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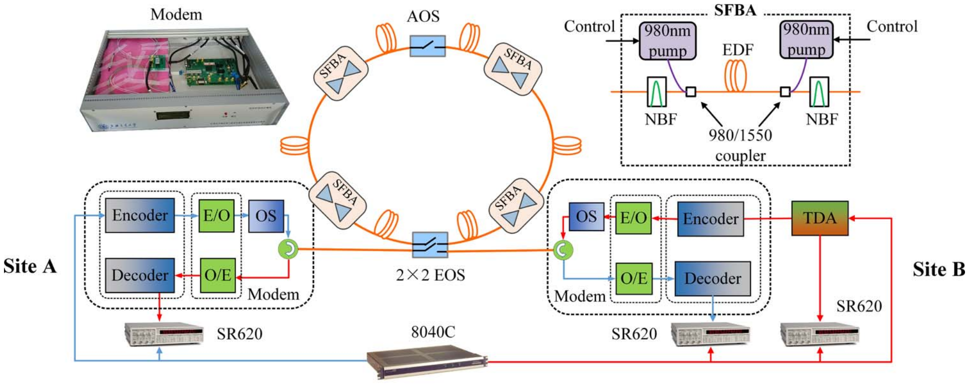

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High-Precision Time Transfer Over 2000-km Fiber Link

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Abstract: The two-way fiber-optic time transfer based on bidirectional time-division multiplexing transmission over a single fiber with the same wavelength (BTDM-SFSW) is an effective way to eliminate the effect of Rayleigh backscattering and reach the maximum bidirectional symmetry at the same time. In this paper, a BTDM-SFSW-based time transfer testbed is built with the employment of loop configuration in the laboratory to evaluate the performance of fiber-optic time transfer over thousands of kilometers, which is confronted with worse signal-to-noise ratio (SNR), more serious fiber dispersion, and so on. The contributions of different factors, including the precision and stability of transmitted wavelengths, the power dependence of transceivers' receiving delays, Sagnac effect, etc., to the uncertainty of time transfer are investigated by theoretical analyses and experimental measurements. A full uncertainty budget for the BTDM-SFSW-based time transfer is provided. Experimental results show that the stabilities of less than 89 ps/s and 23 ps/10^5 s can be achieved for the time transfer over a 2000-km fiber link. The theoretical expanded uncertainty with the coverage factor $k = 2$ can be less than 100 ps without the requirement of a fiber link calibration, which is validated by experimental results as well.

Index Terms: Fiber optics system, instrumentation and metrology.

1. Introduction

Time transfer plays a vital role in many fields, such as time and frequency metrology, navigation, and radio astronomy [1]. The satellite-based time and frequency transfer [GPS or two-way satellite time and frequency transfer (TWSFTF)] is prevalent and capable of reaching a geographic distance of about 10000 km. Its precision, however, is limited by multipath effects and propagation delay fluctuations caused by the troposphere and the ionosphere [1]. Fiber-optic time transfer is extensively considered to be a promising approach to realize higher precision time transfer over long distance due to its unique advantages of high stability, broad bandwidth, low loss, and so on [2], [3]. Up to now, fiber-optic time transfer over several hundred kilometers has been demonstrated [4]–[7] with the employment of bidirectional amplification techniques in a single fiber [7]–[9], including in laboratory and in field through telecom networks.

