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High-accuracy calibration of CMM using temporal-coherence fiber interferometer with fast-repetition comb laser

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Abstract. A coordinate measuring machine (CMM) is a measuring system with the means to move probing system and capability to determine spatial coordinates on working surface. CMM is used in many industry fields from few micrometers of work pieces to a 5-meter truck. The verification method of CMM is done following international standard. The artifacts for calibrated reference length are the end standards, such as gauge block and step gauge, or laser interferometer for large size CMM. The current laser interferometer is operated by continuous laser and interference fringe counting. One constraint of continuous laser is an incremental measurement. The measurement path cannot be interrupted during the measurement period. We developed a new absolute interferometer system from a short-pulse mode-locked fiber laser. A Fabry–Pérot etalon (FPE) is used to select high-frequency parts of repetition-frequency modes of the mode-locked comb laser at the wavelength of 1.55 μm. The 5-GHz repetition-modified laser beam, which is realized by a new fiber-type FPE, is transmitted to a fiber-type Michelson interferometer. The interference fringes exhibit a temporal coherence interference and can be used for measuring spatial positioning. The temporal coherence between different pairs of modified pulse trains is referred to as absolute length standards. The performance of CMM was determined directly from different positions of two interference fringe patterns.

1. Introduction

Nowadays, the Coordinate Measuring Machine (CMM) becomes an important machine in many fields of industry, because its ability to measure three dimensional artifact with the complex shape. In practical, the performance of CMM had to be monitored otherwise its can effect to the final products. The concepts to evaluate the performance are expressed in many concept ideas [1-3]. Anyhow, the standard method as standard protocol from ISO document is stated to use the physical standard (gauge block, step gauge, ball plate etc.) or the laser interferometer [4]. The present laser interferometer system is base on continuous He-Ne laser and fringe counting. The restriction of this method is the measuring path cannot be interrupt during the measurement period.

The recent researches show that a femtosecond mode-locked pulse is a reliable source of measurement in the fields of ultrashort pulse lasers by development of a carrier-envelope-phase stabilized laser [5-7]. The pulse train has a discrete frequency spectrum, regularly spaced lines known as a frequency comb. The frequency comb is used as the frequency standard when the frequency repetition and the carrier-envelop-offset are referenced to an SI standard, like an atomic clock. These unique properties allow the frequency comb to be applied for time and frequency metrology [8-9]. 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 [10]. 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 [11].

In this work, to avoid the difficulty about measurement path interruption of He-Ne laser, we apply a femtosecond mode-locked pulse laser for CMM performance verification and use a temporal coherence property of the optical frequency comb to determine the length as a length standard. The temporal coherence pattern is used as the precise ruler length for us. This idea can use in practical and we reported the idea of use optical frequency comb as a standard for distance measurement in 2011 [12] and gauge block calibration in 2012 [13]. To increase the temporal coherence pattern, a Fabry-Pérot's etalon system, FPE (etalon)system, is developed to increase repetition-frequency of a mode-locked fiber laser. In actual fact, 100-MHz repetition-frequency rate of the femtosecond mode-locked laser is transferred to a 5-GHz filter by the FPE developed. For every 50th-harmonics frequency that is passed out from the etalon and the repetition rate after passing changes to 5-GHz. The stability of the modified laser is in order of 10^{-9}, which is considerably smaller than the targeted measurement uncertainty in typical CMM verification [14].

2. Principle

In this section we briefly review the general idea of time-resolved experiments from pulse laser, the unbalanced-arm Michelson interferometer as shown in Fig. 1. An optical pulse from the laser is split into two photons 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. The distance, l_d, between the pulses in a spatial space is derived by $l_d = c/nf_{rep}$. 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:

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

where: a is an integer number, c is speed of light, n is 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.

