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研究论文

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基于双向时分复用同纤同波传输的时间同步系统

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摘要 设计了一种基于双向时分复用同纤同波传输的时间同步系统。为了消除钟差，实现从端与主端的时间同步，利用双向时分复用同纤同波时间比对得到从端与主端的钟差，通过校频和比例-积分-微分控制算法调整从端压控晶振的输出频率。双向时分同纤同波传输链路双向传输的时延对称性，使系统只需进行端机标定，无需对不同长度的光纤链路进行标定。在实验室盘纤和实地光纤链路上的实验结果表明，不同长度光纤链路下，本系统同步后的平均钟差均优于 10 ps；在长约 60 km 的实地光纤链路上，本系统同步后的平均钟差小于 9 ps，3σ 钟差优于 285 ps，时间偏差优于 16 ps/s（短稳）、7 ps/10^4 s（长稳）。

关键词 光纤光学；时间同步；双向时分复用；时钟驯服

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1 引 言

高精度时间和频率同步在导航定位、航空航天、电力和军事安全等领域扮演着重要角色[1-2]。相比传统的卫星、网络时间同步方式，光纤时间同步具有同步精度高、传输损耗低、抗干扰能力强等优势[3-4]。基于光纤的时间传输主要有单向法和和双向法两种[5-7]。双向法通过双向传输能有效消除环境对光纤链路的影响，因此得到了人们广泛的研究[8-15]。捷克教育科研网采用波分复用技术完成了长度为 744 km 的光纤双向时间比对实验，比对后的时间偏差（TDEV）达到 110 ps/s[11]。上海交通大学用双向时分复用同纤同波（BTDM-SFSW）传输系统演示了长度为 6000 km、TDEV 优于 190 ps/s 的双向时间比对[12]，该系统能在保持光纤双向传输时延对称性的同时抑制后向散射，且无需链路标定，但未实现时间同步。为进一步实现从端与主端定时信号的同步，陆军工程大学利用单纤双向波分复用技术，在两站点时间比对的基础上，利用时钟驯服技术在光纤高精度时间伺服系统和光纤环形网多点时频传递系统中实现了时间同步[13-15]。由于两个方向采用的波长不同，该系统存在光纤色散导致的双向时延及波动的不对称性，因此需要高精度的光纤链路时延标定，且标定引起的时间传递不确定度随光纤长度的增加而增加[16-17]。

本文研究设计了一种基于 BTDM-SFSW 时间比对与时钟驯服的时间同步系统。利用 BTDM-SFSW 时间比对得到两站的钟差，根据钟差调整压控晶振（VCXO）的频率，在从端输出与主端同步的定时信号。在不同长度的盘纤和长约 60 km 的实地光纤链路上进行了实验，结果表明，用本系统对时间同步端机进行标定后，在无链路标定情况下，不同长度光纤同步后的平均钟差均优于 10 ps；在长约 60 km 的实地光纤链路上，本系统同步后的平均钟差优于 9 ps，3σ 钟差优于 285 ps，TDEV 优于 16 ps/s（短稳）、7 ps/10^4 s（长稳）。

2 系统原理

基于 BTDM-SFSW 时间比对与时钟驯服的时间同步系统如图1所示。其中，A站点用波长为λ的

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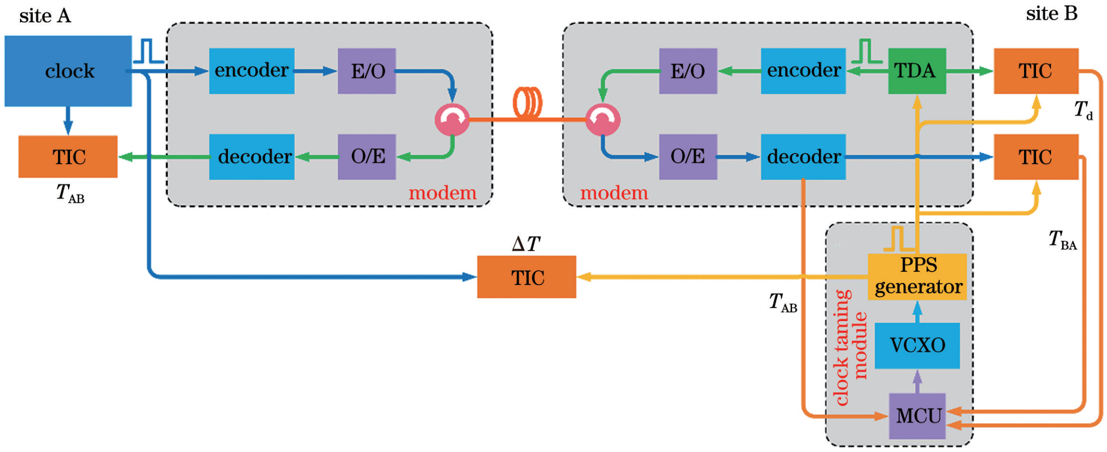

