# Optical Amplification for BTDM-SFSW-Based Time Transfer

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***Abstract*—Optical amplification, which is necessary for extending the distance of fiber-optic time transfer, has significant impacts on the time transfer performance. In this paper, we investigate and optimize the optical amplification for the time transfer based on bidirectional time division multiplexing transmission over a single fiber with the same wavelength (BTDM-SFSW). Three optical amplification schemes, namely single fiber bidirectional amplifier (SFBA), single fiber bidirectional amplifier with magneto-optical switch (SFBA-MOS), and single-fiber bidirectional-transmission unidirectional optical amplifier (SFBT-UOA) are considered. For each optical amplification scheme over different fiber links, the timing jitter and uncertainty of time transfer are theoretically and experimentally analyzed. A simple timing jitter optimization method for the BTDM-SFSW links is proposed. Further evaluations are performed from the point of view of system complexity, operation cost, and compatibility with telecom optical networks. Results show that SFBA is more suitable over shorter fiber links for its lower complexity and cost, while SFBA-MOS or SFBT-UOA should be employed for longer fiber links to achieve the accepted time transfer performance.**

***Index Terms*—Fiber optics system, instrumentation and metrology, time transfer.**

## ACRONYMS USED IN THIS PAPER.

| | |
|---|---|
| OA | Optical amplifier |
| SFBA | Single fiber bidirectional amplifier |
| EDF | Er-doped fiber |
| SNR | Signal-to-noise ratio |
| BTDM-SFSW | bidirectional time division multiplexing transmission over a single fiber with the same wavelength |
| SFBA-MOS | single-fiber bidirectional amplifier with magneto-optical switch |
| MOS | Magneto-optical switch |
| SFBT-UOA | single-fiber bidirectional-transmission unidirectional optical amplifier |
| UOA | Unidirectional optical amplifier |
| TDEV | Time deviation |
| SRB | Single Rayleigh backscattering |
| DRB | double Rayleigh backscattering |
| NBF | Narrow bandwidth filter |
| ASE | Amplified spontaneous emission |
| CU | Control unit |
| OS | Optical switch |
| SFP | Small form-factor pluggable |

## I. INTRODUCTION

THE increasing demands in a variety of applications, such as time and frequency metrology, navigation, and astronomy etc., have sparked immense interests in fiber-optic time transfer [1]. For long-haul transfer, it is imperative to compensate for the transmission attenuation via optical amplifiers (OAs). As almost all the high-precision fiber-optic time transfer schemes employ single-fiber bidirectional transmission to mitigate the influences from fiber link propagation delay and its variation, the OAs [2]–[9] for time transfer are much different from the ones for fiber telecom networks. In addition to optical signal amplification, the OAs should have high bidirectional delay symmetry so as to avoid the performance degradation and the complicated link calibration. The single fiber bidirectional amplifiers (SFBAs) [8], [10] have been proposed by removing the directional optical components, such as isolators, and circulators etc., from the conventional OA. The bidirectional optical signals are amplified in a single Er-doped fiber (EDF). Though the maximum bidirectional delay symmetry can be guaranteed, Rayleigh backscattering etc. will significantly degrade the receiving signal-to-noise ratio (SNR) and hence limit the maximum transmission distance for an acceptable level of timing jitter [11]. Recently, we proposed a novel time transfer method based on bidirectional time division multiplexing transmission over a single fiber with the same wavelength (BTDM-SFSW) [9], [10], and two associated optical amplification schemes with the features of bidirectional-transmission and unidirectional-amplification. One is the single fiber bidirectional amplifier with magneto-optical switch (SFBA-MOS) [12], and the other is the single-fiber bidirectional-transmission unidirectional optical amplifier (SFBT-UOA) [13]. The former employs two MOSs as the direction-variable optical isolators to change the transmission direction of SFBA alternately, while the latter enables the bidirectional optical signals to pass through the same UOA in different time slots via a 2 × 2 optical switch.