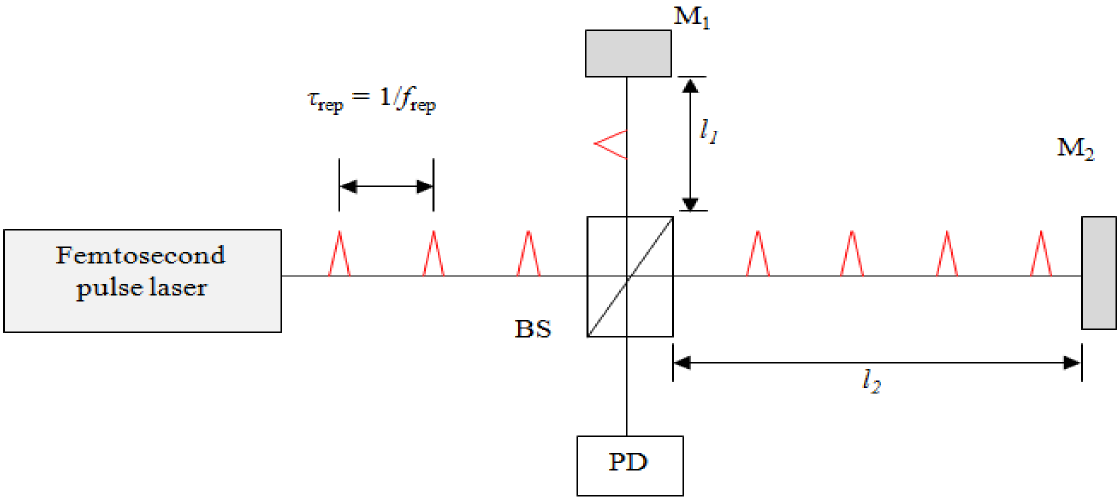


Fig. 1 Schematic setup for time-resolved experiments using femtosecond mode-locked pulse laser (frequency comb laser)

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 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. A spectral transmission function from Fabry-Pérot etalon can be calculated by the following equation:

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

Where: R is reflectivity of surface. 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 $f_{\mathrm{rep}} = c/2nl$. 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 too.

$$f'_{rep}=mf_{rep} \tag{3}$$

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:

$$a\cdot\frac{l_d}{2}=\frac{ac}{2nmf_{rep}}, \tag{4}$$

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 an appropriate reference fringe position for a CMM.

3.Fabry-Pérot's etalon

Two type of etalon is used in this study, a mirror FPE and a fiber FPE. The both type low-finesse FPE is apply in series instead of one high-finesse FPE to generate repetition-modified laser.

3.1 Fiber Fabry-Pérot's etalon

The mirror-type FPE has an advantage on flexibility on adjustable free spectral length but the difficult of mirrors alignment is required skill of operator and time consuming. The idea of FPE made from fiber for compensate the disadvantage of Mirror FPE. Fig 2 shows a single mode fiber (SMF-28) is cut in specific length for create FSR at 1-GHz and 1.25-GHz. The both ends of fiber have a FC connector with 90% reflectivity coating on the surface.

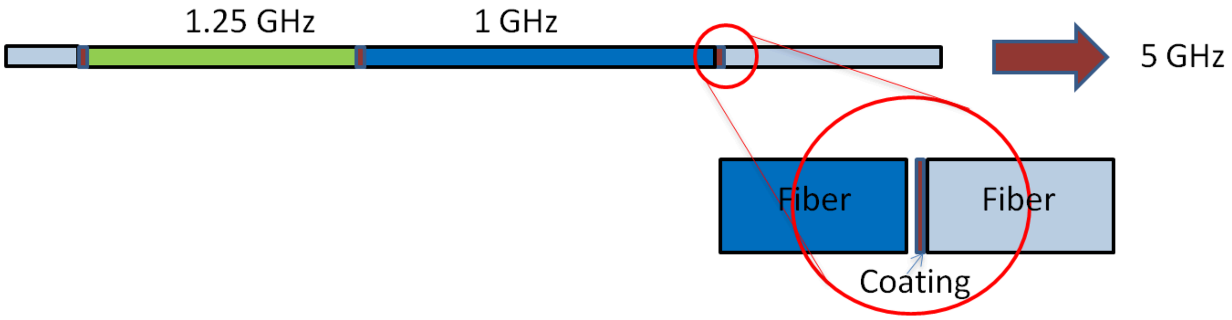
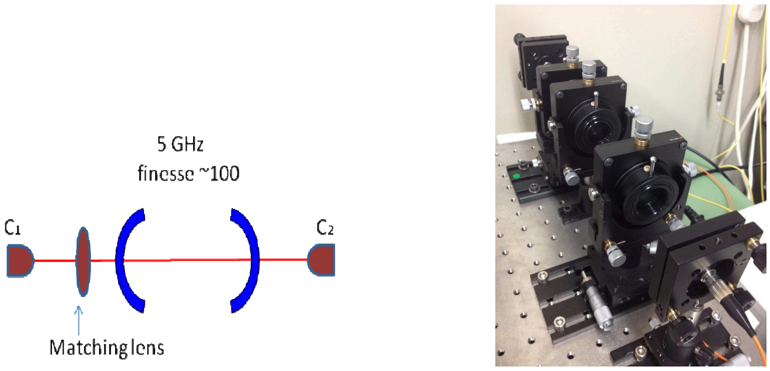


Fig. 2 A series of 1-GHz and 1.25-GHz fiber-type Fabry-Pérot etalons with the 90%-reflectivity, finesse about 30, for each etalon

3.2 Mirror Fabry-Pérot's etalon

The concave-mirror-type FPE was selected for this experiment. A pair of 300-mm-radius concave-mirrors, one inch diameter, 97% reflectivity, dielectric coating, was used to setup as 5-GHz etalon. The visible light laser alignment and 2-meters distant screen had been used to parallel-alignment of the FPE.



