Timing jitter reduction over 20-km urban fiber by compensating harmonic phase difference of locked femtosecond comb

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A novel timing jitter reduction system over a round trip 20-km urban fiber link is reported. The phase difference of the ninth harmonic of a high-repetition-rate mode-locked laser between the local and the returned signals is obtained. Based on the phase difference, the system uses an optical delay line (ODL) to compensate the optical fiber link. The root-mean-square (RMS) timing jitter is reduced from 50 to 8.9 ps in 80 min.

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Accurate long-distance distribution of radio-frequency (RF) and optical timing signal has a lot of applications. There have been a few ways available including direct radio communication, satellite communication, and global positioning system (GPS)[1−4]. However, radio communication systems are not able to leverage the high-stability, low-averaging-time frequency distribution, because the communication channel would be seriously affected by environment in the long-term transfer. A good candidate for distribution of high-stability frequency timing references is an optical fiber link[5,6]. Although fiber link is a promising method for high precision timing distribution, it suffers from the environment perturbations such as vibration and temperature fluctuations, which introduce phase fluctuations (or noises) and result in timing jitter[7−9]. The phase fluctuations and timing jitter can be reduced by compensating the optical path difference and can be compensated by acousto-optic modulators (AOMs) or optical delay line (ODL)[10−14]. Holman *et al.* reported a remote transfer of high-stability signal via a mode-locked fiber laser through a 6.9-km round trip fiber network[15]. Kim *et al.* reported a high precision timing distribution system with optical cross-correlation to measure the jitter and to stabilize the fiber link with a fiber stretcher, where the timing signal was emitted from an Er-doped fiber laser[16,17]. However, the optical method is difficult to be applied to measure the fluctuations and jitter in a fiber link as long as tens of kilometers, because the fiber length variation can be longer than the optical pulse width[13−15]. To realize the long-distance fiber link stabilization, we introduce a RF detection and compensation system to stabilize a 20-km urban fiber link for the timing jitter reduction.

Our experiment was performed to transfer the femtosecond mode-locked laser pulses with repetition rate of 100 MHz over a 20-km round trip communication fiber link. The timing jitter of returned RF signal will be reduced by compensating the phase difference of the 900-MHz signals (ninth harmonic of the mode-locked laser pulses). The system using 900-MHz signals (ninth harmonic) presents two advantages in experiment compared with other harmonics. Firstly, using the high harmonics can improve the resolution of compensation. A shorter wavelength presents more accurate compensation of phase fluctuation. Secondly, we can apply RF devices to 900 MHz in operation, because many microwave devices are designed to work in 900-MHz RF band.

Figure 1 shows the schematic diagram of the fiber link, which is the communication fiber between the Network Center of Peking University and the Third Hospital of Peking University with the round trip of 20 km. Figure 2 shows the experimental setup for timing jitter reduction over an urban fiber link. We utilized a femtosecond mode-locked fiber laser to stabilize a long fiber link and transfer a low timing jitter RF signal. The timing signal was from a mode-locked Er-doped fiber laser at the repetition rate of 100 MHz. The pulse width was less than 1 ps and the bandwidth was 10 nm. The average output power was 40 mW. The output of the fiber laser was split into two portions. One was sent to the optical fiber link via an ODL and the other was directly detected via a PIN photodiode.

Both the two portion signals detected by photodiodes were amplified, and the 900-MHz signal, ninth harmonic of the signal, was extracted through a band pass

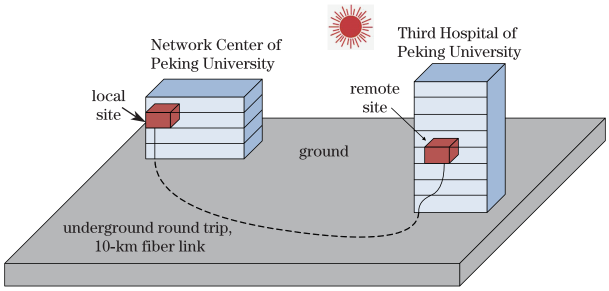

Fig. 1. Link schematic diagram between local site and remote site.