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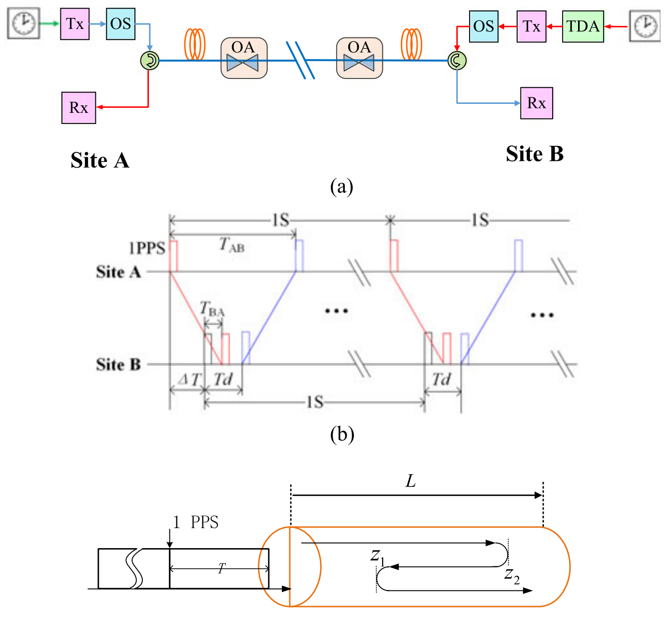


(a)

(b)

(c)

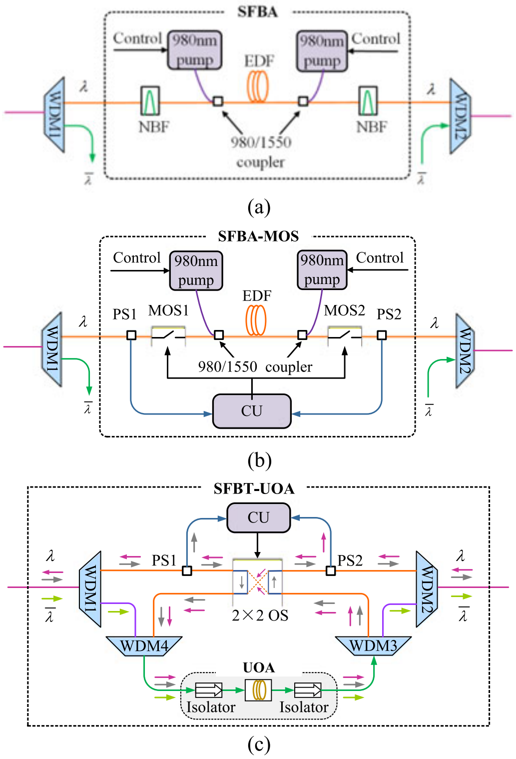
Fig. 1. (a) system configuration; (b) principle; (c) schematic diagram of BTDM-SFSW based time transfer; OS: optical switch; OA: optical amplifier; $T_{AB}$ ($T_{BA}$): the time difference between the local 1PPS and the received one at site A (site B); $T_d$: the delay of the local 1PPS at site B; *T*: optical carrier duration in front of 1 PPS; *L*: fiber link length.

This paper investigates and optimizes the optical amplification for BTDM-SFSW based time transfer. The timing jitter and uncertainty of time transfer over different fiber links are theoretically analyzed. Further evaluations are performed from the point of view of the system complexity, operation cost and compatibility with telecom optical networks etc. A simple optimization method for the BTDM-SFSW links is proposed to minimize the timing jitters and validated experimentally. The rest of the paper is organized as follows. Section II gives the analysis and optimization of BTDM-SFSW links with OAs. Section III presents the experimental results and discussions. Section IV concludes our work.

## II. ANALYSES AND OPTIMIZATION OF BTDM-SFSW LINKS WITH OAS

### A. *Principle of BTDM-SFSW Based Time Transfer and Optical Amplification Schemes*

The BTDM-SFSW based time transfer is illustrated in Fig. 1. The time signals, e.g., one-pulse-per-second (1 PPS) signals, at site A and site B, are modulated onto the optical carriers with the same wavelength of λ to maintain the bidirectional propagation delay symmetry, and then launched into the fiber link. It should be noted that, unlike the traditional method of transmitting the local time signal immediately, the time signal at site B is delayed by an interval of $T_d$ until the optical signal from site A is received completely. In this way, the single Rayleigh backscattering (SRB) originating from the local light sources [9] can be easily blocked by launching the optical carriers into the fiber link only during the time signal transmission.



(a)

(b)

(c)

Fig. 2. Block diagram of (a) single fiber bidirectional amplifier (SFBA), (b) single fiber bidirectional amplifier with magneto-optical switch (SFBA-MOS), and (c) single-fiber bidirectional-transmission unidirectional optical amplifier (SFBT-UOA). NBF: narrow bandwidth filter; PS: power splitter; CU: control unit.

