Ultra-Precision Angle Sensor Based on Michelson Interferometry

Kuang-Chao Fan, Bo-Hsun Liao

Department of Mechanical Engineering, National Taiwan University, Taipei, 10617, Taiwan

Corresponding author:fan@ntu.edu.tw

Abstract - A homodyne interferometer exploits the polarizing theory and four-detector-array based on Michelson interferometry is proposed for angle measurement. The angular displacement of the object mirror will cause the optical path difference between the two reflected beams so as to produce interference. The quadrature signals with 90° phase shift will be collected by photodetectors. With pulse counting and phase subdivision processing the angular movement can be calculated. The proposed structure is also featured by its miniature design. The optical system is only 45mm by 45mm 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 miniature optics can be permanently pressed together without air gap in between. Experiments show that the resolution is 0.01", the accuracy is less than 0.2" for the measurement range of ±120 arc seconds.

Keywords - Michelson interferometer, Angle interferometer, optical bonding, alignment tolerance

I. INTRODUCTION

Applications of non-contact angle measurement can be found in many fields, such as monitoring the angle of a mirror in a star-tracking telescope used in astrometry, construction of electro optical assemblies, calibration of machine tools and so on. Autocollimators [1-2] are most commonly used for linearity calibration because of clear physical principle and simple structures, in which the spot shift of the reflected beam is detected by a position sensor. A typical commercial autocollimator provides convenient angle measurement with sensitivity of ~0.1 rad for a few centimeter beam diameter. An improved method is to employ projecting fringe 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 way for small angle measurement is based on internal reflection effects [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, though it is extremely sensitive to the external disturbances and hard assembling, its superiority in accuracy and resolution make it still be applied for precise angle measurement [9-10].By counting interference fringes the tiny displacement of object mirror can be detected and converted into angle value. The resolution can be improved by techniques of phase subdivision [11-13]. For laser interferometry, many efforts are made to stabilize the readings, minimize the total volume and facilitate the process of assembling. The details of the proposed approach are discussed below.

II. PRINCIPLE OF THE ANGLE INTERFEROMETER

The optical structure of the proposed system is shown in Fig. 1. Its principle is based on Michelson interferometry. The beam from the laser diode is separated by the polarization beam splitter PBS1, hence the P-polarized beam passes through and the S-polarized beam is reflected to the left. In order to let two beams have equal intensity, it's important to rotate the laser diode carefully.

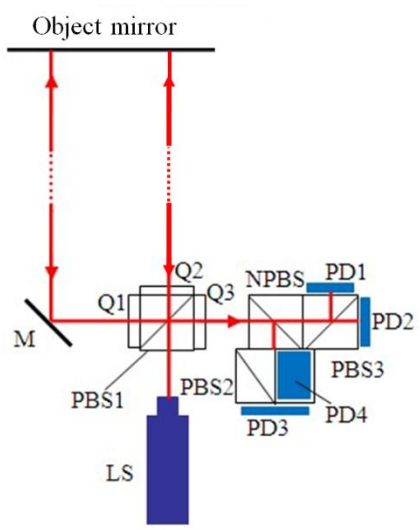

Fig. 1 Structure of Michelson angle interferometer (LS: laser diode, PBSi: ith polarizing beam splitter, M: mirror, NPBS: non-polarizing beam splitter, Qi: ith quarter waveplate, PDi: ith photodetector.)

Then, the reflective mirror M1 deflects the left beam by 90 degrees and parallel to the other beam. These two beams which normal to the object mirror served as the metrology probe for the angular measurement. The angular displacement of the object mirror will cause the optical path difference between the two reflected beams so as to produce interference. 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. These two waveplates are designed 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 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.

