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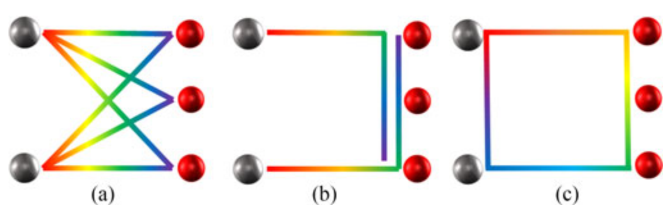

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Ultrastable Multiclock Frequency Injection and Dissemination in a Ring Fiber Network

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Abstract: Owing to the characteristics of ultralow loss and antielectromagnetic interference, using optical fiber to deliver time and frequency signals has been a preferred choice for high-precision clock dissemination and comparison. As a brilliant idea, one has been able to reproduce ultrastable signals from one local station to multiple users. In this paper, we take a step further and propose a concept of multiclock (in different locations) dissemination for multiterminals. By injecting frequency signals into one stabilized ring-like fiber network, the relative stabilities of 3.4×10^{-14}@1 s for a master clock dissemination and 5.1×10^{-14}@1 s for a slave clock dissemination have been achieved. The proposed scheme can greatly simplify the future “N” to “N” radio-frequency dissemination network, especially in the situation of multiclock comparison.

Index Terms: Optical fiber, frequency dissemination, multiclock comparison.

1. Introduction

With the unprecedented progress of atomic clocks, the short-term stability of a commercial cesium standard has achieved to 10^{-13}, while the instability of an optical frequency reference is now better than 10^{-18} [1]–[3]. To drastically utilize these ultra-stable reference, hundreds of clocks all over the world are linked and compared to each other to access their weighting factors, and that is the origin of International Atomic Time (TAI) [4]. The common methods of low loss coaxial cable for short distance and two-way satellite time and frequency transfer (TWSTFT) for long distance dissemination can no longer satisfy the performance that are currently achieved. Due to properties of low attenuation and anti-electromagnetic interference, optical fiber has been proved to be an efficient intermediary to deliver such high precision time and frequency signals by several research groups [5]–[8]. However, these schemes are restricted to point to point transfer by round-trip method. Until recently, two solutions to overcome the limit were proposed. One brilliant idea is to extract signals anywhere along the trunk fiber [9]–[12]. The other effective implementation is to make the

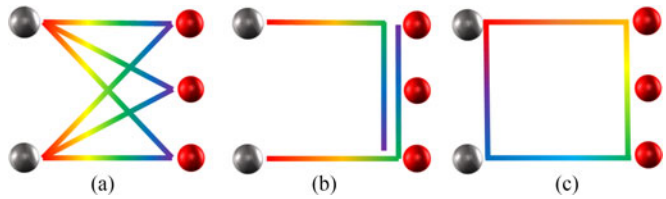

Fig. 1. Example of dissemination methods in multipoint network showing the cost of fiber links. (a) Point to point method. (b) Multi-access technique. (c) Proposed ring-like injection solution.

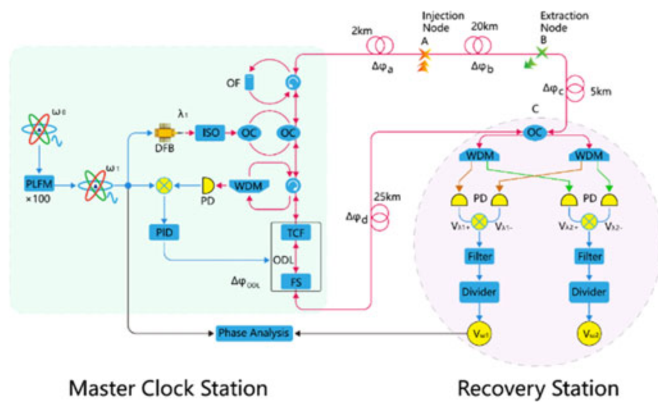

Fig. 2. Outlines of the multi-clock dissemination system. DFB: distributed feedback laser, ISO: isolator, WDM: wavelength division multiplexer, OC: optical coupler, OF: optical filter, ODL: optical delay line, PID: proportional-integral-derivative, PD: photo-detector, PLFM: phase-locking frequency multiplier, TCF: temperature controlled fiber, FS: fiber structure.

compensation structure serve in remote sites [13]–[15]. Both schemes bring great convenience for multiple users to access signals from one high precision clock. Whereas, a problem still leaves in all existing schemes that one can only reproduce the ultra-stable signals from one local station to many users. In fact, a sound time and frequency distribution network should include a host of atomic clocks. That is to say, a more economic and easier "N" to "N" dissemination solution is still expected.