In order to suppress the effect of Rayleigh backscattering on signal timing jitter in optical fiber, WDM based schemes have been presented [5], [6]. Although such schemes can effectively

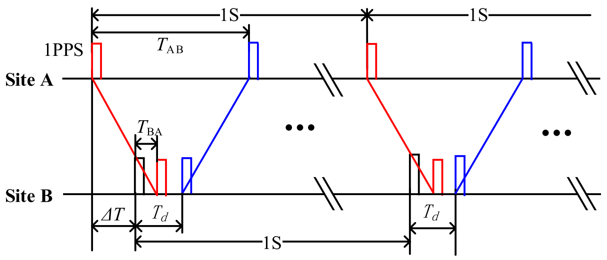

Fig. 1. Principle of the BTDM-SFSW based two-way fiber-optic time transfer. ΔT: the clock difference between two sites; T_{AB} (T_{BA}): the time difference between the local 1 PPS and the received one at site A (site B); T_d: the delay of the local 1 PPS at site B.

suppress the impact of single Rayleigh backscattering by optical filtering, high precision calibration is needed to determine the bidirectional asymmetry of fiber link induced by fiber dispersion and its temperature dependence. The fiber link calibration not only has an uncertainty increasing almost linearly with the length of fiber but adds the complexity and cost of operation and maintenance as well when considering the requirement to stabilize fiber link and the complex scenarios in practical long fiber links. The fiber-optic time transfer method employing the modems for TWSTFT [2], [4], [10] can maintain the bidirectional propagation symmetry and suppress Rayleigh backscattering effectively by the same wavelength in a single fiber and code division multiple access (CDMA) techniques. The hardware and techniques related to TWSTFT, however, are sophisticated and very expensive.

In [7], we proposed a two-way fiber-optic time transfer scheme based on bidirectional time division multiplexing transmission over a single fiber with the same wavelength (BTDM-SFSW). The results confirm that the scheme can suppress the impact of Rayleigh backscattering effectively and reach the maximum symmetry simultaneously up to 300 km fiber link without the requirement of fiber link calibration, complicated hardware, and techniques. However, the fiber-optic time transfer over ultra-long haul will confront with more intricate situations, such as worse signal-to-noise ratio (SNR), more serious fiber dispersion and its temperature dependence, larger temperature distribution and fluctuation along the fiber, more installed optical devices (optical filters, optical amplifiers, optical switches, etc.), and so on. In order to investigate the effects of these factors on the stability and uncertainty of BTDM-SFSW based time transfer, and evaluate its performance over ultra-long haul, we build an optical time transfer testbed with a loop structure in laboratory and experimentally test the performance of BTDM-SFSW based fiber-optic time transfer over thousands of kilometers in this paper. Different factors contributing to the uncertainty of time transfer, such as the precision and stability of transmitted wavelengths, the power dependence of transceivers' receiving delays, Sagnac effect, etc., are investigated in detail by theoretical analyses and experimental measurements. A full uncertainty budget for the BTDM-SFSW based time transfer is provided. A 2000 km BTDM-SFSW based fiber-optic time transfer with stabilities of less than 89 ps/s and 23 ps/10^5 s is demonstrated, and an expanded uncertainty of better than 100 ps is achievable with no fiber link calibration.

This paper is organized as follows: Section 2 illustrates the principle of BTDM-SFSW based optical time transfer and the experimental testbed with loop configuration. The performance comparison between a single point-to-point fiber link and a loop configuration is also discussed in the section. Section 3 presents the measured stabilities of time transfer over different fiber lengths. In Section 4, the detailed uncertainty evaluation for the proposed scheme is performed based on experimental measurements and theoretical analyses. Section 5 draws the conclusion.

2. Principle and Experimental Configuration

The principle of BTDM-SFSW based two-way fiber-optic time transfer is shown in Fig. 1. ΔT is the clock difference between two sites. The time signal (e.g. 1 PPS, one-pulse-per-second) at site A is sent to site B over an optical carrier with a wavelength of λ. The time signal at site B is

