# Chapter 32
# Fiber Based Time and Frequency Synchronization System

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**Abstract** We build up a time and frequency synchronization system via the 80 km urban fiber link between Tsinghua University and the National Institute of Metrology in Changping city. Using the system, we demonstrate simultaneous time and RF signal distribution via optical fibers. The measured frequency dissemination stability of a 9.1 GHz RF signal is $7 \times 10^{-15}$/s, $5 \times 10^{-19}$/day, and the measured time synchronization accuracy is 50 ps. Relevant results were published on the Scientific Reports of Nature Publishing Group. To further build up a regional time and frequency network, integrated-designed modules are needed. Its long term continuous running stability and commonality should be tested. In this paper, we introduce the design of the frequency dissemination modules. After 135 days' continuously running, we get the million-second frequency dissemination stability of $8 \times 10^{-19}/10^{6}$ s. We also introduce our multiple-access download module, which improves the frequency dissemination scheme from the traditional point to point protocol to be a tree structure protocol, and greatly improves its applicability. Using it, the stability of the receiving frequency signal at arbitrary accessing point is almost 4 orders of magnitude better than that using directly accessing method. All of these modules will be applied to build up the regional time and frequency network.

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## 32.1 Introduction

With the definition of second changing from astronomical second to atomic second, in order to measure and further improve the accuracy of atomic second, a regular time and frequency comparisons between atomic clocks located in different locations are required. These requirements give birth to a new research directions-precise time and frequency synchronization [1]. More importantly, precise time and frequency synchronization has important applications in navigation systems. In the satellite based global positioning systems (such as COMPASS, GPS, and GLONASS), the entire system shares one common clock frequency and one common highly synchronized system time. The entire system's time is often synchronized at the nanosecond accuracy level.

At present, the time and frequency synchronization between different atomic clocks is mainly realized via the satellite link. Using the two-way satellite time and frequency transfer (TWSTFT) [2] or GPS common view (CV) [3] method, the frequency transfer stability at $10^{-15}$/day level and the time synchronization accuracy at nanosecond level can be realized [4, 5]. With significant progress of the precise atomic clock, the oscillator with frequency stability of $10^{-16}$/s [6] and the optical clock with fractional frequency uncertainty of $10^{-18}$ [7] have been realized. The conventional frequency dissemination methods can no longer satisfy the requirement of measurement and comparison below $10^{-16}$/day. Due to its prosperities of low attenuation, high reliability, and continuous availability, the ubiquitous fiber network has become an attractive option for long-distance dissemination of time and frequency signals. Recently, the transfer of ultrastable optical [8–13], microwave [14–21], and even frequency comb signals [22, 23] via fiber link have been demonstrated.

The Joint Institute of Measurement Science (JMI) is co-established by Tsinghua University (THU) and the National Institute of Metrology (NIM). There are regular requirements of the time and frequency comparisons between THU and NIM. We build up a time and frequency synchronization system via the 80 km urban fiber link between THU and NIM in Changping city, and demonstrate simultaneous time and RF signal distribution via the optical fibers. The measured frequency dissemination stability of a 9.1 GHz RF signal is $7 \times 10^{-15}$/s, $5 \times 10^{-19}$/day, and the time synchronizing accuracy is 50 ps [14]. Next step, since we will build up the regional time and frequency network together with other research institutions in Beijing area, integrated-designed modules are needed and its long term continuous running stability and commonality should be tested. In this paper, we introduce the designs of the frequency transmitting module and the receiving module, respectively. We also test their 135 days continuously running stability, and a million-second frequency dissemination stability of $8 \times 10^{-19}/10^{6}$ s has been demonstrated. Although frequency transfer via fiber link has higher stability than that of using conventional satellite links, the latter still occupies the dominant position in practical time and frequency dissemination. One of the main drawbacks of the fiber link is its limited accessibility of the dissemination frequency signal. For satellite link, it can disseminate frequency signals to cover essentially the entire globe, while for fiber link, one can only reproduce the disseminated frequency signal at specific locations using all current schemes. To realize a branching time and frequency network, we design a multiple-access download module [20]. Using it, the download frequency signal is about 4 orders of magnitude in improvement on the relative frequency stability compared to those of directly download signals.