(a) (b)

Fig. 3 A tandem low coherent interferometer with a high-precision translation stage.

3.3 Fabry-Pérot's etalon system

The Fabry-Pérot's etalon system (FPE system) is a combination of a fiber FPE and mirror FPE as a series to increase an efficiency of the low finesse etalons as shown in Fig. 4. 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 laser was applied to the a series of 1-GHz and 1.25-GHz fiber-type Fabry-Pérot etalons by single mode fiber optic. The first repetition-modified laser is amplified using Erbium Doped Fiber Amplifier (EDFA). Then, the laser was applied to the mirror FPE by collimators (Thorlabs, F810APC-1550, beam diameter 7.0 mm) and the output from the etalon was measured by a spectrum analyzer (Advantest, R3265). The frequency spectrum was shown in Fig. 5.

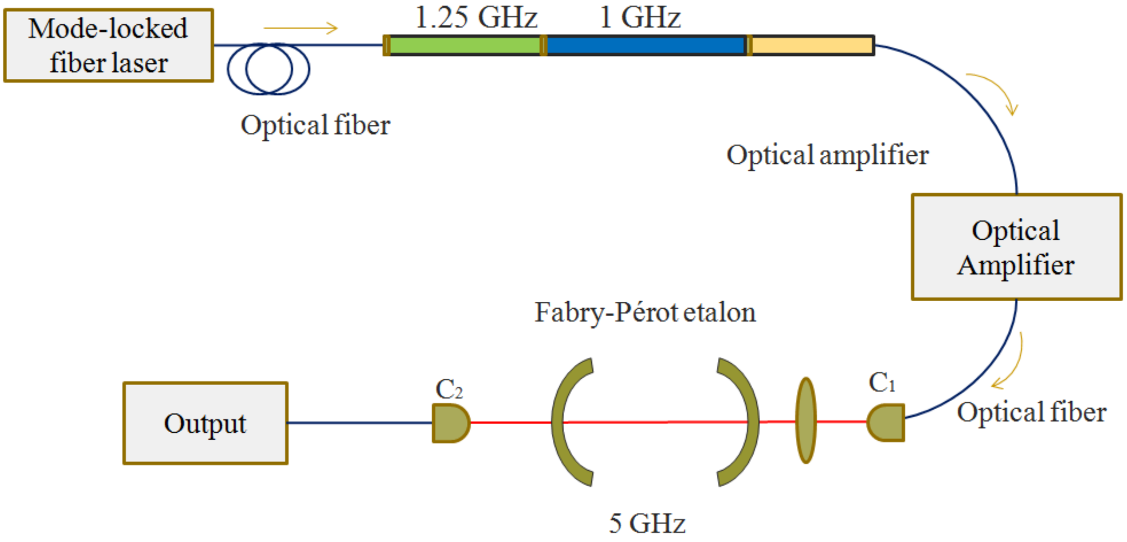


Fig. 4 The schematic diagram of FPE system.

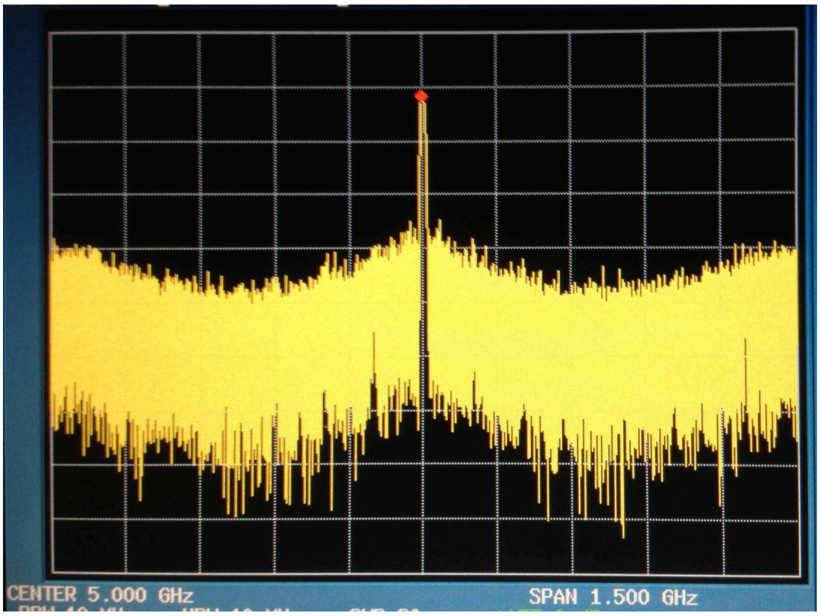


Fig. 5 The frequency spectrum after passing through FPE.

