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Remote and high precision step height measurement with an optical fiber multiplexing interferometric system

Yunzhi Wang, Fang Xie*, Sen Ma, Liang Chen

Optical Science and Technology Laboratory, Department of Physics, School of Science, Beijing Jiaotong University, Beijing 100044, PR China

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ABSTRACT

An optical fiber multiplexing low coherence and high coherence interferometric system, which includes a Fizeau interferometer as the sensing element and a Michelson interferometer as the demodulating element, is designed for remote and high precision step height measurement. The Fizeau interferometer is placed in the remote field for sensing the measurand, while the Michelson interferometer which works in both modes of low coherence interferometry and high coherence interferometry is employed for demodulating the measurand. The range of the step height is determined by the low coherence interferometry and the value of it is measured precisely by the high coherence interferometry. High precision has been obtained by searching precisely the peak of the low coherence interferogram symmetrically from two sides of the low coherence interferogram and stabilizing the Michelson interferometer with a feedback loop. The maximum step height that could be measured is 6 mm while the measurement resolution is less than 1 nm. The standard deviation of 10 times measurement results of a step height of 1 mm configurated with two gauge blocks is 0.5 nm.

1. Introduction

In order to control the quality of the products in the fields of microelectronics, micro-electric-mechanical system, flat panel displays, and photovoltaic cells, etc. there is a great requirement for the measurement of step heights ranging from several micrometers to larger than 1 mm. As optical fiber measurement systems have the advantages of non-contact, compactness, light weight, immunity to electromagnetic interference, high resolution, low cost and without the need of adjusting optical elements, there is a great interest of developing optical fiber measurement systems [1–15]. As the measurement range of an optical fiber low-coherence interferometric measurement system (OFLCIS) which is illuminated with a broadband light source is not limited by the wavelength, OFLCIS has become an important technique for the absolute measurement of static and quasi-static parameters, such as displacement, temperature, pressure, strain, refractive index, and step height.

In order to obtain high measurement precision, it is very important for OFLCIS to identify precisely the peak position of the low coherence interferogram (PPI) obtained during the period the optical path difference (OPD) of the interferometer is tuned linearly. But the top area of the low coherence interferogram is flatten and thus it is very difficult to address precisely the PPI. Rao [3] used two light sources with two different wavelengths to make the peak prominent, which needs two light sources and the system is expensive and complicated.

The proposed optical fiber multiplexing interferometric system, which includes a Fizeau interferometer and a Michelson interferometer is suitable for remote and absolute measurement of step height with high precision. The Fizeau interferometer which is inserted in the remote sensing field is used for sensing the measurand, while the Michelson interferometer which is stabilized by a feedback loop works in both modes of low coherence interferometry and high coherence interferometry. The range of the measured step height is determined by the low coherence interferometry, while the resolution of the measurement is decided by the high coherence interferometry. High precision of addressing the PPI has been obtained by symmetrical peak-searching method. The maximum step height that can be measured is 6 mm while the measurement resolution is less than 1 nm. The standard deviation of 10 times measurement results of a step with the height of 1 mm which is configurated with two gauge blocks is 0.5 nm.

2. Principle of the optical fiber multiplexing interferometric measurement system

2.1. Optical fiber measurement system

The proposed optical fiber measurement system is shown in Fig. 1. It includes a Fizeau interferometer and a Michelson interferometer.

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* Corresponding author. Tel.: +86 10 51688333; fax: +86 10 51840433.
E-mail address: fxie@bjtu.edu.cn (F. Xie).

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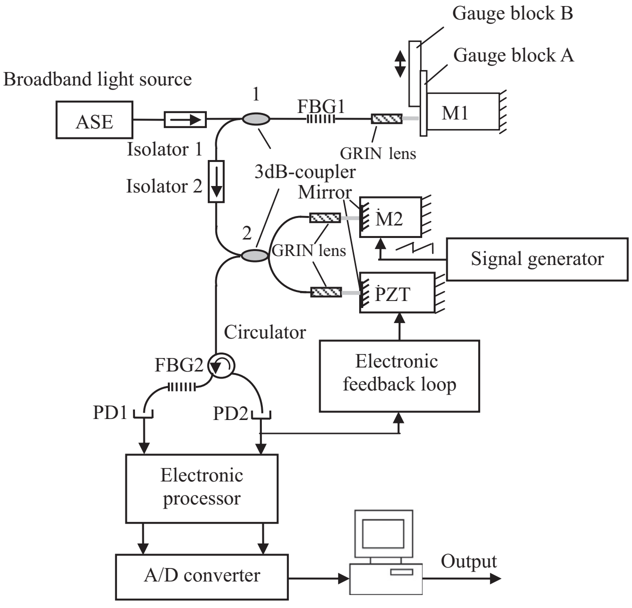

Fig. 1. The scheme of the principle of the measurement system.