Moreover, the total double Rayleigh backscattering (DRB) field at the end of the fiber link can be expressed as [14]

$$\varepsilon_{DRB}(t,L)=\int_0^L\int_0^{z_2}\varepsilon_{dir}\left(t-\frac{2\,(z_2-z_1)}{c},L\right)\cdot e^{-2(\alpha/2+j\beta)(z_2-z_1)}\rho(z_1)\rho(z_2)dz_1dz_2 \qquad (1)$$

where *L* is the fiber link length, *c* is the speed of light in vacuum, the $\varepsilon_{dir}(t,z)$ is the complex amplitude of the direct traveling field at location z, $z_1$ and $z_2$ are the locations where the DRB is generated, $\alpha$ is the total intensity attenuation coefficient, $\beta$ is the propagation constant, and $\rho(z)$ is the differential Rayleigh backscattering coefficient. As shown in Fig. 1(c), $z_1$ and $z_2$ are related to the optical carrier duration, *T*, in front of 1 PPS. Therefore, the effects of DRB from the transmitting light on the received 1 PPS can be mitigated if the following condition is satisfied,

$$T\le 2nL/c \qquad (2)$$

where *n* is refractive index of fiber.

Fig. 2 summaries three optical amplification schemes for BTDM-SFSW based time transfer. As shown in Fig. 2(a), SFBA [10] adopts two WDMs at two ports for the purpose of wavelength selection. Two narrow bandwidth filters (NBFs) can be applied as well to further diminish the amplified spontaneous emission (ASE) noise. The passband of the NBFs only need to cover the spectral width of the employed optical carriers

TABLE I
SIGNAL SOURCES FOR TIME TRANSFER OVER A FIBER LINK WITH ONE SFBA

| **Noise Source** | | | **Related to *T*** |
|---|---|---|---|
| Time signal | $P_{in}^2$ | $G^2$ | × |
| Shot noise | $P_{in}$ | G | × |
| Thermal noise | — | — | × |
| Laser intensity noise | $P_{in}^2$ | $G^2$ | × |
| Laser phase-intensity conversion noise | $P_{in}^2$ | $G^2$ | × |
| DRB (amplified three times) | $P_{in}^2$ | $G^6$ | √ |
| DRB (amplified once) | $P_{in}^2$ | $G^2$ | √ |
| Signal-DRB (amplified three times) beating | $P_{in}^2$ | $G^4$ | √ |
| Signal-DRB (amplified once) beating | $P_{in}^2$ | $G^2$ | √ |
| ASE | — | $G^2$ | × |
| Signal-ASE beating | $P_{in}$ | $G^2$ | × |

1. $P_{in}$ is the input optical power.
2. $G$ is the optical gain of the SFBA.

(indicated by λ) since the bidirectional transmitted wavelengths are identical. Two pumps are collaborated to balance the optical gains forth and back [15]. Fig. 2(b) illustrates the scheme of SFBA-MOS [12]. The bidirectional optical carriers for time transfer arrive at SFBA-MOS in different time slots, and are selected by WDM1 and WDM2, respectively. The transmission direction of MOSs is configured by the level of control signal from the control unit (CU). The optical signals back and forth are allowed to be transmitted and amplified uni-directionally along a single EDF alternately. In the SFBT-UOA [13] (depicted in Fig. 2(c)), the forward and backward optical carriers are picked out by WDM1 and WDM2, respectively, and sent in turn to the conventionally-configured UOA via the 2 × 2 optical switch (OS). The amplified optical carrier for time transfer service is then selected by WDM3, and outputs to the corresponding port of SFBT-UOA according to its transmission direction via the 2 × 2 OS.

## *B. Analyses of BTDM-SFSW Links*

The BTDM-SFSW links with different optical amplification schemes can be compared qualitatively as follows:

1) Bidirectional delay symmetry. The SFBA and SFBA-MOS can guarantee the bidirectional delay symmetry due to the same wavelengths along a single fiber, and hence have no contribution on the time transfer uncertainty. For SFBT-UOA, the optical signals forward and backward go almost through the same path except for the ones within the 2 × 2 OS. The delay difference in a 2 × 2 mechanical OS can be less than 0.5 ps [13]. Thus a high bidirectional delay symmetry can also be guaranteed in SFBT-UOA.
2) Noise suppression. Table I lists the main noise sources for the time transfer over a fiber link with one SFBA. Due to the lack of directional optical devices in SFBA, some undesired signals, such as the DRB travelling around one or more SFBAs, and the SRB of ASE etc., will be amplified more than once, and accumulate seriously at the remote receiving site. Subsequently, the SNR or timing jitter of the received time signal is deteriorated. In contrast, the transmitted optical signals forth and back are only allowed to pass through SFBA-MOS or SFBT-UOA uni-directionally in different time slots. The backscattering noises suffering from SFBA (item 6 and 8) are blocked, leading to an improved SNR.
3) System complexity. For a proper operation of BTDM-SFSW based time transfer, a special link access control mechanism to set the states of the MOSs in SFBA-MOS or the 2 × 2 OS in SFBT-UOA is needed [12], [13]. It is the cost for the noise suppression and distance extension.
4) Compatibility with telecom optical networks. The SFBA-UOA has the capability to simultaneously function as a conventional OA for WDM network services over other wavelengths (indicated by $\bar{\lambda}$ in Fig. 2) [16]. However, the SFBA and SFBA-MOS can only support fiber-optic time transfer service, and another UOA is required to sustain other WDM network services.

