Ultra-stable Optical Frequency Transfer via 609 km Communication Fiber Link

Xiang Zhang
National Time Service Center
Chinese Academy of Sciences
Xi'an, China

zhangxiang@ntsc.ac.cn

Qi Zang, Xue Deng, Dan Wang, Qian Zhou, Meng fan Wu, Tao Liu, Ruifang Dong
University of Chinese Academy of Sciences
Chinese Academy of Sciences
Beijing, China
Key Laboratory of Time and Frequency Primary Standards
Chinese Academy of Sciences
Xi'an, China

***Summary*—In this paper, we demonstrated coherent optical frequency transfer via 609 km communication fiber link. The phase noise per-unit-length of this fiber links at 1Hz and 10Hz are 175 rad^2/(Hz*km) and 5 rad^2/(Hz*km), respectively. After being compensated, optical frequency transfer achieves a fractional frequency instability of 2.7×10^{-15} at an integration time of 1 s and 2.2×10^{-19} at 16000 s in terms of Mod-ADEV.**

***Keywords*—optical frequency transfer; phase noise cancellation; Modified Allan deviation.**

I. INTRODUCTION

In recent years, with the realization of 10^{-18} level accuracy and instability of the optical clock [1-3], high-precision frequency standards have played a significant role in various fields of research, such as metrology [4], fundamental physics, relativistic geodesy [5], radio astronomy and remote clock comparison [7]. Therefore, high-precision optical frequency transfer has received extensive attention and been comprehensively investigated. In Europe, a stable and reliable thousand kilometers fiber link has been established by using the Fiber Brillouin amplification (FBA) in PTB and optical regeneration (RLS) in LSL, with a fractional frequency instability of 10^{-19} [8-11].

In China, a high-precision time and frequency transfer network via a total ten-thousands kilometers dedicated optical fiber will be established. As a part of the investigation on the possible long-distance optical frequency transfer techniques, we demonstrate an optical frequency transfer over 609 km flied-fiber link with a transfer instability of 2.2×10^{-19} at the averaging time of 10000 s in terms of Mod-ADEV.

II. METHODS/RESULTS

Figure 1 depicts the experimental setup of coherent optical frequency transfer with the active noise cancellation (ANC) technology. At the local site, the line width of the commercial CW fiber laser (NKT E15) is reduced to below 1 Hz by locking it to an ultra-stable optical reference cavity.[32] The transmitted light has a central frequency of 193.4 THz, and its power is further split into two portions with a 90/10 OC. The large proportion of transmitted light passes through an AOM1 driven by a 110 MHz radio-frequency (RF) signal deriving from a direct digital synthesis (DDS), which is then transmitted to a remote site through the 609 km fiber link. At the remote site, the transmitted light is connected to AOM2 driven by a 50 MHz RF signal, which is applied to discriminate the wanted roundtrip light signal from the stray reflections between fiber connectors and splices. Eight Bi-EDFAs are installed along with the fiber link to compensate for the power attenuation of the transmitted light. The gain of each amplifier is limited to less than 18 dB to prevent the self-oscillation phenomenon between Bi-EDFAs.

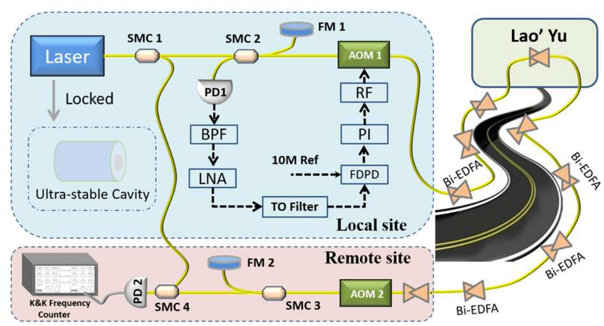

Fig.1 xperimental setup for optical frequency transfer over a 609 km noisy fiber link using active noise control (ANC) technology, optical coupler (OC), an acoustic-optic modulator (AOM), Faraday mirror (FM).

The map of the flied fiber link provided by communication operators are shown in Fig.2(b). The length of the single-span fiber from NTSC to Shenyang is approximately 304.5 km, the corresponding length and attenuation of each fiber spans are shown in Fig.3(a).

