Data Processing Optimization and System Characterization of Frequency Comb-Based Time and Frequency Transfer

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***Abstract*—We established a frequency comb-based two-way time and frequency transfer system, which is adequate for the comparison of state-of-the-art optical clocks. However, the surrounding environment (such as temperature and vibration) and data processing methods will affect the measurement precision of the system for clock offset. In the setup, we used homemade fiber box housing most of optical fibers in our system to suppress the impact of temperature fluctuations. For data processing, we filtered the interference signals generated by linear optical sampling by digital bandpass filter. Hilbert transform was applied to extract the envelopes, then used parabolic fitting to figure out the peak of the envelopes (one-way time delays). The optical two-way time transfer test through a short fiber link shows that the noise floor-equivalent fractional timing stability is 0.07 fs at a gate time of 0.4 s.**

Keywords*—*frequency comb, data processing, linear optical sampling

I. INTRODUCTION

Optical clock is playing an increasingly important role in many applications, such as precision navigation and timing[1]-[2], gravitational-wave detection[3], future redefinition of the second [4]-[7] and dark-matter searches [8]. Ultra-precision time and frequency transfer technology underpins the applications of state-of-the-art optical clock [9]-[10].

Frequency comb-based time and frequency transfer can provide femtosecond-level resolution, which is adequate for the comparison of state-of-the-art optical clocks. Compared with conventional pulse arrival times photodetection with picoseconds level, frequency comb-based time and frequency transfer implement linear optical sampling for femtosecond-level timing.

We established a frequency comb-based two-way time and frequency transfer system. Due to the influence of temperature and vibration on optical fibers, timing noise will be generated when pulse trains are transmitted through optical fibers. For the data processing, we use Hilbert transform to extract the envelopes of cross-correlation signal, then figure out the peak of the envelopes to obtain the one-way time delays. However, due to the low-frequency noise in the signal, there are multiple peak values on the signal envelope, which affect the measurement precision of one-way time delays.

Therefore, we used homemade fiber-couple housing most of optical fibers to suppress the impact of temperature and vibration. For data processing Optimization, we filtered the interference signals by digital bandpass filter, then used parabolic fitting to figure out the peak of the envelopes. The optical two-way time transfer test through a short fiber link shows that the noise floor-equivalent fractional timing stability is 0.07 fs at a gate time of 0.4 s.

II. EXPERIMENTAL SET-UP

The detailed experimental setup of frequency comb-based two-way time and frequency transfer system as shown in Fig. 1. In our system, the high performance cavity-stabilized laser serves as the frequency reference. The combs at two co-located sites sharing the same cavity-stabilized laser via a fiber noise compensation (FNC) module, allowing quantify the residual timing deviation. The combs at two sites generated coherent pulse trains by phase-locking to the optical oscillator, but with different repetition rates by Δf. A repetition rate of $f_{rep}\approx$250 MHz for one site, and $f_{rep}+\Delta f\approx$250.001 MHz for the other site. The pulse trains of two combs are exchanged between sites through short single-mode fiber path(blue solid lines in Fig.1), most of fiber devices in our system are housing in the homemade fiber box to suppress the impact of temperature and vibration fluctuations.

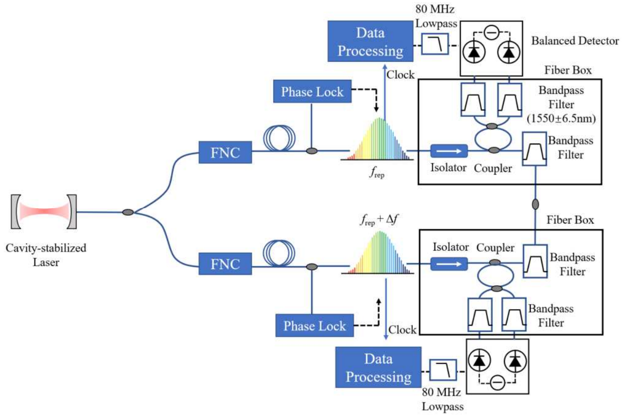

Fig. 1 Schematic of frequency comb-based two-way time and frequency transfer system. The blue solid lines are fiber link and the black dashed lines are electric wires.

