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High-resolution Angle Measurement based on Michelson Interferometry

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Abstract

In this paper a reconfigured Michelson interferometer for high-resolution angle measurement is proposed. The angular displacement of the object mirror will cause optical path difference that generates interference. With an optical phase shift module the photodetectors will collect quadrature signals with 90° phase shift. With pulse counting and phase subdivision processing the optical path change can be calculated and then converted to angular displacement. The proposed structure is also featured by its miniature design. The optical system is only 55mm by 55mm in area. In order to facilitate the alignment of optical components and improve the signal quality, a new optical bonding technology by mechanical fixture is proposed so that the optics can be permanently pressed together without air gap in between. Experiments show that the resolution is 0.01", the accuracy is less than 0.03", and the repeatability is within 0.1" for the measurement range of ±50 arc seconds.

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1. Introduction

Techniques of non-contact angle measurement find applications in many fields, such as construction of electro optical assemblies, calibration of machine tools, precise alignment of mechanical systems and so on. Autocollimators [1-2] are commonly used optical tools for linearity calibration. They have clear physical principle and simple structures, in which the spot shift of the reflected beam is detected by a position sensor. An improved method is to employ a grating for position sensing to enlarge the measuring range [3-5]. The resolution and accuracy of both these methods, however, are limited by the spot shift detection. Another approach for small angle measurement is based on the effect of total internal reflection [6-8]. In the vicinity of critical angle with the angle movement a notable changing of polarization can be detected, but the output has obvious nonlinearity. Laser interferometry, with its superiority in accuracy and resolution, has also been applied for angle measurement [9-11]. By counting interference fringes the tiny displacement of objective point can be detected and converted into angle

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value. The resolution can be improved by techniques of phase subdivision [12-14]. For laser interferometry, many efforts are made to stabilize the readings and minimize the total volume. The authors' group has developed a miniature interfering system with good performance in measuring uncertainty and signal quality.

2. Principle of the angle interferometer

The optical structure of the proposed system is shown in Fig. 1. The principle is based on the classic model of Michelson interferometer. The approximately linear polarized beam from the laser diode is separated by the polarization beam splitter PBS1. The P-polarized beam passes through and the S-polarized beam is reflected to the left. With careful rotation of the laser diode these two beams will have equal intensity.

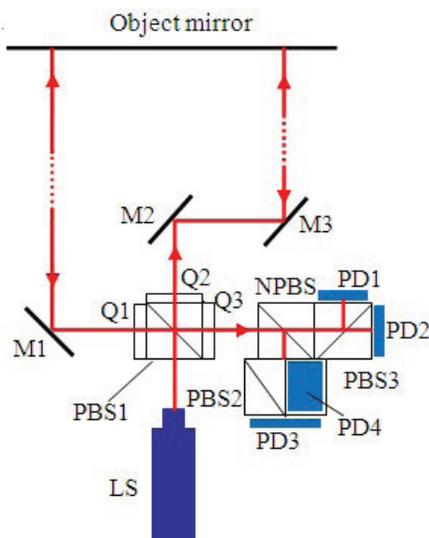


Fig. 1. Structure of Michelson angle interferometer (LS: laser diode, G: grating, PBSi: ith polarizing beam splitter, Mi: ith mirror, NPBS: non-polarizing beam splitter, Qi: ith waveplate, PDi: ith photodetector)

Then, the reflective mirrors M1, M2 and M3 make these two beams propagate to the object mirror in parallel. When the object mirror has an angle displacement, the change of the optical path difference will cause interference of two returned beams after joining together, which can be converted into corresponding angle value. After passing through the quarter waveplate Q1 twice, the left-arm beam will be converted into P-polarized beam and pass through PBS1. The right-arm beam has the similar feature. This design is to avoid the beam returning back to the laser diode. After passing through Q3 the left-arm beam and right-arm beam will be converted into right-circular and left-circular polarized beams, respectively. The NPBS divides both beams into two split beams of equal intensity. These four beams will be separated by 0-90-180-270 degrees by PBS2 and PBS3 (set fast axis to 45 degrees) and interfere with each other.