图 1 基于 BTDM-SFSW 的时间同步系统

Fig. 1 Time synchronization system based on BTDM-SFSW

光载波将包含定时信号 1PPS(One pulse per second)的时间码发送给 B 站点;B 站点将驯服模块中 PPS 发生器(PPS generator)产生的 1PPS 经时间延迟单元(TDA)以及编码器(encoder)编码后,利用同一波长、同一光纤发送给 A 站点。两站接收到的光信号都分别经过光电转换器(O/E)与解码器(decoder)。A 站点将时间间隔计数器(TIC)测得的时间间隔编码后通过光纤链路传输给 B 站点。B 站点利用 A 站点测得的时间间隔以及本地两台 TIC 测得的时间间隔计算钟差,从而实现双向时间比对。

图 2 为 BTDM-SFSW 系统的时间比对时序图,两站点的钟差可表示为[10]

$$\Delta T=\frac{1}{2}\left[(T_{AB}-T_{BA}-T_{d})+(\tau_{AB}^{F}-\tau_{BA}^{F})+(\tau_{A}^{T}-\tau_{B}^{T}+\tau_{B}^{R}-\tau_{A}^{R})\right], \qquad (1)$$

式中,T_{AB} 和 T_{BA} 分别为 A 和 B 站点 TIC 测得的本地 1PPS 和从对端收到的 1PPS 的时间间隔,T_d 为 B 站点驯服模块产生的 1PPS 延迟时间。τ_{AB}^{F}(τ_{BA}^{F})为 A 站点到 B 站点(B 站点到 A 站点)的链路传输时延,由于采用同一根光纤和相同波长传输光信号,可认为 $\tau_{AB}^{F}=\tau_{BA}^{F}$。$\tau_{A}^{T}$($\tau_{B}^{T}$)和 τ_{A}^{R}(τ_{B}^{R})分别为 A 站点(B 站点)的发送和接收时延。

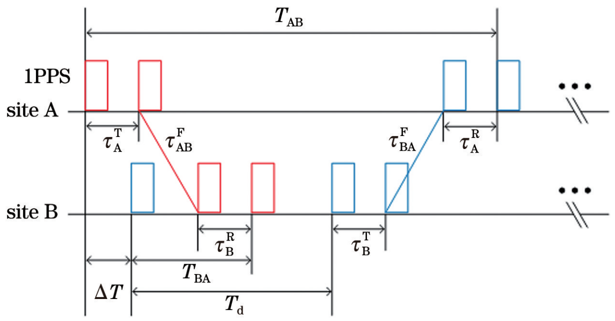

图 2 BTDM-SFSW 系统的时间比对时序图

Fig. 2 Time sequence diagram of the BTDM-SFSW system

通过 BTDM-SFSW 系统的时间比对结果得到两站点的钟差后,驯服模块中的微控制器(MCU)根据该钟差调整被驯服的 VCXO 频率。由信号频率与时间的关系,计算得到 VCXO 频率的调整量为[18]

$$\Delta f=-\frac{\Delta t}{t}\cdot f, \qquad (2)$$

式中,$\Delta f=f_A-f_B$ 为两站频率的差值,f 为标称频率,$\Delta t=\Delta T_1-\Delta T_2$ 为前后两个时刻钟差的变化量,t 为钟差测量的周期。

根据频率调整量,用比例-积分-微分(PID)控制器调整 VCXO 的输出频率以实现时间同步。PID 控制器由比例(proportional gain)、积分时间(integral time)和微分时间(derivative time)三个控制单元构成[19],其结构如图 3 所示。将设定值(set value)与反馈值(feedback value)之间的差作为 PID 控制器的误差控制信号(error),通过比例、积分、微分单元处理并求和,得到控制器的输出值(output value)。根据输出值调整 VCXO 的输出频率,进而调整 PPS 发生器输出的 1PPS 相位。调整后的 1PPS 经比对系统得到新钟差,将新钟差对应的频率调整量作为 PID 控制器的反馈值,从而形成一个反馈控制系统。

