STUDY ON LENGTH MEASUREMENT METHODS USING OPTICAL FREQUENCY COMBS MODULATED IN THE RADIO FREQUENCY DOMAIN

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Abstract - The optical frequency of an optical frequency comb can be expressed in terms of frequencies in the microwave band and is called a measure of light. Optical frequency comb devices are expensive laser transmitters, and they are difficult to conduct research using commercially available products. In this study, we measured distances using a low-cost optical frequency comb device and quantitatively evaluated the error. To measure the phase difference, we adjusted the electrical signal using a frequency doubler, double-balanced mixer, and preamplifier.

Keywords - Measurement, Frequency Comb, Repetition frequency.

I. INTRODUCTION

In recent years, with the development of the automobile industry and precision engineering, highly accurate measurements are required. To enable highly accurate measurements, it is necessary to guarantee measurement accuracy. Assuring accuracy is called calibration, and it is defined by the International Organization for Standardization (ISO) metrological traceability.

The optical frequency comb is called the "measure of light". In 1983, the definition of "meter" was modified and defined by the physical constant, the speed of light in a vacuum. The meter is now the length of the path light travels in a vacuum in 299 792 458 of a second. The International Committee of Weights and Measures proposed three methods to realize the meter: the time measurement method, the wavelength measurement method, and the radiometric method. Absolute measurement of optical frequency in the wavelength measurement method is difficult because the frequency is too high for direct measurement with existing electronics technology. On the other hand, the absolute frequency measurement of visible lasers could be realized for the first time by the frequency chain technique. This frequency measurement is performed using several large microwave generators and lasers, which increases the uncertainty and is not desirable from the viewpoint of precision measurement. Therefore, a long and accurate optical yardstick capable of measuring a wide range of frequencies was long awaited. The optical frequency of an optical frequency comb can be expressed in terms of frequencies in the microwave band that can be measured with existing electronics equipment, and it has come to be called a "measure of light". The ability to coherently link a wide range of frequency bands has made it possible to link radio and light waves, and to link frequency standards and length standards.

Optical frequency comb devices are expensive laser transmitters, and they are difficult to conduct research using commercially available products. In this study, we measured the phase difference using a low-cost optical frequency comb and calculated the distance from the phase difference. To measure the phase difference, we adjusted the signal using a frequency doubler and preamplifier.

II. PRINCIPLE OF OPTICAL FREAQUENCY COMB

2.1. Features of Optical Frequency Comb

Optical frequency comb is an ultrashort pulsed laser. It also has the property of combining two light source technologies, an ultrashort pulsed laser and an ultra-precise continuous wave laser. Figure 1 shows the laser emitted by an optical frequency comb and its variation on the time axis. Figure 2 shows the spectrum on the frequency axis.

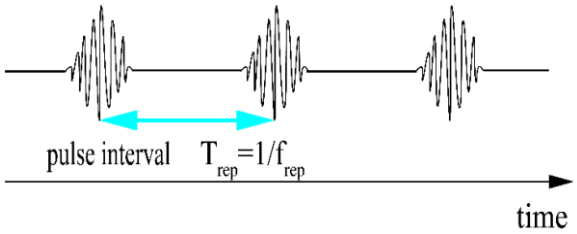


Fig.1. Pulse variation on the time axis of an optical frequency comb

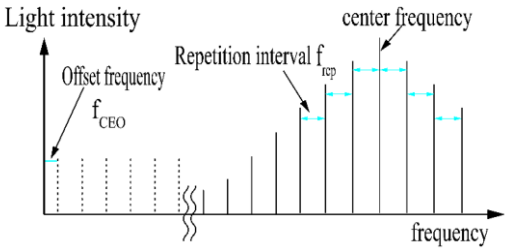


Fig.2. Spectrum on the frequency axis of an optical frequency comb

As shown in figure 1, the optical frequency comb is a pulsed laser, so the emitted laser is blinking. When the optical frequency comb is Fourier transformed, the spectrum of the optical pulse train is generated as shown in figure 2. The center frequency is the frequency of the continuous wave laser emitted in the optical frequency comb device. Sidebands (optical frequency mode trains) are generated at equal intervals around this frequency. This interval is the repetition frequency in the figure 2. Since these equally spaced mode trains resemble a comb, a laser with this characteristic is called an optical frequency comb. The phase-aligned light of all the optical frequency modes is emitted from the optical frequency comb. The characteristics of the optical frequency comb are that the optical frequency modes are equally spaced and that the phase of the light in the mode sequence is aligned. Let f_n be the optical frequency of the nth comb counted from 0 on the frequency axis. f_n is expressed by the following equation.

$$f_n = n \cdot f_{rep} + f_{CEO} \#(1)$$

f_{rep} is the repetition frequency, at which the laser is blinking. f_{rep} is the carrier envelope offset frequency. It is the lowest frequency when the optical frequency mode sequence is extended to 0 Hz. The carrier envelope offset frequency is caused by the difference between the phase velocity and the group velocity. The repetition frequency and carrier envelope offset frequency are in the microwave band and can be measured with existing electronic equipment. The control and measurement of these two frequencies can also be used to control the frequency of the comb over a wide range of optical frequency combs.

