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# DESIGN AND DEVELOPMENT OF A SELF CALIBRATED OPTICAL CHIP INTERFEROMETER FOR HIGH PRECISION ON-LINE SURFACE MEASUREMENT

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## ABSTRACT

***Surface characterization plays an important role in many manufacturing processes. In this paper we propose the development of a hybrid optical chip interferometer device which will allow online surface measurement at high precision with improved autonomy. The research methodology involves the integration of individual optoelectronic components onto a silicon daughterboard which is then incorporated on a silica motherboard to produce the final hybrid structure. The fundamental principle of operation of the device is based on wavelength scanning interferometry and optical phase measurement techniques. The integrated optics chip device combined with an optical probe will be compact and robust and may be used for high precision surface measurement and absolute distance measurement.***

**Keywords:** Surface metrology, integrated optics, interferometry, wavelength scanning, phase shifting

## 1 INTRODUCTION

Surface metrology is used in engineering to understand the creation and behaviour of surfaces topographies. As the dimensions of the product become smaller the importance of the surface and its properties become a dominant factor in the functionality of the product [1]. Modern deterministic/structured surfaces are actually being specifically designed to provide certain functionality. As such it is vital to have proper understanding of the surfaces and their properties. With advanced measurement techniques, the possibility of improving material processing and reliability of manufacture can be enhanced in terms of high added-value critical components.

High and ultra precision manufactured surfaces are for a growing number of state of the art optical elements or devices; for example lenses and mirrors which are integral component to many other value added products such as mobile phone cameras, laser printers, flat bed scanners, displays, telecommunication, photonics and biomedical devices [2]. However the fundamental limiting factor in the manufacture of such surfaces is the lack of adequate measurement techniques or tools having both large measurement range and high resolution either in academic research or industry [3]. More importantly, the overwhelming requirement within precision manufacturing is for on-line surface metrology methods for the efficient characterisation of surfaces. Currently, almost all available metrology instrumentation is either too bulky, slow, destructive in terms of damaging the surfaces with a contacting stylus or is carried out off-line [4].

In this approach the aim is to develop a novel integrate-optic on-line surface metrology tool based on optical interferometry and a spatial light wavelength scanning method [5]. This design replaces mechanical stylus scanning as well as the bulky free space and fibre interferometers, making it a highly miniaturised optical tool for surface measurement. The device operates in the reflective mode in that the surface information is obtained by collecting the reflected light from the test surface. The developed metrology tool will have a compact configuration, much smaller size with reduced cost and provide stable and fast >1 Hz online surface measurement at very high precision. The fully integrated optical chip for online surface measurement will resemble the design as shown in figure 1.

## 2 THE METROLOGY SENSOR SYSTEM

The metrology sensor system is developed using a hybrid integration approach [6]. 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 is based on the wavelength scanning technique and incorporates a hybrid tuneable laser, a directional coupler, and a photodetector producing a single optical chip to form a miniaturised and robust online surface measurement system. Previous work has a simple fibre configuration but it requires a very expensive and large-scale tuneable laser [7]. In addition it requires a complex active stabilisation technique to deal with the random optical path length variation and polarisation evolution inherent with optical fibre. Replacing optical fibre with integrated optics technology can provide the required compactness while also increasing the stability of the apparatus substantially over the optical fibre equivalent. To make the system usable for online surface measurement, it needs to be compact and flexible enough to be mounted on a machine tool.

A previously reported incarnation of a miniaturised integrated optic tuneable laser (shown in figure 2) still requires substantial performance improvement in terms of linear tuning and single mode operation during the wavelength scan [8]. Furthermore it is necessary to design and integrate several modules such as an isolator, phase shifters and wavelength de-multiplexing units on chip to realise the full measurement system.

The integrated-optic chip unit outlined so far, together with the optical probe completes the physical structure of the aforesaid on-line surface metrology tool. The basic principle of operation of the proposed metrology tool is based on two interferometric techniques; wavelength scanning and phase shifting. The optical probe being the 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. The working of two basic probe types to be employed for surface profile and absolute distance measurements are discussed below.

