High accuracy gauge block measurement using 2-GHz repetitions mode of a mode-locked fiber laser

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KEYWORDS : Measurement, Mode-locked fiber laser, Fabry–Pérot etalon, Gauge block, Temporal-coherence interferometer

We develop a Fabry–Pérot etalon to select high-frequency parts of repetition frequency modes of a short pulsed, mode-locked fiber laser of repetition frequency 100 MHz. The 2-GHz repetition-modified laser developed is transmitted to a Michelson interferometer with the gauge blocks of nominal lengths 75mm and 150mm and its platen. The interference fringes generated have a temporal-coherence interference fringe pattern and can make positioning in space. The phase difference between gauge block and platen interference fringes was measured from the peaks of the interference fringes and the length of gauge block had been determined with a high accuracy of 60 nanometers without a long translation stage.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

c = speed of light in vacuum 299,792,458 m/s^{-1}
n = refractive index of air

1. Introduction

Recent researches in the fields of ultrashort pulse laser have led to use femtosecond mode-locked pulse as a reliable source of length measurement by development of carrier-envelope-phase stabilized laser [1-3]. The pulse train has a discrete frequency spectrum, seperated regularly spaced line known as a frequency comb. The frequency comb is used as frequency standards when the frequency repetition and the carrier-envelop-offset are referenced to a frequency standard, like an atomic clock of frequency. These unique properties allow the frequency comb to be applied for time and frequency metrology [4-5], fundamental physics [6-7], and high-precision spectroscopy [8-9]. The frequency comb also can be extended into the extreme ultraviolet (XUV) for x-ray imaging, precision Quantum Electro Dynamic (QED) tests [10]. In 2002, practical experiments were proposed using high temporal coherence between a pair of pulse trains for measurement of the group refractive index of air [11]. The phase relationship of pulse-to-pulse 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 that depends on the type of the laser and is typically on the order of 100 MHz. Even it may be possible to increase the repetition rate, it expensive and requires a lot of knowledge in the practical use. An alternative would be to use an external Fabry-Pérot etalon to generate high-frequency pulses [17].

In this work, Fabry-Pérot etalon with a fineness of about 100 is developed to increase repetition frequency of a mode-locked fiber laser by several twenty times with keeping the high -accuracy of the optical frequency comb. Actually, 100 MHz repetition frequency rate of the femtosecond mode-locked laser is transferred to a 2-GHz-frequency filter by the Fabry-Pérot etalon developed. The every 20th-harmonics frequencies pass out from the etalon and the repetition rate after passing changes to 2-GHz with a high accuracy. The temporal coherence between different pairs of modified pulse trains is referred as length standards and transferred to gauge blocks which are used in industry.

2. Principle

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

$$l_2 - l_1 = a \cdot \frac{l_d}{2} = \frac{ac}{2nf_{rep}}, \quad (1)$$

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

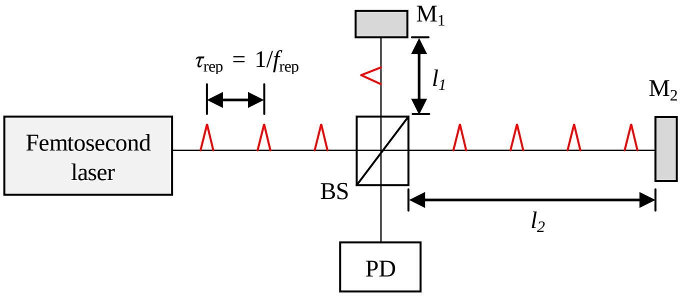


Fig. 1 Schematic setup for time-resolved experiments using femtosecond mode-locked pulse laser

Then, we increase the repetition frequency used by select only high-frequency parts of repetition frequency mode of frequency comb laser. The Fabry-Pérot etalon (FPE) is developed for this propose. The FPE is an optical cavity in which a beam of light undergoes multiple reflections between two reflecting surfaces, and whose resulting optical transmission is periodic in optical frequency spectrum. The several important parameters to describe the etalon are the optical spectra of maximum transmission, the free spectral range (FSR), and the finesse. The spectra of maximum transmission occur periodically because the spectra are fairly known. 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 fineness are calculated by the following equations:

$$FSR = \frac{c}{2nl_c}, \quad Fineness = \frac{\pi\sqrt{R}}{1-R}, \quad (2)$$

where c is the speed of light in vacuum, n is the refractive index, l_c is the cavity length and R is the reflectivity of the mirrors used for the etalon. A spectral transmission function from the Fabry-Pérot etalon is calculated from following equation:

$$T(f,R,l) = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(2\pi f l / c)} \quad (3)$$

