Long-Haul Fiber-Optic Time and Frequency Synchronization

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Summary*— Looking toward future very large telescope arrays and fifth-generation/sixth-generation (B5G/6G) scenarios, building a large-scale fiber-based time and frequency synchronization network will be vital support. To solve the distance limitation caused by dispersion in long-distance frequency dissemination, a chirped fiber Bragg grating (CFBG) enhanced bidirectional erbium-doped fiber amplifier (Bi-EDFA) design is proposed. With this design, frequency dissemination tests are carried out on the 500 km fiber link (50 km-100 km-150 km-100 km-100 km). Stabilities of 1.7×10^{-14}/s and $6.7\times10^{-18}/10^5$ s are obtained. In addition, we apply the concept of time reversal in fiber-optic time synchronization. Owing to time reversal, the clock offset of two sites can be measured without calculating the fiber link delay. Finally, we have carried out the time and frequency integrated synchronization over the 514 km field fiber link. The frequency synchronization stabilities of 2.2×10^{-14}/s and $2.2\times10^{-17}/10^5$s have been obtained. The time synchronization performance characterized by TDEV of 10 ps at 1 s and 1.2 ps at 10000 s have been realized. [1]

Keywords—time and frequency synchronization; dispersion compensation; long distance; time reversal; multiple access

I. Introduction

In recent decades, fiber-optic time and frequency synchronization (FOTFS) has played a fundamental role in many fields, such as metrology [1], radio astronomy [2], geodesy [3], navigation as well as telecommunication [4]. The good immunity of fiber to electromagnetic interference makes FOTFS a suitable timing and synchronization solution in scenarios where electromagnetic silence is needed or electromagnetic interference is high.

With the increasing abundance of fiber resources worldwide and the increasing demand for high-precision time and frequency synchronization, building a large-scale fiber-based time and frequency synchronization network is necessary for some scenarios in the future. For example, in the next-generation Very Large Array, the maximum baseline length can reach ~1000 km [5]. Timing and synchronization over such a large area will become a major challenge. In addition, it is foreseeable that in future fifth-generation/sixth-generation (B5G/6G) scenarios, a large-scale FOTFS network will provide strong support to achieve full-area three-dimensional coverage and broadband access [6].

For a large-scale frequency synchronization network, the RF-over-fiber (RFoF) transmission method may be the most suitable solution due to its low cost and ability to run continuously for long term. However, fiber dispersion is one of the main limiting factors on distance. The traditional solution is using dispersion compensating fiber (DCF), but there are problems of high insertion loss, high latency and a large footprint. Chirp correction, based on chirped fiber Bragg grating (CFBG), has advantages of lower insertion loss, lower time delay and smaller size than using DCF.

As for fiber-optic time synchronization (FOTS), due to the finite speed of light, both two-way time transfer [1], [7] and round-trip time transfer [8], [9] required to calculate the fiber link delay first in order to achieve time synchronization. For two-way time transfer method, the data layer during transmission is required to exchange the measured timing information. Therefore, encoder and decoder are required at both ends, which increases the complexity of the system and theoretically limits the accuracy of time synchronization. Moreover, since the time delay information exchanged is specific to the two ends, it is difficult to realize multiple-access time synchronization. This greatly limits the scalability of the time synchronization system.

In this paper, we demonstrate the CFBG enhanced bidirectional erbium-doped fiber amplifier (Bi-EDFA) design, which can simultaneously achieve dispersion compensation and asymmetrical optical amplification [10]. We build a 500 km fiber link by connecting 50 km-100 km-150 km-100 km-100 km spools and 4 CFBG enhanced Bi-EDFAs are used. The great challenge introduced by the section of the 150 km spool has been overcome and stabilities of 1.7×10^{-14}/s and $6.7\times10^{-18}/10^5$ s are realized. Moreover, we apply the concept of time reversal in the FOTS, which provide a new idea for FOTS: calculating the fiber link delay is no longer necessary. The advantages derive from time reversal are as follows. First, time synchronization can be achieved without exchanging the

This work was supported in part by the National Natural Science Foundation of China under Grants 61971259, in part by National Key R&D Program of China under Grant 2021YFA1402102, and in part by Tsinghua Initiative Scientific Research Program.

time delay data between two sites. Therefore, the data layer is no longer needed, which effectively reduces the complexity of system. Second, the synchronization process is very simple, requiring only two steps: synchronization request and synchronization response, which can provide the possibility to realize the time synchronization with star-shaped networked topology. Third, it is feasible to achieve multiple access.

