Robust optical frequency transfer in a noisy urban fiber network

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Abstract—Optical fibers have been recognized as one of the most promising host material for high phase coherence optical frequency transfer over thousands of kilometers. In the pioneering work, the active phase noise cancellation (ANC) technique has been widely used for suppressing the fiber phase noise introduced by the environmental perturbations, in which an ideal phase detector with high resolution and unlimited detection range is needed to extract the fiber phase noise, in particular for noisy fiber links. We demonstrate the passive phase noise cancellation (PNC) technique without the need of phase detector could be preferable for noisy fiber links. To avoid the effect of the radio frequency (RF) from the time base at the local site in the conventional active or passive phase noise cancellation techniques, here we introduce a fiber-pigtailed acousto-optic modulator (AOM) with two diffraction order outputs (0 and +1 order) with properly allocating the AOM-driving frequencies allowing to cancel the time base effect. Using this technique, we demonstrate transfer of coherent light through a 260 km noisy 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 $4.9 \times 10^{-14}$ at the integration time of 1 s and scales down to $10^{-20}$ level at 10,000 s in terms of modified Allan deviation over the 260 km noisy urban fiber link. The frequency uncertainty of the retrieved light after transferring through this noise-compensated fiber link relative to that of the input light achieves $(0.41 \pm 4.7) \times 10^{-18}$. The proposed technique opens a way to a broad distribution of an ultrastable frequency reference with high coherence without any effects coming from the RF reference and enables a wide range of applications beyond metrology over fiber networks.

Index Terms—Optical clock, optical frequency transfer, passive phase stabilization, metrology.

I. INTRODUCTION

This work was supported in part by the National Key Research and Development Program of China (Grant No. 2016YFB0200200), in part by the National Natural Science Foundation of China (NSFC) (91636101, 91836301 and 11803041), in part by the West Light Foundation of the Chinese Academy of Sciences (Grant No. XAB2016B47), and in part by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB21000000). Corresponding author: Tao Liu and Ruifang Dong.

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OPTICAL frequency timekeeping with trapped atoms or ions [1], [2], [3] is progressively becoming ideal tools for precision measurements and fundamental physics tests, such as general relativity [4], [5], temporal variation of the fundamental constant [6], searching for dark matter [7], chronometric geodesy [8], and gravitational waves [9], [10], [11]. Unfortunately, these clocks are typically cumbersome and expensive and only available at national metrology institutions and several universities [1], [2], [12], causing a strong motivation to develop a robust and cost-effective system for comparing and distributing these sources of ultraprecise frequency signals. Among different frequency transfer methods, optical fiber links have been widely demonstrated as one of the most powerful tools for the dissemination and comparison of current state-of-the-art optical clocks with the stability and uncertainties at a few $10^{-21}$ level [13], [14], [15]. However, the temporal optical length variations of the fiber link, coming from mechanical and thermal perturbations along the fiber link, will imprint optical phase noise onto the transmitted optical signal and ultimately deteriorate the optical frequency transfer stability and uncertainty. One of the most pioneering technique, namely active phase noise cancellation (ANC), has been widely adopted for mitigating this fiber-induced Doppler noise, where the phase noise of the fiber link is detected by comparing the local signal with the round-trip one and be used to implement a feedback control onto the phase compensator [13]. Nevertheless, there exist obvious and inherent disadvantages for this ANC technique that it requires the complicated phase noise detection unit and the inherent disadvantages for this ANC technique that it requires the complicated phase noise detection unit and the sophisticated servo controller. The overall performance of the phase noise rejection capability is strongly dependent on the proper setting of the loop parameters. At the same time, an ideal phase detector with high resolution and unlimited detection range is needed to extract the fiber phase noise. One common way to extend the phase detection range is to adopt an analog phase detector with an assistance of a high frequency dividing ratio [16] or a digital phase detector with the proper phase unwrap algorithm [17]. Consequently, a complicated phase noise detection circuit has to be used in a noisy fiber link with a large phase noise per-unit-length such as 4 rad$^2$/Hz/km (USA) [18], 0.5 rad$^2$/Hz/km (Germany) [19], 3 rad$^2$/Hz/km (France) [16], [20], 20 rad$^2$/Hz/km (Italy) [15], 20 rad$^2$/Hz/km (Japan) [21] at the 1 Hz offset frequency. The phase noise is even larger in China. For example, the phase noise per-unit-length at the 1 Hz is about 38.5 rad$^2$/Hz/km for a 260 km urban fiber link connecting LinTong District and HuYi District and the integrated phase from 0.1 Hz to 100
kHz are approaching to 240 rad (see the following text). For an analog phase detector, a frequency divider with a ratio of more than 240 is needed to extract the phase noise introduced by the fiber link. To secure the enough phase detection range caused by the fluctuations of the fiber link phase noise, the frequency divider with the larger frequency divider is needed. This could still not be enough for the phase noise of the fiber link fluctuated by more than one order of magnitude, resulting in the appearance of the cycle slips [16]. Moreover, before adopting the frequency divider with the high dividing ratio, the beatnote signal at the local site typically needs to be up-converted as implemented in [16]. This process will introduce additional phase noise coming from the frequency mixer and amplifier stages.