## *C. Optimization of BTDM-SFSW Links*

Similar to the non-BTDM links, BTDM-SFSW links can be optimized by minimizing the corresponding timing jitters of the received time signals [11]. The total link noise, and hence the timing jitters of BTDM-SFSW links can be calculated according to Table I. It is worth noting that, different from the non-BTDM links, the DRB dependent noises in BTDM-SFSW links vary with the fiber length and *T,* see (1).

Fig. 3 shows the calculated timing jitters of 100 km, 200 km and 1000 km BTDM-SFSW links with different optical amplification schemes, respectively. The launched optical power is 3 dBm. From the figure, we can see that the timing jitters over the links with SFBA decrease first and then increase as the optical gain increases from a low value. It can be explained as follows. In the low optical gain region, the gain-related noises (such as ASE noise, DRB noise, signal-DRB beating noises, laser phase-intensity conversion noise [17] etc.) are negligible. The thermal noise, which is not related to the optical gain, accounts for a substantial part of the total noise. In the case, better SNR or timing jitter is obtained as the receiving signal increases with the optical gain. As the optical gain increases, all the gain-related noises increase, especially for the DRB related noises, since they travel around the SFBA and are amplified several times. When the optical gain becomes high enough, the DRB related noises will become the dominant one. In the case, the timing jitter will increase with the optical gain since the multiple-amplified DRB noises increase faster than the received optical signal. The steeper increase of timing jitter over a longer fiber link (Fig. 3(c) and (e)) results from the DRB increase with the fiber link extension [14]. For the two types of uni-OAs (SFBA-MOS and SFBT-UOA), similar results are observed in the low optical gain regions (see Fig. 3) for the similar reasons. The difference

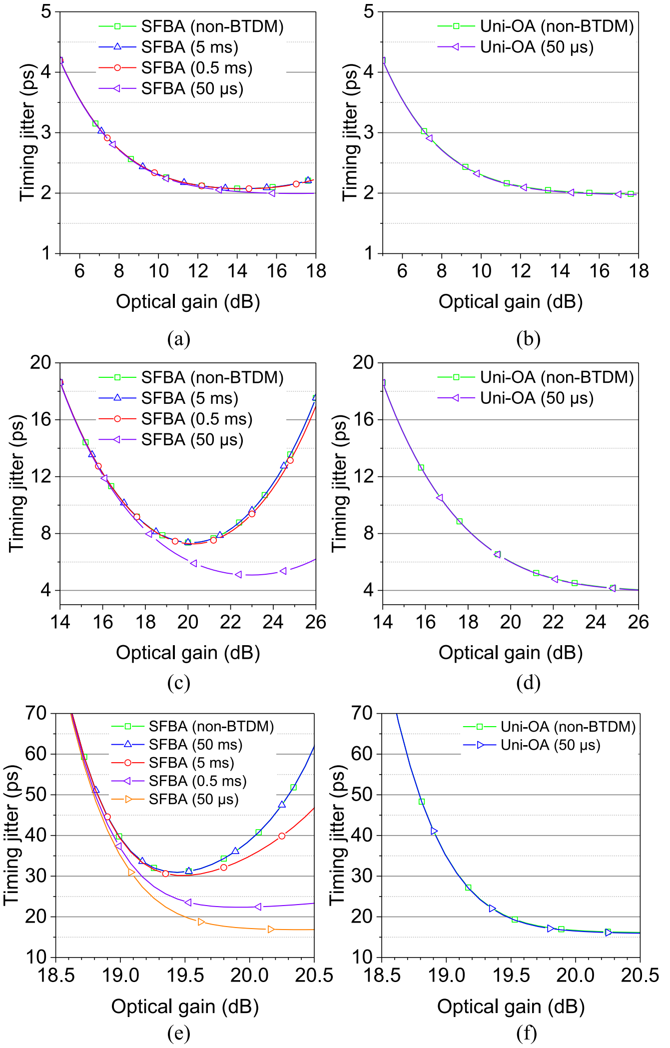


Fig. 3. Calculated timing jitters of the received time signals for different optical gains over the links of (a) 100 km with SFBA, (b) 100 km with uni-OA, (c) 200 km with SFBA, (d) 200 km with uni-OA, (e) 1000 km with SFBA and (f) 1000 km with uni-OA, respectively.

