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A novel absolute displacement measurement technology based on wavenumber resolved low coherence interferometry

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ABSTRACT

This paper proposed a novel absolute displacement measurement technology which is based on the wavenumber spectrum of low coherence interferometry. The signal from a Michelson interferometer, which is derived from a broadband light source, is dispersed by a bulk dispersing grating. The interferometric signal of each wavelength is detected by a linear array charge coupled device (CCD). By transforming the wavelength spectrum of the signal into wavenumber spectrum, absolute displacement can be measured precisely by measuring the wavenumber difference between two neighboring peaks of the wavenumber spectrum. Unlike the normal low coherence interferometric measurement systems (LCIMS) which have to scan the optical path difference (OPD) of the interferometer in order to demodulate the measurand, there is no need of scanning action during the measurement procedure, which not only simplifies the measurement system but also improves the measurement speed greatly. A fiber Bragg grating (FBG) is employed to produce a feedback signal which is used to stabilize the Michelson interferometer so as to obtain high measurement precision. A step height with the calibrated value of 50 μm that is configurated with two gauge blocks is measured by the system. The measurement resolution is 6.03 nm and the standard deviation of 10 times measurement results is 6.8 nm.

1. Introduction

Optical interferometry has been widely used in precision measurement [1–14] because of its prominent advantages such as non-contact, high measurement resolution, etc. Compared to a high coherence interferometric measurement system (HCIMS) which is derived from a high coherence light source, a low coherence interferometric measurement system (LCIMS) which is sourced by a broadband light source has the advantages that can realize absolute displacement measurement and does not have the problem of 2π phase ambiguity which endows the measurement system with non-limited measurement range [13,14]. In order to demodulate the measurand, it is needed for a low coherence interferometric measurement system to scan the optical path difference (OPD) of the interferometer to obtain a low coherence interferogram [13]. The scanning action needs additional scanning device which makes the measurement system complicated and expensive. What is more, the scanning action during the measurement procedure has lowered the measurement speed greatly. Besides, during the relative long measurement period, the environmental disturbances will affect the measurement results violently.

In this paper, we developed a novel absolute displacement measurement system which is based on the wavenumber spectrum of a LCIMS. The measurand is demodulated by measuring the wavenumber difference between two neighboring peaks of the wavenumber spectrum which is obtained by transforming the wavelength spectrum of the signal from the LCIMS. The measurement range is no longer limited by the wavelength because of the problem of 2π phase ambiguity. There is no need of scanning action in the measurement procedure, which not only simplifies the measurement system greatly but also improves the measurement speed effectively. In addition, by introducing a feedback loop to stabilize the interferometer, the influences resulted from environmental disturbances is erased thoroughly and high measurement precision can be obtained. A step height with the calibrated value of 50 μm that is configurated with two gauge blocks is measured by the system. The measurement resolution is 6.03 nm and the standard deviation of 10 times measurement results is 6.8 nm.

2. The principle of the optical measurement system

The principle of the measurement system is shown in Fig. 1. An optical fiber Michelson interferometer which is stabilized with an electronic feedback loop in order to eliminate the influences that

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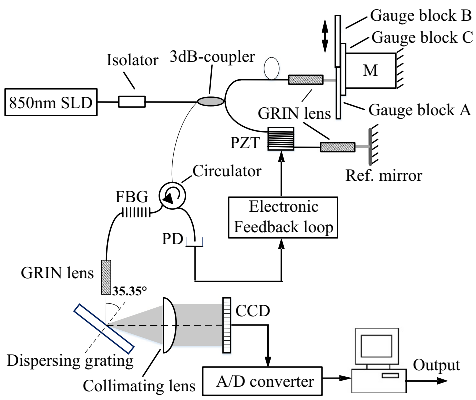

Fig.1. The scheme of the principle of the measurement system.

are resulted from the environmental disturbances is employed to perform the measurement task. A fiber Bragg grating (FBG) is used as a single-wavelength in-fiber reflective mirror to produce the feedback interferometric signal for stabilizing the optical fiber interferometer.