2.2. Oscillation Principle of Optical Frequency Comb

The oscillation principle of an optical frequency comb is based on a Fabry-Perot electro-optic modulator.The structure of a Fabry-Perot type electro-optic modulator is shown in figure 3.

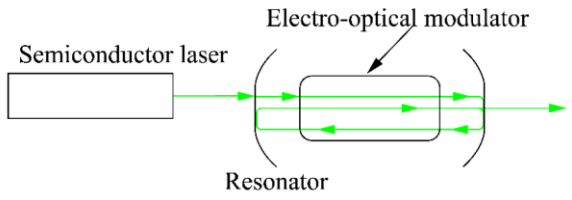


Fig. 3. Structure of Fabry-Perot type electro-optic modulator

First, the emitted laser enters the Fabry-Perot resonator. This laser is a single-frequency laser, and this frequency is the center frequency. The input frequency is modulated by passing through the electro-optic modulator inserted in the Fabry-Perot resonator, and the frequency changes. This modulated laser travels back and forth in the resonator, resulting in multiple modulations. In addition, because it is a resonator, it becomes a pulsed laser associated with the free spectral range of the resonator, and an optical frequency comb is generated. Since the modulation frequency of the electro-optic modulator is set to an integer multiple of the free spectral range of the resonator, a modulation sideband is generated that is only an integer multiple of the input frequency. The optical frequency comb oscillates according to the above principle.

III. PRINCIPLE OF MEASUREMENT

The principle of length measurement using an optical frequency comb is shown in figure 4.

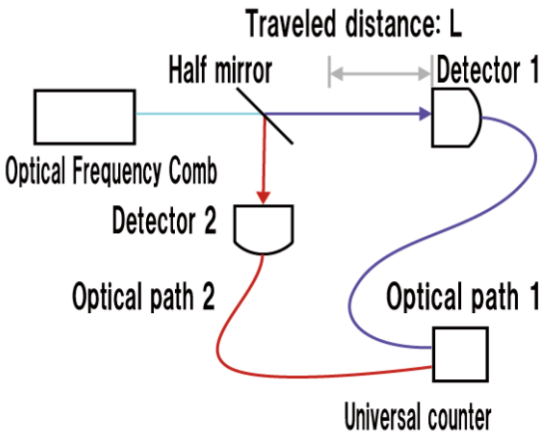


Fig. 4. Schematic diagram 1 of length measurement method using optical frequency comb

The distance to be measured is L in figure 4. The laser emitted from the optical frequency comb is divided into two directions by a half-mirror. In optical path 1, the laser travels straight through the half mirror and onto the detector. In optical path 2, the laser is reflected by the half-mirror in the downward direction and enters the detector. In both optical paths 1 and 2, after the laser enters the detector, it is converted into an electrical signal that proceeds to the universal counter. The universal counter measures the phase difference between optical paths 1 and 2. The distance L is calculated by eq (2).

$$L = \frac{c}{f}\left(N + \frac{\varphi}{2\pi}\right) \#(2)$$

c : Speed of light

f : Repetition frequency

φ : Phase difference measured by universal counter

N : Arbitrary integer

In this method, the difference between optical path 1and optical path 2 is found when the transmission distance from the detector to the universal counter is equal. However, in this study, it is difficult to equalize the signal transmission time. Therefore, the mirror in optical path 1 is moved to obtain the

distance L'. Figure 5 shows a Schematic diagram 2 of length measurement method using optical frequency comb.

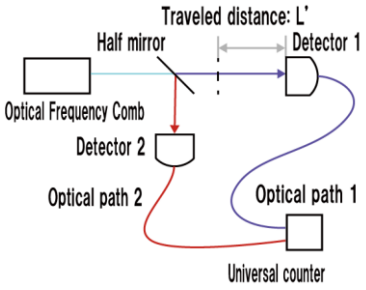


Fig. 5. Schematic diagram 2 of length measurement method using optical frequency comb

In the Schematic diagram of length measurement method using optical frequency comb 1, the distance L was obtained by measuring the phase difference once. The position of the detector before moving is position 1, and the position after moving is position 2. The phase difference is measured at each position, and the difference of the phase difference between position 1 and position 2 is calculated. The difference of the phase difference between position 1 and position 2 is obtained. The moving distance L' is calculated from the difference in phase difference using eq (3).

$$L' = \frac{c}{f}\left(N + \frac{\varphi'}{2\pi}\right) \#(3)$$

φ' : Phase difference for travel distance L'

IV. EXPERIMENT

4.1. Objective

The configuration of the experiment for distance measurement using phase difference is shown in figure 6.

