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Coherent Transfer of Optical Frequency over 112 km with Instability at the 10^{-20} Level *

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We demonstrate optical-carrier transfer over a 112-km single-span urban fiber link. By actively compensating the phase noise induced along the fiber link, a noise suppression of 55 dB at 1 Hz is obtained. A fractional frequency instability of 2.5×10^{-16} at 1 s is achieved, and reaching 7.5×10^{-20} at 10000 s. The system is stable and able to run for a long time. This work will contribute to optical frequency distribution and remote comparison among atomic clocks.

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Modern optical clocks have achieved the uncertainty and instability at 10^{-18} level,[1,2] which enable high performance applications in many fields such as metrology,[3] fundamental physics,[4] and relativistic geodesy.[5,6] In particular, the high-precision long-distance frequency transfer is essential for comparison of remote clocks and related applications. In recent years, by actively compensating the phase noise introduced along the fiber links, fiber links have been extensively used to transfer ultra-stable optical frequency with instability several magnitudes superior to satellite-based transfer means.[7–11] In 2008, an 86-km urban fiber link was used to transfer optical frequency of 194.5 THz with an instability of 2×10^{-16} at 1 s in a 10-Hz measurement bandwidth.[12] In 2013, a 1840-km fiber link transferring optical frequency across Germany had been established, reaching instabilities of 2×10^{-15} in 1 s and 4×10^{-19} in 100 s with a modified Allan deviation expression.[8] Diverse methods for fiber noise compensation have been researched.[13,14] Moreover, research on frequency transfer and time synchronization, optical frequency comparison and optical distribution networks have been investigated in recent years.[3,14–17]

In this Letter, we demonstrate ultra-stable optical frequency transmission via a 112-km urban fiber link between the National Time Service Center (NTSC) in Lintong and the Hangtiancheng (HTC) in Chang'an. To achieve better phase noise cancellation, we install an all-fiber, compact and removable setup consisting of noise-proof optical modules and low-noise electronic circuits. Without any optical amplification, the system is able to maintain a long-time running with a fractional instability of 7.5×10^{-20} at 10000 s which surpasses the best optical clocks by an order of 2. To evaluate the performance of the urban fiber link, we compare the 112-km urban fiber link with a 110-km spooled fiber link, and the comparison results are analyzed. Our work will conduce to longer distance frequency transfer and distribution.

Figure 1 shows the fiber link from NTSC to HTC with a single-trip length of 56 km. About 88% of the fiber link is buried under the ground, which provides a quiet and stable circumstance for frequency dissemination, while the rest of the fiber is hanged and easily influenced by the ambient noise. We observe a clear daily variation in the optical phase that is mainly induced by temperature fluctuation and traffic disturbance along the fibers. To evaluate the transfer fidelity with self-reference method, we join the ends of two parallel fibers in HTC, and demonstrate a 112-km fiber link with both sender site and receiver site in NTSC. The total loss of the fiber link is about 26 dB, corresponding to a loss of 0.23 dB/km.

The experimental setup is shown in Fig. 2. The laser source applied in the experiment is a self-made ultra-stable laser at 1550 nm with a linewidth of 3 Hz.[18] The laser output is split into two parts by a 90:10 single mode coupler (SMC1), the major part of the light is used for transfer, while the small part is used as a reference signal. The transmitted light is split into two parts by SMC2, and one part is directly reflected to the photo detector (PD1) by a Faraday mirror (FM1), while the other part passes through an acousto-optical modulator (AOM1), and is transmitted to the receiver site through the single-mode communication fiber (SMF-28). AOM1 shifts the optical frequency of 110 MHz and serves as the noise compensating element. On the receiver site, the transmitted laser passes AOM2 and most part is returned to the

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PD1 on the sender site by FM2. The Faraday mirrors are used to maintain 90° rotation regarding to the polarization state of the input light. Hence, the returned optical signal from the receiver site and the reference signal reflected by FM1 have the same polarization state to generate a stable beat signal. The error signal is extracted from the beat signal detected by PD1 and is used to cancel the fiber-induced Doppler frequency shifts through AOM1. AOM2 at the receiver site is used to provide a 50 MHz frequency shift and helps to discriminate the return signal from the stray reflections by the connectors and splices. PD2 is used to characterize the transmission instability by measuring the beat signal of the reference laser from the sender site and the transmitted laser on the receiver site.