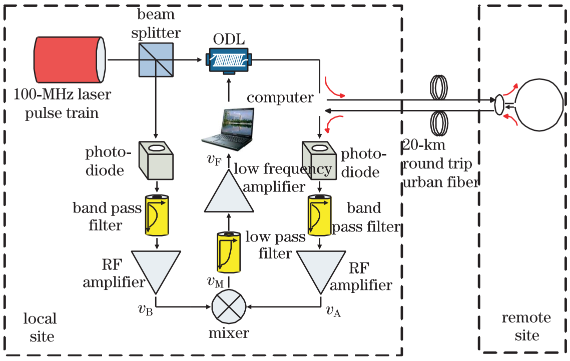

Fig. 2. Experimental setup for timing jitter reduction over an urban fiber link.

filter (BPF) in each arm. The resultant RF signals were mixed in a low noise mixer. The low frequency component was filtered out and converted into a feedback signal to drive an ODL. The ODL, a mechanical device, was used to introduce an optical path delay and cancel the optical noise. Our delay line device delivered a time delay as much as 500 ps.

The voltages of 900-MHz harmonics are given by

$$v_A = A\cos(\omega t + \theta_0), \tag{1}$$

$$v_B = B\cos(\omega t + \theta_0 + \Delta\theta), \tag{2}$$

where v_A is the detected voltage of 900-MHz harmonic when the beam is transmitted directly in this routine; v_B is the detected voltage of 900-MHz harmonic when the beam is transmitted over the 20-km urban fiber in this routine; ω is the ninth harmonic angular frequency; θ_0 is the initial phase; $\Delta\theta$ is the phase difference when the beam is transferred over 20-km fiber link; A is the amplitude of v_A and B is the amplitude of v_B.

The two harmonic voltages (v_A,v_B) were mixed in the low noise mixer multiplier. By filtering the low frequency component, the phase difference which contained the information of optical path length difference was obtained. The voltage of output signal after the mixer is given by

$$\begin{aligned} v_M &= v_A \cdot v_B = A\cos(\omega t + \theta_0), \\ & B\cos(\omega t + \theta_0 + \Delta\theta) \\ &= -\frac{AB}{2}\left[\cos(2\omega t + 2\theta_0 + \Delta\theta) + \cos(\Delta\theta)\right]. \end{aligned} \tag{3}$$

The output of the mixer includes two frequency components. One is the direct current (DC) component and the other is the double-frequency (2ω) one. We used a low pass filter (LPF) to remove the 2ω component and remain the DC one. Then the weak DC signal was amplified to 50 times by a low frequency amplifier in the system. The voltage of output signal after amplifier is given by

$$v_F = -\frac{ABG}{2}\cos(\Delta\theta), \tag{4}$$

where G is the gain of the low frequency amplifier.

Since we use the ninth harmonic to obtain the optical path difference, the timing jitter Δt is deduced to

$$\Delta t = \frac{\Delta L}{c} = \frac{\lambda\Delta\theta}{2\pi c} = \frac{\Delta\theta}{\omega}, \tag{5}$$

where ΔL is the optical path difference; λ is the RF wavelength of 900-MHz harmonic; c is the light velocity.

Based on Eqs. (4) and (5), the relationship between Δt and v_F is given by

$$\Delta t = \frac{\Delta\theta}{\omega} = \frac{1}{2\pi f}\arccos\left(-\frac{2v_F}{ABG}\right). \tag{6}$$

The amplified DC signal was directed into a computer via a 16-bit analog-to-digital card. The computer calculated Δt as Eq. (6) and converted Δt into a voltage signal to drive the ODL in the link.

We measured the phase difference for the open and the closed loops, respectively. Both measurements took 80 min. The phase difference signal measured in computer was a low frequency voltage v_F, as described in Eq. (4). Figure 3 shows the measured results for open and closed loops. Figure 3(a) shows that the difference varies by 0.4 V for the open loop within the measurement time. On the contrary, Fig. 3(b) shows that the difference becomes flat as the system is stabilized by the feedback with the active ODL.

We calculated the measured voltages shown in Fig. 3 and carried out the timing jitter calculation with Eq. (6). Figure 4 shows the calculated root-mean-square (RMS) timing jitter for the open and closed loop fiber links. The RMS timing jitter for the open loop is about 50 ps, while that for the closed loop is reduced to 8.9 ps.

