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Absolute precision measurement for space coordinates metrology using an optical-comb pulsed interferometer with a ball lens target

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Abstract
This paper presents an absolute-length measuring system based on a single-mode fiber optical-comb pulsed interferometer. The repetition rate of an optical comb was transferred to 1 GHz by a Fabry-Pérot fiber etalon. Subsequently, the pulsed interferometer was established based on the principle of unbalance-arm Michelson interferometer, and a ball lens with the refractive index of 2 was used as the target. A general collimated beam and a special focusing beam were employed for this experiment. Both collimated types can be preliminary used to measure absolute lengths up to 3 meters with a maximum standard deviation approximately 1.65 µm. The proposed technique can provide sufficient accuracy for non-contact measurement in coordinates metrology such as large size CMM verification.

Keywords: Optical comb, Pulsed interferometer, Absolute length, Length measurement, Non-contact measurement

1. Introduction

The large space metrology systems such as the large size coordinate measuring machines (CMM), must be calibrated on installation and verified periodically during their operation to perform their accuracy. The verification standards are based on sampling the length-measurement capability of a CMM to decide whether its performance can conform to the specification [1]. Using end standards, the measurement ranges are limited by the length of end standards [2]. The multilateration measurement method using four-portable tracking laser interferometer is very useful for measuring large 3D structure, but it is not absolute-length measurement method and it is required more space for setup [3].

Recently, an optical frequency comb has been considered as a useful tool for length measurement, because of their high-frequency accuracy and stability [4-6]. This research mainly develops a measuring system for large size CMM verification using an optical-comb pulsed interferometer with a probe target. The paper presents a single-mode fiber optical-comb pulsed interferometer and the preliminary absolute-length measurement, which a ball lens of the refractive index 2 was used as the target, and two types of collimated beam were considered. This technique can provide sufficient accuracy for non-contact measurement in applications up to 3 m.

2. Principle of measurement

The mode-locked lasers generate ultrashort optical pulses by fixing the relation phases of all of the lasing longitudinal modes. The spectrum of each pulse train is separated by the repetition rate of an optical comb, and the spectral line is called an optical frequency comb [4]. The principle of an optical-comb pulsed interferometer is shown in Figure 1(a). Laser pulses are divided into two beams by an optical beam splitter (BS). One beam is reflected on a scanning mirror (M1). The other is transmitted through a sapphire window plate (reference position) to a target mirror (M2).

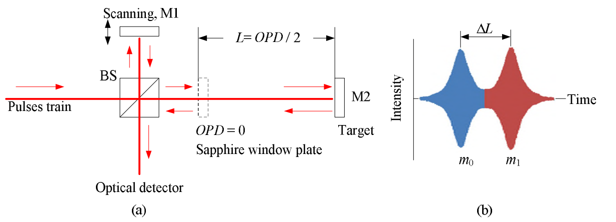

Figure 1. (a) Diagram of optical-comb pulsed interferometer, (b) envelope interference fringes of the reference position (m_0) and the target (m_1).

Subsequently, the reflected light pulses are recombined to produce interference fringes when the optical path differences (*OPD*) of the two arms satisfies the following Eq. (1) [5, 6].

$$OPD = \frac{mc}{n_{air} f_{rep}} \quad (1)$$

where m is an integer, c is the speed of light in vacuum, n_{air} is the refractive index of air, and f_{rep} is the repetition frequency.

If the fringes provide a slight displacement (ΔL), the envelope interference fringes will be separated, as shown in Figure 1 (b). Therefore, the absolute length, L under measurement is determined as Eq. (2).

$$L = \frac{OPD}{2} + \Delta L \quad (2)$$

where ΔL is the distance of the envelope peak-to-peak of interference fringes.

In the experiment, a ball lens (Ohara) with diameter of 10 mm, and the refractive index of 2 was used as the target. The effective focal length of the ball lens (*EFL*) is calculated as Eq.

(3), which becomes 5 mm, and the effective focal length of the ball lens (BFL) is zero.

$$EFL = \frac{nD}{4(n-1)} \tag{3}$$

where n is the refractive index of the ball lens and D is a diameter. Consequently, the absolute lengths are determined from the distance of a front face of the sapphire window plate and the back surface of the ball lens.

3. Experiments

First, a fiber type collimator was used to collimate the laser beam. The measurement setup diagram is shown in Figure 2. An optical comb (C-Fiber Femtosecond Laser, Menlo Systems), the repetition frequency of 100 MHz is transferred to 1 GHZ by a fiber type Fabry-Pérot etalon.

