Highly stabilized optical frequency comb interferometer with a long fiber-based reference path towards arbitrary distance measurement

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Abstract: An optical frequency comb interferometer with a 342-m-long fiber-based optical reference path was developed. The long fiber-based reference path was stabilized to 10^{-12}-order stability by using a fiber noise cancellation technique, and small temperature changes on the millikelvin order were detected by measuring an interferometric phase signal. Pulse number differences of 30 and 61 between the measurement and reference paths were determined precisely, with slight tuning of the 53.4 MHz repetition frequency. Moreover, with pulse number difference of 61, a 6.4-m-wide scanning for the relative pulse position is possible only by 1 MHz repetition frequency tuning, which makes pulses overlapped for arbitrary distance. Such wide-range high-precision delay length scanning can be used to measure arbitrary distances by using a highly stabilized long fiber-based reference path.

OCIS codes: (120.3940) Metrology; (120.3180) Interferometry; (000.0000) General.

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1. Introduction

An optical frequency comb is an essential tool for high-accuracy, long-range absolute distance measurements [1–12]. An optical frequency comb interferometer (OFCI), which uses interference between pulses in a mode-locked laser as a light source [13], is one such technique. In a general case of interferometry, optical path length scanning is necessary in order to measure the phase and to determine the absolute distance, i.e., integer multiples of the phase. Conventionally, a mechanical moving stage is used to scan the optical path, and a long-range mechanical moving stage is required for a wide scanning range. In this case, mechanical uncertainty in the displacement owing to various factors, such as yawing and pitching of the stage and motion-induced instability, causes interference signal deterioration. With an OFCI, the optical path difference between the two pulses can be scanned precisely by tuning the repetition frequency (f_{rep}) of the frequency comb [11, 14]. On the other hand, meter-wide scanning of the relative optical path length is essential for an OFCI, because pulse-to-pulse interference signals are observed only when the optical path difference between the measurement and reference paths corresponds to a multiple of the pulse separation, $n_g L$, which is equal to c/f_{rep}, where c is the speed of light in vacuum, L is the geometrical pulse separation, and n_g is the effective group refractive index of the interferometer medium, such as air or glass. However, it is difficult to realize a wide scanning range corresponding to $n_g L$, because the tunable range of f_{rep} (Δf_{rep}) is limited by the laser cavity configuration.

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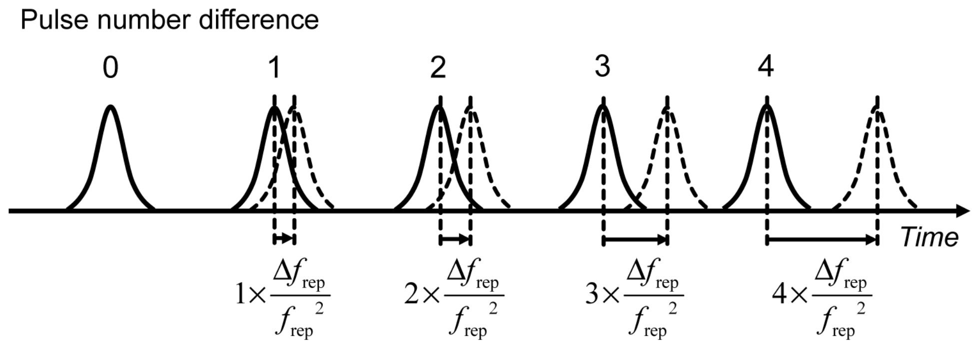

Fig. 1. Multiplication effect with slight f_{rep} tuning. Since each pulse-to-pulse separation is changed by the same amount by repetition frequency tuning Δf_{rep}, the peak position of the *m*-th pulse (delay) is changed by *m* times the interval change.

Because of the narrow linewidth and long coherence length of each mode of the comb, an interference signal is observed between separated pulses in a mode-locked pulse train. Therefore, an unbalanced interferometer, utilizing interference between the measurement and the reference pulses with a large optical path length difference, can be realized. Such a pulse-to-pulse interferometer with an unbalanced path has a so-called "multiplication effect" [15–20], as indicated in Fig. 1.

