New optical distance measurement without prism using an optical frequency comb laser

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At present, the scientific and industrial technologies for manufacturing are updating, so the precision measurement of geometrical quantity in the manufacturing process is needed gradually. In this research, we propose a new method of optical distance measurement using an optical frequency comb laser. The optical frequency comb laser that has invented in recent years is obtained from the ultra short pulsed laser. The feature of the laser is to have many optical frequencies that are in the broadened wide range of the frequencies with the remarkably-constant frequency interval. Therefore, we develop a new optical system and measure precisely the phase of the laser signal. The system has a possibility of measuring contactless and rapidly the distance under test with the remarkably-high resolution.

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1. Introduction

At present, the scientific and industrial technologies for manufacturing are updating, so the precision measurement of geometrical quantity in the manufacturing process is widely needed. In the field of the mechanical engineering, the measurement of the distance including the length with high precision and high efficiency is especially needed. When this measurement technology is established, this technology may make products to high quality and we can use sometimes this technology as the measurement standard. The measurement standard can correct all past results of a new measurement. In this research, we pay attention to the use of the comb laser light to measurement technique. The so-called optical measurement is enabled to the noncontact and precise measurement and the monochromatic light with a single spectrum is used for the conventional optical measurement. However, the method is not good in resolution. In this research, we propose the using of the optical frequency comb that is the group of the many monochromatic lights for the optical measurement with high resolution without prism. The optical frequency comb laser is the multispectral light and is generated by the mode-locked ultra short pulsed laser. Using this optical comb laser, we realize the distance measuring technique with high resolution of several tens micrometers.

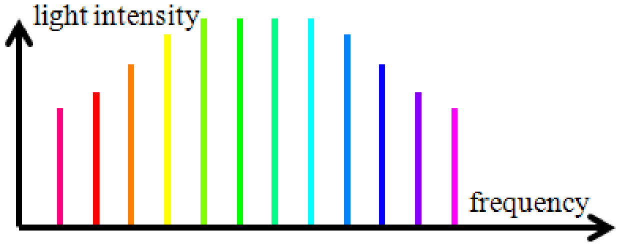


Fig.1 The image of the optical frequency comb.

2. The experimental apparatus and the principle of the distance measuring

2.1 The oscillator of the optical frequency comb laser

The optical frequency comb laser is generated by the high non-linear fiber and a laser diode. If we apply the Fourier transformation to the mode-locked ultra short pulsed laser, we can get the light that has the broad spectrum. When this pulsed laser light is entered into the high non-linear fiber, the artificial optical frequency group is generated, that the optical frequency intervals are very equal as shown in Fig.1. The signal is observed like a comb in the frequency generation. This is called the optical frequency comb. The frequency interval is shown as the interval of the comb in Fig.1, and is called the repetition frequency. The comb is extended to the area of several THz at equal interval. The schematic diagram of the oscillator of the optical frequency comb laser is shown in Fig.2. We use the laser diode (FITEL, FOL1425RUZ), laser diode driver (YAMAKI, KLD-1ALT) and the loop fiber to generate the ultra short pulsed laser by the effect of mode-lock. In the part of the loop fiber, we fusion bonded the optical elements, the single mode fiber and the Erbium

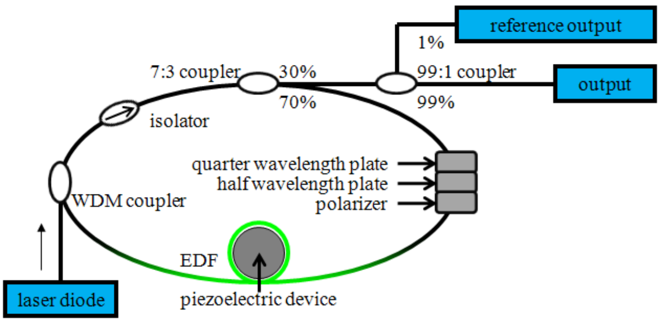


Fig.2 The experimental setup. The light from the laser diode passes through the ring fiber that works as the resonator many times.

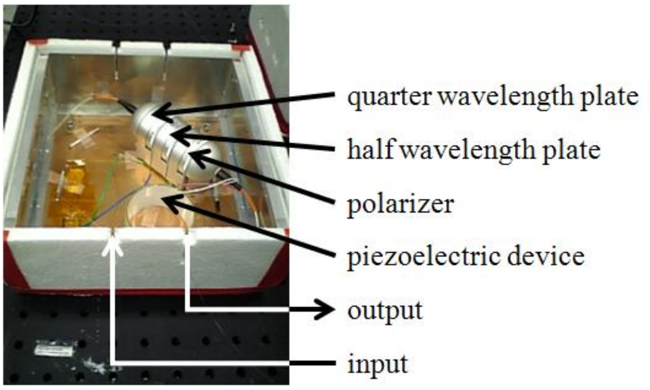
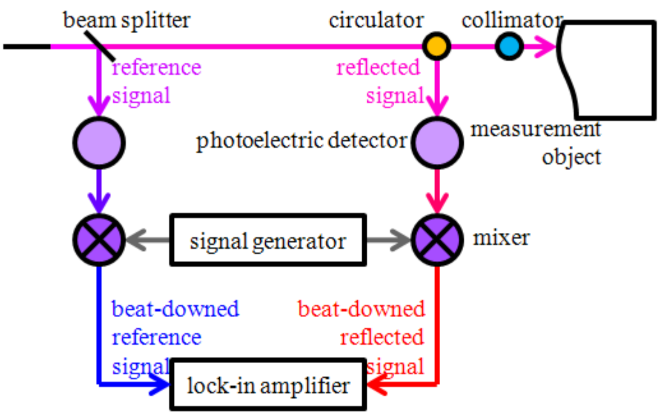
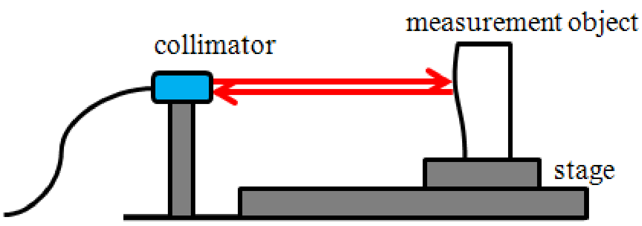


Fig.3 The image of the oscillator.



(a)



(b)

Fig.4 (a) The schematic diagram of the measuring system. The light goes through the air between the collimator and the measurement object. (b) This is the side view between the collimator and the measurement object.

Doped Fiber (EDF) as the highly-nonlinear fiber. The diameters of the single mode fiber and the EDF are 125μm and these fibers are made of quartz. The EDF glows green when the light travels in the core of the EDF. As the optical elements we use an isolator, wavelength division multiplexing (WDM) coupler, 7:3 coupler, quarter wavelength plate, half wavelength plate and polarizer. In the loop fiber, light travels in the constant direction and revolved many times by the effect of the isolator and the 7:3 coupler. And by the effect of the WDM coupler, the light resonates. The quarter wavelength plate, the half wavelength plate and the polarizer adjust the polarization state of the light in the loop fiber. So the loop fiber functions as the resonator by these optical elements and when the loop fiber functions as the resonator the repetition frequencies become very equal. The output is split in the proportion of one part to ninety-nine parts by the 99:1 coupler. The reference output is observed using the spectrum analyzer (ADVANTEST, R3265). Another output is used in the measuring system (we explain at 2.2).The resonator length of the experimental apparatus in this research is about 4.32 m, the pulse interval is 21.6 ns and the repetition frequency is 46.28484 MHz. 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 optical resonator length. To make the repetition frequency a definite value, we use the piezoelectric device. The fiber wound around the piezoelectric device. When the piezoelectric device operates, the length of the fiber around the device changes and the repetition frequency keep the definite value. Therefore, the resonator is very important to generate the optical frequency comb laser, so we must diminish the effect of the disturbance. We put the resonator in the box made of the styrene foam that is 20 cm square by 10 cm deep. The resonator and the box are shown in Fig.3. The quarter wavelength plate, the half wavelength plate and the polarizer include in the silver oval-shaped element and the piezoelectric device is shown as the white tube.

2.2 The measuring system

The schematic diagram of the measuring system is shown in Fig.4 (a). The measuring system contains the elements that are a circulator (OPNETI, M06-185-02A), a collimator (THORLAB, F260FC-1550), a photoelectric device (THORLAB, DET01CFC) and a mixer (MINI-CIRCUITS, ZX05-43H-S+) and the equipment that are the signal generator (ANRITSU, MG3632A) and the lock-in amplifier (NF, LI5630). The existing measuring method installed the mirror as the measurement object. But in this research, we are aiming at the method of using non reflecting mirror. This method is useful for noncontact measurement and the measurement object isn't damaged. But the reflected light from the measurement object is weak easily, and the device that acquires the reflected light to high sensitivity is necessary.

