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A new method for high-accuracy gauge block measurement using 2 GHz repetition mode of a mode-locked fiber laser

Narin Chanthawong, Satoru Takahashi, Kiyoshi Takamasu and Hirokazu Matsumoto

Department of Precision Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

E-mail: narin@nanolab.t.u-tokyo.ac.jp

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Abstract
We developed a Fabry–Perot etalon to select high-frequency parts of repetition-frequency modes of a short pulsed, mode-locked fiber laser at the wavelength of 1.55 μm. The 2 GHz repetition-modified laser is transmitted to an unbalanced Michelson interferometer with gauge blocks wrung on a platen. Two interference fringes were generated from the gauge block and platen at different positions. The interference fringes have a temporal coherence pattern and can make positioning in space easy. The length of the gauge block was directly determined from different positions of the two interference fringes, without using the excess fractions method.

Keywords: measurement, mode-locked fiber laser, Fabry–Perot etalon, gauge block, temporal-coherence interferometer

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recent research in the field of ultrashort pulse lasers has led to the use of a femtosecond mode-locked pulse as a reliable source of measurement by developing a carrier-envelope-phase stabilized laser [1–3]. The pulse train has a discrete frequency spectrum (regularly spaced lines known as a frequency comb). The frequency comb is used as a frequency standard when the frequency repetition and the carrier-envelope-offset are referred to an SI standard, like an atomic clock. These unique properties allow the frequency comb to be applied to time and frequency metrology [4, 5], fundamental physics [6, 7] and high-precision spectroscopy [8, 9]. The frequency comb can also be extended into the extreme ultraviolet (XUV) for x-ray imaging and precision quantum electrodynamics (QED) tests [10]. In 2002, practical experiments were proposed using high temporal coherence between a pair of pulse trains for the measurement of the group refractive index of air [11]. The pulse-to-pulse phase relationship of the light emitted by the optical frequency comb has created new directions for high-accuracy long-range distance measurement [12–16].

The mode spacing of such a comb is given by the pulse repetition rate, which depends on the laser type and is typically on the order of 100 MHz. It may even be possible to increase the repetition rate, though it is expensive and requires a lot of knowledge for practical use. An alternative would be to use an external Fabry–Perot etalon (FPE) to generate multiple pulses [17].

In 2006, the idea of a mode filtering method was presented [18] and the optical frequency comb was used for gauge block measurement. However, the optical frequency comb was used as a frequency standard for external-cavity laser diodes (ECLD) for multi-wavelength interferometry. The length of the gauge block was measured by means of multi-wavelength interferometry using multiple beams of different wavelengths consecutively, provided by an optical frequency synthesizer [19]. The length of the present method is given as $L = (\lambda/2)(m+\Delta\phi)$, where m is an integer ($m = 0, 1, 2, \ldots$) and $\Delta\phi$ is the excess fraction ($0 \leqslant \Delta\phi < 1$). Then it requires several number of wavelengths to remove the ambiguity of m.

In this work, to avoid the difficulty related to the excess fractions method, we use a temporal coherence property of the optical frequency comb to determine the length of the gauge block directly. The temporal coherence pattern is used as the precise ruler length. To increase the temporal coherence pattern, a FPE (with a finesse of about 100) is developed to increase repetition frequency of a mode-locked fiber laser. In fact, 100 MHz repetition-frequency rate of the femtosecond mode-locked laser is transferred to a 2 GHz filter by the FPE developed for every 20th-harmonic frequency passing from the etalon and the repetition rate after passing changes to 2 GHz. The stability of the modified laser is in the order of 10^{-9}, which is considerably smaller than the targeted measurement uncertainty in typical gauge block calibration [20, 21]. The temporal coherence between different pairs of modified pulse trains is referred to length standards and transferred to a gauge block which is commonly used in industry.