### 2.1 Lateral Scanning probe:

In Fig. 1, a configuration of the lateral scanning probe that we propose is shown. The lateral scanning probe is a noncontact optical stylus based on a spatial light scanning technique using a dispersive component e.g. a diffraction grating. 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,

$$d\left(\sin\alpha + \sin\beta\right) = m\lambda \tag{1}$$

where $\lambda$ is the wavelength of light, d is the grating pitch, $\alpha$ is the incident angle, $\beta$ is the diffraction angle, 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.

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 in the form of an interferogram is then analysed using the phase shifting techniques [9] to obtain the optical phase which relates directly to the surface shape.

### 2.2 Single point scanning probe:

In addition, this chip interferometry system based on wavelength scanning can be extended to absolute distance measurement applications using methods similar to those described by Hussam et al. (2010). For measuring absolute distance a single point probing technique is used. Figure 1 shows the configuration of the absolute distance measurement probe. The wavelength scanning introduces a phase change, the rate of which depends on the optical path difference. Thus by calculating the actual phase change of the interference signal, it is possible to calculate the absolute distance. In our study we have employed a Fourier transform method to calculate the phase because it is fast, accurate and insensitive to intensity noise [10]. The phase of an interference signal $\varphi(x, y; k)$ is given by

$$\varphi\left(x, y; k\right) = 2\pi k h\left(x, y\right) \tag{2}$$

The phase shift owing to the wave number shift as the laser scans from start to stop wavelength is

$$\varphi\left(x, y; \Delta k\right) = 2\pi \Delta k h\left(x, y\right) \tag{3}$$

Finally the optical path difference can be calculated as,

$$h(x,y)=\frac{\varphi(x,y;\Delta k)}{2\pi\Delta k} \tag{4}$$

The principle of operation of the aforementioned metrology tool is based on wavelength scanning interferometry and as such the performance of the optical chip device is more or less conditioned to the performance of the chip tuneable laser. Therefore it is important to thoroughly understand the tuning behaviour of the laser and to optimise it in order to get the best measurement performance. The chip tuneable laser is an external cavity laser with a very wide wavelength tuning range of approximately 90 nano-meters with the output power of 5 mW. A primary area of concern is the tuning behaviour of laser which is ideally continuously single mode and linear. One limiting factor is mode hopping which prevents truly continuous tuning of the External Cavity Diode Laser (ECDL) causing increased intensity noise in the total intensity of the laser output. This will have consequences on the phase measurements in the lateral scanning probe mode leading reduced precision at nanometre level.

## 3 EXPERIMENT

### 3.1 Experimental setup

The experimental setup for testing the performance of tuneable laser is shown in figure 3. In the setup shown in figure, the CIP chip tuneable laser was used as a light source. The table below shows the specifications of the developed CIP chip tuneable laser.

| | |
|---|---|
| Output power | 5mW |
| Tuning Range | 1510-1600nm (90nm) |
| SMSR | ≥ 45dB |
| Package dimensions | 10 cm X 5 cm X 2 cm |

**Table 1 Specification of the developed chip tuneable laser**

The laser enclosure temperature and injection current were controlled using an ILX lightwave LDT-5910 temperature controller and an ILX lightwave LDX-3412 precision current source respectively. The laser light was coupled into single mode fibre to allow a collimated beam to strike the uncoated glass slide using the GRIN collimator. The returning laser beam, Fresnel reflected (approximately 4 % power) from the uncoated glass slide is collected by a 125 MHz New Focus PIN photodiode. A control unit linked to a PC and a NI PCI6221 data acquisition device allows the laser to be scanned over its tuning range and the reflected interferometer output was recorded using the photodiode. Optical feedback was minimized by using the minimum number of connectors and high quality optical isolators so that the back reflections from the laser beam cannot re-enter the laser causing optical instability. The recorded intensity was then analysed using Matlab to study the operational behaviour.

