Long-term stable frequency transfer over an urban fiber link using microwave phase stabilization

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Abstract: We report a novel technique for highly stable transfer of a frequency comb over long optical fiber link. The technique implements an electronic compensation loop to cancel out the phase fluctuations that is introduced by the fiber. We utilized this technique to transfer a stable microwave frequency through a 20 km urban fiber link and an 80 km open air fiber link respectively. For the 20 km urban fiber link, the active compensation system reduced the phase fluctuation from 75 mrad (118 ps) to 4 mrad (6.3 ps) in 48 hours, and the frequency stability was improved by three orders of magnitude. For the 80 km open air fiber link, the active compensation system reduced the rms phase fluctuation from 580 mrad (914 ps) to 10 mrad (16 ps) in 24 hours, and the frequency stability was improved by two orders of magnitude.

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1. Introduction

High-stable microwave and optical frequency transfer has a lot of applications in time and frequency metrology, fundamental physics and accurate navigation. Currently, remote frequency distribution is usually achieved by satellite-based techniques such as Two-Way Satellite Time and Frequency Transfer or Global Positioning System (GPS) [1–3], but these techniques are unable to preserve the stability delivered by high frequency source standards. In contrast, recent experiments have demonstrated the transfer of microwave and optical frequencies over optical fiber link with high stability, a few orders of magnitude higher than satellite-based techniques [4–16]. This optical technique takes advantage of the fact that fiber has low attenuation and high reliability [5,16,19]. Although fiber link is a promising method for high stable frequency distribution, it suffers from the environment perturbations such as physical vibration and temperature fluctuations which result in the phase fluctuations (or noises). The phase fluctuations can be reduced by adjusting the optical path [16–19]. Kim et al. reported a high precision timing distribution system with optical cross-correlation to measure the jitter and stabilize the fiber link of 300 m with a fiber stretcher [20]. Holman et al. reported the precise transfer of a high-stability and ultralow-jitter timing signal through a fiber network [21,22]. Lopez et al. introduced a new dissemination system of ultra-stable reference signal at 100 MHz on a standard fiber network via electronic phase fluctuations compensator [23]. However, it is difficult for common spatial adjusting devices to cancel the phase fluctuations in a long fiber link, because the phase drift may be beyond the adjusting-range of the devices. In our paper, we report on a novel technique for stable distribution of a mode-locked laser pulse over a long communication fiber link. The technique utilizes an electronic phase shifter to compensate the phase fluctuations.

2. Objective and phase fluctuations compensation system

The goal of this work is to transfer a high stable frequency signal of 100 MHz synthesized from a rubidium (rb) clock, without degradation of the phase fluctuation and noise. We previously employed a phase compensation system with a spatial optical delay line (ODL) for a 20 km urban fiber link [18]. However, we found that the phase would drift longer than 15 cm equivalent fiber length, and the drift is beyond the adjusting-range of the ODL. The key technology for compensating the phase fluctuations over such a long fiber in this work is to pre-correct the phase of the mode-locked laser before the frequency comb is transferred, analogous to the optical frequency transfer scheme in the reference [7]. We proved that this technique can offer large phase delay compensation with high bandwidth.

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Figure 1 shows the experimental setup of frequency transfer with the electronic phase compensation over an urban fiber link. The link is made of cascaded two 10 km twin fibers connecting Peking University (PKU) and Third Hospital of the University (THPKU). A 1.55μm mode-locked Er: fiber laser emits sub-ps optical pulses at a repetition rate of 100 MHz. The mode-locked laser is phase-locked to a signal from an Rb clock, and a Direct Digital Synthesis (DDS) device as an electronic phase shifter. The output of the mode-locked laser is split into two optical paths. One beam is transmitted to the 20 km round-trip urban fiber and the other is directly detected via a PIN photodiode for the laser phase-locking. The round-trip beam amplified by an erbium-doped fiber amplifier (EDFA) is detected by a high speed PIN photodiode. The phase error signal is constructed by mixing the amplified round-trip signal with the local reference signal synthesized from the same rb clock. The error signal is feedbacked to the DDS phase shifter, and then the phase correction is applied for compensating the phase fluctuations. A phase fluctuations analysis is accomplished with a high resolution voltage acquisition instrument, and a frequency-counting technique is used to provide the way of a measurement of the frequency stability. The signal-to-noise ratio (SNR) of the detected RF fundamental signal is a critical parameter and should be considered [21]. We can adjust the output power of the laser and the gain of the EDFA to maximize the detection SNR. In our experiment, the maximal SNR (75 dB) is obtained by ensuring the average output power of the laser source to be 45 mW so that the signal power from the photodiode to be −5 dBm.

