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Development of a non-contact precision measurement technique using optical frequency combs

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Abstract. We develop a new method for high-resolution, contactless distance measurement based on self-frequency beats of optical frequency combs. We use two optical frequency comb lasers with Rb-stabilized repetition frequencies for accurate distance measurement. The repetition frequencies of the optical frequency combs differ, allowing down-conversion of gigahertz to several megahertz self-beats without an RF frequency oscillator. A high-resolution, high-sensitivity lock-in amplifier measures the phases of the megahertz frequency signals. The method is applied to distance measurement for objects with rough surfaces separated by several meters.

1. Introduction

There is a need for better techniques for accurately measuring manufactured products such as airplanes to increase product quality. Factories that produce large machines and equipment require new methods for high-resolution, fast, contactless distance measurement. Many kinds of methods for measuring lengths and distances are developed.

In general, the method with modulated CW laser is used. In this method, we can consider modulation of the CW laser as a scale. High resolution measurement is achieved by applying modulated frequency of 28 GHz. [1] In this case we need high frequency and high power source for generating microwaves. Thus, the problem that the influence of cyclic error becomes significant occurs. [2]

Whereas, measurement method with a beat signal of two mode He-Ne lasers is proposed. [3] However, it is not easy to stabilize the frequency of the laser, and it is difficult to make modulation frequency higher. Thus, measuring distances precisely with this method is difficult.

In recent years, the method with optical frequency combs is proposed. [4][5] Optical frequency combs has many beat signals. Thus we can use these beat signals as modulated signals, and we can make modulation distance meter with optical frequency combs. In this method, we can make the influence of periodic error small because external modulators are not necessary, and high resolution measurement is easily achieved because we use broadband optical frequency combs.

In this research, we propose a new method using two optical frequency combs and a frequency-synthesized oscillator for non-contact measurement. A rubidium oscillator stabilizes the optical frequency combs, making uncertainty of the repetition frequencies very small (less than 10^{-10} in this study). The rubidium oscillator also stabilizes the frequency-synthesized oscillator, allowing for selection of the wavelength used for distance measurement by changing the RF frequency output.

2. Measurement Principle

An optical frequency comb is a mode-locked pulsed laser that is stabilized for its repetition period. Thus, its frequency component is represented as $NF_{rep} + F_{ceo}$ (for integer $N \geq 0$). F_{rep} is the repetition frequency, and its uncertainty is very small (less than 10^{-10} in this study). F_{ceo} is the carrier envelope offset frequency. The proposed method uses the self-beat signal of optical frequency combs, meaning F_{ceo} has no influence. We used two optical frequency combs, comb 1 and comb 2, with 100 MHz and 58.4175 MHz repetition frequencies, respectively. A rubidium oscillator stabilizes these repetition frequencies. Self-beat signals, represented by NF_{rep}, are obtained when we detect the optical frequency comb's beam. This paper proposes a new measurement method using the self-beat signals of two optical frequency combs.

