

# NON-CONTACT MEASUREMENT TECHNIQUE FOR DIMENSIONAL METROLOGY USING OPTICAL COMB

Wiroj SUDATHAM<sup>1</sup>, Hirokazu MATSUMOTO<sup>1</sup>, Satoru TAKAHASHI<sup>2</sup> and Kiyoshi TAKAMASU<sup>1</sup>

<sup>1</sup> Department of Precision Engineering, The University of Tokyo, Hongo 7-3-1 Bukyo, Tokyo 113-8656, Japan  
wiroj@nanolab.t.u-tokyo.ac.jp

<sup>2</sup> Research Center for Advanced Science and Technology, The University of Tokyo, Komaba 4-6-1, Meguro, Tokyo 153-8904, Japan

## Abstract:

This paper proposes non-contact pulse interferometer for dimensional metrology using the repetition frequency of the optical frequency comb. The repetition frequency of 100 MHz of a general optical frequency comb is transferred to that of 1 GHz by using a Fabry-Pérot Etalon, which is firstly developed by single mode optical fiber. Therefore, temporal-coherence interference fringes are generated at each several cm and then compact absolute position-measuring system is realized for practical non-contact use with a high accuracy measurement. The stability and accuracy of measurements are compared with commercial incremental laser interferometer. The drifts of both systems are the same tendency. The maximum drift difference between two interferometer systems is about 0.1  $\mu\text{m}$ . And the maximum difference of length measurement of both systems is about 0.18  $\mu\text{m}$  at the length of 150 mm while the maximum standard deviation of pulse interferometer is better than incremental interferometer about 10 times. Then, the pulse interferometer is constructed and a metal sphere ball is used as a target of interferometer. The average standard deviation of distance/length measurement is about 0.6  $\mu\text{m}$  for the measuring length up to 1.5 m. This new technique can provide a high accuracy for non-contact measurement system such as a simple pulse tracking system.

**Keywords:** Non-contact measurement, Pulse interferometer, Absolute length measurement, Dimensional metrology

## 1. INTRODUCTION

Recently, demand of high accuracy measurement for dimensional metrology is rapidly increase. To respond this requirement, many applications of the optical frequency comb were developed for the absolute distance/length measurement because it is high accuracy and high stability of their frequencies which are traceable to the definition of time (second) [1-5].

This paper presents an optical comb application for absolute distance/length measurement using pulse interferometer technique. The repetition frequency of 100 MHz of a general optical frequency comb is transferred to that of 1 GHz by using a Fabry-Pérot Etalon. A metal ball with rough surface is used as a target of the interferometer for obtained the distance/length under measurement. Because the metal ball or metal sphere ball mainly reflected laser beam returned to single mode fiber interferometer and also provides three dimensional target positions. Therefore, it can be developed for the pulse tracking system or can be used to verify a CMM by using Multilateration method. [6]

Firstly, the principle of an optical comb, an etalon and pulse interferometer are described to provide some background of the absolute distance/length measurement. Secondly, the measurement of stability is considered because it is a factor that shows the reliability of measurement system versus the change of ambient environmental conditions. This measurement system is compared with the commercial incremental interferometer. The drifts of both interferometer systems are considered in air-uncontrolled laboratory. Subsequently, the surface roughness of metal ball targets is analyzed. It directly influences to envelope inference fringe because the single-mode fiber system is used as the interferometer. Additionally, the requirement of the laser beam alignment is also consideration. Finally, the distance up to 1500 mm was measured by an optical pulse interferometer which a metal ball is used as the target of interferometer. The phase sensitive analyzing method is used to obtain envelope interference fringes and the measurement results are compensated the refractive index of air due to the change of environmental conditions. This optical pulse interferometer technique provides the stability of about 0.25  $\mu\text{m}$  during one hour of measurement. The maximum standard deviation is about 1  $\mu\text{m}$ .

