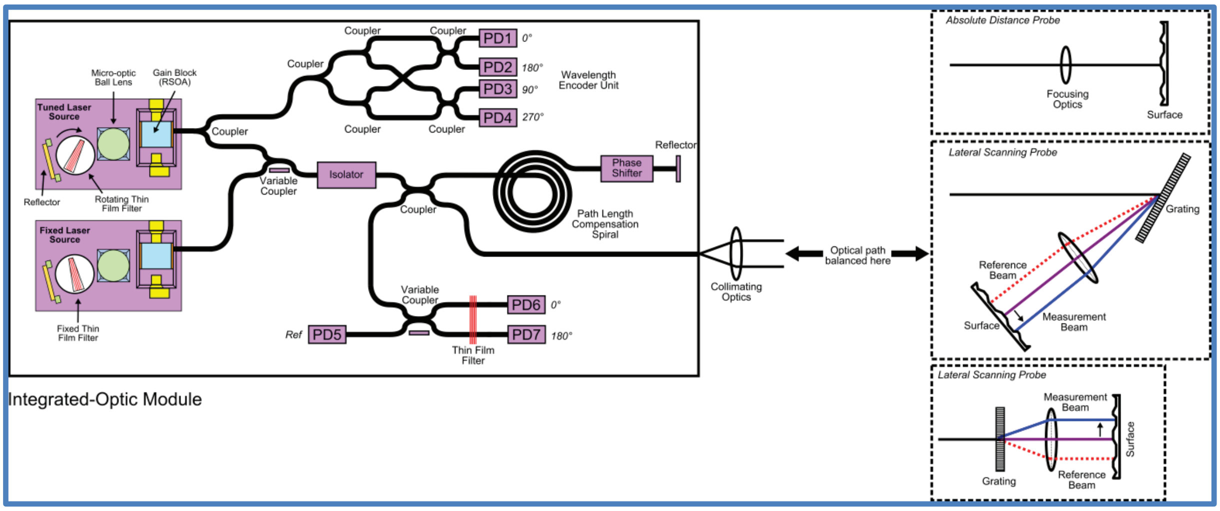

Figure 1: Metrology sensor system

3 LATERAL SCANNING PROBE: WORKING PRINCIPLE

The lateral scanning confocal probe is a noncontact flying spot confocal microscope containing a diffraction grating as an encoder to relate wavelengths into spatial information of the surface under test. A configuration of the lateral scanning probe that we propose is shown in figure 2. By tuning the wavelength of the light source and by suitably selecting a grating, it is possible to steer the beam of light over a desired angular range. The basic principle of operation of a grating is given by the equation,

$$d\left(\sin\alpha + \sin\beta\right) = m\lambda \qquad 1$$

where λ is the wavelength of light, d is the grating pitch, α is the incident angle, β is the diffraction angle and m is the diffraction order. The diffraction angle follows the increase in wavelength and this forms the basis of the spatial scanning across the test surface. The spatial scanning gives a line scan along the surface and the points of focus along the line represent individual wavelengths from the beam spectrum. The position of the individual light spots in the object plane depends on the scan angle provided by the grating. In this way the laser beam is swept across the surface and retro-reflected light is collected by the optical probe. The collected light intensity is analysed using the phase shifting technique [7] to obtain the optical phase which relates directly to the surface shape. A single mode fibre output pigtailed to the chip integrated device will act as a pinhole both for the illumination and the detection. This also provides a simple approach for pinhole alignment to the image of point on the sample created by objective system.

In a surface profile measurement application resolution (vertical and lateral) is the most basic performance characteristics parameter of the non-contact optical probe. A light source having wide tuning range will facilitate larger scan and high axial resolution while the high output power will provide better signal to noise ratio. The use of wavelength scanning interferometry with the phase shifting techniques in the aforesaid device enables sub-nanometer vertical resolution. According to diffraction equation angle β_i corresponding to the wavelength λ_i is given by,

$$\sin\beta_i = \frac{m\lambda_i}{d} - \sin\alpha \qquad 2$$

Diffraction angle β_i is basically the tilt angle provided by the grating as a beam scanner. The diffraction angle β_i is related to tilt angle β in the telecentric plane by,

$$\beta = \frac{f_2}{f_3}(\beta_i) \quad (3)$$

The position of the scanned spot in the object plane is defined by the tilt angle β along the y axis. The field of view in the object plane is proportional to the tangent of the angle β in the telecentric plane. The FOV is given by,

