Coherent Optical Frequency Transfer via Aerial Fiber Link with 10^{-19} of Instability

Qian Zhou[1,2,3] , Xiang Zhang[1,2], Qi Zang[1,2], Xue Deng[1,2], MengFanWu[1,2], Jie Liu[1,2], Dan Wang[1,2,3], Ruifang Dong[1,2,3]* ,Tao Liu[1,2,3]*, Shougang Zhang[1,2,3]
1 National Time Service Center
2Key Laboratory of Time and Frequency Primary Standards, Chinese Academy of Sciences
Xi'an, China
3 University of Chinese Academy of Sciences
Beijing, China

***Summary*— In this paper, to the best of our knowledge, the first long-term stable dissemination of the optical frequency via an aerial fiber link with a length of 148 km with passive phase noise cancellation and the first characterization of phase noise PSD characteristics about optical frequency transmission over aerial fiber links is demonstrated in this paper. Different from buried fiber, the phase noise PSD of the aerial link in the free-running case is empirically with a slope of $1/f^3$, at Fourier frequency between 1Hz and 1kHz. The level of the phase noise PSD tested overhead fiber optic links is hundreds or even thousands of times that of similar buried links, but our final frequency transmission results are not much different from those of buried fiber optic cables of the same magnitude, and a transfer frequency instability of 7×10^{-19} at 4000 s are achieved, This result means that aerial fiber links are also a viable option when building long-haul fiber optic networks, when buried fiber optic cables are not available or are too costly.**

Keywords—Aerial fiber; Phase noise PSD; instability;

I. INTRODUCTION

In recent years, the instability and uncertainty of optical clock systems having reached the order of 10E-18, which have outperform the current cesium-based clock standards by more than two orders of magnitude [1]. Therefore, there is an increasing demand for realizing a high-precision frequency reference transmission. Among the existing transmission methods, fiber-based optical frequency transfer technique has been recognized as one of the most ideal solutions because of its advantage of low optical attenuation, broaden bandwidth, etc. [2] Up to now, the majority research of fiber-based optical frequency transmission are demonstrated via buried links and submarine links.[3],[4],[5] However, aerial suspended fiber link, as a low cost and easy to maintain routing solution, is widely employed and have been an important part of the thousands level optical fiber network. Aerial fiber links are subject to greater mechanical stress due to greater exposure, and their phase noise is consequently greater than that of buried fiber links of the same length in principle. But until recently, the only reported study of optical frequency transmission using aerial links is by a research group from the University of Western Australia [6], which shows some feature of the ariel fiber link, but only a few minutes of stable transmission of the optical frequency via 32.6 km are achieved, and no complete analysis of the phase noise of the link was carried out. As we all know, one factor that limits the performance of long-distance frequency transmission is the phase noise imposed on the optical signal by the mechanical stresses on the fiber link. A fiber link with a high level of phase noise will lead to false phase identification and increase the phase slip in the transmission system. Aerial fiber links are subject to greater mechanical stress due to greater exposure, and their phase noise is consequently greater than that of buried fiber links of the same length in principle. To account for the fluctuation of phase noise in the optical fiber link and ensure a sufficient phase detection range, a larger frequency divider is necessary. The phase noise of the fiber link varied by more than one order of magnitude, leading to the occurrence of cycle slips. Hu et al. proposed a passive phase noise cancellation (PNC) technique to address the challenges in optical frequency transfer. The technique involves detecting phase noise with a pilot optical signal and pre-compensating the same amount of phase noise on the other forward optical signal. This results in the phase noise compensated light being automatically received at the remote site.[7]

In this paper, to the best of our knowledge, the first long-term stable dissemination of the optical frequency via an aerial fiber link with a length of 148 km with passive phase noise cancellation and the first characterization of phase noise PSD characteristics about optical frequency transmission over aerial fiber links is demonstrated in this paper. Different from buried fiber, the phase noise PSD of the aerial link in the free-running case is empirically with a slope of $1/f^3$, at Fourier frequency between 1Hz and 1kHz. The level of the phase noise PSD tested overhead fiber optic links is hundreds or even thousands of times that of similar buried links, but our final frequency transmission results are not much different from those of buried fiber optic cables of the same magnitude, and a transfer frequency instability of 7×10^{-19} at 4000 s are achieved, This result means that aerial fiber links are also a viable option when building long-haul fiber optic networks, when buried fiber optic cables are not available or are too costly.