II. METHODS/RESULTS

A. CFBG enhanced Bi-EDFA

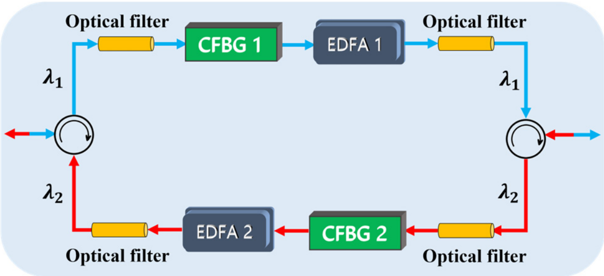

Fig. 1. Schematic diagram of CFBG enhanced Bi-EDFA. A CFBG and two optical filters are placed on each path.

A schematic diagram of the proposed CFBG enhanced Bi-EDFA is shown in Fig. 1. There is a single CFBG on each path to compensate fiber dispersion in two directions. Two optical filters on each path are used to suppress the backscattering optical signal and the amplified spontaneous emission (ASE) noise from the EDFA. Such design has two purposes. First, since CFBG is a unidirectional device and susceptible to changes in environmental factors, such a design can reduce the one-way phase fluctuation caused by CFBG. Second, it can be applied to more challenging fiber links where a high gain for optical amplification is needed.

B. Frequency dissemination results on a 500 km fiber link

Through the proposed CFBG enhanced Bi-EDFA, we have extended the distance of the frequency dissemination over fiber link to 500 km. The fiber link is made up of 100 km-100 km-150 km-100 km-100 km G652.D fiber spools. The total optical attenuation of this link is 97.2 dB. The attenuation of the 150 km fiber is ~28.7 dB, which posing major difficulties for optical amplification, ASE noise suppression, and Rayleigh backscattering suppression. In this link, 4 CFBG enhanced Bi-EDFAs are used. The detailed setup of the whole link is shown in Fig.2.

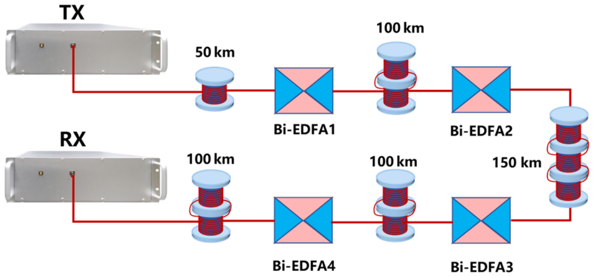

Fig. 2. The setup of the 500 km fiber link and 4 Bi-EDFA.

Due to the special setup of the link, the gain of each Bi-EDFA in two directions (TX-RX direction and RX-TX direction) is asymmetric. Asymmetric optical amplification of the nodes requires that the gain in both directions of the Bi-EDFA is independently and precisely controllable. Therefore, the Bi-EDFA design with good internal symmetry proposed in [11] is not applicable in this case. The gain in two directions of each Bi-EDFA is shown in Table I.

TABLE I. THE GAIN IN TWO DIRECTIONS OF EACH BI-EDFA

Bi-EDFA	Gain in TX-RX (dB)	Gain in RX-TX (dB)
Bi-EDFA1	15.3	32.5
Bi-EDFA2	24.8	35.5
Bi-EDFA3	34.7	23.7
Bi-EDFA4	32.8	22.1

It can be seen from Table I that there is obvious asymmetry for each Bi-EDFA. And the maximum gain is 35.5 dB for Bi-EDFA2 in the RX-TX direction, which poses a significant challenge for optical amplification as well as ASE noise suppression. We carry out the frequency dissemination test on the 500 km fiber link. The detailed setup of our RFoF system can be found in [10]. The duration of the continuous test is about 14 days. During the 14 days, the phase time difference of the time synchronization is within 3 ps, indicating good frequency synchronization performance of our system. As shown in Fig. 3, stabilities of 1.7×10^{-14}/s and $6.7\times10^{-18}/10^5$s are achieved. The good frequency dissemination stabilities obtained in this special link demonstrate the applicability of the chirp control enhanced RFoF system in long-haul optic-fiber frequency dissemination.

