NEW OPTICAL DISTANCE MEASUREMENT WITHOUT A PRISM REFRECTOR USING AN OPTICAL FREQUENCY COMB LASER

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Abstract:

New distance measurement method is developed by using an optical frequency comb which is many monochromatic spectra with an equal interval frequency with a high resolution without a prism reflector. The optical frequency comb is generated by mode-locked ultra-short pulsed fiber laser. The modes of the optical frequency comb are selected by mixing the photo-detected modes with RF signals such as 1.5 GHz which is traceable with the national frequency standard. The phase measurement of the signal is achieved by a phase-sensitive detection (so called as lock-in amplifier) for improving the sensitivity of measurement.

The distance measurement is experimentally evaluated with a standard deviation of 18 μm using the gauge blocks whose lengths are known with an accuracy of 0.2 μm and the measurement discrepancy between them is smaller than 18 μm. Also, cyclic error measurement is studied to evaluate the stray light beams. Next, the measurement without a prism reflector is studied by using an aluminum foil surface with a roughness of *ra*=0.07 μm. From this experiment, the standard deviations of measurement are confirmed to be 12 μm at a distance of 20 cm and 10 μm at a distance of 70 cm. Therefore, this method is found to be useful for non-prism distance measurement and is applicable to more-long distance measurement.

Keywords: Optical frequency comb, Distance measurement, Non-contact, High-resolution measurement

1. INTRODUTION

At present, the scientific and industrial technologies for manufacturing are in fast progress, so the precision measurement of geometrical quantity in the manufacturing process is widely needed for high quality and safety. In the field of the mechanical engineering, the measurement of distances with high precision and high efficiency is especially needed. When this technology is established, it may make many products to high quality and safety as shown in Fig.1 and we can use sometimes this technology as the calibration standard. Moreover, the calibration standard can correct all past results of various measurements.

In this research, we pay attention to the use of optical frequency comb laser to distance measurement technique, because 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 distance-measurement methods [5,6,7]. One application is to utilize pulsed interferometry using with the optical comb source [8] and the improved optical comb realizes the measurement of long base lines at each 1.5 m up to about 300 m. The so-called optical measurements enable to the noncontact and precise measurement, and the amplitude-modulation method with single spectrum is used for the optical measurement. However, the amplitude-modulation method is not good in resolution. Therefore, we propose the using of the optical frequency comb that is the group of the many monochromatic lights for the new-type optical measurement with high resolution without the prism reflector. The optical frequency comb laser is generated by the mode-locked ultra-short pulsed laser. Using this optical comb laser, we realize the distance measurement technique with high resolution for several tens meters.

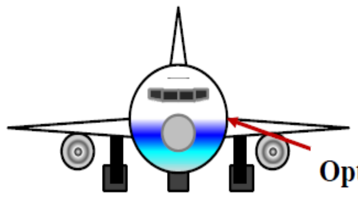

Fig.1 Example of required metrology.

2. THE PTINCEPLE OF MEASUREMENT

2.1 Optical Frequency Comb Laser

The optical frequency comb laser is generated by high non-linear optical fiber and a laser diode. If we apply the Fourier transformation to the mode-locked ultra short pulsed laser, we can get the light source that has the broad spectrum with a very-narrow optical frequency whose frequency interval is equal as shown in Fig.2. This is called the optical frequency comb. The frequency interval is shown by fr in Fig.2, and is called the repetition frequency. The optical comb is extended to the frequency area of several THz. The schematic diagram of the oscillator of the optical frequency comb laser is shown in Fig.2. We use IMRA America laser as an optical frequency comb.

The optical length of the experimental apparatus in this research is about 6 m, the pulse interval is about 20.8 ns and the repetition frequency is about 48 MHz. The output power is about 20 mW. The pulse interval depends on the fiber length and the refractive index of the quartz. And the frequency interval is defined as the reciprocal of the pulse interval, so the repetition frequency depends on the laser resonator length. The optical frequency spectra are changed by a dial knob the wavelength range of 1560 nm, 1700 nm, and 1900 nm, respectively. In this experiment, we used the spectra of 1560 nm. The laser head was covered by using insulation material for stabilizing the repetition frequency. As a result, the variations of the comb was about several Hz for several tens minutes.

