Paper:

Automatic Recording Absolute Length-Measuring System with Fast Optical-Comb Fiber Interferometer

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The optical frequency comb has a short pulse, broad spectra, many spectral lines, and high temporal coherency. In this paper, a new absolute length-measuring technique with a high resolution of 0.05 μm is developed by using the temporal-coherence interferometry of the optical comb. A new fiber Fabry-Perot etalon (etalon) of a free spectral range with a frequency of 15 GHz is developed to improve fine positioning in space, so a short translation stage of up to a 10 mm movement is realized for various ranges of length. Moreover, the interference fringe peak is automatically detected by developing a new analog electrical circuit. The ambiguity of the interference-fringe orders is determined by using the etalon at a frequency 14.9 GHz within a time of 1 second for various length ranges.

Keywords: length measurement, high repetition frequency, optical comb, absolute metrology

1. Introduction

In the field of length/distance metrology, precision and then efficiency of measurement are the current demands. The manufacturing industry in particular requires ultimate precision of measurement for the production of high-quality products, and precise measurements are also important in the assessment of safety in society. For example, it is vitally important that the shape and form of aircraft and engines be absolutely measured with the utmost precision. Under such circumstances, studies have long been carried out using a continuous wave (CW) laser interferometers or pulse lasers, but the use of such technology is restricted to special applications. Recently, ultra-short, optical, new pulse generation has become significant, and broad-band spectra are being utilized again. The development of femtosecond mode-locked laser technology has been particularly rapid. In addition, high-speed optical communication technology has also been studied. With the advent of photonic crystal fiber, mode-locked pulse laser technology has become very attractive in the field of optical metrology, and the laser has come to be called an "optical frequency comb," or "optical comb." The optical comb has various useful characteristics.

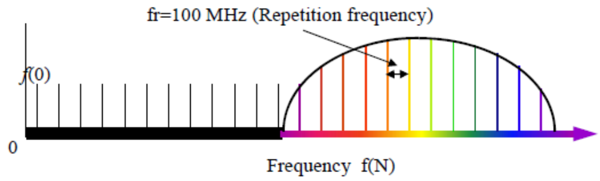

Fig. 1. Outline of optical frequency comb. $f(N) = f(0) + N \cdot f_r$ $(N: \text{integer})$.

Here, we report the results of experimental investigations done on a new, highly accurate method of measuring absolute length using the pulse interference of the optical comb. The technique uses only the temporal coherence (pulse) interferometry of the optical comb, so the measuring system is simple and very accurate. It is therefore useful for absolute length measurements with an accuracy of 0.05 μm for measurements of up to several hundred meters.

2. Optical Frequency Comb

2.1. Outline of Optical Frequency Comb

The optical frequency comb has many narrow spectral lines in equal frequency intervals in the frequency domain, as shown in **Fig. 1**. However, there is sometimes carrier envelop offset frequency, and it is not easy to control. On the other hand, in the time domain, the laser is a pulse train with very short pulse width, and the intervals are precisely constant. The time interval is easily stabilized to frequency standards, such as a rubidium optical clock system. The stability of the time interval is very good, with an accuracy equivalent to 10^{-11} [1]. Moreover, for industrial metrology in various factories, the optical comb with an all optical fiber system has been found to be profitable, because it was not strongly affected by the surrounding condition.

The principle of position measurement using temporal-

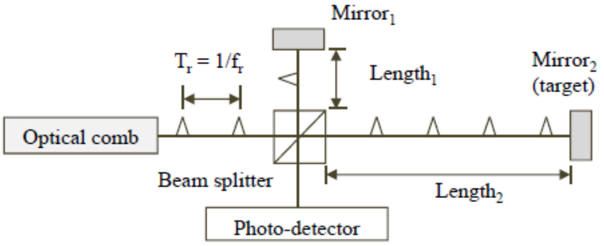

Fig. 2. Temporal coherence interferometry using the repetition f_r of optical pulses(T_r; time interval).

coherence interferometry is shown in **Fig. 2**. Interference fringes are generated when the difference between the measurement path length L_1 and the reference path length L_2 is $mc/2f_r$. Here, m is an integer, c is the speed of light through air, and f_r is the repetition frequency of the optical comb used [2]. The interference is generated in the range of length of several tens of micrometers in space, depending on the pulse width of the optical comb. This technique is very useful for various types of positioning with a high spatial accuracy because the f_r has an accuracy of more than 10^{-11}. In general, the technique is useful for absolute distance measurement, and distance measurement with a high reproducibility of several μm has been realized at about 403 m in general industrial fields [3–5]. Therefore, temporal coherence interferometry has proven useful for measuring lengths in industry and society, because it is not affected by air turbulence and mechanical vibration due to its ultra-short pulse characteristics.

Therefore, the optical comb offers an absolute measuring system using a simple system for in-situ metrology and temporal coherence interferometry which does not utilize the carrier envelop offset frequency control. It has a wide range of measurement from 0 to several hundred meters. However, the interference fringes generated are limited to the distance region of each 1.5 m time m in the case of a 100 MHz repetition frequency, so more than 1.5 m of the translation stage must be scanned for generating the interference fringe.

2.2. Fast Optical Frequency Comb

In general, the repetition frequency that optical combs can produce relatively easily is in the frequency range of 40–150 MHz because the optical fiber is relatively long for laser oscillation. Temporal coherence interference fringe is therefore generated at spatial positions of intervals longer than 1 m. Consequently, the length fields that can be used in measurements in industry and society may be limited to special isolated measurements. Therefore, it is important to develop a high-frequency repetition (fast) optical comb. For realizing this resolution, a new fiber-type Fabry-Perot etalon (etalon) has been developed for increasing the repetition frequency of optical comb from around 100 MHz to around 10 GHz. Fortunately, since the optical comb has a discrete spectrum, a high-accuracy length of etalon is not required.

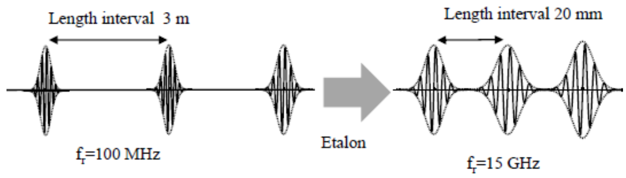

Fig. 3. High frequency comb produced by filtering with Fabry-Perot etalon.

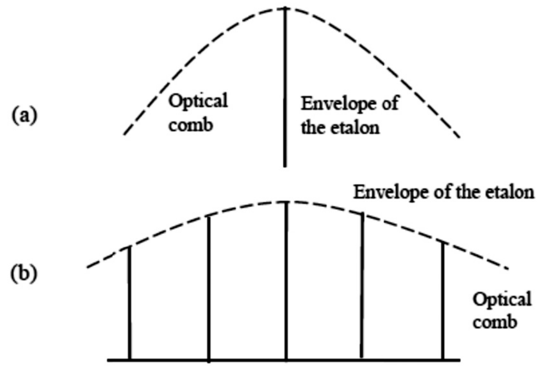

Fig. 4. Filtering of optical comb; (a) high-finesse etalon, (b) low-finesse etalon.

An optical fiber-type etalon has been developed, as shown in **Fig. 3**, because the fiber-optic etalon is not strongly affected by variations in air temperature or mechanical vibrations. Since the free spectral range is not required to be accurate, the length of the etalon cavity fiber (device) is cut according to the free spectral range required and is sometimes sandwiched between the general optical fibers with the reflective coating and the FC/PC connectors. In this case, one optical line should be selected by the etalon of high finesse, but the power of the light is reduced, as shown in **Fig. 4(a)**. The accuracy of the fast optical comb is the same as that of the original optical comb, which has a repetition frequency of 100 MHz. On the other hand, if we use the etalon of low finesse, the power is not largely reduced, but several lines are selected similar to multi-mode He-Ne gas lasers, and the selected optical comb laser is similar to those of multi-mode gas lasers as shown in **Fig. 4(b)**. In this case, the accuracy of the repetition frequency is dependent on the length of the etalons used. We can easily suppose that the length stability of the etalon is better than about 0.5 ppm, as that of the multi-mode He-Ne laser [6]. Finally, etalons with free spectral ranges of 15.0 GHz and 14.9 GHz have been developed by polishing the length of a ferrule fiber device. The length is measured by using a low coherence interferometer in polishing process. In this case of 15 GHz, the geometrical length of device is 6.8063 mm, because the group refractive index of the optical fiber is 1.4682. The reflectivity of the etalon fiber has been coated to be 98% (finesse; about 150) by dielectric multilayer coating. Therefore, the etalon reduces the output power of optical comb from about 12 mw to about 0.1 mw, but the SN

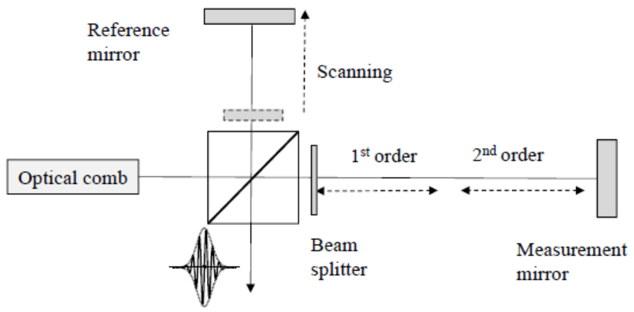

Fig. 5. Interference fringe generation according to the pulse interval.

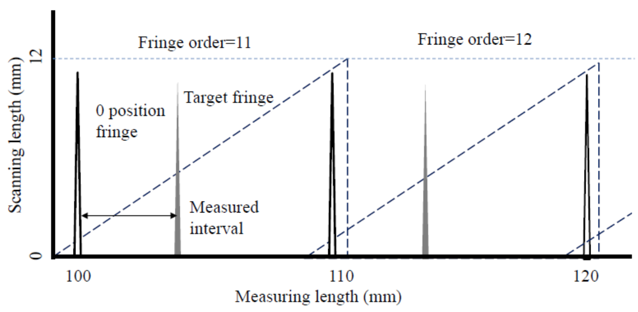

Fig. 6. Measurement principle of absolute distances with high-frequency optical comb.

ratio of interference fringe was no problem in high resolution measurements of about 50 nm. If necessary, we may use an optical fiber amplifier for more-high accuracy measurement.

3. Absolute Ranging Method

3.1. The Principle of Absolute Measurement

In order to form an interference fringe pattern, the reference optical path length must be scanned over several tens of millimeters according to the length of etalon used. For example, in the 1 GHz etalon, the optical spacing of the etalon is 150 mm. Since 1.4682 is the group refractive index of the optical fiber, the size of the etalon free spectral range is about 100 mm. Therefore, the scanning stage must be 150 mm or longer.

We will now discuss the length measurement for using the repetition frequencies of 15.0 GHz and 14.9 GHz. The scanning range of the stage is about 14 mm long. **Fig. 5** shows an outline of the distance measurement with an unbalanced arm interferometer and a scanning stage. To reduce the effect of the drift in the measurement system, the zero-point of each interference fringe order is generated using a window plate, and the detected signal is always displayed at each order. The object mirror is at the position of the target mirror in spatial measurement.

The interference fringes at 0 mm are always generated at the same position by scanning over 14 mm. On the other hand, the interference fringes of the target are generated at every position corresponding to the length being measured within a 14 mm scan. This is because the 15 GHz repetition frequency is equal to the 10 mm interval. **Fig. 6** shows the behavior of interference fringe generation in the length range of 100 mm to 120 mm. In the measurement, the interval between the 0 position signal and the measurement position signal is determined by the displacement of the stage with an accuracy of higher than 0.1 μm. Secondly, the order of the interference fringe is determined by the same measurement by the 14.9 GHz repetition frequency of the comb.

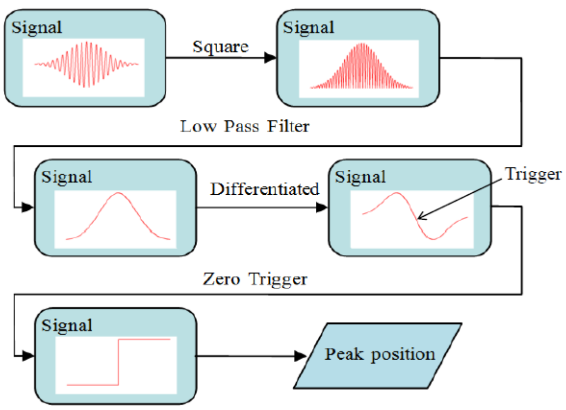

Fig. 7. Interference fringe automatic-processing using an electric circuit.

3.2. Automatic Measurement

Figure 7 shows an outline of the automatic processing of interference fringes for determining the length [7, 8]. First, the photo-detection signal of the interference fringes is squared, and then it is filtered by a low-path filter. The output signal is differentiated by an electrical circuit. Finally, the pulse signal is generated at the zero-crossing position to trigger a short traditional length-measurement sensor with a resolution of 10 nm.

4. Experiment

4.1. Interferometer and its System

The measurement system we have developed is shown in **Fig. 8**. The optical comb is incident to a two-beam interferometer through an etalon and a fiber circulator. About 14 mm of the reference path is scanned because the free spectral range of the etalon used is 15 GHz, which corresponds to about 10 mm in length. The ultrasonic linear stage is used because it is compact. The measurement path has a window plate (0 point) and a reflecting mirror (target). The generated interference fringes are detected by a photodiode and are amplified with a high SN ratio by a frequency selective amplifier. The SN ratio of the final signal is high enough for automatic measurements.