II. METHODS

The PNC technique for optical frequency transfer via a fiber is illustrated in Fig. 1. A portion of the light source is used as the local reference, while the rest is injected into AOM1, resulting in two diffracted outputs (0 and −1 order). The laser outputs from the two fiber-pigtails are combined and coupled to AOM2, which works at the angular frequency of ωl (upshifted mode, +1 order), and then transmitted to the remote site through the fiber link. At the remote site, another AOM3 (upshifted mode, +1 order) is used to distinguish the desired optical signal from the stray reflections caused by the fiber connectors and splices, which works at the angular frequency of ω_r. The process involves retro-reflecting the light back to the local site and recovering the phase noise of the fiber link using photodetector 1 (PD1). The frequency of the detected signal is then divided by 2 and used to drive AOM1 with the -1st diffraction order. At the remote site, the phase noise is automatically canceled without any effect on the time base. The transmitted light output from the 0th order of AOM1 is used to obtain the round-trip signal which contains the information of the fiber-induced phase noise. The output from the -1st order is used for the optical phase noise compensation. The characterization of the optical frequency transmission and the phase noise can be measured by the out-of-loop photodetector PD2. The experiments were conducted in Shaanxi Province, China, utilizing a fiber routing map provided by the communication carrier (see fig.1b).

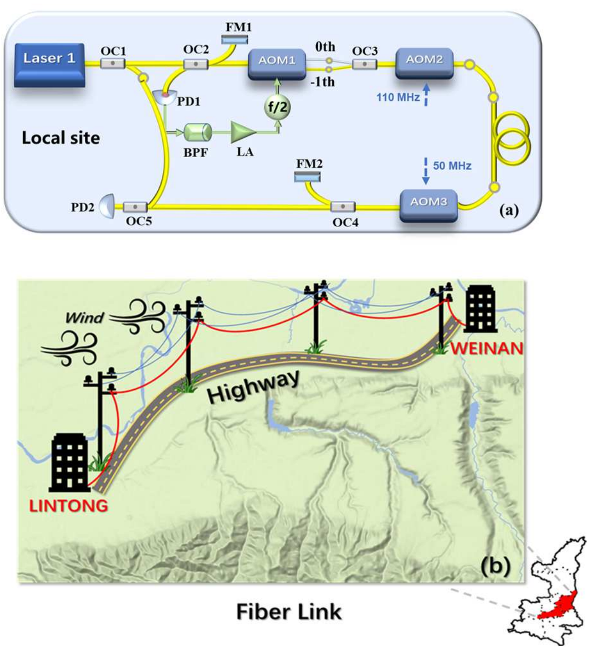

Fig. 1. (a) Schematic of optical frequency transfer via a 148 km aerial fiber link AOM:acousto-optic modulator, FM: Faraday mirror, Bi-EDFA: bi-directional erbium-doped fiber amplifier, OC: optical coupler, FD: frequency divider, PD: photo-detector, BPF: band-pass filter, LA: logarithmic amplifier. Relevant locations and overhead fiber link routes investigated in this experiment

The tests were carried out on four cores of a 37 km fiber link connecting Weinan to the Lintong site. The entire length of the link is 148 km, with a one-way loss of 42 dB. Three EDFAs were employed to compensate for the loss of the link.