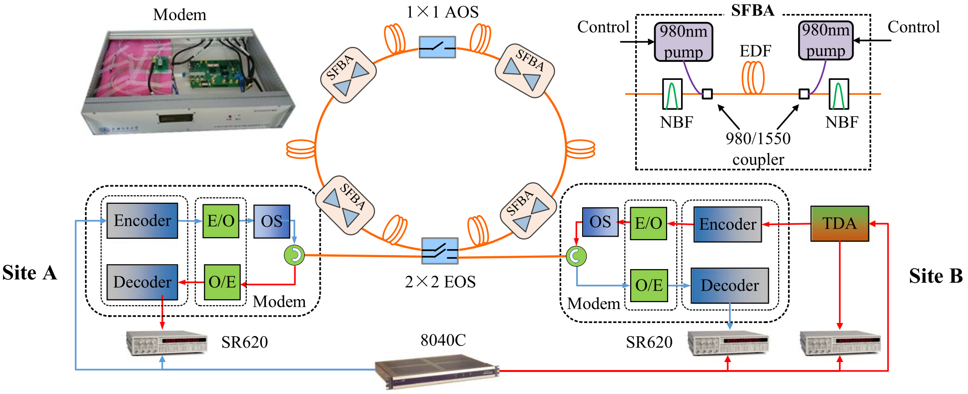

Fig. 2. Experimental testbed of two-way fiber-optic time transfer using BTDM-SFSW. OS: optical switch, EOS: electro-optic switch, AOS: acousto-optic switch, SFBA: single fiber bidirectional amplifier, NBF: narrowband optical filter.

not transmitted immediately as traditionally but delayed by an interval of T_d until site B completes the receiving of time signal from site A. The delayed time signal at site B is sent to site A on the same wavelength of λ over the same fiber. The optical carriers at two sites are launched into fiber only during time signal transmission, and are switched off in the leisure duration. In such a way, the bidirectional propagation symmetry of fiber link is guaranteed by using the same wavelength over a single fiber. Meanwhile, the effect of single Rayleigh backscattering (SRB) originating from the local light source can be completely eliminated since each site does not send light into fiber link during time signal receiving. The impact of double Rayleigh backscattering (DRB) from the transmitting light can also be suppressed partly since the optical carrier in the front of transmitted time code is switched off in the BTDM based transmission and there is no DRB originating from this part accordingly, which will exist and impact the jitter of time signal in non-BTDM based scheme.

The clock difference between two sites can be expressed as (1), shown below, where T_{AB} (T_{BA}) is the time difference between the local input 1PPS and the received one at site A (site B); τ_{AB}^F (τ_{BA}^F) is the propagation delay of fiber link from site A (site B) to site B (site A); and τ_A^T (τ_B^T) and τ_A^R (τ_B^R) are the sending and receiving delays at site A (site B), respectively. In (1), τ_{AB}^F and τ_{BA}^F can be considered equal in slowly varying circumstance as is the usual case since the forward and backward transmissions are over the same fiber using an identical wavelength. The sending and receiving delays at two sites, τ_A^T, τ_B^T, τ_A^R, τ_B^R, can be calibrated by high-precision measurements in the electric and/or optical domains since they are only related to the electric/optical cables and devices at two sites. Therefore, the clock difference between two sites can be determined by T_{AB}, T_{BA}, and T_d measured at site A and B

$$\Delta T = \frac{1}{2}\left[(T_{AB} - T_{BA} - T_d) + \left(\tau_{AB}^F - \tau_{BA}^F\right) + \left(\tau_A^T - \tau_A^R + \tau_B^R - \tau_B^T\right)\right]. \tag{1}$$

The experimental testbed of two-way fiber-optic time transfer based on BTDM-SFSW is shown in Fig. 2. The whole system is in a normal air-conditioned room with an hourly temperature fluctuation of more than 3 °C. In order to eliminate the effect of clock drift on the test, the 1 PPS from a common Rb clock (Symmetricom, 8040C) is provided to the time transfer modems at site A and site B simultaneously. The 1 PPS at site A is encoded into a time code by a dedicated encoder with a low delay variation, which employs a coding implementation method similar to the one presented in [11]. The delay of 1 PPS at site B is completed by a time delay adjuster (TDA) implemented in FPGA. Then the delayed 1 PPS is also encoded into a time code. The time code has a frame length of 200 bits and a bit rate of 100 Mb/s, which only occupies a time slot of 2 μs. The generated time codes are launched into the fiber link using DWDM small form-factor