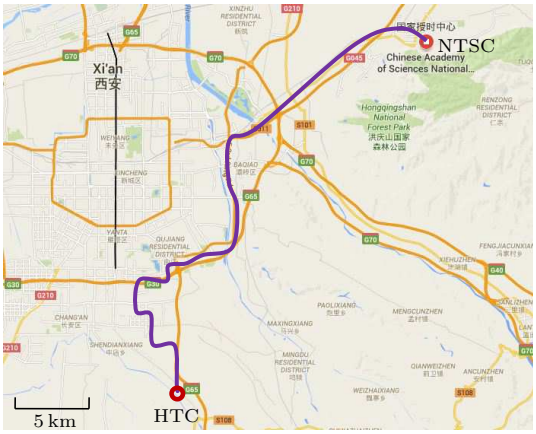

Fig. 1. Schematic diagram of the urban fiber link. NTSC: National Time Service Center. HTC: Hangtiancheng. Here the graph is based on the Google map.

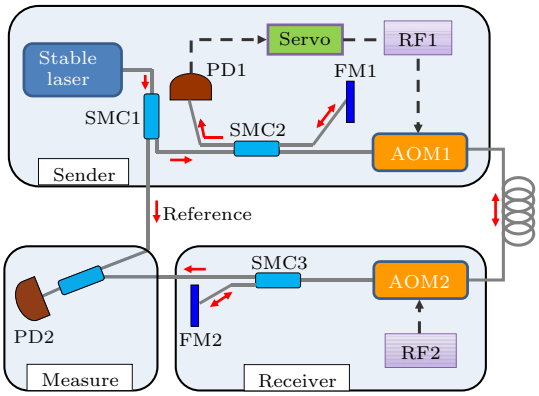

Fig. 2. Schematic diagram of the optical frequency transfer system. PD: photo detector; AOM: acousto-optical modulator; FM: Faraday mirror; RF1/RF2: driver of AOMs; and SMC: single mode coupler.

In the ideal case, the light that goes through the round trip experiences double phase noise of the single trip, thus the out-loop phase noise can be compensated perfectly by canceling in-loop phase noise detected by PD1. However, there are imperfections caused by the reference arms in the in-loop and out-loop sections, which would restrict the noise cancellation. To minimize the influence of the imperfections, the reference arm length in the in-loop section is reduced to 0.2 m by fusing the fibers between couplers and FM1, PD1 and FM2. Furthermore, all the other optical paths between the components are shortened, and the sender and receiver optical modules are laid in the sealed aluminum boxes which are covered with sponge to insulate environmental acoustic noise with isolation more than 30 dB. After the miniaturization, we obtain a lower system noise floor, while the in-loop signal is still stabler than the out-loop signal attributed to the time delay in the fiber.

In the servo loop, a 6-order helix cavity filter and a low noise amplifier are used to detect the beat signal. In particular, a logarithm amplifier is applied to reduce the fluctuation of the signal amplitude within 0.3%, which effectively restrains the amplitude noise resulting from the laser source or detection process.

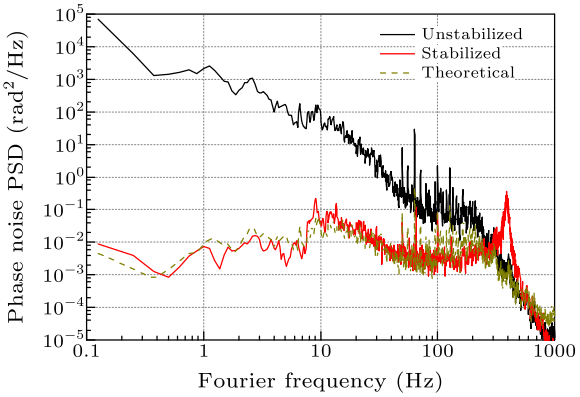

Fig. 3. Phase noise power spectral density of the urban fiber link. The PSD of the free running link (black line), stabilized link (red line) and theoretical expectation (yellow line) are shown.

The fiber noise cancellation is investigated by measuring the phase noise power spectral density (PSD) of out-loop beat signal with a fast Fourier transform analyzer (FFT). The PSD of the 112-km urban link before and after compensation is shown in Fig. 3. Similar to the report of Newbury *et al.*,[19] we also observe that the destabilized phase noise has a slope of $1/f^2$ in the range of 0.1–10 Hz, which indicates a white phase noise disturbance in the urban fiber link. At the Fourier frequency $f = 1$ Hz, the PSD of the destabilized link is measured as 2×10^3 rad^2/Hz, and this value is two magnitudes higher than the 146-km urban link in Ref. [20]. As most of our fiber link is buried along the highway and part of the fibers are hanged winging, the traffic and temperature fluctuations make much disturbance on the fiber link. As also seen in the plot, for the Fourier frequency higher than 300 Hz, there is no effective noise cancellation, which is mainly limited by the servo control bandwidth[19] of $1/4\tau$. According to the theoretical noise reduction ratio $1/3(2\pi\tau f)^2$, with f being the Fourier frequency, and τ being the single-trip delay time,[19,21] the corresponding residual phase noise is calculated as shown by the yellow line. The phase noise of the stabilized link is coincident with the yellow line which illustrates that the loop control bandwidth is the main reason limiting the system performance.

