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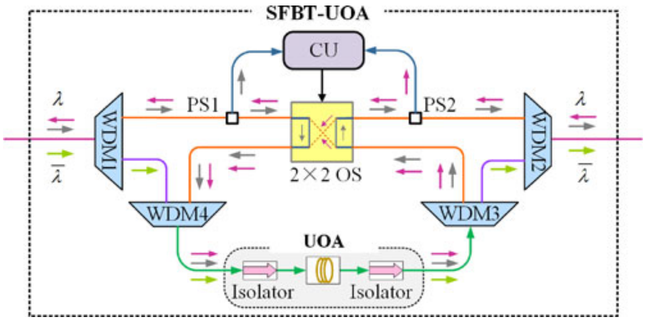

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# High-Precision Ultralong Distance Time Transfer Using Single-Fiber Bidirectional-Transmission Unidirectional Optical Amplifiers

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**Abstract:** This paper demonstrates a fiber-optic time transfer over a 6000 km noncalibrated fiber link using proposed single-fiber bidirectional-transmission unidirectional optical amplifiers (SFBT-UOAs). The proposed SFBT-UOA employs a $2 \times 2$ optical switch to enable the time-division-multiplexed time signals for both directions to pass through the same UOA in different time slots. The bidirectional delay symmetry is guaranteed to the maximum extent by allowing the time signals to be transmitted back and forth using the same wavelength over a single fiber. Meanwhile, the noises suffered in the systems employing single fiber bidirectional optical amplifiers (SF-BOAs), such as double Rayleigh backscattering, are effectively suppressed. Consequently, high-precision fiber-optic time transfer can be implemented over ultralong distance by adopting the proposed SFBT-UOAs. Moreover, the SFBT-UOA can support the conventional network services via wavelength division multiplexings (WDMs) and, therefore, offers the potential to perform high-precision time transfer over long-haul commercial fiber links. Over 6000 km, the measured time deviations of fiber-optic time transfer in the laboratory are less than 190 ps/s and 61 ps/$10^5$ s, respectively. The calculated combined uncertainty is not beyond 70 ps, which agrees well with the experimental verification over the noncalibrated fiber link.

**Index Terms:** Fiber optics system, instrumentation and metrology

## 1. Introduction

Fiber-optic time transfer [1] is considered to be a promising method to realize high-precision time transfer due to its unique advantages of broad bandwidth, low loss, and high immunity to environmental perturbation, etc. It is expected to play key roles in widespread applications such as time and frequency metrology, navigation, astronomy and precise tests of fundamental physics, etc. Previously, we proposed a two-way time transfer scheme using bidirectional time division multiplexing transmission over a single fiber with the same wavelength (BTDM-SFSW) and demonstrated a high-precision fiber-optic time transfer over 2000 km employing specifically-designed single fiber bidirectional optical amplifiers (SF-BOAs) [2], [3]. In SF-BOAs, no optical isolators are used in order to allow bidirectional transmission over a single fiber and achieve high delay symmetry [2], [4]–[6]. However, the inherent noises due to the lack of optical isolators, such as double Rayleigh backscattering (DRB) travelling around one or more amplifiers [7] and the single Rayleigh backscattering (SRB) of backward amplified spontaneous emission (ASE) noise, etc., significantly degrade the signal-to-noise ratio (SNR) of the received time signals. Subsequently, the total fiber link length has to be limited in order to reach an acceptable time transfer precision [7], [8]. Though unidirectional optical amplifiers (UOAs) with optical isolators for each direction have been proposed for the WDM based fiber-optic time transfer, the bidirectional delay asymmetry between the different wavelength channels inside the optical amplifiers requires calibration with high precision [9]–[11]. The calibration uncertainty scales with the number of the deployed optical amplifiers, and the calibration adds complexity and expenses to the operation and maintenance, especially over long-haul fiber links [12].

Moreover, it is very desirable to embed a high-precision long-distance time transfer into commercial fiber links over conventional telecom networks considering the implementation and operation cost. As is known, almost all long-haul commercial fiber transmission links in conventional telecom networks employ UOAs to simultaneously boost all transmitted signals in a single fiber. Up until now, all the presented optical amplification schemes for time transfer cannot be compatible with the unidirectional optical amplifiers in conventional telecom networks, and therefore, it is hard to support the long-haul time transfer over conventional networks.

