SUPER-HETRODYNE INTERFEROMETRIC LENGTH MEASUREMENT USING THE REPETITION FREQUENCY OF AN OPTICAL FREQUENCY COMB

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Abstract:
A high-accuracy length measurement method using an optical frequency comb is developed, which is traceable to the national frequency standards. The repetition frequency is phase-locked to the frequency standards of an Rb frequency clock. Moreover, a laser diode is phase-locked with an offset frequency of Δ_1 to one frequency (f_1) of the lower optical frequency modes in the optical comb (frequency; about 200 THz), and the second laser diode is phase-locked to another frequency (f_2) of the higher optical frequency modes in the optical comb. Therefore, we can generate a high beat-frequency (f_1-f_2) such as some THz. In this case, the laser diodes have off-set frequencies of Δ_1 and Δ_2 to the mode of the optical comb, respectively. As a result, we can obtain a super heterodyne frequency of (Δ_2-Δ_1)= several tens kHz for length measurements based on the optical frequency comb. For example, 15 THz corresponds to a synthetic wavelength of 20 µm. Also, a unique determination of the fringe order is achieved in the new system. Finally, we can measure an absolute length with an accuracy of 40 nm up to several tens meters.

Keywords: Optical frequency comb, Length traceability, Heterodyne interferometry, Length measurement, Laser diode

1. INTRODUTION

Recently, the society is requiring the safety and high-quality of products, infra-structure and eco-technique. For the reason, in the metrology fields of recent science and industry, high precision measurements of lengths from pico-meters to kiro-meters are strongly demanded and they are useful in low cost and efficient use. Moreover, the metrology is required for extending the reliability of measurements and then is traceable to the SI Unit.

On the other hand, optical ultra-high speed pulsed laser technology has opened new laser source, so called as "optical frequency comb" [1-3]. The optical comb is very useful for measuring the absolute optical frequencies of various stabilized lasers and then was designated as the National standard of length in July 2009 in Japan [4]. Moreover, the optical comb has many possibilities of developing new practical length-measurement methods [5, 6]. One application is to utilize a pulsed interferometry with the optical comb source [7] and the improved optical comb realizes the measurement of base lines at each 1.5 m to about 100 m. Moreover, the offset optical frequency (carrier envelope delay) of the optical comb source was evaluated by combining a stabilized laser diode with the optical comb and generating the interference fringes [8].

We propose new length-measuring method which uses two laser diodes with an optical comb. Two laser diodes, which have different wavelengths, are offset-locked to the modes of the optical comb, and then super heterodyne interferometry is achieved by different offset frequencies of the laser diodes. As a result, the influence of carrier envelop offset frequency of the optical comb is cancelled by the heterodyne technique and absolute length is measured up to several tens meters with high accuracy.

2. OPTICAL FREQUENCY COMB TECHNIQUE

2.1 Optical Frequency Comb and Laser Diodes

Mode-locked fiber laser based on femto-second pulsed laser may give many monochromatic laser lines whose frequency intervals have the equality of better than an accuracy of 10^{-12} order. Therefore, the beat frequency is enough accurate for constructing the length-measuring system. Its application of the fiber laser is compact and low cost. Therefore, this laser is easy to be traceable to the national frequency standard. On the other hand, laser diode is considerably stable and low cost at present. For example, the laser diodes of LD1 and LD2 are stabilized with offset frequencies Δ_1 and Δ_2, to optical frequencies f_1 and f_2 of the optical comb respectively, as shown in Fig.1. Here, f_0 is the offset frequency of the carrier envelope of the optical comb and fr is the frequency of mode repetition. Moreover, other laser diodes are phase-locked with offset frequencies Δ_3 and Δ_4, respectively.

The following is obtained;

$$f_{1,2} = f_0 + m_{1,2} fr, \quad f_2 - f_1 = (m_2 - m_1) fr \qquad (1).$$

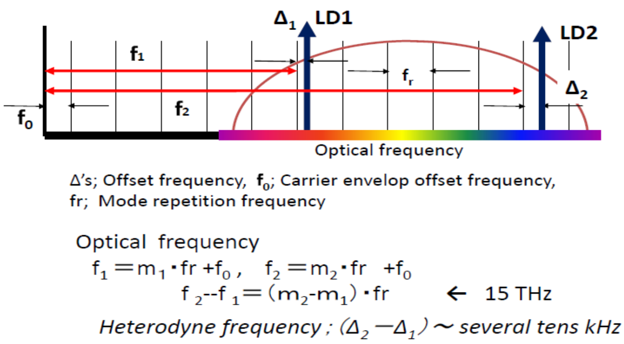

Fig. 1 Optical frequencies of laser diodes and an optical comb.