is that, the timing jitters keep decreasing in the high optical gain region. The main reason is that the multiple-amplified DRB noises are suppressed since the DRB cannot travel around the uni-OAs. In the case, the other gain-related noises and the received signal have the same gain while the thermal noise holds the same. Therefore, the timing jitters will still decrease slowly in the large optical gain region. The results also indicate that the uni-OA can have a much larger range of optical gain for an optimal system operation. It should be noted that the optical gain cannot be too high to avoid the fiber nonlinearity.

The timing jitters under different optical carrier durations $T$ are also given in Fig. 3. As $T$ decreases, the timing jitter for SFBA drops down to the one of uni-OA in the high optical gain region. This is because the DRB dependent noises decrease with $T$ when the condition in (2) (e.g., 1 ms for 100 km, 2 ms for 200 km etc.) is satisfied. Nevertheless, for the links using uni-OA, the timing jitters do not depend on $T$ (see Fig. 3(b), (d), and (f)).

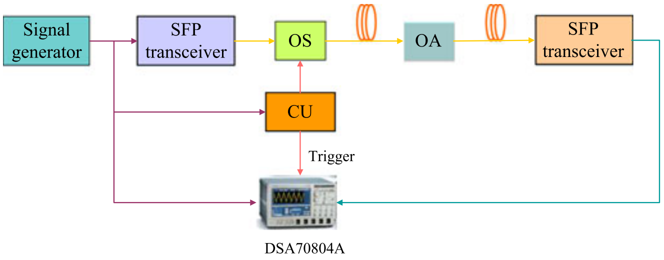


Fig. 4. Experimental setup for timing jitter measurement of fiber-optic time transfer with different OAs. SFP: small form-factor pluggable.

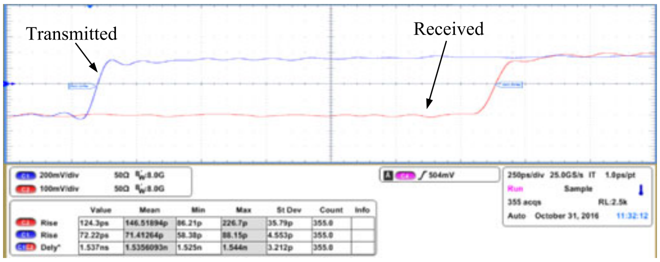
Comparing the results for different optical amplification schemes, we can see that the shorter fiber links with SFBA have similar optimal timing jitters as the ones with uni-OA. Therefore, SFBA is preferred for shorter fiber links to achieve a desired time transfer performance with lower complexity and cost. For longer fiber lengths, links with SFBA can only reach the optimal timing jitter for very short $T$, while the links with uni-OA can always reach the optimal one under any $T$. Considering the optimal gain range and the difficulty to reach very short $T$, SFBA-MOS or SFBT-UOA should be employed for long haul at the cost of link access control.

Moreover, from Fig. 3(a), (c), and (f), we can see that the optimal timing jitters in both short BTDM links with SFBA and long BTDM links with uni-OA are very close to the ones in the corresponding non-BTDM links with the same optical amplification schemes. The results indicate that the short or long BTDM links with the proposed optical amplification schemes can be optimized using the method for non-BTDM links to reduce the tough calculation of DRB noises.

## III. EXPERIMENTS AND RESULTS

The timing jitters of the received time signals over short fiber links with different optical amplification schemes are measured through the experimental setup shown in Fig. 4. A small form-factor pluggable (SFP) transceiver with a wavelength of 1549.32 nm is on-off modulated by a 100 MHz square signal from a signal generator. An OS with a switching time of about 50 $\mu$s is used to cut out a section of the generated optical signal every second under the control of CU. In each cut-out optical signal segment, corresponding to an optical carrier duration in BTDM-SFSW based time transfer, one rising edge of the modulating signal is designated as the on-time point. The generated optical signal segments are sent into the fiber link with an OA in the middle. At the remote site, the arrived optical signal is received by another SFP transceiver. The time interval from the designated rising edge in the received signal to a referenced rising edge in the transmitted signal is measured by an oscilloscope (Tektronix, DSA70804A) under the control of CU. In order to guarantee the evaluation validation, the measured values in at least 300 s under each parameter setting are used. After removing the influence of temperature-dependent propagation delay by linear fitting, the timing jitter is determined by calculating the standard deviation of the measured time intervals.