## 2. PRINCIPLES

### 2.1 Optical frequency comb

Generally, a laser is not only one wavelength or one frequency, but has some natural bandwidth which is related to the gain medium and the optical cavity. In the optical cavity, the light waves, will constructively and destructively interfere with itself, become to the formation of standing waves. The discrete set of frequencies of standing waves is called longitudinal modes. These modes are only the frequencies light which are allowed to oscillate by the resonant cavity and oscillate independently. The laser output has many thousands of modes. So, the output intensity will become nearly-constant and it is known as the continuous wave, CW. If all of CW laser is fixed in phase relationship, the lasers will periodically interfere with one another. As the result, it produces the pulse train of light and it is said to be mode-locked. Therefore, mode-locked lasers generate a repetitive ultrashort optical pulses train by fixing the relative phases of all of the lasing longitudinal modes [7]. These pulses occur by separation in time by Eq. (1).

$$\tau = \frac{2L}{c} \quad (1)$$

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

$$\Delta\nu = \frac{1}{\tau} \quad (2)$$

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

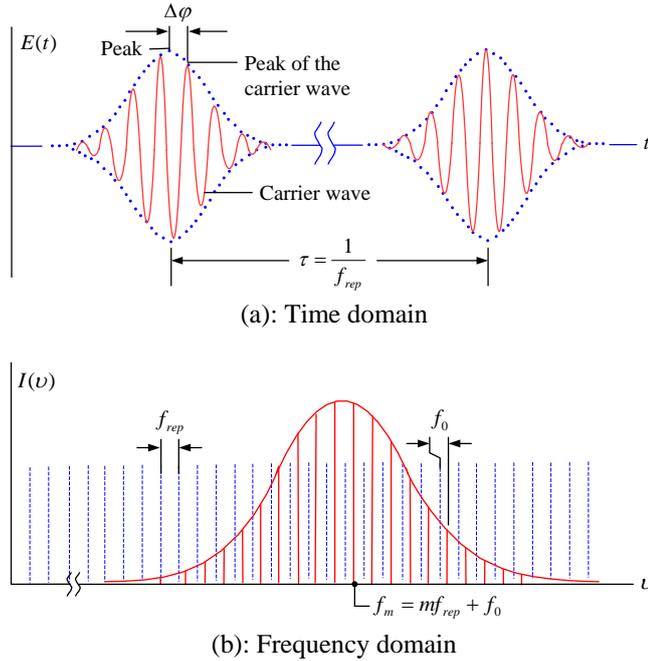


Fig. 1: Time domain and frequency domain of an optical frequency comb

In the time domain, the pulse train is emitted as the same time by mode-locked laser which the pulse-to-pulse is separated by  $1/f_{rep}$  where  $f_{rep}$  is the repetition frequency of the optical frequency comb. The pulse-to-pulse states in the phase of pulses emitted by the mode-locked laser due to the phase and group velocities inside the cavity are different. In the frequency domain, each shape lines are 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 because pulse-to-pulse phase shift ( $\Delta\phi$ ). The time and frequency domains of an optical frequency comb are shown in Fig. 1.

## 2.2 Etalon

A Fabry-Perot Etalon (etalon) is an interferometer which a beam of laser undergoes multiple reflections between two reflecting mirrors [8]. The resulting optical transmission is periodic in wavelength and the transmission of the etalon is a maximum when the phase difference for a round-trip is.

$$\theta = \frac{2\pi}{\lambda} 2nl\cos\theta = 2m\pi \quad (3)$$

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

$$\nu = m \frac{c}{2nl\cos\theta} \quad (4)$$

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

$$FSR = \Delta\nu = \nu_{m+1} - \nu_m = \frac{c}{2nl\cos\theta} \quad (5)$$

When an etalon is applied, the repetition frequency of an optical frequency comb is transferred to the high frequency such as several GHz. In this present, if 1 GHz etalon is connected to an optical comb which has repetition frequency 100 MHz, the output will be 1 GHz following an etalon. Moreover, the output intensity is reduced when the laser pulse goes through an etalon. Therefore, an optical amplifier is required for some applications.

## 2.3 Optical pulse interferometer

An optical pulse interferometer remains the principle of an unbalance-arm Michelson's interferometer. As shown in Fig. 2, an optical comb generates pulses train. Laser pulses are divided into two beams by optical beam splitter (BS). One beam is reflected in the direction of reference mirror (M1) while the other is transmitted through a semi-permeable mirror to the target mirror (M2).