2.1. *The optical interferometer measurement system*

A broadband light source of superluminescent diode (SLD) with flatten spectrum at wavelength of 850 nm is used in the system. The SLD gives an output power about 22 mW with 44.16 nm FWHM spectrum. The spectrum of the light source which has flatten profile is shown in Fig. 2. The FBG used in the system has the Bragg wavelength at 818.00 nm with 3 dB bandwidth 0.2 nm. Light emitted from the SLD passes through the isolator and the 3 dB-coupler and is split into two beams which are collimated respectively by two graded index lenses (GRIN lenses). The two collimated beams are projected onto the surface of the measured object and the reference mirror respectively, and then are reflected back into the measurement system by the measured surface and the reference mirror independently. The two reflected beams are combined again at the 3 dB-coupler. The combined light from the first port of the 3 dB-coupler cannot reach the light source because of the isolator. The combined light from the other port of the 3 dB-coupler goes through the circulator and reaches the FBG. The light with wavelength 818.00 nm is reflected by the FBG while the light with the left wavelengths transmits through the FBG and is collimated by another grin lens. The collimated optical beam is projected to a bulk dispersing grating with the incident angle of 35.35° and is dispersed to be a fan-shaped optical plate in which

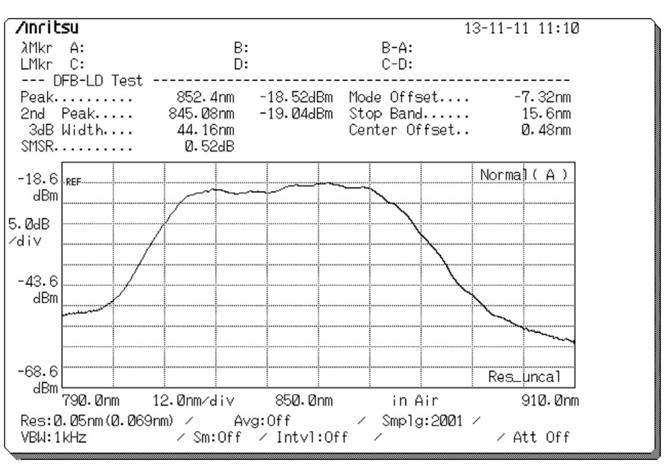

Fig.2. The spectrum of the broadband light source.

different wavelength is distributed continuously in space. The fan-shaped optical plate is collimated with a cylindrical convex lens to be a parallel optical plate and is detected by a linear array charge coupled device (CCD). The interferometric signal of different wavelength is detected by the different pixel of the CCD. The detected signal from each pixel is converted to be digital data by the A/D convertor and is input to a computer for further processing. The interferometric signal reflected by the FBG is directed by the circulator again and is detected by a photo-detector (PD).

The detected interferometric signal of the wavelength λ_i by a pixel of CCD can be expressed as

$$I_i = A_{i0} + A_i \cos\left(\frac{\Delta}{\lambda_i} \times 2\pi\right) \tag{1}$$

where A_{i0} is the DC amount in the interferometric signal, A_i is the visibility of the interferometric signal, Δ is the OPD of the interferometer, and λ_i is the optical wavelength.

Rewrite Eq. (1) as Eq. (2)

$$I_i = A_{i0} + A_i \cos(k_i\Delta) \tag{2}$$

where $k_i = {}^{2\pi}/_{\lambda_i}$ is the wavenumber.

From Eq. (2), it is known that when

$$k_i\Delta = 2n\pi \tag{3}$$

where n is an integral, and I_i will be its maximum. There will be

$$I_i = I_{\max} = A_{i0} + A_i \tag{4}$$

During two neighboring peaks of the curve shown in Eq. (2), $n = 1$ and the wavenumber difference Δk_i between two neighboring peaks can be obtained by processing the signal detected by CCD. The OPD of the interferometer Δ can be measured by

$$\Delta = \frac{2\pi}{\Delta k_i} \tag{5}$$

Based on Eq. (5), the measurement system has the capability of performing absolute displacement measurement.

2.2. *The compensating electronic feedback loop*

As an optical interferometer is very sensitive to the environmental disturbances, it is needed for obtaining high measurement precision and on-line measurement to stabilize the interferometer. In the presented measurement system, the interferometric signal detected by PD is used to eliminate the random phase drift resulted from the environmental disturbances with an electronic feedback loop. The schematic diagram of the circuit of electronic feedback loop is shown in Fig. 3. PD is connected to current-to-voltage converter U_1 which has low input impedances. The output voltage from U_1 will have the form shown in

$$u_1 = u_0\left[1 + u\cos\left(\phi_d + \phi_s\right)\right] \tag{6}$$

where u_0 is related to the input optical power and the gain of U_1, u is the interferometric fringe visibility, φ_d is the static differential phase between the two interfering arms, and φ_s is the differential phase induced by environmental disturbances. After passing through the electronic differentiator U_2, the direct voltage part in u_1 will be erased, and the output from U_2 will be shown as

$$u_2 = -U\sin\left(\phi_d + \phi_s\right) \tag{7}$$

where U is the conversion gain of the interferometric signal from U_2. After passing through the electronic integrator U_3, the output from U_3 is the value shown in

$$u_3 = U_1\cos\left(\phi_d + \phi_s\right) \tag{8}$$