In our system, timing differences and fiber-path-length variations will cause additional time offset

$$T_1(\tau) = T_{path}(\tau) + \Delta T(\tau) \tag{1}$$

and

$$T_2(\tau) = T_{path}(\tau) - \Delta T(\tau) \tag{2}$$

for two sites, respectively. The $T_{\text{path}}(\tau)$ is the time-of-flight across the fiber link, the $\Delta T(\tau)$ is the cumulative timing difference between two sites, which is our interest quantity. The two-way time difference is

$$\Delta T(\tau) = (T_1 - T_2)/2 \tag{3}$$

The time offset can be reflect by femtosecond level pulse to pulse timing jitter. We implement a linear optical sampling (LOS) to achieve the necessary femtosecond resolution. With the repetition rates differ of few kHz, the local comb pulse is heterodyned with the signal comb pulse from the other site, which generates interferogram on the balanced detector as shown in Fig.2. In time domain, the time at which the peak of interferogram signal envelope can be mapped onto the time offset between the underlying pulse trains. With the low-frequency noise in the detected interferogram signal, there are multiple maximum values in the signal envelope, which affect the measurement precision of one-way time offset. To suppress the impact of low-frequency noise, we filtered the interferogram signal by 60-70 MHz digital bandpass filter, then extract the smooth signal envelopes by Hilbert transform. Then used parabolic fitting to figure out the peak of the envelopes to extract the one way time offset(T_1 or T_2).

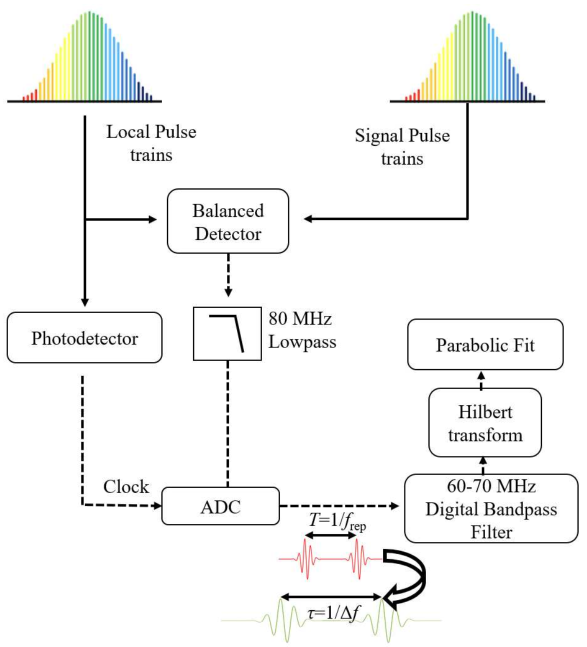

Fig. 2 Schematic of data processing module.

III. Result and Discussion

The interferogram were detected by a 100MHz balanced detector, low-pass-filtered at 80MHz, and the data processing module saved 512 samples across peak of the interferogram. Fig.3 presents the comparison between the original interferogram and the interferogram filtered by

