A Round-Trip Fiber-Optic Time Transfer System Using Bidirectional TDM Transmission

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***Abstract*—We propose a round-trip fiber-optic time transfer scheme over single optical fiber utilizing the same wavelength in both directions. It can suppress the impact of the Rayleigh backscattering and the dispersion-induced symmetric deviation over fiber link by using bidirectional time division multiplexing (TDM) mechanism. A 200 km time transfer over single optical fiber with identical optical wavelength in both directions is demonstrated. The measured stabilities in terms of TDEV are less than 40ps/s and 10ps/d, respectively. The uncertainty induced by uncalibrated fiber links up to 200km is less than 27 ps, which is mainly limited by the performance of used time interval counters.**

Keywords—time transfer; optical fiber; round-trip; time division multiplexing.

I. INTRODUCTION

Fiber-optic time transfer has attracted widespread research interest [1-7] because of its advantages of low loss, high reliability, wide bandwidth and high stability, and satellite-based time transfer is difficult to eliminate the effects of fluctuations and interferences induced by atmosphere [8-9]. Up to now, fiber-based time transfer mainly concentrates on two-way [1-2] and round-trip [3-7] dissemination using bidirectional wavelength division multiplexing (WDM) transmission that can suppress the impact of the Rayleigh backscattering by using WDM filter. The bidirectional WDM-based scheme, however, will cause bidirectional propagation delay mismatch induced by the chromatic dispersion, which will degrade the precision and accuracy of time transfer. Although some calibration methods can be used to measure the propagation delay mismatch, the uncertainty and difficulty to calibrate the mismatch will increase with the increase of fiber link length since the effect of the measurement errors of the dispersion coefficient and wavelength will increase linearly with the increase of fiber length.

We have proposed a bidirectional time division multiplexing (TDM) based two-way time transfer scheme [1], which can suppress the effects of the Rayleigh backscattering and keeps the bidirectional symmetry of fiber propagation delay at the same time. In this paper, we propose a bidirectional TDM based round-trip time transfer scheme over signal fiber with same wavelength to disseminate time signals from reference clock directly to user with high-precision.

II. SYSTEM CONFIGURATION

Figure 1 illustrates the proposed round-trip time transfer system based on bidirectional TDM transmission schematically. The time signal (one-pulse-per-second, 1PPS) from the clock at site 1 is entered into the local modem. In the modem, the input time signal from clock is encoded into a time code by an encoder [7], and carried on the light with a wavelength of λ through an optical transmitter (E/O converter). The light from the optical transmitter is launched into the optical fiber link by switching on the optical switcher (OS) 1, which is switched off in non-transmission durations of time code. As the light carrying time code arrives at site 2, the optical signal is converted to electrical signal by an O/E converter, which is sent to decoder to extract the time signal in it. The recovered time signal is delayed by a Time Delay Adjuster (TDA) until the whole time code has been received. The delayed time signal is then encoded into a time code again and transmitted back to site 1 over the same fiber link with the same wavelength λ after turning on the OS 2, which is also switched off in non-transmission durations of time code. The time signal in the returned time code is extracted, and the round trip delay of fiber link is measured by TIC (time interval counter) 1. The time delay of TDA at site 2 is also measured by a TIC (TIC 2 in Fig.1).

Figure 1 (b) illustrates the timing sequence diagram for the bidirectional TDM based round-trip time transfer scheme. We have

$$
\begin{aligned}
T_{LR} &= \tau_T^L + \tau_F^{LR} + \tau_R^R \\
T_{RL} &= \tau_T^R + \tau_F^{RF} + \tau_R^L \\
T_{LL} &= T_{LR} + T_{RL} + T_A
\end{aligned}
\tag{1}
$$

