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Non-contact measurement technique for dimensional metrology using optical comb

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ABSTRACT

This paper proposes a non-contact pulsed interferometer for dimensional metrology using the repetition frequency of an optical frequency comb. A compact absolute-length measuring system is established for practical non-contact measurement based on a single-mode fiber interferometer. The stability and accuracy of the measurements are compared with those from a commercial incremental laser interferometer. The drifts of both systems have the same tendency and a maximum difference is approximately 0.1 μm. Subsequently, preliminary absolute-length measurements up to 1.5 m were measured. The signal-to-noise ratios of the small signals are improved by a frequency-selective amplifier. It is apparent that the noise is rejected, and the intensity of the interference fringes is amplified, achieving a maximum standard deviation of measurement approximately 1 μm. The proposed technique can provide sufficient accuracy for non-contact measurement in applications such as a simple laser-pulse tracking system.

1. Introduction

Recently, demand for high-accuracy measurement for dimensional metrology has increased rapidly. To respond to this requirement, many applications using an optical frequency comb were developed for absolute-length measurements because optical frequency combs have very high accuracy and a high stability of their frequencies. However, those applications, the measuring systems and the optical components are different [1–7].

This paper presents an optical comb application for absolute-length measurement using a single-mode fiber pulsed interferometer technique, which an optical comb is used as the laser source. A repetition frequency of 100 MHz of a general optical frequency comb is transferred to 1 GHz by a fiber type Fabry-Pérot etalon. The stability of the pulsed interferometer is considered because it is a factor that reflects the reliability of the measurement system versus changes in ambient environmental conditions. The experimental results are compared to measurements obtained with a commercial incremental interferometer. The drifts of both interferometer types are considered in a laboratory without control of air temperature and humidity. Subsequently, a metal ball with a rough surface is used as a target of the interferometer to obtain the length under measurement because the rough metal ball mainly reflects the laser beam to the single-mode fiber interferometer. It is easy to align the laser beam, and this setup also provides three-dimensional target positions. The surface roughness of the metal ball targets is analyzed because it directly influences the envelope inference fringes. Additionally, the requirement of a laser-beam alignment is considered. Finally, a preliminary absolute-length measurement up to 1500 mm was measured by an optical-comb pulsed interferometer, in which a rough metal ball is used as the target. A phase-sensitive analyzing method is used to obtain envelope interference fringes, and

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the measurement results are compensated for the group refractive index of air [8,9] owing to changes in environmental conditions. The proposed measuring system can possibly be used to develop a length-measuring tracking system, and can be applied to verify the coordinate measuring machine (CMM) by the multilateration measurement method [10,11].

2. Measurement principle

2.1. Optical frequency comb

Generally, a laser does not have only one wavelength or frequency, but has some natural bandwidth that is related to the gain medium and the optical cavity. In the optical cavity, the light waves will constructively and destructively interfere with themselves, becoming a formation of standing waves. The discrete sets of frequencies of standing waves are called longitudinal modes. These modes are the only frequencies of light that is allowed to oscillate by the resonant cavity and to oscillate independently. The output of a laser has several thousands of modes. Thus, the output intensity will become nearly constant; this is known as a continuous wave, or cw. If all of the modes of a cw laser are fixed in phase relationship, the lasers will periodically interfere with one another. As a result, the laser produces pulse trains of light and it is said to be mode-locked. Mode-locked lasers generate repetitive, ultrashort optical pulse trains by fixing the relative phases of all of the lasing longitudinal modes [12–15]. These pulses are separated in time that is given by Eq. (1).

$$\tau = \frac{2L}{c} \tag{1}$$

where L is the length of the optical cavity and c is the speed of light in vacuum. Therefore, the mode spacing of the laser will be

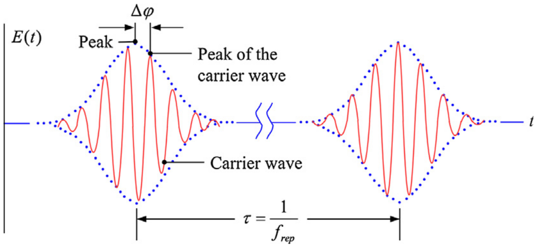
$$\Delta\upsilon = \frac{1}{\tau} \tag{2}$$

For that reason, the spectrum of each pulse train is separated by the repetition rate of the laser, and the spectral lines are called an optical frequency comb.

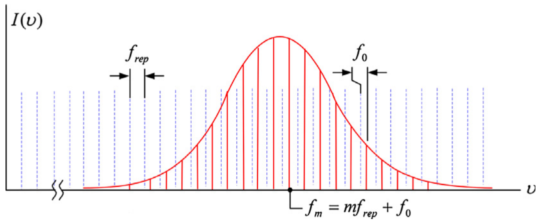
The time and frequency domains of an optical frequency comb are shown in Fig. 1. In the time domain, the pulse train is emitted by a mode-locked laser in the same time as the pulse-to-pulse separation time, $1/f_{rep}$, where f_{rep} is the repetition frequency of the optical frequency comb. In the frequency domain, each shape line is separated equally. The optical frequencies f_m of the comb lines is described as $f_m = mf_{rep} + f_0$, where m is a large integer of order 10^6 and f_0 is the offset frequency resulting from the pulse-to-pulse phase shift ($\Delta\phi$).

2.2. Fabry-Pérot Etalon

A Fabry-Pérot Etalon (etalon) is an interferometer in which the beam of a laser undergoes multiple reflections between two reflecting mirrors [16]. The resulting optical transmission is periodic in wavelength. The transmission of the etalon is at a maximum when the phase difference for a round-trip follows Eq. (3):



(a) Time domain.



(b) Frequency domain.

Fig. 1. (a) Time domain and (b) frequency domain of an optical frequency comb.

$$\frac{2\pi}{\lambda} 2nl\cos\theta = 2m\pi \tag{3}$$

where l is the cavity length of an etalon, θ is the transmission angle, n is the refractive index of the medium and λ is the laser wavelength. Expressing the maximum condition in terms of frequency, the location of transmission peak locations can be written as follows:

$$\upsilon = m\frac{c}{2nl\cos\theta} \tag{4}$$

Therefore, the frequency separation between successive peaks can be determined. The peak-to-peak frequency separation is called the free spectral range (FSR), and it is given by Eq. (5):

$$\mathrm{FSR} = \Delta\upsilon = \upsilon_{m+1} - \upsilon_m = \frac{c}{2nl\cos\theta} \tag{5}$$

As a result, when an etalon is applied, the repetition frequency of an optical frequency comb is transferred to the high frequency of the FSR. However, the output intensity is reduced when the laser pulse passes through an etalon. Therefore, an optical amplifier is required for some applications.

2.3. Optical comb pulsed interferometer

The diagram of an optical-comb pulsed interferometer is shown in Fig. 2. It is the operating principle of the unbalanced-arm Michelson interferometer. An optical comb generates a pulse train, and the laser pulses are divided into two beams by optical beam splitter (BS). One beam is reflected in the direction of a scanning mirror (M1), while the other is transmitted through a reference position ($OPD = 0$) to a target mirror (M2).

Both reflected light pulses are recombined with the beam that returned from M1 to produce interference fringes when the optical path difference (OPD) of the two arms satisfies the following Eq. (6) [1–3]: