

# ABSOLUTE MEASUREMENT OF BASE LINES UP TO 400 M USING TEMPORAL COHERENCE HETERODYNE INTERFEROMETER OF OPTICAL FREQUENCY COMB

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**Abstract:** A heterodyne interference system is developed for base-lines measurement by using an acoustic optical modulator and a stabilized optical-frequency comb. The temporal coherence interference with the optical-frequency comb happen at discrete positions, where a pair of pulse trains overlaps with each other. An optical delay of the interferometer with a piezo-electric transducer is realized to find the peak position of interference fringe pattern and the absolute distance is obtained with a high accuracy. The interferometer is applied to a distance of base-lines up to 403 m and the experimental result shows of possibility of measuring within an accuracy of several micrometers.

**Keywords:** optical frequency comb, absolute distance measurement, temporal coherence interferometry, heterodyne interferometry.

## 1. INTRODUCTION

Absolute long distance measurement with high accuracy is required in both industrial and scientific areas. In particularly, it is important to evaluate the quality and safety of fudge institutions. Recently, optical frequency comb has been considered as a useful tool to realize such measurement systems because of its high frequency-stability and high accuracy, which is traceable to the definition of second. Therefore, it can be used not only as absolute measurement tool of the frequency standards but also as absolute measurement tool of distances directly [1-10]. Moreover, the optical frequency comb was designated as the National Length Standards of Japan.

Any mode within an optical comb can be expressed by two parameters, carrier envelop offset frequency ( $f_{ceo}$ ) and repetition rate ( $f_r$ ). The frequency of  $N$ -th mode is  $f = Nf_r + f_{ceo}$ , where  $N$  is an integer. Various stabilized lasers are accurately measured using the optical comb and is in practical use for calibration of laser frequency [12, 13]. On the other hand, in the case of in-situ measurement in long distance range, the interferometer is sometimes affected by air turbulence and mechanical vibration, and therefore is not easy to apply it for long distance. On the other hand, the optical-frequency comb may also be used directly as the light source of long-path interferometers, which has

prompted various efforts to investigate new possibilities of distance measurements. Particularly, temporal coherence interferometry is useful to measure the distance between the positions in space [14-15]. Figure 1 shows the principle of the interference fringe positioning between two different-index pulses. The interference fringes are generated when ( $L_2-L_1$ ) is equal to  $McT_r$ . Here,  $M$  is an integer,  $c$  is the speed of light in vacuum and  $T_r$  is the interval between the pulses which is high accuracy with  $10^{-10}$ , because the fr is stabilized by using the Rb frequency standards. In general, Mirror 1 is scanned for generating the interference fringe pattern such low coherence interference fringe.

We have developed a new heterodyne temporal-coherence interferometer to reduce the effects of air turbulence and mechanical vibration and the interference fringes at the positions of zero-optical path and target are generated by changing optical delay of the interferometer. Experimental results show good data of high accuracies of several micrometers at distances up to 403 m.

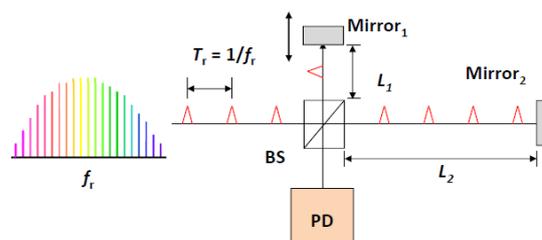


Fig.1 The interference fringe position between two different-index pulses (Optical frequency comb; National Designated Length Standards in Japan).

## 2. PRINCIPLE AND INTERFEROMETER

In general, the frequency power spectra of air fluctuation and mechanical vibration are within 1 kHz. Therefore, heterodyne technique is useful to reduce the effect of the surrounding conditions, as shown Fig.2. The optical frequencies of the optical frequency comb are shifted by  $\Delta = f_r + f_h$  with an acoustic optical modulator, where  $f_r$  is the repetition frequency of the optical frequency comb. In order

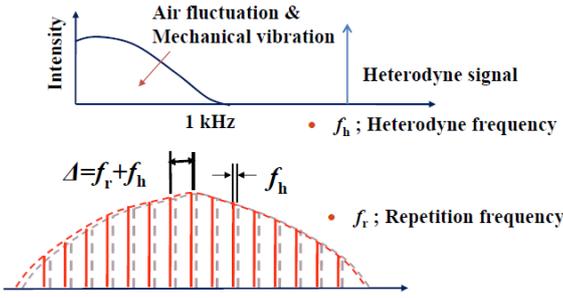


Fig.2 Frequency shift ( $\Delta$ ) of optical comb using an acoustic optical modulator (AOM) .

to reduce the effect of surrounding conditions,  $f_h$  is important to be higher than 10 kHz and is called heterodyne frequency.