For high-frequency selection propose, the optical-filter mode-spacing is set to an integer multiple m of the laser repetition frequency f_{rep} by adjust the FPE length such as $f_{rep} = c/2nl$. The filter cavity then transmits exactly every m-th modes while the unwanted modes in between many modes are strongly suppressed. The new repetition frequency f'_{rep} of the femtosecond mode-locked laser becomes.

$$f'_{rep} = mf_{rep} \quad (4)$$

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

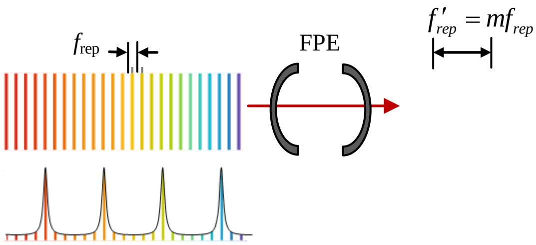
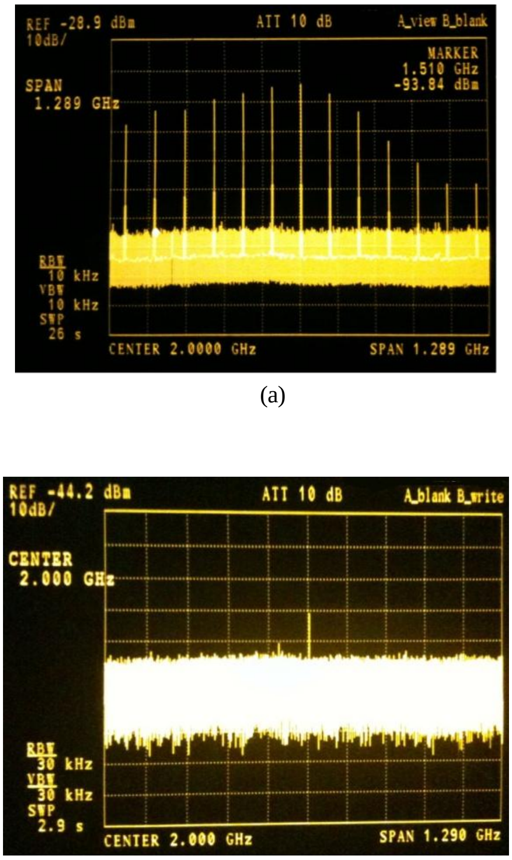


Fig. 2 Transmission process of the repetition frequency.



(a)

(b)

Fig. 3 The frequency modes around 2 GHz (a) before (b) after passing through the FPE.

The variation of distance in eq.(1) depend on our new repetition frequency f'_{rep} of the laser. The variable step of f'_{rep} is referred to f_{rep} from eq.(4). It is important that the frequency stability of f'_{rep} is the same to that of f_{rep}. It offers a good solution for absolute length measurement.

3. Experimental setup

Figure 4 shows the schematic setup for a high-accuracy length measurement using high-frequency repetitions of a mode-locked fiber laser. A 100-MHz repetition fiber laser (MenloSystems, C-fiber femtosecond laser, Wavelength 1560 nm, Output power 12 mW) where repetition frequency is stabilized by a Rb frequency standard with a stability of 10^{-11} is used as an optical light source. The carrier-envelop-offset frequency (f_{ceo}) stability is monitored by beating with 10^{-11} high-stability acetylene stabilized diode laser (NEOARK, C2H2LDS-1540). The laser is transmitted to a 2-GHz FPE. The 97%-reflectivity and 300-mm-radius concave-mirrors compose the FPE producing the cavity fineness at F~100. The 2-GHz repetition modified is transmitted to unbalanced Michelson interferometer. In the interferometer, the laser is split to two paths of a measurement path with a gauge block (GB) wringing with a platen and a reference path [18]. In, scanning path, a mirror is attached with the peizo-electric transducer (PZT) for scanning interference fringes. The interference fringes are observed by a photo detector (PD).

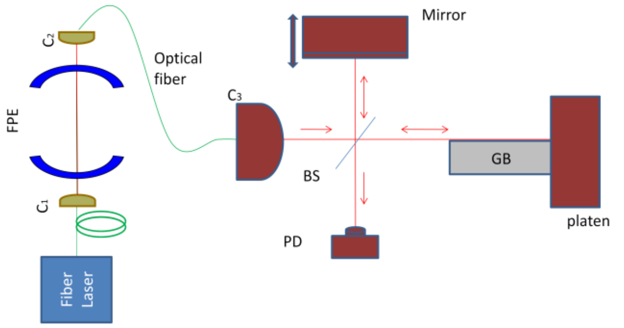


Fig. 4 Schematic steup for high-accuracy gauge block measurement using high-frequency repetitions of a mode-locked fiber laser

