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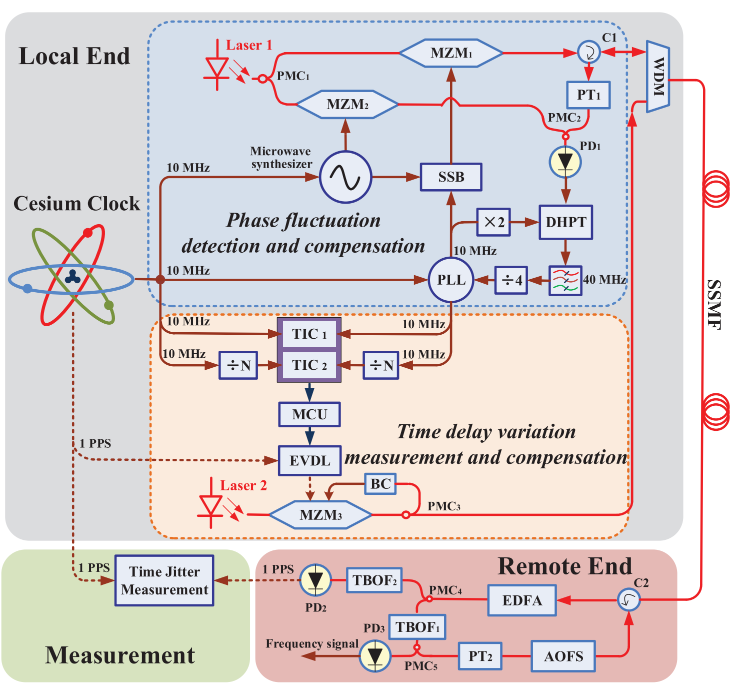

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Joint Frequency and Time Transfer Over Optical Fiber With High-Precision Delay Variation Measurement Using a Phase-Locked Loop

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Abstract: We demonstrate a simultaneous frequency and time reference dissemination system over 80 km fiber with a phase-locked loop. The phase fluctuation of the transferred radio-frequency (RF) signal is compensated by adjusting the frequency of the voltage-controlled oscillator (VCO), ensuring a highly stable RF signal at the remote end. The high-precision fiber delay variation is simultaneously obtained with a resolution of sub-picosecond by monitoring the phase of the VCO. In order to break the limitation of phase ambiguity and obtain wide-range delay variation measurement, we employ an auxiliary frequency-divided phase measurement branch. A stable time reference transfer is realized after the accurate delay compensation. Experimentally, the frequency stability of the dissemination system with an Allan deviation achieves 1.2×10^{-17} at 10 000 s averaging time, and the time stability with the time deviation reaches 0.97 ps at 4000 s averaging time. The root mean square jitter of the time distribution system is about 6.6 ps.

Index Terms: Microwave photonics, fiber optic systems, time and frequency transfer.

1. Introduction

The dissemination of a frequency reference between two distant sites plays an important role in the fundamental physical constant measurements, relativistic geodesy, and gravitational wave detection etc. [1]–[3]. Along with the development of high-precision atomic clocks, the conventional satellite-based transfer system cannot meet the requirements for the reference stability and precision [4], whereas the optical fiber link shows incomparable advantages such as the low loss, large bandwidth and electromagnetic immunity [5]. However, mechanical stress and temperature variations of the fiber link cause transmission delay variations, which degrade the stability of the transferred reference at the remote end. To date, most works have focused on the dissemination of the frequency reference via optical fiber [6]–[13], and the transfer instability is carefully compensated. While the simultaneous frequency and time dissemination is less studied, which is also important in some particular applications such as the antenna arrays for deep space exploration [14], [15].

To realize stable frequency and time transferring via an optical fiber link, there are generally two types of schemes. One is to implement two-way frequency and time transfer over the same fiber [16], [17]. The local signal and the received signal are compared on both sides. The impact of the propagation delay fluctuation can thus be significantly reduced. Therefore, it is often used to realize the reference comparison between two sites rather than to distribute the frequency and time reference to the remote end. The other method is based on the round-trip detection to measure the phase fluctuation and propagation delay. A feedback system is often adopted to compensate for the fluctuation of the reference signal [18]–[20]. Adopting a common optical carrier modulated by the frequency and time signal can reduce the system complexity [18], [19], but it will induce serious crosstalk interference between the frequency signal and the time signal. To avoid the crosstalk interference, the frequency signal and time signal are often transmitted separately by two independent systems [20]. Thus the phase fluctuation of the frequency signal and the time delay variation of the time signal need to be measured separately, resulting in a bulky and complex system setup. In addition, the transmission delay is usually measured with a time interval counter (TIC) directly, which limits the measurement precision to several ps or tens of ps.