In this paper, we propose a single-fiber bidirectional-transmission unidirectional optical amplifier (SFBT-UOA). With a 2 × 2 optical switch, the forward and backward time signals pass through the same UOA in different time slots. By this means, the excess noises suffered from the lack of isolators in SF-BOAs are sufficiently eliminated while the maximum delay symmetry for both directions is guaranteed by employing BTDM-SFSW. Furthermore, the proposed amplification scheme for time transfer is compatible with the UOAs in conventional telecom networks in principle and has the potential to support both time transfer and conventional network services at the same time. We successfully demonstrate a BTDM-SFSW based time transfer adopting 60 equivalent SFBT-UOAs over 6000 km in our long-haul testbed. Without fiber link calibration, the combined uncertainty of less than 70 ps is reached. The time deviations of less than 190 ps/s and 61 ps/$10^5$ s, respectively, are obtained.

This paper is organized as follows: Section 2 presents the configuration of the proposed SFBT-UOA and the link access control mechanism. Section 3 demonstrates the ultra-long time transfer experiment in laboratory testbed. The stability measurement over a 6000 km fiber link is performed. In Section 4, the uncertainties for time transfer over various non-calibrated fiber links are provided and experimentally validated. Section 5 draws the conclusion.

## 2. Principle

Fig. 1 illustrates the structure of the proposed SFBT-UOA. For the BTDM-SFSW based time transfer, the forward and backward optical time signals are carried on the same wavelength of $\lambda$ and arrive at each SFBT-UOA in different time slots. They are picked out by WDM 1 and WDM 2, respectively, and sent in turn to the conventionally-configured UOA through the control of 2 × 2 optical switch (OS). The amplified time signal is output to the corresponding port according to its direction via the 2 × 2 OS. Since there are optical isolators in the UOA, the noise terms like the DRB travelling around one or more amplifiers and the SRB of backward ASE, etc., are blocked efficiently. Thus the SNR of the received time signals can be improved significantly. As Fig. 1 shows, the optical time signals forth and back go almost through the same optical path in the SFBT-UOA (except for the short paths within the 2 × 2 OS). Therefore, the maximum bidirectional delay symmetry can be obtained. It is worth noting that the conventional network services indicated by $\bar{\lambda}$ can also be fed into the UOA to be amplified simultaneously by using the four WDMs, which are employed to separate and combine the optical signals of time transfer and conventional network services.

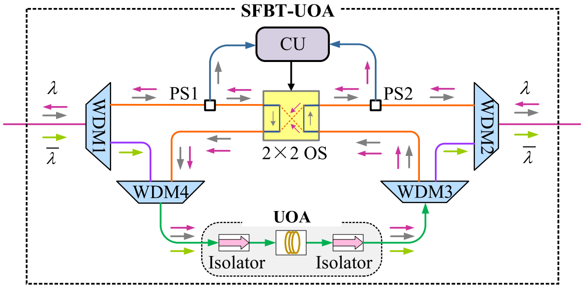


Fig. 1. Schematic structure of the proposed single-fiber bidirectional-transmission unidirectional optical amplifier (SFBT-UOA). PS: power splitter, CU: control unit, OS: optical switch, λ: channel for time transfer, $\bar{\lambda}$: channels for WDM network services.

In order to implement a BTDM-SFSW based time transfer employing SFBT-UOAs over the long haul, the 2 × 2 OSs in SFBT-UOAs along the fiber link should be set to the right states before the arrival of the corresponding time signals. The proposed link access control mechanism is illustrated in Fig. 2. In Fig. 2(a), site A sends local time signals (e.g. one pulse per second, 1 PPS) to site B over the fiber link with a wavelength of λ. It switches off the optical carrier after the transmission of the time signal. Each SFBT-UOA along the fiber link configures its 2 × 2 OS to allow forward transmission (from site A to B) at the time ($t_{i,u} + T$) according to the receiving moment of the latest time signal from site A, $t_{i,u}$, and the transmission period of time signal, $T$ ($T = 1$s for 1PPS). Since a time signal can only pass through a SFBT-UOA configured in advance, site A needs to send at least $N$ local time signals to configure $N$ SFBA-UOAs. When site B receives a time signal from site A, it delays the received time signal by $T_3$ and then feeds it back to site A over the same fiber with the same wavelength of λ. Likewise, only during the transmission of the delayed time signal the optical carrier at site B is launched into fiber. It should be pointed out that the delay time, $T_3$, should be set appropriately to avoid the overlap of optical signals from two directions in the same fiber. Each SFBT-UOA in the fiber link is configured for backward transmission (from site B to A) using the same method as that for forward transmission. After returning at least $N$ time signals, the backward transmission state of all SFBA-UOAs along the link is configured. Once site A receives a returned time signal from site B, the delay range of the local time signal at site B can be determined for the operation of BTDM transmission as follows:

$$T_d \in (T_2, T - T_1 + T_2 + T_3) \tag{1}$$

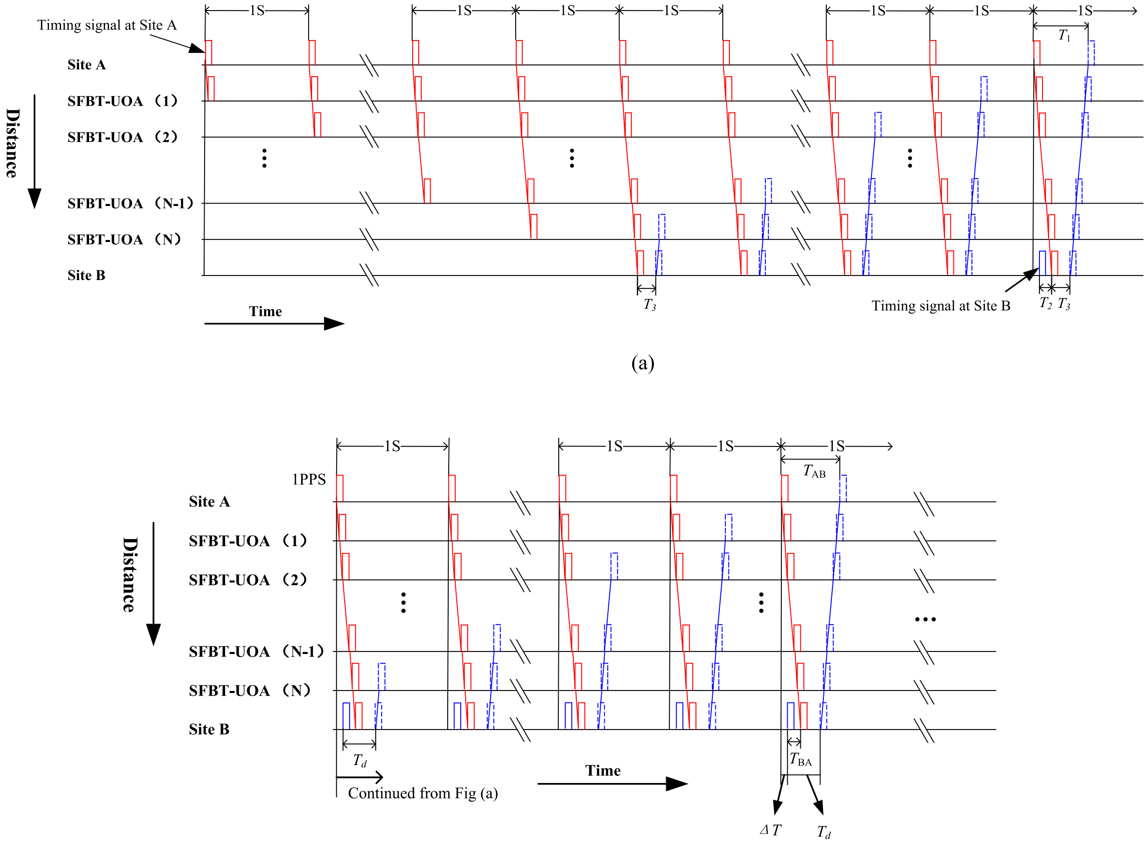
where $T_d$ is the designated delay of time signal at site B, $T_1$ is the round-trip time acquired at site A, and $T_2$ is the measured time interval at site B between the local time signal and the received one from site A.

From the analysis above, we can see that the appropriate delay, $T_d$, for the time signals at site B is obtained after 2N + 1 time signals. After that, each local time signal of site B is delayed by $T_d$, and then sent to site A. The backward transmission state of each SFBT-UOA is re-adjusted using the similar process above to enable the delayed local time signal from site B to pass through the whole fiber link (see Fig. 2(b)).