Fig. 5 shows the rising edges of the 100 MHz signals transmitted from the signal generator and the one received in the



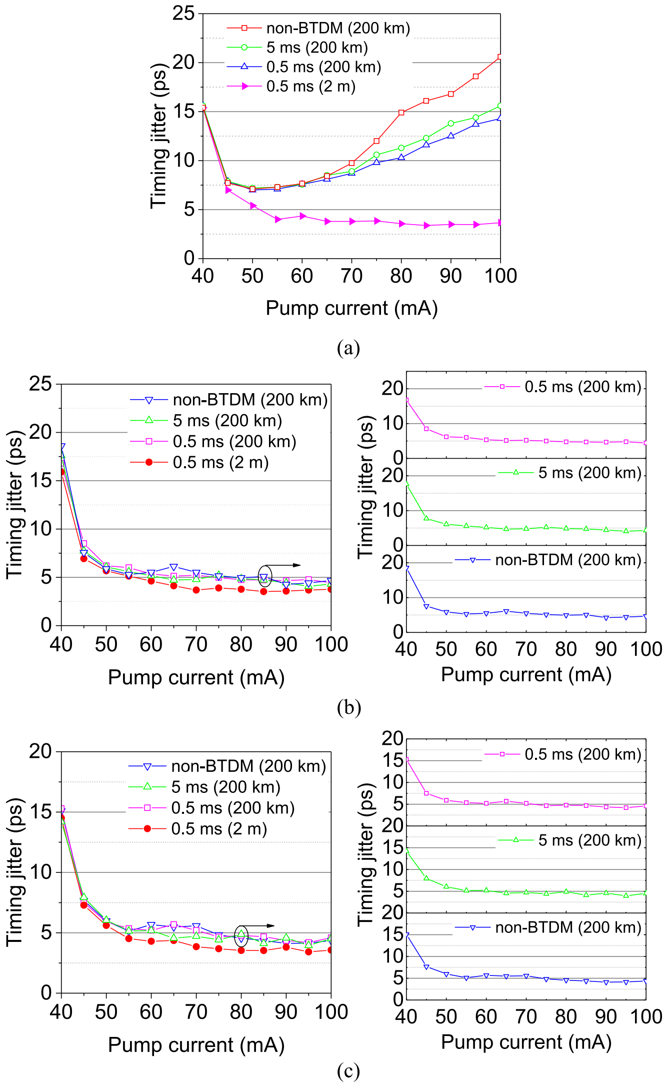
C1 200mV/div 50Ω $B_W$:8.0G
C2 100mV/div 50Ω $B_W$:8.0G

C4 504mV

250ps/div 25.0GS/s IT 1.0ps/pt
Run Sample
355 acqs RL:2.5k
Auto October 31, 2016 11:32:12

| | Value | Mean | Min | Max | St Dev | Count | Info |
|---|---|---|---|---|---|---|---|
| C2 Rise | 124.3ps | 146.51894p | 86.21p | 226.7p | 35.79p | 355.0 | |
| C1 Rise | 72.22ps | 71.41264p | 58.38p | 88.15p | 4.553p | 355.0 | |
| C1 C2 Dely* | 1.537ns | 1.5356093n | 1.525n | 1.544n | 3.212p | 355.0 | |

Fig. 5. Rising edges of the transmitted signal from the signal generator and the one received at the remote site.



(a)

(b)

(c)

Fig. 6. Measured timing jitters of the received time signals under different optical carrier durations over a 200 km fiber link using a (a) SFBA, (b) SFBA-MOS, and (c) SFBT-UOA.

SFP transceiver at the remote site, respectively. The transmitted signal from the signal generator has a rise time of about 71 ps and a timing jitter about 1.8 ps. Owing to the limited bandwidth of SFP transceiver etc., the rise time of the received signal at the remote site worsens to about 147 ps, regardless of fiber lengths. The timing jitter of the received signal, measured without any fiber spans and OAs, is about 2.2 ps.