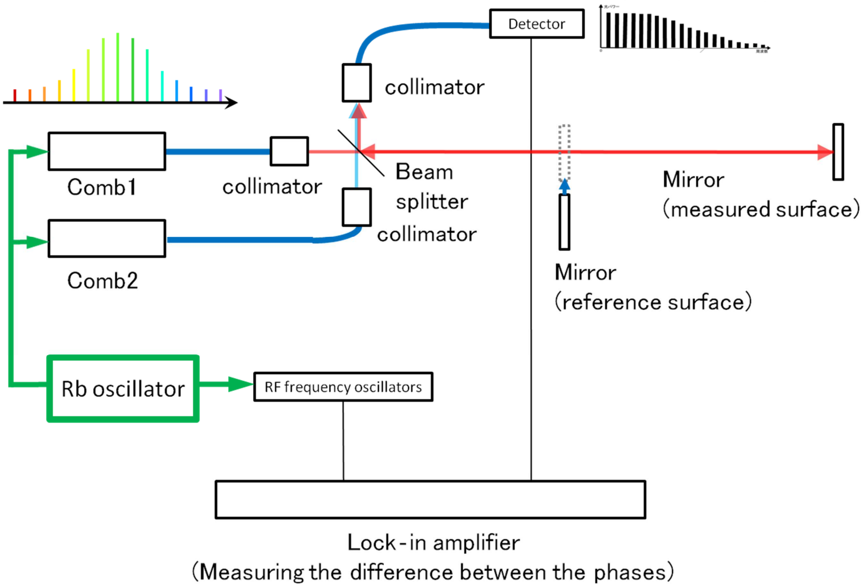

Fig. 1. Experimental system

Figure 1 shows the experimental system for this measurement method. In this system, the measured surface reflects the beam from comb 1. The beam is next reflected by the beam splitter and condensed by the collimator, which also condenses the beam from comb 2. Thus, the same photodetector detects the beams from the two optical frequency combs, and the signals are electronically down-converted to low-frequency signals. The phase of comb 1's self-beat signals changes when a reference surface is inserted into the optical path because comb 1's optical path length is altered. We measure the phase change and calculate the distance between the reference surface and the measured surface. Given that $\Delta\phi$ $(0 \leq \Delta\phi < 2\pi)$ is the phase change and Δx is the distance between the reference and measured surfaces,

$$\Delta x = \frac{mc}{2F} + \frac{c\Delta\varphi}{4\pi F} \quad (1)$$

In this equation, integer $m \geq 0$, F is comb 1's self-beat frequency, and c is the speed of light. We can calculate the distance by measuring the phase change and using Eq. (1). Here, m is determined by using many beat frequencies from comb 1.

Using many self-beat frequencies allows for precise measurement. Figure 2 shows an example of using a self-beat signal of 1800 MHz. We can see the 10.958 MHz beat signal between 1800 MHz (comb 1) and 1810.958 MHz (comb 2). Changing the phase of comb 1's self-beat signal also changes the phase of the beat signal between comb 1 and comb 2 by the same amount. To detect the phase change, we create the same frequency (10.958 MHz) using

