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Actively Stabilized Optical Fiber Interferometry Technique for on-line/in-process Surface Measurement

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In this paper we report the recent progress in optical-beam scanning fibre interferometry technique for potential on-line nano scale surface measurement based on the previous research. It attempts to generate a robust and miniature measurement device for future development into a multi-probe array measurement system. In this research, both the Fibre-Optic-Interferometry and the Wavelength-Division-Multiplexing techniques have been used, so that the optical probe and the optical interferometer are well-spaced and fast surface scan can be carried out, allowing flexibility for on-line measurement. In addition, this system provides a self-reference signal to stabilize the optical detection with high common-mode noise suppression by adopting an active phase tracking and stabilization technique. Low-frequency noise was significantly reduced compared with unstabilized result. The measurement of a sample surface also shows a repeatability of 3.3nm.

4350ki, 42.87.-d, 07.60.Ly, 07.60.Vg

1. Introduction

The broad use of ultra precision finishing processes such as lapping, diamond turning, CNC super polishing has highlighted one of the most fatal problems of micro and nano scale manufacture, namely, fast surface measurement (e.g. flatness and roughness) for quality control on the production line. It has been reported that currently the quality of fabrication depends largely on the experience of the engineer through an expensive trial-and-error approach.

Assessing product surface on the production line is promising for saving manufacturing time and reducing scrap rate. On-line surface measurements can be used for real time, closed loop control of manufacturing processes, and the information gathered from these measurements can also be used to detect malfunctions such as tool wear and breakage. Optical on-line/in-process surface measurements have been continuously reported by many research groups around the world during the last thirty years. Most measurement principles for on-line and in-process surface measurement have been dominated by light scattering techniques (e.g. speckle and diffuse methods) [1] [2] [3] [4] [5] [6] [7] [8] [9]. In these techniques, the scattered/diffused radiation pattern or speckle pattern from the part to be inspected was recorded and was related to the surface parameters, e.g. roughness, that measured by a stylus instrument. These techniques can provide a qualitative evaluation of surface texture or detect defects with micro scale features. Their main drawback is that they can not be used to quantitatively assess sub-micro scale features of surface texture with traceability. Their effectivities are usually affected by the surface material and the type of machining.

A highly stabilized multiplexed fibre interferometer for on-line surface metrology was reported by our previous research work [10] [11]. Two Michelson fibre interferometers were combined and share most of the optical path. One of the fibre interferometer acts as a measurement interferometer to carry out fast scanning and accurate phase measurement. The other interferometer is used to monitor the environmental perturbation. A feedback system was implemented to compensate for the phase noise caused by the environmental perturbations, e.g. temperature drift and mechanical vibration. As a result of shared optical path, the environmental noise in the measurement interferometer can be effectively eliminated. The main drawback of this system is that the reference interferometer can only be stabilized over a short range due to using a conventional optical phase modulator (cylinder PZT twisted with long-length fibre), which has a limited phase compensation range.

An improved optical fibre interferometry system is then proposed in order to solve the above problem [12]. It uses a single self-stabilized optical fibre interferometer with a near common-path configuration to replace the original multiplexed fibre interferometer. The beauty of the measurement system lies on the implementation of the 0th order diffraction beam as the reference beam of the interferometer, so that it remains still when the measuring beam scans the surface. Most of the environmental noise in the fiber is eliminated without any servo control system as there being no beam split across the fibre. A measurement accuracy of 4.1 nm has been achieved in the displacement measurement experiment. Although attractive, the system still suffers minor DC shifts due to environmental disturbance, especially mechanical vibration.

In this paper we propose a new configuration of measurement system based on the previous researches. The basic idea for this technique is to use a light-beam scanning to replace a conventional contacting stylus scanning, and to use compact fibre interferometer to replace the conventional bulky interferometer. In addition, a reference interferometer is combined with the measurement interferometer in order to cancel the environmental noise introduced during manufacturing progress. Experiments were conducted to test the measurement technique.

