Investigation of some critical aspects of on-line surface measurement by a wavelength-division-multiplexing technique

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Abstract

A multiplexed fibre interferometer (MFI) based on wavelength-division-multiplexing (WDM) technique is proposed for on-line surface measurement. It combines two fibre interferometers, measurement and reference interferometers, which share a large proportion of their optical paths. The reference interferometer incorporating with fibre Bragg grating (FBG) is used to compensate for environmental fluctuations so that the measurement interferometer can execute high stability and high precision measurements. An active phase tracking homodyne (APTH) technique is applied for signal processing to achieve a phase resolution of 10^{-6} rad. WDM-FBG techniques provide implementation of phase-to-depth and wavelength-to-field detection and offer a large dynamic measurement ratio (range/resolution) with a high signal-to-noise ratio (robustness). Two types of optical probes, using a dispersive prism and a blazed grating respectively, are investigated to realise wavelength-to-spatial scanning. The experimental results testified the feasibility of on-line surface measurement by this methodology.

Keywords: multiplexed fibre interferometer, wavelength-division-multiplexing, fibre Bragg grating, on-line surface measurement

1. Introduction

Nanotechnology applications, such as automotive air bags sensors, ink jet printer nozzles, micro lens arrays, pressure sensors and epitaxial semiconductor wafers, etc. are now becoming more common [1-3]. The projected expansion of the use of MST devices is predicted to be enormous and not limited to particular sectors such as electronic devices. The fabrication of integrated circuits and MST/MEMS devices is now a mature technology in many senses, however their broad use across a number of sectors has highlighted one of the problems of micro and nano scalar manufacture namely, large region surface measurement (for form and waviness) and fast quality control in the production field [4-8].

In the last decade, a few investigations have been devoted to on-line surface measurement by using optical methods [9-12]. All of them were intended to carry out the measurements for surface profile rather than surface roughness. The latter obviously demands higher measurement accuracy and resolution though the large measurement range is preferred as well.

On other hand fast on-line measurement techniques with ultra precision accuracy and large measurement range/resolution has been required in industrial applications. Up to now there has been no technique that meets the requirement. The modern manufacture and its supporting metrology face a great challenge to develop novel measuring approaches to achieve ultra high measuring precision with less cost for micro and nano scale engineering products.

In this paper, an on-line surface measurement principle is demonstrated in which the combination of wavelength division multiplexing (WDM) and fibre Bragg grating (FBG) techniques are used [13, 14]. The optical measurement system multiplexes two Michelson fibre interferometers with shared optical path in the main part of the optical system, one of which is used as a reference interferometer to monitor and control the high accuracy of the measurement system under environmental perturbations; the other offers remote measurement with high precision in workshop environment. Spatial light-wave scanning over the surface to be measured is used to reduce the requirement of mechanic scanning that is major source of spurious signal. A prototype measurement system is built to demonstrate the feasibility and applicability of the optical principles. This technique is expected to be employed in the Silicon processing industry, nano-manufacturing environments, ultra precision machining, and biomedical implant testing etc.

2. Principle and System configuration

The basic configuration of a surface measurement system employing the proposed technique is illustrated in Figure 1. The realisation of the fast on-line optical measurement is based on the WDM-FBG Multiplexed optical fibre interferometer combined with a dispersive optical probe. The interferometer adopts a Michelson configuration incorporating an FBG in one arm to form a multiplexed structure [14]. Two light sources, a laser diode and a tuneable laser, are used in this multiplexed interferometer. The light from the laser diode is reflected by the FBG to form a reference fibre Michelson interferometer independent of the surface to be measured. This reference interferometer is stabilised by a servo feedback system to suppress fluctuation in output phase of the interferometer induced by environmental perturbation [8-9]. A dispersive optical probe is mounted on one arm of the interferometer. The light beam from the tuneable laser is passed through this optical probe and launcheded onto the surface to be measured, and is reflected and then collected by the optical probe. When the operating wavelength differs from that of the laser diode the system multiplexes two Michelson fibre interferometers with shared optical path in the main part of the optical system.