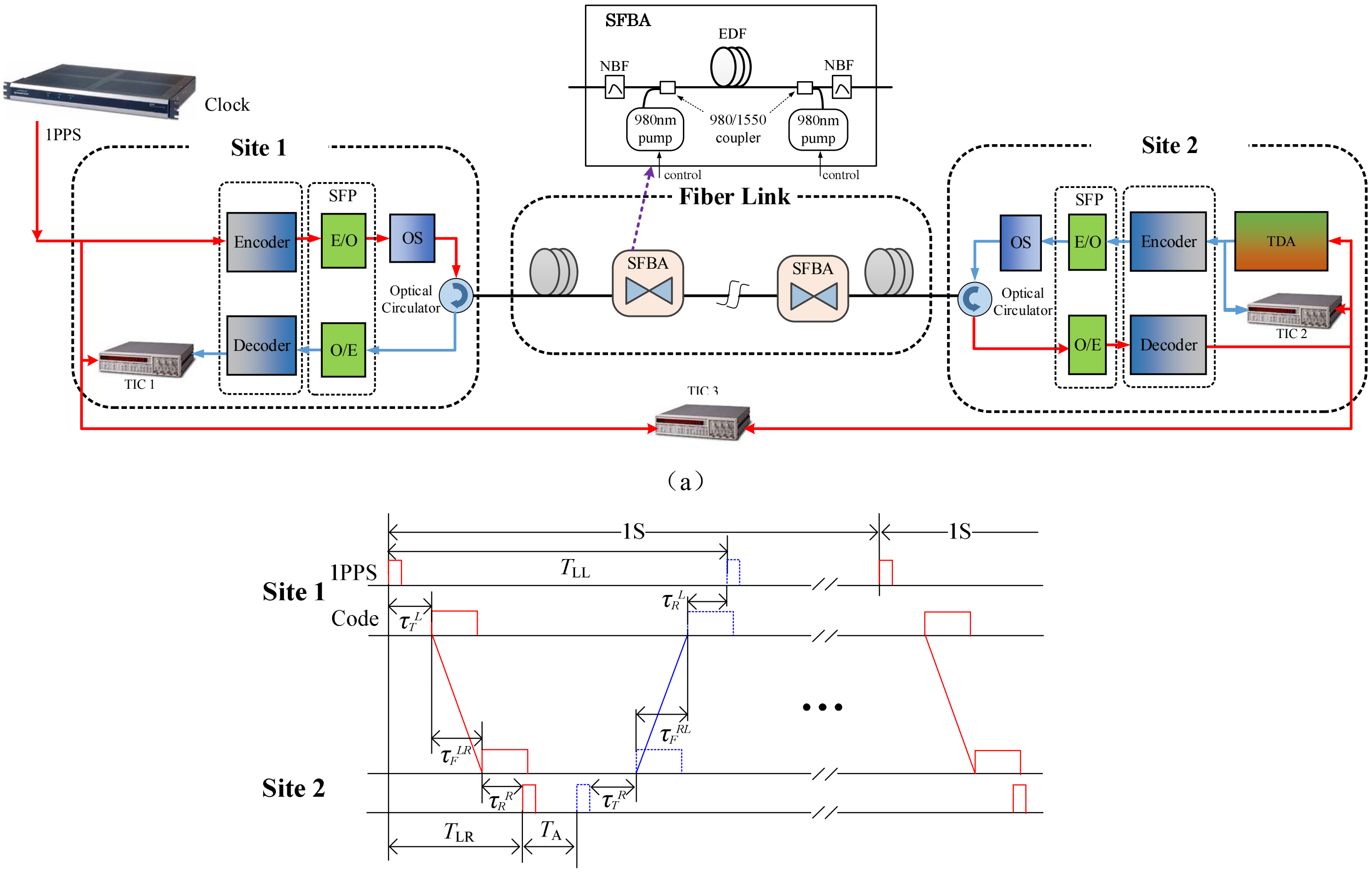
where, T_{LR} (T_{RL}) is the one-way propagation delay from site 1(2) to site 2(1); T_{LL} is the round trip delay measured by TIC 1 at site 1; $\tau_F^{LR}(\tau_F^{RL})$ is the propagation delay of optical fiber link from site 1 (site 2) to site 2 (site 1); $\tau_T^L(\tau_T^R)$ is the time delay from the input of encoder to the optical output port in site 1 (site 2); $\tau_R^R(\tau_R^L)$ is the time delay from the optical input port to the output of decoder in site 1 (site 2) ; T_A is the time delay of the TDA measured by TIC 2 at site 2.

From Eq (1), one can obtain:

$$\begin{aligned} T_{LR} &= \frac{1}{2}\left[T_{LL}-T_{A}-T_{RL}+T_{LR}\right] \\ &= \frac{1}{2}\left[T_{LL}-T_{A}+\left(\tau_{F}^{LR}-\tau_{F}^{RF}\right)+\left(\tau_{T}^{L}-\tau_{R}^{L}+\tau_{R}^{R}-\tau_{T}^{R}\right)\right] \end{aligned} \quad . (2)$$

Since the two directions employ identical wavelength in the same fiber, $\tau_F^{LR}$and τ_F^{RL} can be considered equal in slowly varying circumstance as is the usual case. The asymmetry of sending and receiving delay between two sites, $(\tau_T^L - \tau_T^R + \tau_R^R - \tau_R^L)$, can be calibrated through high-precision measurements in electric and/or optical domain since they only are related to the electric/optical cables and devices at local and remote ends. Therefore, the one-way propagation delay from site 1 to site 2 can be calculated by the measured T_{LL} and T_A, and the time transfer from site 1 to site 2 can be implemented.