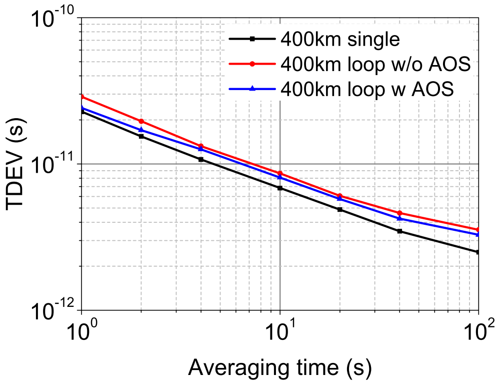

Fig. 3. Stabilities (TDEV) of time transfer over 400 km fiber links with different link configurations.

pluggable (SFP) transceivers by turning on the corresponding optical switch (OS) with a switching time of about 1 ms at the maximum. The optical switches are off after each time code is transmitted. In order to avoid transient effects, a guard time of about 1 ms should be used in the front of time signals. The 1 PPS in each receiving time code is extracted by the decoder at the corresponding site. The time interval between the local input 1 PPS and the received one is determined by the time interval counter (TIC, Stanford Research System, SR620) at each site. The delay of the TDA at site B is also measured by a SR620.

The test is performed over a bidirectional single optical fiber loop composed of a 2 × 2 electro-optic switch (EOS) with a switching time of less than 300 ns, 400 km G.652 fiber and four single (erbium-doped) fiber bidirectional amplifiers (SFBA). Time transfer over fiber link longer than 400 km is imposed by recirculating the time codes with designated revolutions in the fiber loop through controlling the 2 × 2 EOS. A SFBA with bidirectional pumps is equipped every 100 km to compensate for the optical transmission loss. The gain of each SFBA is carefully set by adjusting the power of two pumps to avoid the occurrence of lasing and optimize SNR. Two narrowband optical filters (NBF) are adopted at two ports of each SFBA, respectively, for the purpose of amplified spontaneous emission (ASE) noise suppression. The bandwidth of NBFs only needs to cover the spectral width of the employed optical carrier since the bidirectional wavelengths are identical. In our test, NBFs with a 3 dB bandwidth of 0.4 nm are used for no narrower filters at hand, although the spectral width of the employed optical carrier is less than 20 pm.

In order to block the noise accumulation in the bidirectional loop configuration, which may seriously degrade the performance of transmitted time signal, the 2 × 2 EOS only keeps loop state during the period when time codes pass through it. We also employ an on-off acousto-optic switch (AOS) with an extinction ratio of about 10 dB to further overcome the noise accumulation when the distance extends to 2000 km. It should be noted that the performance degradation induced by the noise in non-transmission duration only occurs in the loop configuration via recirculation. For point-to-point fiber links, such noise will have a negligible effect on the time signal since they are separated in the time domain. We have carried out a comparison experiment to confirm it. Fig. 3 shows the time deviation (TDEV) of BTDM-SFSW based time transfer over 400 km fiber links in three configurations. Referring to the figure, it can be seen that the TDEVs in loop configurations are always larger than that in a point-to-point single span fiber link, even when the AOS is used. This is because 1) the additional noises owing to recirculation in the loop cannot be eliminated completely since the AOS and EOS have limited extinction ratio. 2) Although the adoption of AOS also partially suppresses the noises that exist in a point-to-point single span fiber link, such as the DRB of forward ASE, and the SRB of backward ASE, etc., such suppression brings very limited change because these noises are far from the time signal in the time domain and, hence, have relatively lower effects on time signal due to fiber attenuation.