The heterodyne frequency between two laser diodes is ($\Delta_1 - \Delta_2$), which corresponds to the frequency (m_2-m_1)fr. For example, (Δ_1 - Δ_2) and (m_2-m_1)fr are several tens kHz and near 15 THz, respectively.

2.2 Super Heterodyne Technique

Therefore, the phase measurement of beat frequency (Δ_1 - Δ_2) corresponds to that of the high optical-beat frequency (m_2-m_1)fr in the region of THz. High-resolution measurement of absolute length is realized by using several laser diodes with different offset frequencies.

The interferometer is composed of the two laser diodes as a probe light and the optical comb as reference light in a two-beam interferometer. For example, laser diode (LD1) and laser diode (LD2) are phase-locked to the modes of the optical comb with offset frequencies Δ_1 (500 kHz) and Δ_2 (900 kHz), respectively. The optical frequency of two modes in the optical comb is separated by 15 THz. As a result, the heterodyne signals of 300 kHz, 500 kHz and 800 kHz in the low frequency region are generated. The signals 300 kHz corresponds to the super heterodyne signal of 15 THz between the laser diode (LD1) and laser diode (LD2). The signal of 300 kHz is selected by a band-pass filter.

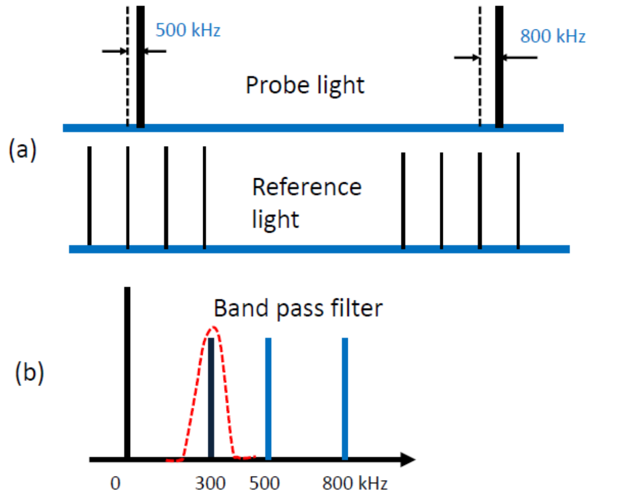

Fig.2 Optical frequencies of laser diodes and an optical comb;(a)optical frequency, (b)detected frequency.

2.3 Measurement Principle

The proposed method is based on first optical beat signals and their secondary beat signals for selecting interesting modes in the many modes of the optical comb, because the beat signals are generated many times in the various optical frequencies due to broadness of the optical comb. The principle of the length measurement is shown in Table 1. Four laser diodes are phase-locked to the modes of the optical comb with different offset frequencies such as 500 kHz, 600 kHz, 700 kHz, and 800 kHz. In this case, the absolute optical frequency of 200 THz is originated. The three secondly super heterodyne signals of 100 kHz, 200 kHz and 300 kHz are generated corresponding to the beat frequencies of 6 GHz, 400 GHz and 15 THz, respectively. As a result, the synthetic wavelengths of 50 mm, 750 μm and 20 μm are obtained. Here, the beat frequency of 100 MHz is omitted since its selection technique is very easy. Therefore, the influence on the carrier envelop offset frequency of the optical comb, which is troublesome, is cancelled by using the beat frequency technique.

Table 1 Synthetic wavelengths and heterodyne frequencies using four laser diodes and an optical comb in the region of optical frequency 200 THz.

Optical frequency (f)	Beat frequency	Offset frequency (Δ) (Heterodyne frequency)	Synthetic wavelength
200 THz		500 kHz	
(200 THz + 100 MHz)	100 MHz	–	3000 mm
200 THz + 6 GHz	6 GHz	600 kHz (100 kHz)	50 mm
200 THz + 400 GHz	400 GHz	700 kHz (200 kHz)	750 μm
215 THz	15 THz	800 kHz (300 kHz)	20 μm

The measurement procedure (flow chart) of the present method is shown in Fig.3. The absolute length L under measurement is measured with an accuracy of 6 mm by the conventional distance-measuring method using the pulse repetition frequency of about 100 MHz of the optical comb. The frequency of 6 GHz (Synthetic wavelength; 60 mm) is selected by the beat-beat method and then the length L is measured within an accuracy of 120 μm. Secondary, the frequency of 400 GHz (Synthetic wavelength;750 μm) is selected and measures the length L within an accuracy of 1.5 μm. Finally, the frequency of 15 THz (Synthetic wavelength; 20 μm) is uniquely selected and we measure the length L with an accuracy of 40 nm. In order to measure long length such as several tens meters using this procedure, it is important to measure the phases of interference fringes