As shown in Fig. 1 the employment of reflective mirror M2 has three notable advantages: First, the left and right beams have equal optical path length, so that the noise and amplitude weakening caused by coherent property is negligible. Even a low-cost laser diode has good performance. Second, it can increase the separation of two beams so as to increase the angle sensitivity. Third, it can compensate the beam shift direction so that the angle displacement of the object mirror will cause the interfering beams move in same direction without separation, as shown in Fig. 2.

Analyzed by Jones vector, the intensity of each photodetector can be expressed as:

$$I_{PD1} = 2A + 2Ae^{i\omega t} \left(\frac{1 - \sin\left(\frac{2\pi d}{\lambda}\right)}{2} \right) \tag{1}$$

$$I_{PD3} = 2A + 2Ae^{i\omega t} \left(\frac{1 + \sin\left(\frac{2\pi d}{\lambda}\right)}{2} \right) \tag{2}$$

$$I_{PD3} = 2A + 2Ae^{i\omega t} \left(\frac{1 - \cos\left(\frac{2\pi d}{\lambda}\right)}{2} \right) \tag{3}$$

$$I_{PD4} = 2A + 2Ae^{i\omega t} \left(\frac{1 + \cos\left(\frac{2\pi d}{\lambda}\right)}{2} \right) \tag{4}$$

By pulse counting and phase subdivision the optical path difference d can be obtained. A robust subdivision software is also developed in this study. Then the angle displacement θ can be expressed by:

$$\theta = \arctan\left(\frac{d}{l}\right) \tag{5}$$

where l is the distance between the two incident points.

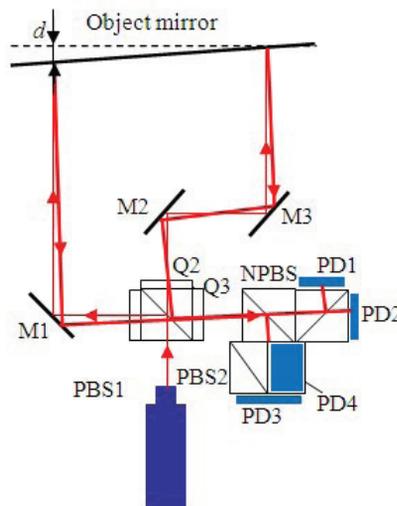


Fig. 2. The movement of reflected beam caused by angle displacement

3. Compact design

The proposed angle interferometer is also featured by its miniature structure. In order to compact the structure and improve the signal quality, a new optical bonding technology by mechanical fixture is proposed so that the miniature optics can be permanently pressed together without air gap in between.

The air gap between two contact surfaces will cause unexpected reflections resulting to some ghost spots. If any ghost spot emits to the object mirror, a high-order harmonic disturbance will be generated, causing alternately changing amplitudes of the interference signals. It is very likely to happen when too many optics are bonded together with adhesive glue [15, 16].

An innovative mechanical clamping fixture is, therefore, designed to firmly press the components together with setting screws, as shown in Fig. 3. This new idea of mechanical bonding technique is simple and definitely no air gap will be occurred. In addition, the same procedure can be easily reproduced by anyone with minor skill training. Moreover, since human errors are entirely removed from this process, all optical components can be selected to the smallest size in order to make the system as compact as possible.

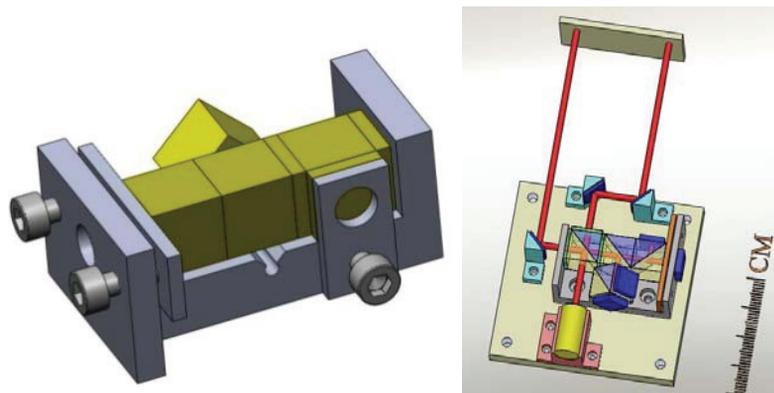


Fig. 3. Mechanical clamping fixture (left) and the system assembly (right)

4. Experimental data

In order to calibrate the measurement precision, a SIOS interferometer is employed as a standard. In the SIOS interferometer there are two individual interfering systems measuring the displacement then the displacement difference can be converted into angle value. The calibration system is shown in Fig. 4. The two interferometers are configured to measure the yaw value of the same object mirror.