To surmount the aforementioned difficulties, Hu. et al first proposed a passive phase noise cancellation (PNC) technique for optical frequency transfer by detecting the phase noise with a pilot optical signal and pre-compensating the same amount phase noise on the other forward optical signal, resulting in the phase noise compensated light automatically received at the remote site [22, 23]. They demonstrated a proof-of-principle optical frequency transmission experiment via a 145 km spooled fiber link with a stability of \(2 \times 10^{-19}\) at 10,000 s in terms of overlapping Allan deviation (OADEV) [22]. Although the PNC technique has been demonstrated with the spooled fiber link [22], the capability for the phase noise rejection in the field-deployed fiber links needs to be experimentally examined as widely done by the ANC technique [14, 15, 18, 24, 16, 25].

Neither the active nor the passive phase compensation schemes can avoid the influence of the time base at the local site, because for a practical application, the radio frequency (RF) signals synthesized from their time bases are independent of the optical frequency reference at the local site. By taking the effect of the time base into consideration, the limitation of the optical frequency transfer stability \(\sigma_y\) can be expressed as:

\[
\sigma_y \approx \frac{\omega_l}{2\omega_s} \sigma_{RF}
\]  

where \(\omega_l\) represents the driving frequency for the local acousto-optic modulator (AOM), and \(\sigma_{RF}\) is the stability of the time base. As our previous work, we have \(\omega_l = 2\pi \times 110\) MHz and \(\omega_s = 2\pi \times 193\) THz. For a typical radio frequency (RF) reference such as a customized OCXO with the stabilities of \(8.7 \times 10^{-11}\) at 1s and \(7.2 \times 10^{-11}\) at 10,000 s, it will constrain \(\sigma_y\) of \(5.0 \times 10^{-17}\) at 1 s and \(4.1 \times 10^{-17}\) at 10,000 s, illustrating that the long-term stability will become the limitation. One way to solve this issue is to discipline the RF reference to the GPS signal [26], but this will increase the complexity of the system and the system performance is strongly dependent on the GPS performance. Therefore, one intriguing question is how to distribute the optical signal without the effect of the time base. In a pioneering work, Wu et al demonstrated the effect of the time base can be effectively removed by cascading one more AOM just after the remote AOM for optical frequency transfer over a branching fiber network [27]. However, adding one more AOM, in particular a fiber-pigtailed one, will introduce the significant outside path, resulting in the increase of the outside phase noise as discussed in [28, 29, 30]. Additionally, the scheme still couldn’t get rid of the effect of the time base at the local site.

In this paper, a fiber-pigtailed acousto-optic modulator (AOM) with two diffraction order outputs (0 and +1 order) is employed as the phase noise compensated device, the retrieved
optical frequency signal is independent of the time base at the local site. Furthermore, we demonstrate the PNC technique has unlimited phase noise detection range and resolution and could be preferred for noisy fiber links. We for the first time demonstrate the proposed technique by coherently transferring an ultra-stable optical frequency signal via a 260 km noisy urban fiber link.