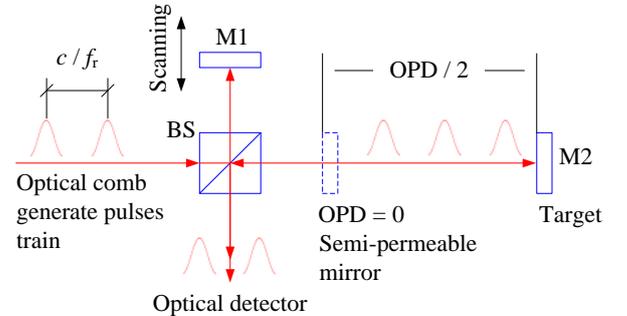


Fig. 2: Principle of pulse interferometer

Both reflected light pulses recombine to produce interference fringe when the optical path difference (OPD) between two arms satisfies the following Eq. (6). [1, 2]

$$OPD = \frac{mc}{nf_{rep}} \quad (6)$$

where  $m$  is an integer and  $n$  is refractive index of air. Generally, two interference fringes will overlap with each other when pulse interferometer exactly satisfies the condition of Eq. (6).

In practical, the envelope peak of interference fringes will be separated if we provide a little displacement, ( $\Delta L$ ). The result illustrates in Fig. 3.

Therefore, the position under measurement is determined as

$$L = \frac{OPD}{2} + \Delta L \quad (7)$$

The distance/length under measurement system was corrected for the refractive index of air due to the change of environmental conditions by Edlén equation [9, 10]. Two envelop interference fringes are presented in the time domain. Consequently, the fringe-scanning device must be calibrated to determine the relationship between time and length scale. A linear gauge with a resolution of 10 nm was used to calibrate the device.

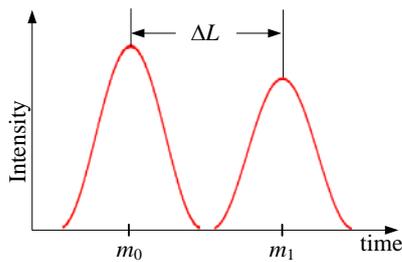


Fig. 3: The interference fringes of  $m_0$  and  $m_1$

### 3. EXPERIMENTS AND RESULTS

#### 3.1 Stability and accuracy of pulse interferometer

To study of the measurement stability, the preliminary measurement was set as Fig. 4. A pulse interferometer was setup pair with the incremental interferometer (Renishaw length-measuring 633 nm He-Ne interferometer)

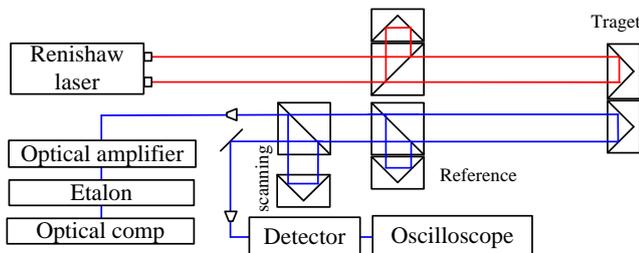


Fig. 4: Preliminary measurement set up for study of stability of pulse interferometer comparing with incremental interferometer

An optical comb, A C-Fiber Femtosecond Laser of MenloSystems was used as a laser pulse train source. The central wavelength is 1560 nm, the output power is about 12 mW and the repetition frequency is 100 MHz which is stabilized by Rb-frequency standard. Both measurement systems were leaved in the air-uncontrolled laboratory. The lengths of 150 mm were measured every ten minutes in one hour. The environmental conditions such as ambient temperature, relative humidity and air pressure also were recorded. Then, the drifts of both systems were calculated and compared which the results are illustrated in Fig. 5.

In the experiment, the average value of ambient temperature, relative humidity and air pressure are 25.60 °C, 36.5 % and 101.02 kPa, and the maximum variation is about 0.2 °C, 1.7 % and 10 Pa, respectively. The results in Fig.5 show that the variations from the average values of both measuring systems have the same drift tendency. The maximum variations of pulse and incremental interferometer are 0.25  $\mu\text{m}$  and 0.21  $\mu\text{m}$ , respectively. The maximum difference between two curves is about 0.1  $\mu\text{m}$ .