In this experiment, the ODL device was a low speed device with the response time of 3 s. Therefore we can only compensate the low frequency part of timing jitter which is the main factor that exacerbates long distance timing distribution. This can be seen from Fig. 4(a), where the phase fluctuation is very slow. Therefore, the

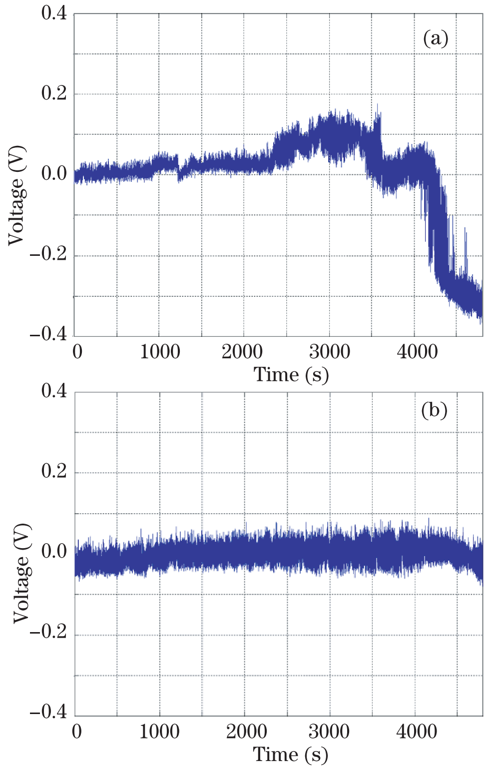

Fig. 3. Measured v_F in (a) the open loop and (b) the closed loop.

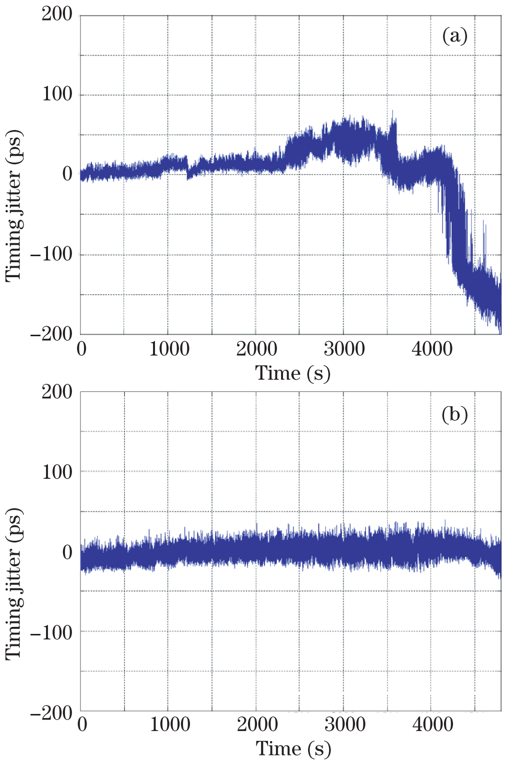

Fig. 4. Timing jitter in (a) the open loop and (b) the closed loop.

low speed of the active ODL is not a limitation for the phase compensation in this experiment. The other limitation could be the limited delay time of the ODL. The ODL used in this experiment offers only a time delay of 560 ps. However, it is also seen from Fig. 4(a) that the time jitter is at most 200 ps within the measurement time, and the limited delay time is not a problem yet.

However, in practical situations for a longer time, the maximum timing jitter of an un-stabilized fiber link can be larger than 500 ps in long-range application. Therefore, a better ODL or an alternative way of compensation should be applied instead. The new technique is under investigation.

In conclusion, a long-range timing jitter compensation technique is demonstrated by comparing the ninth harmonics phase difference of mode-locked laser pulses between the emission and the round trip returned beam. This stabilization system introduces a novel method using high harmonic of mode-locked laser pulses to compare the phase difference in urban fiber link. With this method, we successfully transfer an ultra-short pulse train through a 20-km round trip urban fiber link. The stabilize fiber link demonstrates a RMS timing jitter of 8.9 ps in 80 min.

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