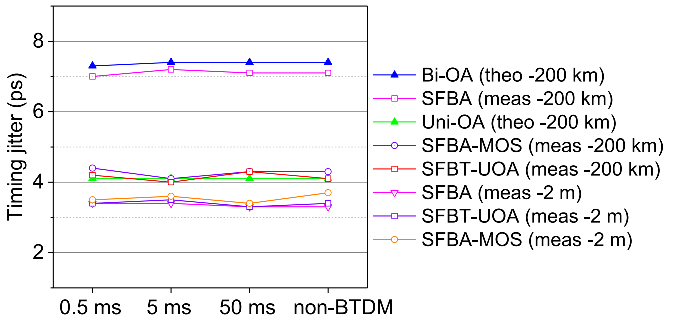
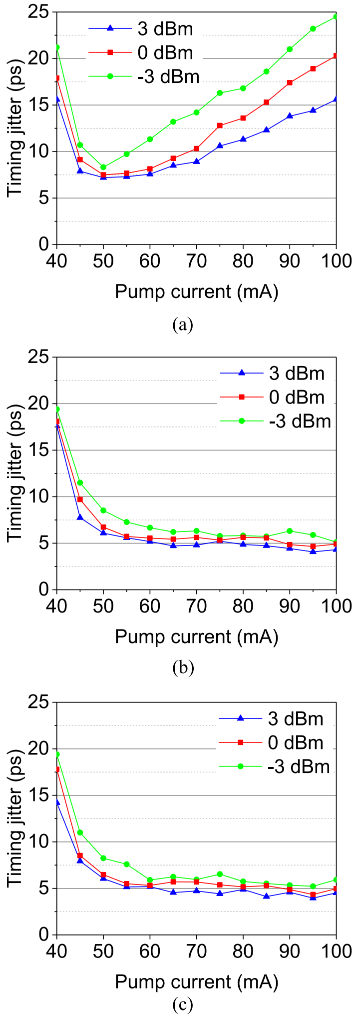


Fig. 7. Theoretical and measured timing jitters for different optical carrier durations under optimal operation condition over 2 m and 200 km fiber links.

Considering the system specifications, the shortest $T$ is set to 0.5 ms. For three kinds of amplification schemes over a 100 km fiber link (see Fig. 4), the measured timing jitters for different optical carrier durations nearly coincide with the theoretical ones in Fig. 3(a). Fig. 6 provides the measured timing jitters under different pump currents of OAs over a 200 km fiber link. The launched optical power is 3 dBm. For SFBA, the measured results in Fig. 6(a) are almost consistent with the theoretical ones in Fig. 3(b) in the low and middle pump current regions. However, some obvious differences can be observed in the high pump current region among different $T$, which can be attributed to the fourth and higher Rayleigh backscattering. When SFBA-MOA or SFBT-UOA is adopted, the timing jitter is almost independent on $T$. And a much larger range of optical gain can be enabled for an optimal system operation (see Fig. 6(b) and (c)). Also plotted in Fig. 6 are the results of substituting a variable optical attenuator with an equal attenuation for each fiber span. From the figure, we can see that the timing jitters with fibers are very close to the ones without fiber spans for SFBA-MOA and SFBT-UOA. It validates that SFBA-MOA and SFBT-UOA can efficiently suppress the DRB dependent noises. Hence a longer transmission distance can be expected under an intended time transfer precision. The theoretical and measured optimal timing jitters under different optical carrier durations over the 2 m and 200 km fiber links are provided in Fig. 7. We can see that the measured results are in well agreements with the theoretical ones.

Furthermore, we investigate the effects of launched optical power on the timing jitters when the condition in (2) is not reached. Fig. 8 gives the measured results for a 200 km fiber link. The optical carrier duration $T$ is 5 ms. From the figure, one can see that a larger launched optical power results in a lower timing jitter. It can be explained as follows. In the low pump current region, the total noise, dominated by the thermal noise, is nearly constant while the received optical signal increases with the launched optical power. Consequently, the resulting timing jitter decreases. In the large pump current region, the receiving SNR becomes better with the increase of the launched optical power since the receiving signal increases faster than the total noise [18]. The results in the large pump current region show that the impact of the launched optical power on the timing jitter for SFBA is larger than the ones for SFBA-MOA and SFBT-UOA. It may be because the DRB traveling around the



(a)

(b)

(c)

Fig. 8. Measured timing jitters with different launched optical powers for (a) SFBA; (b) SFBA-MOS; (c) SFBT-UOA over 200 km fiber links.