As the transfer distance extends to longer than 400 km by recirculating the time codes in the fiber loop through keeping the EOS loop state during the period of time code, additional noises

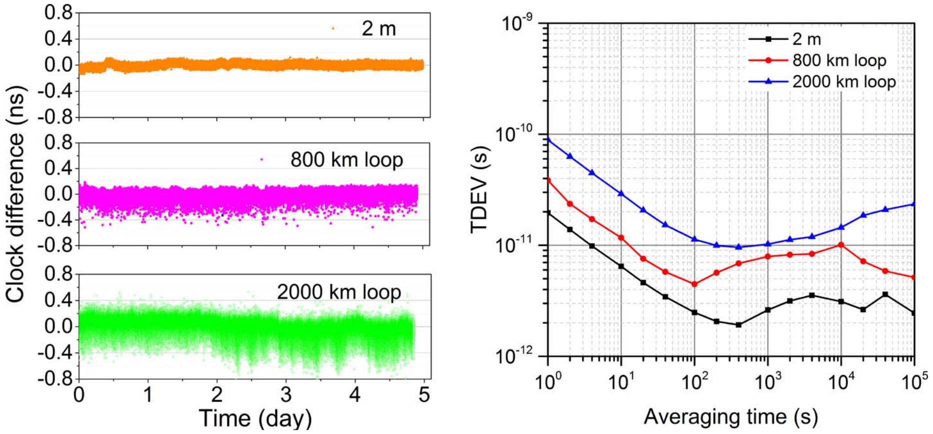

Fig. 4. Clock differences and their stabilities (TDEV) of time transfer over different fiber lengths.

will accumulate further via recirculation. Therefore, the loop link configuration with AOS in our experiment will still represent a worse case in comparison with a single span point-to-point fiber link. Furthermore, the loop configuration with AOS can also approximately represent the BTDM based time transfer over a point-to-point fiber link employing bidirectional SFBAs with fast switches, which is a potential way to suppress background noises in a point-to-point fiber link for the BTDM based time transfer scheme.

3. Stability Measurements and Analyses

Fig. 4 shows the clock differences and their stabilities in terms of TDEV for the BTDM-SFSW based fiber-optic time transfer over different fiber lengths. The TDEV of time transfer over 2 m fiber link, which is less than 20 ps/s and 3 ps/10^5 s, can be regarded as the stability floor of our experimental setup in the test conditions since the fiber is so short. The floor is mainly determined by the codecs, SFP transceivers and the TICs used at two sites. The TDEV of time transfer is deteriorated with the extension of fiber link, and can be always less than 90 ps over 2000 km fiber length. The degradation of short-term (1–100 s) stability of time transfer over longer fiber links is mainly because of the degradation of SNR of received signal as the fiber link extends. The TDEV at the averaging time in the range of 100–10000 s is almost linearly degraded with the fiber link length in contrast to the floor one. It is reasonable since the long-term stability is mainly related to the fluctuations of propagation delay asymmetry caused by the variations of temperature and wavelength difference, which are proportional to the fiber length. The large deviation to the linear relationship after 10000 s may mainly come from the different ambient temperature fluctuations per day during the test over different fiber lengths.

4. Uncertainty Analyses and Evaluations

The components of uncertainty budget for the BTDM-SFSW based time transfer over 2000 km fiber in a field implementation are summarized in Table 1 and analyzed as follows.

The first term includes the uncertainty in determining the time differences (T_{AB} and T_{BA}) and the delay (T_d) of TDA. We evaluate the uncertainty of the three time intervals as a whole, $(T_{AB} - T_{BA} - T_d)/2$, to eliminate the temperature-dependent propagation delay of fiber link in the time differences of T_{AB} and T_{BA}. The type A uncertainty of the term 7.3 ps is calculated on 200 observations which are measured over a 2000 km fiber link. The type B uncertainty of SR620 is 25 ps [2]. Hence, the uncertainty (A&B) of time interval measurements in our test is 22.9 ps. Obviously, advanced TICs with a lower type B uncertainty such as 5 ps can be used to reduce the uncertainty in determining time differences [12].