The repetition frequency  $f_r$  of the optical frequency comb (MenloSystems, Femtosecond C-Fibre Laser) is stabilized with a stability of  $10^{-11}$  by using a Rb oscillator (frequency standards). In Fig.3, a heterodyne interference system with the optical comb is shown based on an unbalanced optical-path Michelson interferometer using optical fibres [14, 15]. The light beam is separated by a fibre beam splitter and the beam of the reference arm passes through a delay path which is scanned with a piezoelectric transducer (PZT) over about 300  $\mu\text{m}$ , and then an acoustic-optical modulator (AOM) is set in the reference arm to generate the frequency shift  $\Delta$ , which can be written as  $\Delta = f_r + f_h$ , where  $f_h$  is only 100 kHz and  $f_r$  is 100 MHz. The AOM is derived by a RF amplified signal of a frequency 100.1 MHz from a frequency synthesizer, which is linked to the Rb frequency standards.

Other beam goes to a part of distance measurement through a fibre circulator and is expanded a beam diameter to 30 mm  $\phi$ . The beam is reflected on the small corner reflector at zero-path position and the target reflector under measurements whose effective size is 60 mm  $\phi$ . Finally, they are combined by a fibre mixer and the interference fringes generated are detected by a photo-diode.

The detected signal inputs the system outline of the electric frequency processing for the phase-sensitive detection (PSD) using a lock-in amplifier (NF Circuit Product) in the heterodyne frequency of 100 kHz ( $= \Delta - f_r$ ). The intensity ratio signal from the PSD is input to a digital oscilloscope. Therefore, this method does not depend on the carrier offset frequency of the optical comb because all envelopes of temporal interference fringes are the same and so the refractive index air is the group one.

The interference fringes are generated when the distance  $L$  between the positions of zero-path corner cube reflector and target corner cube reflector is equal to  $c/2nf_r$ , where  $c$  is the light speed and  $n$  is the group refractive index of air. In this case,  $L$  in the nominal condition (ait temperature 20  $^{\circ}\text{C}$ , humidity 50%,  $\text{CO}_2$  concentration 400 ppm) is calculated to be  $c/(2 \times 1.000270 \times 100 \text{ MHz}) = 1498.55576 \text{ mm}$ . The interference fringes are in the length range of several tens micrometers due to the pulse width of about 150 fs, if the fibre lengths of the measurement arm and the reference arm are equal because of no-dispersion effect.

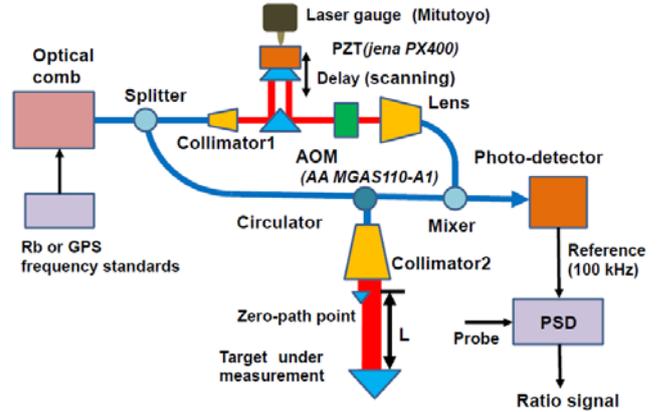


Fig.3 Outline of heterodyne interferometer of optical comb with an optical acoustic modulator (AOM) .