When the optical path difference $n_g l$, between the measurement and reference paths, is $m \times n_g L$ (m: an integer for the pulse number difference between the measurement and reference pulses), interference fringes between the measurement and reference pulses are observed. In this case, when f_{rep} is changed by Δf_{rep} by changing the laser cavity optical length, the relative position between the two pulses, i.e., the optical delay length, is changed by $m \times n_g \Delta L$. In this way, the range of optical delay length scanning, i.e., the effective optical path length scanning ($n\Delta l$) to generate pulse-to-pulse interferometric signals for both the envelope and the internal fringe, is multiplied by m; thus, wide-range scanning can be realized even with a slight change in Δf_{rep}, as follows:

$$n\Delta l = m\left(\frac{c}{f_{rep}} - \frac{c}{f_{rep} + \Delta f_{rep}}\right) \approx m\frac{c}{f_{rep}^2}\Delta f_{rep} \tag{1}$$

where n is the refractive index of the interferometer medium, which can be either group- or phase-refractive index (i.e., n_g and n_p) for envelope or fringe scanning, respectively. In this study, the refractive indices were determined at the center of gravity of the ultrashort pulse spectrum with the spectral width of 10 nm, and the uncertainty in the determination of the center wavelength was in the range of 0.5–1 nm. For the simplicity of discussion, the right hand side of Eq. (1) was approximated because the change in f_{rep} is at most few % (i.e., $f_{rep} >> \Delta f_{rep}$). However, this effect is useful for very long-distance measurements only, e.g., in the case of a mode-locked laser with f_{rep} = 53.4 MHz, $n_g L = c/f_{rep}$ = 5.6 m, where a scanning range of $n_g \Delta l$ = 2.8 m is required to realize a pulse overlap in the worst case when one of the pulses, such as a reference pulse, is in the middle of a pair of others, such as signal pulses. When the maximum Δf_{rep} is 1 MHz (1.9% of f_{rep}), a minimum of m = 28 is required to yield a sufficient multiplication effect to achieve the full scanning range through Δf_{rep} tuning only. Thus, an optical path difference above 157 m (5.6 m × 28 = 156.8 m) is required, and this effect is applicable to measure absolute distance above 157 m. Thus, it is difficult to utilize this effect in distance measurements that range from a few meters to even 100 m, which is important for many scientific and industrial applications.

The multiplication effect has been utilized for autocorrelation measurements [15, 19], refractive index measurements [14, 16], three-dimensional measurements [17], THz spectroscopy [18], and Fourier-transform spectroscopy [20]; however, a precise

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demonstration of the multiplication effect for interferometric phase measurements of arbitrary distance has not been reported.

In this study, we developed an OFCI for measuring arbitrary distances, not limited only to very long distances. Here, we utilize a long fiber-based reference path (Fig. 2) instead of relying on a long distance to be measured, i.e., a long measurement path. The measurement path can be both space- and fiber-based. In this scheme, although a fiber-based reference path has advantages with respect to the system compactness, unwanted issues such as optical length fluctuation and large phase noise in long fibers cause interference signal instability. In order to overcome this problem, a correction of the interferogram instability, e.g., by using a digital signal processing algorithm, was demonstrated [20]. In contrast, we applied fiber noise cancellation techniques [21–26] to the OFCI with a long fiber-based optical reference path. As a result, the fiber-based reference path was stabilized at nm-level stability in the optical path up to a distance of 342 m, which corresponds to a fluctuation on the order of 10^{-12}.

Moreover, a pulse number difference of m = 61 was precisely determined with slight repetition frequency tuning (Δf_{rep} = 2 Hz) because of high stability and accuracy in the phase measurements. Large pulse number difference of m = 61 yields a wide scanning range of $n\Delta l$ = 6.4 m only by the repetition frequency change of Δf_{rep} = 1 MHz; thus, the measurement and reference pulses can be made to overlap at arbitrary distances without requiring a mechanical moving stage. The developed interferometer can be applied to absolute distance measurement without prior measurements, such as in separate time-of-flight measurements [2, 10], and can be also applied to a high-sensitivity millikelvin-order temperature sensing.

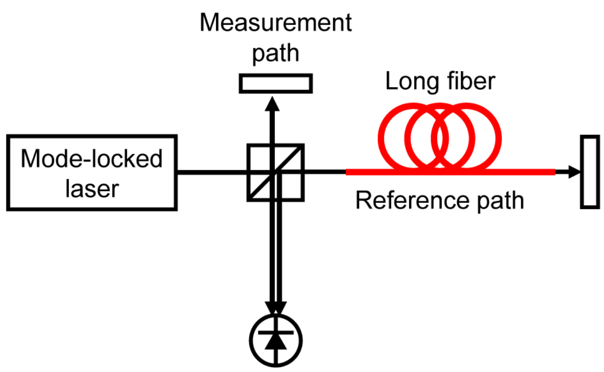

Fig. 2. The optical frequency comb interferometer with a long fiber reference path.