The optical dispersive probe converts the spatial information of the surface into an optical signal and determines the lateral scanning range/resolution. The probe is designed as an independent unit that can be spaced far away from the main interrogation body, allowing a great flexibility to accommodate on-line applications. Figures 2 and 3 shows the schemes of optical probe using different dispersive elements. In Fig. 2, the optical probe consists of a fibre GRIN lens, a dispersion device (e.g., optical prism), and a collimating lens. After passing through the dispersive prism the light beam is launched in different angle corresponding to the laser wavelength, and collimated by the collimating lens and then projected onto the surface to be measured. While in Fig. 3 a blazed grating is used to diffract the light with different wavelengths. The light spot on the diffraction grating is positioned at the focus point of the lens so that the light through the lens is vertically incident on the sample and reflected back along the same path. The light reflected from the surface will have the surface information and travel over the same optical path in the reversed direction to the fibre coupler.

3. Experimental study

3.1 The performance of Laser Diode and FBG

According to the analysis of section 2, the function of the FBG is to enable the reference light (with the wavelength of λ_o) to be reflected back while to let the measurement light (with the wavelength of λ_m) pass through it. As is shown in Fig. 4, the central wavelength of the used laser diode (LD) is around 1550.2nm with fluctuation of no more than 0.2nm. Accordingly the FBG was specially designed to have a relatively broad band-pass of wavelengths. Fig. 5 describes the characteristics of one FBG we used, in which the light with the wavelength range of 1548.2nm to 1551.3nm can be reflected by the FBG. The reflection bandwidth of the grating used is clearly larger than the wavelength fluctuation of the LD used, therefore the light from the LD can always be reflected back. It should be pointed out that in the real application both LD and FBG must be well stabilised to eliminate this kind of uncertainty. The LD will provide stable spectral response by using precise temperature and operating current control. The perturbation to the FBG can be minimised by using some mature packaging technology.

3. Wavelength-to-spatial scanning by two dispersive components

As mentioned in section 2.1, a dispersive prism combined with an objective lens can be utilized to divide the light with different wavelengths; or alternatively a chromatic objective lens can be directly used to realize the WDM (the light is projected onto the edge of the lens). The advantages of using the dispersive prism to separate light with different wavelengths are relatively convenient adjustment and less cost. This method can lead to design a very compact and tiny structure probe, and be developed to measure wall surface finish in a high accurate component.

However, the scanning range of a dispersive prism structure's probe will be limited due to the dispersion property of the prism material. To extend the scanning range, an alternative scheme using a blazed grating is applied to diffract the light with different wavelengths, which is demonstrated in Fig. 3. From the grating equation we can get:

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

where d is the grating pitch, α and β are the incidence and diffraction angles respectively, m is the diffraction orders and λ is the wavelength.

A reflection blazed grating was adopted in our system. In normal applications of the blazed grating, the diffraction angle should be equal to the incidence angle so as to obtain the maximum efficiency, that is: $\alpha=\beta=\theta$, where θ is the blazed angle. Whereas to enable the convenient placement of the objective lens, the incidence angle α needs to be adjusted to be a bit larger or smaller than the blazed angle θ. According to Eq. (1), different diffraction angles β_i are derived from varied wavelength λ_i, which are determined by:

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

It is easy to know that the scanning range of surface (S) can be demonstrated as:

$$S = f\,(\sin\beta_{\max} - \sin\beta_{\min}) \tag{3}$$

where f is the focal length of objective lens. Assuming the blazed grating has a 1st order maximum diffraction (m=1) and substituting Eq. (2) into Eq. (3), we can get:

$$S = f\cdot\frac{\Delta\lambda}{d} \tag{4}$$

Where $\Delta\lambda = \lambda_{\mathrm{max}} - \lambda_{\mathrm{min}}$, is the range of wavelength scanning. The reflected signals are recorded by an optical spectrum analyser (OSA). The surface information is obtained by means of phase detection and signal processing. It is noted that similarly to other optical measurement methods, the surface to be measured should not be too rough otherwise the collected signal will be too weak to detect. This can usually be satisfied in the measurement of high-precision machined surface.

In the experiment a blazed grating (produced by Jobin Yvon Ltd, model: 5109720) was adopted to realise the WDM. The basic parameters of the grating are: grating pitch d=1.11μm; its central blazed wavelength λ_B = 1550nm; and the efficiency of diffraction at around the central blazed wavelength η = 60%, as is shown in Fig. 6. The spectra of reflected light from the sample were recorded and demonstrated in Fig. 7. We can find the light intensity is flat for the wavelengths between 1560nm to 1620nm for the phase measurement of surface. The transverse scanning range along the sample is around 5mm. Fig. 8 demonstrates the comparison between the schemes using the dispersive prism and diffraction grating respectively. From the point of view of available measurement range the blazed grating can provide much larger dispersion, thus larger diffracted angle than the prism does, indicating a larger transversal scanning range.