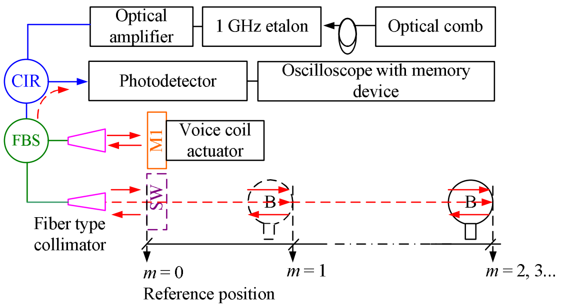

Figure 2. Diagram of an absolute-length measurement with a ball lens target.

Laser beam was amplified by an optical amplifier after passing through an etalon. The beam passed an optical fiber circulator (CIR) to a fiber beam splitter (FBS), and then the beam was divided into two paths by the FBS. One beam fall onto a scanning mirror M1, which was fixed on a voice coil actuator for scanning fringes, the other passed a sapphire window plate (SW) to a ball lens target (B). Then, the reflected beams were recombined to produce interference fringes, and returned to the output port of the CIR. The fringes were detected by a photodetector, and can be obtained by an oscilloscope. The target was moved by approximately 150 mm in each position, and each length was measured 5 times to determine the repeatability of the measurement.

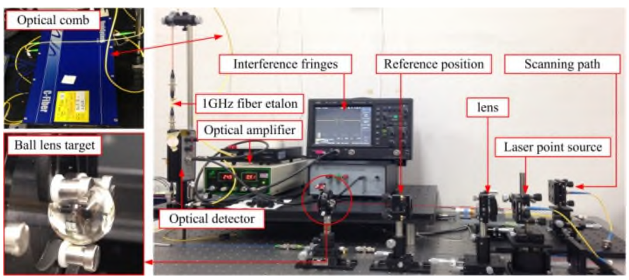

Figure 3. Photograph of preliminary absolute-length measurement.

Next, a fiber type collimator in Figure 2 was removed and replaced by a lens with a focal length of 30 mm. The lens position was adjusted by a micrometer until a small spot of the laser beam located at the position approximately 1.5 m from the reference position. The photograph of measurement setup is shown in Figure 3. By changes the positions of the target up to 3 m, each length was measured 5 times to determine the repeatability of the measurement.

4. Measurement results

The performances of measurements were evaluated by the measurement repeatability of each position as shown in Figure 4. Those results were compensated the group refractive index of air by Ciddor's equation [7]. The environmental conditions during experiment were recorded under the air temperature, relative humidity and air pressure approximately (23.46±0.15) °C, (48.6±0.2) %RH, and (101.09±0.01) kPa, respectively.

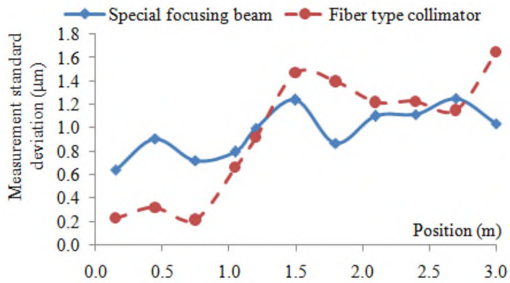

Figure 4. Measurement results up to 3 m: a solid line uses a special focusing beam, and a dash line is a fiber type collimator.

The measurement results in Figure 4 shows that a maximum standard deviation of measurement is approximately 1.65 µm and 1.25 µm by using a fiber type collimator and a special focusing beam, respectively. Both types of collimated laser beams can be preliminary used to measure absolute lengths up to 3 meters. However, not only type of collimators that affect the repeatability of the measurement, but also the environmental conditions, especially air fluctuation and mechanical vibration. In addition, using a fiber type collimator, the reflected beam will be weak if a laser beam diameter is larger than the target. On the other hand, using a special focusing beam provides a strong signal than a fiber type collimator, and the length of measurement will be extended more than 3 m, which depend on the position of the focusing point of the laser beam.

5. Conclusion

Preliminary experiments on absolute-length measurement up to 3 meters have been conducted based on a single-mode fiber optical-comb pulsed interferometer. Both a fiber type collimator and a special focusing beam can be employed for the applications. The maximum standard deviation from the experiment is approximately 1.65 µm. This technique can provide sufficient accuracy for non-contact measurement in applications such as large size CMM verification. Further research will be undertaken in the future to study the volumetric errors of CMMs.

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