The experimental setup shown in Fig. 1 can be used to evaluate the in-loop transfer performance. The actual out-of-loop transfer performance, as seen at the remote sites, should be also measured. In practice, the out-of-loop performance can be measured by ensuring that the remote site actually is inside the same laboratory, and directly comparing the half-way point signal to the reference source. With this scheme, the beam should be directly reflected at the remote site for ensuring the return signal travels backward on only one fiber. However, the urban fiber link we used is a public communication system and has a lot of physical connection nodes. These nodes will reflect the transmitted beam, affecting on the detection of the return signal from the remote sites. It is not possible to remove and replace these nodes because the fiber link is a real public communication system. Therefore, we replaced the urban fiber link with an 80 km experimental communication fiber deployed at the outdoor environment, to imitate the urban fiber link for measuring the out-of-loop frequency transfer performance. The experimental setup of frequency distribution over the 80 km fiber link is shown in Fig. 2.
The link is obtained by connecting an 80 km experimental communication fiber between the local and remote sites. Both sites are collocated in the laboratory, and the round-trip optical path is 160 km. The output of mode-locked laser is also split into two optical paths. One beam passed through a circulator is transmitted to the 80 km optical fiber and the other is directly detected via a PIN photodiode for the laser phase-locking. At the remote link site, the beam first passes a bidirectional EDFA, and then is reflected by a fiber reflector. A 90:10 coupler outputs the lower beam for the measurement. The error signal constructed by comparing the local reference source and the returned repetition signal delivered from the circulator is amplified, integrated, and fed to the DDS phase shifter.

\[ \phi_{\text{remote}}(t) = \phi_{\text{ref}}(t) + \phi_{c}(t) + \phi_{b} + \phi_{f}(t), \]  

where \( \phi_{\text{remote}}(t) \) is the phase of laser signal at remote site. Equation (1) presents the total one-way phase drift from local site to remote site. Generally, a two-way frequency distribution using the same optical fiber can determine the phase fluctuations accumulated along a full round trip with the hypothesis that the forward and the backward signal are corrupted by the same perturbation [23]. Therefore, at the local site of the link, the phase of round trip signal is expressed as
\[ \varphi_{\text{returned}}(t) = \varphi_{\text{of}} + \varphi_f(t) + \varphi_0 + 2\varphi_f(t), \quad (2) \]

where \( \varphi_{\text{returned}}(t) \) is the phase of round-trip laser signal at local site. From Eq. (2), the phase fluctuation in the round-trip fiber link is \( 2\varphi_f(t) \), and it is easy to obtain the round-trip phase fluctuation by mixing the round-trip RF signal with the reference frequency source. In order to stably distribute a frequency signal to a remote site, a phase correction applied to emission signal must be equal to the opposite of one-way phase fluctuations. Simply it is:

\[ \varphi_f(t) = -\varphi_f(t). \quad (3) \]

The compensation circuit carries out the phase correction according to the round-trip phase fluctuation, and delivers the correction to the electronic phase shifter for compensating the one-way phase fluctuation.