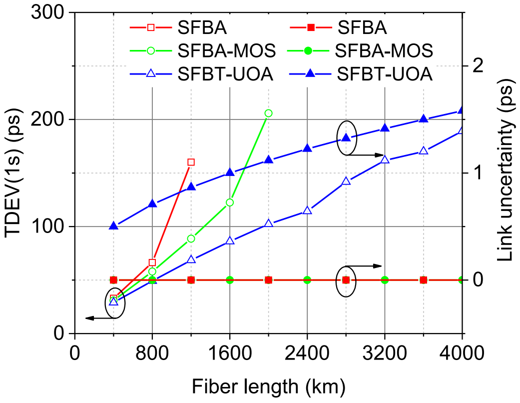


Fig. 9. Time deviations (TDEVs) of BTDM-SFSW based time transfer at 1 s averaging time as a function of fiber lengths when using different kinds of optical amplifiers. Also plotted is the link uncertainty resulting from the optical amplification.

TABLE II
MAIN FEATURES OF THREE OPTICAL AMPLIFICATION SCHEMES

| | SFBA | SFBA-MOS | SFBT-UOA |
|---|---|---|---|
| Bidirectional delay asymmetry | 0 | 0 | < 0.5 ps |
| Noise suppression | bad | well | well |
| System complexity | simple | complex | complex |
| Compatibility with telecom optical network | × | × | √ |
| Suitable link length | < 400 km | > 800 km | > 800 km |

SFBA scales with the launched optical power and is multiply amplified (see Table I).

For experiment over longer fiber links, the tests were performed on a BTDM-SFSW based time transfer testloop with a circumference of 100 km and one OA (please refer to [9] for other system setup details). The TDEV (1 s) of the measured clock difference as a function of fiber length is shown in Fig. 9. When the fiber link is shorter than 400 km, similar TDEV (1 s) is achieved for three optical amplification schemes under the optimal system operation. The noise performance difference among three amplification schemes gets more obvious as the fiber link extends beyond 800 km. Due to the high bit error for a poor SNR, SFBA can only extend the BTDM-SFSW based time transfer to about 1200 km with the TDEV (1 s) of 160 ps. However, 2000 km can be reached with the TDEV (1 s) of 206 ps for SFBA-MOS, and 4000 km with the TDEV (1 s) of 189 ps for SFBT-UOA. It should be noted that the measured TDEV (1 s) is much worse than the one along point-to-point single fiber link for the recirculation noises. One can also see that the performance of SFBA-MOS is not as good as the one of SFBT-UOA, which is not obvious in Fig. 6. It may be caused by the optical gain difference between the forward and backward transmitted signals for passing through the same EDF in two opposite directions in SFBA-MOS [15]. As the fiber link extends, the optical power difference between two directions becomes larger with the number passing-through the same SFBA-MOS in the loop. And the optical signal in one direction will not be able to get enough power to be efficiently detected by the SFP transceiver at the remote site. Therefore, the receiving SNR at the corresponding site will be appreciably deteriorated against the increase of fiber length, which will degrade the performance of time transfer as well and may block the system operation for an unacceptable bit error. Further investigation on the reasons will be carried out in our next work. From the figure, SFBA and SFBA-MOS have no effects on the time transfer uncertainty since they can always maintain the bidirectional delay symmetry. At the same time, SFBT-UOA can achieve a time transfer uncertainty of less than 2 ps over a 4000 km fiber link with 40 2 × 2 OSs.

The results validate that the SFBA can be a simpler amplification solution for the BTDM-SFSW based time transfer over a shorter fiber link without a link access control mechanism. As the link extends, the SFBA-MOS or SFBT-UOA is required to maintain a proper operation of time transfer and achieve higher precision at the cost of an excess link access control mechanism. The main features of three optical amplification schemes are summarized in Table II.

## IV. CONCLUSION

In summary, the system performance related to the optical amplification for BTDM-SFSW based time transfer, such as timing jitter and uncertainty, system complexity and compatibility with telecom optical network etc. is theoretically investigated. The experimental validation is performed for different optical fiber lengths and different optical amplifier parameters. Results clearly show that, in comprehensive consideration of the expected transfer precision and the system complexity, the SFBA is preferred over shorter fiber links, while the SFBA-MOS or the SFBT-UOA should be deployed for longer fiber links. Moreover, only SFBA-UOA has the capability to function as a conventional OA for WDM network services. The results and analysis provided make for the system design of fiber-optic time transfer and optimize its corresponding operation performance.

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