The second term includes the uncertainty in calibrating the sending and receiving delay asymmetry of two sites together with the used electrical cables, which is determined by connecting

TABLE 1

Uncertainty budget for BTDM-SFSW based time transfer over 2000 km fiber link in field implementation

Uncertainty Source	Coefficient	Estimated value	Uncertainty contribution	Uncertainty type
Time interval	1	22.9 ps	22.9 ps	A&B
Modem	1	38.7 ps	38.7 ps	A
Wavelength difference	$0.5DL$	1 pm	17 ps	B
PMD	$0.5\sqrt{L}$	0.05 ps/ √ km	1.1 ps	B
Sagnac effect	$2\omega/c^2$	δA_E	6 ps	B
Combined standard uncertainty		48.5 ps		A&B

the two sites with a short fiber (2 m in our test). When any electrical cable is changed, the modems should be recalibrated. A clock difference standard deviation of 27.6 ps is determined with SR620s for 200 measured data points, which indicates the type A uncertainty of 2 ps. The above uncertainty of calibration at two sites is only obtained in a certain input optical power. However, SFP transceivers have power-dependent delays. This should also be included. The power-dependent delay variation of used SFP transceivers is measured by adjusting the input power of each O/E convertor through variable optical attenuators (VOA). The measurement gives the power-dependent delay variation of 38.7 ps for the input optical power variation from −7 dBm to −31 dBm. The uncertainty can be less than 10 ps when the optical power variation is kept within 2 dB. Hence the delay of used SFP transceivers may be calibrated with an uncertainty of less than 10 ps by matching the input optical power in the calibration process with the one in operation. Considering the input optical powers for fiber length from 2 m to 2000 km are changed in a larger range, we take the higher value in the uncertainty calculation. Since the time delays are measured using SR620s in our test, the result may be improved by adopting TICs with a lower uncertainty.

The third term results from wavelength-difference dependent fiber chromatic dispersion, which increases linearly with fiber length. In an ideal condition, the forward and backward wavelengths are set to the same in BTDM-SFSW scheme. In practice, however, the wavelengths from two different SFP transceivers cannot be completely identical for the limitation of practical technique and different wavelength fluctuation characteristics. Fig. 5 shows the wavelength difference of the two employed SFP transceivers in 45 hours measured by an optical wavelength meter (AQ6151, YOKOGAWA). Also plotted in the figure are the external temperatures of each SFP transceiver. Both the wavelength difference and its fluctuation are always less than 1 pm when the external temperatures of SFP transceivers vary between 28 °C and 31 °C. We can observe that the wavelength difference could be less than 0.5 pm when external temperature fluctuation of SFP transceiver is well controlled within 1 °C. The uncertainty caused by wavelength difference for 2000 km fiber is calculated by using the typical fiber dispersion coefficient of 17 ps/nm/km. It is worth to note that the temperature-dependence of chromatic dispersion coefficient [13] has no contribution to the uncertainty budget of our scheme thanks to using the same wavelength in both directions. The uncertainty from polarization mode dispersion (PMD) (term 4) is calculated with the coefficient of 0.05 ps/√km [6].

The uncertainty from the correction of Sagnac effect (term 5) is calculated by $4\delta A_E\omega/c^2$ [14], where ω and c are the rotation speed of the Earth and the speed of light respectively, δA_E is the uncertainty in determining the equatorial projection area of the surface swept by the vector from the center of the Earth and moving along the fiber. Theoretical calculated maximum uncertainty from Sagnac effect is less than 6 ps for any two sites with the geographic distance of 2000 km on the earth (considered as an ideal sphere) when the accuracy of positioning fiber path is better than 1 km.