The article is organized as follows. We illustrate the concept of coherent optical phase dissemination with the PNC technique without the effect of the time-base in Sec. II. We present the experimental set-up and experimental results in Sec. III. Finally, we give a conclusion in Sec. IV.

II. CONCEPT OF CANCELLING THE TIME BASE EFFECT IN AN OPTICAL FREQUENCY TRANSFER NETWORK

Figure 1 illustrates a schematic diagram of optical frequency transfer via a fiber with the PNC technique. Part of this light source is extracted as the local reference, while the remaining part is injected into an acousto-optic modulator (AOM1) with two diffracted outputs (0 and -1 order). The laser outputs from the two fiber-pigtails are further combined and coupled to the AOM2 working at the angular frequency of \( \omega_l \) (upshifted mode, +1 order) and then propagated to the remote site via the fiber link. At the remote site, another AOM3 (upshifted mode, +1 order) working at the angular frequency of \( \omega_r \) is used to discriminate the desired optical signal from the stray reflections by the fiber connectors and splices. The light is retro-reflected back to the local site and the phase noise of the fiber link is recovered by the photodetector 1 (PD1) at the local site. Subsequently, the frequency of the detected signal is divided by a factor of 2 and then drives the AOM1 with the -1 diffraction order. At the remote site, the phase noise is automatically cancelled at the remote site without the effect of the time base at the local site. The detailed principle of optical frequency transfer is as follows. The initial optical frequency signal can be denoted as,

\[ E_1 \propto \cos(\omega_s t + \phi_s) \tag{2} \]

where \( \omega_s \) and \( \phi_s \) respectively represent the angular frequency and initial phase value of the optical signal. Assuming the optical fiber phase noise induced by environmental perturbations in either direction is equal, the electric field of the light which is reflected by the Faraday Mirror 2 (FM2) and transferred back to the local site can be written as,

\[ E_2 \propto \cos[(\omega_s + 2\omega_l + 2\omega_r)t + \phi_s + 2(\phi_l + \phi_f + \phi_r)] \tag{3} \]

where \( \phi_l \) and \( \phi_f \), respectively, represent the initial phases of the driving frequencies of the AOM2 and AOM3, and the \( \phi_f \) is the optical fiber induced phase noise. At the local site, the heterodyne beat-note between \( E_1 \) and \( E_2 \) is detected by the PD1. We select the electrical signal with the angular frequency of \( 2(\omega_l + \omega_r) \), which contains the fiber phase noise information, by using a narrowband pass RF filter, resulting in,

\[ E_3 \propto \cos[2(\omega_l + \omega_r)t + 2(\phi_l + \phi_f + \phi_r)] \tag{4} \]

Afterwards, the angular frequency of \( E_3 \) is divided by a factor of 2, obtaining,

\[ E_4 \propto \cos[(\omega_l + \omega_r)t + (\phi_l + \phi_f + \phi_r)] \tag{5} \]

To passively compensate the phase noise along the fiber link, we feed the amplified electrical signal \( E_4 \) to the AOM1. The phase noise compensated light output at remote site can be expressed as,

\[ E_5 \propto \cos(\omega_s t + \phi_s) \tag{6} \]

As can be seen, the frequency and phase of the retrieved optical signal are independent of all the RF signals. Consequently, the RF signal source with the high frequency stability in our scheme is no longer needed, which will simplify the system and make it cost-effective. It is important to emphasize that the above description does not take the fiber propagation delay into the account. As demonstrated by Williams et al., the phase noise rejection capability is limited by the propagation delay \( \tau_p \). The residual phase noise power spectral density (PSD), \( S_{\alpha}(f) \), at the remote site in terms of the single-pass free-running phase noise PSD, \( S_{\text{fiber}}(f) \), and the single-pass fiber link \( L \) propagation delay, \( \tau_o \), can be expressed as \[ S_{\alpha}(f) \approx \frac{7}{3}(2\pi f \tau_o)^2 S_{\text{fiber}}(f). \tag{7} \]