2. Principle

In most time-resolved experiments, the pump-and-probe pulses result from an unbalanced-arm Michelson interferometer and the same optical pulse which is split into two portions by an optical beam splitter. The basic elements of this scheme are shown in figure 1. The laser pulse from the mode-locked fiber laser is split into two beams and recombined after passing through various optical delays. The short arm has a piezo electric transducer (PZT) for scanning while the long arm is placed over an arranged distance. A pulsed source generates a train of optical pulses where the time repetition τ_{rep} in between subsequent pulses is $\tau_{\text{rep}} = 1/f_{\text{rep}}$. The spatial distance, l_d, between the pulses is derived by $l_d = c/nf_{\text{rep}}$, where f_{rep} is the repetition frequency of the frequency comb used. The interference fringe position between the two different-index pulses is observed when the path difference between two arms of the interferometer is equal to half the distance:

$$l_2 - l_1 = a \cdot \frac{l_d}{2} = \frac{ac}{2nf_{\text{rep}}}, \tag{1}$$

where a is the number of different indices between two pulses ($1, 2, 3, \ldots$), c is the speed of light in vacuum and n is the phase refractive index of air. The interference fringe position is inversely proportional to f_{rep}. High repetition frequency means more accurate interference fringe positioning in space. However, the high-repetition-frequency comb laser is expensive and requires a lot of knowledge in practical use.

As an alternative, we increase the repetition frequency used by selecting only high-frequency parts of repetition-frequency modes of a frequency comb laser. The FPE is developed for this purpose. A FPE is an optical cavity in which a beam of light undergoes multiple reflections

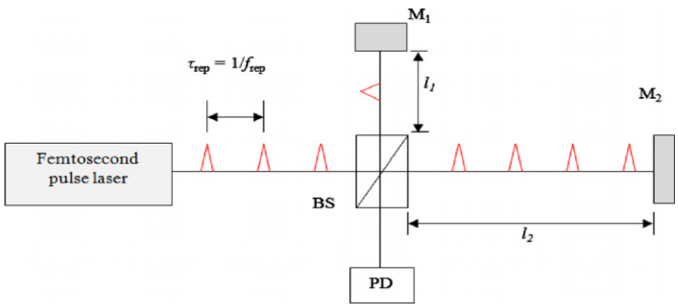


Figure 1. Schematic setup for time-resolved experiments using femtosecond mode-locked pulse laser (frequency comb laser).

between two reflecting surfaces, and whose resulting optical transmission is periodic in optical frequency spectrum. Several important parameters to describe the etalon include the optical spectra of maximum transmission, the free spectral range (FSR) and the finesse. The spectra of maximum transmission occur periodically and are easily recognized. The spacing between adjacent maxima is called the FSR. The finesse describes the narrowness of the peaks relative to the spacing between the peaks. The FSR and finesse are calculated by the following equations:

$$\text{FSR} = \frac{c}{2nl_c}, \tag{2}$$

$$\text{Finesse} = \frac{\pi\sqrt{R}}{1-R}, \tag{3}$$

where l_c is the cavity length and R is the reflectivity of the mirrors used for the etalon. A spectral transmission function from FPE can be calculated by the following equation:

$$T(f, R, l_c) = \frac{(1-R)^2}{(1-R)^2 + 4R\ \sin^2(2\pi f l_c/c)}, \tag{4}$$

where f is the frequency with high-frequency selection and the optical filter mode spacing is set to an integer multiple m of the laser repetition frequency f_{rep} by adjusting the FPE length such that $f_{\text{rep}} = c/2nl$. The filter cavity then transmits exactly every mth mode while the unwanted modes in between are largely suppressed. The new repetition frequency f'_{rep} of the frequency comb laser becomes.

$$f'_{\text{rep}} = mf_{\text{rep}}. \tag{5}$$

The transmission process of the repetition frequency is shown in figure 2.

Therefore, the half pulse distance, $l_d/2$, also changes due to the new repetition frequency. The new half pulse distance is changed to

$$a \cdot \frac{l_d}{2} = \frac{ac}{2\,nmf_{\text{rep}}}, \tag{6}$$

which means more reference positions in space, and can be changed by adjusting the FPE. We can select a new repetition frequency to create a reference fringe position close to the gauge block length. Through this method, we can determine the length of the gauge block directly from the temporal coherence pattern without the excess fractions method.