After completing the link access control procedure above, the conventional operation of BTDM-SFSW based time transfer [2] can be performed to determine the clock difference $\Delta T$ between two sites

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

where $T_{AB}(T_{BA})$ is the measured time difference between the local time signal and the received one at site A (B), $\tau_{AB}^F(\tau_{BA}^F)$ is the propagation delay of fiber link from site A to site B (site B to site A), and $\tau_A^T(\tau_B^T)$ and $\tau_A^R(\tau_B^R)$ are the sending and receiving delays at site A (site B), respectively.



(a)

(b)

Fig. 2. Schematic diagram of the link access control mechanism for fiber-optic time transfer with SFBT-UOAs. (a) Forward link configuration and the determination of $T_d$. (b) Backward link configuration. $T_1$: Measured round-trip time at site A. $T_2$: Time interval between the local time signal at site B and the received one from site A. $T_3$: Delay of the received time signal from site A at site B. $\Delta T$: Clock difference between two sites. $T_{AB}$ ($T_{BA}$): Time difference between the local time signal and the received one at site A (site B). $T_d$: Delay of the local time signal at site B.

## 3. Experiment and Results

In order to evaluate the proposed amplification scheme, the loop transmission testbed is established for long-haul fiber-optic time transfer, which contains 400 km G.652 fiber and four SFBT-UOAs (as shown in Fig. 3). The whole system is placed in a normal air-conditioned laboratory with an hourly temperature fluctuation of about 3 °C. The 1 PPS from a common Rb clock (Symmetricom, 8040C) is provided as the local time signals for both sites to eliminate the effect of clock drift on the test. The self-designed low-delay-variation codecs [13] are employed at both sites to encode the 1 PPS into the time codes and extract the 1 PPS from the received time codes. The generated time codes are modulated on the optical carriers through commercially available small form-factor pluggable (SFP) transceivers. The SFP transceivers have an output power of 0 dBm, a central wavelength of 1549.32 nm and a linewidth of 20 pm. By the control of the corresponding OS with a switching time of about 1 ms in maximum, the optical signals at both sites are launched into the fiber link only during the transmission of the time codes. The optical signals are recirculated in the fiber loop with designated revolutions by controlling a 2 × 2 electro-optic switch (EOS) with the maximum switching time of 300 ns. A SFBT-UOA is equipped every 100 km fiber with an attenuation between 21 dB and 24 dB. In the SFBT-UOA, a commercially available EDFA (Two SFBT-UOAs with bidirectional pumps, two SFBT-UOAs with a single pump), four WDMs with a channel spacing of 0.8 nm, and a

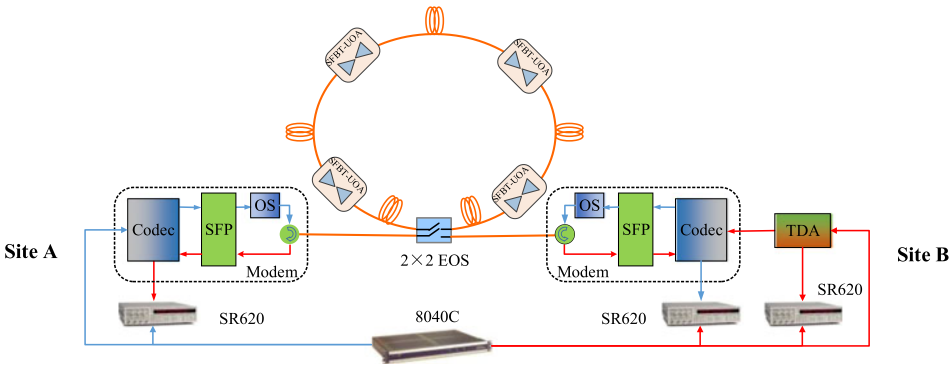
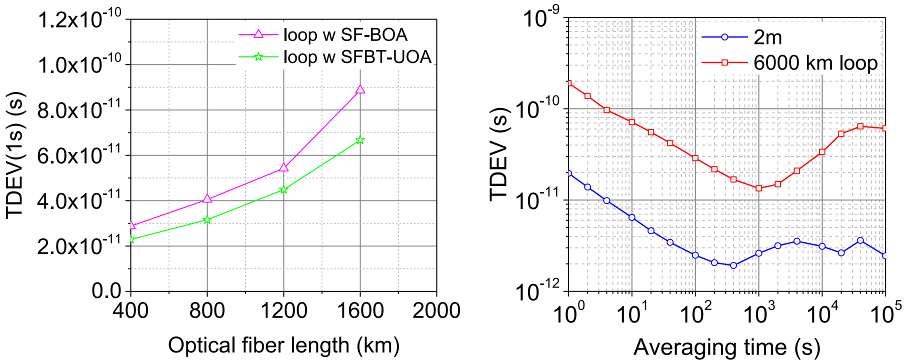


