High stability multiplexed fibre interferometer and its application on absolute displacement measurement and on-line surface metrology

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Abstract: We propose a self-reference multiplexed fibre interferometer (MFI) by using a tunable laser and fibre Bragg grating (FBG). The optical measurement system multiplexes two Michelson fibre interferometers with shared optical path in the main part of optical system. One fibre optic interferometer is used as a reference interferometer to monitor and control the high accuracy of the measurement system under environmental perturbations. The other is used as a measurement interferometer to obtain information from the target. An active phase tracking homodyne (APTH) technique is applied for signal processing to achieve high resolution. MFI can be utilised for high precision absolute displacement measurement with different combination of wavelengths from the tuneable laser. By means of Wavelength-Division-Multiplexing (WDM) technique, MFI is also capable of realising on-line surface measurement, in which traditional stylus scanning is replaced by spatial light-wave scanning so as to greatly improve the measurement speed and robustness.

OCIS codes: (120.3180) Interferometry; (060.2310) Fiber optics; (120.5050) Phase measurement; (120.6660) Surface measurements

References and links

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1. Introduction

Optical fibre interferometer has been widely used for modern on-line metrology due to its prominent advantages such as non-contact, compactness, high resolution and low cost [1-4]. However, it suffers from the problem of environment disturbance from temperature and air drift, etc. With the overwhelming requirement for ultra high precision industry (including the micro-mechanic system and nano technology), attention has to be paid to establish an advanced fibre interferometer with high stability and robustness.

A multiplexed fibre interferometer (MFI) with the function of self-reference is therefore proposed. It multiplexes two Michelson fibre interferometers with the same optical paths for most part of the optical system. In one arm of MFI, a fibre Bragg grating [5] is used to reflect the light of reference interferometer. A feedback system using a cylinder piezo-electronic transducer (PZT) twisted with optical fibre is applied to stabilise the reference interferometer [6]. The measurement interferometer is then also stabilised as it shares most optical path with that of the reference interferometer, accordingly the influence of environment noise can be effectively reduced. An active phase tracking homodyne (APTH) technique [2] is applied to achieve high resolution for MFI.

A tunable laser is adopted as the light source, such that high precision and large range absolute displacement measurement (ADM) is feasible to perform by different combination of wavelengths. The problem of phase ambiguity in normal optical coherence interferometers [7] is overcome. The experimental results as well as measurement principle for ADM are given. Meanwhile, by means of the optical probe design with phase diffractive grating and objective lens, MFI can also be applied in the area of on-line surface metrology using the wavelength-division-multiplexing (WDM) technique. The traditional stylus or other mechanical scanning [8,9] is replaced by spatial light-wave scanning, thereby the measurement speed and stability will be improved to a great extent.

2. Theory and system setup

2.1 Multiplexed fibre interferometer (MFI)

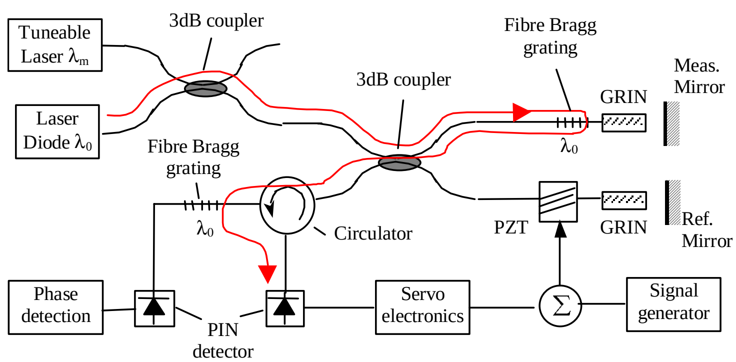

Fig. 1. The schematic of multiplexed fibre interferometer

The multiplexed fibre interferometer (MFI) combines two Michelson fibre interferometers with shared optical path in the main part of the optical system, as is shown in Fig. 1. The first fibre optic interferometer is used as a reference interferometer to eliminate environmental noise. It is probed by a laser diode with the wavelength λ_o and phase-locked by tuning the optical fibre phase modulator. The light with the wavelength λ_o is reflected by a fibre Bragg grating (FBG) that is placed just before a collimator GRIN, such that it has no phase information caused by moving the mirror but the phase fluctuation caused by environmental perturbation to the fibre interferometer. The interference light from the other output of 3dB coupler that combines the measurement and reference beams is reflected by the second FBG and received by a PIN detector. An active phase tracking homodyne (APTH) technique is adopted in which a PZT fibre phase modulator is incorporated into the reference arm of the

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interferometer and acts as part of a servo feedback loop to maintain the fibre interferometer locked at its quadrature status [2,3]. A high resolution, 10^{-6} rad in phase measurement, can be achieved in our system.