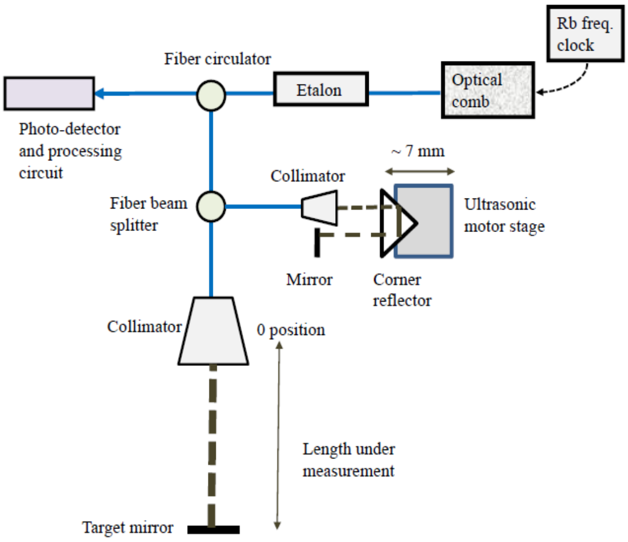

Fig. 8. Temporal coherence interferometer for absolute length measurements.

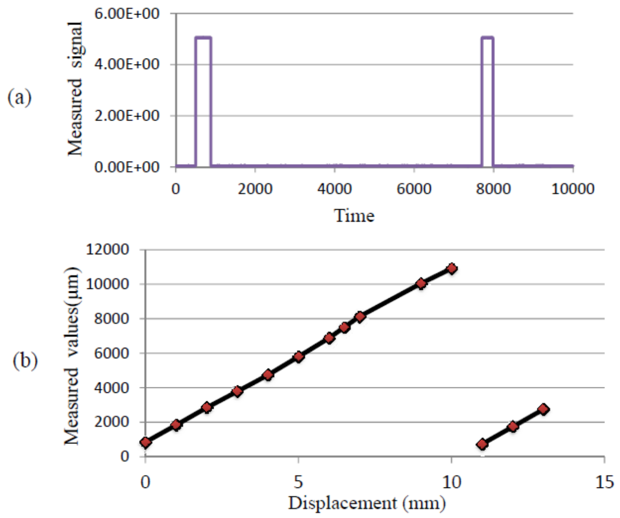

Fig. 9. Results of the experiment.

4.2. Results

With our new system, the length/distance measurements were preliminary achieved; the results of the experiment are shown in **Fig. 9**. **Fig. 9(a)** shows the processed signal for the triggering of measurements, and **Fig. 9(b)** shows the results of the measurements. The standard deviation of the measured values is less than 0.05 μm, though the accuracy of displacement is relatively poor because the micrometer was operated by manual operation. Moreover, higher-reliability measurements has been achieved by taking the average of several measurements. The result shows that the new system may be able to measure lengths or distances of up to several hundred meters by utilizing various etalons of different free spectral ranges. The total time for taking the overall measurement has been made within several seconds, but it may be improved by using a fast scanning stage.

4.3. Discussion

As indicated above, the present measurement system is not much affected by air turbulence or mechanical vibration. However, the resolution is not small, because the peak of the interference fringe pattern is achieved using the effect of the electrical circuit. Since the optical comb of the spectral width of 60 nm is used, the half-width of the fringe pattern is about 20 μm. Considering the SN ratio of the pattern, a measurement resolution of better than 0.05 μm may be expected by using professional software. Therefore, the present system may be useful for measurements of relatively large objects, though it is very useful for measurements of small objects.

5. Conclusion

A new absolute distance-measuring technique with a high resolution of 0.05 μm has been developed using the temporal-coherence interferometry of an optical frequency comb and a short translation stage for various distance ranges. A new fiber Fabry-Perot etalon having the frequency of 15 GHz of the etalon has been developed to improve fine positioning in space. Therefore, the scanning length for generating the temporal coherence interference fringe is only about 14 mm. Moreover, the interference fringe peak has been automatically achieved by developing a new analog electrical circuit.

The present system with an optical comb is applicable to the measurement of lengths up to several hundred meters. It is particularly applicable to industrial metrology because it is not much affected by surrounding conditions.

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