III. EXPERIMENTAL SETUP AND RESULTS

A. Experimental setup

We have demonstrated the proposed technique by using the configuration as shown in Fig. 1. The interferometer is built with fiber optics. A laser source, which is stabilized to a high-finesse Fabry-Perot cavity at a frequency near 193 THz, is adopted as an optical reference. The optical fiber is composed of a pair of 130 km fiber link connecting the NTSC (National Time Service Center) at Lintong and two communication rooms of CTCC (China Telecom), with a total optical attenuation of 75 dB. To compensate the optical loss, four bi-directional erbium-doped fiber amplifiers (Bi-EDFAs) are independently installed along this fiber link. In this experiment, we set \( \omega_l = 2\pi \times 110 \text{ MHz} \) and \( \omega_r = 2\pi \times 50 \text{ MHz} \). In order to conveniently evaluate the performance of this coherent frequency transmission system, a two-way optical frequency comparison setup is adopted as described in [30]. We use non-averaging II-type frequency counters to record the beating frequency. Additionally, to measure the phase noise of optical frequency transfer, a commercial phase noise analyzer (Rohde & Schwarz, FSWP) is used.

B. Residual phase noise PSDs at the remote site

Figure 2(a) shows the measured PSDs of the free-running (blue curve) and stabilized (red curve) 260 km urban fiber link. The frequency resolution bandwidth is set as 1 mHz, resulting in 11 minutes for a single measurement. The free-running phase noise PSD falls off approximately as \( 10000/f^2 \) between 0.1 Hz and 10 Hz, the \( f \) stands for the Fourier frequency. The results shows that the long-haul fiber link performs a higher level of phase noise per-unit-length at the 1 Hz (about 38.5 rad²/Hz/km), which is much larger than the fiber noise observed in previous reports, such as 4 rad²/Hz/km (USA) [18], 0.5 rad²/Hz/km (Germany) [19], 3 rad²/Hz/km (France) [16, 20], 20 rad²/Hz/km (Italy) [15], 20 rad²/Hz/km...
C. Cycle-slip free optical frequency transfer

To examine the phase noise rejection capability of the ANC and PNC techniques, we measured end-to-end frequencies in these two configurations. The corresponding results are shown in Fig. 3(a). In the ANC configuration, the angular frequency of \( E_3 \) indicated in Eq. 4 is divided by a programmable frequency divider and sent to a phase comparator. The rule of thumb for the frequency dividing ratio is that the integrated phase jitter of the RF signal after frequency divider has to be much less than 1 rad. As shown in Fig. 3(a), the optical frequency transfer system couldn’t perform properly when the frequency division ratio is 64. By increasing the ratio to 320, the system could be successfully locked, but there still exist many occasional cycle-slips because the free-running phase noise of this fiber link is not stationary as shown in Fig. 3(b). The system could operate properly when the division factor is increased to 1280. Fig. 3(b) shows the temporal behavior of the end-to-end frequencies in the passively stabilized fiber link, demonstrating that the PNC configuration could run properly without the clear indication of the cycle-slips. As can be seen from the above experimental results, the active system needs a reasonable design for the frequency dividing ratio and the loop parameters, while the PNC-based optical frequency transfer system is more efficient, simple, and robust employed in a noisy fiber link.

D. Demonstration of the time base free optical frequency transfer

To illustrate the effect of the time base at the local site \([13], [14], [15], [22], [23]\), before feeding the RF signal onto the AOM1 we mix it with a RF signal \([14], [15], [22], [23]\), before feeding the RF signal onto the AOM1 we mix it with a RF signal of the frequency of the fiber output light depends on the time base and the OADEV as illustrated the red circle markers in Fig. 4. We can clearly see that, once \( E_n \) is employed in the system, the frequency dividing ratio F is removed, the relative frequency instability is 4.9 \( \times 10^{-15} \) at 1 s averaging time, and is limited to the \( 10^{-18} \) level at the long averaging time due to the effect of the time base. Once \( E_n \) is removed, the relative frequency instability is 4.9 \( \times 10^{-15} \) at 1 s averaging time and scales down to 5.1 \( \times 10^{-19} \) at 10,000 s averaging time (black squares), independent of the time base

Fig. 3. Temporal behavior of the end-to-end frequency values of the stabilized 260 km urban fiber link respectively with the traditional ANC configuration (a) and the PNC configuration (b).

