Length measurement based on Pulse repetition interval of a femtosecond optical frequency comb

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Abstract

We proposed pulse repetition interval-based Excess Fraction (PRIEF) method which can be realized in a modified Michelson interferometer for an arbitrary and absolute length measurement directly linked to a femtosecond optical frequency comb. In the modified Michelson interferometer an arbitrary and absolute distance can be estimation as an integral multiples and a fraction of the pulse repetition interval. The PRIEF method can be regarded as a multi-pulse repetition interval version of the multiple pulse train interference-based length measurement method. We can measure a fraction part by determining the distance between the peaks of an obtained multiple pulse trains interference fringes, and use conventional Excess Fraction method to decide integer part for an arbitrary and absolute length.

1 Introduction

Femtosecond optical frequency comb (FOFC) is a mode-locked pulse laser, owing to the outstanding frequency stability and the easy-to-use optical frequency measurement capability, which was specified for the national standard tool for measuring length in Japan in 2009. Motivated by the analogy between wavelength of a monochromatic light source and pulse repetition period of a pulse laser, we proposed the pulse repetition interval-based Excess Fraction (PRIEF) method, which is expected to be useful for an arbitrary and absolute length measurement.

2 Principle [1, 2]

An arbitrary and absolute length can be expressed as a function of either the wavelength or the pulse repetition interval by the following equation:

$$L = \frac{\lambda_n}{2}(N_\lambda + \varepsilon_\lambda) = \frac{c_n \times T_R}{2}(N_{T_R} + \varepsilon_{T_R}). \qquad (1)$$

This analogy suggests that the basic principle of length measurement based on the wavelength of a monochromatic laser source can also be applied for the distance estimation as a function of the pulse repetition interval of an FOFC.

3 Preliminary experiment [3]

The optical setup for the pre-experiment is shown in follows. A pulse train from an FOFC is introduced into a double Michelson interferometer. The double Michelson interferometer consists of two Michelson interferometers. Two Michelson interferometers consist of identical beam splitter and reference mirror, and different object mirrors as an object mirror$_1$ and an object mirror$_2$. The object mirror$_2$ is located far from the object mirror$_1$ at an arbitrary length. During the measurement, by moving the common reference mirror, we can observe the interference fringes, which reflect the fraction part between the two object mirrors. An example of length (fraction part) measurement for a 1.5-m long gauge block is shown in details in Ref. [3].

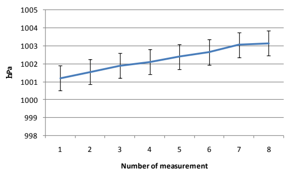
Theoretically, the PRIEF method should be performed by at least three different pulse repetition frequencies according to conventional Excess Fraction method. This work is currently in progress.

4 Analysis of measurement uncertainty

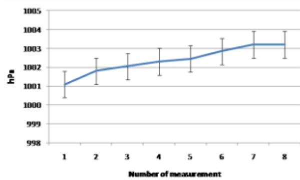
In the following, the individual major terms of the uncertainty of the experiment system will be discussed in detail. The uncertainty by the thermometer used for the temperature measurement of the air and the gauge block stands out. The minor terms of the uncertainty (for example, uncertainty by repetition interval of pulse train, uncertainty by the peak decision, uncertainty by the angle of incidence degree of the both reflect surface, etc) are ignored in this paper.

To determine the distance in air, we need to use Edl'en equation for the refractive index of air. In Edl'en equation, the refractive index of air is treated as a function of humidity, pressure, temperature of environment and carbon dioxide concentration. In this experiment we did not monitor humidity and carbon dioxide.

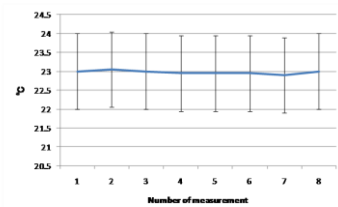
For pressure and temperature measurements, we need to estimate their measurement uncertainty caused by variations in the measurement and measurement uncertainty due to the distribution of the target. In the experiment, the uncertainty because of the distribution of the measurement object was estimated to be an amount of the change of the measurement value at 30 minutes. Then, the uncertainty by the variations in the measurement was estimated to be an amount of the measurement value change in the acquisition time of the interference fringes (about 5 minutes). The change of the atmospheric pressure in the both time is shown in Figure 1 (a,b) , respectively. The change of the air temperature in the both time is shown in Figure 1 (c,d) , respectively.



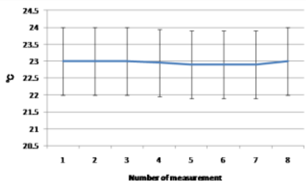
a)



b)



c)



d)

Figure 1: Pressure change during measurement interval (a) and during data acquisition (b), Air temperature change during measurement interval (c) and during data acquisition (d)

Uncertainty caused by variations in atmospheric pressure during the measurement and uncertainty due to the distribution of pressure were 0.7 hPa, the standard uncertainty of pressure measurement was 2×L×0.7×0.27 ppm = 2×L×0.189 ppm. Uncertainty caused by the variations in temperature during the measurement and uncertainty due to the distribution of the measurement were 1 ℃, the standard uncertainty of temperature measurement was 2×L×1×1 ppm = 2L ppm.

Combined standard uncertainty is given by the sum of the squares of the uncertainty depends on the length and uncertainty does not depend on the length. After calculation, the expanded uncertainty of the measuring system(coverage factor (k = 2)) was 5.1 μm. The difference between the measurement result of using the proposed method and the calibration value of the gauge block was 6.3μm. Both are similar, the experimental results is reasonable. Due to less number of sensors to monitor temperature and pressure, the estimated expanded uncertainty seems to be smaller.

5 Summary

The novel method of high-accuracy for an arbitrary and absolute length measurement directly linked to an FOFC is proposed. In the proposed method, the traceability of length standards is established using pulse repetition interval. The proposed method was applied to a 1.5-m long gauge block measurement, and the expanded uncertainty of the preliminary experiment is a few micrometres. In future works, we will test the PRIEF method and perform a detailed uncertainty estimation of the proposed method.

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