Coherent Optical Frequency Transfer via a Fiber Link Laid Along a Railroad

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***Summary*—In this paper, we measured and analyzed the phase noise and frequency instability of optical signal, which is transmitted via fiber links laying along railroad lines at different time periods. The frequency instability of the optical signal in terms of Allan Deviation (ADEV) is on the order of 10^{-13} at an integration time of 1 s. The free-running phase noise PSD of the fiber link reached 10^5 rad^2/Hz at an offset frequency of 2 Hz. We demonstrated optical-carrier transfer over a fiber link by actively compensating for the phase noise. This paper analyzed phase noise characteristics of fiber link along the railway and explored the method to address the transmission of complex links in the future.**

Keywords— optical frequency transfer, railroad fiber link, phase noise PSD

I. Introduction

High-precision time and frequency signals have important applications in many scientific fields, such as fundamental physics, geodesy, navigation, etc.[1-3] There is an increasing demand for high-precision time and frequency signals transmission due to the realization of 10^{-19} level instability of optical clocks in recent years.[4] Presently, optical fiber links are a promising method for remote optical clocks comparison, as they improve the resolution by more than four orders of magnitude over current satellite techniques.[5, 6] The free-running phase noise induced by the fiber links is one of the major factors limiting the performance of optical frequency transmission over a long-haul fiber network, the magnitude of which is mainly determined by the environmental interferences of the communication fiber links. Various situations of the fiber links environment cause rather different phase noise characters, especially, the fiber links laid along the busy railroad lines show enormous noise amplitude and variations range. Currently, the coherent transfer is focused on the underground fiber links laid in a field or along the highway. Hence, it's necessary to investigate optical frequency transfer along with the complicated fiber link.[7, 8]

Optical fiber frequency transfer is very sensitive to mechanical stress and vibration on the link. Especially, the mechanical stress variations of fiber links laid along the railroad lines are complex due to vibrations caused by passing trains, which will introduce high-level phase perturbations on the fiber link. In this paper, the characterization of optical frequency transfer over 156 km fiber links laid along busy railroad lines was investigated and transfer performance was presented.

II. Experimental setup

Figure 1 shows the map of the fiber link buried along the busy railroads. Two cores of 82.2 km fiber link from Zhengzhou to Xinxiang in Henan province were tested in the experiments. The total loss of the 164.4 km fiber link is 45.4 dB corresponding to a loss of 0.27 dB/km. Two bidirectional erbium-doped fiber amplifiers (EDFA) were used in total fiber links to compensate for the optical loss. One EDFA was installed at Xinxiang another EDFA was installed before the receiver site at Zhengzhou.

Fig1. The map of the fiber link laid along the railroad

Figure 2 shown the experimental setup for characterizing the railway fiber-based optical frequency transfer system, basing on the scheme pioneered by Ma et al.[9] The laser source applied in the experiment is a CW fiber laser (NKT E15) working at 1550.12 nm with a linewidth of 100 Hz. The optical signal is split into two parts by a 99:1 single-mode coupler. The small part was used as an optical reference for out-of-loop performance measurement. Another part was continued transmitted and then split into two parts in succession. One part was reflected to PD1 by a Faraday mirror (FM) as the reference signal. After passing through a servo acousto-optical modulator (AOM) driven by a 50 MHz radio-frequency (RF) signal, the transmitted laser was transmitted to the receiver site through the 164.4km fiber links. In which site, transmitted laser passed through AOM2 driven by a 30 MHz radio-frequency (RF) signal and then the most part was reflected by FM2 and passes through the 164.4 km fiber link again back to PD1. The beating signal of 160 MHz between the round-trip signal and local reference signal was detected by the PD1 to characterize the instability and additional phase noise of the fiber link. For obtaining the phase error signal, the 160MHz beat signal was divided by a factor of 128 and then mixed with a local RF reference signal. For canceling the fiber-induced phase noise, the error signal is applied to complete a feedback control by serving the RF driving frequency of the AOM1.