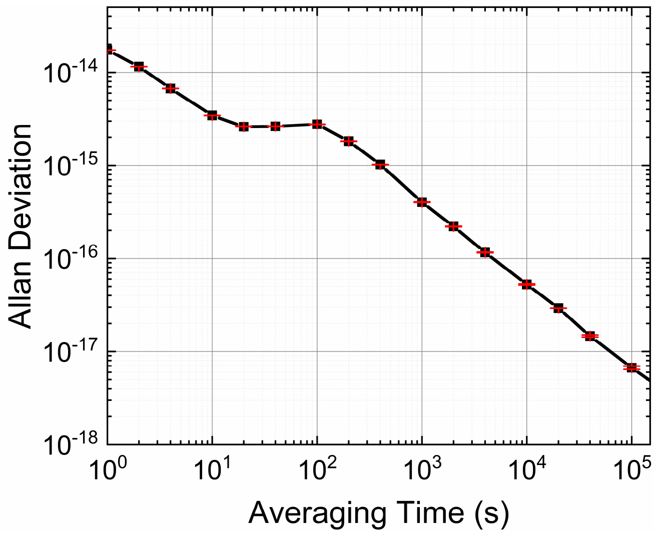

Fig. 3. Allan deviation of frequency dissemination over 500 km fiber link versus averaging time.

C. Time reversal in fiber-based time synchronization

Time reversal is an operation of reversing the direction of time based on the transform: $t \rightarrow -t$ or $t \rightarrow C - t$, where t

represents the time and C is a constant [12], [13]. Time reversal of a time signal can be understood as adding a negative time delay and making time run backward. In practice, however, negative time delays cannot be generated. Hence, a feasible approach is to generate a positive time delay in the form of $C-t$ (C is a constant delay). In this paper, the FOTS based on time reversal is proposed. The schematic diagram of the proposed method is shown in Fig. 4.

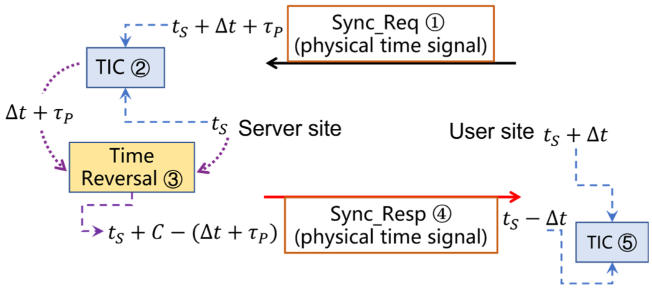

Fig. 4. Schematic diagram of the FOTS based on time reversal. TIC, time interval counter.

As shown in Fig. 4, the proposed time synchronization method based on time reversal can be regarded as Request-Response operation. Only two processes are required to achieve time synchronization: synchronization request (Sync_Req) process and the synchronization response (Sync_Req) process. The time signals of server site and user site are expressed as t_s and t_u, respectively. There exists a clock offset $\Delta t=t_u-t_s$. To achieve the time synchronization, we need obtain the clock offset. Hence, in the Sync_Req process, the time signal at the user site is sent to server site via a fiber link. At the server site, the time difference between the local time signal t_s and the received time signal is measured as $\Delta t+\tau_P$. τ_P is the one-way fiber link delay. If we can reverse the local time signal t_s by $\Delta t+\tau_P$, then the reversed time signal can be expressed as $t_s-(\Delta t+\tau_P)$. However, the negative delay cannot be achieved in practical applications. Therefore, we can add a positive time delay $C-(\Delta t+\tau_P)$ to the time signal t_s and the time signal $t_s+C-(\Delta t+\tau_P)$ can be obtained. At this point, we have already achieved the time reversal for the fiber link delay τ. When the reversed time signal is transmitted back to the user site, the fiber link delay in two directions can be directly eliminated. The receiving time signal at user site can be used to calculate the clock difference of two sites. Thus, the time synchronization can be realized without calculating the fiber link delay.

D. *Time and Frequency integrated synchronization on 514 km field fiber link*

Based on the proposed frequency synchronization method and time synchronization method above, we have carried out the time and frequency integrated synchronization test on a 514 km field fiber link. This 514 km field fiber link starts from Tsinghua University (THU), goes through Yizhuang, Niucheng, Xiongxian East, and finally reaches Xushui West in Hebei province. Then this fiber link loops back from another parallel fiber at Xushui West and finally returns to THU. For convenience, the transmitter and receiver of the integrated system are both located in the same lab at THU. The total loss of the 514 km G652.D fiber link is ~112 dB. We placed 5 Bi-EDFAs for bidirectional optical amplification and dispersion compensation in the link. The dispersion compensation amount in each direction is 500 km. The detailed principle of the Bi-EDFA design is shown in Fig. 5. The wavelengths of C38 and C39 are used for the sub-system of frequency synchronization, and the the wavelengths of C28 and C29 are used for the sub-system of time synchronization. The dense wavelength division multiplexer (DWDM) is used to combine and split the optical signal and suppress the Rayleigh backscattering and ASE noise.