$$FOV = 2 \times f_{obj} \times \tan(\beta) \quad (4)$$

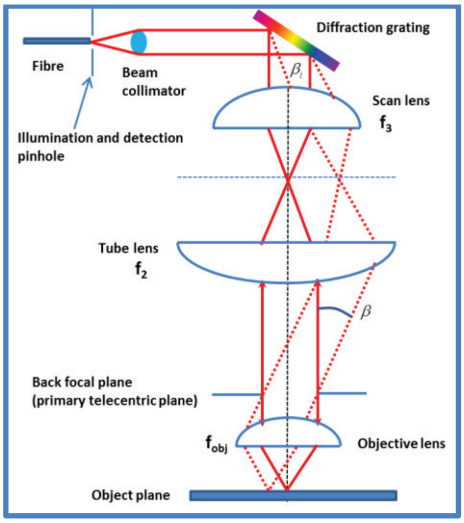

Figure 2: Lateral scanning profilometer

4 OPTICAL DESIGN SIMULATION

In order to be used as an embedded metrology tool the lateral scanning optical probe must satisfy an important requirement, namely a compact size. The microscope objective size is one of the major constraints that limit the overall size of the probe. The difficulty is the non-availability of high NA miniaturised microscope objectives with a small diameter and similar working distance, FOV and aberration control compared to the available bulky objectives. However by beam folding using optical elements such as mirrors and prisms it is possible to reduce the overall size of the probe. In order to appraise the performance of a confocal optical probe the system is designed and evaluated using the Zemax optical design software. Here we have employed sequential ray tracing technique to model the confocal optical probe. Figure 3 shows the optical layout design of the optical probe simulated in Zemax. The system consists of (1) input beam, (2) diffraction grating, (3) and (4) relay lenses, (5) microscope objective and (6) the object.

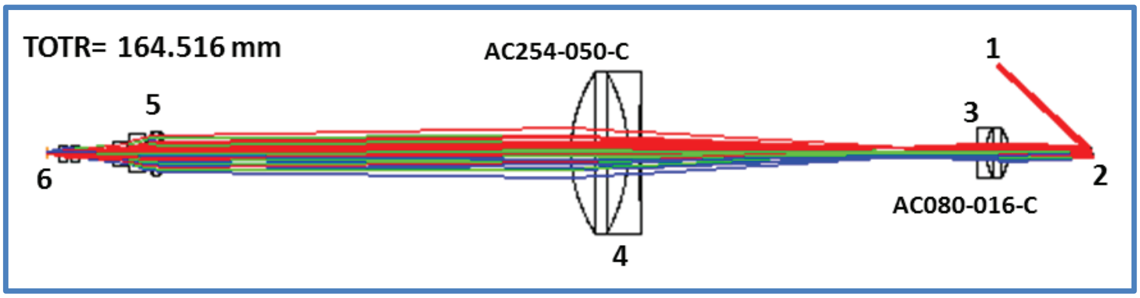

Figure 3: Optical layout of the probe in Zemax. The blue green and the red lines represent the scanned laser beam at the design wavelengths

The scan lens and the tube lens are chosen from the Zemax lens catalogue. The initial parameters such as wavelengths, field angle, and entrance pupil diameter of the beam are inserted into the software. The entrance pupil diameter of the source beam is taken as 0.8 mm corresponding to the effective aperture of the microscope objective to avoid any beam vignetting. The field angle is set at zero as the beam scan is provided by the grating scanner. The ray tracing is performed at three wavelengths (1500nm, 1550nm, 1600 nm) in the infrared region. In order to obtain estimated lateral resolution a microscope objective close to the specifications of the Mituyoto M Plan Apo 10X NIR series was chosen. The microscope objective (K_013 ZEBASE) was selected from Zebase. The microscope objective has an NA of 0.26 and a magnification of 10 X. For the relay system (scan lens + tube lens) commercially available Achromatic lenses (AC080-016-C and AC254-050-C Thorlabs) were used. The spatial frequency of the diffraction grating used had 800lines/mm. Four mirror combinations (7-8, 9-10) have been used in design 2 while in design 3 contains two mirrors (7-8) and two prism (9-10) combinations as shown in figure 4(a) and 4(b) respectively. The mirror and prism combinations and two mirrors have been used in the design to give a compact configuration to the probe design. The prism pair in design 3 is tilted (~5 deg) to avoid any reflections from the cavity formed by the prism pair or the lens prism combination. The glass material for the prism used is BK7.

