Coherent Optical Frequency Dissemination with Passive Phase Noise Cancellation

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***Summary*—Optical fibers have been regarded as one of the most promising materials for coherent optical frequency dissemination over thousands of kilometers. For suppressing the fiber-induced phase noise along the fiber network, we demonstrate the passive phase noise cancellation (PNC) technique without the need of phase detector could be preferable for noisy fiber links. A fiber-pigtailed acousto-optic modulator (AOM) with two diffraction order outputs (0 and −1 order) has been installed at the local site and been employed as the phase compensated device in the optical frequency transfer system. With a 550 km noisy fiber link, we demonstrate a fractional transfer frequency instability of $\mathbf{1.3\times10^{-14}}$at the integration time of 1 s and scales down to $\mathbf{5.5\times10^{-19}}$at 10,000 s in terms of modified Allan deviation.**

Keywords—optical frequency transfer; optical clock network; phase noise; noise cancellation;

I. INTRODUCTION

Optical lattice clocks operating at optical frequency domain chop up the second into much finer intervals, demonstrating an unprecedented frequency instability and uncertainty of better than one part in 10^{-18} [1]. Ultra-precision optical clock network will play an important role in radio astronomy [2], testing of fundamental physics [3], chronometric geodesy [4] and gravitational waves. Consequently, these are strong motivating factors to develop reliable transfer and comparison systems for the ultra-precise clock signals. Among these existing transmission schemes, optical fibers have been recognized as one of the most promising host materials for coherent optical frequency transmission over thousands of kilometers, with the fractional transfer instability of 10^{-20} level. Recently, the European metrological network of 4802 km optical fiber has been established and employed for transferring the coherent optical frequency signal, which have promoted a wide range of physical applications [5].

During the transmission process, the temporal optical length variations of the employed urban fiber link, coming from environmental (mechanical and temperature) perturbations, will imprint phase noise onto the transmitted optical signal and ultimately deteriorate the optical frequency transfer instability and uncertainty. For the previous widely adopted active phase noise cancellation (ANC), the phase error of the fiber link can be obtained at local site by comparing the local signal and the round-trip one and be further used to implement a feedback control onto the phase compensator. In addition, there will be a servo bump in the frequency domain and its intensity will gradually accumulate in the cascaded fiber links, which will deteriorate the performance of phase locking and transmission. In our previous work [], we demonstrated a passive phase noise cancellation (PNC) for coherent optical frequency transfer through a 260 km-long urban fiber. Neither precise phase detector with the large dynamic range nor phase locked loop are longer needed in this PNC-based optical frequency transfer system, lowering the probability of cycle-slips for a noisy fiber link.

In this paper, we established a pair of field-fiber link connecting the National Time Service Center (NTSC) in LinTong District and YangXian District, with a round trip length of 550 km. For suppressing the additional phase noise introduced by the environment disturbance along the fiber link, a fiber-pigtailed acousto-optic modulator (AOM) with two diffraction order outputs (0 and -1 order) is employed as the phase noise compensated device [6]. As a result, the retrieved optical frequency signal is independent of the time base at the local site. Using this technique, we demonstrate transfer of coherent light through this 550 km urban fiber link. The results show the effect of the RF reference can be successfully removed. After being passively compensated, we demonstrate a fractional frequency instability of 1.3×10^{-14} at the integration time of 1 s and scales down to 5.5×10^{-19} at 10,000 s integration time in terms of modified Allan deviation. The frequency uncertainty of the retrieved light after transferring through this noise-compensated fiber link relative to that of the input light achieves 10^{-18} level.