3.3 Phase measurement of multiplexed fibre interferometer

The environment disturbance such as the fluctuation of temperature and vibration can seriously influence the stability of a single fibre interferometer. However, it was successfully compensated by the feedback system of MFI that can trace the phase drift of the interferometer in real time. As shown in Fig. 9, the output of the measurement interferometer has been kept very stable after the reference interferometer was stabilised.

In order to look at the performance of the measurement interferometer a piezo-electronic transducer (PI-FOC PZT) was used to drive a mirror that acted as the surface to be measured while reference interferometer was stabilised. A large DC voltage was first applied to the PZT. As a result, a sine-wave output was obtained, as shown in Fig. 10.

A small dither signal was also applied to the PZT and the output of the measurement interferometer was detected. A resolution of 10^{-6} rad in phase measurement was obtained while the multiplexed fibre interferometer was operated in the laboratory environment and the operating wavelength of the tuneable laser was fixed at 1570nm. This indicates that the measurement system can sustain the environmental perturbation and provide high measurement resolution (this phase resolution implies a theoretically available spatial resolution of 0.25pm when operated around this wavelength).

5. Conclusion

We have demonstrated a multiplexed fibre interferometer and its feasibility in the application of surface roughness measurement. In addition to the implementation of basic principle of wavelength-to-field detection by WDM technique we have investigated the performance of multiplexed fibre interferometer. Two types of optical probes have been studied. The phase measurement of the measurement interferometer has been carried out while the reference interferometer was used to stabilise the interferometer and set the operating point of the measurement system. In the experiments now the optical probe is comprising of several discrete components, which introduces larger system noise than expected. The practical surface measurement could be realised by scanning the tuneable laser and measuring the phase shift of it reflected optical signal when the integration of the optical probe is completed.

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Figure captions:

Figure 1. The schematic for the novel surface measurement device using the WDM technique

Figure 2. The scheme of wavelength scanning by prism and chromatic lens

Figure 3. The scheme of wavelength scanning by blazed diffraction grating

Figure 4. The output spectrum of Laser Diode (the drift of central wavelength is no more than 0.2nm)

Figure 5. The Reflectance Spectrum of Fibre Bragg Grating (FBG)

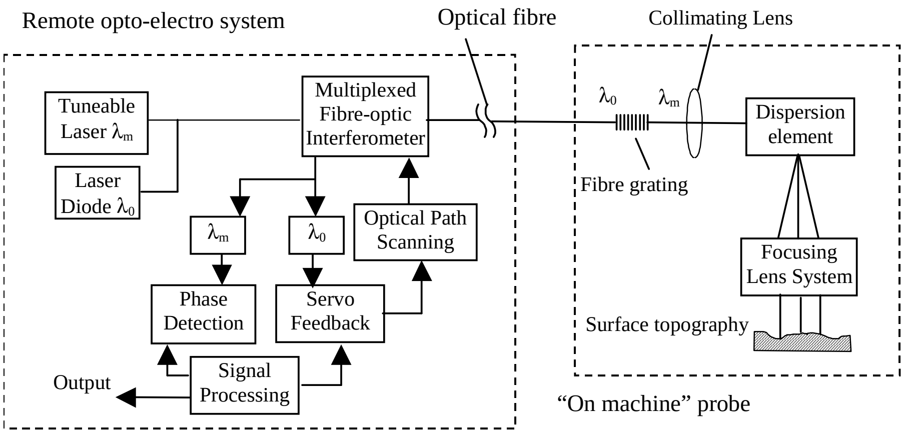
Figure 6. The Response curve of blazed diffraction grating

Figure 7. The spectra of reflected signal from the sample to be measured (by blazed grating)

Figure 8 The transverse scanning range in terms of varied wavelength by using the dispersion prism and diffraction grating

Figure 9. The variation of light intensity of the multiplexed fibre interferometer (MFI) before and after stabilisation