Previously, we have shown the usage of a phase-locked loop (PLL) for stabilizing a frequency reference distribution [13]. In this letter, we further propose a joint frequency and time dissemination system with high-precision delay variation measurement. When the PLL is locked, the phase fluctuation of the frequency signal induced by the fiber propagation delay variation is compensated by the voltage-controlled oscillator (VCO), ensuring a stable radio-frequency (RF) signal at the remote end. Meanwhile, the real-time delay variation of the fiber link can be accurately obtained by comparing the phase difference between the VCO and the frequency reference, which avoids the additional propagation delay measurement equipment and crosstalk interference. Moreover, an auxiliary frequency-divided phase measurement branch is employed to extend the measurement range. An accurate time dissemination system is finally realized after the delay variation compensation. We experimentally demonstrate a one pulse per second (1 PPS) time dissemination system accompanying a stable 20.02 GHz RF signal transfer via 80 km standard single-mode fiber (SSMF). The frequency stability with Allan deviation is measured to be 1.2×10^{-17} at 10000 s averaging time. The root mean square (RMS) jitter of the time transmission system is about 6.6 ps, and the time deviation reaches 0.97 ps at 4000 s averaging time.

2. Principle

The schematic diagram of the joint frequency and time dissemination system is shown in Fig. 1. A cesium clock is used as the reference clock that generates a 10 MHz frequency standard and a 1 PPS time standard at the local end. The local end can be divided into two modules by functionality. The first part realizes the phase fluctuation detection and compensation of the frequency signal. The second part measures and compensates the time delay variation of the time signal. In order to avoid the interference between the frequency signal and the time signal, two lasers carrying the frequency and time signal are transferred from the local end to the remote end via the same fiber link independently. At both ends of the optical transmission link, optical circulators (C1, C2) are used to separate the transmitted and received signals. The stable frequency signal and accurate time signal dissemination is realized as follows.

2.1 Phase Fluctuation Detection and Compensation

In the phase fluctuation detection and compensation module, the 10 MHz frequency standard is used as the external reference to synchronize a microwave synthesizer that generates the RF signal. Then a 10 MHz VCO signal from the PLL modulates the RF signal with a single-sideband modulator (SSBM) for phase pre-compensation. The modulated RF signal then modulates the laser 1 with a carrier-suppressed double-sideband (CS-DSB) scheme in a Mach-Zehnder modulator (MZM).

At the remote end, an erbium-doped fiber amplifier (EDFA) is used to compensate for the power loss caused by the long-haul transmission. Two tunable bandpass optical filters (TBOF) are adopted