### 3.1 Experimental results and discussions

A Fizeau interferometer is formed by an uncoated glass microscope slide having a thickness of approximately 0.14 mm (see figure 3). Several identical wavelength scans were performed over an approximate tuning range of 1540-1560. During the wavelength scan, the converted voltage output from the PIN detector was sampled at 50 kHz. The laser injection current was approximately 450mA and the temperature stabiliser maintained a package temperature of $23^0$C throughout the course of the experiment.

In figure 4 the output sinusoid seems inconsistent throughout the scan suggesting nonlinear tuning behaviour of the laser. Also there is an increase in intensity at longer wavelengths. Before measuring the effect of wavelength tuning it is necessary to determine the system noise when the laser is stationary. The overall noise of the system was measured by keeping the laser at a set wavelength and in single mode operation at an injection current of 450mA. In figure 5 the interferometer intensity output was measured at three points, which in relation to figure 4 are: bottom of the third trough, the quadrature point to its right and the final peak. The peak to peak value and the RMS value at the bottom, quadrature and peak position are shown in table 2. The numbers in the table 2 show the noise figures expected in the system without wavelength tuning. The noise value is uniform at all the three positions of the interferometer output. In order to get much more detail about the tuneable laser it is necessary to look more closely at the output sinusoid obtained from the interferometer.

| Fringe Position | Peak to peak (mV) | RMS (mV) |
|---|---|---|
| Bottom | 4.00 | 0.302 |
| Quadrature | 4.44 | 0.303 |
| Peak | 4.44 | 0.303 |

**Table 2 Table showing the RMS and peak to peak value of the noise**

Figure 6 shows the bottom of the third trough shown in the figure 4 (at about 750-790 ms). The discrete tuning nature is quite obvious, the tuning steps forming the sinusoid suggesting the tuning moving in one direction. The large steps jumps in the output indicate the mode hopping behaviour. There are noticeable step changes in the output both up and down. These jumps are of similar magnitude to the anticipated noise value shown in table 2. Figure 7 shows the zoomed portion at the quadrature point where the interferometer shows maximum sensitivity to the wavelength. At the quadrature point in between the steps waveform is relatively smooth compared to the peak of the output sinusoid shown in figure 8. In the output sinusoid there are secondary structures appearing as irregular spikes in the waveform. These are due to secondary interference occurring in the system as a result of parasitic back reflections. These secondary structures are much more pronounced at the peak of the output sinusoid with increased intensity. Figure 9 shows the output power of the tuneable laser. The 10% tapped output of the laser was measured using an optical spectrum analyser (OSA) at different wavelengths within the scan range. Single mode operation at each wavelength within the range 1510-1600nm was confirmed before measuring the output power of the laser. The increased intensity in the interferometer output (shown in figure 6) can be explained based on the increased laser output power with the wavelength as can be seen figure 9.

In order determine whether the instabilities on the interferometer output were due to multimode effects from the laser tuning, an automated test routine was set up to step the laser drive motor at 2 µm increments and measure the laser output with the OSA after each step. The laser wavelength and linewidth were recorded for each step of the drive motor. In addition the number of peaks of >30dB above the main peak in the laser output was recorded. If this figure was more than one, it was logged as a multimode event. A full run took 3647 encoder steps and an approximately 2 hours to complete the full scan. The laser was kept temperature stable at $23^0$C and an injection current of 450mA was maintained throughout the run. The results of one full tuning run are shown in figure 4. Multimode events clearly make up a fairly large proportion (~ 17%) of the total number of tuning steps.

## 4 CONCLUSIONS

The developed integrated-optical chip has a tuneable laser as the primary component and as such forms the basis of the rest of the metrology instrument. A large wavelength tuning range, reasonably high output power and single longitudinal mode operation are all important features for surface measurement. Wavelength scanning Fizeau interferometry was applied to test the performance of the developed chip tuneable laser. It is found that the secondary structures are more pronounced at the peak of the output sinusoid and is due to the secondary reflection at the fibre ends in the system. Multimode behaviour of the tuneable laser is confirmed by running an automated routine to record the multimode events using OSA. The result showed substantial amount of multimode events while the OSA is scanned across the whole tuning range. Future work will determine methods of improving the laser performance in terms of reducing multimode behaviour and secondary structures. In addition to this a suitable probes will be designed and built to produce a full metrology system. Suitable software routines for control and signal processing will be created. Finally, the performance of the metrology instrument will be determined in both absolute displacement and lateral scanning modes.

