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Absolute Measurement of Baselines up to 403 m Using Heterodyne Temporal Coherence Interferometer with Optical Frequency Comb

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A heterodyne interference system is developed for baseline measurement by using an acoustic optical modulator and an optical frequency comb stabilized by a rubidium atomic clock. Temporal coherence interference occurs at discrete spatial positions, when two pulse trains overlap. An optical delay of the interferometer with a piezoelectric transducer is created to determine the peak positions of the interference fringe patterns, and the absolute distance is obtained at a high resolution of several tens of nanometers. The experimental results at baseline distances up to 403.2 m show a high reproducibility of about 6 µm. © 2012 The Japan Society of Applied Physics

Long-distance absolute measurements with high accuracy are required when constructing huge industrial and scientific facilities. In particular, the quality and safety of such facilities must be evaluated through measurements of hundreds of meters with accuracy better than 10 µm. Recently; an optical frequency comb has been considered a useful tool for realizing such measurement systems, because of its precise pulse-repetition frequency, which is an accuracy of 10^{-11}. Therefore, an optical frequency comb can be directly used for absolute measurement not only of frequency levels[1–3] but also of various distances.[4–6] When performing *in situ* long-distance measurements, conventional interferometers are affected by air turbulence and mechanical vibration, and therefore, are not easy to apply. However, an optical frequency comb can be used directly as the light source of a long-path interferometer,[7–16] and this has prompted various research efforts to develop new distance measurement devices.

We have developed a new heterodyne temporal-coherence interferometer in order to reduce the effects of air turbulence and mechanical vibration. The interference fringes along optical paths between the zero and target positions are generated by changing the optical delay of the interferometer to be within 250 µm. Experimental results show a high accuracy of several tens of nanometers for relatively short distance measurements. Furthermore, *in situ* measurements of distances up to 403.2 m under typical conditions have high accuracies of about 6 µm.

All modes within an optical frequency comb can be expressed using two parameters — the carrier envelope-offset frequency (f_{ceo}) and the pulse-repetition frequency (f_{r}). For integer N, the frequency of the Nth mode is described as $f = Nf_{\mathrm{r}} + f_{\mathrm{ceo}}$. For *in situ* long-distance measurements, conventional interferometers are affected by air turbulence and mechanical vibration, and therefore, are not easy to apply. In such cases, heterodyne interferometry is highly valuable, since this method is less influenced by the surrounding conditions. Optical frequency combs have a strong potential for use in heterodyne interferometry, because they are characterized by pulse-repetition frequencies that are traceable to the definition of second with a high accuracy of 10^{-11}. For example, the frequency of an optical frequency comb is easily stabilized to the standard frequencies of a rubidium (Rb) optical atomic clock or a global positioning system.

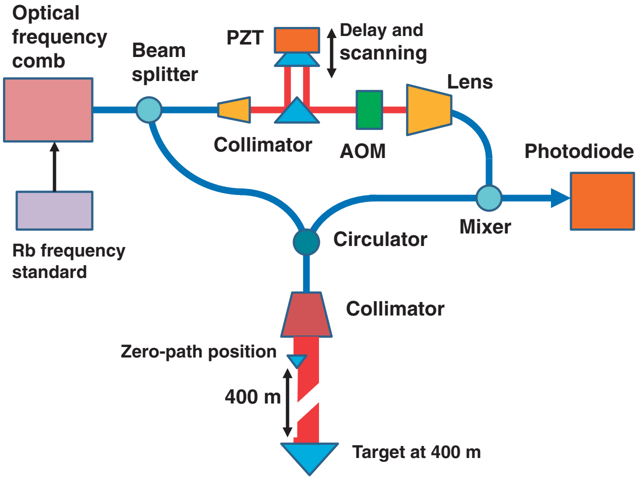

Fig. 1. Outline of heterodyne interferometer with optical frequency comb.

An optical frequency comb (MenloSystems C-Fibre Femtosecond Laser) with an output power of about 12 mW, a repetition frequency of 100 MHz, and a pulse width of about 180 fs is used as the light source in the current study, and the repetition frequency is stabilized by a Rb clock to accuracies better than 10^{-11}. This optical frequency comb is practical when conducting *in situ* measurements, because the laser can easily be transmitted by using an optical communication device, such as an optical fiber. Therefore, the optical frequency comb used can realize high-accuracy measurements outside of the laboratory.