Figure 10. Demonstration of measurement of the multiplexed interferometer



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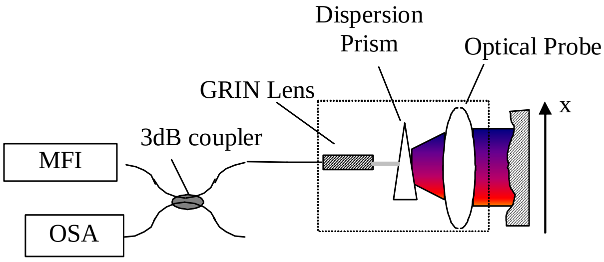

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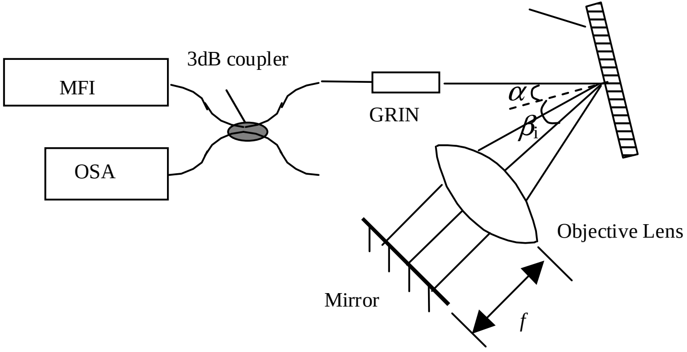
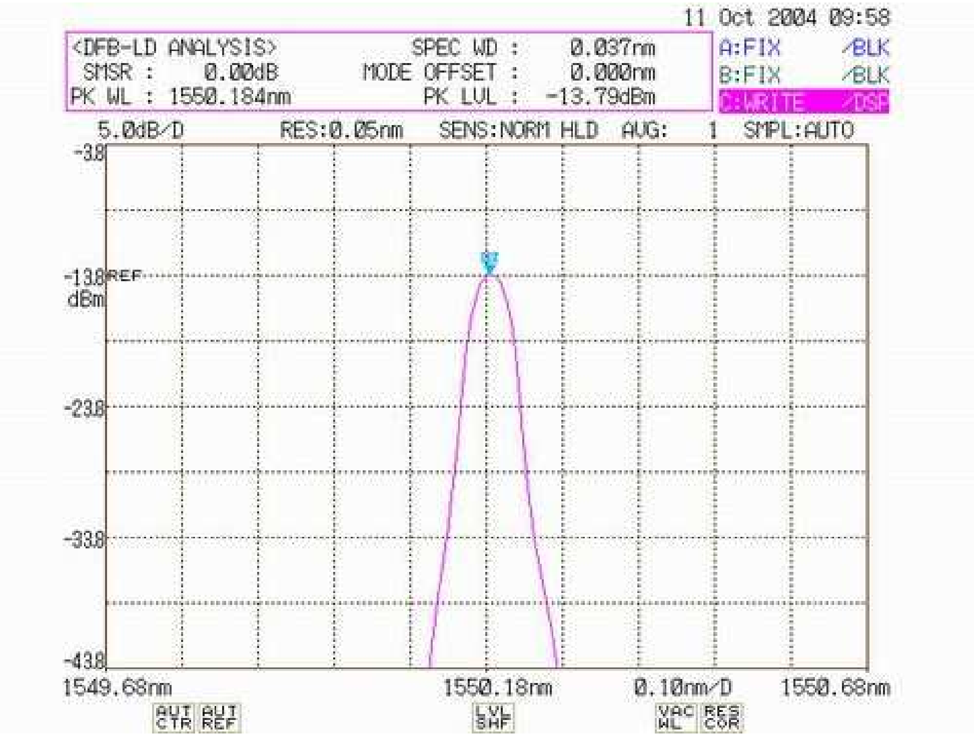