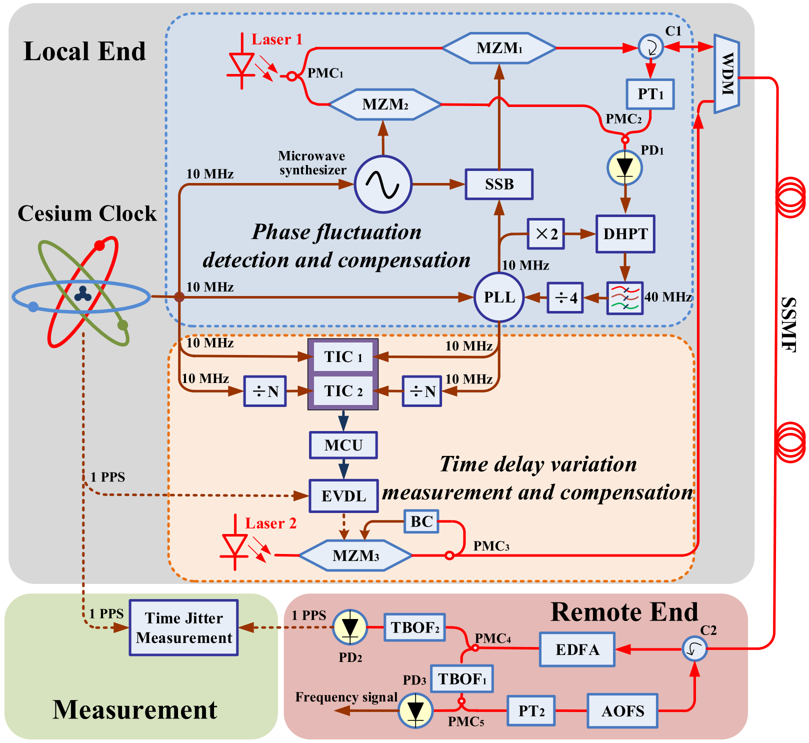

Fig. 1. Schematic diagram of the joint frequency and time dissemination system. EVDL, electronic variable delay line; MCU, microprocessor control unit; TIC, time interval counter; MZM, Mach-Zehnder modulator; BC, bias control; SSBM, single sideband modulator; PLL, phase-locked loop; WDM, wavelength division multiplexer; SSMF, standard single-mode fiber; PT, polarization tracker; PD, photodetector; DHPT, dual-heterodyne phase error transfer; EDFA, erbium-doped optical fiber amplifier; AOFS, acousto-optic frequency shifter; TBOF, tunable bandpass optical filter; $\times$ 2, frequency doubler; $\div$N, frequency divider.

to suppress the amplified spontaneous emission noise and guarantee the spectral purity of the frequency and time signal. The remote RF signal can be obtained with a high-speed photo-detector (PD), which can be expressed as

$$E_{RF}(t) = \cos\left[2\left(\omega_{RF} + \omega_{VCO}\right)t - 2\left(\omega_{RF} + \omega_{VCO}\right)\tau(t) + 2\varphi_v(t)\right], \tag{1}$$

where ω_{RF} and ω_{VCO} are the angular frequency of the RF signal and the VCO, respectively; $\tau(t)$ is the propagation delay variation of the fiber link; $\varphi_v(t)$ is the instantaneous phase of the VCO. It can be seen that the phase fluctuation $(\omega_{RF} + \omega_{VCO})\tau(t)$ is caused by the fiber delay variation $\tau(t)$, which can be compensated by adjusting $\varphi_v(t)$ of the VCO.

Due to high reciprocity of the forward and backward signal path, the returning signal experiences approximately the same fiber noise as the forward signal, i.e., the round-trip signal exhibits twice the one way phase fluctuation and suffers fourfold the phase fluctuation according to (1). At the local end, the round-trip frequency signal will require an additional twice $\varphi_v(t)$ for phase compensation. Through the proposed dual-heterodyne phase error transfer (DHPT) scheme [21] and a series of electric mixing processing, the phase fluctuation of the RF signal induced by the fiber delay variation is identically transferred to a 40 MHz intermediate frequency (IF) signal, which can be written as

$$E_{IF}(t) = \cos\left[4\omega_{VCO}t - 4\left(\omega_{RF} + \omega_{VCO}\right)\right]\tau(t) + 4\varphi_v(t). \tag{2}$$

After fourfold dividing the $E_{IF}(t)$ and comparing it with the 10 MHz cesium clock, the phase error discriminated by a digital phase and frequency detector is first integrated into a loop filter and then is used to control the VCO. When the PLL is locked, the phase relationship between $E_{IF}(t)$ and the cesium clock will satisfy the relation

$$\varphi_v(t) - (\omega_{RF} + \omega_{VCO})\,\tau(t) = \varphi_{Ce}, \tag{3}$$

where φ_{Ce} is the initial phase of the cesium clock, and it is considered as a constant.

By substituting (3) into (1), we obtain

$$E_{RF}(t) = \cos\left[2(\omega_{RF} + \omega_{VCO})\,t + 2\varphi_{Ce}\right]. \tag{4}$$

It yields that the delay variation induced phase fluctuation has been canceled, and a highly stable RF signal is obtained at the remote end. The stability of the frequency reference transmission paves the way for the time reference distribution.