II. METHODS

Figure1 shows a schematic diagram of optical frequency transfer via a fiber with the PNC technique. Along the 550 km fiber link, eight bi-directional erbium-doped fiber amplifiers (Bi-EDFAs) are installed to compensate the total optical attenuation, the optical gain of each Bi-EDFA is set less 18 dB for avoiding the aliasing effect. As described by Ref.[6], the

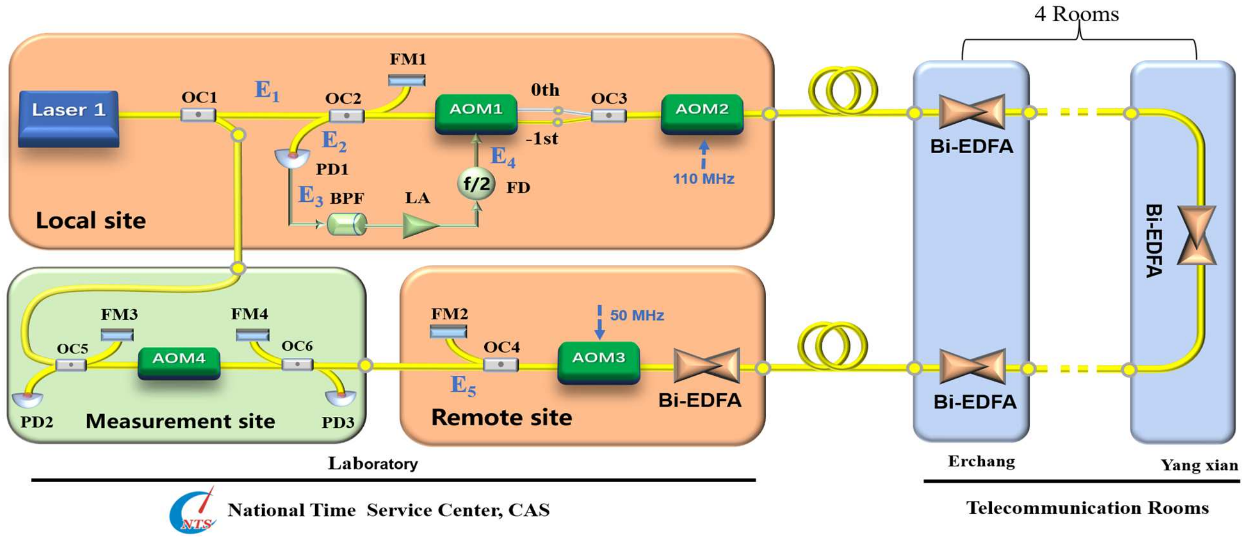

Fig. 1 Experimental setup of the optical frequency transfer with passive noise cancellation technology. AOM: acousto-optic modulator, FM: Faraday mirror, Bi-EDFA: bi-directional erbium-doped fiber amplifier, OC: optical coupler, FD: frequency divider, PD: photo-detector, BPF: band-pass filter, LA: logarithmic amplifier. Figure from Ref. [6].

transmitted optical signal through the 0th output is used to complete a round trip for obtaining the phase error at local site. And the RF signal with conjugate phase is used to drive the 1 × 2 fiber pigtail AOM, which means the transmitted optical signal output from the -1st order is the wanted retrieve light at the remote site.

III. RESULTS

Figure2 shows the time domain characteristic of the PNC based optical frequency transfer via the 550 km fiber link. The fractional frequency instability of the end-to-end frequency

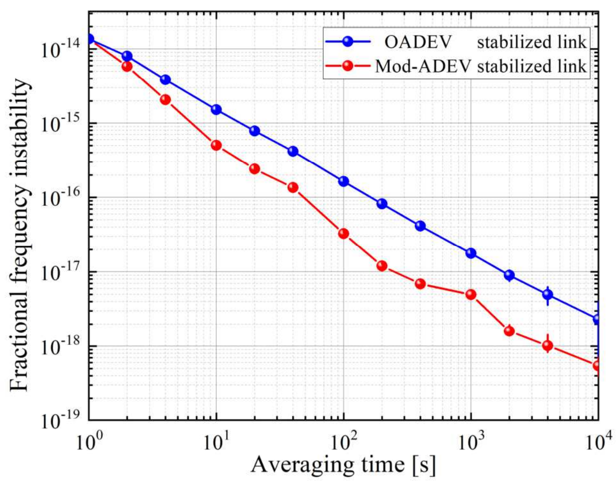

Fig. 2 The fractional instability of the stabilized 550 km frequency transfer fiber link. The data are obtained by using a K&K frequency counter in Λ–type mode. The blue circles and red circles represent the Overlapping ADEV and Modified ADEV of the 'out-loop' beat signal, respectively.