We explain the measuring method. At first, the beam splitter splits the optical frequency comb laser to the reference light and the reflected light that irradiates on surface of measurement object. These two lights are entered into the photoelectric detectors respectively, and converted into electric signals. And then, the mixer generates the beat from the signal generator and the electric signal.

The optical circulator is an optical element using Faraday rotator as well as isolator. The circulator has a function that makes the light from the beam splitter to enter into the collimator, and the reflected light from the measurement object to enter into the photoelectric detector but the reflected light does not go back.

2.3 The basis of the distance measuring

We explain the measuring method using the beat signal. The beat signal is generated by the difference between f generated from the frequency of the optical frequency comb laser and f' generated from the frequency of the signal generator. The beat signal is the radio frequency which is easily to measure the phase. The beat frequency becomes several kHz though f and f' are several GHz, and the beat frequency lowers very much. The low frequency is easy to measure the phase precisely with lock-in amplifier, and the phase is measured precisely with high sensitivity.

The frequency of the signal generation is phase-locked by the using Global Positioning System (GPS) in the future and the signal is traceable to the SI unit.

3. The experiment of the distance measuring

We made the performance assessment of the produced experimental apparatus. The change in the phase corresponding to the distance of the moving stage with the micrometer was measured as a performance assessment by using the mirror as a measuring object. When $\Delta\varphi$ is assumed to be a phase change and Δx is assumed to be a distance of the displacement stage, the relation of them is shown by Eq.(1).

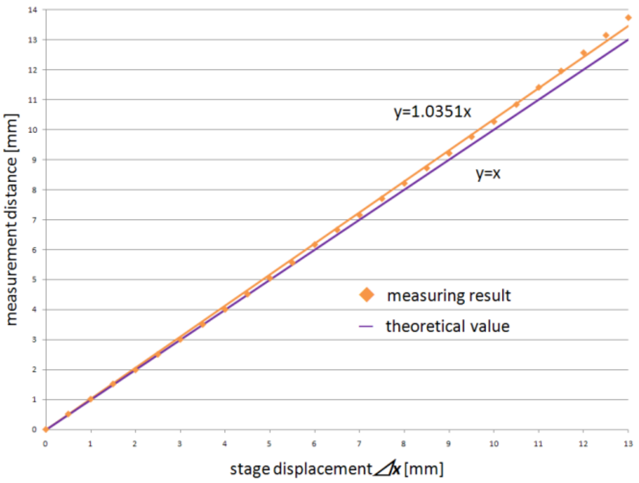


Fig.5 Result of the measurements using the micro stage. The results are in agreement with the theoretical value when the displacement is not over the 6mm.

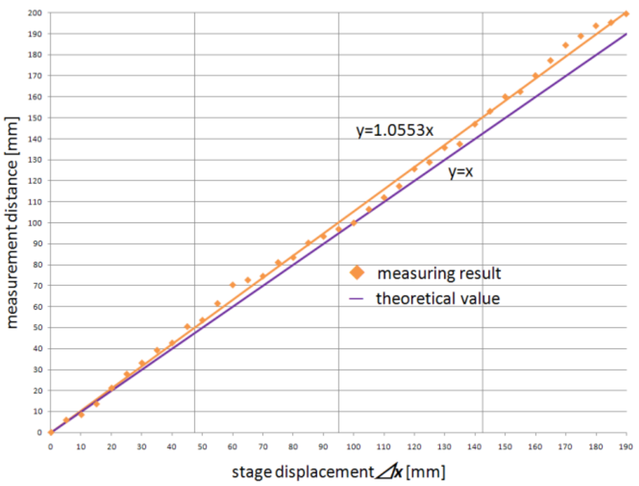


Fig.6 Result of the measurements using the electric stage. When the displacement is from 0mm to 45mm and from 95mm to 140mm, the results are agreement with the theoretical value. And the results of the other area are not agreement. This is the cyclic error.

$$\Delta x = c\Delta\varphi / 4\pi f \qquad (1)$$

c is a light speed and *f* is a frequency from the optical frequency comb laser. A frequency *f'* of the signal generator is 1573.695 MHz and the output of the laser diode is 200 mA. The mirror is moved by using the displacement stage at an interval of 500 μm and the value calculated from Eq. (1) are shown in Fig.5. *f* is integral multiples that are the nearest *f'* at repetition frequency (46.28484 MHz), and *f* is 1573.685 MHz that becomes 34 times at repetition frequency. Then, we confirmed the existence of the cyclic error; the mirror is displaced by 2 wavelengths of 1573.685 MHz using the displacement stage (SIGMAKOKI, SGGP26-200) on the same condition is shown in Fig.6. Because light shuttles by the distance where the stage moves, the distance of about 190 mm corresponds to 2 wavelengths.