2. Optical frequency comb interferometer with fiber noise cancellation technique

Figure 3 shows a schematic of the OFCI with a fiber noise cancellation technique. The setup consists of two Mach-Zehnder type interferometers, i.e., "main" and "monitor" interferometers, with an Er:fiber-based comb and a single frequency CW laser as the light sources, respectively. The main interferometer (red dashed line in Fig. 3) is used to measure the interference signal. The monitor interferometer (black dashed line in Fig. 3) is used to stabilize the reference path length fluctuation that is caused by environmental instability.

In the main interferometer, we used a home-built diode-laser-pumped nonlinear-polarization-rotation mode-locked Er:fiber ring laser with a central wavelength of 1574 nm as a light source. The laser system was similar to the one described in [27, 28], and the f_{rep} and the carrier-envelope-offset frequency (f_{ceo}) were fully stabilized to the microwave frequency reference synthesized from an Rb frequency standard. The f_{rep} was 53.4 MHz, and it could be varied precisely by using a piezoelectric transducer, and coarsely up to 1 MHz by using a fiber delay line integrated into the laser cavity. The fiber delay line consisted of a fiber collimator, a corner reflector, and a moving stage (Santec ODL-330, delay: 300 ps, insertion loss variation: <0.5 dB). During f_{rep} tuning, the mode-locking operation was maintained and the output power variation was below 1%.

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The fiber comb output was spectrally filtered by using a band pass filter (BPF) (central wavelength: 1574 nm, bandwidth: 10 nm), to avoid nonlinear and dispersion effects in the optical fiber, and its output was divided into two optical fiber paths by an optical fiber coupler. The optical path difference ($n_g l$) was preset to a multiple of $n_g L$ = 5.6 m, i.e., $n_g l$ = 168 m and 342 m, which corresponded to m = 30 and 61. In the reference path, an acousto-optic modulator (AOM) was introduced for two purposes: 1) to stabilize the reference path as is described later, and 2) to shift the comb mode to 77 MHz for heterodyne interferometric detection [29]. To minimize the effect of pulse deformation, in addition to the mentioned BPF that was used to shape and narrow the spectrum, the reference path consisted of a polarization-maintaining fiber (PMF) and a dispersion compensation fiber (DCF) for net dispersion compensation. In future applications for distance measurements, further consideration of pulse deformation, which could arise for the measurement path, might be needed. The interference signal between the measurement and reference pulses was detected by PD1.

In the case of the monitor interferometer, we used a single frequency CW laser with a central wavelength of 1560 nm (PLANEX, RIO) to stabilize the reference path fluctuation. The optical frequency of the CW laser was also stabilized to the Rb clock by using another frequency comb (not shown in the figure) and shifted to 77 MHz by the AOM, and the phase fluctuation in the reference path was detected as intensity change in the signal of the monitor interferometer by PD2. The detected signal was used as the error signal and was fed back to the AOM via a servo-loop, and the AOM shifted the optical phase by using diffraction, following which the reference path was stabilized [21–26]. The CW laser interference signal followed the phase refractive index n_p of the medium. In the main interferometer, the detected pulse-to-pulse interference signals also followed n_p. Thus, the stabilization method with the CW laser is effective even for the long-term fluctuation of the interference signal. The signals of two interferometers from PD1 and PD2 were sent to the signal port of the lock-in amplifier 1 and 2 (SR844, Stanford Research Systems Inc.), and they were converted into the phase signals, ϕ_{mea} and ϕ_{ref}.