In Fig. 1, our developed heterodyne interference system with the described optical frequency comb is shown. This system is based on an unbalanced optical-path Michelson interferometer. The light beam is separated by a beam splitter and the reference beam passes through a delay path in which the beam is scanned to up to 250 µm with a piezoelectric transducer (PZT). An acoustic-optical modulator (AOM; AA Optoelectronic MGAS110-A1) is used to generate a frequency shift $\Delta = f_{\mathrm{r}} + f_{\mathrm{h}}$ in the reference beam, where f_{h} for heterodyne detection is only 100 kHz and f_{r} is 100 MHz. The measurement beam performs distance measurement by passing through a fiber circulator and being expanded to a beam diameter of 30 mm by a collimator. The beam is reflected at two positions by a small corner reflector (the zero-path position) and the target. Finally, the two

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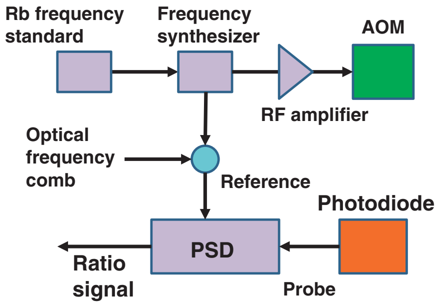

Fig. 2. Reference signal generation for PSD and driving frequency generation for AOM using Rb frequency standard and frequency synthesizer.

beams are recombined by a mixer and the interference fringes generated are detected by a photodiode.[17)]

The interference fringes are generated when the distance L between the zero path and target positions is equal to $Mc/2nf_r$, where M is an integer (interference fringe order), c is the speed of light, and n is the refractive index of air. In this case, L is calculated to be $Mc/(2 \times 1.000268 \times 100\,\mathrm{MHz}) = 1498.561 \times M\,\mathrm{mm}$ at 20 °C and 101.3 kPa in air[18)] and the interference fringes are generated in the range of several tens of micrometers at L of about 1.50 m ($M = 1$), 3.00 m ($M = 2$), 4.50 m ($M = 3$), ... Moreover, since this method uses the envelope of the interference fringes, the measurement accuracy is independent of the carrier offset frequency.

Figure 2 shows a schematic of the electronic frequency processing system used to perform phase-sensitive detection (PSD). This system employs a lock-in amplifier (NF) at the heterodyne frequency of 100 kHz, which is derived from a Rb clock and a frequency synthesizer. In addition, the RF signal of an AOM is generated from a 0.7 W RF signal of 100.1 MHz with the frequency synthesizer. In this experiment, PSD is vital for obtaining highly accurate data. The signal from the phase-sensitive detector is obtained by using intensity ratio signals to eliminate the influence of f_{ceo}. The detected signal is input to the phase-sensitive detector as a probe signal, and the phase signal from the phase-sensitive detector is then output to a digital oscilloscope. A time constant of 100 µs was selected for this study.

In situ measurements were performed taking into account the practical application of this method. Thus, evaluation experiments were conducted in the corridor of the High Energy Accelerator Research Organization (KEK), which is taken as an example of a measurement at a vast facility, under environmental conditions considered typical in the field. Figure 3 shows an example of the signal detected at a distance of 403.2 m ($M = 269$); this signal is considered to be of high quality even though the interference fringe is generated by the temporal interferometry. The positioning of the interference fringe is determined after filtering the signal because the signals contain noise by air fluctuation and mechanical vibration. At first, the values p_1 and p_2 of delays at the half-intensities of the interference fringe generated are obtained and the average of p_1 and p_2 is utilized for the positioning of the interference fringes. Namely, the difference between the interference fringe positions is calculated by $[(p_4 + p_3) - (p_2 + p_1)]/2$.

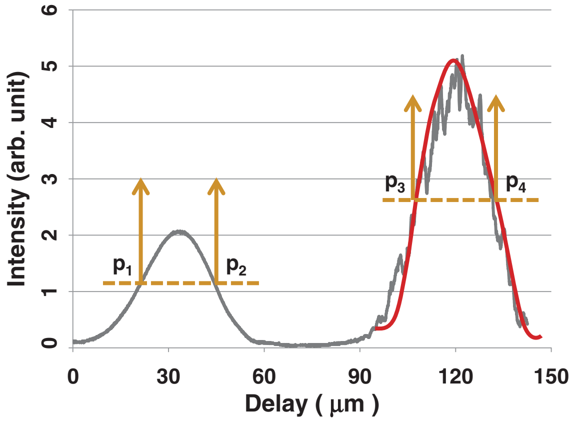

Fig. 3. Original interference fringes obtained by delay scanning, and data processing method.

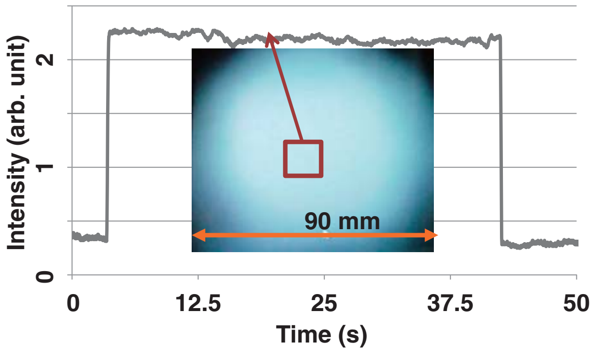

Fig. 4. Intensity fluctuation of the optical comb beam at a distance of 199.5 m ($M = 133$).