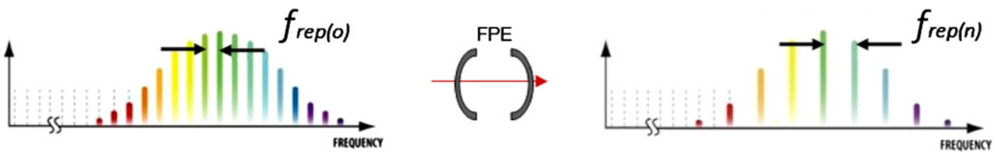
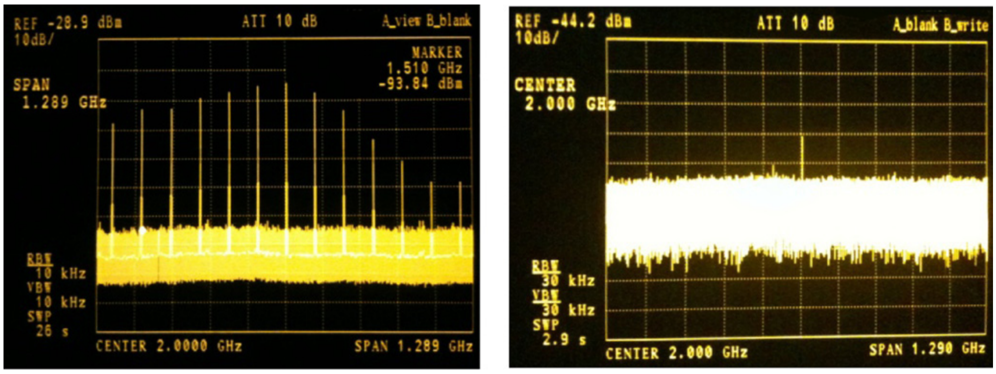
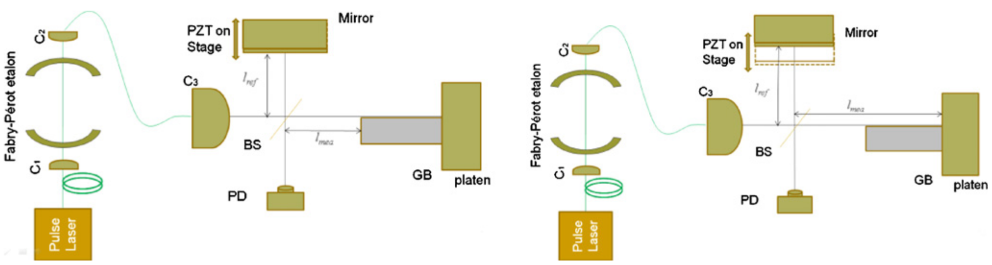


Figure 2. Transmission process of the repetition frequency.



(*a*) (*b*)

Figure 3. Frequency spectrum (*a*) before and (*b*) after passing through FPE.



(*a*) (*b*)

Figure 4. Schematic setup for high-accuracy gauge block measurement using high-frequency repetitions of a mode-locked fiber laser (*a*) when performing a measurement on top of the gauge block and (*b*) on the platen.

3. Experimental setup

The 100 MHz fiber laser is incident on the FPE: the multiplier index was set to $m = 20$ and repetition frequency to 2 GHz. The experiment however can be performed on a gauge block of size 75 mm and its multiples. Two pieces of gauge blocks, nominal length 75 mm and 150 mm, are used in this study.

3.1. Fabry–Perot etalon

The concave-mirror-type Fabry–Perot etalon (FPE) was selected for this experiment. A pair of 300 mm radius concave mirrors (1 inch diameter, 97% reflectivity, dielectric coating) was used to set up the etalon. Visible light laser alignment and 2 m distant screen were used for the parallel-alignment of the FPE. A 100 MHz repetition fiber laser (MenloSystems, C-fiber femtosecond laser, wavelength 1560 nm, output power 12 mW), whose repetition frequency is stabilized by an Rb frequency standard (Stanford Research Systems, FS725), is used as an optical pulse source. The carrier-envelope-offset frequency (f_{ceo}) stability is monitored by the beat signal from a 10^{-11} high-stability acetylene stabilized laser diode (NEOARK, C2H2LDS-1540). The laser was applied to the etalon by collimators (Thorlabs, F810APC-1550, beam diameter 7.0 mm). The length of the etalon is adjusted into position and the output from the etalon was measured by a spectrum analyzer (Advantest, R3265). The frequency spectrum is shown in figure 3 with the output power 0.01 mW.