In the proposed scheme, the optical carriers at two sites are launched into fiber only during the transmission of time code, and are switched off during the non-transmission of time code. In such a way, although the two directions employ the same wavelength over a single fiber to achieve the maximum bidirectional symmetry of fiber propagation delay, the effect of single Rayleigh backscattering originating from local light sources can still be completely eliminated. Moreover, the effect of double Rayleigh backscattering from the transmitting light can also be suppressed partly since only the double backscattering generated in the duration of the transmitting time signal can overlap with it in time domain.



（a）

（b）

Fig.1. The scheme (a) and timing sequence of the round-trip fiber-optic time transfer based on bidirectional TDM transmission. SFP: Small Form-factor Pluggable; OS: optical switcher; SFBA: single-fiber bidirectional amplifier.

III. EXPERIMENTAL RESULTS AND DISUSSION

An experimental system based on the proposed scheme in Fig.1 is setup. In the system, the 1PPS from a Rb clock (Symmetricom, 8040C) is sent from site 1 to site 2. The dedicated codecs with synchronization function proposed in [7] are used to encode/decode the time signal into/from a time code. Two DWDM small form-factor pluggable (SFP) transceivers with the same wavelength are used to send and receive time codes with a bit rate of 1Mb/s. The optical switch used at each site has a switching time of several milliseconds. The TDA at site 2 is implemented in FPGA. Two SR620s

(Stanford Research System) are adopted to measure the round trip delay and the TDA delay, respectively. The one-way propagation delay from site 1 to site 2 is also directly measured by a SR620 (TIC 3 in Fig.1) for the evaluation of the system.

Figure 2 shows the adopted time code format. Its frame length is 200 bits corresponding to 200μs for 1Mb/s. The pulse-width coding rule is the same as the Inter-Range Instrumentation Group time code B (IRIG-B) [8], where binary “1”, “0”, and “P” are represented by the pulses with duration of 50%, 20% and 80%, respectively. The first 100 bits in the time frame are used to carry the reference mark, the time and control information. The reference mark consists of two consecutive “P” codes where the leading edge of the second “P” code indicates the on-time of 1 PPS. The following two 50 bits are used to carry the measured round trip delay at site 1, and the measured delay of the TDA, respectively.

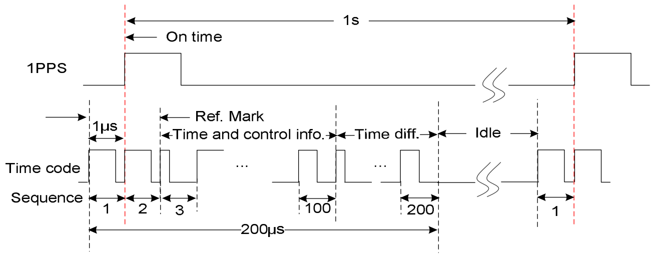


Fig.2. The time code format.

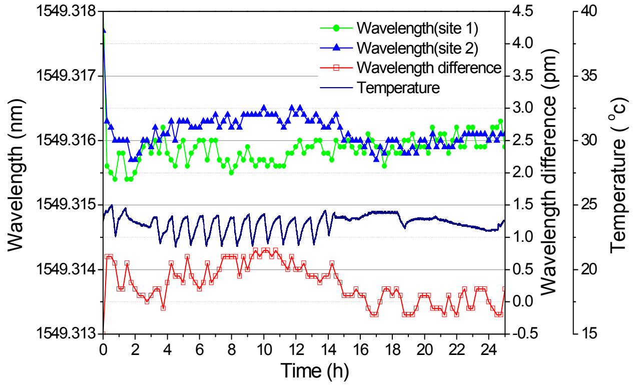


Fig.3. The measured wavelength of two SFPs.

Figure 3 shows the measured wavelength of the two adopted SFPs in an air-conditioned room in 24 hours using an optical wavelength meter with an accuracy of 0.3pm (YOKOGAWA, AQ6151). We can see that the wavelength difference of the two SFPs is always less than 1pm when the temperature fluctuates between 22°C and 25°C. The wavelength difference of 0.5pm can be reached when the temperature fluctuation is controlled in 1.5 °C. That indicates a bidirectional propagation delay asymmetry of less than 8.5 ps for a 1000 km fiber link with a typical dispersion coefficient of 17 ps/nm/km.

The performance of time transfer is evaluated by the difference, ΔT, between the one-way propagation delay obtained by proposed scheme and the one directly measured by TIC 3 in Fig.1. Fig.4 shows the TDEVs of bidirectional TDM based round-trip time transfer over optical fibers of 100 km and 200 km, respectively. To compensate the fiber loss, a special-designed single fiber bidirectional amplifier (SFBA), see the inset in Fig. 1, is added after about 100 km transmission in the time transfer over 200 km fiber. From the figure, we can see that the stabilities of the time transfer in both cases are better than 40ps/s, and 10ps/d, respectively. We can also see that the inserted SFBA in 200km fiber-optic link has no significant effect on the stability of time transfer.