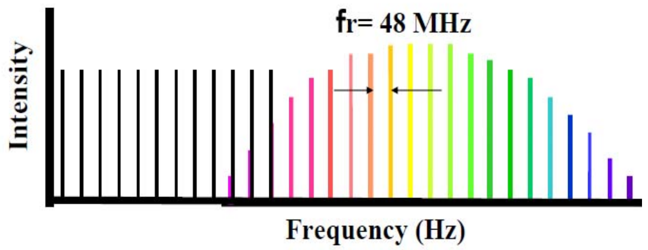

Fig.2 Outlines of optical frequency comb.

2.2 The Measuring System

The schematic diagram of the measuring system is shown in Fig.3. The measuring system contains the elements that are a beam splitter, a collimator and two photo-diodes. The laser beam is incident to a single-mode optical fiber and is transmitted to the measurement place. The laser is collimated to a beam of 7 mm ϕ and is divided by a beam splitter. One beam is detected by a photo-diode as reference signal and other beam is reflected by an object under test. The reflected beam is detected by a photo-diode as probe signal. The phase between the probe signal and the reference signal is measured with a high resolution by a phase meter. Here, a lock-in amplifier (NF, LI5630) is used as a phase meter. This method is useful for noncontact measurement and so the test object isn't damaged. But the reflected light from the test object is weak due to rough surface, and the device that detected the weak reflected light to high sensitivity is necessary. Therefore, the lock-in amplifier is useful. Finally, the distance D is determined by the following equation;

$$D = \frac{c}{2n_g f}\left(N + \frac{\phi}{2\pi}\right)$$

Here, c is the light speed, ng is the group refractive index of air, f is the frequency of an RF signal generator, N is an integer and ϕ is the phase measured by experiment. From this equation, the resolution of the distance measurement is known to be improved by using high RF frequencies.

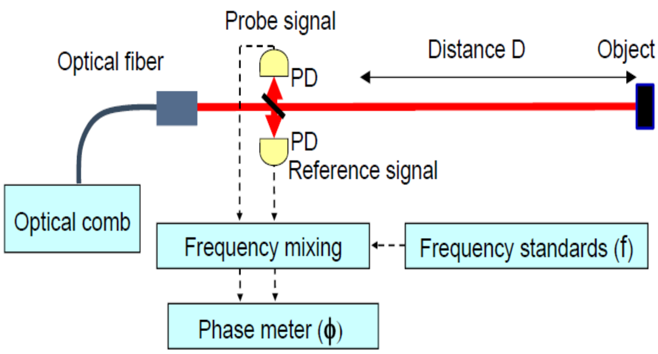

Fig.3 Outlines of distance measurement by an optical frequency comb based on the national frequency standards(**f**).

2.3 The Beat Frequency and Phase Measurement

We explain the measuring method using the beat signals by heterodyne technique (Fig.4). In this case, the standard is an RF signal generator (ANRITSU, MG3632A), which is stabilized by the national frequency standard such as an optical clock of Rb. The 33rd harmonic frequency of the repetition frequency fr=48 MHz is mixed in an RF mixer with about f=1584 MHz signal of the RF signal generator and a beat signal of about 10 kHz is generated through a low-pass filter. The signals at frequency 10 kHz are input to the lock-in amplifier and the phase between the signals is measured with a resolution of 0.1 degrees, which correspond to the distance of 26 μm. Finally, the integer N is determined by measuring the distance under test with a beat frequency of 48 MHz.

Therefore, the signal from the RF signal generator is the standards of length from the definition of light speed, and the present method is traceable to the national frequency standard, because the frequency of the signal generation is phase-locked by using Global Positioning System (GPS) in the future and the signal is also traceable to the SI unit.