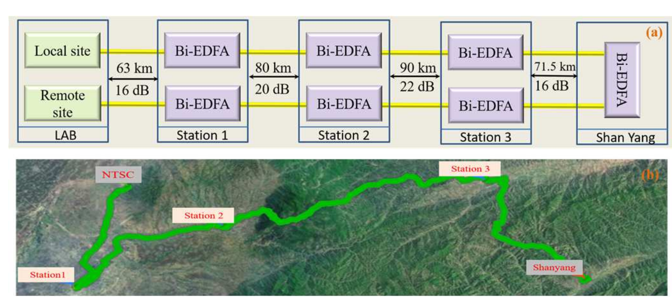

Fig. 2 (a) The length and attenuation of each fiber spans. (b)The routing map of this 609 km fiber link.

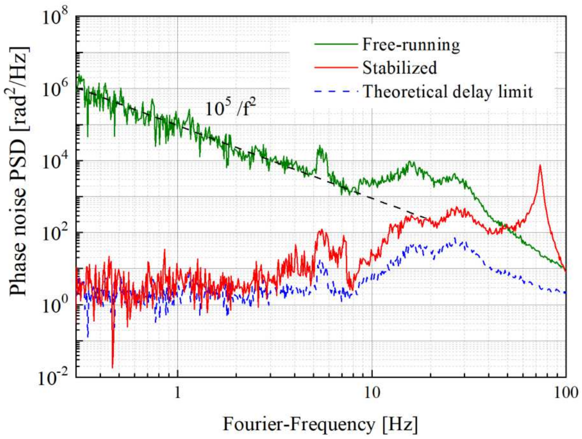

Fig. 3 The measured phase-noise PSDs in the free-running case (green curve) and stabilized case (blue curve), respectively. The servo bump is approximately 74 Hz because of the propagation delay is shown. The green dotted curve represents the theoretical compensation limitation.

As shown in Fig.3, the free-running phase-noise PSD of this 609 km fiber link approximately follows a power-law relationship $S_{free} \sim h_0 f^{-2}$, for the Fourier frequency below approximately 10 Hz, indicating that the white frequency noise is dominant under the noise uncompensated condition. The h_0 is up to approximately 106500 in this study, indicating that the phase noise per unit length of this fiber link at 1 Hz is 164 rad^2/(Hz*km), and which achieve 5 rad^2/(Hz*km) at 10 Hz, as shown in Fig.5. In addition, the uncompensated phase-noise PSD shows a broad peak at the frequency between 10 and 20 Hz, which has been reported as similar behavior in previous results and has been attributed to the building and ground vibrations.

After actively compensating the fiber-induced phase fluctuation, the residual phase noise PSD showing that the remaining noise is mostly determined by the white phase noise at the frequency below 10 Hz.

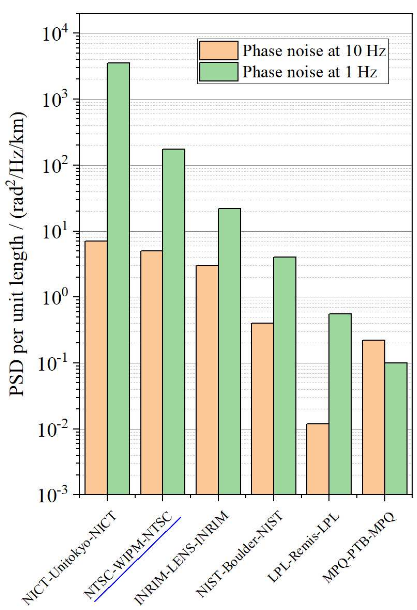

Fig. 4 The comparison of the phase noise per-unit-length of some long-distance links at 1 Hz and 10 Hz.

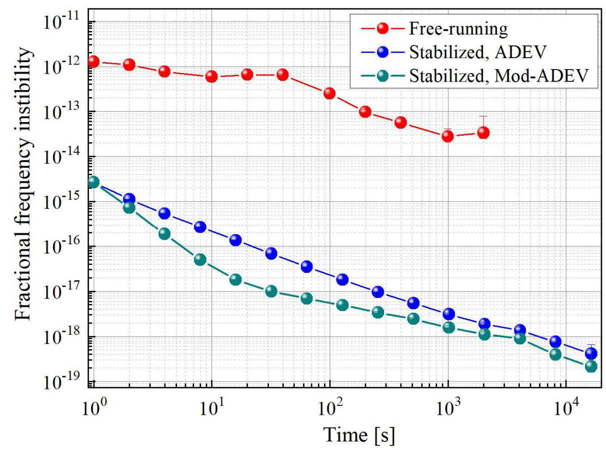

Fig. 5 The measured fractional frequency instability for the free-running fiber link and stabilized case.