2. Experimental setup and measurement principle

The measurement system is a multiplexed interferometer with the combination of a reference interferometer and a measurement interferometer with shared optical path, as shown in Figure 1. Light from a tunable laser and a single wavelength laser diode is combined by the optical coupler. An all-fibre polarization scrambler is used to modulate the polarization state of the light in order to eliminate the polarization fading problem encountered in conventional fibre interferometric system. Circulator 1 is implemented to prevent light returning to the light sources. Light output from port 2 of circulator 1 is collimated by the gradient index lens and is then diffracted by the phase grating. The 1st and 0th order diffraction beams are projected onto the sample surface and a reference mirror respectively. The retro-reflected light is finally collected by the optical probe. The interference signal is detected by detector 1 through combining the 0th order and 1st order diffraction beams, in which, the 0th order diffraction beam acts as a reference and the 1st order diffraction beam as the measuring beam, with the grating acting as a beam splitter. The phase of the interference signal is modulated by the surface topography. Surface profile measurement can be conducted when the tunable laser is in the sweeping mode.

The reference interferometer illuminated by the laser diode is dedicated to monitoring the environmental disturbance such as mechanical vibration, temperature drift and air turbulence. The phase noise can be compensated by driving the PZT to move the reference mirror. As the two interferometers share most of the optical path except slight separation between the 1st orders diffraction beams, most of the environmental noise can be eliminated, thus facilitates the system applicable in a workshop environment. In addition, since both light from the tunable laser and that from the laser diode are incident on the same sample and reference mirror, any optical path change due to the mechanical vibration of the sample is effetely compensated by the servo feed back system. A computer controlled GPIB card is implemented to synchronize the different parts of the system in order to perform fast and precise phase scanning and measurements.

Extraction of phase data from the output of an interferometer is a well researched topic. In this system the 4 step Carré phase shift algorithm was implemented.

3. Experimental results

An actively stabilized interferometer as described above was established to evaluate the effectiveness of the proposed technique. In the experiments, the wavelength output from tunable laser (Ando Electric Co., Ltd) is swept between 1560 nm and 1580 nm, the phase grating features grooves of 900 lines/mm, a biconvex lens with a focal length of 6 cm was used to focus the light beam onto the sample surface to be inspected, thus a lateral scan width of 1.08 mm was realized.

Figure 2 (a) shows the measurement interferometer output over 1 minute with the reference interferometer turned on and off. Figure 2 (b) shows the power spectral densities of these two signals. The measurement interferometer shows a much improved stability when the reference interferometer is turned on and locked. Low-frequency noises, such as those due to air turbulence and temperature drift were significantly reduced. The signal-to-noise ratio was improved by over 100 times.

The surface profile of a mirror was measured 6 times in an environment with air turbulence of about 90 Hz, as shown in Figure 3. The overall slope and partial undulation of acquired data also represents some surface incline and waviness of the mirror.

Figure 4 shows the standard deviation of the 6 measurements, ranging from 1.9 nm to 6.6 nm. The mean value of these deviations is 3.3 nm.

4. Discussion

Compared with interferometery surface measurement technique using a two-dimensional detector, e.g. a CCD camera, the proposed method is more flexible in terms of dynamic range, area examined and data density due to using point detector. The measurement speed is mainly limited by the wavelength sweep speed (100nm/s) of the tunable laser implemented in the experiment. Currently, a fast tunable laser with tuning speed of 2mm/s is available. Real-time measurement is possible when such a tunable laser is employed.

Furthermore, multiple on-machine probes can be connected to a single main body through a fibre switch with a fast response speed, as shown in Figure 5. This configuration is to facilitate the measurements of many points of a large sample without readjusting the probe, and make full use of the expensive tunable laser.

The biggest challenge to the system performance is the objective lens. An aberration corrected microscope objective lens should usually be implemented to improve the measurement lateral resolution. In order to collect the light retro-reflected from the sample surface, the sample and the grating in Figure 1 should be placed at the front focal point and rear focal point respectively. However, for a standard commercial achromatic microscope objective lens, the rear focal plane usually resides in the centre of an internal glass lens element, which makes it difficult to place the grating. A specially designed microscope lens is required to solve this problem.

Future research work will be focused on designing a microscope objective lens with large aberration corrected angle and long rear focal length for the system in order to improve the lateral resolution, and attempt to develop a multi-probe measurement instrument for fast on-line micro/nano scale surface measurement.