Although the compensation principle is simple, as shown in Eq. (3), the system suffers from some limitations in operation [23]. First, the phase correction is limited by the dynamic bandwidth of the phase shifter. The regulation time of the electronic phase shifter is below 100 ns, i.e. its dynamic bandwidth is from DC to 10 MHz. In practical fiber link, the phase fluctuation affected by environment is less than 10 MHz, and the bandwidth of the phase shifter meets the requirement of the compensation. Second, the electronic devices will introduce excess phase noise. In our experiment, the phase-shifter and phase-detector have an ultra-low phase noise of \(-80 \text{ dBC/Hz@100 MHz}\) at 10 Hz offset and \(-160 \text{ dBC/Hz@100 MHz}\) at 10 MHz offset. The phase noise introduced by long-distance fiber link is larger than that introduced by the devices. Therefore, the phase-shifter and the phase-locking of laser contribute little to the total phase noises of the system. The last limitation is the phase-shift resolution which primarily determines the precision of compensation. Our digital electronic phase shifter has a 12 bits resolution in full 360 degrees at 100 MHz, and the minimal compensation phase is below 2 mrad (3 ps).

3. Experimental results and discussions

Based on the novel compensation technique, we tested the transfer of a high-stable frequency over a 20 km urban fiber link, and evaluated the in-loop transfer performance. Then, we utilized the same technique to transfer the frequency over an 80 km fiber link in open air, measuring the out-of-loop transfer performance.

![Figure 4. Phase fluctuations for frequency distribution. (a) Through 20 km urban fiber link. (b) Through 80 km open air fiber link.](image)

Figure 4(a) shows the phase fluctuations of the distribution through the 20 km urban fiber link. The rms fluctuation in open loop is larger than 75 mrad (118 ps). While in the closed loop, the phase compensation reduces the phase drift to 4 mrad (6.3 ps). Figure 4(b) shows the phase fluctuations of the distribution through the 80 km fiber link. The rms fluctuation in open loop is larger than 580 mrad (914 ps). While in the closed loop, the phase drift is reduced to 10 mrad (16 ps). As expected, the fiber-induced phase noise is reduced by \(-20 \text{ dBC/Hz}\) at low single-band frequency. The noise reduction is limited by the noise floor of our frequency synthesizer. Further experiment would require a lower noise synthesizer.
Figure 5 shows the frequency stability of the stable distribution over the two fiber links. For the 20 km urban fiber link, the stability in the open loop is $\sim 10^{-7}$ for a 1-s gate time and higher than $10^{-8}$ for a 1000-s gate time (filled triangle in Fig. 5). The active phase compensation reduces it by three orders of magnitude to less than $9 \times 10^{-10}$ for a 1-s gate time and three orders of magnitude to less than $10^{-11}$ at 1000-s gate time (filled circle in Fig. 5). For the 80 km fiber link, the stability in the open loop is also $\sim 10^{-7}$ for a 1-s gate time and a few higher than $10^{-9}$ for a 1000-s gate time (filled diamond in Fig. 5). The active phase compensation reduces it by three orders of magnitude to $8 \times 10^{-10}$ for a 1-s gate time and two orders of magnitude to less than $8 \times 10^{-11}$ at 1000-s gate time (filled cross in Fig. 5). The frequency stability for the closed loop is approaching to that of the reference signal. This shows that the compensation technique ensures the transmitted signal preserving the stability in the long-term transfer. The reference frequency stability (filled square in Fig. 5) is merely the upper bound of the stability incurred during transfer of microwave signal. Further experiment would require a more stable reference source.

The advantage of the system is that the compensation range is from 0 to $2\pi$. The maximum phase fluctuation of an uncompensated practical fiber link will be larger than $2\pi$, and this system can also compensate it by skipping a cycle. The resolution of phase compensation could be the key factor to the stabilization, and our electronic phase shifter offers a 1 mrad resolution. A new technique with higher shift-resolution is under investigation for the case requiring lower phase fluctuations.

4. Conclusions

A long-term stable frequency transfer utilizing a microwave phase stabilization technique is demonstrated. This novel stabilization system introduces a digital electronic phase shifter to compensate the phase fluctuations introduced by fiber link. With this method, the stabilized 20 km urban fiber link reduces an rms phase fluctuation from 118 ps to 6.3 ps in 48 hours and improves the frequency stability by three orders of magnitude. The stabilized 80 km open air fiber link reduces an rms phase fluctuation from 914 ps to 16 ps in 24 hours and improves the frequency stability by two orders of magnitude. Further improvement is possible by locking the laser to a more stable reference.

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