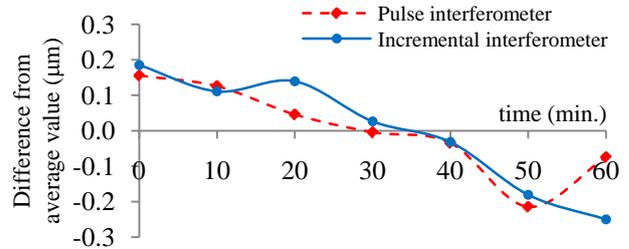
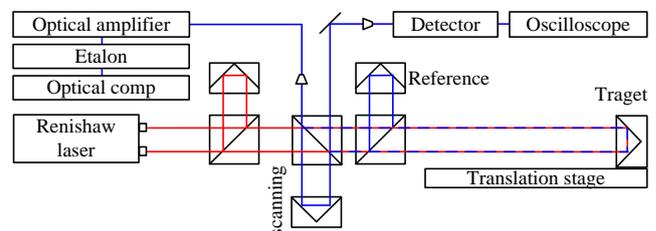
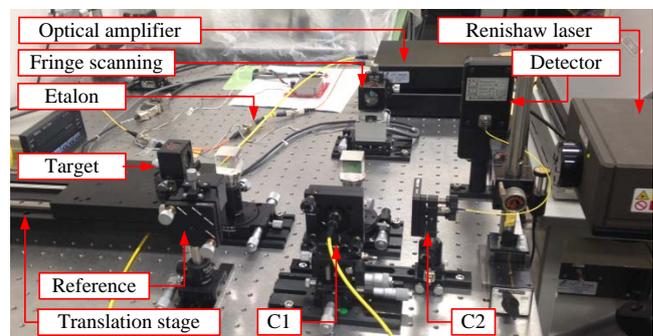


Fig. 5: The comparison of the stability between pulse interferometer and incremental interferometer

Subsequently, the accuracy of pulse interferometer was considered by comparing with the commercial incremental laser interferometer. According to incremental interferometer, the comparison requires the long precise translation stage. Therefore, the comparison setup diagram is shown in Fig. 6 (a). Both measuring lengths share the same target to avoid the errors of the motion translation. The measurement setup is illustrated in Fig. 6 (b).



(a): The comparison setup between pulse interferometer and incremental laser interferometer



(b) Measurement setup for the comparison

Fig. 6: The comparison setup diagram (a) and the picture of measurement setup (b) between pulse interferometer and incremental laser interferometer

In the measurement comparison, a precise translation stage was controlled by a resolution of 0.05  $\mu\text{m}$  which was moved by 150 mm. Then the length was measured by the incremental interferometer and the interference fringes were also recorded which occur from an optical pulse interferometer. The environmental conditions also were recorded for calculated and compensated the refractive index of air by using an update Edlén equation [9, 10]. The measurement results are shown in Table 1.

Table 1: Measurement results

Environmental conditions			
	101.02 kPa	25.60 °C	36.5 %RH
No.	Pulse interferometer (mm)	Incremental interferometer (mm)	Difference ( $\mu\text{m}$ )
1	149.85692	149.85689	0.03
2	149.85693	149.85694	-0.01
3	149.85692	149.85682	0.09
4	149.85692	149.85689	0.03
5	149.85693	149.85710	-0.18
SD	0.01	0.10	$\mu\text{m}$

SD: Standard deviation

### 3.2 Surface roughness and their fringes of balls target

The measuring length accuracy of pulse interferometer also depends on the quality of pattern interference fringes. It is directly involved the laser power that returns from surface of the target because the single mode fiber system is used as the interferometer.

In the experiment, two balls were measured at the reference position (OPD = 0). The measurement setup is illustrated in Fig. 7. The surface roughness ( $R_a$ ) of a smooth metal ball is around 0.025  $\mu\text{m}$  (a). The other is around 0.2  $\mu\text{m}$  (b), respectively.

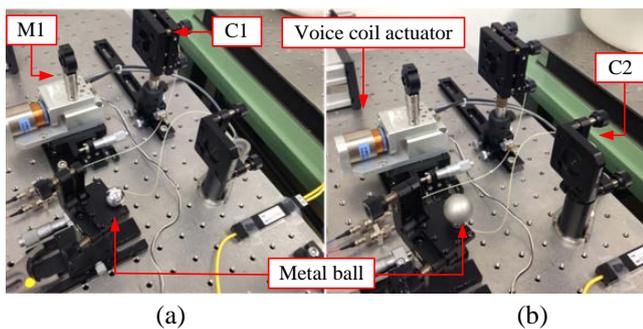


Fig.7: Pulse interferometer setup with metal balls at the optical path length of zero or  $m = 0$ .