To characterize the performance of the optical fre-

quency dissemination link in the time domain, we use a frequency counter (Agilent 53230 A) to count the beat frequency detected by PD2. Figure 4 shows the frequency distribution of a 14-hour measurement with the counter in the reciprocal mode (1 s gate time). The frequency distribution satisfies a Gaussian shape with a mean deviation of 38 μHz, which is caused by the time-base error between the oscillators and frequency counter.

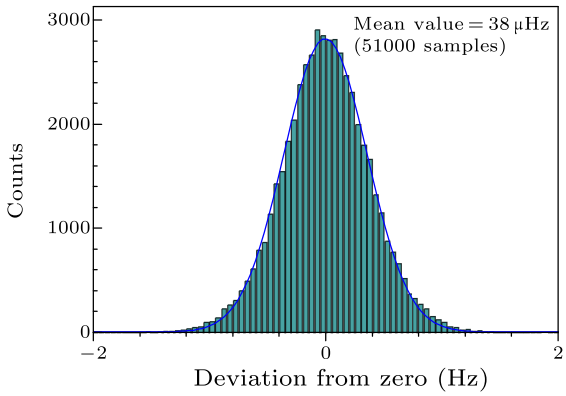

Fig. 4. Out-loop beat frequency deviation from the expected value.

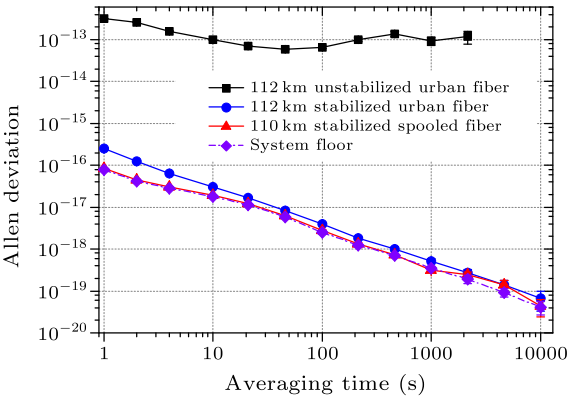

Fig. 5. Allan deviation of the optical frequency transfer system. Instabilities of the free-running urban link (squares), stabilized urban link (circles), stabilized spooled fiber link (triangles) and system floor (diamonds) are shown. All the frequency data are counted by using the reciprocal mode with 2 Hz bandwidth measurement.

The optical frequency transfer instability of the 112 km urban link is shown in Fig. 5. The transfer instabilities of the destabilized urban link are shown by the squares, and the circles are instabilities of the stabilized link. We achieve a transfer instability of 2.5×10^{-16} at 1 s averaging time with 2 Hz measurement bandwidth and the instability reaches 7.5×10^{-20} at 10000 s. The 2 Hz measurement bandwidth is achieved by using a low-pass filter. A τ^{-1} slope of the instability versus the averaging time is shown.

As a comparison, the transfer instability of a 110-km spooled fiber link is also investigated. Although the spooled fiber is laid in a noisy laboratory environment without careful shielding, the destabilized fiber phase noise is much smaller than the urban link. The instabilities of its stabilized link are shown by the triangles in Fig. 5. An instability of 8.5×10^{-17} at 1 s is obtained and it goes for 4.4×10^{-20} at 10000 s. The results with a spooled fiber link are very close to our system floor (diamonds), as well as the urban fiber link. Thus the performance of the present fiber dissemination system is limited by the system floor. We find that the system floor in the long term is mainly restricted by the performance of the local oscillator (here we used a signal generator, SG382). In the next step we will focus on the optimization of the system floor.

In conclusion, we have established a 112-km optical-carrier dissemination system based on an urban fiber link between NTSC in Lintong and HTC in Chang'an. The phase noise of the fiber link is suppressed effectively which is limited by the loop delay. The transfer instability is measured to be 2.5×10^{-16} at 1 s averaging time, and 7.5×10^{-20} at 10000 s with 2 Hz bandwidth measurement bandwidth. Next, we will work on the improvement of the system performance. This could be achieved by the optimization of system noise floor of the electric control system and better isolation of the optical modules. A new cascaded optical frequency distribution is under development on this link at this moment as well.

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