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Time division approach to separate overlapped interference fringes of multiple pulse trains of femtosecond optical frequency comb for length measurement

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ABSTRACT

In this study, we attempt the separation of overlapped interference fringes arising from multiple pulse trains of a femtosecond optical frequency comb for length measurement. Based on an optical experiment, we test the performance of the separation of two overlapped interference fringes by time division for an absolute length measurement, which is about one adjacent pulse repetition interval length. We compare our results with those of a commercial He–Ne interferometer system. The two sets of results show an agreement within 0.7 μm.

1. Introduction

The meter, which is the standard unit of length, is defined by the speed of light c in vacuum. One means of practical realization of the definition of the meter is in terms of wavelength via optical frequency standards (e.g., [1]). This approach exploits the relationship $c = \lambda \times f$ that relates the wavelength λ and frequency f, because the speed of light in vacuum c is a constant. Consequently, stabilizing the frequency of a laser can stabilize its wavelength. As regards length measurement, the displacement corresponding to a wavelength can be measured by means of a Michelson interferometer.

In the above backdrop, femtosecond optical frequency combs (FOFCs) exhibiting high frequency stability have recently been reported (e.g., [2]). The FOFC is a representation of multiple phase-coherent frequencies. These frequencies are ranged with the same frequency interval, i.e., the pulse repetition frequency f_{rep}. The pulse repetition frequency is a parameter that needs to be stabilized to obtain a highly frequency-stabilized FOFC. The pulse repetition frequency and the adjacent pulse repetition interval length (APRIL, which represents the physical length associated with the pulse repetition period), Λ, are related as $c = \Lambda \times f_{\text{rep}}$. Thus, stabilization of the pulse repetition frequency indicates APRIL stabilization in the spatial domain. In addition, the displacement corresponding to APRIL can be measured with a Michelson interferometer system [3–5]. From the detection possibilities of a Michelson interferometer and the stability derived from the frequency parameter, we have previously proposed the practical realization of the meter in terms of APRIL via the repetition frequency (e.g., [6–8]).

We have also previously proposed multiple-pulse-train interferometry for arbitrary length measurements [9]. The proposed multiple-pulse-train interferometer has two mirrors in its object arm: one is denoted the zero-position mirror that indicates the zero-position of the measurement while the second is a target mirror that indicates the measurement point. As can be seen in the principles section in this paper, the problem with this setup is that we cannot distinguish the interference fringes of pulse trains reflected by the zero-position mirror and the target mirror when the reflected pulse trains are temporally and spatially overlapped. Thus, in this study, we propose the separation of these two interference fringes by time division for length measurement. Further, we compare our measurement result with that of a commercial He–Ne interferometer system.

This paper is organized as follows. First, the problem with APRIL-based length measurement is highlighted in Section 2. The optical experiments for length measurement with the use of time division, the corresponding results, and error analysis are described in Section 3. Finally, the main conclusions are provided in Section 4.

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2. Methods

By changing the light source of a Michelson interferometer to an FOFC, we can only measure a length that is equal to an integral multiple of the APRIL [3]. We note here that different pulse trains can interfere with each other only when they overlap. Consequently, to solve this problem, we propose the approach of multiple-pulse-train interferometry [9].

The difference between the multiple-pulse-train interferometer and the conventional Michelson interferometer lies in the object arm. As shown in Fig. 1(a), in a conventional Michelson interferometer, there is only one mirror in the object arm. The movement of this mirror induces a displacement that we want to measure. On the other hand, as shown in Fig. 1(b), the proposed multiple-pulse-train interferometer has two mirrors in the object arm. One mirror is the object mirror that indicates the zero-position of the measurement, and it is referred to as the zero-position mirror. The second mirror is an object mirror at the measurement point, and it is labeled the target mirror. The distance between these two mirrors is the distance that we want to measure. When representing the length in terms of APRIL, an arbitrary absolute length can be represented by an integer part, p, and a fractional part, q, of the APRIL of choice. After obtaining the integer and fractional parts, the total length can be obtained as $L = (p + q) \times \Lambda$.