2.2 Time Delay Variation Measurement and Compensation

In the time delay variation measurement and compensation part, when the loop is locked, the output of the PLL can be expressed as

$$E_{VCO}(t) = \left[\cos\omega_{VCO}t + (\omega_{RF} + \omega_{VCO})\,\tau(t) + \varphi_{Ce}\right]. \tag{5}$$

It can be seen that the phase of the VCO is equal to the phase fluctuation of the RF signal which characterizes the fiber propagating delay variation $\tau(t)$. Therefore, by measuring the phase difference between the VCO and the cesium clock signal, the time delay variation can be obtained, avoiding additional delay measurement process. More specifically, the delay variation can be expressed as

$$\tau(t) = \frac{\varphi_v(t) - \varphi_{Ce}}{\omega_{RF} + \omega_{VCO}}. \tag{6}$$

It should be highlighted that the sensing of the fiber propagating delay is in the RF level rather than in the IF level. The higher the frequency of the signal is transmitted, the higher the resolution and accuracy of the delay variation measurement will be achieved. Thus the proposed delay variation measurement has very high resolution. However, the range of the phase measurement is limited within one period of the transmission RF signal, which is known as the phase ambiguity. In order to break this limitation and achieve a wider measurement range, we add an auxiliary phase measurement branch where the VCO signal and the cesium clock are divided by an integer N to a lower frequency [22]. In this case, the distinguishable delay range is increased by N times.

The phase difference between the VCO and the cesium clock is measured in the two branches simultaneously by two TICs (TIC1 and TIC2). The real-time delay variation is calculated with a microprocessor control unit (MCU) by combining the two measured phase differences from the two branches. The branch without frequency division ensures the precision while the frequency divided branch greatly extends the measurement range. The MCU then feedback control an electronic variable delay line (EVDL) through which the 1 PPS time signal from the cesium clock first passes for time pre-compensation. The time-shifted 1 PPS signal then modulates the laser 2 with another MZM and is transferred to the remote end. A bias-controller (BC) is used to lock the MZM at its quadrature point.

For the proposed delay variation measurement, we use laser 1 to detect the delay variation of the fiber link and use laser 2 to transfer the 1 PPS signal so that the frequency signal and the time signal will not interfere with each other. The dispersion-induced delay variation difference between the two wavelengths can be expressed as

$$\Delta\tau = \Delta L * \Delta\lambda * D, \tag{7}$$

where ΔL is the equivalent fiber length variation induced by temperature and strain variation; $\Delta\lambda$ is the wavelength difference between the two laser; D is the fiber dispersion coefficient (about 17 ps/nm/km for SSMF). Even if the fiber is tens of kilometers long, ΔL is still usually within 1 m. Thus the $\Delta\tau$ is in the order of tens of fs, which can be reasonably omitted. Compared with the constant wavelength difference, the relative stability of the two lasers is more essential because

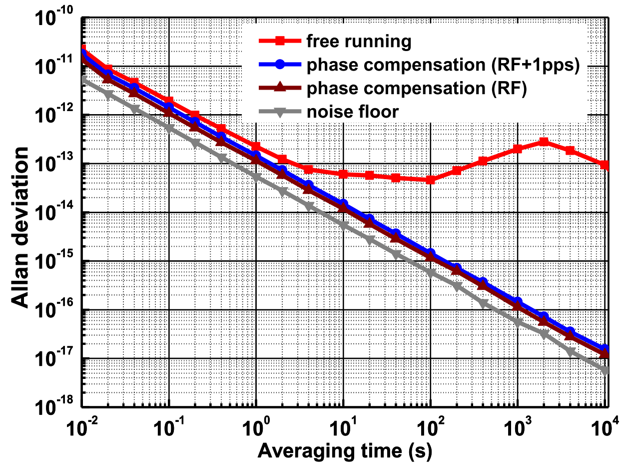

Fig. 2. The frequency stability of the dissemination system in the condition of phase-locked 80 km fiber, free running, and phase-locked 1 m fiber.

the dispersion will change the total transmission delay of the frequency and time signal. In order to achieve a compensation precision better than 1 ps for an SSMF link of 100 km, the relative drift of the two lasers should be within 100 MHz. In addition, by using dispersion compensation fiber, the chromatic dispersion between different wavelengths can be eliminated completely.

3. Experiment and Results

An experiment based on the configuration in Fig. 1 is implemented. The remote end is connected with the local end via 80 km SSMF. The wavelengths of laser 1 and laser 2 are set to 1550 nm and 1553 nm with high stability to minimize the dispersion induced delay variation. The synchronous microwave synthesizer generates a 10 GHz signal. Then a 20.02 GHz RF signal can be obtained at the remote end due on the CS-DSB scheme. The TIC 1 and TIC 2 (SRS SR620) with a resolution of 25 ps are used for delay variation measurements. The precision of the EVDL (SDI DL-1) in our system is 0.5 ps.