Fig. 3. Experimental testbed of the BTDM-SFSW based time transfer with SFBT-UOAs. OS: optical switch, EOS: electro-optic switch, TDA: time delay adjuster, SFP: small form-factor pluggable transceiver, SFBT-UOA: single-fiber bidirectional-transmission unidirectional optical amplifier.



(a) (b)

Fig. 4. (a)Time deviation (TDEV) at 1 s averaging time of BTDM-SFSW based time transfer under the same loop configuration, except for the employed optical amplifiers. (b) TDEV of BTDM-SFSW based time transfer using SFBT-UOAs over different fiber links.

$2 \times 2$ OS with a switching time of 1 ms in maximum are employed. Each required time intervals in (2) are determined by the time interval counters (TICs, Stanford Research System, SR620).

Under the same loop configuration, the time deviations (TDEVs) at 1 s averaging time of BTDM-SFSW based time transfer for two different amplification schemes are plotted in Fig. 4(a). From the figure, the performance improvement in terms of TDEV (1s) gets more obvious as the fiber link extends. Over a 1600 km fiber link, the TDEV (1 s) drops from 88.6 ps down to 66.7 ps. Thanks to the noise suppression by the employment of UOAs, we can extend the fiber link to 6000 km. Fig. 4(b) illustrates the stability of time transfer over a 2 m and a 6000 km fiber link. The TDEVs over the 2 m fiber link amounts to less than 20 ps/s and 3 ps /$10^5$s. The values are dominated by the adopted codecs, SFP transceivers and the TICs in the experiment since the influence of such a short fiber is negligible. As the link extends to 6000 km, the TDEVs deteriorate to 190 ps/s and 61 ps/$10^5$s, with the lowest value of 13 ps at 1000 s averaging time. The aggravation of the short-term stability [14] mainly comes from the degradation of SNR against the increase of fiber length and the excess noises in the recirculation [3]. However, the degradation of the long-term stability over longer fiber [14] is mostly due to the increased fluctuation of the bidirectional propagation delay asymmetry, caused by the variations of fiber temperature and the transmitting wavelength difference. For a point-to-point single fiber link under the same conditions, a better short-term stability can be expected for no recirculation noises while the long-term stability will approximate to that of loop configuration.

TABLE I
Uncertainty Budget for Time Transfer With SFBT-UOAs Over a 6000 km Fiber Link

| Uncertainty Source | Coefficient | Estimated value | Uncertainty contribution | Uncertainty type |
|---|---|---|---|---|
| Time interval | 1 | 14.2 ps | 14.2 ps | A |
| | $\sqrt{3}/2$ | 25 ps | 21.7 ps | B |
| Modem | 1 | 38.7 ps | 38.7 ps | A |
| Wavelength difference | $0.5DL$ | 1 pm | 51 ps | B |
| PMD | $0.5\sqrt{L}$ | $0.05\ \text{ps}/\sqrt{\text{km}}$ | 1.1 ps | B |
| Sagnac effect | $2\omega/c^2$ | $\delta A_E$ | 7 ps | B |
| SFBT-UOA | $0.5\sqrt{60}$ | 0.5 ps | 2 ps | A |
| Combined standard uncertainty | | 69.5 ps | | A & B |

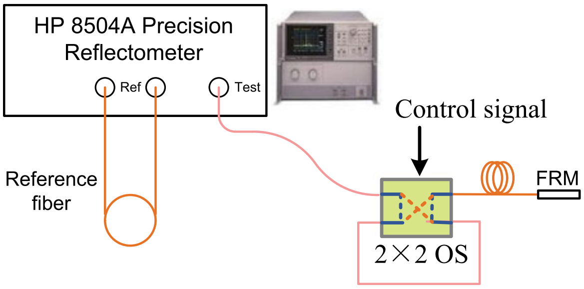


Fig. 5. Measurement setup of delay difference between two paths in the 2 × 2 OS in SFBT-UOA. FRM: Faraday rotation mirror.