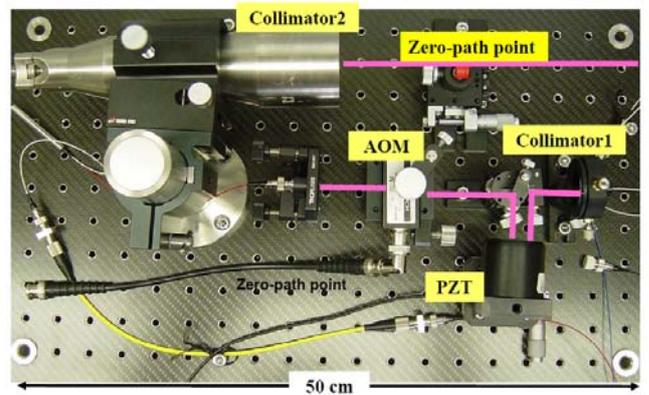


Fig.4 Picture of optical comb heterodyne interferometer.

Figure 4 shows a picture of the main interferometer, which is really compact (size; 30 cm x 50 cm) and simple for realizing in-situ field measurement. The optical fibre system is weak for maintain the polarization state, and the distance measurement system does not utilize the effect of polarization.

### 3. EXPERIMENTS

#### 3.1 EXPERIMENTAL CONDITION

The in-situ measurement was achieved considering the application of this method and the condition of evaluation experiment is conventional in the field of use. This experiment was achieved at the corridor of High Energy Accelerator Research Organization (KEK) in Tsukuba. The experimental place is the passage of 500 m distance beside the electric power sources and the electric controllers for the corridor system. The floor is constructed by thick concrete and the effect due to the floor vibration is very small. The indoor is controlled at 25  $^{\circ}\text{C}$  by the air conditioners each 5 m distance. However, the maintenance workers go sometimes through the passage, under experiment.

The base lines for experiment are constructed of low-thermal expansion material and strong-strength devices, as shown in Fig.5. The effect due to the mechanical vibration is very small and is very good for the evaluation of the distance measurement system developed. The light from the

floor of the base lines is about 105 cm, which is determined for future application. The intervals of the base lines are measured with an accuracy of several tens millimetre by a conventional non-mirror distance-meter, which uses the principle of triangular technique. The focus alignment of the collimator is achieved by using an image camera in the wavelength region of 1.55  $\mu\text{m}$ . The beam size of the optical comb laser is about 80 mm  $\phi$  and the dancing of the laser beam at 403 m was less than about 20 mm and so the S/N ratio is better than 1 because of the dancing less than 20 mm.

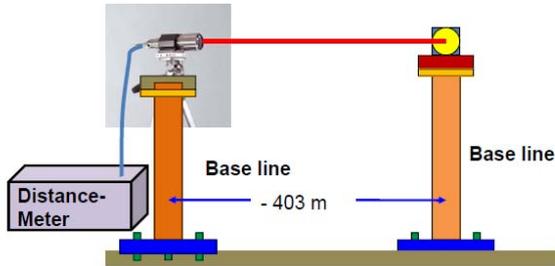


Fig.5 Practical application for constructing the next-generation photon factory.

### 3.2 EXPERIMENTAL RESULTS

The interference fringe is generated due to the temporal interferometry. Figure 6 shows the typical detected signal at a 403-m distance which is considerably very good. The automatic processing is very easy. In this study, the determination of the peak interval of the interference fringes is firstly made to processing low-path filtering of the signal obtained and the both fringes ( $p_1$  and  $p_2$ ) of the signal were used for positioning, because the signals have some noises. This technique is simple and easy for practical use. Especially, the laser beam of the optical comb used is steady and is easy in the in-situ measurement.

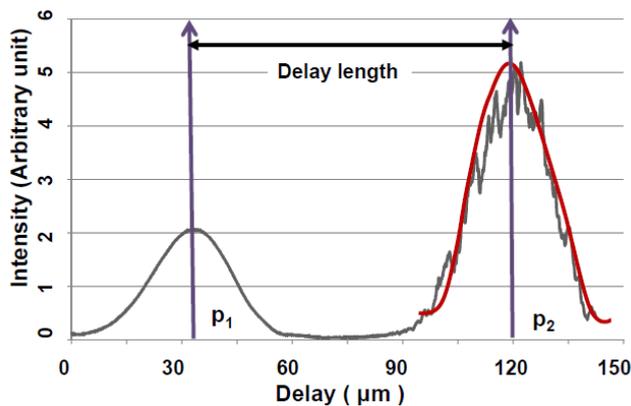


Fig.6 Experimental fringe signal at 403 m and its processing technique.