4. Discussion

In Fig.6, when the displacement is from 0 mm to 45 mm and from 95 mm to 140 mm, the result is agreement with the theoretical value and the result of the other part is different from the theory value. We consider that the result repeats always and this is cyclic error. In Fig.7, we show the error that is the measuring result minus the theoretical value in Fig.6. We verified the proportional relation between the stage displacement and the approximation line. This relation is due to the effect of temperature change. If the length of fiber changes with the effect of temperature change, the optical resonator length will change. So the repetition frequency, *f* in Eq.(1) changes and the measurement error occurs. We didn't use the piezoelectric device in these experiments, so the repetition frequency was no controlling. To verify the cyclic error, we calculate that the error minus the value of the approximation line. The cyclic error is shown in Fig.8. The cyclic error when the displacement is from 0 mm to 45 mm and from 95 mm to 140 mm is similar. Moreover the cyclic error when the displacement is from 45mm to 95 mm and 140 mm to190 mm is similar too. We displaced the stage by about 2 wavelengths, and so consider this error to be cyclic.

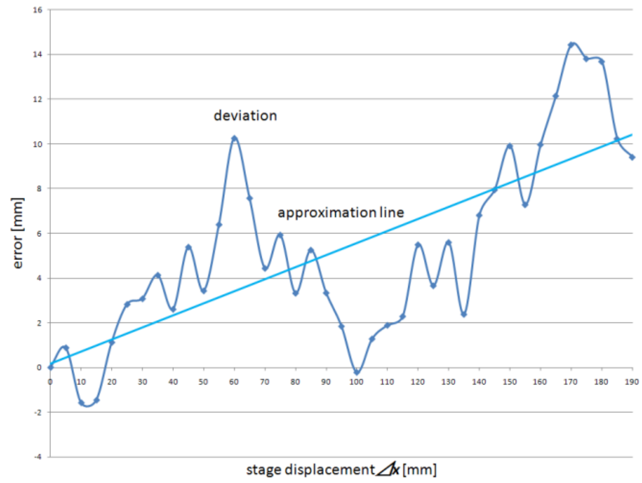


Fig.7 Result of the measuring result minus the theoretical value deviation in Fig.6. The approximation line has proportional relation with the stage displacement.

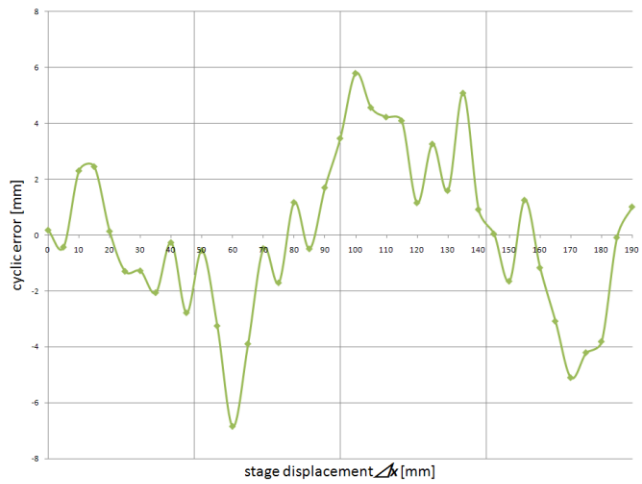


Fig.8 Result of the deviation error minus the value of the approximation line in Fig.7. This is the cyclic error.

Now, we think that the cause of the cyclic error is the optical circulator and the collimator. The circulator is the optical element controlling the 3 optical paths. In the usual case, the circulator uses light to travel from the laser diode to the measurement object and from the measurement object to the photoelectric detector. We found that the surface of the output fiber has a reflection of about 15 db for anti reflection coating. So we think that this error easily becomes to the cyclic error. And the collimator is the optical element controlling the light direction by the aspheric lens. If there are the reflections from the lenses, these cause the cyclic error. However, in this experiment the anti reflection coating was enough.

5. Conclusion

In these experiments, we propose the basis of the new distance measuring, and verified the cyclic error. The error source was found to be caused from the end surface of the circulator. We propose the non-prism type distance meter for using on roughed surface under test since its high sensitivity due to the act of lock-in amplifier.

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