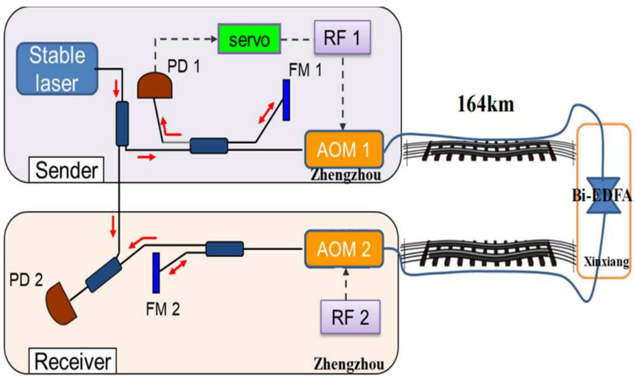

Fig2. Schematic of the fiber characterization system and 2 × 82.2 km fiber link with two optical amplifiers. PD, photodetector; AOM, acousto-optic modulator; FM, Faraday mirror; RF1/RF2: driver of AOMs.

III. EXPERIMENTAL RESULTS

We measured the frequency data of the out-loop beat signal respectively in the free-running and stabilized cases by using a K&K frequency counter with a gate time of 1ms. Figure 2 compared the frequency data of the fiber in the field and the fiber laid along the railroad in the free-running case. The magnitude of the frequency fluctuations of the fiber link along the railroad line changed drastically in a short period. The large span of the frequency data of fiber link laid along the railroad achieved 130 kHz. And even the magnitude of the frequency fluctuations in a small period, the frequency span can still reach 20 kHz, which is one order of magnitude higher than the field fiber link with a fiber length of 136.1 km.

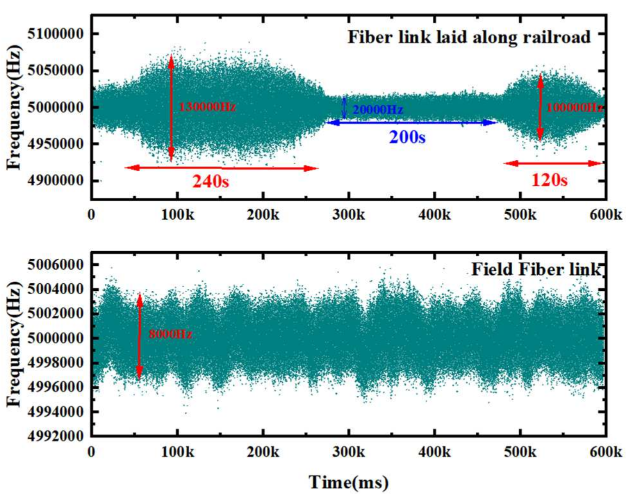

Fig.3. Frequency data of the free-running fiber links

The phase-noise PSD is calculated by the frequency data of fiber links in the free-running and stabilized case. The different magnitude of frequency data is analyzed in Fig. 4. We find the fiber link exhibited the free-running phase noise with the power-law dependence on Fourier frequency, *f*, of $S_{fiber}(f) \sim h/f^2$,[10] between 1Hz-5Hz. No matter how the magnitude of frequency data fluctuation changed. The magnitude of the phase noise, h, is approximately equals to 20,000 rad^2/Hz in this paper. As also seen in Fig. 4, there is a broad peak at the Fourier frequency between 5 and 40 Hz, which was broader than in previous results of fiber links laid along the highway or laid in the field. The wide peak may be caused by the noise introduced by the busy railroad along the way. For Fourier frequency from 40 Hz to 500 Hz, the phase-noise PSD calculated by the big span frequency data was one magnitude higher than the phase-noise PSD calculated from the small span, which indicated that the irregular high-frequency noise and the factor of insufficient frequency division in the servo circuit ma-y be the reason why the phase noise cancellation system cannot be locked for a long time. After being compensated, the phase noise PSD suppression at 2Hz can achieve about 50dB. The residual phase-noise PSD was agreed with the theoretical compensation limitation $1/3(2\pi f\tau)^2$, which is calculated and shown by the orange dash line. f is the Fourier frequency, and τ is the single-trip delay time.