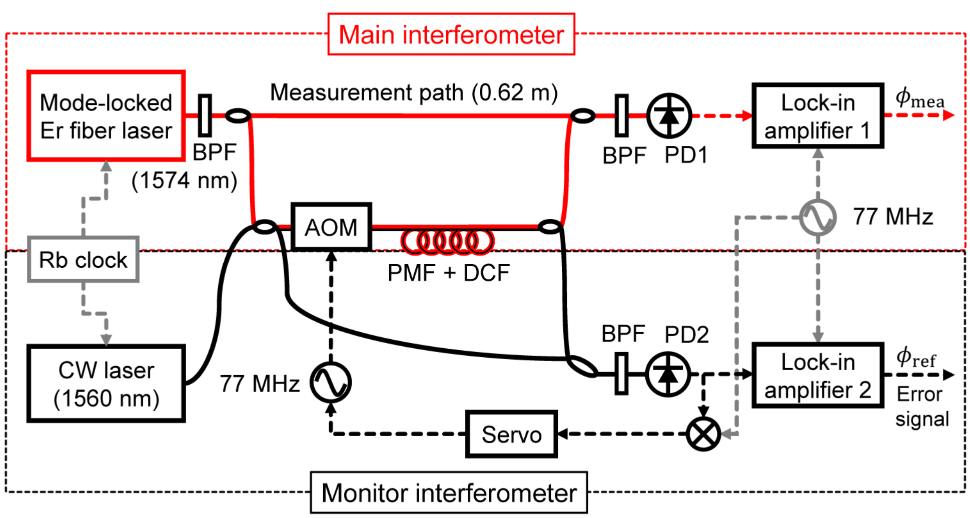

Fig. 3. Optical frequency comb interferometer with a fiber noise cancellation technique. CW: Continuous wave; BPF: Band pass filter; AOM: Acousto-optic modulator; PMF: Polarization-maintaining fiber; DCF: Dispersion compensation fiber; PD1 and PD2: Photodetectors 1 and 2, respectively. Optical path difference $n_g l$ between the measurement and reference paths is preset to 168 m and 342 m, which corresponds to 30 and 61 times the pulse separation of 5.6 m. The indicated fiber length is the optical length including the fiber refractive index.

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3. Evaluation of fiber noise cancellation

Figure 4 shows the error signal of the servo control for the fiber noise cancellation in the monitor interferometer. When the fiber noise cancellation was conducted at the time of 10 s, the observed error signal was stabilized to a constant with a standard deviation of 0.01 V, indicating that the servo control was successful.

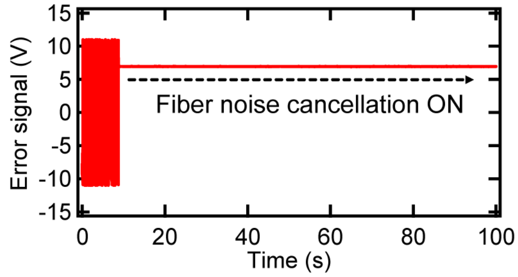

Fig. 4. The error signal of the servo control for the fiber noise cancellation. The error signal is the variation in the intensity of the monitor interference signal generated by the CW laser. The transitions between −11 V and 11 V correspond to a half wavelength change in the optical path.

In order to evaluate the performance of the fiber noise cancellation, we tested the short-term stability of the system with the reference path lengths set to 168 m and 342 m, respectively. Figure 5 shows the measured stability for the two interference signals, i.e., those from the monitor interferometer (black curve, ϕ_{ref}) and those from the main interferometer (red curve, ϕ_{mea}), when the fiber noise cancellation was conducted to the monitor interferometer. In the case of the monitor interferometer, ϕ_{ref} indicates the residual instability of the interference signal, which is mainly owing to the reference path fluctuation, because the fiber length for the other path is much shorter (0.56 m). The observed result is very stable, with a standard deviation of the residual fluctuation on the 1.0 nm level, corresponding to the order of 10^{-12} for each reference path length, e.g., 168 m and 342 m, respectively. Because the residual stability does not depend on the reference path length, it is suggested that the residual fluctuations reflect the stability of the fiber noise cancellation system, which is small enough to realize nm-precision length measurements. On the other hand, in the case of the main interferometer, the observed ϕ_{mea} exhibits fluctuations with standard deviations of 15.7