The experiments are performed as shown in Fig.4. The optical comb laser in measurement path is reflected at top surface of gauge block and scanning mirror on PZT, and then the optical path lengths of both paths are equal. The pulse train is spitted and travels on both paths. The interference fringe from same pulse train is detected at the photo detector. Another interference fringe is created when measurement path is reflected at platen. The lengths of both paths are different, and one path is added by the length of gauge block but another path is the same. Therefore, the optical-path difference is equal to the gauge block length. The interference fringe is generated when the path difference, l_d, between two paths is

$$l_d = k \cdot \frac{c}{2mnf_{rep}}, \tag{5}$$

where n = the refractive index of air, c = the speed of light in vacuum, m = Fabry-Pérot etalon multiplier index, k = pulse index difference (±1, ±2, ±3 …), f_{rep} = the repetition frequency of optical frequency comb used. The absolute length of gauge block, l_{GB}, is determined from the length difference between interference fringes:

$$l_{GB} = l_d + l_{PZT}, \tag{6}$$

where l_d = the repetition length of pulse laser and l_{PZT} = the moving length of the PZT. The length of gauge block can be determined without a requirement of a long translation stage. The less movement means easier to setup, more stable system and inexpensive compare with a long translation stage system.

4. Results

4.1 position determination

After observed temporal interference fringes from different pairs of modified pulse trains, we have to determine the peak position from it. The standard length from modified pulse trains is determined from peak-to-peak of autocorrelation pattern from different indies. In the first step the input autocorrelation pattern is squared to get unsigned data as shown in Fig.5. After received unsigned data from squared results, signal is passed through the low-pass filter to get the envelop shape of interference fringes. Then, the signal is differentiated and is used as trigger to determine the peak position.

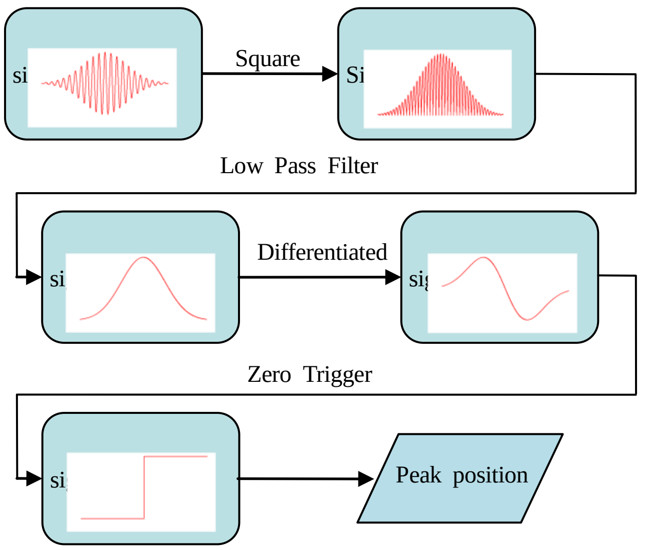


Fig. 5 Process of position determination

4.2 Measurement results

The gauge blocks of nominal lengths 75 mm and 150 mm are used for this study. The initial repetition frequency of the laser beam from MenloSystems fiber laser is 100.000000 MHz and Fabry-Pérot etalon changes the frequency to multiplier index m=20 namely 2,000,000,000 Hz. Therefore, the closest interference fringe is obtained from 1st and 2nd pulse index difference, respectively at each 75-mm length. The experiment is made under the chamber, and the environmental conditions (temperature, pressure, and humidity) was controlled and monitored during experiment. The measurement results of the gauge blocks are shown in Table 1. The standard deviation of the measurement is about 0.1 μm. It is shown that the repetition-transformation technique can be worked properly from the result.

5. Conclusion

Nominal length (mm)	Certificate value (mm)	Measurement value (mm)	Difference (μm)	Standard deviation (μm)
75	N/A	75.00033	N/A	0.10
150	150.0001	150.00004	0.06	0.06

Table 1. Experiment results of nominal lengths 75 mm and 150 mm gauge block comparing with certificate values and experimental standard deviation

The absolute length measurement system for gauge blocks of short nominal lengths 75 mm and 150 mm is studied. The absolute len -gth is determined from the pulse trains of a mode-locked fiber la-ser. The repetition frequency of mode-locked fiber laser is modif-i ed by a Fabry-Pérot etalon for short gauge blocks. The Fabry - Pérot etalon with fineness about 100 is developed to increase the repetition frequency of a mode-locked fiber laser by several twe-nty times. The output power from the first etalon is amplified by an optical system. The changes of repetition frequencies are usef-ul by changing the free spectral range of the etalon in order to de -termine the absolute lengths of various nominal-length gauge blo-cks.

ACKNOWLEDGEMENT

This research work was financially supported by the Development of System and Technology for Advanced Measurement and Analysis Industrial Innovation Program at the Japan Science and Technology Agency (JST) and Global Center of Excellence (COE) Program on “Global Center of Excellence for Mechanical Systems Innovation” granted to The University of Tokyo.

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