## 4. Uncertainty Analyses and Validation

For the fiber-optic time transfer system, it is essential not only to investigate the noise properties, but also to explore the uncertainty of the measured clock difference between remote time scales. The components of the uncertainty budget for BTDM-SFSW based time transfer using SFBT-UOAs over 6000 km are summarized in TABLE 1.

In the table, the type A uncertainty of 14.2 ps in term 1 is obtained on 200 observations [15] over the 6000 km fiber link. The type B uncertainty of time interval measurements (listed in term 1), and the uncertainties from term 2-5 are calculated similar to that in Ref [3] over the 6000 km fiber link since the adopted modems, TICs, SFP transceivers (with the measured wavelength difference and its variation in the range of 1 pm) and fiber are the same, and the receiving powers are within the same calibration range. The term 6 results from the different paths in the 2 × 2 OSs of SFBT-UOAs since the bidirectional lights transmitted over the same wavelength go through the same path in other components. A precision reflectometer (Hewlett Packard, 8504A) is used to determine the propagation delay of each path in the 2 × 2 OS (relative to the reference fiber) by reflecting the light from the output port back through the 2 × 2 OS in different operation states, as shown in Fig. 5. The results show that the path delay difference in the 2 × 2 OS is always less than 0.5 ps. Accordingly, the uncertainty budget for 60 equivalent SFBT-UOAs is less than 2 ps. Finally, the calculated combined standard uncertainty budget is 69.5 ps for 6000 km fiber-optic time transfer. Clearly, the impact of the path delay difference from the proposed SFBT-UOA could be neglected. For our test in laboratory where the experimental system is co-located, the calculated combined standard uncertainty is 69.1 ps, excluding the Sagnac term.

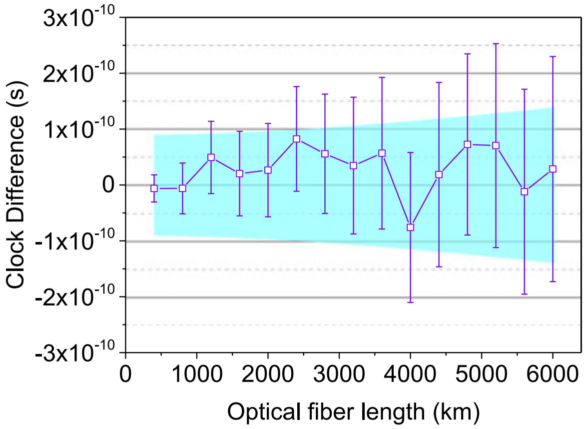


Fig. 6. Measured clock differences over different non-calibrated fiber links with the light blue background indicating the theoretical calculated expanded uncertainty (coverage factor k = 2).

After calibrating the asymmetry of sending and receiving delays of time transfer modems at two sites [3] $(\tau_A^T - \tau_A^R + \tau_B^R - \tau_B^T)$, the measured clock differences over various fiber lengths are plotted in Fig. 6 without fiber link calibration. The calculated expanded uncertainty with the coverage factor of 2 is also shown as light blue background [15], [16]. One can see that the averages of clock differences are within the expanded uncertainty [6] and do not exceed 100 ps as the fiber link extends from 400 km to 6000 km. With a common clock in the test, theoretically, the averages of the clock difference should be zero. The deviation mostly comes from the wavelength difference and its fluctuation of the adopted SFP transceivers, the receiving optical power-dependent delay of SFP transceivers, and the uncertainty of SR620. A better performance can be expected when the receiving optical powers of SFP transceivers used in calibration and test are matched [17], [18], and the bidirectional wavelength difference and its fluctuation is minimized by temperature control of SFP transceivers.

## 5. Conclusion

In conclusion, we proposed and implemented a single-fiber bidirectional-transmission unidirectional optical amplifier (SFBT-UOA), and successfully demonstrated a BTDM-SFSW based time transfer over a 6000 km fiber link in the laboratory environment. The time deviations of 190 ps/s and 61 ps/$10^5$s are reached, respectively. The calculated combined uncertainty is not beyond 70 ps without the requirement of fiber link calibration. The calculated results are verified by experiments as well. The proposed optical amplifier has the potential to support both time transfer and conventional network services at the same time, thus providing the possibility to embed a high-precision time transfer into long-haul commercial fiber transmission links.

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