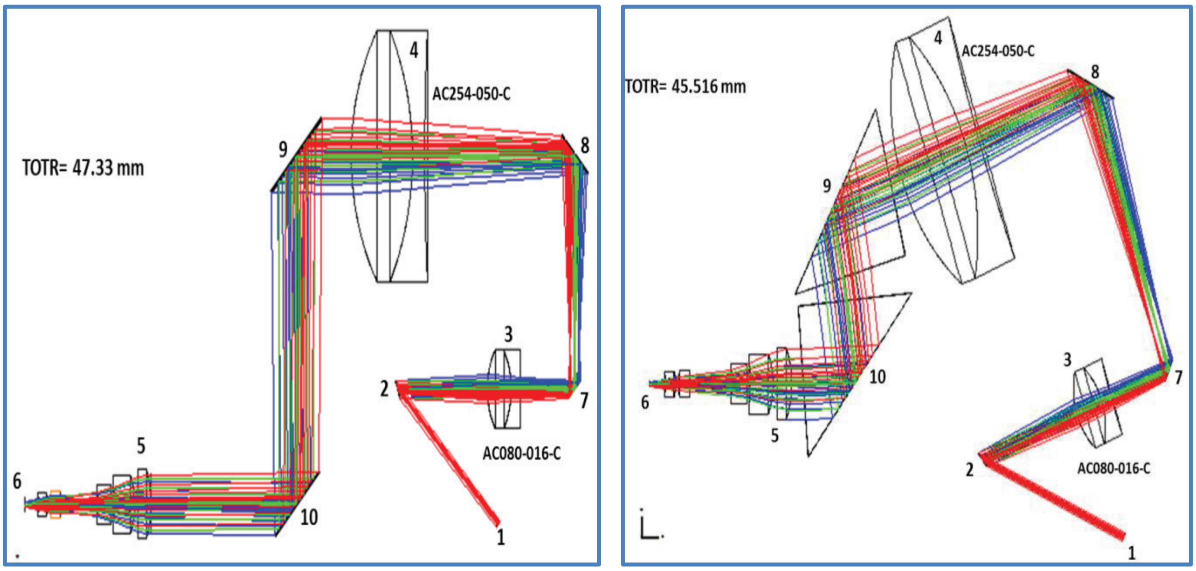

Figure 4: Optical layout of the compact probe in Zemax using the (a) Design 2: mirror pair (7-8, 9-10) and (b) Design 3 mirror (7-8) and prism pair (9-10) combinations.

The telescope system which consists of scan and tube lens is optimised making it purely an afocal system. The axis of all the optical components are perfectly aligned relative to the central wavelength (1550nm) using the tilt and decentre elements. The grating is placed at the back focal plane of the scan lens. The grating to scan lens distance is further optimised for better beam collimation. The objective lens is then inserted. A slider tool is used to optimise the distance between the tube lens and the microscope objective. The optimum distance between the tube lens and the objective is obtained to avoid any beam vignetting. Further analysis is performed to evaluate the performance of the system. The spot size and the Huygens point spread function (PSF) are drawn at three design wavelengths and analysed. The field of view (FOV) over the full illumination spectrum (design wavelengths) is calculated using equation 4 is approximately 0.4 mm. The lateral resolution of the system is observed first to indicate the performance of the system. The lateral resolution assessment is calculated by studying the spot sizes and ray patterns in comparison to the airy disk radius. The results of the simulations are shown in the figure 5 spot size diagram. As evident from the figure 5 the spot rays lie well within the airy radius indicating that the diffraction- limited performance is obtained at all the three design wavelengths. A minimum spot size of 0.261 µm is obtained for 1550 nm while it degrades at the other two wavelengths on either sides of central position of FOV. Figure 6 plots the Huygens PSF at all three design wavelengths. The PSF gives the Strehl ratio which is the measure of optical image quality for very high quality imaging system.