## 32.2 The Frequency Transmitting, Receiving, and Download Module

### *32.2.1 The Frequency Transmitting Module*

The fiber based frequency dissemination system is composed by the frequency transmitting module, receiving module and the multiple-access download module. Figure 32.1a gives the schematic diagram of the frequency transmitting module. It needs a 100 MHz frequency signal ($V_{ref}$) working as the reference of the whole system. The 100 MHz signal may come from a Hydrogen Maser. To achieve a higher signal-to-noise ratio error signal for compensation, $V_{ref}$ is boosted to 9.1 GHz. There are also two oscillators phase locked to $V_{ref}$ with oscillation frequency of 9.0 GHz ($V_1$) and 9.2 GHz ($V_2$), respectively. They work as two assistant frequency references which is used to generate the error signal. A stable oscillator containing a voltage-controlled crystal oscillator (VCXO) and a phase-locked dielectric resonant oscillator (PDRO) generates a 9.1 GHz frequency signal $V_0$. The phase of $V_0$ can be controlled by the PLL. In this way, the phase noise induced by fiber dissemination can be compensated. $V_0$ is amplified by AMP and used to modulate the amplitude of the 1,550 nm laser light. After passing through a polarization scrambler and EDFA1, the modulated laser carrier is split into two parts. One part is detected by FPD1, and the generated signal $V'_0$ used to detect and compensate the phase noise of the out-of-loop devices [16]. The other part, passing through an optical circulator, couples into the fiber link. After the round-trip transfer in the fiber link, the feedback light (see Sect. 32.2.2) carries the round-trip phase noise of the fiber link and returns to the transmitting module again through the optical circulator. The returned feedback light is amplified by EDFA2 and detected by FPD2 (generate signal $V_4$). We mix down the signal $V_1$ and $V'_0$ to obtain $V_{e1}$, and mix down the signal $V_2$ and $V_4$ to obtain $V_{e2}$. Then, by mixing the signal $V_{e1}$ and $V_{e2}$, we get the error signal $V_e$. Passing through a PLL, the error signal $V_e$ is fed to VCXO. In order to reduce the influence of temperature

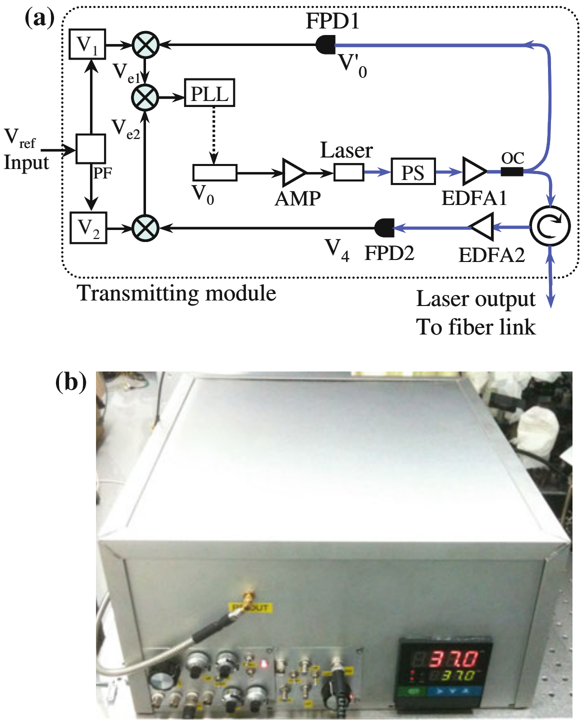


**Fig. 32.1** The frequency transmitting module. **a** The schematic diagram of the module, where *PF* RF power splitter, *PLL* phase lock loop, *AMP* RF power amplifier, *PS* polarization scrambler, *EDFA* erbium-doped fiber amplifier, *OC* fiber coupler, *FPD* fast photo detector. **b** The photo of the transmitting module

fluctuation on the frequency dissemination stability, the optical parts (blue link in Fig. 32.1a) inside the module is temperature controlled. Figure 32.1b is the photo of the temperature-controlled transmitting module.