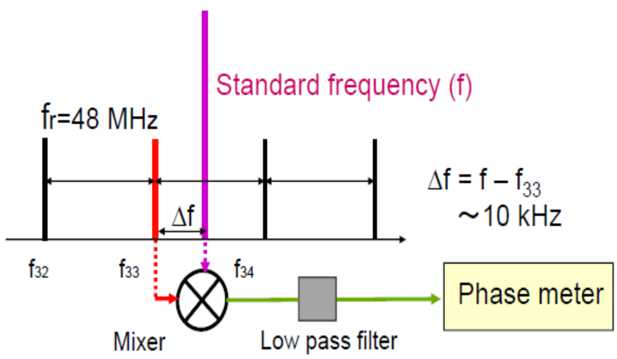

Fig.4 Generation of beat frequency by mixing the signal with the national frequency standard .

3. THE EXPERIMENT

3.1 With a Reflecting Mirror

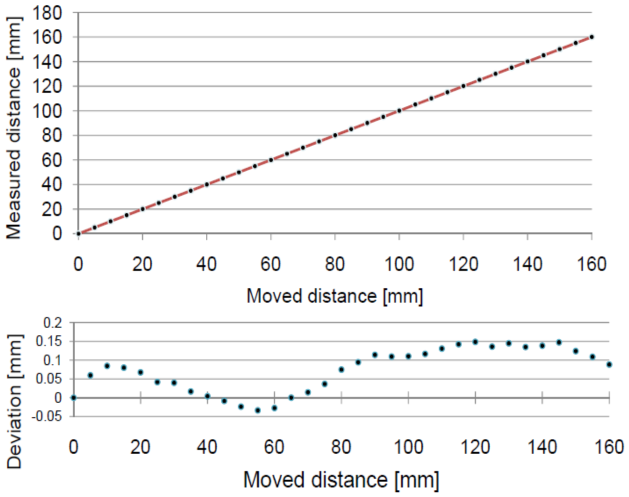

Fig.5 Experimental result ; (a) measured distance, and (b) their deviations from the theoretical value.

We made the performance assessment of the developed measurement system. The change in the phase of the system corresponding to the distance of the moving stage with a linear encoder was measured by using a plane reflecting mirror as a object under test. The phase ϕ measured determines the distance D as shown in Fig.5. Then, we confirmed the problem of the cyclic error; the plane mirror is displaced by 2 synthetic wavelengths of 1584 MHz using the displacement stage (SIGMAKOKI, SGGP26-200). The result shows good linearity, but very small cyclic error exists. However, the value of the cyclic error is less than 0.3 degrees in phase and it may be generated by the direction variation of the moving stage.

Next, we made the accurate performance assessment of the system, because the stage used is not good and the correct assessment is difficult. Therefore, we measured gauge blocks of nominal lengths 100 mm and 500 mm whose values are known with an accuracy of 0.2 µm. The result is shown in Fig.6 and shows good coincidence with a practical standard of length; a standard deviation of 12 µm and absolute difference of 0.5 µm.

3.2 Without Reflecting Mirror

The object (aluminum foil) with rough surface of *ra*=0.07 µm is moved by using the displacement stage at an interval over 980 µm The Experimental result and the value calculated from the theory are shown in Fig.7. *f* is near to the integral multiply of the repetition frequency (48 MHz), and *f* is about 1584 MHz. The 33rd mode of the optical comb was used. The deviation and a standard deviation of measurement are 18 µm and 12 µm at a distance of 20 cm, respectively. The accuracy of measurement is not much decreased and is enough for application to the industrial engineering.

Figure 8 shows the experimental result in the case of collecting the scattering light by a parabolic reflecting mirror of a diameter of 50 mm ϕ . The light power collected is increased by about 1000 times. The deviation and a standard deviation of measurement are 15 µm and 10 µm at a distance of 70 cm, respectively. The result also shows good accuracy, though the collecting optical system is not complete. If we use a photo-diode with a large-size, the object may be measured at distances of several meters. At present, this experiment is under measurement.