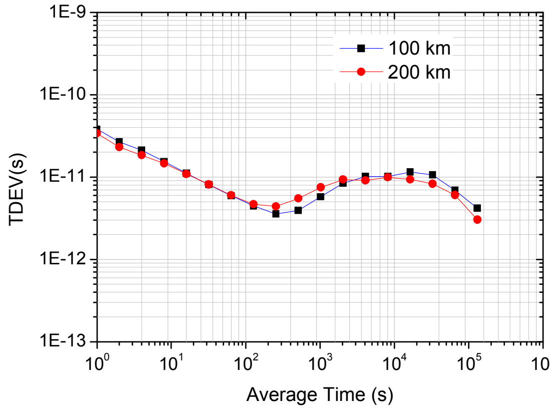


Fig. 4. The stabilities of bidirectional TDM-based round-trip time transfer over 100km and 200km

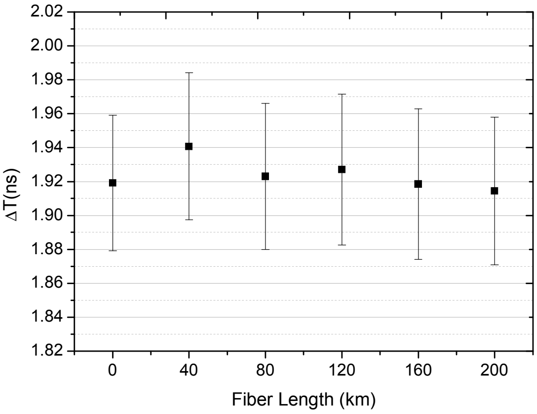


Fig. 5. The ΔT over different fiber length.

Figure 5 shows the averages and standard deviations (Std) of ΔT in one hour over different lengths of fiber. In the experiment, the measured ΔT over 2 m fiber, 1.919 ns can be considered as the asymmetry of sending and receiving delay between two sites, $(\tau_T^L - \tau_T^R + \tau_R^R - \tau_R^L)$. We can see that the average of the ΔT almost keeps constant with the increase of fiber length from 2 m to 200 km. The maximum fluctuation of the average of ΔT with fiber length is less than 27 ps. Since the resolution of SR620 is about 25ps, the measured fluctuation of ΔT is mainly come from SR620.

The above results indicate that the proposed scheme can achieve a time transfer over several hundred (even thousand) kilometers optical fiber with a precision of less than 100ps without any calibration of fiber links. It is worth to note that based on the point-to-point scheme shown in Fig.1, a point-to-multipoint fiber-optic time transfer scheme based on bidirectional TDM transmission can also be realized to perform high-precision distributed time dissemination, see Fig.6.

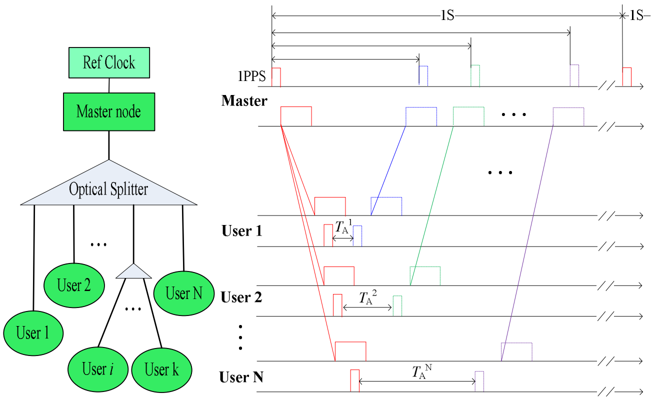


Fig.6. The scheme of distributed round-trip fiber optic time transfer based on bidirectional TDM transmission.

IV. CONCLUSIONS

We propose a high-precision bidirectional TDM based round-trip fiber-optic time transfer scheme, which can suppress the impact of the Rayleigh backscattering and reaches the highest bidirectional symmetry of fiber propagation delays at the same time, to disseminate time signals from reference clock directly to users. The principle of the scheme is experimentally validated over 200 km optical fiber with a SFBA. The stability of less than 40ps/s is reached over 200km optical fiber link. The measured wavelength difference shows that the uncertainty induced by 200 km uncalibrated fiber can be less than 2 ps. The uncertainty induced by 200 km uncalibrated fiber measured in the experiment is less than 27 ps, which is mainly limited by the uncertainty of used TICs. A point-to-multipoint fiber-optic time transfer scheme based on bidirectional TDM transmission is also presented. Our next work includes to demonstrate the fiber-optic time transfer over more than 1000 kilometer and the distributed fiber-optic time dissemination by using the proposed scheme.

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