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STEP GAUGE MEASUREMENT USING HIGH-FREQUENCY REPETITIONS OF A MODE-LOCKED FIBER LASER

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Abstract: A high-frequency part of repetition frequency modes of mode-locked fiber laser is selected by a tandem Fabry–Pérot etalon. The 3-GHz repetition-modified laser is transmitted to a Michelson interferometer. The interference fringes generated have a temporal coherence pattern and can make positioning in space. The optical system of the interferometer is designed as double-path beams. A center between two beams is located at the position of a measuring probe of CMM. Using this design, we can apply the mode-locked fiber laser to artifacts following contact method. The advantage of the contact method can measure variety-shape artifacts, i.e. step gauge etc, that non-contact method cannot be used.

Keywords: mode-locked fiber laser, tandem Fabry–Pérot etalon, high-frequency repetition, step gauge, CMM.

1. INTRODUCTION

Recent researches in the fields of ultrashort pulse lasers have led to using a femtosecond mode-locked pulse as a reliable source of measurement by development of a carrier-envelope-phase stabilized laser [1-3]. Moreover, one technique using the carrier envelope pattern of non-stabilized laser has developed with a high-accuracy measurement [4]. The pulse train has a discrete frequency spectrum, regularly spaced lines known as a frequency comb. 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 with longest distance up to 403m [5-9]. However, the mode spacing of such a comb is given by the pulse repetition rate that depends on the laser type and is typically on the order of 100 MHz. It may be even possible to increase the repetition rate, it's expensive and requires a lot of knowledge for practical use. An alternative would be to use an external Fabry-Pérot etalon to generate multiply pulses [10] and it is used in the high-accuracy length measurement [11].

In this work, tandem Fabry-Pérot etalons with finesse about 30 and 100 are developed to increase repetition frequency of a mode-locked fiber laser. The temporal coherence between different pairs of modified pulse trains is referred as length standards and transferred to step gauges. A new double-path interferometer system with double corner reflector is designed for step gauge measurement. An advantage is those pitch and yaw motion errors are automatically compensated at the center between two arm beams.

2. PRINCIPLE

In most time-resolved experiments, the pump-and-probe pulses result from an Michelson interferometer and the same optical pulse which is split into two portions by an optical beam splitter. The laser pulse from the mode-locked fiber laser is split into two beams and recombined after passing through various optical delays, as shown in Fig. 1. 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 of the pulse distance:

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

where a is a number of different indies between two pulses (1, 2, 3…), c is speed of light in vacuum and n is 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.

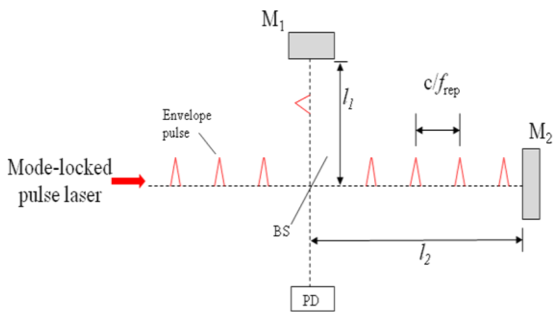


Fig. 1 Schematic setup for time-resolved experiments using mode-locked pulse laser (frequency comb laser)

Therefore, we increase the repetition frequency by selecting only high-frequency parts of repetition frequency modes of a frequency comb laser. The Fabry-Pérot etalon (FPE) is developed for this purpose. 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. 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 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:

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

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

where l_c is the cavity length and R is the reflectivity of the mirrors is used for the etalon. A spectral transmission function from Fabry-Pérot etalon 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, 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 as $f_{rep} = c/2nl$. The filter cavity then transmits exactly every m-th mode while the unwanted modes in between many modes are largely suppressed. The new repetition frequency f'_{rep} of the frequency comb laser becomes to.

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

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

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

Which means more reference position in space and it can be changed by adjusting the FPE. We can select a new repetition-frequency to create a reference fringe position close to step size of the step gauge.

3. EXPERIMENTAL SETUP

The system is split in three sections; tandem FPE, CMM's probing signal, and double-path interferometer system. The first section, tandem FPE is used to select high-frequency part from the optical comb. The repetition-frequency of optical comb can be modified by this technique.

