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Precision absolute distance measurement technique onto rough surface object using self-beat signals of optical frequency comb

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Abstract

In this report, we propose a new method of a non-contact distance measurement onto rough surface by using the coincident method of multi-frequency beams of optical frequency comb. The signals called "self-beat signals" are obtained when the beam of optical frequency comb is detected on the optical sensor. Hence, the wavelength of self-beat signal is used for distance measurement. In this method, the beam from an optical frequency comb incident to the measured rough surface which is moved by a linear stage. The change of phases of self-beat signals detected by the detector is corresponds to the change of the optical path length due to the movement of the measured surface. We measured the phase shifts of the self-beat signals at the different distances which are 50 mm, 75 mm and 100 mm with the standard deviation was 0.03 mm, 0.07 mm, and 0.065 mm respectively. The measurements were conducted using two self-beats (f_1=3.5 GHz and f_2=3.6 GHz, self-beat wave lenths are λ_1 = 85.655 mm and λ_2 = 83.276 mm)..

Keywords: Optical frequency comb, rough surface, absolute distance measurement

1. Introduction

It is well known that the accuracy of measurement determines the accuracy of machining. Hence, it is important to increase the accuracy of measurement to improve the quality of manufactured products.

These days, optical frequency comb is used for many kind of measurements. Optical frequency comb is a pulse laser that the relative uncertainty of the interval length of pulses is very small. Due to the accuracy of the interval of the pulses, it is widely used for interferometer as distance measurement method [1] [2]. The signals called "self-beat signals" are obtained when the beam of optical frequency comb is detected by the optical sensor, and the length of self-beat is used for distance measurement [3].

In our research,an absolute distance measurement method for rough surface object with optical frequency comb by using coincident method of multi-frequency beam of optical frequency comb is proposed.

2. Measurement principle

2.1. The features of optical frequency comb

When the beam of optical frequency comb is detected by optical sensor, the signals called self-beat signals can be obtained. These signals are the beat signals between any two modes of the spectrum of optical frequency comb. The spectrum of the the optical comb is shown in figure 1. The frequency interval of any two adjacent modes is the same. This frequency is called as a repetition frequency (f_{rep}). The relative uncertainty of f_{rep} is 10^{-10} in our laboratory. The frequency of Nth mode of self-beat signals (f_n) is reperesented as $f_n = Nf_{rep}$.

Moreover, the peak of the pulses of the beam corresponds to the phase (θ is zero in cos $2\pi Nf_{rep}+\theta$) of the self-beat signals, so the self-beat signals can be considered as if they propagate in the air with the pulses (figure 2). In our research, this feature of self-beat signals is used for distance measurement.

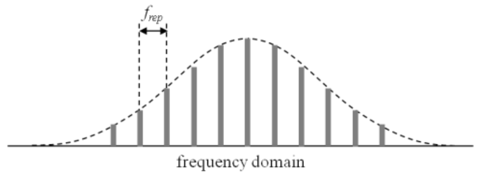

Figure 1. Spectrum of optical frequency comb

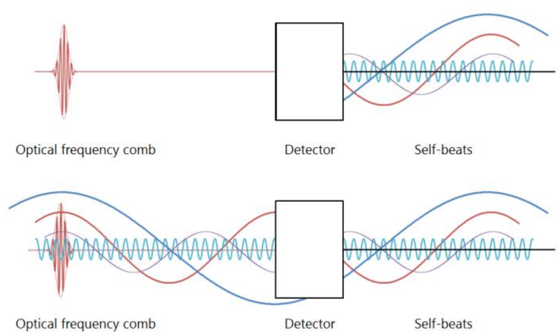

Figure 2. Virtually propagating of the self-beat signals based on optical frequency comb

2.2. Measurement with self-beat signals

Our basic measurement system is illustrated in Figure 3. The beam from an optical frequency comb incident to the measured surface which is placed on a linear stage. The reflected beam from measured surface is detected by a detector. The phases of self-beat signals detected by the detector is changed by moving measured surface. The absolute distance L which is the distance from the surface at starting position to the last position of measured surface is represented as eq. (1).

$$L = \frac{mc}{2fn} + \frac{c\Delta\varphi}{4\pi fn} \qquad (1)$$

Where, f is the frequency of self-beat signal, $\Delta\varphi$ is detected phase change, c is the speed of light, n is the refractive index of air, and m is an integer that is determined by the coincidence method. It is necessary to determine m If L is longer than the wavelength corresponding to f. In our research, m is determined by the coincidence method which is conducted by using multi frequencies of self-beat signals (figure 4).