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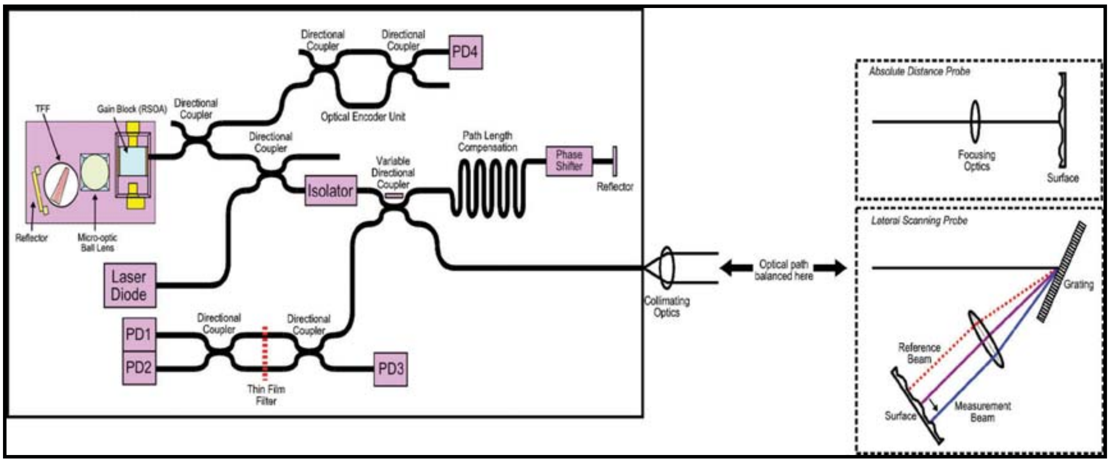
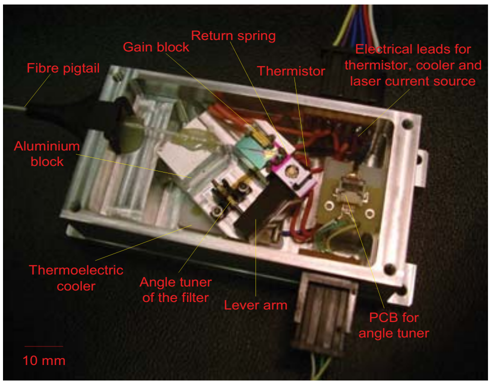


Figure 1: Schematic of the integrated optical chip device online surface measurement



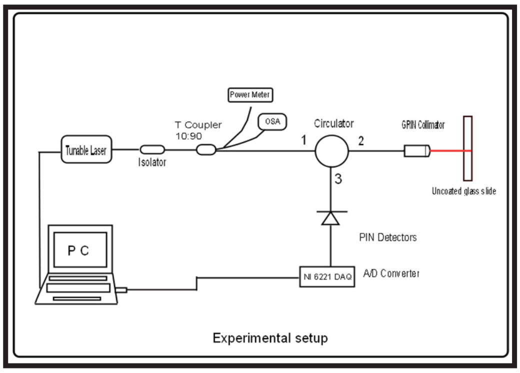
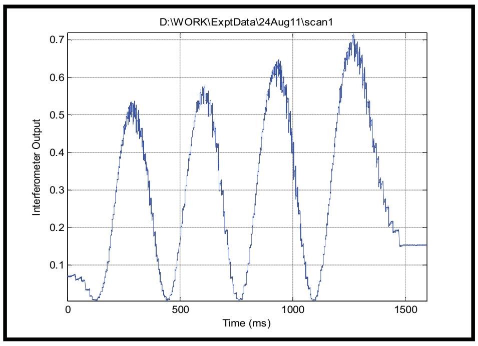


