Real-Time Synchronization of Clocks at Femtosecond Level Through a 113 km-Free-Space Link

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***Summary*—High-precision time comparison and synchronization is required with the increasing application of the optical clocks in precise navigation, gravitational sensing, and relativity experiments. However, previous works at femtosecond-level time synchronization did not extend beyond dozens of kilometers. Here we demonstrate real-time synchronization of two optical clocks over a turbulent 113-km free space link via optical two-way time and frequency transfer. Despite optical power attenuation of 80dB due to atmospheric turbulence, the time deviation between two synchronized time scales is below 50 fs over a 15-hour measurement period, and a stability of less than 1.6×10^{-19} at 10,000 s is achieved through an out-of-loop time-frequency transfer link. The ability to synchronize two distant optical clocks can support future precision navigation, and it also provides technical foundation for the future femtosecond clock synchronization over ground-to-satellite free-space paths.**

Keywords—Time synchronization; Optical two-way time and frequency transfer; free space; Real-time phase processing

Ⅰ. INTRODUCTION

High-precision time and frequency transfer enables applications such as navigation, gravitational sensing, precision spectroscopy and fundamental physics experiments, and optical clocks have reached absolute accuracies up to level of 10^{-19}. To remotely access the reference optical clocks and establish a global-scale network, it is necessary to disseminate time–frequency over long distances with an accuracy of a similar level of 10^{-19}. Previous work has demonstrated that the optical two-way time-frequency transfer (TWTFT) technique can support frequency transfer at 10^{-19} fractional stability and real-time synchronization at femtosecond-level [1] across a free-space optical link. However, the system has only reached dozens of kilometers, which limits applications in many long-distance scenarios with stronger air turbulence. Recently, we have reported time–frequency dissemination with an offset of $6.3 \times 10^{-20} \pm 3.4 \times 10^{-19}$ and an instability of less than 4×10^{-19} at 10,000 s through a free-space link of 113 km. Key technologies including the deployment of high-power frequency combs, high-stability and high-efficiency optical transceiver systems and efficient linear optical sampling are utilized [2].

On this basis of time comparison, we pursue the much more challenging problem of time synchronization at the femtosecond level between the two optical time scales over a long distance of 113km. It can be a significant step but also a big challenge for technical implementation, because it requires real-time measurement of time offset between clocks, real-time two-way data communication over long distance and real-time frequency adjustment of the synchronized clock. To overcome these challenges, we implement the real-time phase processing algorithm in a field programmable gate array (FPGA) controller to measure the time difference at each site, with an update rate of 2.5 kHz, and laser communication technique based on optical fibers is used to exchange data information between two sites. Besides, a feedback loop is utilized in the slave site to compensate the clock difference. With these techniques, femtosecond-level synchronization is achieved despite strong turbulence-induced fluctuations of the received light intensity, of which power loss up to 80dB.

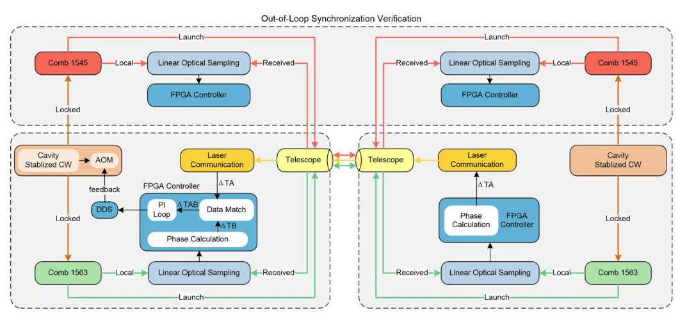

Fig. 1 The experimental setup diagram for the time synchronization of two distant optical clocks, one located at Nanshan and one located at Gaoyazi, via optical two-way time-frequency transfer over a 113km turbulent air path.

Ⅱ. METHODS

The synchronization experiment was carried out in Urumqi, Xinjiang Province. Figure 1 shows the system setup diagram. Two terminals (A and B) are located at Nanshan and Gaoyazi with a distance between them of 113 km. At each site, there is an ultra-stable laser (USL) with a 3×10^{-15} frequency instability at 1 s at a wavelength (λ) of 1,550.12 nm, which acts as an optical oscillator. Two optical frequency comb (OFC) with different wavelengths of 1563nm and 1545nm are phase locked to the USL, used as the carrier and reference signals of the local sampling. By an optical transceiver telescope, the interference pulses between local and received comb are detected by the linear optical sampling (LOS) modules, and then the detected interferograms are transmitted to a FPGA controller, which is responsible for real-time phase processing. By frequency multiplexing the common free-space channel, we establish two independent two-way time–frequency transfer links, of which the 1563nm comb transfer link is performed as the in-loop synchronization setup, while the 1545nm comb transfer link is used as the out-of-loop verification.