The second interferometer with the wavelength λ_m is used as a measurement interferometer to obtain information from the measurement mirror. This interferometer shares almost all the optical paths as the first interferometer except having an optical probe section. The light source for the second interferometer that is provided by a tuneable laser operates at a different range of wavelengths from the first. It passes through the FBG and is collimated by GRIN to project on the measurement mirror, and then reflected back. When it passes through the second FBG and received by the other PIN detector, the displacement of the measurement mirror is determined by phase detection. As a result of the shared optical fibre paths the second interferometer will be capable of measuring the displacement without phase fluctuation from environment once the first interferometer is “locked”. To eliminate the effect of polarisation fading [10], a fibre polarisation scrambler is inserted between the light source and MFI.

2.2 Absolute displacement measurement by MFI

A problem of normal optical interferometric technique is the interference phase ambiguity of 2π. One way to extend the range of applications for interferometry is to measure the interferometric phase at two distinct wavelengths. There have been a number of proposed systems based on this idea [11]. By means of MFI we present, it is convenient to realise absolute displacement measurement (ADM) with the range much larger than one wavelength. Different composition of wavelengths from a tunable laser (or a broadband light source with FBGs) enables the ADM for various requirements of measurement range and resolution.

The detected interference phase θ from a monochromatic light source illuminated interferometer can be described as

$$\theta = Mod(2\pi \cdot \frac{nL}{\lambda}) \tag{1}$$

where n is the effective refractive index of the fiber, λ the wavelength of the source, L the optical path difference of the interferometer where the information of measurement mirror is included. The function *Mod* returns the remainder modulo 2π. Obviously the unambiguous phase change is limited to 2π, indicating a displacement range of only 1.55μm as the operating wavelength is around 1.55μm. When the interferometer is illuminated with two wavelengths λ_1 and λ_2, a synthetic phase Θ can be obtained with an expression similar to Eq. (1), that is

$$\Theta = Mod(2\pi \cdot \frac{nL}{\Lambda}) \tag{2}$$

where $\Lambda = \lambda_1 \cdot \lambda_2 / (\lambda_1 - \lambda_2)$, is the synthetic wavelength. There is no ambiguity in the measurement as far as nL is less than Λ. For a wavelength difference of 1nm, the measurement range can be extended to 2.4mm.

2.3 On-line surface metrology by MFI

The basic configuration of an on-line surface roughness measurement system employing MFI is demonstrated in Fig. 2. Light from a tunable laser (λ_m) and a laser diode (λ_0) is coupled into MFI. The optical probe is mounted in one of the interferometer arms. The light beam emits onto the surface to be measured, reflected and collected by the optical probe. The surface roughness information then modulates the phase of the reflected light beam. The wavelength-spatial transformation of optical chromatic dispersion device is employed in the optical probe to convert the spatial scanning of the surface into a wavelength scanning. As the tunable laser allows fast sweeping tuning a straight line can be quickly scanned over the surface.

#5443 - $15.00 US Received 7 October 2004; revised 5 November 2004; accepted 7 November 2004

An optical probe is designed by the combination of a phase diffraction grating and an objective lens. The phase grating, whose first diffraction order is the maximum, enables the collimated light with different wavelengths to be diffracted in different angles. 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 scanning range of surface (*S*) is demonstrated as

$$S = f \cdot \frac{\Delta\lambda}{d} \quad (3)$$

where *f* is the focal length of objective lens, *d* is the pitch of phase grating and $\Delta\lambda$ is the range of wavelength scanning. The reflected signals are recorded by an optical spectrum analyser (OSA). The information of surface is obtained by means of phase detection and signal processing. As the optical probe and the sample can be placed far away from the main system, on-line surface measurement will be realised.