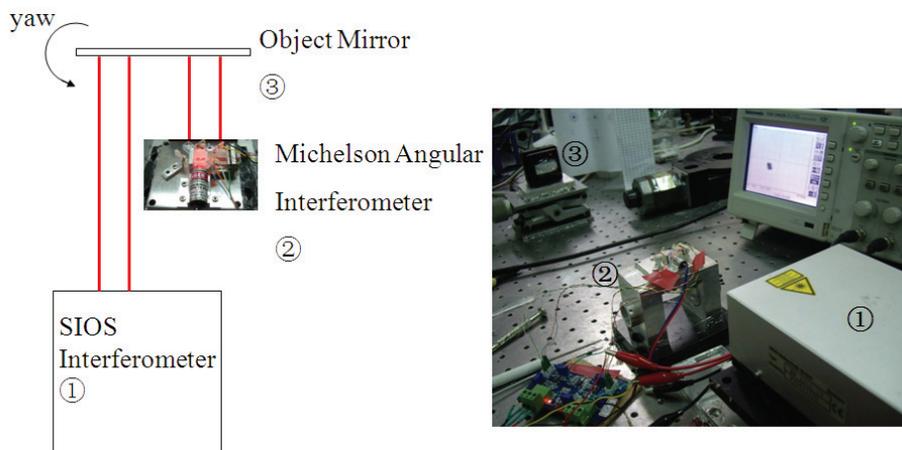


Fig. 4. Calibration system

Then with least-squares linear fitting the residual errors can be obtained, as shown in Fig. 5. The calibration experiment is repeated three times. The residual errors are within 0.2 arcsec.

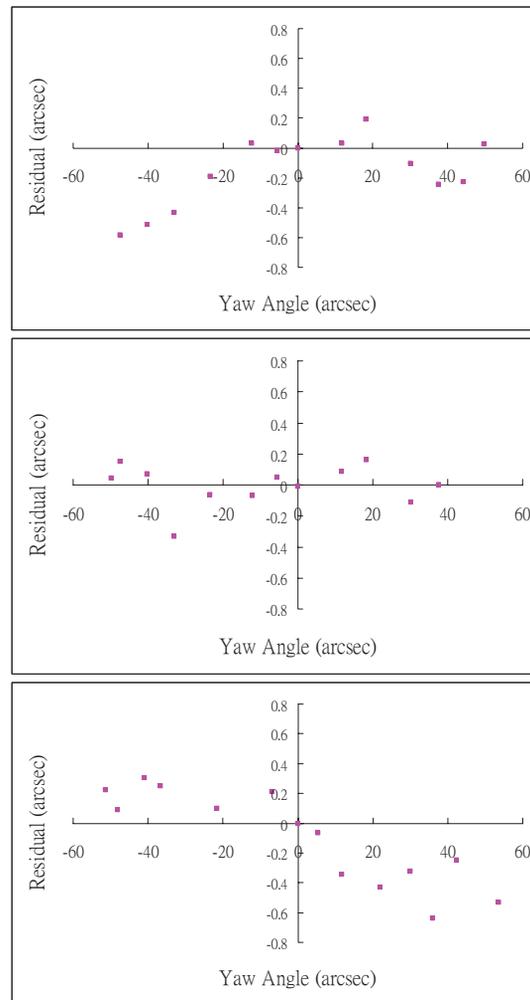


Fig. 5. Residual errors of calibration

5. Conclusions

In this paper a developed Michelson angle interferometer is proposed. This novel interferometer has following features:

1. High resolution and precision.
2. Miniature design: the optical system is only of 55mm by 55mm in area.
3. The interfering beams have equal optical paths.
4. The angle displacement will not separate the interfering beams so that the signal intensity keeps stable.
5. Redundant reflection elimination with mechanical clamping fixture.
6. Low cost.

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