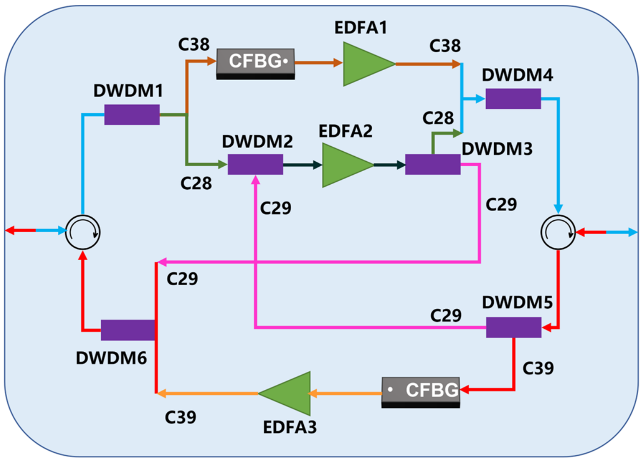

Fig. 5. Schematic of the Bi-EDFA design.

The frequency synchronization performance is evaluated by an Allan deviation test set (model 5125A, Microsemi Corporation). The result is shown in Fig. 6, with the stabilities of 2.2×10^{-14}/s and $2.2\times10^{-17}/10^5$s achieved.

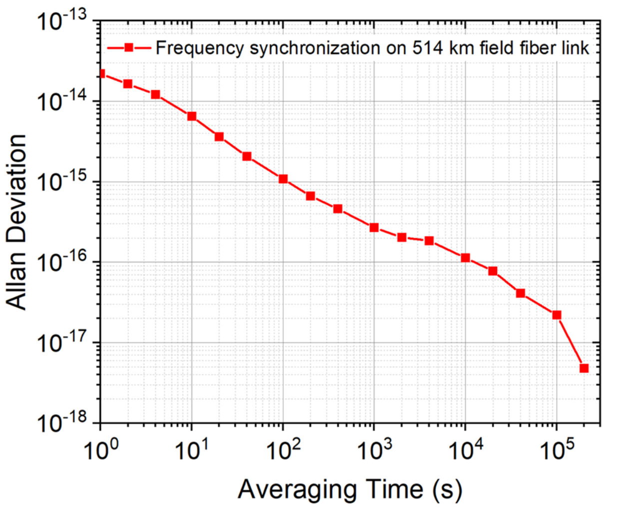

Fig. 6. Frequency synchronization performance on 514 km fiber link.

The time difference of time synchronization is measured by a time interval counter (model 53230A, Keysight Corporation). Then we can use the Stable 32 software to calculate the time deviation (TDEV). The TDEV result of time synchronization on 514 km field fiber link is shown is Fig. 7. The TDEV of 10 ps at 1 s and 1.2 ps at 10000 s have been obtained.

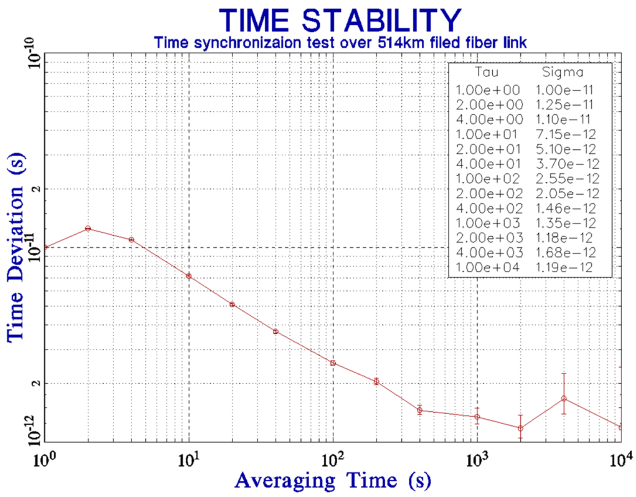

Fig. 7. Time synchronization performance on 514 km fiber link.

III. Conclusions

In this paper, we demonstrate the CFBG enhanced Bi-EDFA design, which can simultaneously realize dispersion compensation and asymmetrical optical amplification. With this design, we carry out frequency dissemination tests over a 500 km fiber link, which is made up of 100 km-100 km-150 km-100 km-100 km spools. Stabilities of 1.7×10^{-14}/s and $6.7\times10^{-18}/10^{5}$ s are obtained. Furthermore, we apply the concept of time reversal in fiber-optic time synchronization. It can calculate the clock offset of two sites without data layer involved, which can reduce the complexity of system. We have carried out the time and frequency integrated synchronization over the 514 km field fiber link. The frequency synchronization stabilities of 2.2×10^{-14}/s and $2.2\times10^{-17}/10^{5}$s have been obtained. The time synchronization performance characterized by TDEV of 10 ps at 1 s and 1.2 ps at 10000 s have been realized.

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