Figure 3. The scheme of wavelength scanning by blazed diffraction grating



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   5.0dB/D        RES:0.05nm   SENS:NORM HLD  AVG:    1  SMPL:AUTO
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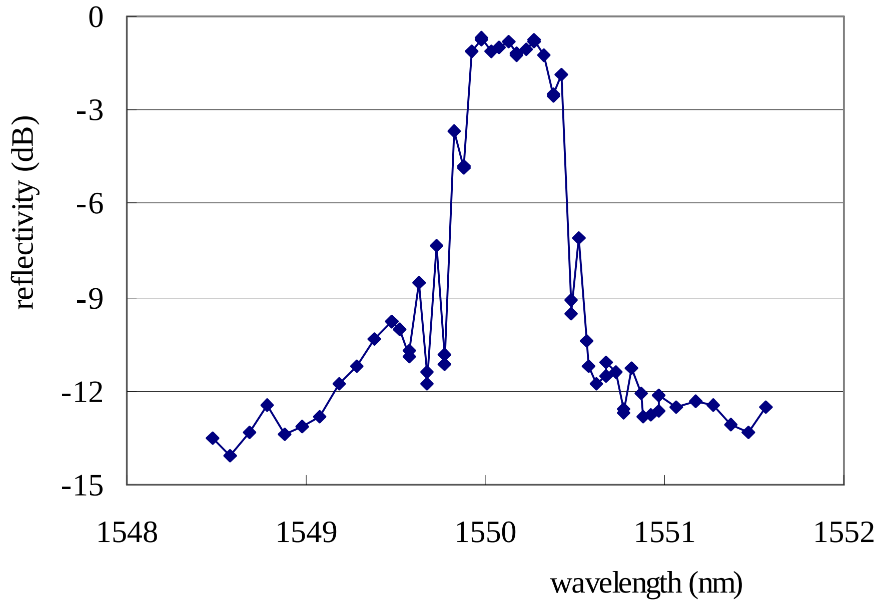

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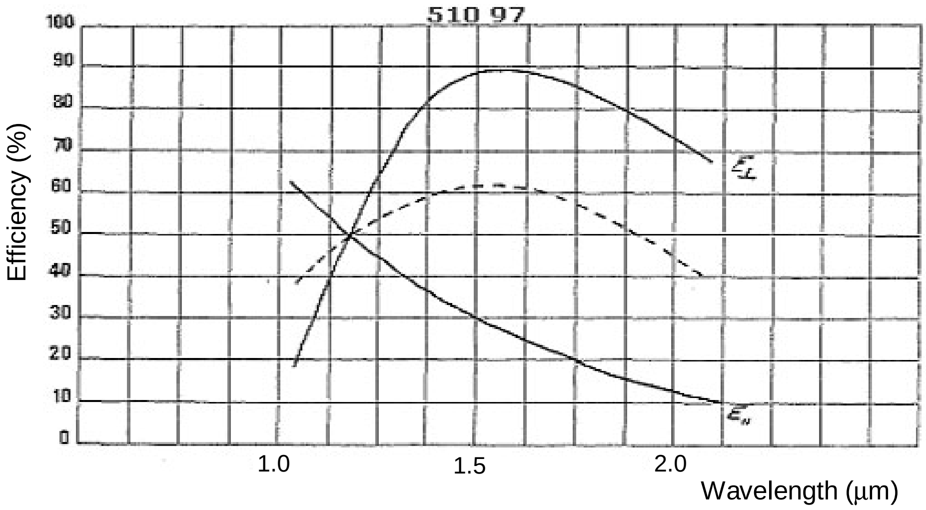

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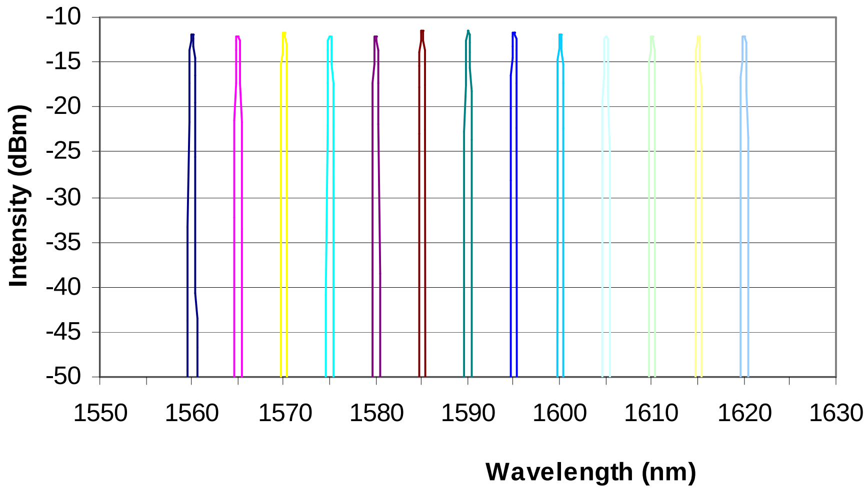