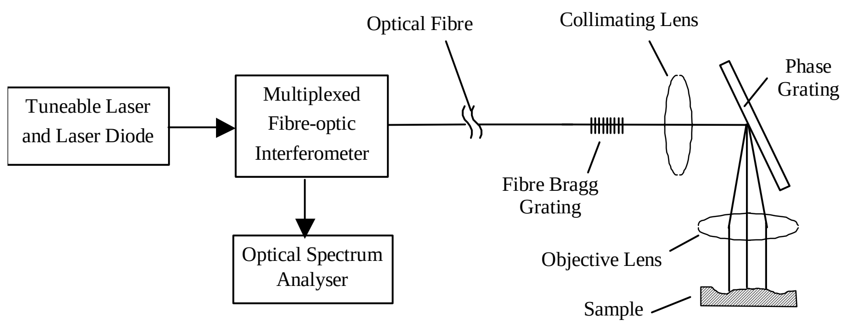

Fig. 2. The schematic of on-line surface measurement by means of MFI

3. Experimental results

3.1 The stability of MFI

The environment disturbance such as the drift of temperature and vibration normally influences seriously the stability of single fibre interferometer, however, were successfully compensated by the feedback system of MFI, as is shown in Fig. 3. A resolution of 10^{-6} rad in phase measurement was obtained.

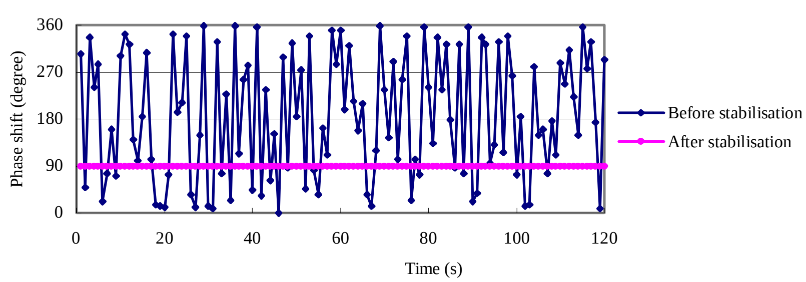

Fig. 3. The phase shift of fibre interferometer before and after stabilization

3.2 The result of ADM by MFI

The measurement wavelengths, λ_1(1555.7nm) and λ_2(1556.2nm), are well away from the reference wavelength λ_0(1540.6nm). The initial wavelength difference between λ_1 and λ_2 is around 0.5nm. The phase of λ_1, λ_2 were detected separately and processed to give the phase information at the synthesised wavelength Λ. A measured result over 200µm range is given in Fig. 4. By means of changing the wavelengths from the tunable laser, different measurement range and sensitivity can be acquired. The measurement result with the wavelength difference of 2nm is also demonstrated in Fig. 4.

The accuracy of synthetic wavelength distance measurement is usually determined by the stability of wavelength and the phase detection [11]. The stability of the wavelength is $\Delta\lambda/\lambda=6\cdot10^{-7}$ in our system. The synthesised phase in this scheme is actually a differential phase of optical signals at two wavelengths λ_1, λ_2. As the OPD for the two wavelengths can not be set at quadrature status simultaneously, the high resolution (10^{-6} rad) and accuracy of phase measurement by APTH technique will be reduced [2]. Moreover, the actual phase change for each wavelength is much larger than 2π when it is applied for large-range measurement. As a result the synthesised phase measurement produces a measurement resolution with the order of source wavelength. To overcome this problem, integrating the methods of synthesised wavelength and individual wavelength (set at quadrature status) will implement both large-range and high-resolution distance measurement.

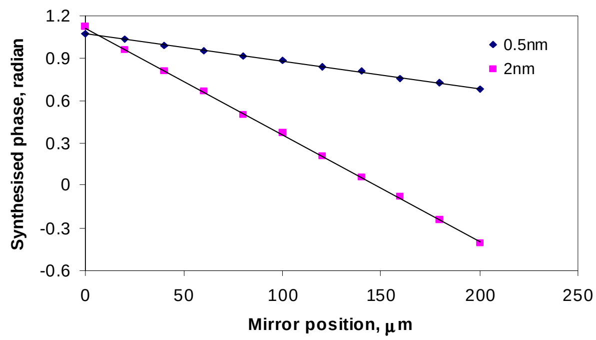

Fig. 4. Experimental results of ADM by synthesised phase over 200µm measurement range