At the master site, once the received optical power extends the detection threshold of the LOS module, valid interferogram is obtained and phase information of terminal A ΔTA will be calculated in the FPGA controller. Then the time information ΔTA will be transferred to terminal B via the laser communication link after coding and electro-optical conversion. While at the slave site, after received in terminal B, the ΔTA is combined with local calculated phase information of site B ΔTB to calculate the clock offset ΔTAB. Then through proportional integral (PI) loop filter and direct digital synthesizer (DDS), a feedback signal which represents clock offset is generated. An acoustic optical modulator (AOM) is driven by this feedback signal, which is applied to adjust the local reference clock offset relative to the master clock of terminal A. With a 5-Hz feedback bandwidth, the two terminals are synchronized via the 1563 comb transfer link. At the same time, we verify the time synchronization by direct “out-of-loop” measurements via the 1545 comb transfer link which is completely independent of the calculated “in-loop” value ΔTAB.

III. RESULTS

The experiment result of time synchronization over 15 hours is summarized in Fig.2. From top to bottom, the first and second panel plot the measured time offset for the in-loop and the out-of-loop link, of which time wander below 10fs and 100fs. The third panel plots the time change of flight Tlink. Tlink varies by 1200ps over the measurement period. The fourth panel plots the feedback frequency correction to maintain synchronization, reflecting the time wander between the two free-running USLs. The frequency transfer performance is presented by the modified Allan deviation (MDEV), as shown in Fig. 3. The fractional frequency stability of in-loop link and out-of-loop link reach 2.4e-20 and 1.6e-19 at 10,000 s respectively, and relative instabilities among two free-space links are in the range of 1.6e-19 at 10,000 s.

IV. CONCLUSIONS

In summary, we have implemented real-time time transfer and synchronization of two optical clocks over a turbulent 113-km free space link via optical TWTFT. The time deviation between two synchronized time scales is below 50 fs over a 15-hour measurement period, and a stability of less than 1.6×10^{-19} at 10,000 s is achieved through an out-of-loop time-frequency transfer link, whereas the link loss is up to 80dB. This performance can enable future networks of optical clocks which require real time synchronization, and it can provide technical foundation for the future femtosecond clock synchronization over ground-to-satellite free-space paths.

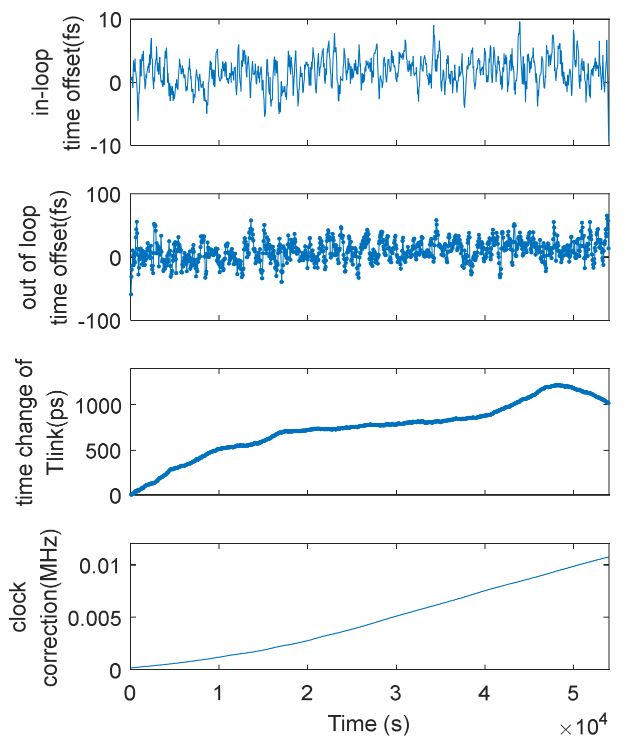

Fig. 2 Experimental results of time synchronization over 15 hours.

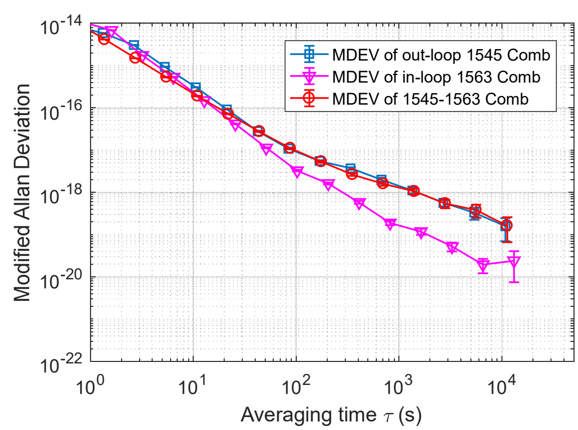

Fig. 3 Modified Allan Deviation for the synchronized time-frequency link.

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