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

$$I_{PD1} = 2A + 2A\exp(i\omega t)\left[\frac{1-\sin(\frac{2\pi d}{\lambda})}{2}\right] \quad (1)$$

$$I_{PD2} = 2A + 2A\exp(i\omega t)\left[\frac{1+\sin(\frac{2\pi d}{\lambda})}{2}\right] \quad (2)$$

$$I_{PD3} = 2A + 2A\exp(i\omega t)\left[\frac{1-\cos(\frac{2\pi d}{\lambda})}{2}\right] \quad (3)$$

$$I_{PD4} = 2A + 2A\exp(i\omega t)\left[\frac{1+\cos(\frac{2\pi d}{\lambda})}{2}\right] \quad (4)$$

By pulse counting and phase subdivision the optical path difference can be obtained. As shown in Fig. 2 and Fig.3, with the object mirror rotate α , two incident beams will have optical path difference $K \times \tan\alpha$, and two reflected beams will have optical path difference $K \times \tan\alpha \times \sec 2\alpha$. When measuring small angle displacement, α is very small so the total optical path difference can be revised as:

$$OPD = 2K\alpha \quad (5)$$

where K is the distance between the two incident points.

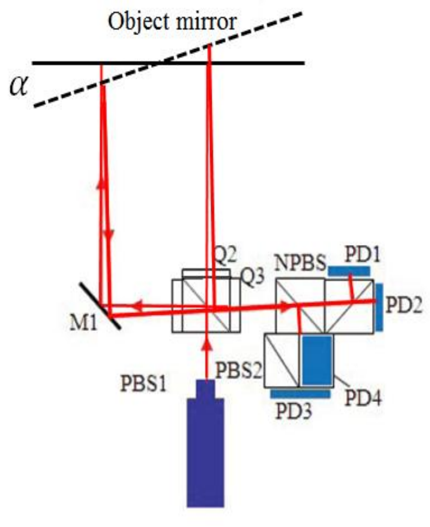

Fig. 2 The movement of reflected beam

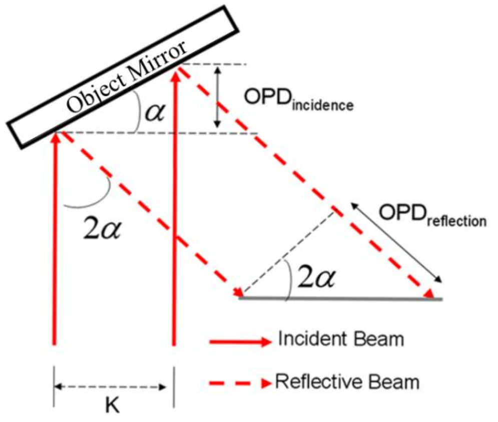

Fig. 3 Optical path difference caused by angle displacement

III. COMPACT DESIGN

The proposed angle interferometer is also featured by its miniature structure. The optical system is only of 45mm by 45mm in area. Otherwise, a new optical bonding method using 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. By this way, the structure is long-lasting robust and the signal quality is better.

In order to confirm the optical components are pressed together, an innovative mechanical clamping fixture is designed by using screws, as shown in Fig. 4, Fig. 5 and Fig. 6. This new idea of mechanical bonding technique is quite simple and definitely assures the air gap will not exist. Besides, it is easy to reproduce the same procedure by anyone with minor skill training. Moreover, all optical components can be selected to the smallest size due to the human errors are entirely eliminated from the process, so the whole system can be as compact as possible.