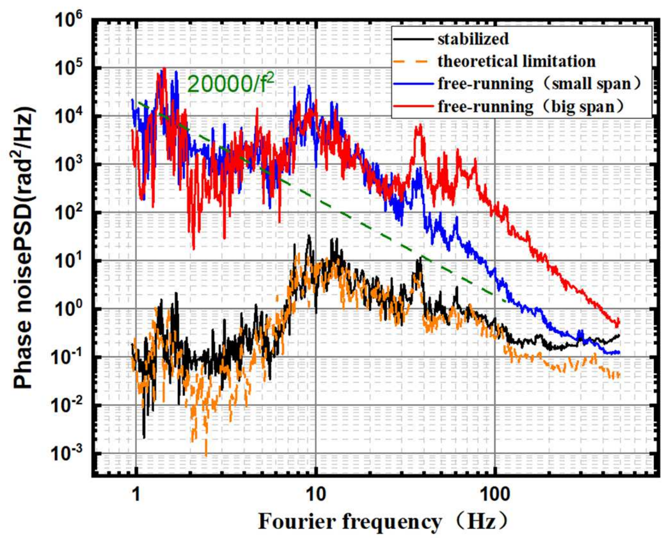

Fig.4. Phase noise power spectral density of the fiber link laid along the railroad. The free-running phase noise PSD of the link calculated by big span frequency data (red line) and small span frequency data (blue line), stabilized link (black line) and theoretical expectation (orange dash line) are shown.

As described in Fig.4, due to the irregular high-frequency phase noise, it was not possible to acquire the long-term instability of the optical frequency transmission for more than a few minutes. We can only actively stabilize the optical transmission for approximately ten minutes and the instability of the free-running and stabilized fiber links are shown in Fig.5. We use a K&K frequency counter to measure the beat frequency detected by PD2 with the Π-mode (1 s gate time). In the free-running case, the frequency instability of the transfer optical signal in terms of Overlapping Allan deviation (OADEV) is on the order of 10^{-13} at an integration time of 1s, and after being compensated, we achieve a transfer instability of 5×10^{-14} at 1s and scale down to 1.1×10^{-15} at 100 s.

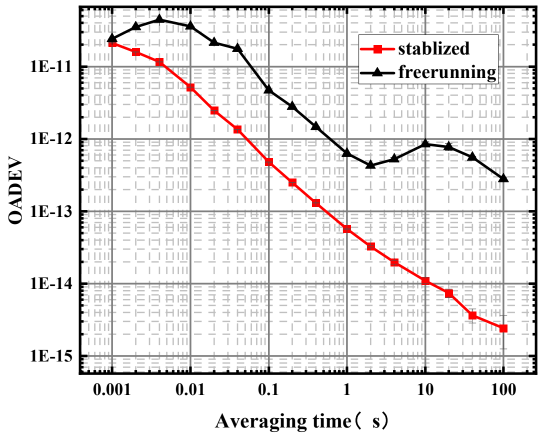

Fig.5. Measured fractional frequency instability

IV. CONCLUSION

We have measured the optical frequency transfer instability and analyzed the phase noise PSD characterizations in the optical signals transmitted over a 164.4 km railway fiber-based optical frequency transfer system. Compared with the fiber links buried in a field and along the highway, the influence of the phase noise PSD attributed to ground vibrations on railroad fiber links is greater. There still exists high-level high-frequency noise in the railroad fiber links that affect the performance of the optical transmission system. In the next work, we will improve the optical frequency transmission performance of the railroad fiber links by increasing frequency division ratios in the servo circuit to confront various situations in the fiber link environment in China.

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