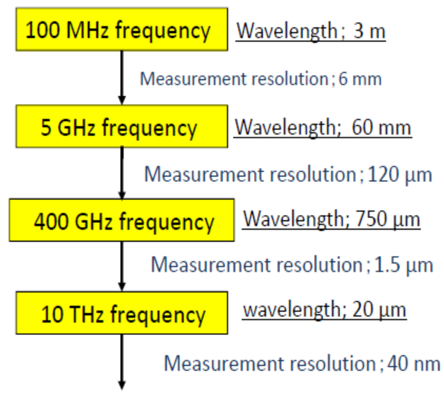

Fig.3 Propose of absolute length measurement by an optical comb with an accuracy of 0.4 % in phase.

within 10 ms to eliminate the effects of the air turbulence and mechanical vibration. In this method, the influence of the carrier envelop offset frequency of the optical comb used is cancelled. Moreover, the frequency of the heterodyne signal is strongly emphasized to be remotely calibrated with the National Frequency Standards by the GPS system and also is transmitted by using a single-mode optical fiber.

3. EXPERIMENT

3.1 Laser System

The laser system developed is shown in Fig.4 The mode repetition frequency, about 100 MHz, of an optical comb (MenloSytems C-Fiber SN LH123) is stabilized with an Rb clock with a stability of 10^{-12}. The laser diodes LD1 and LD2 (RIO), which are stabilized with a stability of 10^{-7}, are combined to the optical comb through optical fiber couplers and then their beat signal is detected by a photodiode. The beat frequency is confirmed with a frequency spectral analyzer and also is feedback to the laser diodes with a PI control. In this method, the absolute length is determined by the repetition frequency of the comb, because the drifts of the laser diodes are cancelled by the phase measurement between the two beat signals.

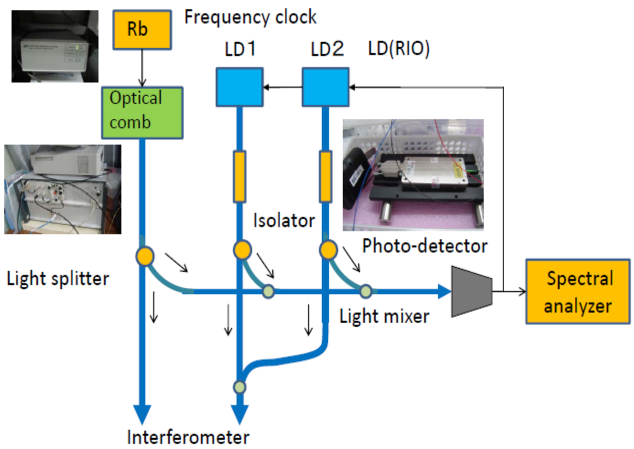

Fig.4 Laser system using single-mode optical fibers and optical devices.

3.2 Interferometer

The two-beam interferometer developed is shown in Fig. 5. The light sources of laser diodes are used as a probe beam of the two-beam interferometer and then irradiate two targets (D1 and D2) under measurement. On the other hand, the optical comb is used as a reference beam, and is overlapped at a beam splitter with the laser diode beams. As a result, super beat-down heterodyne signals corresponding to D1 and D2 are generated at the beam splitter and are detected by photodiodes. The phase difference between the detected signals is measured with a high speed of faster than several milliseconds. The drift of the measurement system is eliminated by measuring simultaneously two base-lines, D1 and D2, by two photodiodes. High resolution phase measurement is required within 0.4 % and also high-speed phase measurement is important to prevent the measurement errors due to the air turbulence and mechanical vibrations.

In general, the frequency of the air turbulence is lower than 100 Hz. At present, we are developing a high-speed phase-meter at the several tens kHz region.

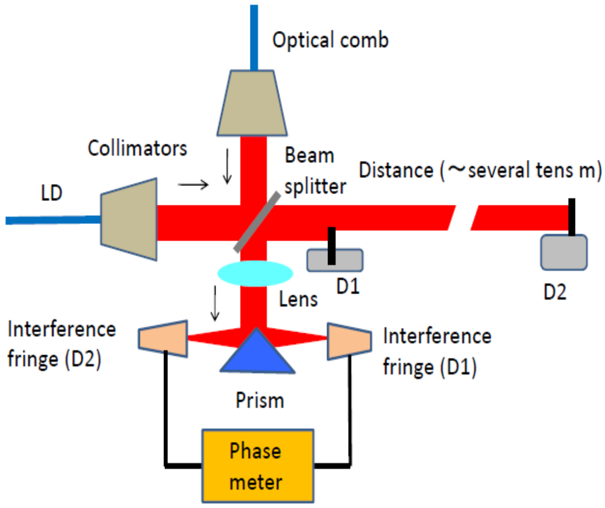

Fig.5 Optical interferometer for length measurements.