We first establish the stable frequency dissemination, which is also the essential basis for precise time signal distribution. As shown in Fig. 1, the 40 MHz beat signal characterizes the phase fluctuation of the remote RF signal according to (1) and (2). Thus it is used for evaluating the frequency stability of the distribution system with an Allan Deviation test set (Microsemi 5125A). The loop bandwidth is mainly determined by the optical fiber link length and phase-noise suppression bandwidth. A large bandwidth may cause the loop instability and the increase of the total phase noise; while a small bandwidth may hinder the system to suppress the phase noise of high-frequency components. The phase locked 80 km system loop bandwidth is optimal to be approximately 200 Hz in our experiment. Fig. 2 shows the Allan deviation of the frequency dissemination system in phase-locked and the free-running. The system noise floor is also measured by replacing the 80 km spooled fiber with a 1 m fiber patch cord. In this case, the signal power is adjusted to the same level of the long fiber case. The frequency stability of the free-running system is 9.4×10^{-14} at 10000 s averaging time. With the feedback phase compensation, the frequency stability is improved nearly four orders of magnitude to 1.5×10^{-17} at 10000 s averaging time. Meanwhile, the frequency stability of the compensation system does not significantly deteriorate under the condition of simultaneous transmission of frequency and time signals. It validates the effectiveness of the proposed simultaneous frequency and time dissemination system for interference suppression. The fitted curves show that the frequency stability is proportional to the τ^{-1}, indicating that the residual noise is white phase noise dominated.

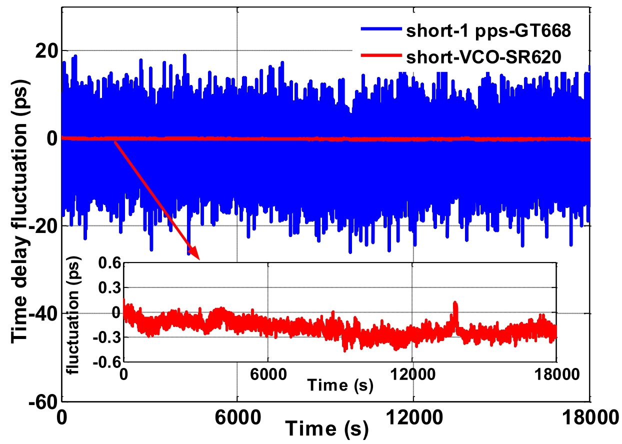

Fig. 3. The delay fluctuation of the 1 m fiber link measured by the proposed phase difference measurement scheme and the traditional 1 PPS detection method.

Once the frequency signal is stably transferred, the fiber delay variation can be simultaneously obtained as described earlier. To verify the accuracy of the proposed fiber delay variation measurement, the 1 m long fiber transfer system is first tested as the measurement noise floor. As a comparison, we transfer a 1 PPS signal and use a TIC to directly measure the delay fluctuation. Due to the limited experimental equipment, the high-precision TIC (Guide Tech GT668, 1 ps time resolution) is used for traditional 1 PPS detection method, and the low-precision TIC1 is used for the proposed phase measurement based scheme with a sample interval of 1 s. As shown in Fig. 3, the long-term fluctuation of the 1 PPS detection method increases to $\pm$20 ps, and its statistical error exceeds 6 ps. While the long-term fluctuation of the proposed phase difference measurement scheme is reduced to approximately $\pm$0.4 ps, and the statistical error drops to about 60 fs. Thanks to the RF-level delay sensing and phase difference measurement instead of the direct time measurement, the proposed scheme with a TIC whose resolution deteriorates by twenty times still improves the measurement accuracy by two orders of magnitude compared with the pulse detection method.

To obtain a wide-range and high-accuracy delay variation measurement for an 80 km fiber dissemination system, both phase difference measurement branches are adopted simultaneously. The frequency-undivided branch is used to obtain high precision measurement benefiting from the RF-level delay variation sensing. Meanwhile, the auxiliary branch divides the VCO and the cesium clock by 125, avoiding the phase ambiguity and reaching a wider measurement range. The MCU then converts the measured phase difference from two branches into the fiber delay variation. After the precise delay variation measurement, the time variation compensation is implemented. The MCU uses the delay variation information to feedback control the EVDL in real time to shift the transmitted 1 PPS signal. The timing jitter of the dissemination system is measured by recording the time delay fluctuation acquired with a TIC (Guide Tech GT668) as shown in the measurement module of Fig. 1. The time delay fluctuation of the system with and without time compensation is shown in Fig. 4. It can be seen that the time variation of 80 km fiber link at free-running is about $\pm$2 ns during 18000 s, which is reduced to about $\pm$20 ps after time compensation. The RMS jitter of the time system is also measured to be about 6.6 ps during 18000 s. The comparison of the time delay fluctuation of 1 m dissemination system in Fig. 3 and the time-compensated 80 km dissemination system in Fig. 4 indicates that the compensation ability in the long fiber case is very close to the system noise floor, proving the feasibility and the validity of the dissemination system.