measurements are expressed in terms of the OADEV (blue cycles) and modified Allan deviation (MDEV, red circles). With the implementation of the PNC technique on the 550 km urban fiber link, we demonstrate an instability of 1.3×10^{-14} at 1 s integration time and scales down to 1.4×10^{-18} at the integration time of 10,000 s for the OADEV with a slope of τ^{-1}, while the MDEV for the same frequency data decreases to 5.5×10^{-19}at 10,000s.

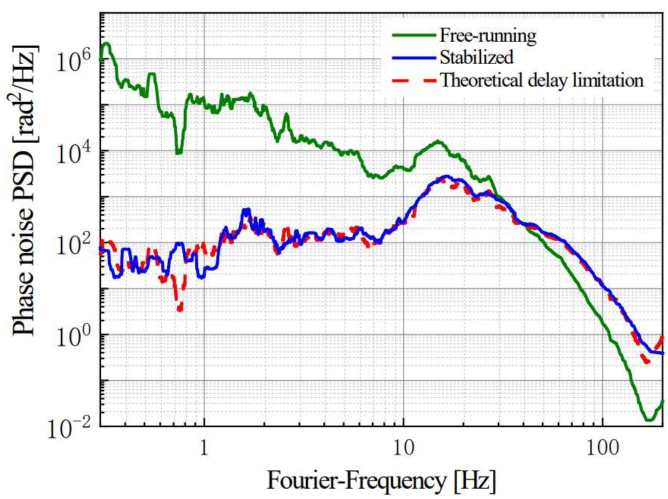

Fig. 3 The measured phase-noise PSDs in the free-running case (black curve) and stabilized case (blue curve).

Figure 3 shows the measured phase noise PSDs of the free-running (green curve) and stabilized (blue curve) 550 km field fiber link. The measured passively stabilized phase noise PSD is in good agreement with the PNC theoretical limitation as indicated in Ref. [6]. More importantly, the strong servo bumps which existing in the ANC technique is disappeared, resulting in the reduction of the integrate timing jitter of the transferred light. The servo bandwidth in the PNC configuration is approximately 35 Hz because of the propagation delay.

IV. CONCLUSIONS

In summary, we have demonstrated a coherent optical frequency transfer system over a 550 km fiber link. After being compensated, a fractional frequency instability of 1.3×10^{-14} at the integration time of 1 s and 5.5×10^{-19} at 10,000 s are achieved. 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] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, “Optical atomic clocks,” Rev. Mod.Phys. 87, 637 (2015).

[2] C. Clivati et al., “A VLBI experiment using a remote atomic clock vcoherent fibre link,” Sci. Rep., vol. 7, no. 1, Feb. 2017, Art. no. 40992.

[3] C. Lisdat et al., “A clock network for geodesy and fundamental science,”Nature Commun., vol. 7, p. 12443, Aug. 2016.

[4] J. Grotti *et al.*, “Geodesy and metrology with a transportable optical clock,” Nature Phys., vol. 14, pp. 437–441, May 2018.

[5] Cantin E, T.nnes M, Targat R L, Amy-Klein A, Lopez Oand Pottie P E.“An accurate and robust metrological network for coherent optical frequency dissemination.” New J. Phys. 23 053027

[6] Xiang Zhang *et al.*, “Passively stable dissemination of ultrastable optical frequency via a noisy field fiber network.” Optics & Laser Technology. 157 2023.