同步后钟差的收敛位置由 PID 控制器的设定值确定,可用短光纤连接时间同步端机,通过调整设定值使同步后的平均钟差稳定在 0 附近,从而实现端机的标定。BTDM-SFSW 的时间比对使链路双向传输的时延高度对称,对不同长度的光纤链路采用相同的设定值,无需链路标定就能实现时间同步。

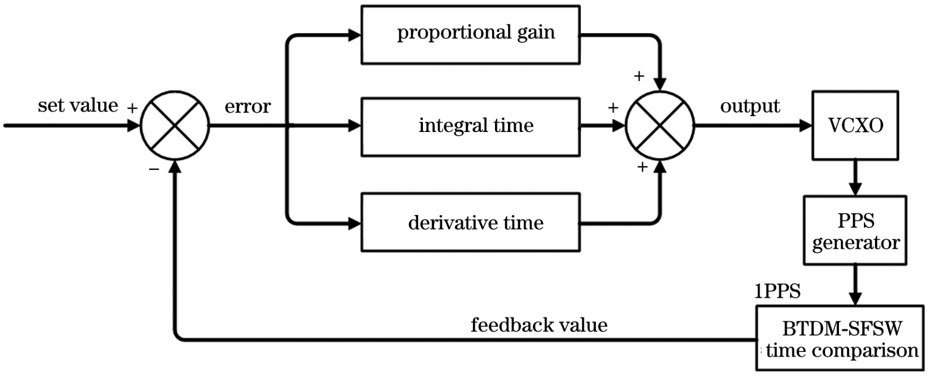

图 3　PID 控制器的结构

Fig. 3　Structure of the PID controller

3　实验结果与分析

按图 1 搭建了实验系统，A 站点的钟源为 Symmetricom 公司的 8040C 铷钟，编码/解码和时间延迟功能在现场可编程门阵列（FPGA）内实现，两站光收发模块的速率为 2.5 Gbit/s，激光波长为 1550.12 nm。两站均使用 Stanford Research Systems 研制的 SR620 测量时间间隔，并用一台 SR620 测量 A 站本地 1PPS 与 B 站同步后 1PPS 的时间差，以评估系统的同步性能。

在实验室内（用空调将温度控制为 23 ℃），用长度为 1 m 光纤连接时间同步端机，通过修改 PID 控制器的设定值调整钟差的收敛位置，使同步后的平均钟差稳定在 0 附近，完成端机的标定。标定后，设定值（−9.1）、比例系数（0.3）、积分系数（0.6）、微分系数（0.01）等 PID 参数不再改变。同步后钟差及其稳定度如图 4 所示，其中，钟差平均值优于 1.5 ps，3σ 钟差优于 228 ps，TDEV 优于 15 ps/s（短稳）和 1.5 ps/10^4 s（长稳）。相比未同步的 TDEV，同步后钟差的长稳有明显改善。

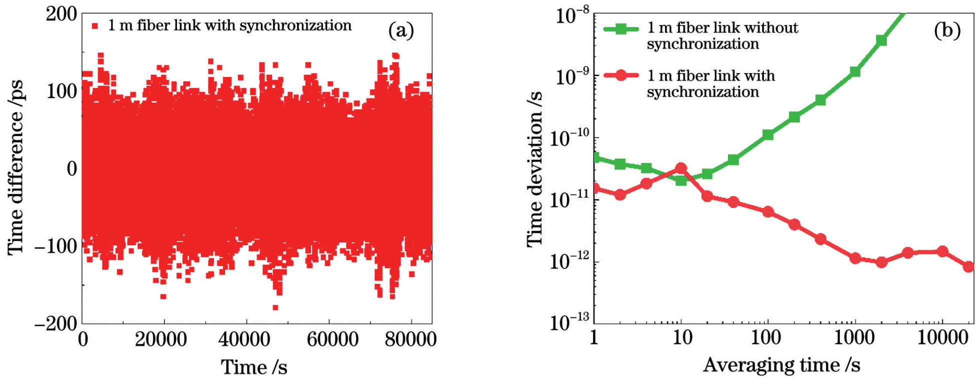

图 4　时间同步的结果。（a）同步后的钟差；（b）钟差的 TDEV

Fig. 4　Result of time synchronization. (a) Clock difference after synchronization; (b) TDEV of the clock difference