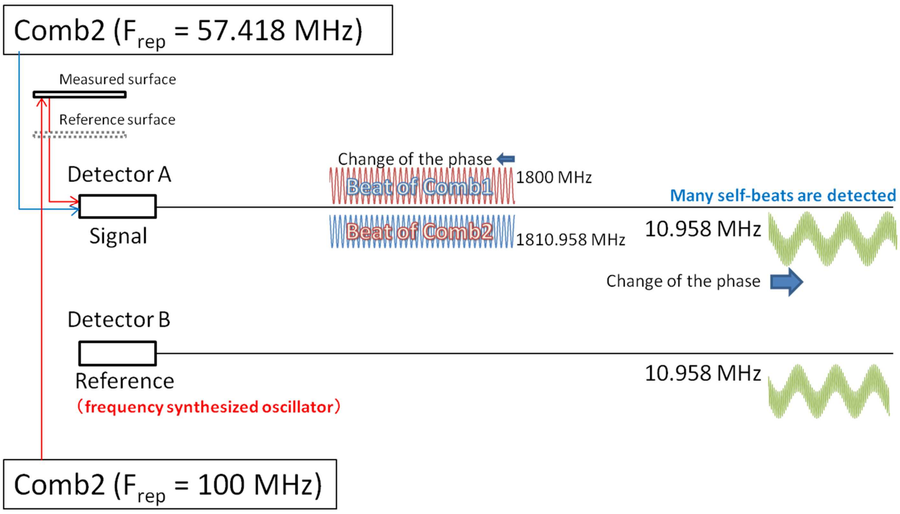

Fig. 2. Distance measurement with 1800 MHz self-beat signal

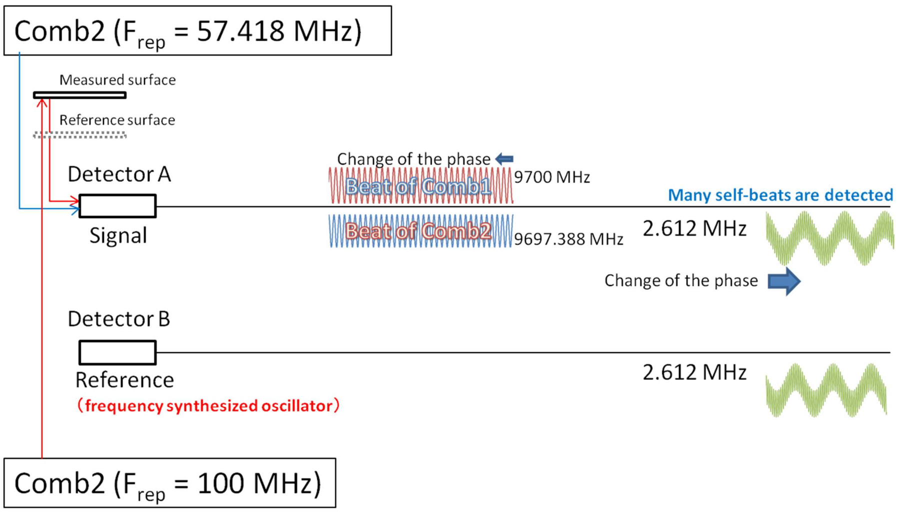

Fig. 3. Distance measurement with 9700 MHz self-beat signal

a frequency-synthesized oscillator, and compare the phases between two signals with a lock-in amplifier. The same rubidium oscillator stabilizes the two optical frequency combs and the frequency-synthesized oscillator. We can calculate the distance from the phase change, and we can use as many self-beats as can be detected. Figure 3 shows an example using a self-beat signal of 9700 MHz.

As shown in Figs. 2 and 3, we can make the frequency of the frequency-synthesized oscillator low, allowing easy and accurate phase change detection. Table 1 shows the self-beat frequencies (heterodyne frequencies) below 10 MHz used as a frequency standards in this research.

Table 1. Frequencies used for distance measurement

Measuring frequency (MHz)	Corresponding wavelength (mm)	Detecting frequency (MHz)
300	999.3081933	7.91
1700	176.3485047	5.878
3100	96.70724452	3.846
4500	66.62054622	1.814
5900	50.81228102	0.218
7300	41.06746	2.25
8700	34.45890322	4.282
10100	29.68242158	6.314

3. Distance Measurement Experiment

We conducted an experiment to verify the accuracy and repeatability of measuring distances by using two optical frequency combs and a frequency-synthesized oscillator. In the experimental system (Fig. 1), we inserted a reference mirror to change the optical path length of the comb 1 beam, and performed 10 measurements of the phase change corresponding to the distance between the reference mirror and the measured mirror to calculate the distance. Figures 4 and 5 show the experimental results.

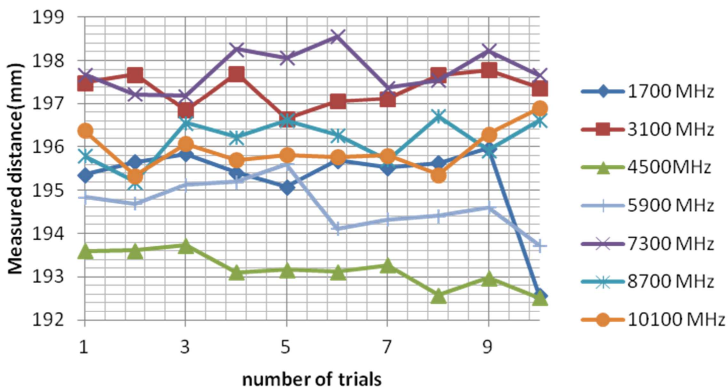

Fig. 4. Measured distances for multiple measuring RF frequencies

Figure 5 shows the standard deviations of the distances obtained with 300 MHz, 1700 MHz, 3100 MHz, 4500 MHz, 5900 MHz, 7300 MHz, 8700 MHz, and 10100 MHz measuring RF frequencies. As the measuring corresponding wavelengths become shorter, the standard deviation of the obtained distances decreases. However, the standard deviation remains largely unchanged (at about 300 μm) when the measuring frequency exceeds about 3000 MHz. Figure 6 shows the standard deviations for phase measurement, which increase as the used RF frequency increases. We are currently searching the error sources, such as mismatches between comb 1 and comb 2.