3.1 TANDEM FABRY-PÉROT ETALONS

The tandem FPE was used in experiment. The Schematic setup for tandem Fabry-Pérot etalons system is shown in Fig. 2 and Fig. 3. A 100-MHz repetition fiber laser (MenloSystems, C-fiber femtosecond laser, wavelength 1560 nm, output power 12 mW), where repetition-frequency is stabilized by an Rb frequency standard (Stanford research systems, FS725), is used as an optical pulse source. The carrier-envelop-offset frequency (f_{ceo}) stability is monitored by beating with a 10^{-11} high-stability acetylene stabilized laser diode (NEOARK, C2H2LDS-1540). The laser is transmitted to a first 3-GHz-repitition-plane-parallel-type Fabry-Pérot etalon. The 93%-reflectivity flat mirrors compose of the cavity finesse of F~40. The first repetition-modified laser is amplified using Erbium Doped Fiber Amplifier (EDFA). After amplification, the laser is transmitted to a second 3-GHz-concave-type Fabry-Pérot etalon. The 97%-reflectivity and 300-mm-radius concave mirrors compose of Fabry-Pérot etalon produced cavity finesse of F~100.

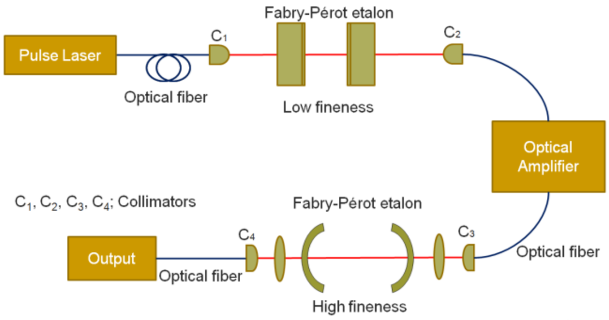


Fig. 2 Schematic setup for tandem Fabry-Pérot etalons

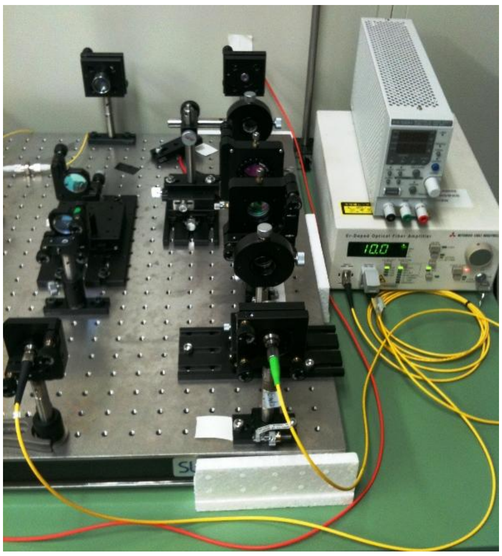


Fig. 3 Tandem Fabry-Pérot etalons system

The FPE is adjusted roughly by a low coherence interferometer with a high-resolution translation stage (Sigmatech, FS-3150PX, 10 nm resolution) and the output from the etalons was measured by a spectrum analyzer (Advantest, R3265). After the FPE is roughly adjusted close to theoretical position, the FPE is fine tuned by monitoring the power output of frequency 3-GHz signal to get the maximum power output. The length of the FPE has less sensitive to the measurement if the finesse is high enough.

The output from tandem Fabry-Pérot etalons system has higher power comparing with a single etalon. Another advantage of tandem Fabry-Pérot etalons system is more suppress unwanted optical frequencies than a single etalon.

3.2 CMM'S PROBING SIGNAL CONNECTION

The aim of this system is applying the mode-locked fiber laser to artifact following contact method. We use a coordinate measuring machine, CMM (Mitutoyo, Falcio Apex 707), as a moving stage and CMM's probe head (Renishaw PH10M) as contact system. The probing signal is a signal from probe head that informs a deflection of stylus when its contact happens. We take the signal out from connector pins no. 5 and no.9 of PL-25 cable which connects between probe head controller (Renishaw, PHC10-2) and probe interface (Renishaw, PI 200), as shown in Fig. 4.

Fig. 4 CMM's probing signal connection

The signal was connected by a special connector and detected by a digital oscilloscope (LeCroy, WaveJet 300A) to find out the signal profile to select the best trigger position. We select the area of trigger signal from small standard deviation area.