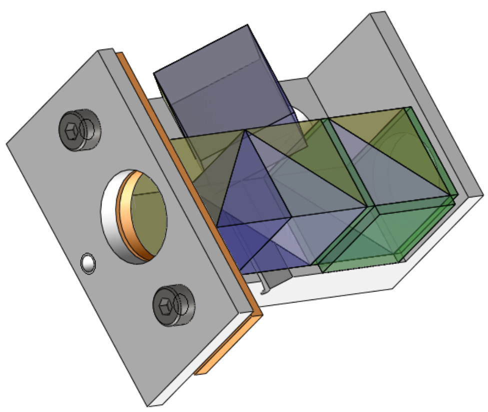

Fig. 4 Mechanical clamping fixture

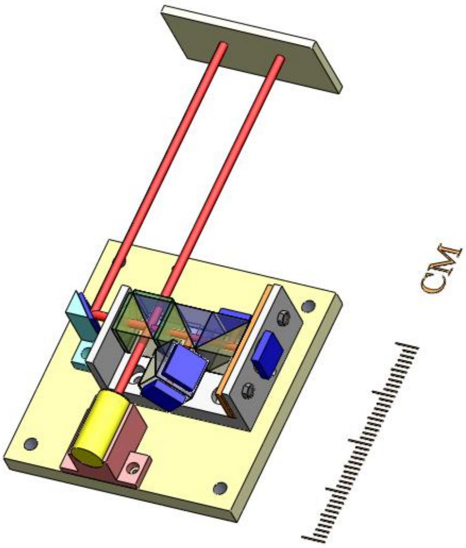

Fig. 5 The system assembly

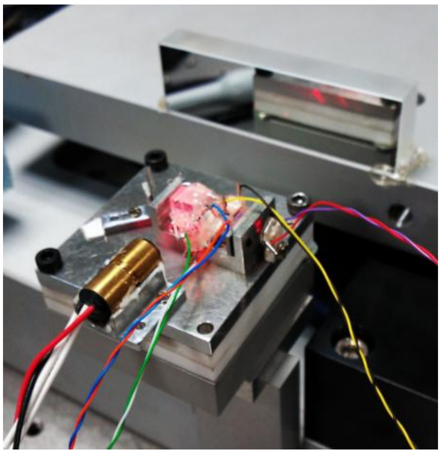

Fig. 6 The photo of the miniature interferometer

IV. CALIBRATION

HP interferometer is employed as a standard to calibrate the measurement precision of the developed miniature angular interferometer (MAI). In the HP interferometer there are two individual interfering systems measuring the displacement that can be converted into angle value. The calibration system is shown in Fig. 7. The two interferometers are configured to measure the yaw value of the same object mirror.

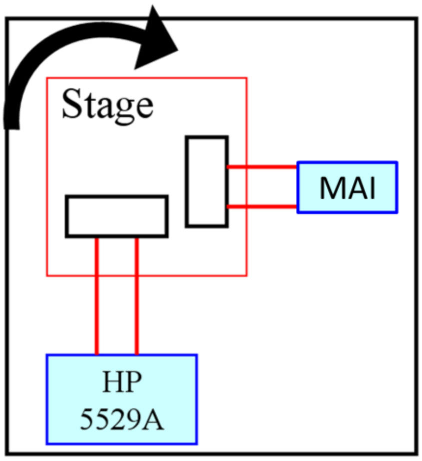

Fig. 7 Calibration system

The calibration experiment is repeated three times. The measurement errors are within 0.25 arc sec in ± 120 arc sec, as shown in Fig. 8 and Fig. 9.

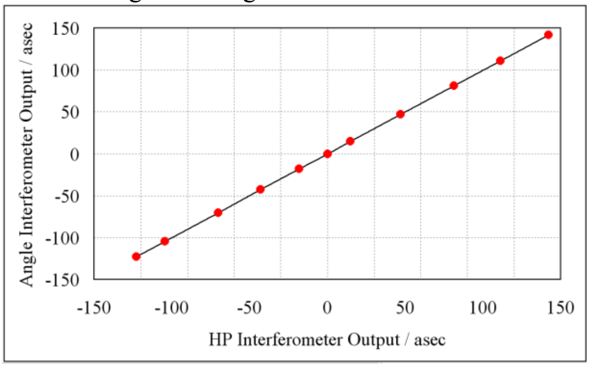

Fig. 8 Readings compare with HP Interferometer

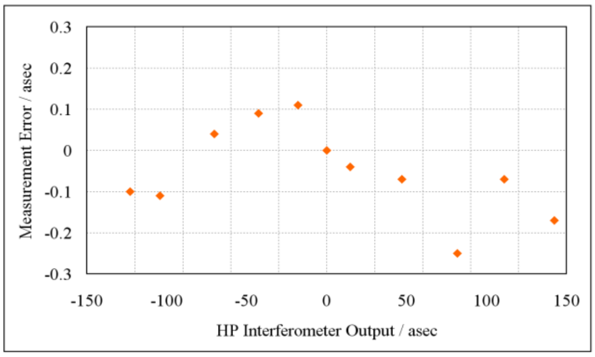

Fig. 9 Measurement errors of calibration

V. ON-MACHINE EXPERIMENTS

A linear stage of one meter long was measured its yaw error during the travel of 800 mm. The reflection mirrors of MAI and the HP5529 angular laser interferometer were mounted on the moving table for comparison, as shown in Fig. 10. The results show almost the same, which confirms the applicability of the developed MAI.