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Figure Captain

Fig. 1. Schematic diagram of fibre interferometer for on-line surface measurement

Fig. 2. (a) Measurement interferometer outputs over 60 seconds when reference interferometer was turned on and off respectively, and (b) comparison of their power spectral density.

Fig. 3. Results of measuring the surface profile of a mirror for 6 times

Fig. 4. Standard deviation of the 6 measurement of the sample surface

Fig. 5. Schematic diagram of a multiple-probe configuration that facilitates the measurements of many points of a large sample without system readjustment

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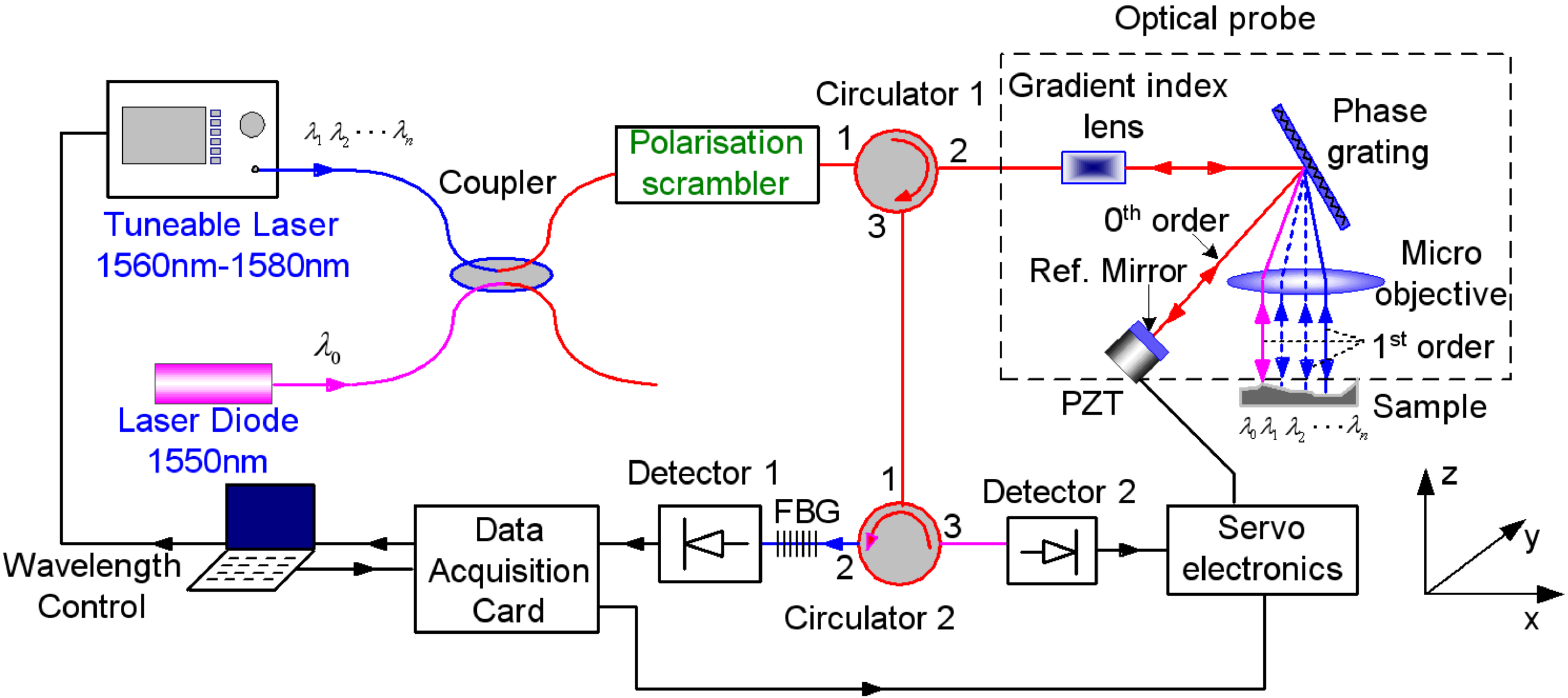
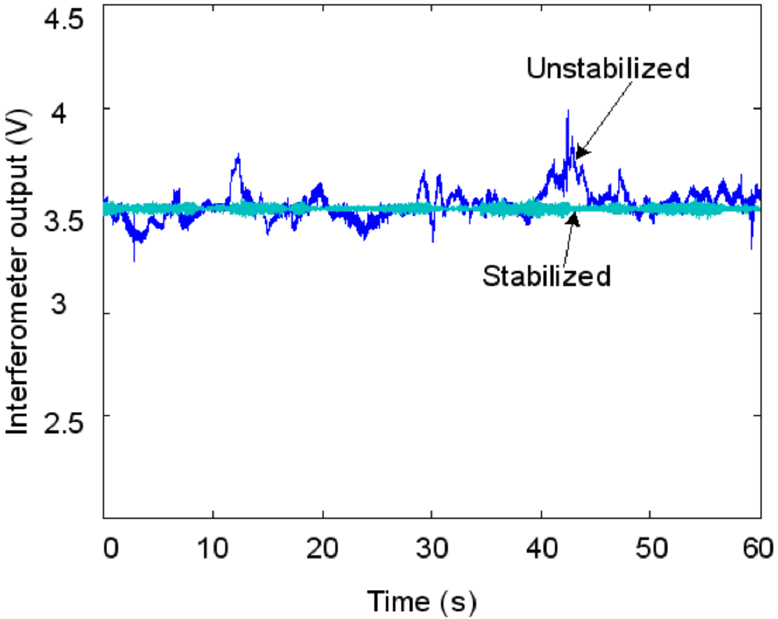
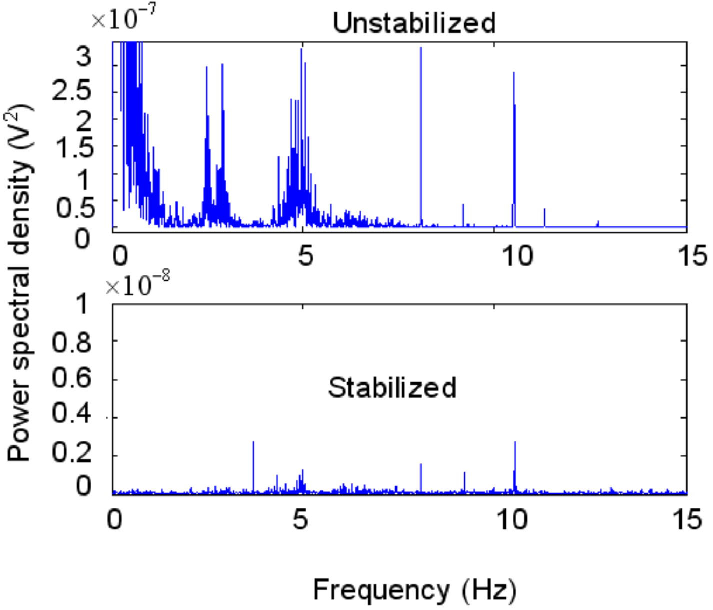
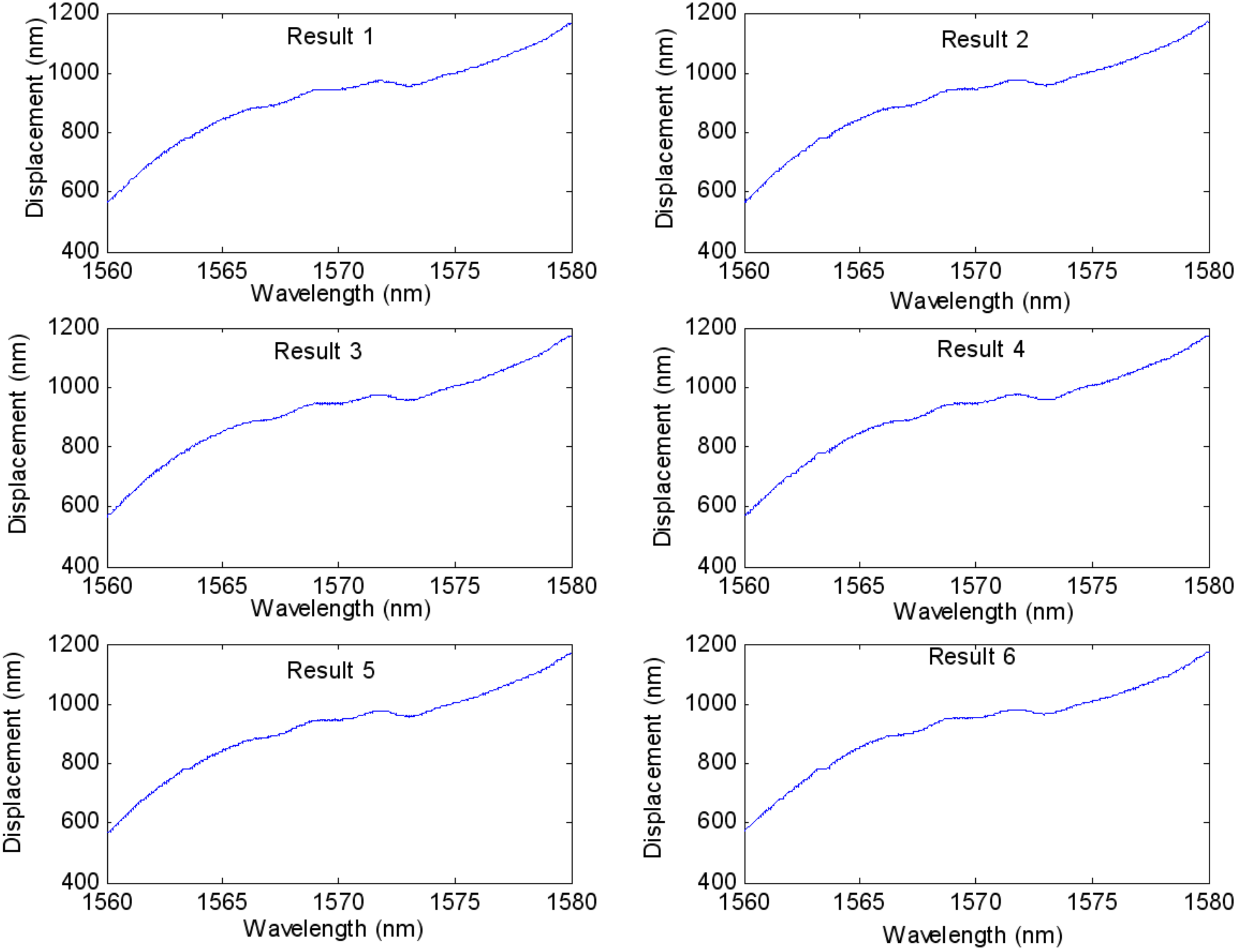