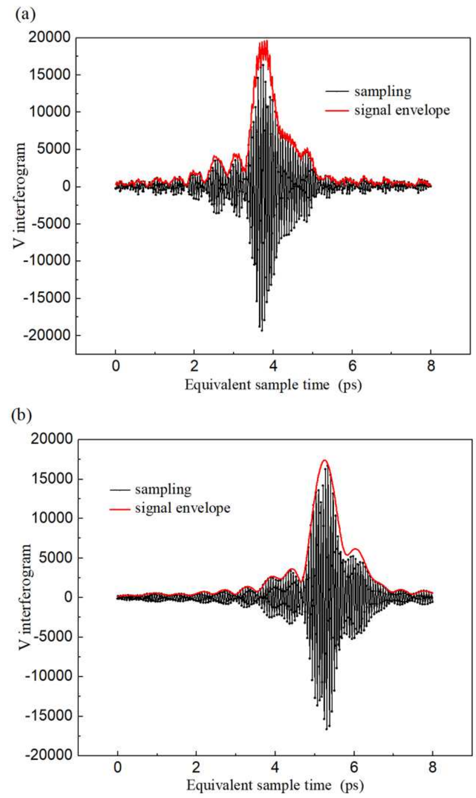

Fig. 3 Comparison between the original interference signal and filtered interference signal

a digital bandpass filter. There are multiple peak values on the envelope of original interferogram as shown in Fig.4 (a), which affect the precision of one-way time offset measurement. Based on the frequency domain characterizations of the interferogram, we filtered the interference signal by 60-70 MHz digital bandpass filter in data processing process to suppress the low-frequency-noise and extract the smooth envelope as shown in Fig.4 (b).

For finely extracting one-way time offset from interference signal envelope, we extract 5 envelope data points across the peak and use parabolic fitting to figure out the peak of the envelopes as shown in Fig.4.

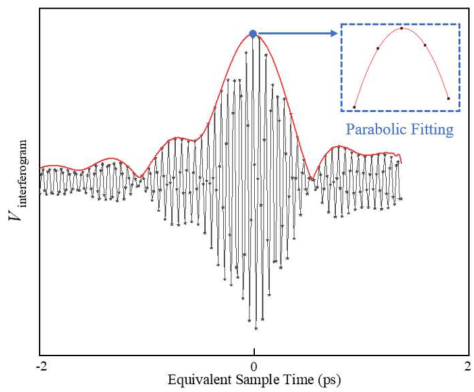

Fig. 4 Example of measured interferogram filtered by digital bandpass filter (black symbol) and smooth envelope (red line). Peak search is conducted by parabolic fitting (blue dashed box).

The time at which the peak of first interferogram signal envelope served as the reference. We compared the peak time of the other signals with the reference to obtain one-way time offset((T_1 or T_2). Then we use Equation (3) to obtain the two-way time difference(ΔT).

To evaluate the performance of data processing optimization, we calculate timing deviation from ΔT as shown in Fig. 5. The optical two-way time transfer test through a short fiber link shows that the noise floor-equivalent fractional timing stability is 0.07 fs at a gate time of 0.4 s, which is well below the instabilities of state-of-the-art optical clocks.

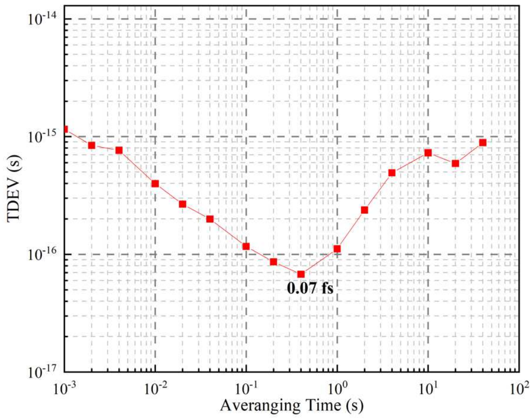

Fig. 5. Timing deviation of optical two-way time-frequency transfer through a short fiber link.

IV. Conclusions

Here we demonstrated a ultraprecise time transfer over a short fiber link and optimized data processing by digital bandpass filter and parabolic fitting. The timing deviation result shows that the noise floor-equivalent fractional timing stability is 0.07 fs at a gate time of 0.4 s. On the basis of data processing optimization and the performance of time transfer, our system will underpins the applications of optical clock for the applications of state-of-the-art optical clocks.

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