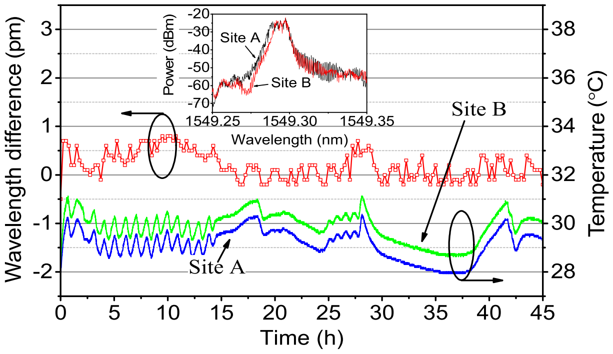

Fig. 5. Measured wavelength difference of two SFP transceivers at two sites and their external temperatures in 45 hours. (Inset) Their optical spectra.

TABLE 2

Measured clock differences over different fiber lengths in the laboratory condition

Link length / km	Measured clock difference / ps	Expanded uncertainty /ps
400	41	93.1
800	58.4	93.2
1200	76.5	93.3
1600	65.2	93.5
2000	-19.8	96.2

According to the above analyses, the calculated combined standard uncertainty budget is 48.5 ps for 2000 km fiber-optic time transfer. It can be lowered to 22.4 ps by using TICs with type B uncertainty of 5 ps and limiting the power-dependent delay variation of SFPs within 10 ps. For our test in laboratory where the experimental system is located in a single room, the Sagnac term is excluded, and the calculated combined standard uncertainty is 48.1 ps for 2000 km fiber-optic time transfer. It should be pointed out that although a large number of passive devices (filters/couplers) are deployed in optical link over long haul, their impacts on the uncertainty can be neglected since the bidirectional transmitted lights go through the same path in the same passive components.

Table 2 summarizes the measured clock differences $[(T_{AB} - T_{BA} - T_d) + (\tau_A^T - \tau_A^R + \tau_B^R - \tau_B^T)]/2$ for the proposed time transfer over different fiber lengths without any fiber link calibration. The asymmetry of sending and receiving delays of two sites, $(\tau_A^T - \tau_A^R + \tau_B^R - \tau_B^T)$, together with the used electrical cables, is calibrated by connected the two sites with a 2 m fiber and a VOA. Since the local input 1 PPSs of two sites are from a common clock, the real clock difference should be zero. Therefore, the measured clock differences indicate the asymmetry of two transmission directions and the measurement uncertainty of our system directly. From Table 2, we can see that the measured clock differences are consistent with the expanded uncertainty (coverage factor $k = 2$) [6] for fiber lengths from 400 km to 2000 km. The uncertainty of system only increases slightly with the extension of fiber link due to employing the same wavelength in both directions in BTDM-SFSW scheme. Considering the received optical power of SFP transceivers during the measurement under each fiber length deviates from the one used for calibration, the combined uncertainty in the test is dominated by the power-dependent delay variation of SFPs (see Table 1), which is independent on fiber length. If they are matched and advanced TICs are adopted, better results could be expected.

V. Conclusion

In summary, we build a fiber-optic time transfer testbed with a loop structure in laboratory to investigate the effects of the factors from ultra-long haul on the stability and uncertainty of time transfer, and evaluate its performance over thousands of kilometers. Different factors related to the uncertainty of time transfer are investigated in detail by theoretical analyses and experimental measurements. A full uncertainty budget for the BTDM-SFSW based time transfer is calculated. A 2000 km BTDM-SFSW based time transfer is demonstrated with the stabilities of less than 89 ps/s and 23 ps/10^5 s, and an expanded uncertainty of better than 100 ps requiring no fiber link calibration. The results confirm the feasibility of time transfer over several thousand kilometers optical fiber link with high precision by using the BTDM-SFSW based time transfer scheme. The next work includes the bidirectional SFBA with fast switches for BTDM-SFSW based time transfer, further distance extension and field test, etc.

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