Figure 4 shows the intensity pattern of the laser beam at a distance of 199.5 m ($M = 133$) and the intensity fluctuation within an $8 \times 8\,\mathrm{mm}^2$ section of this pattern denoted by the square box. The intensity fluctuation is relatively small; however, the beam dancing is large. Therefore, the beam diameter is larger than that of the target corner reflector. Figure 5 shows the experimental results, which are averaged over 10 measurements each 100 s at distances of 199.5 and 403.2 m. Thus, the total time for the experiment was about 1000 s. The amplitude of the signal from the lock-in amplifier is independent of the offset frequency of the optical frequency comb used here. During the experiment, the environmental conditions did not change, according to one air temperature sensor (resolution: 0.1 °C) and one pressure sensor (resolution: 10 Pa). The experimental data are steady, with standard deviations (SD) of 2.8 µm at 199.5 m ($M = 133$) and 6.2 µm at 403.2 m ($M = 269$), and thus, the results show high reproducibility. By employing accurate air sensors, the refractive index of the air during the experiment would be corrected with a high accuracy of 10^{-8}.

Moreover, the accuracy of the system was evaluated by changing f_r by 1–5 Hz.[17)] The experiment was carried out for nine data points collected over a duration of 600 s (Fig. 6). The results show that the average value of ΔL is 107.2 µm, and that the standard deviation of each measurement is about 2.6 µm after compensating for the frequency f_r. To the best

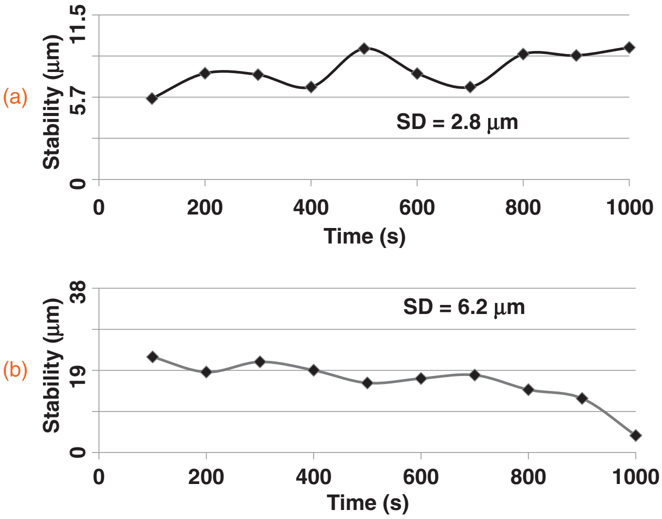

Fig. 5. Absolute-measurement stability (drift) for 1000 s at distances of (a) 199.5 ($M = 133$) and (b) 403.2 m ($M = 269$).

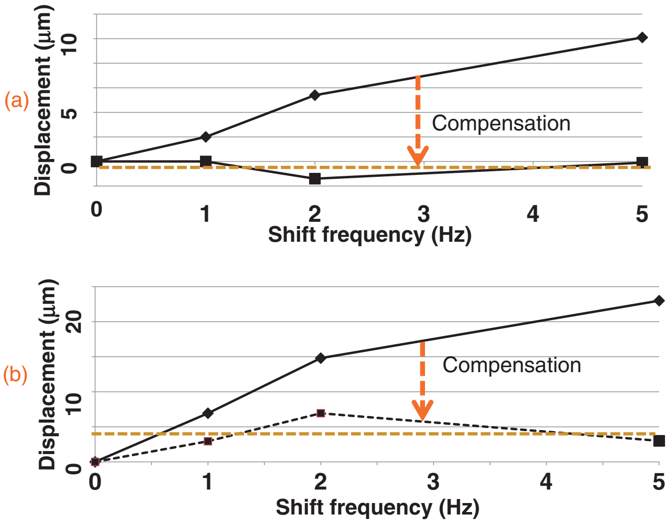

Fig. 6. Measurement of absolute displacements versus frequency shifts of the optical frequency comb for distances of (a) 199.5 ($M = 133$) and (b) 403.2 m ($M = 269$).

of our knowledge, these are the most accurate measurements reported to date in the field of long-distance metrology.

We have presented a new heterodyne technique using an optical frequency comb to suppress the noise that leads to a reduction in the measurement accuracy when performing long-distance absolute measurements. The technique is demonstrated to improve the measurement accuracy and provides promising results for metrology. In the future, we will investigate two-color method using the second harmonic technique to correct the air refractive index automatically.

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