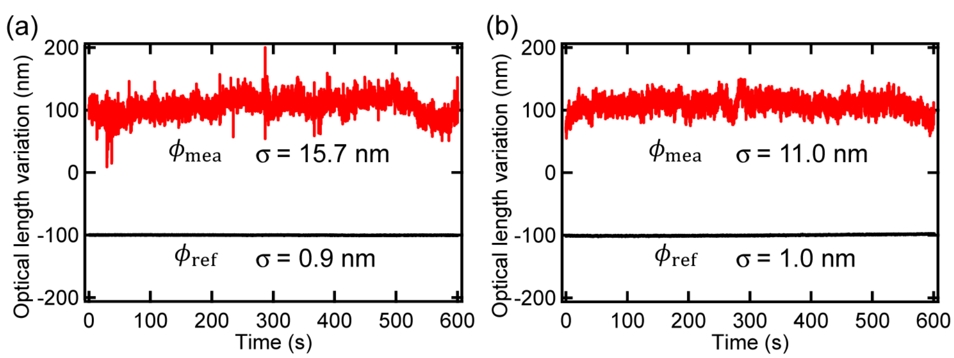

Fig. 5. Optical path length variation with fiber noise cancellation performed with a 168 m (a) and with a 342 m (b) reference optical path. ϕ_{ref} is the error signal corresponding to the reference path stability (black), and ϕ_{mea} is the interferometric signal corresponding to the residual optical length fluctuation in the measurement path (red). The vertical origins of plots ϕ_{ref} and ϕ_{mea} are shifted for clarity.

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nm [Fig. 5(a)] and 11.0 nm [Fig. 5(b)], respectively. Although the signals contain the residual fluctuation, the interference signals were precisely detected regardless of the long fiber-based reference path.

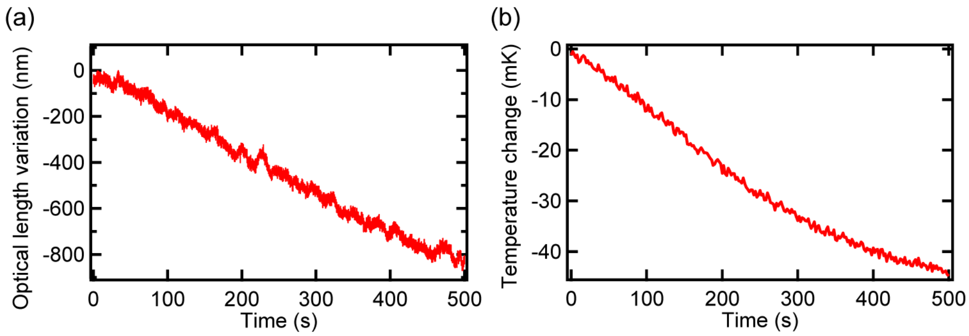

Fig. 6. (a) Variation of interferometric signal with stabilized 342-m-long reference path with fiber noise cancellation, showing the average drift of −1.7 nm/s. (b) Temperature change around the measurement path, showing the average drift of 0.09 mK/s.

In the case of the main interferometer, the residual variation in the ϕ_{mea} could be caused by the variations in the optical path, which were attributed to the ambient temperature variation. In order to estimate the effect of temperature change, we measured the ambient temperature in the experimental setup and interference signal simultaneously, when the temperature change was rather large. In this experiment, the entire setup, except the measurement fiber path, was covered by a thermal insulator. Figure 6(a) shows the measured optical path length variation corresponding to the residual variation of ϕ_{mea} when the reference path of 342 m was stabilized. The data shows an average drift of −1.7 nm/s, similar to the temperature drift of −0.09 mK/s around the experimental setup [Fig. 6(b)]. In this case, by setting the optical length of the measurement fiber to 0.62 m, and the temperature coefficient of refractive index dn/dT of silica fiber to 10^{-5}, we estimated the corresponding temperature drift as −0.40 mK/s. This result is on the same order of magnitude as the observed temperature drift. Though the two values are not same, the result suggests the applicability of the developed technique to detect small temperature variation with millikelvin-order resolution.