3.3 DOUBLE-PATH INTERFEROMETER SYSTEM

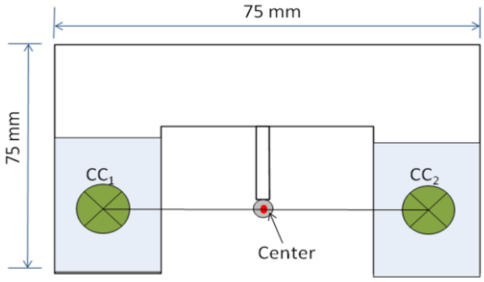
A double-path interferometer system is a Michelson interferometer in which the center between two arm beams is located at the position of measuring probe. An advantage of this design is to apply the mode-locked fiber laser to artifact following contact method. The length standard is transferred to artifact directly from the mode-locked fiber laser. Fig. 5 shows the schematic setup for the double-path interferometer system.

The laser from the optical comb is launched to tandem FPE system. Then, the laser is split in two directions by a fiber splitter, reference and measurement. On the reference path, beam launch to collimator, C_1, the mirror is placed on the piezo positionner (CEDRAT TECHNOLOGIES, OPP120SM), PZT, to create optical path delay for scanning. In another path of measurement path, the laser is launched from a collimator, C_2, to a left side corner reflector, CC_1. The beam is return and passing through a collimator, C_3, to a right side corner reflector, CC_2. Both of the reference beam and the measurement beam are combined by a mixer and detected by an InGaAs photoreceiver (Newfocus, 2011-FC), PD.

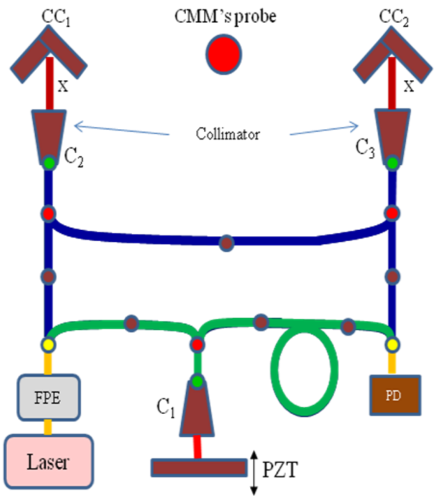
The measurement procedure is explained in Fig.6, the CMM's probe signal and temporal coherence were aligned into same position at first touch, on another side, the second touch and temporal coherence were different. PZT is used to adjust the temporal coherence into CMM's probe position. The position is obtained from a peak of interference fringes. The length of step gauge (l_{step}) can be evaluated from the following equation:

$$l_{step} = (a \cdot \frac{l_d}{2} + l_{PZT})/2 - \varnothing_{probe} \tag{7}$$

where l_d is the repetition length of FPE multiplied pulse train, l_{PZT} is the moving length of the PZT, and $\varnothing_{probe}$ is the CMM's probe diameter. The different pairs of modified pulse trains are referred as length standard. Moreover, advantages of the interferometer developed are to be not affected by air turbulence and to compose of compact system, because it was designed by optical fiber components.



(a)



(b)

Fig. 5 (a) Double corner reflector probe, (b) Schematic setup for double-path interferometer system

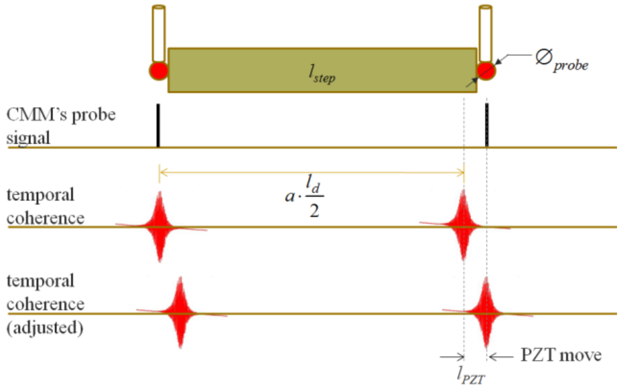
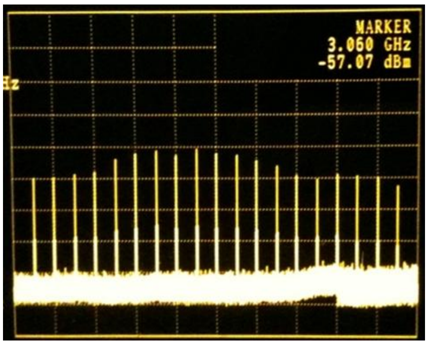