As shown in Fig. 2(a), when the fractional part, q, is large, two interference fringes are observed: one is formed between the reference mirror and the zero-position mirror, and the other is formed between the reference mirror and the target mirror. These two fringes are clearly separated. In this case, we can measure the fractional part based on the fringe analysis method [9,10]. On the other hand, when the fractional part is small (as shown in Fig. 2(c)), while we observe interference phenomena between the two interference fringes [11], we cannot detect the envelope peak of the overlapped interference fringes. Therefore, it is impossible to perform a length measurement. Fig. 2(b) and (d) show examples of experimentally observed interference fringes.

To measure small values of the fractional part, we propose to separate these two interference fringes by using a time division approach for length measurement. It is possible to avoid the superposition of both the interference fringes by moving the zero-position mirror to introduce a spatial division at the expense of the introduction of a position error of the zero-point.

The idea of time division is simple. The problem here is that two interference fringes caused by different pulse trains overlap temporally and spatially. Thus, we open or close a shutter in the path of the light beam to control the presence or absence of reflected light. For example, to select the reflected light from the target mirror, we open the shutter in the path of the target mirror. At the same time, we close the shutter in the path of the zero-position mirror to block the reflected light from the zero-position mirror.

3. Optical experiments and results

We first discuss the selection of the optical scheme for the realization of time division.

Fig. 3 shows two possible amplitude-division approaches to achieve time division. In Fig. 3(a) and (b), the relay mirror is "cut" in or out of the beam to achieve time division by changing the direction of light. In Fig. 3(c) and (d), the relay mirror partially obscures the beam path, following [12]. The relay mirror bends half of the light perpendicular to the original traveling direction. Further, the reflected light is selected by opening or closing the appropriate shutter.

In our study, we utilized the second scheme for our optical experiments, since this scheme does not require position control of the relay mirror. In preliminary experiments, we repeatedly set the relay mirror to a certain position. The reproducibility of the position of the relay mirror was about 1 μm. On the other hand, with the first scheme, the position of the reference mirror changes for each measurement, which can severely affect the measurement accuracy of the zero-position mirror.

We next describe our optical experiments. Our setup consists of an FOFC-based interferometer system and commercial He–Ne interferometer system (Agilent, 10,766 A). The schematic of the experiment is shown in Fig. 4. First, we present the FOFC interferometer system.

We first discuss the FOFC light source utilized in our setup. By tracing the frequency signal of the Global Positioning System, we use a frequency standard (pendulum, GPS-12R) to generate a signal of 10 MHz with a frequency stability on the order of 10^{-11}. This stable 10-MHz signal is sent to a high-frequency signal generator (Digital Signal Technology, DPL-3.2GXF), which generates a frequency close to the pulse repetition frequency of the FOFC. The pulse repetition frequency of the FOFC is stabilized by locking the pulse repetition frequency of the FOFC to the stable frequency

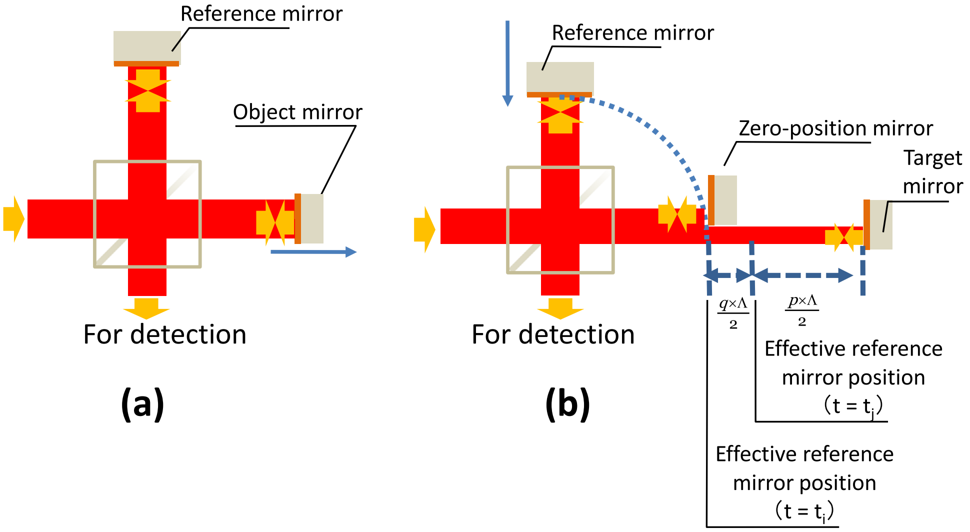

Fig. 1. Schematic of (a) Michelson interferometer and (b) multiple-pulse-train interferometer.