4. Evaluation of multiplication effect

In order to evaluate the multiplication effect for the developed OFCI with a fiber-based reference, we determined the pulse number difference (m) by measuring the interferometric phase ϕ_{mea} changes when the f_{rep} change was applied. The evaluation was conducted for the optical path differences ($n_g l$) of 168 m and 342 m, i.e., 30 and 61 times the value of $n_g L = 5.6$ m, respectively. Figure 7 shows the effective optical path length variation ($n_p \Delta l$) for the interferometric fringe scanning, which was obtained by the measured interferometric phase ϕ_{mea} changes when Δf_{rep} was swept to 2.0 Hz with a 0.2 Hz step by using a PZT actuator in the laser cavity. The fiber noise cancellation was applied during the measurements. By using linear regression on the data measured by changing ϕ_{mea} while sweeping Δf_{rep}, we estimated m and the measurement uncertainty from the slope and its standard deviation. In this evaluation, $m = 30.2 \pm 0.3$ ($n_g l = 168$ m) and $m = 60.8 \pm 0.2$ ($n_g l = 342$ m) were obtained; thus, we determined m of 30 and 61 without ambiguity, within the measurement uncertainty. These obtained m values agreed with the multiples of $n_g L$ that were estimated from the actual path lengths. Although the Δf_{rep} scanning range of 2.0 Hz was small compared with the f_{rep} of 53.4 MHz, m could be determined accurately owing to the high stability associated with the fiber noise cancellation technique. Therefore, the developed OFCI can be used to measure distances in terms of the m values. Moreover, we demonstrated 30 and 61 times multiplication effects precisely for long reference paths, which can be used to measure arbitrary distances,

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even to short measurement paths. Because the maximal Δf_{rep} of our fiber-based frequency comb was 1 MHz, a wide scanning range of $n_g \Delta l$ = 6.4 m could be realized between the measurement and the reference pulses. Thus, at an arbitrary distance, pulses in the OFCI could be made to overlap only by using f_{rep} tuning without a mechanical stage, and the pulse-to-pulse interference signal could be measured precisely. For distances shorter than 157 m, the length of a fiber-based reference path was set to over 314 m in our case (f_{rep} = 53.4 MHz, Δf_{rep} = 1 MHz). Thus, the optical path length difference $n_g l$ is always maintained above 157 m, and a multiplication effect for m above 28 is always achieved, and any pulses can be made to overlap only by using through f_{rep} tuning. On the other hand, for measurement paths longer than 157 m, the reference path is replaced with a short length fiber, and a multiplication effect for m above 28 is always achieved with a conventional long measurement-path interferometer. This implies that the developed OFCI with a long fiber-based reference path and fiber noise cancellation could demonstrate the efficacy of the developed technique for high-precision measurements of arbitrary distances.

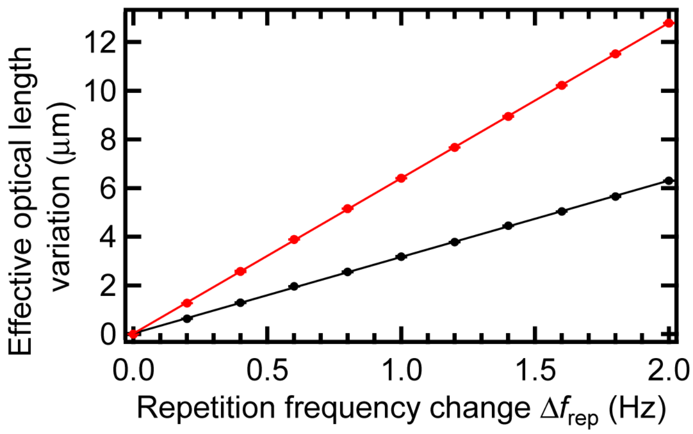

Fig. 7. The effective optical path length variation $n_p \Delta l$ for f_{rep} tuned with $n_g l$ = 168 m (black line) and $n_g l$ = 342 m (red line).

5. Conclusion

In conclusion, we have developed an optical frequency comb interferometer with a long fiber-based reference path and fiber noise cancellation technique, and we have demonstrated the efficacy of the interferometer for arbitrary distance measurement. The long fiber reference of 342 m was stabilized to a nm-level fluctuation by the fiber noise cancellation, and the interference signals were measured precisely. By employing this highly stabilized interferometer, temperature changes on the order of millikelvin were detected, and pulse number differences m of 30 and 61 between the measurement and reference pulses were determined without ambiguity within the measurement uncertainty. These obtained m values agree very well with the multiples of pulse separation that are estimated from the actual path lengths. Thus, the developed method is applicable to absolute distance measurement in terms of precise values of m. Such a good agreement was achieved owing to the high stability associated with the fiber noise cancellation. Because of a long fiber-based reference path with the fiber noise cancellation, multiplication effects of f_{rep} tuning can be used to measure arbitrary distances. Moreover, the multiplication effect of m = 61 with Δf_{rep} = 1 MHz corresponds to a wide scanning range of 6.4 m, which is more than the pulse separation. Therefore, pulses can be overlapped without a mechanical moving stage, and high-accuracy interferometric measurements of arbitrary distances can be realized.

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