Fig. 6 measurement process

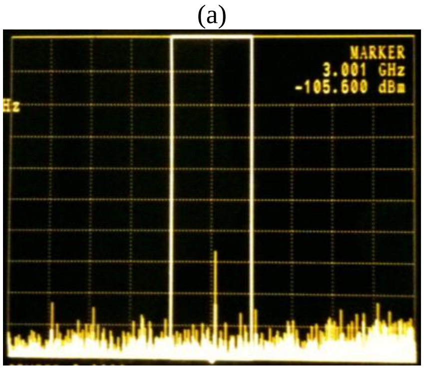
4. RESULTS

4.1 FREQUENCY SELECTION

The output from the etalons was monitored by a spectrum analyzer (Advantest, R3265). The original 100-MHz repetition from the fiber laser and the 3-GHz repetition-modified laser were shown in Fig. 7. The unselected frequencies were suppressed by effect of tandem FPE.



(a)



(b)

Fig. 7 The repetition frequency spectrum of (a) the original 100-MHz repetition from fiber laser, (b) the 3-GHz repetition-modified laser

4.2 EXPERIMENT RESULT

The 20 mm calibrated gauge block is used as step gauge. The experiment is done in the chamber; 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 [12]. The measurement results are shown in Table 1 and corrected for refractive index of air and temperature of gauge block to the reference temperature [13]. A standard deviation of 10-time measurements is about 70 nm. The measurement results imply that the repetition-transformation technique can be applied successfully with high accuracy

Table 1: Experiment result Unit: mm

Nominal size	Calibrated value	Measured value
20	20.00003	20.000046

This technique can be performed on other step size of step gauge by variation of the FPE length to select another repetition rate.

4.3 UNCERTAINTY OF MEASUREMENT

In accordance with the ISO-recommended guideline [14], the overall uncertainty evaluation was made for the gauge block calibration performed in this study. The sources of uncertainty are shown in Table 2.

Table 2: Uncertainty of measurement Unit: nm

Sources of uncertainty	Uncertainty value	Value for l_0=10 mm
FPE modified pulse laser	$2.89\times10^{-9}\cdot l_0$	0.03
Refractive index of air	$1.63\times10^{-8}\cdot l_0$	0.16
piezo positionner	29	29
Measurement repeatability	22	22
CMM's probe diameter	40	40
System and gauge alignment	$1.3\times10^{-7}\cdot l_0$	1.3
Thermal expansion of gauge	$1.15\times10^{-7}\cdot l_0$	1.15
Combined standard uncertainty (*k*=1)		55

The first uncertainty consists of laser stability at $2.89\times10^{-9}\cdot l_0$ where l_0 is the nominal length of the step gauge given in meters. Other sources from the laser such as repetition rate and carrier offset frequency can be negligible because the accuracy ratio with the step gauge is large, more than 100 times bigger. The uncertainty for the refractive index of air was calculated to be $1.63\times10^{-8}\cdot l_0$ from the measurement errors of air temperature, pressure and humidity together with the uncertainty on updated Edlen's equation. The PZT was calibrated by using a He-Ne laser interferometer, Renishaw ML-10. Mostly the PZT has a hysteresis problem, but the one-way positioning was good enough from calibration results. Then, PZT was used by one-way scanning during experiment. The uncertainty of the

PZT was evaluated to be 29 nm. The uncertainty of 10-times repeatability of measurement was observed to be 22 nm, the uncertainty of CMM's probe diameter was estimated to be 40 nm. The system and gauge alignment error was approximated at $1.3\times10^{-7}\cdot l_0$. Finally, the uncertainty of the thermal expansion of the gauge block was estimated at $1.15\times10^{-7}\cdot l_0$.

The combined standard uncertainty is calculated to be 55 nm (k=1).

5. CONCLUSION

The new double-path interferometer system with double corner reflectors for step gauge measurement is studied in three sections. The Fabry-Pérot etalons is developed to increase the repetition frequency of a mode-locked fiber laser. The interval between different pairs of modified pulse trains is referred as length standard for an artifact. The optical path of the interferometer is designed as double-path in which a pitch and yaw motion errors are automatically compensated at the center between two beams. The interferometer is not affected by air turbulence because it was designed by optical fiber components. And the CMM's probing signal is used as contact triggering signal for measurement.

6. ACKNOWLEDGEMENTS

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