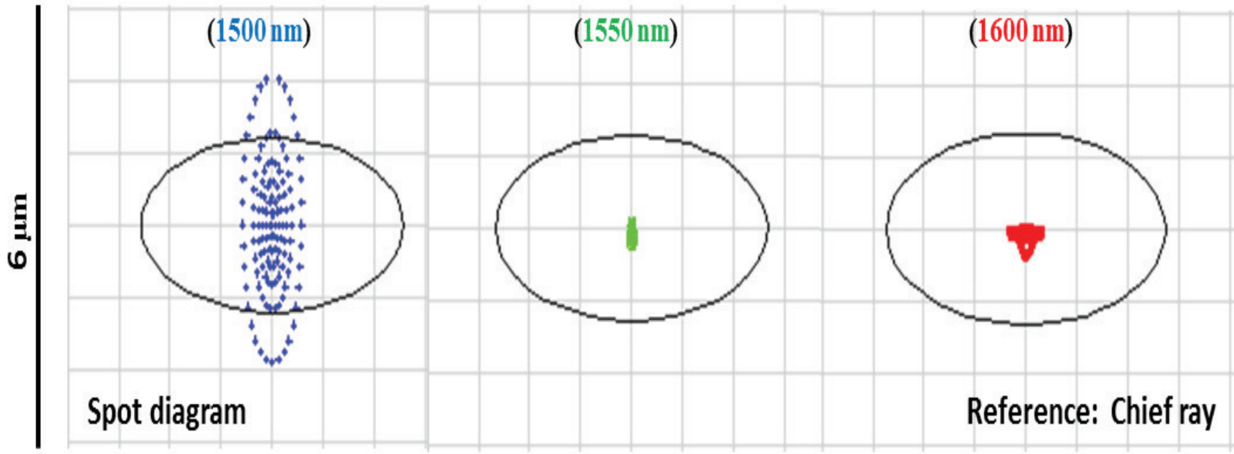

Figure 5: Simulated spot size diagrams of the probe system (a) at 1500 nm (b) 1550 nm (c) 1600 nm

	Wavelength1 (1500nm)	Wavelength2 (1550nm)	Wavelength3(1600nm)
Airy radius (µm)	6.347	6.558	6.77
RMS radius (µm)	3.694	0.261	0.724
GEO radius (µm)	8.123	1.053	1.543

Table 1: Airy, RMS and GEO Radius value at three design wavelengths

The Strehl ratio is defined as the peak intensity of the diffraction PSF divided by the peak intensity of the diffraction PSF in the absence of aberrations. Strehl ratio takes the value between 0 and 1 with a perfect optical system having the value unity. Strehl ratio at wavelength 1500nm is 0.7 while at other two wavelengths the value is unity. This suggests that the probe system is aberration free except for minor degradation at 1500 nm. Similar performances have been observed in the case of design 2 (mirror pair) and design 3(mirror prism pair) which provides the device a compact and portable configuration.

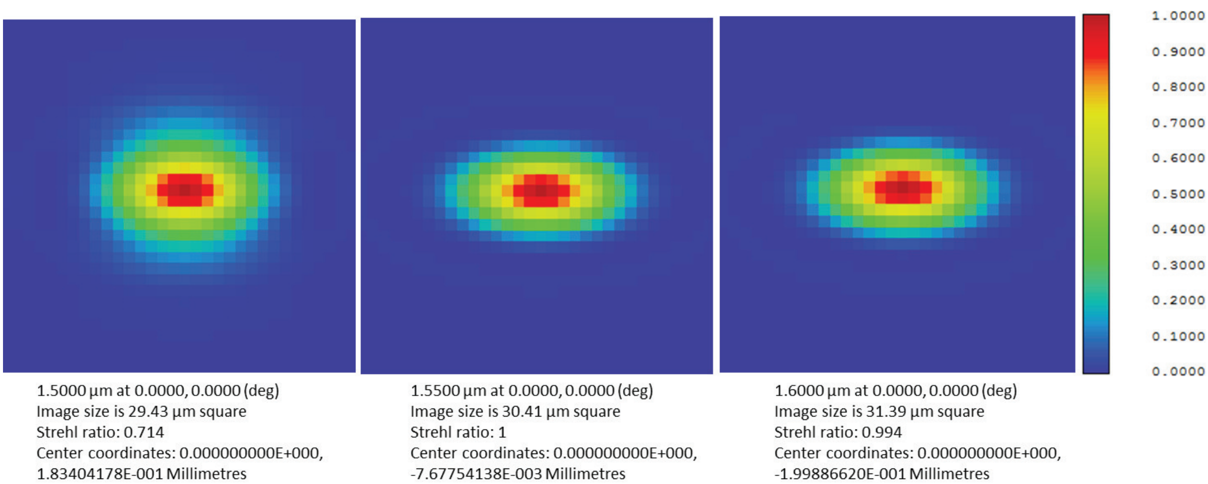

Figure 6: Huygens Point spread function at (a) 1500 nm (b) at 1550 nm (c) 1600 nm