Optical probe
Tuneable Laser
1560nm-1580nm
$\lambda_1\ \lambda_2 \cdots \lambda_n$
Coupler
Polarisation scrambler
Circulator 1
1
2
3
Gradient index lens
Phase grating
0^{th} order
Ref. Mirror
Micro objective
1^{st} order
PZT
Sample
$\lambda_0\ \lambda_1\ \lambda_2 \cdots \lambda_n$
λ_0
Laser Diode
1550nm
Detector 1
FBG
1
2
3
Detector 2
Servo electronics
Data Acquisition Card
Circulator 2
Wavelength Control
z
y
x

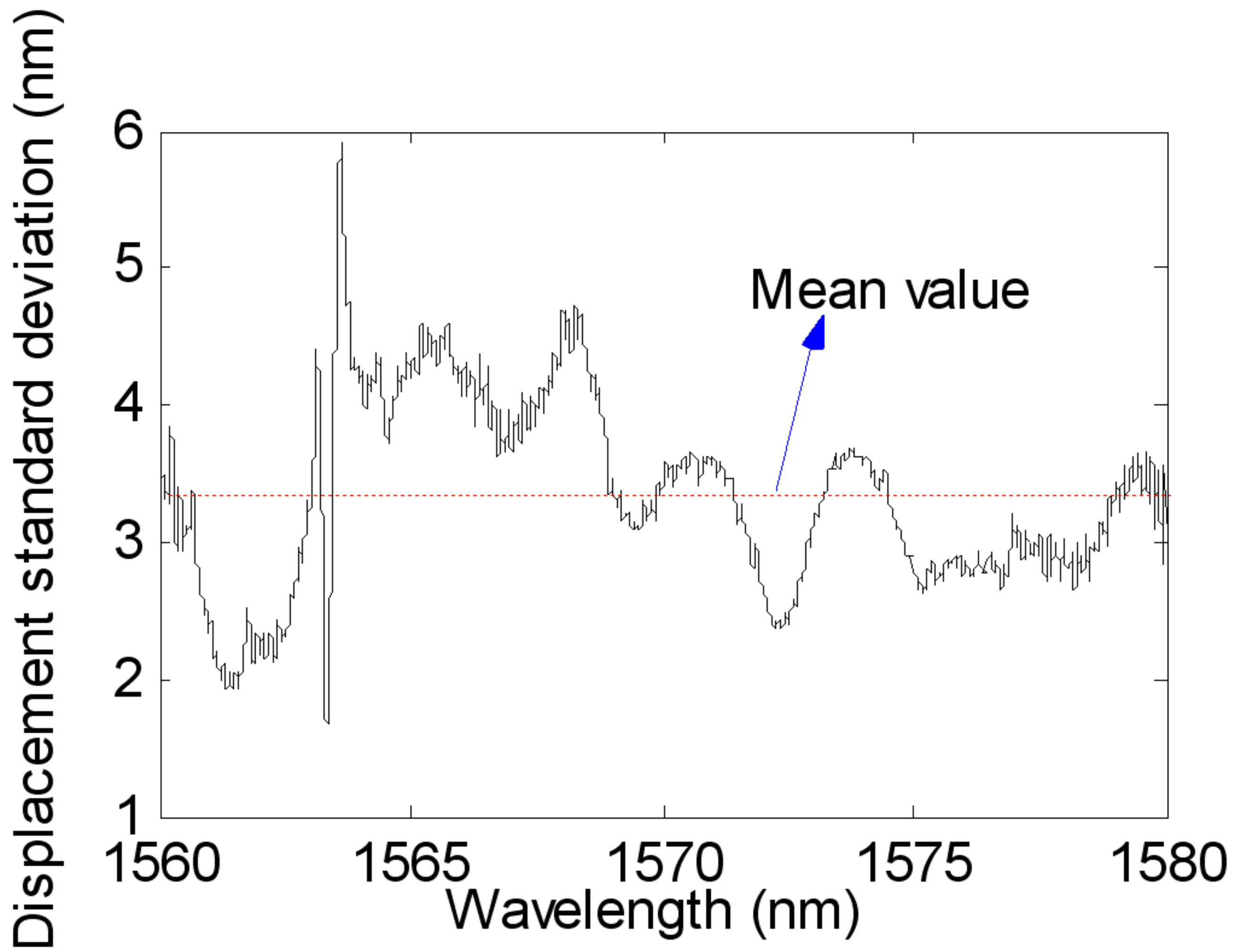

Interferometer output (V)
4.5
4
3.5
3
2.5
Unstabilized
Stabilized
0
10
20
30
40
50
60
Time (s)