将上述光纤标定后的时间同步端机分别用长度为 30，50，80，100 km 的标准单模光纤连接（SMF-28e+® LL，Corning 公司）并进行实验，同步后的钟差如图 5 所示，其中，误差棒为标准差。可以发现，同步后钟差的平均值均不大于 10 ps。实验结果表明，设计的时间同步系统只需用短光纤完成端机标定，无需链路标定，即可在不同长度光纤链路上实现高精度时间同步。

在上海交通大学闵行校区和徐汇校区的实地标准单模通信光纤链路上进行了现场测试，测试结果如图 6 所示。其中，光纤链路的长约为 60 km，链路

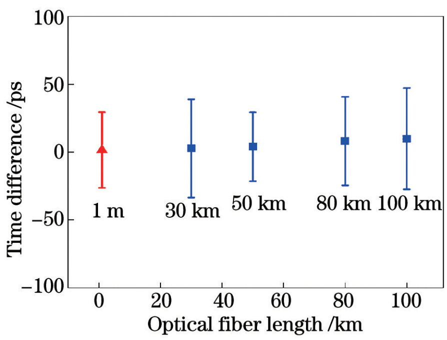

图 5　不同长度光纤时间同步后的钟差

Fig. 5　Clock differences after time synchronization of different length optical fibers

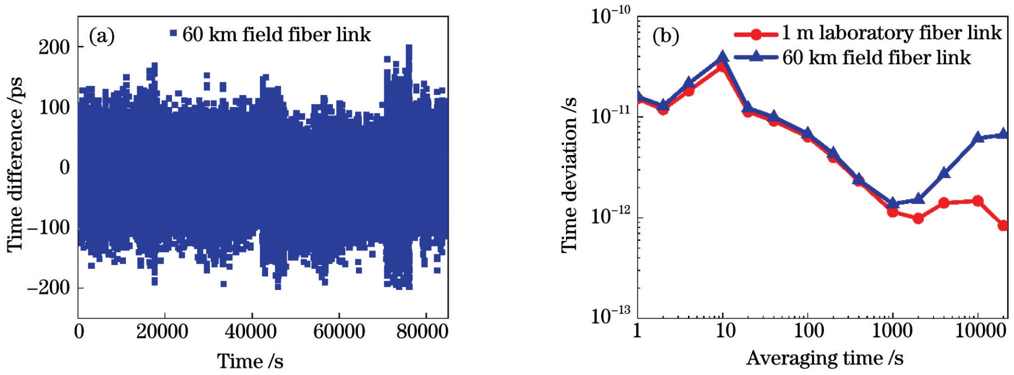

图 6 60 km 实地光纤链路时间同步结果。(a)同步后的钟差;(b)钟差 TDEV

Fig. 6 Result of time synchronization over 60 km field fiber link. (a) Time difference after synchronization; (b) TDEV of the time difference

总衰减约为 24 dB。可以发现,同步后的平均钟差小于 9 ps,3σ 钟差优于 285 ps,时间同步的稳定度优于 16 ps/s、7 ps/10^4 s。与长度为 1 m 的光纤同步后的 TDEV 相比,在实地光纤链路下,同步后的短稳没有明显变化,而长稳有明显恶化。原因是长稳主要与光纤传输的时延对称性有关,双向传输时间和残余波长的不一致性,导致光纤越长,光纤传输时延的对称性越差。图 6(b)中 TDEV 在 10 s 附近的隆起是由驯服模块对 VCXO 频率调整的滞后性引起。

4 结 论

基于 BTDM-SFSW 时间比对方案与时钟驯服技术研究设计了时间同步系统。由于 BTDM-SFSW 时间比对的高双向传输时延对称性,本系统完成时间同步端机的标定后无需链路标定就能实现时间同步。实验室和实地光纤链路测试结果表明,不同长度光纤链路下本系统同步后的平均钟差均小于 10 ps;长约 60 km 的实地光纤链路实验结果表明,本系统同步后的平均钟差优于 9 ps,3σ 钟差优于 285 ps,TDEV 优于 16 ps/s、7 ps/10^4 s。下一步还需基于 BTDM-SFSW 时间比对和驯服技术研究更长距离及分布式的时间同步系统。

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Time Synchronization System Based on Bidirectional Time-Division Multiplexing Transmission over Single Fiber with Same Wavelength

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Abstract

Objective Ultraprecise time synchronization plays an important role in scientific research and commercial applications. Owing to the advantages of optical fiber's low transmission loss, high reliability, and stability, optical fiber time synchronization has been considered as a promising solution for high-precision time synchronization. This paper adopts a highly precise optical fiber time comparison scheme proposed by Shanghai Jiao Tong University, which uses bidirectional time-division multiplexing transmission over a single fiber with the same wavelength (BTDM-SFSW). The scheme can effectively suppress both effects of the Rayleigh backscattering and dispersion-induced bidirectional asymmetry simultaneously, whereas it does not achieve time synchronization. This study, which realizes time synchronization, adopts the scheme to obtain the time difference between two clocks and uses the clock servo technique to eliminate the time difference between two clocks.