5 CONCLUSIONS

In summary we presented a compact design and beam profile characterization of a lateral scanning optical probe using the Zemax optical design software. Two other probe design using mirror and prism pair combinations are investigated. The beam profile characteristics show that the diffraction limited imaging performance can be achieved in all the designs covering the entire illumination spectrum. High quality beam profile and the compact design of the probing system will prove valuable for the overall performance and size of the metrology sensor system. Next stage job is to simulate and optimise a collimated fibre delivery using a collimating lens keeping the aperture wide open to minimize the fibre pinhole effect which reduces the depth of focus allowing maximum light reflected collection from the test surface. Once the optimum design is obtained it is required to build and evaluate a bench top prototype for scanning using a suitable optical cage mounting system (figure 7). Experimental investigations will evaluate the actual capability of the optical probe system for surface measurement applications. Further it is required perform technical investigation of the final hybrid device containing fixed reference laser, phase shifter and wavelength encoder in terms of noise and wavelength uncertainty. Finally the combined optical probe and hybrid chip interferometer device is to be evaluated in terms of vertical range/resolution, uncertainty, repeatability etc.

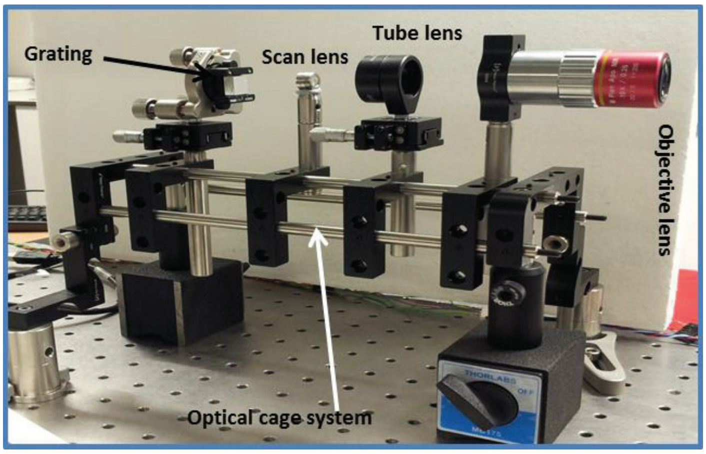

Figure 7: Setup of prototype probe onto an optical cage system

REFERENCES

[1] T V Vorburge and E C Teague,"Optical techniques for online measurement of surface topography", Precision Engineering, Volume 3, Issue 2, April 1981.
[2] I. Sherrington, E.H. Smith," Modern measurement techniques in surface metrology: part II; Optical instruments" Wear, Volume 125, Issue 3, 1 August 1988.
[3] D. K. Hamilton, T. Wilson," Three-dimensional surface measurement using the confocal scanning microscope", Applied Physics B, April 1982, Volume 27, Issue 4, pp 211-213
[4] M. Minsky," Memoir on inventing the confocal scanning microscope" Scanning, Vol 10, 28-138,1988.
[5] M Petran, M Hardravsky, D Egger & R Galambros," Tandem scanning reflected light microscope" J. Opt. Soc. Am. A, 58:661-664,1968.
[6] Jabbour, J.M., Saldua, M.A., Bixler, J.N. & Maitland, K.C. "Confocal endomicroscopy: instrumentation and medical applications", Ann Biomed Eng, (2012).
[7] Rajadhyaksha, M., Anderson, R.R. & Webb, R.H. " Video rate confocal scanning laser microscope for imaging human tissues in vivo", Appl Opt, 2105–2115 (1999).
[8] Graeme Maxwell. "Hybrid Integration Technology for High Functionality Devices in Optical communications", Optical fibre communication, Invited paper OWI3, (2008).
[9] Creath K.," Phase measurement interferometry techniques". Progress in Optics, 1988, Vol. 26, pp. 349-93.