III. RESULTS

A. Phase noise PSD

The phase noise of the free-running aerial fiber link was characterized with an open servo loop. The phase noise PSDs were measured using a K&K frequency counter at a gate time of 1ms. Different from field fiber links, we find our link exhibits a phase noise with the power-law dependence on Fourier frequency, f, of $S_{Fiber}\sim\ h/f^3$, between 1-1kHz. The magnitude of the noise, h, will presumably vary for different links and beyond $10^5\ rad^2/Hz$here. For the same fiber lengths, the field fiber had 20–25 dB less noise than the aerial fiber. According to the noise suppression theory, the stabilized phase noise S_{locked} satisfies the following relationship with the phase noise S_{Fiber} in the free running case,$S_{locked}=\frac{7}{3}*(2\pi f\tau)^2*\ S_{Fiber}$,which prediction falls exactly on the measured curve. After actively compensating the fiber-induced phase fluctuation, the phase-noise PSD reduction at 1 Hz achieves approximately 50 dB.

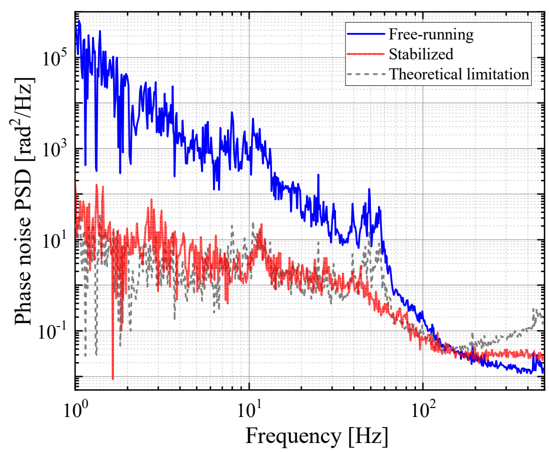

Fig.2. The measured phase-noise PSDs in the free-running case (blue curve) and stabilized case (red curve). The black dash line represents the theoretical compensation limitation.

B. Frequency instability

In this paper, the long-term locking of a 148km long aerial fiber link was achieved. The frequency of the out-of-loop signal at the user end in the time domain was measured using a K&K frequency counter with a gate time of 1s. The counting method is Π-type, measuring the frequency of the out-of-loop signal at the user side in the time domain and using the Modified Allen deviation (Mod ADEV) as a statistical measure of frequency stability. Figure 3 shows the Mod ADEV of the out-of-loop signal before (blue) and after (red) phase compensation. For a free-running 148 km aerial fiber link, the instability averages1×10^{-12} at the integration time of 1 s and fluctuates around the 10^{-12} level. With the implementation of the fiber noise cancelation, optical frequency transfer achieves a fractional frequency instability of 1.5×10^{-14} at an integration time of 1s, and drops to the order of 7×10^{-19} at an integration time of 4000s.

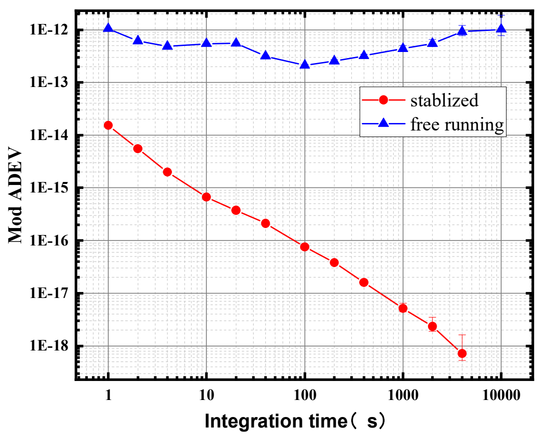

Fig.7. Fractional frequency instability of the 148km free-running aerial fiber link (black curve) and the stabilized link (red curve) derived from a non-averaging (Π-type) K&K frequency counter and expressed as the Mod-ADEV.

IV. Conclusions

We for the first time characterized the phase noise of optical signals transmitted and achieved the long-time transfer of optical frequency over aerial fiber links up to 148 km in length. The line shape of aerial fiber is very different from buried fiber links, the phase noise of the aerial link in the free-running case is empirically with a slope of $1/f^3$, at Fourier frequency between 1Hz and 1kHz. Long-term locking of overhead optical cables was demonstrated by a passive phase noise cancellation (PNC) technique, the fractional frequency instability can reach 7×10^{-19} at 4000s. Therefore, aerial fiber links may provide a useful alternative for optical frequency transmission when buried fiber is not available or is too costly.

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