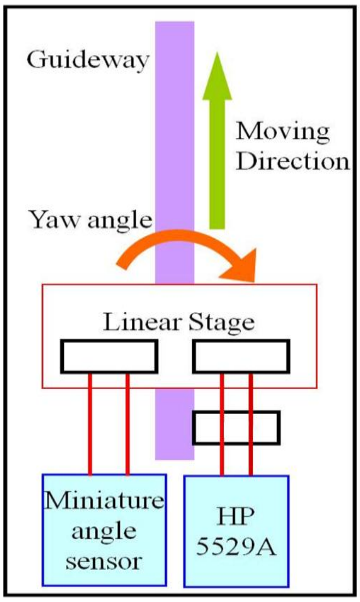

Fig. 10 On-machine comparison: setup

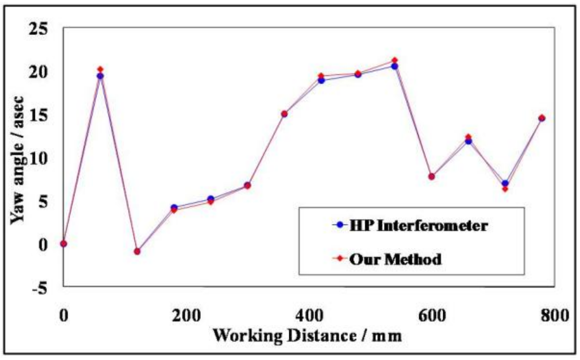

Fig. 11 Measured results

VI. 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 45mm by 45mm in area.

3) The angle displacement will not separate the interfering beams so that the signal intensity keeps stable.

4) Redundant reflection elimination with mechanical clamping fixture.

5) Easy to reproduce the same procedure of assembling.

6) Low cost.

REFERENCES

[1] P. R. Yoder, J. E. Schlesinger, and J. L. Chickvary, "Active annularbeam laser autocollimator system," *Appl. Opt.14,* 1890–1895 (1975).

[2] I. K. Ilev, "Fiber-optic autocollimation refractometer," *Opt. Commun.* 119, 513–516 (1995).

[3] S. S. Nukala, S. S. Gorthi and K. R. Lolla, "Novel composite coded pattern for small angle measurement using imaging method", *Proc. SPIE*, Vol.6289 1D-2-11 (2006)

[4] T. Suzuki, Hideki Nakamura and Osami Sasaki, "Small-rotation-angle measurement using an imaging method", *Opt. Eng*. 40(3) 426–432 (March 2001)

[5] T. Suzuki, T. Endo and J. E. Greivenkamp, "Wide range two-dimensional small rotation-angle measurement by use of fringe projection", *Proc. of SPIE*, Vol.5363, 185-192(2005).

[6] P. S. Huang and J. Ni, "Angle measurement based on the internal-reflection effect using elongated critical-angle prisms" *Appl. Opt*. 35 2239-41(1995).

[7] Ming-Horng Chiu and Der-Chin Su, "Angle measurement using total-internal-reflection heterodyne interferometry" *Opt. Eng*. 36 1750-53 (1997).

[8] Ming-Hung Chiu, Shinn-Fwu Wang, and Rong-Seng Chang, "Instrument for measuring small angles by use of multiple total internal reflections in heterodyne interferometry" *Appl. Opt*. 43, 5438-42 (2004).

[9] M. Ikram and G. Hussain, "Michelson interferometer for precision angle measurement," *Appl. Opt.* 38(1), 113–120 (1999).

[10] Inseob Hahn, M. Weilert, X. Wang, and R. Goullioud, "A heterodyne interferometer for angle metrology" *Rev. Sci. Instrum*. 81, 045103 (2010).

[11] K.P.Brich. "Optical Fringe Subdivision with Nanometric Accuracy," Precision Engineering, 12 (4): 195-198(1990).

[12] K. C. Fan and F. Cheng, "Nanopositioning Control on a Commercial Linear Stage by Software Error Correction," *Nanotechnology and Precision Engineering*, 4(1), 1-9 (2006)

[13] F. Cheng, K. C. Fan, and Y. T. Fei, "A robust control scheme of nanopositioning driven by ultrasonic motor",*Proc. of SPI*, Vol.7130: 71301O-71301O-6 (2008)