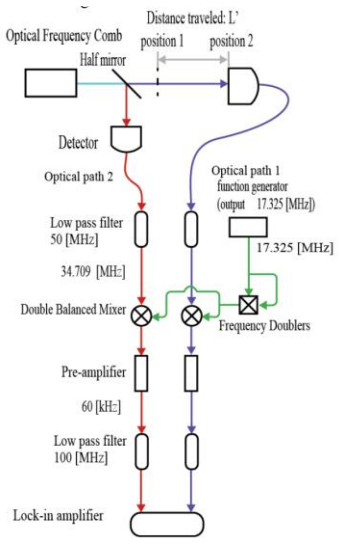


Fig. 6. The configuration of the experiment for distance measurement using phase difference

The optical frequency comb signal was changed to a frequency that could be handled by the lock-in amplifier using a frequency doubler and a double-balanced mixer and synchronized. The distance was calculated from the phase difference measured by moving the detector.

In this study, we used an optical frequency comb with a repetition frequency of 34.709 MHz In optical path 1, the laser travels straight through the half mirror and onto the detector. In optical path 2, the laser is reflected by a half-mirror in the downward direction and enters the detector.

After entering the detector, it passes through a low-pass filter and enters a double-balanced mixer. The 17.325 MHz signal output from the function generator is doubled to the 34.65 MHz signal by the frequency doublers. The optical frequency comb signal is beaten down from the frequency doubler signal by a double balanced mixer. As a result, a signal of 60 kHz is output from the double balanced mixer. The 60 kHz signal passes through the preamplifier and low-pass filter, and is input to the lock-in amplifier.

Lock-in amplifier uses the signal from optical path 1 as the input signal and the signal from optical path 2 as the reference signal, and performs phase difference measurement. In order to measure the distance, it is necessary to move the detecter1. The initial position of the mirror was position 1, and the position after the movement was position 2. The moved distance was 10 mm and 20 mm. The phase difference was read ten times at each position, and the distance was obtained from the average of the readings.

V. RESULTS

Tables 1 and 2 show the measurement results.The moving distance of the detector was measured using a laser interferometer.

	Moving distance [mm]	Position1 - Position2 [deg]
1	10.0715	0.475
2	10.0880	0.473
3	10.0062	0.417
4	10.0539	0.353
5	10.0261	0.360
6	10.0169	0.418
7	10.0186	0.358
8	10.0397	0.425
9	10.0380	0.420
10	10.0258	0.441
Average	10.0385	0.414

Table1: Results for 10 mm travel distance.

	Moving distance [mm]	Position1 - Position2 [deg]
1	20.0307	1.100
2	20.0250	0.805
3	20.0723	0.930
4	20.0770	0.870
5	20.0468	0.770
6	20.0244	0.810
7	20.0425	0.790
8	20.0765	0.800
9	20.0287	0.750
10	20.0358	0.795
Average	20.0460	0.842

Table2: Results for 20 mm travel distance.

When the moving distance is 10 mm, calculate L′from the movement from the difference in phase difference.

c：Speed of light (299 792 458 m/s)

f：Frequency used in length measurement (34.7 MHz)

$$L' = \frac{c}{f}\left(N + \frac{\varphi'}{2\pi}\right) \#(4)$$

$$L' = \frac{299\,792\,458}{34.7 \times 10^6}\left(0 + \frac{0.414}{360}\right) \#(5)$$

$$L' = 9.935 \text{ mm} \#(6)$$

$$\text{Error rate} = \frac{|9.935 - 10.03|}{10.03} \times 100$$

$$= 1.03\ \% \#(7)$$

Perform the above calculation when the moving distance is 20 mm.

$$L' = \frac{299\,792\,458}{34.7 \times 10^6}\left(0 + \frac{0.842}{360}\right) \#(8)$$

$$L' = 20.20 \text{ mm} \#(9)$$

$$\text{Error rate} = \frac{|20.20 - 20.04|}{20.04} \times 100$$

$$= 0.78\ \% \#(10)$$

VI. CONCLUSIONS

By adjusting the electrical signal using a frequency doubler, preamplifier, and double-balanced mixer, it became possible to measure the length by phase difference using an optical frequency comb. In length measurement, signal frequency was beaten down using a double balanced mixer to adapt the lock-in amplifier. It was found that the longer the measurement distance, the lower the error rate.

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