The results in Fig. 8 show that a smooth surface ball provides a large interference fringe and the spectrum intensity is also higher than a rough surface ball. In addition, a surface roughness scale plate was used to observe interference fringes which reflected from its surface. If  $R_a$  of a surface roughness plate is higher than 0.2  $\mu\text{m}$ , interference fringe disappears because the pulse train did not return back

to interferometer. Conversely, the intensity of interference fringe was enhanced if  $R_a$  is better than 0.025  $\mu\text{m}$ .

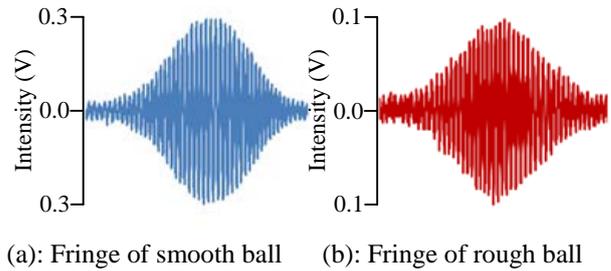


Fig.8: Interference fringes of a smooth (a) and a rough surface metal balls (b), respectively.

### 3.3 Absolute length measurement up to 1500 mm

Finally, the absolute position/length was measured up to 1500 mm by an optical pulse interferometer. According to the previous experiments, we know that the intensity of laser was reduced by an etalon and the roughness of the surface target also affects to laser intensity that is returned to the interferometer. As a result, the interference fringe signal will be weak and it is difficult to detect by simple photo-detector. Therefore, in this experiment we added an optical amplifier to amplify optical signal before detecting by the photo-detector. And we also applied a frequency-selective amplifying technique for obtaining interference fringes. Fig. 9 illustrates the measurement setup diagram and Fig. 10 shows the results of measurement. The maximum standard deviation is about 1  $\mu\text{m}$  for 10 times of measurement repeatability.

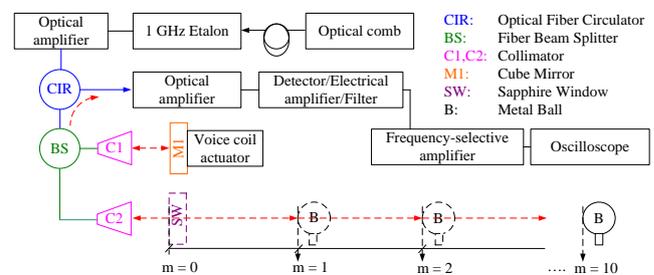


Fig.9: Measurement set up diagram for absolute position/length measurement

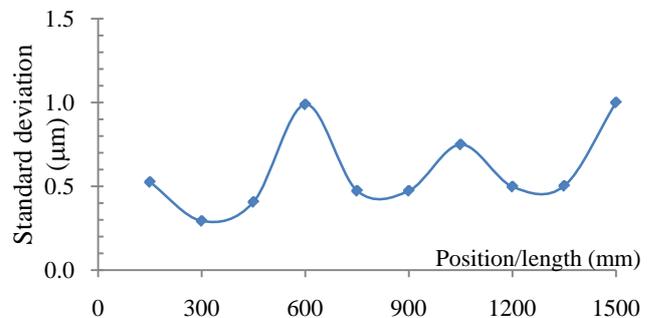


Fig. 10: Measurement result of absolute position/length measurement up to 1500 mm

#### 4. DISCUSSIONS

The stability of pulse interferometer causes error in length measurement due to the change of refractive index of air. The drift of measurement was about  $0.25 \mu\text{m}$  in one hour. This result expresses that the drift was mainly caused by changes in the environmental conditions, while the noise of interference fringe was caused by air fluctuation and mechanical vibration. It is a source of measurement uncertainty which we must consider for precise measurement. Also, more accurate sensors are required in order to recode a change of environment along the entire optical path for compensation.