Sometimes, the repetition mode order of the interferometric system may be confirmed by using a practical reference standard and the interference fringes (E1 and E2) with a phase meter as shown in Fig.6. In this case, the number of the used mode of the optical comb is easily confirmed, because the value of 100 MHz/15 THz is only about 6 ppm, which is easily confirmed.

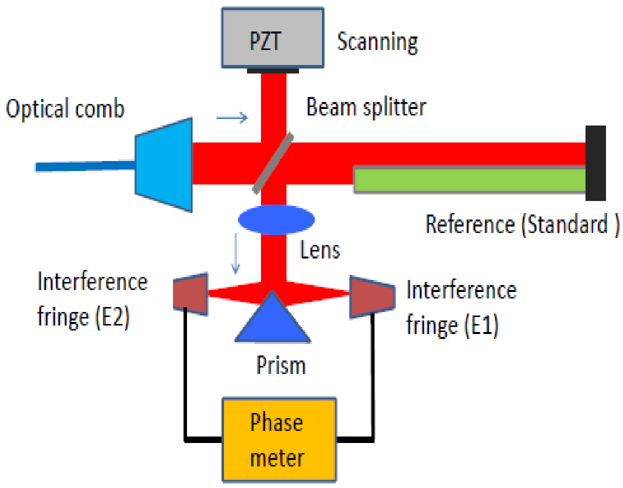

Fig.6 Optical interferometer for evaluating the system.

3.3 Preliminary Experiment

We have made preliminary measurement using a new length measuring system. Figure 7 shows the spectral signal of the new laser system. The offset frequencies of the laser diodes were observed at 41.9 MHz and 35.4 MHz. Moreover, the second beat signal of 6.5 MHz was observed. The quality of the signal is good and its phase measurement is easy with a high accuracy.

At present, length measurement is under progress.

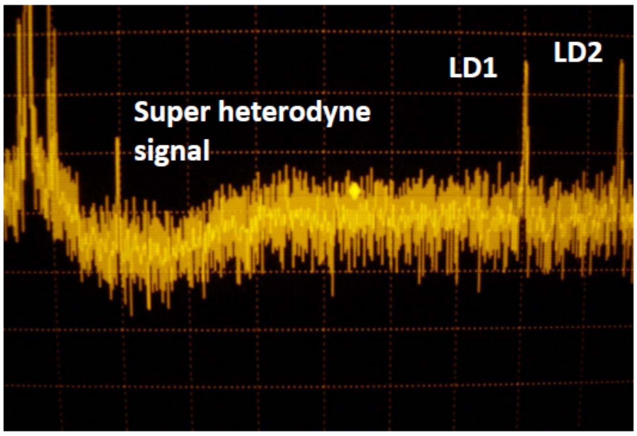

Fig.7 Offset frequency signals obtained.

4. DISCUSSION AND CONCLUSIONS

We have developed a new length-measuring system with an optical frequency comb and several laser diodes. This method is based on new super heterodyne technique. In this technique, several laser diodes, which have different wavelengths, are phase-locked to the modes of the optical comb with different offset frequencies. As a result, the second beat frequency between the normal beat frequencies correspond to the frequency between different modes of the optical comb. The frequency reaches to 15 THz and then the length is measured by using the beat frequency within a resolution of 40 nm..

This method is useful as follows;

(1) The influence of the carrier envelop offset frequency of the comb is canceled by the super heterodyne technique.

(2) The laser diodes used resolve the low-power problem of each mode in the optical comb and the frequency variation of the laser diode is cancelled.

(3)This method is effective for the effects due to air turbulence and mechanical vibration because the heterodyne frequency is higher than the frequency of the effects.

(4) This method is applicable to the transmission of the light sources by an optical fiber net works because the beat frequency is not changed by the fiber.

(5) The method is easily calibrated by the traceable frequency standard through the GPS system because the repetition frequency of the mode of the optical comb is stabilized by the system.

(6) The length measurement system is simple and low cost.

In future, the users may utilize the optical comb laser through the optical networks and can apply it to various fields.

ACKNOWLEDGEMENTS

This research work was financially supported by the Development of System and Technology for Advanced Measurement and Analysis" Industrial Innovation Program at the Japan Science and Technology Agency (JST).

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