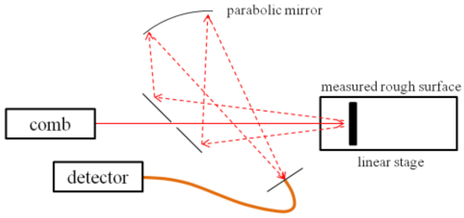

Figure 3. Basic measurement system for precision absolute distance measurement technique of rough surface object using self-beat signals of optical frequency comb

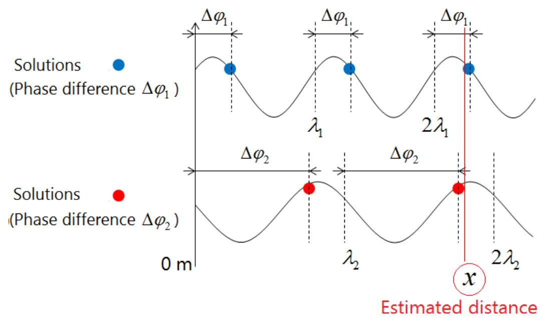

Figure 4. Absolute distance which is decided using the coincident method of multi-frequency beams

3. Experimental results and discussion

We performed the absolute distance–measurement onto a rough surface object by using the experimental setup which is illustrated in figure 5. The absolute distance at the different distances (50 mm, 75 mm and 100 mm) have been measured by using phase shifts of the self-beat signals. Three times measurements were conducted using two self-beats (f_1=3.5 GHz and f_2=3.6 GHz, self-beat wave lenths are λ_1 = 85.655 mm and λ_2 = 83.276 mm).

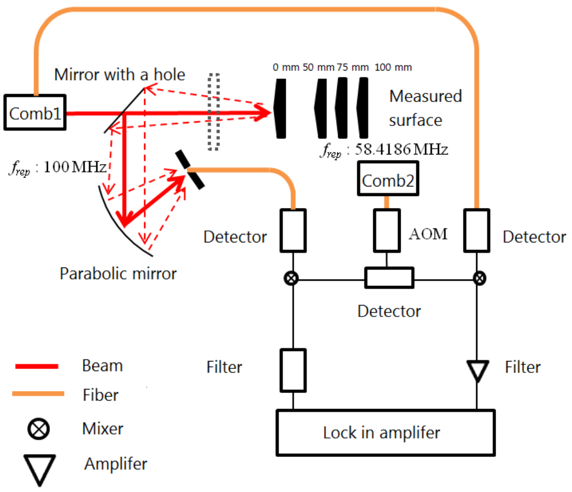

Figure 5. Experimental setup of the absolute distance measurement technique for rough surface objects using self-beat signals of the optical frequency comb

The experimente results is shown in figure 6, where the blue lines show theoritical phase shifts. From figure 6, the phase difference at each points have an error of 0.3～0.6 deg, and the phase shift of 0.09 deg which is equivalent to 10 μm in distance. The average of measured movement was 50.062 mm to the movement of 50 mm, 75.072 mm to the movement of 75 mm, and 100.038 mm to the movement of 100 mm. The standard deviation of measurement was 0.03 mm to the movement of 50 mm, 0.07 mm to the movement of 75 mm, and 0.065 mm to the movement of 100 mm (Table 1).

Absolute measurement of moved surface was conducted by the coincidence method with two self-beat sigmals shown in Table 2. The calculated distance with m (m = 0, 1, 2) was shown in Table 2. From the data of Table 2, we assumed that m = 1 is suitable for this situation. According to table 1, the results obtained by the coincidence method was in good agreement with the expected values (movement of the stage).

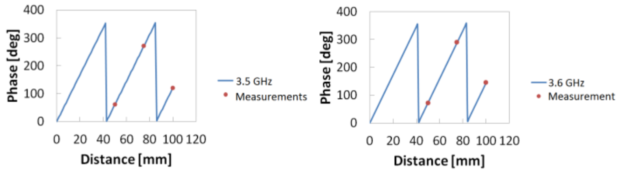

Figure 6. Results of the measurement with two frequency beam

Table 1 Absolute distance measured by self-beat signals: average values and standard deviations

movement of the stage [mm]	measurement result (3 times)	
	average [mm]	standard deviation [mm]
50	50.062	0.030
75	75.072	0.070
100	100.038	0.065

Table 2 Absolute distance calculated by the coincidence method and the value of m (50 mm movement was measurement)

	f_1 =3.5 GHz ($\Delta\varphi_1$ = 60.291 deg, λ_1 = 85.655 mm)	f_2 = 3.6 GHz ($\Delta\varphi_2$ = 72.299 deg, λ_2 = 83.276 mm)
m [-]	Distance [mm]	Distance [mm]
0	7.201	8.342
1	50.029	49.980
2	92.856	91.618

4. Summary

We proposed absolute distance measurement method to rough surface object using two frequency of self-beat signals of the optical frequency comb. We measured the phase shifts of the self-beat signals at the different distances. The standard deviation of measurement was 0.055 mm in average.

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