Fig. 2. (a) Measured phase noise power densities (PSDs) for the running 260 km urban fiber link (blue curve), the stabilized fiber link (red curve) and the theoretical prediction (gray curve) (b) Measured phase noise PSDs of the 260 km free-running fiber for a whole day. The average phase jitter integrated from 0.1 Hz to 100 kHz of this free-running 260 km fiber link is about 240 rad.

(Japan) \([21]\). Furthermore, the phase noise PSD of this free-running fiber link exists obvious broad bumps around 1.4 Hz and 15 Hz. The peak variations around these two frequencies appear to be related to human activities, we can reasonably attribute this feature to infra-sound perturbations arising from urban traffic \([32]\). To further characterize the free-running link with the different times, we measured phase noise PSDs of the 260 km free-running fiber for a whole day. The measured total 138 curves are shown in Fig. 2(b). We can observe, the phase noise at the frequency range \( f < 1 \) Hz will fluctuate more than one order of magnitude. We attribute the high phase noise to the fact that this 260 km fiber link is laying underground along a noisy urban area. The measured passively stabilized phase noise PSD (red curve) also shown in Fig. 2(a), which is in good agreement with the PNC theoretical limit (gray dash line) as indicated in Eq. 7. 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 \([22], [23], [29]\).
Complementary to the frequency-domain feature, the time-domain characterization of the corresponding fractional frequency instability in the 260 km noisy urban fiber link is shown in Fig. 5. The fractional frequency instability of the end-to-end frequency measurements are expressed in terms of the OADEV (black squares) and modified Allan deviation (MDEV, red circles). With the implementation of the PNC technique on the 260 km urban fiber link, we demonstrate a stability of $4.9 \times 10^{-14}$ at 1 s integration time and scales down to $4.7 \times 10^{-18}$ at the integration time of 10,000 s for the OADEV with a slope of $\tau^{-1}$, while the MDEV for the same frequency data decreases to $5.1 \times 10^{-20}$ at 10,000 s as a slope of $\tau^{-3/2}$. The results indicate that the white noise is dominated in the phase-compensated fiber link. In our experiment, we observe that the stability of optical frequency transfer is improved by three orders of magnitude at the integration time of 10,000 s by activating the PNC setup.

**Fig. 6.** (a) Frequency comparison between sent and transferred optical frequency through the 260 km urban fiber. The 58,000 data points were taken with a dead-time free II-type frequency counters with a gate time of 1 s (dark cyan points, left axis). The unweighted arithmetic means for all cycle-slip free 500 intervals have been calculated, resulting in 116 data points (orange dots, right axis). (b) Histograms and Gaussian fits for the obtained frequency values. A relative difference between sent and transferred frequency of $(0.41 \pm 4.7) \times 10^{-18}$ is calculated.

**F. Frequency transfer accuracy analysis**

To reveal the existing frequency offset of the transmitted light which may not be disclosed in the instability analysis, we further perform the evaluation of the optical frequency transfer accuracy. Figure 6(a) shows the frequency deviation of the beat-note’s data, recorded with a 1 s gate time and the total 58,000 data (left axis). By averaging the data every 500 seconds, resulting in 116 data points as shown in the right axis of Fig. 6(a). The total 116 data points have an arithmetic mean of 78.9 mHz ($4.1 \times 10^{-15}$) and a standard deviation of 9.2 mHz ($4.7 \times 10^{-17}$), which is a factor of 500 smaller than the ADEV at 1 s as expected for this II-type evaluation. Considering the long-term stability of frequency transfer as illustrated in Fig. 5, we conservatively estimate the accuracy of the transmitted optical signal as shown in the last data point of the ADEV, resulting in a relative frequency accuracy of $4.7 \times 10^{-18}$. We can conclude that there is no systematic frequency offset between the sent and transferred frequencies at a level of a few $10^{-18}$.

**IV. DISCUSSION AND CONCLUSION**

In summary, we for the first time demonstrated coherence transfer of an optical frequency through a 260 km-long urban
fiber with the PNC technique without the effect of the time-base at the local site. Neither precise phase detector with the large dynamic range nor phase locked loop are longer needed.

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