4. fiber-type interferometer for CMM verification

Figure 6 shows the schematic setup for a CMM verification using 5-GHz repetitions mode of the mode-locked fiber laser. The 5-GHz repetition modified laser from the etalon is transmitted to a fiber-type interferometer. In the interferometer, the laser is split to two paths by fiber coupler. One is a measurement path with a retro refractor was attached at CMM's probe. Another is a scanning path where a mirror is attached with a objective piezo positionner (PiezosystemJena, PX400), PZT, to scan interference fringes. The laser from two paths is combined by fiber mixer. The distance between the interference fringes are detected by an InGaAs photoreceiver (Newfocus, 2011-FC), PD, during one-direction scanning of the reference mirror by PZT to avoid a hysteresis.

The experiment was performed on Mitutoyo CMM Apex 707, starts by launch the laser to 50/50 fiber coupler. The measurement path is applied to fiber circulator and collimator, C1, the beam incidence on retro reflector and return to collimator. The reference path is operated on another set of fiber circulator and collimator, C2, the beam incidence on a mirror which is attached on PZT and return to collimator. The output from both circulators are combined by fiber mixer and detected by PD. The measurement can perform on every 30 mm of CMM movement base on 5-GHz repetitions.

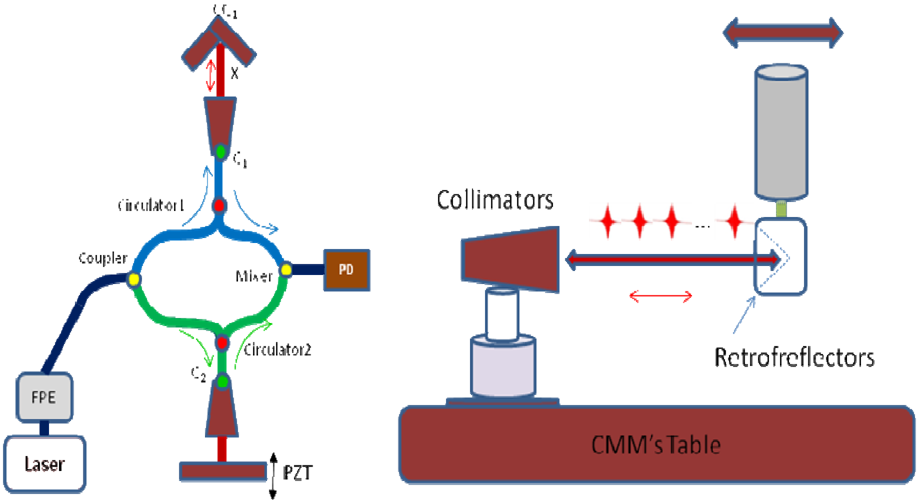


Fig.6 Schematic setup for CMM evaluation using high-frequency repetitions of a mode-locked fiber laser.

5. Results

The experiment is done in the environmental conditions room (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 [15]. The measurement results are shown in Table 1 and corrected for refractive index of air to the reference temperature [16]. A standard deviation of the measurement is about 0.1 □m. The measurement results imply that the repetition-transformation technique can be applied successfully with high accuracy.

Table 1 Experiment results on 300 mm CMM performance verification

CMM Length	Mode-locked fiber laser length (mm)				Average	Standard deviation	different
mm	1st	2nd	3rd	4th	mm	µm	mm
29.9729	29.97299	29.9729	29.97296	29.97293	29.97294	0.04	1.6
59.9414	59.94141	59.94142	59.94148	59.94149	59.94145	0.04	-1.2
89.9164	89.91641	89.91634	89.91644	89.91648	89.91642	0.06	2.6
119.8852	119.8851	119.8852	119.8852	119.8853	119.8852	0.05	0.0
149.8542	149.8541	149.8543	149.8543	149.8542	149.8542	0.06	-2.3
179.8278	179.8278	179.8279	179.8279	179.8277	179.8278	0.08	0.1
209.8002	209.8002	209.8002	209.8003	209.8002	209.8002	0.06	1.2
239.7689	239.7688	239.7689	239.7689	239.7688	239.7689	0.06	-1.4
269.7431	269.7431	269.7432	269.7432	269.743	269.7431	0.09	1.5
299.7123	299.7124	299.7124	299.7124	299.7122	299.7124	0.10	-0.6

6. Conclusions

The new design of CMM performance verification 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 system with a combination of fiber FPE and mirror FPS is developed to increase the repetition-frequency of a mode-locked fiber laser by selecting every 50th mode of the optical frequency comb. The 2-hours stability shows that the modified optical comb is good enough as standard for a CMM. The absolute length is determined from half pulse interval distance of the FPE-modified pulse laser and the performance of CMM was determined from interference fringes. The measurement system is based on fiber-type interferometer; it offers more convenient system for CMM performance verification.

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