The roughness of the target surface is significant to the measurement accuracy. It directly affects the fringes acquisition. The suitability surface of metal balls is a factor to consider for accuracy requirement and its applications. Moreover, the ball roundness and the ball diameter tolerance also should be considered for applications. When we use a ball diameter of 25 mm, the beam alignment of  $\pm 0.2 \text{ mm}$  from the center of ball will cause the error around  $1 \mu\text{m}$ . However, it depends on the surface roughness, roundness, beam diameter and the length of measurement. Some area of ball surface doesn't smooth enough which influence to the error of measurement. Using the focusing beam, the accuracy of measurement is improved than using a small beam and a large beam diameter respectively. However, it will be missing a signal when the ball is moved far away from a position. Conversely, the signal is not lost for using a small beam and a large beam diameter, but it has a large standard deviation. Therefore, the SN ratio of the signal will be improved by a phase sensitive detector method.

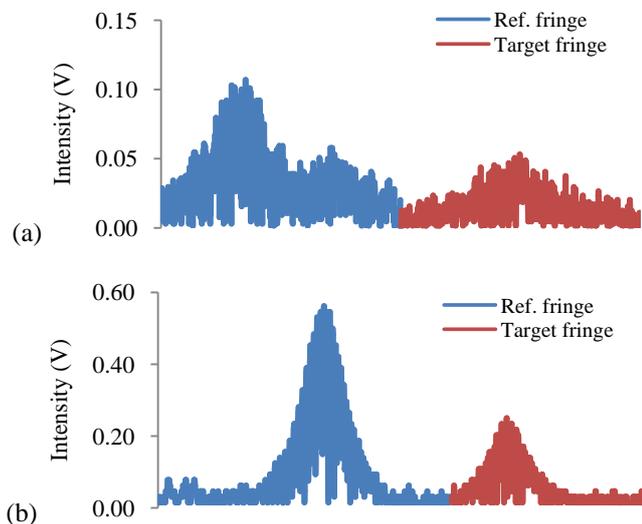


Fig.11: The interference fringes (a) before and (b) after through a frequency-selective amplifier

Although an etalon plays a role of frequency mode selector, the laser power is reduced. Therefore, the sapphire window was selected to used as reference position, ( $m = 0$ ) because its transmission property is suitable for the laser wavelength around  $1.56 \mu\text{m}$ . It means the laser power is small reduced while it goes through sapphire window.

Furthermore, an optical amplifier was used to gain the laser power and the interference fringe signal was amplified by a frequency-selective amplifier. It is used to amplify the small signal to be measured. Therefore, phase sensitive detection method is powerful to gain signal and reduce noise. Although the interference fringe signals are reduced by an etalon and are also influenced by the roughness surface of the ball targets, the SN ratio of the small signals are improved by a frequency-selective amplifier.

The comparisons of interference fringes (a) before and (b) after the signals through a frequency-selective amplifier illustrate in Fig. 11. It is apparently that the noise is rejected and the spectrum intensity is amplified. For that reason, the interference fringes are captured and the observation lengths are also measured.

#### 5. CONCLUSIONS

Experiments on absolute distance/length measurement up to 1500 mm have been conducted using an etalon of 1 with optical comb, and then a metal ball is used as the target of the interferometer. Mainly measurement accuracy involves the quality of envelope interference fringes which correspond to surface roughness of metal balls. This result expresses that the drift is mainly sourced by changes in the environmental conditions, while the noise of interference fringe is caused by air fluctuation and mechanical vibration. The stability and accuracy of measurements are compared with commercial incremental laser interferometer. The drifts of both systems are the same tendency. The maximum drift difference between two interferometer systems is about  $0.1 \mu\text{m}$ . And the maximum difference of length measurement of both systems is about  $0.18 \mu\text{m}$  at the length of 150 mm while the maximum standard deviation of pulse interferometer is better than incremental interferometer 10 times. The results show that the non-contact measurement for dimensional metrology using optical comb is reliable. This technique can provide accuracy enough for non-contact measurement such as a simple laser tracking system. The measurement system is easy to alignment and it also provides accuracy enough for linear verification of industrial CMM. It will be developed to verify geometrical errors of a CMM in the further.

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