Figure 2: Tunable laser

Figure 3: Experimental setup for testing the Chip Tuneable Laser



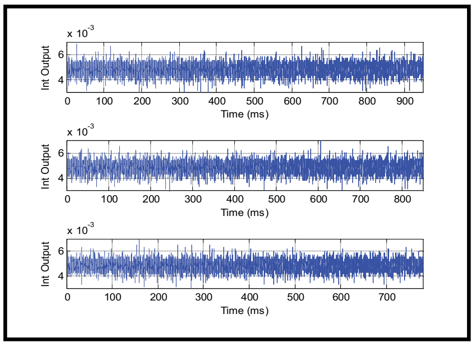
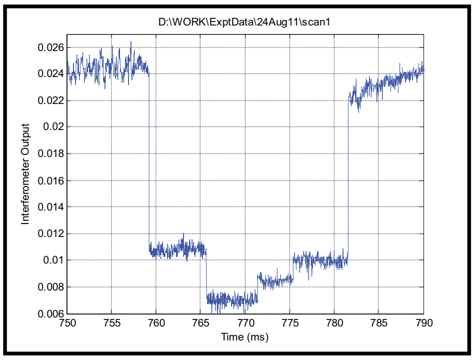


**Figure 4 Interferometer output over a scan range of 20nm (1540-1560 nm), Figure 5 Noise of the system when the laser is stationary at peak, quadrature and bottom position**



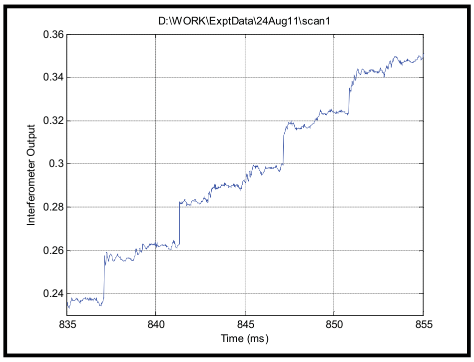
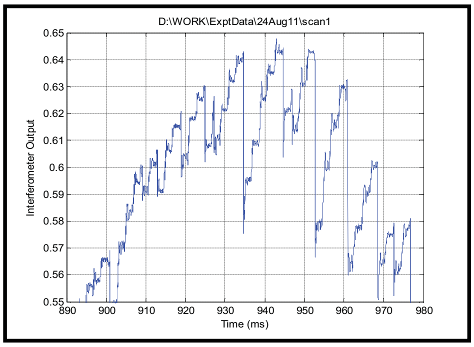


**Figure 6 Bottom of the third trough from left**

**Figure 7 Quadrature of the third trough from left**



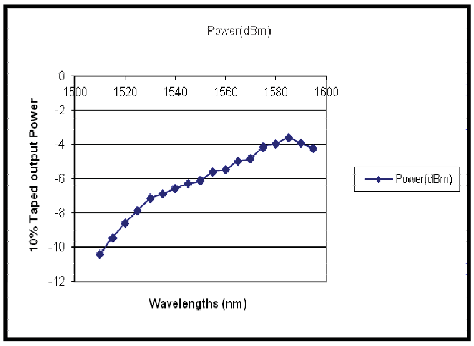


**Figure 8 Peak of the third trough from left**

**Figure 9 Output power of the Tuneable Laser**

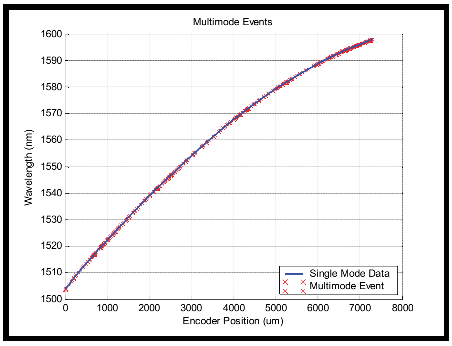


**Figure 10: Multimode events occurring during Run 1**