Figure 7(a) shows the experimental results which are obtained by ten-times in each 100 s and so the total time for experiment is about 1000 s. The amplitude signal from the lock-in amplifier does not depend to the offset frequency of the optical comb used. The variations of the measurement

values are only several micrometers which corresponds to an accuracy of  $10^{-9}$  and they are 15  $\mu\text{m}$  within 1000 s. In the time, the environmental conditions are not much changed though the temperature and pressure sensors of the air were not measured. However, the experimental data are very steady and so the result is also good reproducibility. However, we may suppose that the drift is due to the change of the air pressure. If we use the good air condition sensors, the refractive index of air under experiment is corrected with high accuracy of  $2 \times 10^{-8}$ [16]. Finally, the measurement of distance should be achieved with an accuracy of  $2 \times 10^{-8}$ .

Figure 7(b) shows the experimental results when the repetition frequency 100 MHz is changed by 1-5 Hz (corresponding to  $(1-5) \times 10^{-8}$ ). The experimental variation of distance is about 23  $\mu\text{m}$ . This accuracy is evaluated to 3  $\mu\text{m}$  because the theoretical variation is 20  $\mu\text{m}$ . The overall accuracy is occluded to be several micrometers which correspond to  $1 \times 10^{-8}$ .

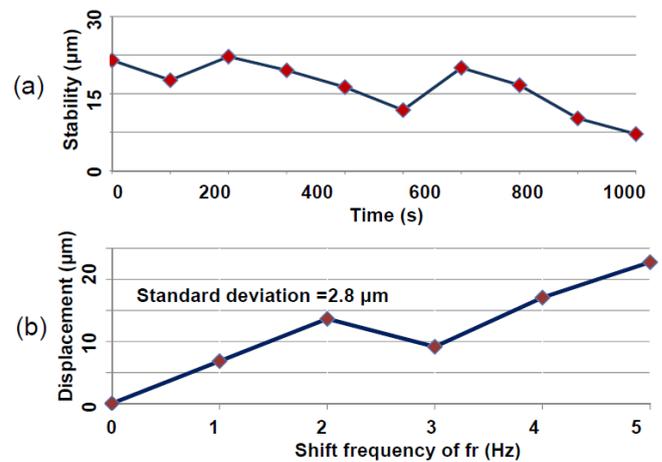


Fig.7 Experimental results for the measurement of 403-m distance.

### 4. CONCLUSIONS

The developed measurement system has a possibility of obtaining the accuracy of  $10^{-8}$ - $10^{-9}$  on distance measurement if the surrounding conditions are good and are measured with high-accuracy air-sensors. This heterodyne method is not very influenced by the air conditions.

Real time measurement of the air conditions in situ is important and is measured a new technique using a special optical fibre sensor for obtaining the absolute distance. Moreover, it is very important to do real-time distance measurement by making automatic processing of the interference fringes. Figure 8 shows an electric system for an automatic measurement system [17]. The method is known as one technique for determining the scale position of line standards with several nanometers to several tens nanometers. The interference fringe patterns are processed by an electric circuit and the tiger signal is generated for determining the scanning delay length by a linear gauge with a resolution of 10 nm.

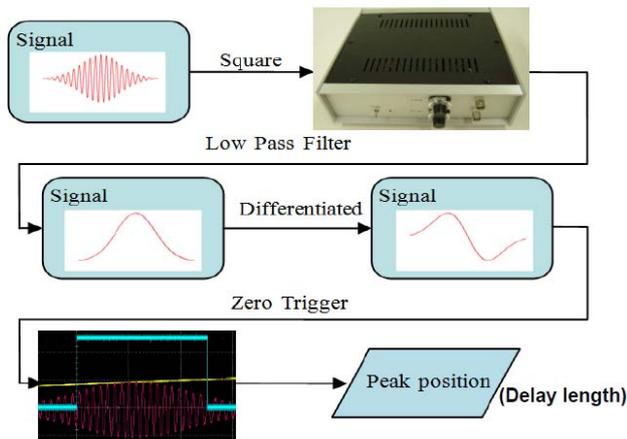


Fig.8 Automatic processing of interference fringes for in-situ measurements.

## 5. ACKNOWLEDGEMENT

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