After we selected the frequency mode of the etalon, the stability of FPE was measured by beat frequency from the 1.990 GHz frequency signal using a synthesized signal generator (Anritsu, MG3632A). The Rb frequency is also used as a reference for the synthesized signal generator. The beat signal was monitored by a universal counter (Iwatsu, SC-7206, 0.1 Hz resolution) for 6 h which is stabilized by the Rb frequency. The beating frequency results show that the stability of a modified laser after passing through the FPE is in order of 10^{-9} over 6 h. Therefore, the repetition frequency is stable enough for a length measurement.

3.2. Gauge block interferometer

Figure 4 shows the schematic setup for a gauge block measurement using 2 GHz repetition mode of the mode-locked fiber laser. The 2 GHz repetition modified laser from the etalon is transmitted to an unbalanced-arm Michelson interferometer. In the interferometer, the laser is split into two paths, with a beam diameter of 7 mm. One is a measurement path with a gauge block wrung on a platen. Another is a scanning path where a mirror is attached with an objective piezo positioner (CEDRAT TECHNOLOGIES, OPP120SM), PZT, over a translation stage (Sigmatech, FS-3150PX, 10 nm resolution) to scan interference fringes. The distance between the interference fringes is detected by an InGaAs photoreceiver (Newfocus, 2011-FC), PD, during scanning of the reference mirror by PZT.

The experiment starts by launching the laser to the collimator, C3, and the beam is incident on both the gauge block's face and the platen at the same time. The first interference fringe was detected from the top of the gauge block and reference mirror when they have equal paths, figure 4(*a*). The second interference fringe was detected when the mirror was moved only a small distance, figure 4(*b*), to create an optical path difference between the platen and the reference mirror equal to several times the half pulse distance, $l_d/2$. The absolute length of the gauge block, l_{GB}, is determined from the difference in length between the peaks of the interference fringes:

$$l_{GB} = a \cdot \frac{l_d}{2} + l_{stage} + l_{PZT}, \tag{7}$$

where l_d is the repetition length of the FPE multiplied pulse train, l_{PZT} is the moving length (about several μm) of the PZT and l_{stage} is the moving length of the translation stage, which is mainly derived from a fraction of the spread (about a hundred micrometers). The measurement can be performed on gauge blocks of size 75 mm and its multiples based on 2 GHz repetitions, and it can measure another multiple step gauge block by variation of FPE length to select another repetition rate.

3.3. Position determination

After observed temporal coherence is generated from different pairs of modified pulse trains, we have to determine the peak position. The standard length from modified pulse trains is determined from the peak-to-peak of the autocorrelation pattern from a different index. In the first step the input autocorrelation pattern is squared to obtain unsigned data. After obtaining the unsigned data from the squared results, the signal is passed through the low-pass filter to get the envelope shape. Then, the signal is differentiated and used for the zero position as a trigger to determine the peak position. The process of position determination is shown in figure 5.

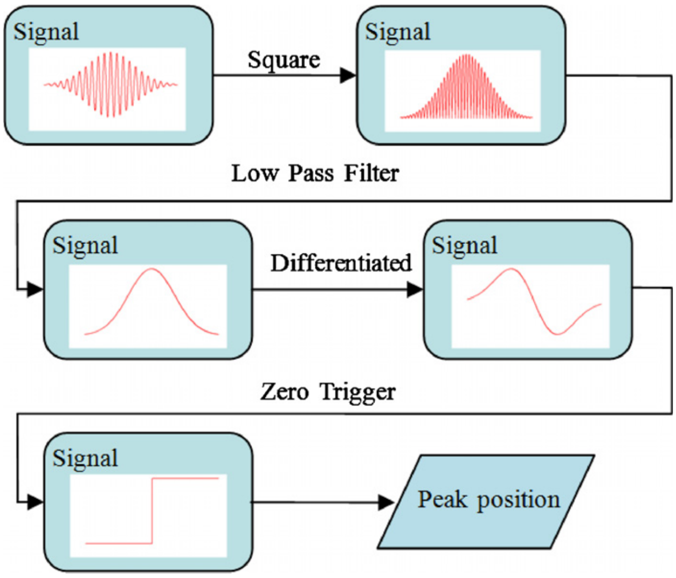


Figure 5. Process of position determination.