Methods A time synchronization experimental system is set up based on the BTDM-SFSW time comparison scheme and clock servo technique (Fig. 1). After using the BTDM-SFSW time comparison scheme to obtain the time difference between two clocks (Fig. 2), the difference between setpoint value and the time difference is used as error signal of proportion-integral-differential (PID) controller (Fig. 3), which is processed and summed by proportional, integral, and derivative units to obtain the output of the controller. The voltage-controlled crystal oscillators (VCXO′s) frequency is adjusted according to the frequency correction algorithm and the controller's output to change the phase of one pulse per second (1PPS) derived from the pulse per second (PPS) generator. New 1PPS is used by BTDM-SFSW time comparison to obtaining a new time difference between two clocks, which is treated as the feedback value of the controller. The above steps constitute a feedback control for the elimination of the time difference.

The time synchronization system adopts the same optical fiber and wavelength, which fully guarantees delay symmetry of the bidirectional link. After the calibration of time-synchronized terminals, there is no need to calibrate the optical fiber link.

Results and Discussions In an air-conditioned laboratory, time-synchronized terminals are connected by a 1 m optical fiber, and the calibration of terminals is completed by modifying the PID controller's setpoint value to adjust the convergence position of the time difference so that the average value of time difference after synchronization is stabilized near zero. After calibration, the PID parameters such as setpoint value, proportional gain, integral time, and derivative time are no longer changed. The average value of time difference after time synchronization is less than 1.5 ps, 3 σ time difference is less than 228 ps (Fig. 4 (a)), and time deviation (TDEV) of time difference is better than 15 ps/s and 1.5 ps/10^4 s respectively (Fig. 4 (b)). Compared with TDEV of time difference without synchronization, the long stability of time difference after synchronization is significantly improved.

Time-synchronized terminals, which have been calibrated over a 1 m optical fiber, are connected by 30, 50, 80, and 100 km standard single-mode optical fibers respectively to perform experiments. The average value of time difference after synchronization is less than 10 ps (Fig. 5). Results of the experiment show that the system can achieve high-precision time synchronization over optical fiber links, that have different lengths by using a short optical fiber to complete calibration of terminals without calibration of the optical fiber link.

The field test is conducted over a standard single-mode optical fiber link between Minhang and Xuhui campuses of Shanghai Jiao Tong University. The length of the optical fiber link is about 60 km, and the total attenuation of the link is about 24 dB. The average value of time difference after time synchronization is less than 9 ps, 3 σ time difference is less than 285 ps (Fig. 6 (a)), and TDEV of time difference is better than 16 ps/s and 7 ps/10^4 s respectively (Fig. 6 (b)). Compared with the TDEV of time difference after synchronization using a 1 m optical fiber to connect terminals, the short stability of the field test's time difference does not change significantly, whereas the long stability worsened over the field optical fiber link. It is reasonable since the long-term stability is mainly related to the fluctuations of propagation delay asymmetry caused by variations in temperature and wavelength difference, which are proportional to optical fiber length. The "bump" of TDEV near 10 s is caused mainly by hysteresis of VCXO frequency adjustment. It indicates that the steering corrections are unable to compensate for the frequency drift completely at certain averaging times.

Conclusions In this study, a time synchronization system is designed based on the BTDM-SFSW time comparison scheme and clock servo technique. The system takes advantage of the high bidirectional transmission delay symmetry of BTDM-SFSW time comparison without calibration of the optical fiber link. Laboratory and field optical fiber link tests are conducted, and results of the experiment show that after completing calibration of time-synchronized terminals, the average value of time difference after synchronization is less than 10 ps over different lengths of optical fiber links, and using a field optical fiber link of about 60 km, the average value of time differences after time synchronization is less than 9 ps, 3σ time difference are better than 285 ps, and TDEV is better than 16 ps/s and 7 ps/10^4 s respectively.

Key words fiber optics; time synchronization; bidirectional time-division multiplexing; clock servo

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