### 32.2.2 The Frequency Receiving Module

At the receiving site, the disseminated frequency is reproduced by the receiving module. Figure 32.2a gives the schematic diagram of the module. The disseminated 1,550 nm laser carrier is coupled into the module by an optical circulator, and is split into two parts. One part is amplified by EDFA3 and transferred back to the transmitting module along the same fiber link. The other part is detected by FPD3 to reproduce the 9.1 GHz frequency signal $V_3$ which is phase locked to the reference frequency signal $V_r$ at the transmitting site. As the locking bandwidth of the fiber noise compensation system is limited by the length of the fiber link, normally, it is below 1 kHz. In other words, if the phase noise of the single-sideband was greater than 1 kHz of the reproduced frequency signal $V_3$, it could not be kept at the normal scale. To solve this problem, at the receiving site, a 9.1 GHz oscillator ($V_5$) should be phase locked to $V_3$ using a narrow-band locking loop. Consequently, the SSB noise of $V_5$ below 1 kHz is follow that of $V_r$, and the

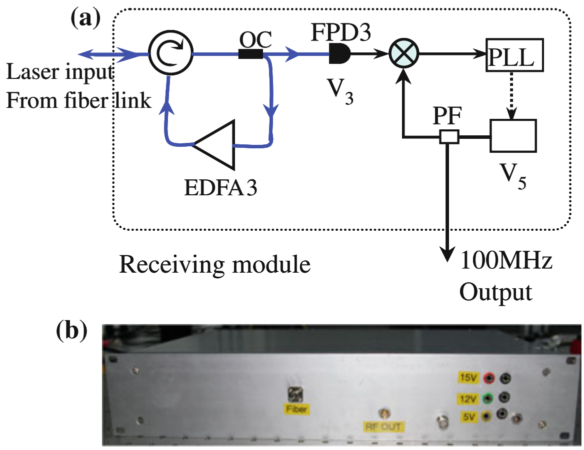


**Fig. 32.2** The frequency receiving module. **a** The schematic diagram of the module, where *PF* RF power splitter, *PLL* phase lock loop, *EDFA* erbium-doped fiber amplifier, *OC* fiber coupler, *FPD* fast photo detector. **b** The photo of the receiving module

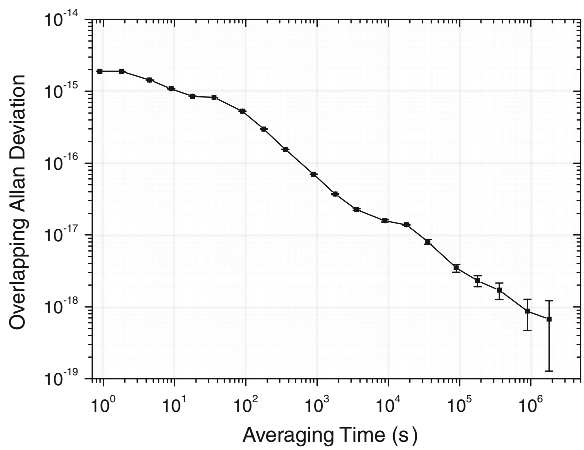


**Fig. 32.3** The measured frequency dissemination stability of the 135 day continuous running via the 50 km fiber spool

SSB noise of $V_5$ above 1 kHz is kept as its own character. Figure 32.2b is the photo of the receiving module.

To test the long term continuously running stability of the fiber based frequency dissemination module, using a 50 km fiber spool, we measure its 135 days continuous frequency dissemination stability. The results are shown in Fig. 32.3, and the frequency dissemination stability is $1.9 \times 10^{-15}$/s, and $8 \times 10^{-19}/10^6$.