A broadband light source of amplified spontaneous emission (ASE) with flatten spectrum of C-band is used in the system. The ASE gives an output power of about 200 mW with a spectral bandwidth 35.8 nm. The FBG1 and FBG2 are used as in-fiber reflective mirrors and have the same Bragg wavelength at 1557 nm with 3 dB bandwidth 0.2 nm. Light emitted from the light source ASE passes through the isolator 1, 3 dB-coupler 1 and reaches FBG1. The light of the wavelength 1557.00 nm is reflected by FBG1 while the light of the left wavelength passes FBG1 and reaches the GRIN lens. As the end face of the GRIN lens is not coated with any film, part power of the light is reflected because of the Fresnel reflection. The left power of light passes the GRIN lens and is collimated at the same time and then is incident perpendicularly on the surface of the gauge block mounted on an one-dimension translation stage (M1) and then is reflected into the system again by the surface of the gauge block. The end face of the GRIN lens and the surface of the gauge block configure the two reflective planes of a Fizeau interferometer. The light reflected by the two planes of the Fizeau interferometer passes FBG1 and is split into two beams by the 3 dB-coupler 1. The beam from one port of the 3 dB-coupler 1 cannot reach the light source because of isolator 1. The beam from the other port of the 3 dB-coupler 1 passes isolator 2 and reaches 3 dB-coupler 2 and then is split into two beams. The two beams reach two GRIN lenses and are collimated respectively. As the end faces of the two GRIN lenses are coated with highly transmissive film, there is no light reflected by the end faces of these two GRIN lenses. The collimated two beams are reflected back into the system again by two mirrors that are mounted respectively on an one-dimension translation stage (M2) and a piezoelectric stretcher (PZT). The reflected beams are combined at the 3 dB-coupler 2 again. The combined light from one port of the 3 dB-coupler 2 cannot reach 3 dB-coupler 1 because of isolator 2, while the combined light from the other port of 3 dB-coupler 2 is guided by the circulator and passes FBG2 and is detected by a photo detector (PD1). The signal detected by PD1 can be expressed by Eq. (1) [9].

$$I = I_0\left\{1+\frac{1}{2}\exp\left[-(2\Delta X/L_c)^2\right]\cos(k\Delta X)\right\} \tag{1}$$

where I_0 is the total optical power arriving at PD1, $\Delta X=(X_1-X_2)$, X_1, $X_2$are the OPDs of the Fizeau interferometer and the Michelson interferometer respectively, L_c is the coherence length of the ASE light source, and k is the wave number. It can be known that any change in ΔX will induce change in both the fringe visibility and the phase of the signal. The signal will be the maximum when $\Delta X = X_1 - X_2 = 0$ and the PPI appears. The OPD of the Fizeau interferometer will vary proportionally with the variation of the measurand and the PPI will also shift correspondently. The key issue of OFLCIS is how to measure the shifting range of the PPI precisely. A Michelson interferometer which works in both modes of low-coherence interferometry and high-coherence interferometry is exploited as the demodulating interferometer to measure the shifting range of the PPI. The shifting range is determined by the low-coherence interferometry and the value of it is measured by the high-coherence interferometry. In order to reduce the influences resulted from the environmental disturbances, the length of the fiber in the two interfering arms of the Michelson interferometer is made to be as short as about 11 mm, just as shown in Fig. 2. Moreover, an electronic feedback loop is designed to compensate for the influences to the Michelson interferometer which is resulted from the environmental disturbances so as to stabilize the Michelson interferometer.

The reflected light from FBG1 passes 3 dB-coupler 1 and isolator 2 and 3 dB-coupler 2 and then is split into two beams. The two beams are collimated by two GRIN lenses and are reflected respectively by two mirrors which are mounted respectively on the translation stage (M2) and the PZT. The two reflected beams are combined at 3 dB-coupler 2 and interfere with each other. The interferometric signal from one port of the 3 dB-coupler 2 cannot reach 3 dB-coupler 1 because of isolator 2. And the interferometric signal from the other port of 3 dB-coupler 2 is guided by the circulator and reaches FBG2 and is reflected by FBG2 and is guided by the circulator again and then is detected by a photo detector (PD2).

The signals from PD1 and PD2 are processed by the electronic processor simultaneously while the signal from PD2 is also input into the electronic feedback loop to produce a correction signal which is applied on the PZT and drives the PZT to adjust the OPD of the Michelson interferometer in order to keep it in quadrature state (the phase between two interfering arms is $\pi/2$). The signal detected by PD1 will be the maximum when the OPDs of the Fizeau interferometer and the Michelson interferometer are equal, just as shown in Eq. (1). As the signal detected by PD2 is a high coherence interferometric signal with the Bragg wavelength of FBG, it will vary periodically with the cosine function law while translation stage M2 tunes linearly the OPD of the Michelson interferometer. The number of the interferometric fringes during the shifting range of the PPI of the low interferogram is proportional to the height of the step. The PPI is searched symmetrically from two sides of the low coherence interferogram, and the value of the step height is measured by the amount of fringes of the signal detected by PD2 during the shifting range of PPI. The measured step height can be calculated by the relationship shown in Eq. (2).

$$\Delta h = \frac{1557}{2} n \tag{2}$$

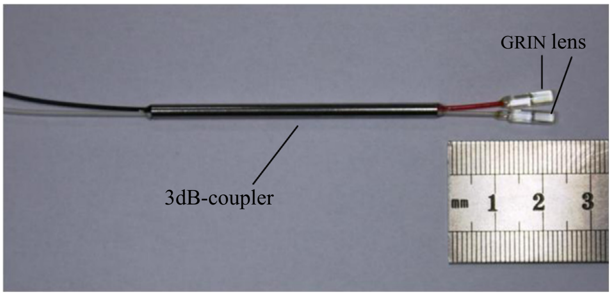

Fig. 2. The optical fiber Michelson interferometer with short interfering arms.