Due to the fiber delay nL/c, with n=1.47 representing the refractive index of the fiber link, c representing the light speed in the vacuum, and L=609 km in our case, a servo bump at 74 Hz in the phase-compensated case is observed, which is close to the calculated servo bandwidth ($\sim 1/4\tau$) of 84 Hz. The residual phase-noise PSD $S_r(f)$ agrees well with the theoretical compensation limitation, which is labeled as, $S_r(f) \sim \frac{1}{3} * (2\pi f\tau)^2 S_{free}$, as described in Ref. [11].

The resulting out-of-loop RF signal of 160MHz detected by PD2 is recorded using a deadtime free frequency counter (K&K FXE) operating at Λ -mode to calculate the frequency instability. Figure 5 illustrates the fractional frequency instability in terms of the Modified Allan deviation (Mod-ADEV), which is calculated from the recorded frequency data. For the free-running, 609 km fiber link, the instability is 1.1×10^{-12} at the averaging time of 1 s and fluctuates around the 10^{-14} level (red curve). With the implementation of the fiber noise cancelation, optical frequency transfer achieves a fractional frequency instability of 2.7×10^{-15} at an integration time of 1 s and scales down to 2.2×10^{-19} at 16000 s.

III. Conclusions

In summary, we have demonstrated a coherent optical frequency transfer system over a 609 km fiber link. After being compensated, a fractional frequency instability of 2.7×10^{-15} at 1 s and 2.2×10^{-19} at 16000 s. The system would be suitable for long-distance and noisy-fiber based optical frequency transmission and would be used for remote optical clocks comparisons in China.

References

[1] B. J. Bloomet al., “An optical lattice clock with accuracy and stability at the 10−18 level,” Nature, vol. 506, no. 7486, pp. 71–75, Feb. 2014.

[2] W. F.McGrew et al., “Atomic clock performance enabling geodesy below the centimetre level,” Nature, vol. 564, no. 7734, pp. 87–90, Dec. 2018.

[3] E. Oelker et al., “Demonstration of 4.8×10−17 stability at 1 s for two independent optical clocks,” Nature Photon., vol. 13, no. 10, pp. 714–719,

Oct. 2019.

[4] T. Takano et al., “Geopotential measurements with synchronously linked optical lattice clocks,” Nature Photon., vol. 10, no. 10, pp. 662–666, Oct. 2016.

[5] C. Lisdat et al., “A clock network for geodesy and fundamental science,” Nature Commun., vol. 7, no. 1, pp. 1–7, Aug. 2016.

[6] C. Clivati et al., “Common-clock very long baseline interferometry using a coherent optical fiber link,” Optica, vol. 7, no. 8, pp. 1031–1037, Aug. 2020.

[7] J. Guéna et al., “First international comparison of fountain primary frequency standards via a long distance optical fiber link,” Metrologia, vol. 54, no. 3, pp. 348–354, May 2017.

[8] S. M. Raupach et al., “Brillouin amplification supports 1×10^{-20} uncertainty in optical frequency transfer over 1400 km of underground fiber,” Phys. Rev. A, vol. 92, no. 2, Aug. 2015, Art. no. 21801.

[9] O. Lopez, A. Haboucha, F. Kéfélian, H. Jiang, B. Chanteau, V. Roncin, C. Chardonnet, A. Amy-Klein, and G. Santarelli, “Cascaded multiplexed optical link on a telecommunication network for frequency dissemination,” Opt. Express, vol. 18, no. 16, pp. 16 849–16 857, Aug. 2010.

[10] D. Calonico et al., “High-accuracy coherent optical frequency transfer over a doubled 642-km fiber link,” Appl. Phys. B, vol. 117, no. 3, pp. 979–986, 2014.

[11] P. A.Williams,W. C. Swann, and N. R. Newbury, “High-stability transfer of an optical frequency over long fiber-optic links,” J. Opt. Soc. Amer. B, vol. 25, no. 8, pp. 1284–1293, Aug. 2008.