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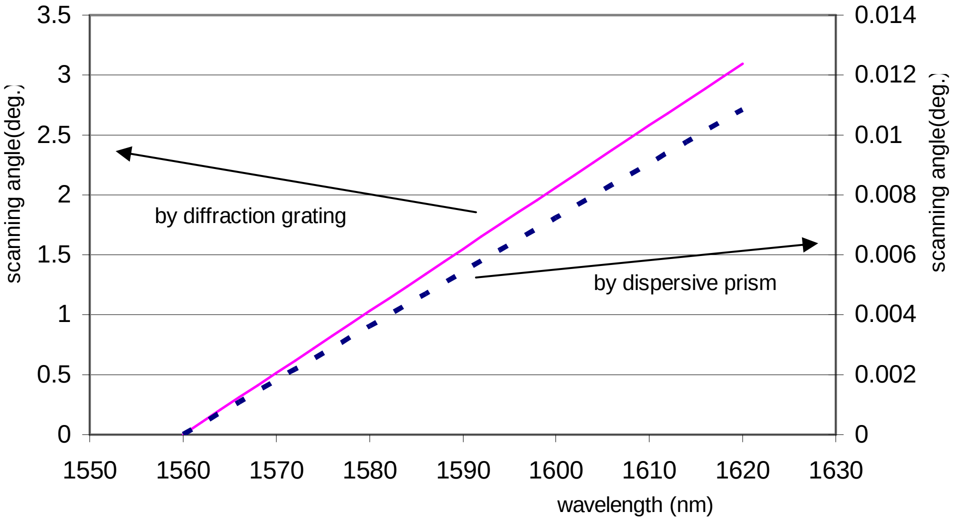

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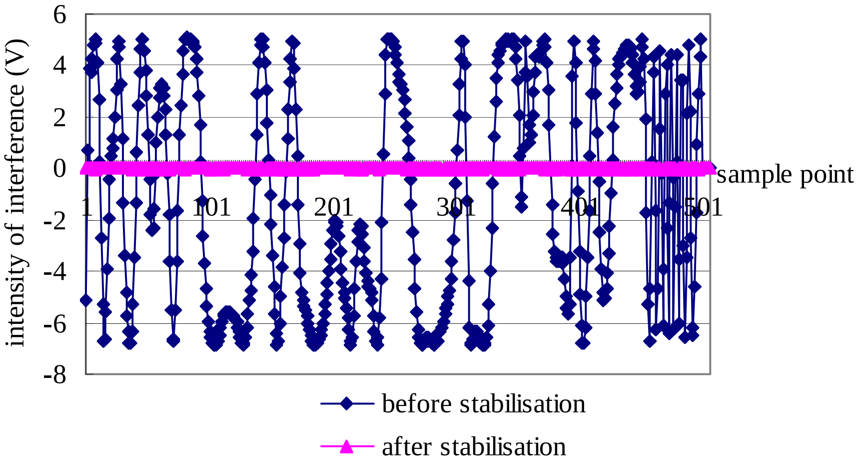

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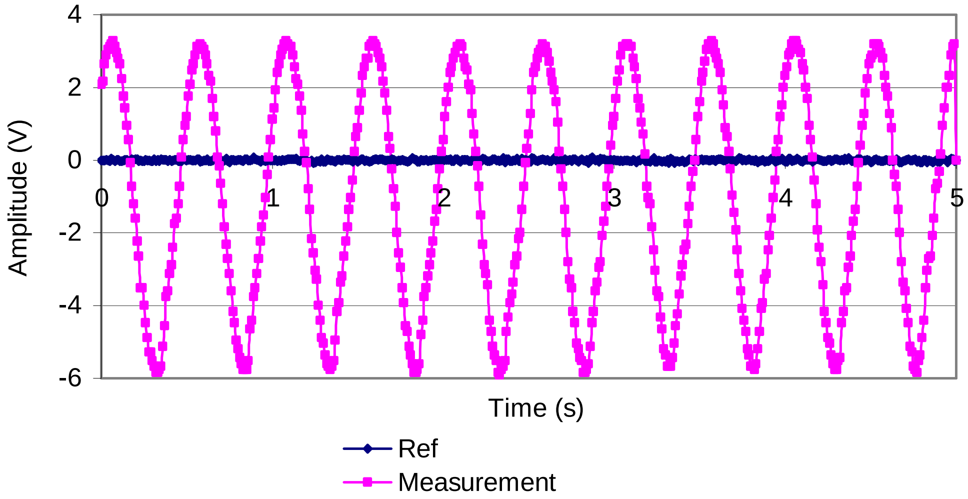

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