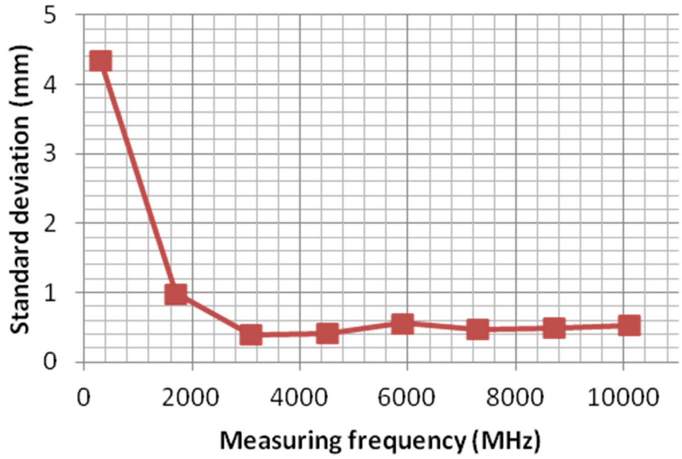

Fig. 5. Standard deviations of the measured distances

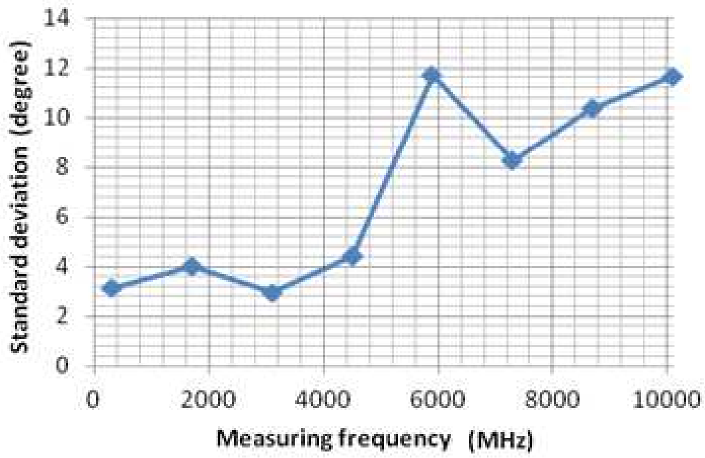

Fig. 6. Standard deviations of the phases

4. Conclusion and Future Work

In this report, we showed the principle and experimentally viability of distance measurement using two optical frequency combs and a frequency-synthesized oscillator. Experiments showed that the standard deviation of the calculated distance does not decrease if the RF frequency exceeds 3000 MHz. This may be due to the uncertainty of the RF signal. The uncertainty of the rubidium oscillator is 10^{-10}. From this, the uncertainty of the RF frequency (1 GHz) used for the measurement are 1 Hz. If the RF frequency increases to 10 GHz, the uncertainty of the RF frequency (1 GHz) also increases to 10 Hz. Thus, the standard deviation of the signal produces random noise in the detected phase difference. To cancel out this effect, we propose a new experimental system (Fig. 7). Future studies will aim at using this new experimental system to reduce the standard deviation of the calculated distance, and investigating whether we can measure distances changed by a linear stage.

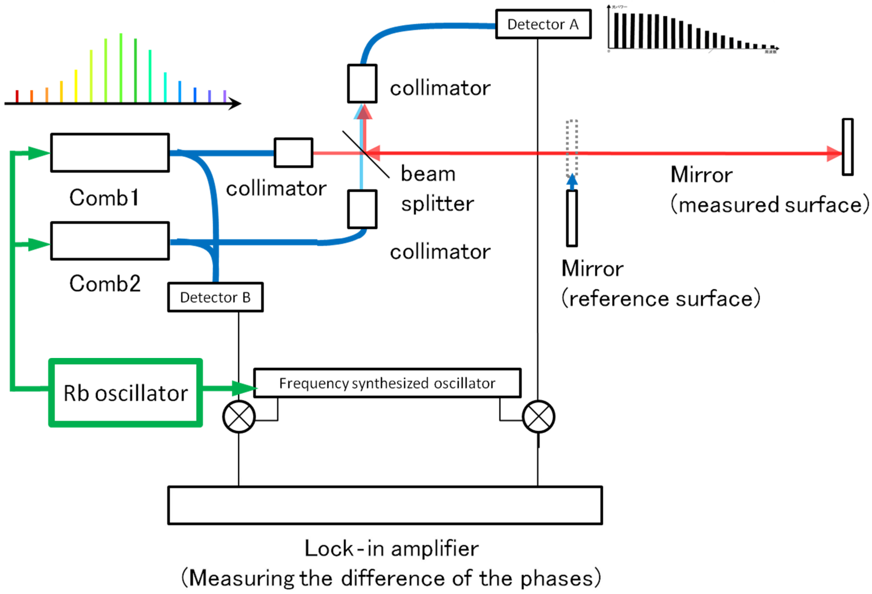

Fig. 7 New experimental system

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