3.3 The investigation for the feasibility of on-line surface metrology by MFI

The recorded optical spectra by OSA are shown in Fig. 5 when the tunable laser was tuned from 1530nm to 1585nm. It can be seen that the reflected signal shows a very flat response over 50nm wavelength range with a central wavelength of 1550nm. A linear spatial scanning of ~10mm on the sample is produced, which is sufficient for most high precision surface measurement. The spatial scanning range can be further increased if a phase diffraction grating with smaller pitch is used. It is noticed that the amplitude of the received signal diminished quickly after 1580nm. This is resulted from the limited numerical aperture of the objective lens as the light with the wavelength higher than 1580nm is diffracted in a too larger angle to be collimated by the objective lens. Lens with larger NA will allow a wider wavelength tuning range with flat response.

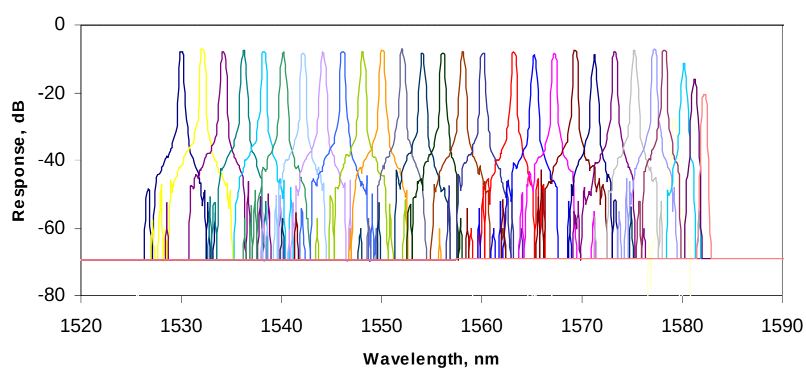

Fig. 5. Captured optical spectra of reflected signal

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3.4 Eliminating the effect of polarisation fading of MFI

It should be noted that stability is an essential character for the MFI. The APTH technique can compensate most random phase fluctuation caused by environmental perturbation. However, the polarisation fading always exists in the fibre interferometer, which could cause serious error in the measurement. This problem was addressed by inserting a fibre polarisation scrambler between the light source and fibre interferometer. The polarisation degree of the light launched into the fibre interferometer was measured before and after using the polarisation scrambler. As shown in Fig. 6, there is a dramatic reduction of polarisation degree. This effectively eliminated the polarisation fading effect during the measurement, however, at the cost of reduced interference visibility that could have some impact for high sensitivity measurement.

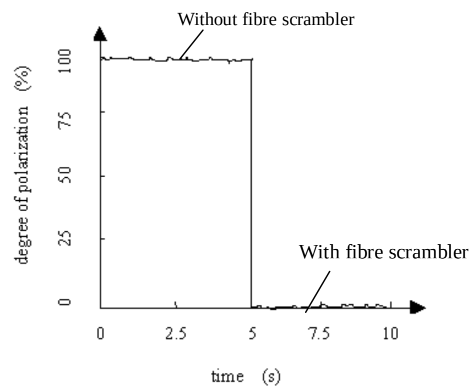

Fig. 6. Reduction of polarisation degree for eliminating the effect of polarisation fading

4. Conclusion

A stable multiplexed fibre interferometer (MFI) by combining a tunable laser with fibre Bragg grating (FBG) is presented. Two Michelson fibre interferometers, respectively act as a measurement interferometer and a reference one, are established which share optical path in the main part of the optical system. A feedback system by a cylinder PZT twisted with optical fibre in the reference arm is utilised to stabilise MFI so as to overcome the environment disturbance. An active phase tracking homodyne (APTH) technique is adopted for the signal processing to achieve high resolution. A fibre polarisation scrambler is inserted between the light source and MFI to eliminate the effect of polarisation fading.

Absolute displacement measurement by means of MFI is investigated theoretically and experimentally. Different measurement ranges can be achieved by various combinations of wavelengths from the tunable laser. According to the method of Wavelength-Division-Multiplexing (WDM), MFI is also feasible for the application of on-line surface measurement. A spatial scanning system is demonstrated by using a phase diffraction grating and optical wavelength scanning. A spatial scanning over 10mm has been obtained with the laser wavelength scanning over 50nm. Comparing with traditional stylus scanning, the wavelength-spatial transformation takes the advantages of more stability, low cost and robustness, etc..

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