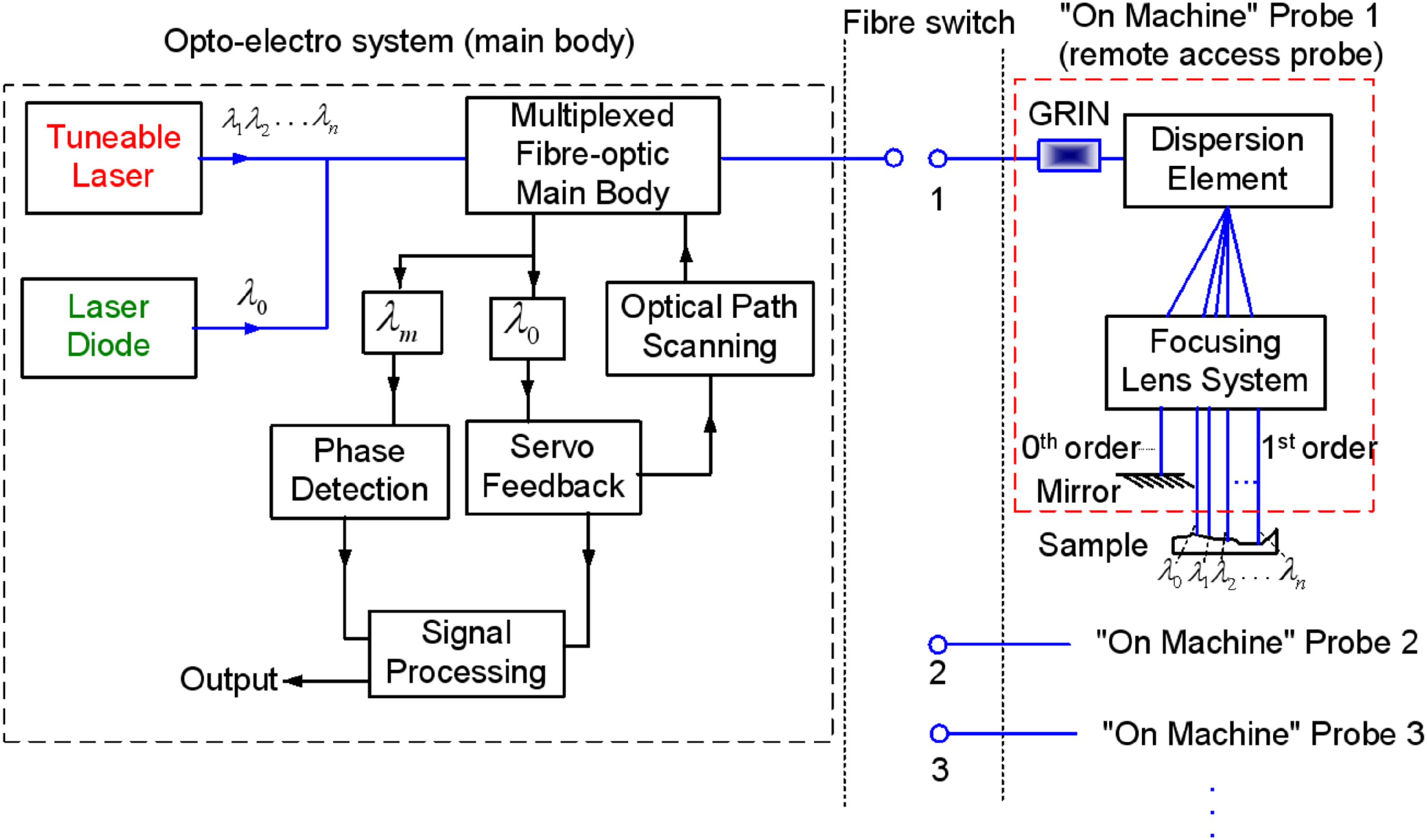
(a)


×10^-7
Unstabilized
Power spectral density (V^2)
3
2.5
2
1.5
1
0.5
0
0
5
10
15
×10^-8
1
0.8
0.6
0.4
0.2
0
Stabilized
0
5
10
15
Frequency (Hz)

(b)


Result 1
Result 2
Result 3
Result 4
Result 5
Result 6
Displacement (nm)
Wavelength (nm)
400
600
800
1000
1200
1560
1565
1570
1575
1580


Displacement standard deviation (nm)
Wavelength (nm)
Mean value
1
2
3
4
5
6
1560
1565
1570
1575
1580


Opto-electro system (main body)
Fibre switch
"On Machine" Probe 1
(remote access probe)
Tuneable Laser
$\lambda_1 \lambda_2 \dots \lambda_n$
Multiplexed Fibre-optic Main Body
GRIN
Dispersion Element
1
Laser Diode
λ_0
λ_m
λ_0
Optical Path Scanning
Focusing Lens System
0^{th} order
1^{st} order
Mirror
Phase Detection
Servo Feedback
Sample
$\lambda_0 \lambda_1 \lambda_2 \dots \lambda_n$
Signal Processing
Output
"On Machine" Probe 2
2
"On Machine" Probe 3
3