The time stability of the dissemination system is shown as a time deviation in Fig. 5. The time-compensated 80 km fiber system improves the stability by nearly three orders of magnitude to 0.97 ps at 4000 s averaging time. The long-term time stability of the time-compensated 80 km system slightly deteriorates that of the short fiber system, which is caused by the imperfect symmetry of the forward and backward transmission paths. Currently, the accuracy and stability of

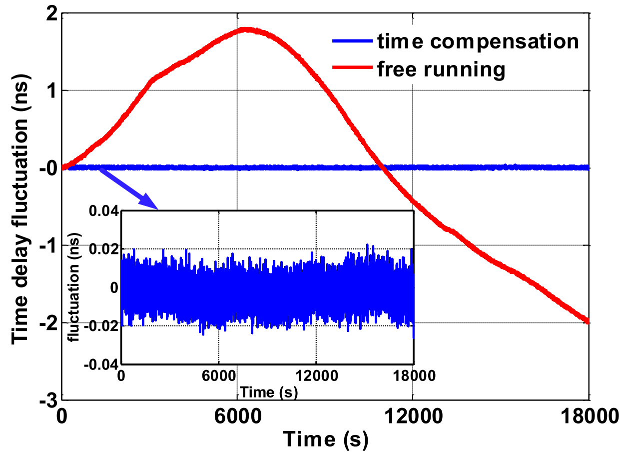

Fig. 4. The time delay fluctuation of the dissemination system with and without compensation over an 80 km fiber link.

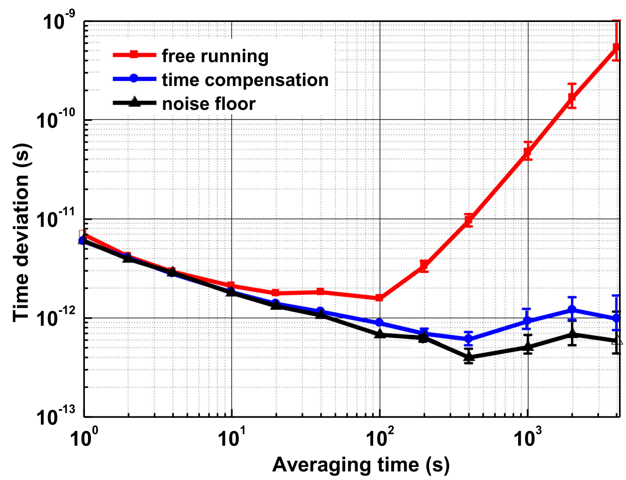

Fig. 5. The time deviation of the dissemination system in condition of time-compensated 80 km fiber, free running, and 1 m fiber.

the time distribution are not limited by the delay variation measurement but mainly by the electrical noise (jitter) of the compensation equipment and the relative stability of the two lasers. Once the compensation precision is improved, the superiority of the proposed delay variation method for the time dissemination will be more prominent. In addition, highly stable lasers can be used to "further" improve system performance.

4. Conclusions

In conclusion, we have realized a time dissemination system along with stable frequency transfer using a phase-locked loop over an 80 km fiber link. After the frequency signal being stably transferred to the remote end, the fiber delay variation is directly obtained from the phase information of the loopback frequency signal, which avoids the additional transfer delay measurement equipment. Transmission delay variation measurement with a resolution of sub-picosecond is achieved without sacrificing the measurement range, thanks to the RF-level delay sensing and dual-branch phase difference measurement. The frequency stability of 1.5×10^{-17} at 10000 s averaging time is achieved. The RMS jitter of time dissemination over 80 km fiber link is 6.6 ps, and the time deviation is measured to be 0.97 ps at 4000 s averaging time. Owing to its high-precision detection and compensation for the delay variation, this joint frequency and time dissemination system can find its versatile applications that require very accurate timing information.

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