### 32.2.3 Multiple-Access Download Module

Figure 32.4 is the schematic diagram of the multiple-access frequency download module. Using a $2 \times 2$ fiber coupler, the module can be connected with the existing main fiber link. The laser carriers transferring forward and backward in

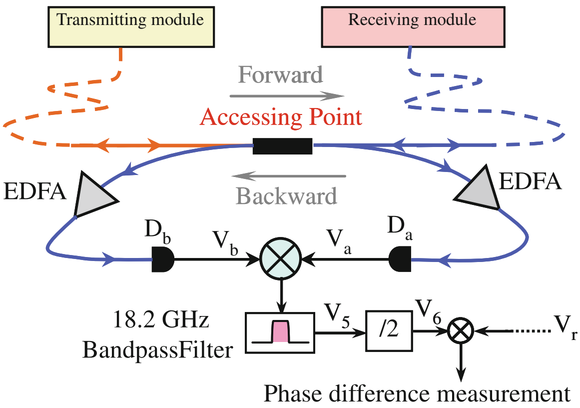


**Fig. 32.4** The schematic diagram of the multiple-access frequency download module, where $D_a$ and $D_b$ fast photo detector, *EDFA* erbium-doped fiber amplifier, $\phi_a$: the phase noise induced by the fiber link between accessing point and the transmitting site, $\phi_b$: the phase noise induced by the fiber link between accessing point and the receiving site

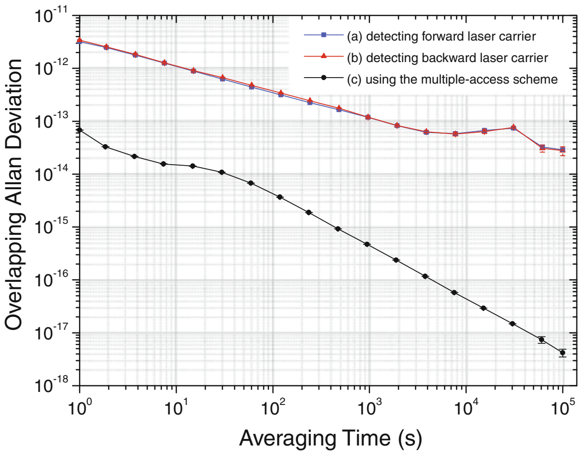


**Fig. 32.5** Measured relative frequency stability of the reproduced frequency signal at the accessing point 3 km away from the transmitting site

the main fiber link can be coupled out. The frequency signal modulated on the laser carriers can be detected and reproduced by two fast photo-detectors $D_a$ and $D_b$. The reproduced signal $V_a$ and $V_b$ are mixed by a frequency mixer and filtered by an 18.2 GHz bandpass filter. Using a divide-by-2 prescaling frequency divider, a 9.1 GHz frequency signal $V_6$ phase-locked to $V_r$ at the transmitting site can be reproduced.

As a performance test, via the 80 km round trip fiber link between THU and NIM, we reproduce the disseminated 9.1 GHz signal at a location 3 km away from the transmitting site and demonstrate the relative stability of the reproduced frequency signal. The measurement results are shown is Fig. 32.5. For the directly download signal $V_a$ and $V_b$, they show very similar stabilities of $3.5 \times 10^{-12}$/s and $3 \times 10^{-14}$/day. While for the frequency signal reproduced by the multiple-access download module, relative frequency stability of $7 \times 10^{-14}$/s and $5 \times 10^{-18}$/day is obtained. It is almost 4 orders of magnitude better than that using directly accessing method.

## 32.3 Conclusions

Based on the THU-NIM precise time and frequency dissemination system, the integrated frequency transmitting module, receiving module, and the multiple-access download module are designed and demonstrated. For the transmitting and the receiving module, we demonstrate their 135 days continuous running stability, and get the million-second frequency dissemination stability of $8 \times 10^{-19}/10^6$ s. Using the multiple-access frequency download module we designed, the stability of the receiving frequency signal at arbitrary accessing point is almost 4 orders of magnitude better than that using directly accessing method. All of these modules will be applied to build up the regional time and frequency network.

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