4. Results

4.1. Measurement results

The experiment is carried out in a chamber where the environmental conditions (temperature, pressure and humidity) were controlled and monitored during the experiment. The refractive index of air was compensated using the updated Edlén's equation in association with the actual environmental condition [22]. The measurement results are shown in table 1 and corrected for refractive index of air and temperature of gauge block to the reference temperature [23]. A standard deviation of the measurement is about 0.1 μm. The measurement results imply that the repetition-transformation technique can be applied successfully with high accuracy.

4.2. Uncertainty evaluation

In accordance with the ISO-recommended guideline [24], the overall uncertainty evaluation was made for the gauge block calibration performed in this study. The sources of uncertainty are shown in table 2. The first uncertainty consists of laser stability at $2.89 \times 10^{-9} \cdot L_0$, where L_0 is the nominal length of the gauge block given in meters. Other sources from the laser such as repetition rate and carrier offset frequency are negligible because the accuracy ratio with the gauge block is large, more than 100 times bigger.

The uncertainty for the refractive index of air was calculated to be $1.63 \times 10^{-8} \cdot L_0$ from the measurement errors

Table 1. Experimental results of 75 mm and 150 mm gauge blocks compared with certificate values and experimental standard deviation from measurements made ten times.

Nominal length (mm)	Certificate value (mm)	Measurement value (mm)	Difference (μm)	Standard deviation (μm)
75	N/A	75.000 33	N/A	0.10
150	150.000 10	150.000 04	0.06	0.06

Note: Certificate value is measured in the center of the gauge block according ISO 3650 [20]

Table 2. Uncertainty evaluation of absolute calibration of gauge blocks. L_0 denotes the nominal length of gauge block in meters.

Sources of uncertainty	Uncertainty value	Value (nm) for $L_0 = 150$ mm
FPE modified pulse laser	$2.89 \times 10^{-9} \cdot L_0$	0.43
Refractive index of air	$1.63 \times 10^{-8} \cdot L_0$	2.45
Translation stage and PZT	32 nm	32.15
Wringing of gauge block	11.55 nm	11.55
Repeatability	19 nm	19
System and gauge block alignment	$1.3 \times 10^{-7} \cdot L_0$	20
Wave-front error	20 nm	20
Flatness and parallelism of gauge block	6 nm	6
Thermal expansion of gauge block	$1.15 \times 10^{-7} \cdot L_0$	17.25
Combined standard uncertainty ($k = 1$)	$\sqrt{(47.6\ \text{nm})^2 + \left(1.74 \times 10^{-7} \cdot L_0\right)^2}$	51

of air temperature, pressure and humidity together with the uncertainty in the updated Edlén's equation. The uncertainty of the translation stage and the PZT includes PZT linearity, and hysteresis is 32 nm. The repeatability of measurement turns out to be 19 nm, the flatness and parallelism of the gauge block is evaluated to be 6 nm. The wringing process produces an uncertainty of 11.55 nm. Finally, the uncertainty of the thermal expansion of the gauge block is estimated to be $1.16 \times 10^{-7} \cdot L_0$. The combined standard uncertainty is calculated to be 43 nm ($k = 1$).

5. Conclusion

The absolute length measuring system for gauge blocks by using temporal coherence of optical frequency comb is studied. The mode-locked fiber laser was stabilized to the Rb clock (frequency standard). The FPE with a finesse about 100 was developed to increase the repetition frequency of a mode-locked fiber laser by selecting every 20th mode of the optical frequency comb. The 6 h stability shows that the modified optical comb is good enough as a standard for a gauge block. The absolute length is determined from half pulse interval distance of the FPE-modified pulse laser and the length of the gauge was determined from different interference fringes. It offers gauge block measurement without the excess fractions method. We can use this method to calibrate another size of gauge block by changing the repetition frequency to create a temporal coherence pattern around the under-calibration gauge block size. This method may not deliver the state of art gauge block measurement system but this method is good enough for measuring a gauge block with accuracy, and it can also measure a gauge block using one laser source with no ambiguous results.

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