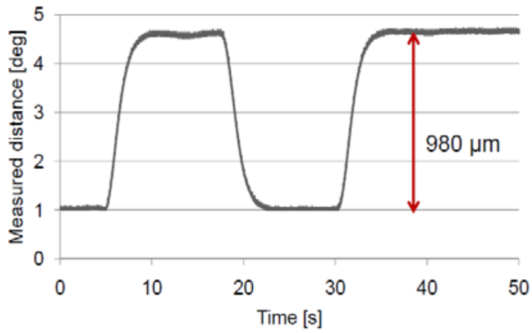

Fig.7 Experimental evaluation of the non-mirror method with an aluminum surface with a roughness ra=0.07 µm.

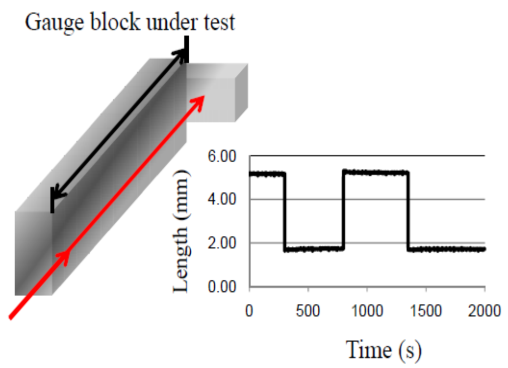

Fig.6 Evaluation by using the gauge blocks as standards; a standard deviation of 12 µm for the 100 mm gauge.

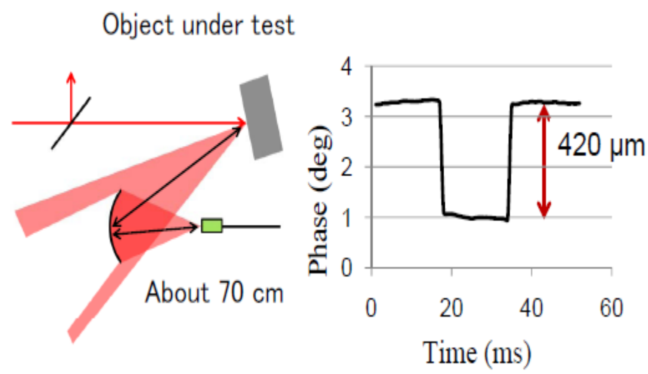

Fig.8 Evaluation of non-contact method at a distance of 70 cm .

4. DISCUSSION

We have developed a new distance meter without a reflecting mirror using the so-call optical frequency comb and have evaluated the performance of the distance meter. The experimental results show the good performance having the various characteristics of the optical comb. (1) The method has a good linearity and free cyclic error of measurement due to no optical modulator which is required for the conventional distance meter. (2) The RF frequency used for the beat down is traceable to the national frequency standard. (3) The sensitive measurement is achieved by using a lock-in amplifier because the frequency is enough low. (4) The measurement is correct because the signal-to - noise ratio of the beat-down frequency is high. (5) It is easy to transmit the laser beam of the optical comb through a conventional single-mode optical fiber since the method uses non-polarization technique.

Therefore, the new method is useful tools for production engineering, and for the safe industry and society with a high reliability. Also, the newtechnology will be applicable to the remote calibration by using a single-mode optical fiber.

5. CONCLUSION

We proposed the basis of a new distance measuring system using an optical frequency comb laser. The experimental result shows that the system has good performances such as high accuracy such as several tens µm, high sensitivity, high linearity and so on. Moreover, the system is very simple and low cost.

Especially, we propose the non-prism type distance meter for measuring rough-surface object since the system is its high sensitivity due to the act of lock-in amplifier. The system is useful for production engineering.

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

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