In this paper, we propose a scheme to address the problem, demonstrating a strategy of injecting high precision time and frequency signals from different locations into a stabilized fiber network to meet the requirements of multi-clock dissemination and comparison. With the solution, the network structure may be simplified such that there are N stations including M clocks in different locations. As shown in Fig. 1(a), disseminating these M clock references (gray dots) to the N-M remote receivers (red dots) by the common point to point method, $M \cdot (N - M)$ segments of fiber are needed in the network. Using the scheme of multi-access technique shown in Fig. 1(b), the cost can be reduced to M, but it still requires M independent active noise compensation servers. Here, in Fig. 1(c), with the proposed scheme all stations can be connected to each other in one ring-like fiber while only one active noise compensator is needed. Namely, each recovery site can reproduce the time and frequency signals from different clocks at the same time with the ring-like structure and special noise suppression strategy.

2. Multiclocks Dissemination Scheme

To explain the basic idea of ring-like injection, we first introduce the structure of one master clock station with one recovery terminal. As a particular case of the scheme where $N = 2$, and $M = 1$, this may seem to be a point to point condition. However, as shown in Fig. 2, we bi-directionally distribute the ultra-stable frequency signal into a fiber optic link in the master clock station, which is different from the round-trip method [16], [17]. The fiber optic link is shaped into a ring-like structure. This structure can make it easier for other clocks to disseminate the stable reference, which we will discuss later.

At the master clock station, the reference frequency from an atomic clock is boosted from 10 MHz to 1 GHz using a phase-locking frequency multiplier (PLFM) for higher signal-to-noise ratio. To jointly suppress the phase noise for all clocks references, optical compensation is chosen to be the suppression actuator. Here, we use an optical delay line [17] including a temperature controlled fiber optic ring (with sensitivity of 40 ps/°C for a 1km temperature controlled ring and 350 ps/°C for a 10 km temperature controlled ring, the sensitivity decreases with increasing length of fiber is due to a less uniform heating of the fiber on the spool) and a fast fiber stretcher (response speed of a few kHz) to stabilize the whole optical link. As previously discussed, the ω_0 ($\omega_0 = 10$ MHz) is the originally frequency signal from master clock and is boosted to ω_1 ($\omega_1 = 1$ GHz). The signal ω_1 modulates a distributed feedback (DFB) laser with wavelength of 1548.5 nm (marked as λ_1) by amplitude modulation and at the output of the laser there is an isolator(ISO) to stop the return light from the fiber link. Without considering its amplitude, it can be expressed as

$$V_{\lambda 1} = \cos(\omega_1 t + \varphi_1). \tag{1}$$

The signal from the output of DFB laser is divided into two equal parts by a 50:50 optical coupler (OC) and all parts inject into the ring-like fiber by another 50:50 OC. Now, in the fiber link, there are two identical signals, a clockwise signal and an anticlockwise signal. The ring-like fiber is artificially divided into four sections. Clockwise signal passes through four sections of the fiber link, successively suffering from phase noise of $\Delta\varphi_a$, $\Delta\varphi_b$, $\Delta\varphi_c$ and $\Delta\varphi_d$. When it returns back to master clock station, signalsare extracted from the fiber by an optical circulator and separated into different channels according to the wavelength. The signal λ_1 detected by a photo-detector (PD), which can be represented as

$$V'_{\lambda 1} = \cos(\omega_1 t + \varphi_1 + \Delta\varphi_a + \Delta\varphi_b + \Delta\varphi_c + \Delta\varphi_d). \tag{2}$$

An error signal can be obtained after a phase discriminator

$$\Delta\varphi_{err} = \Delta\varphi_a + \Delta\varphi_b + \Delta\varphi_c + \Delta\varphi_d. \tag{3}$$

After the process of proportional-integral-derivative (PID), we apply this error signal to drive the optical delay line, making it actuate a phase correction of$\Delta\varphi_{ODL} = -\Delta\varphi_{err}$, which means the clockwise signal is stabilized after a full circle

$$\Delta\varphi_a + \Delta\varphi_b + \Delta\varphi_c + \Delta\varphi_d + \Delta\varphi_{ODL} = 0. \tag{4}$$

In the meantime, the anticlockwise signal propagates in the same fiber link but in opposite direction. While returning back to the master station, an optical filter (OF) is used to avoid the propagating light of λ_1 back into the fiber link repeatedly (the OF is a band-stop filter and can only filter out λ_1). Suffering the common noise fluctuation terms, the total phase drifting of the anticlockwise signal over one round is also eliminated.

The recovery station can be inserted anywhere along the fiber link. Here we take point C which is 25 km away from the master clock as illustration. Shown in Fig. 2, an optical couple (OC) is used to download the light in two directions from the circle link. Dense wavelength division multiplexing technology is applied to extract the light of λ_1 from the master clock station, the 1548.5 nm channel of the WDM (yellow line). Other wavelength channels are left for slave clocks. The clockwise and anticlockwise signal extracted in this station can be expressed, respectively, as

$$V_{\lambda 1+} = \cos(\omega_1 t + \varphi_1 + \Delta\varphi_a + \Delta\varphi_b + \Delta\varphi_c) \tag{5}$$

$$V_{\lambda 1-} = \cos(\omega_1 t + \varphi_1 + \Delta\varphi_d + \Delta\varphi_{ODL}). \tag{6}$$

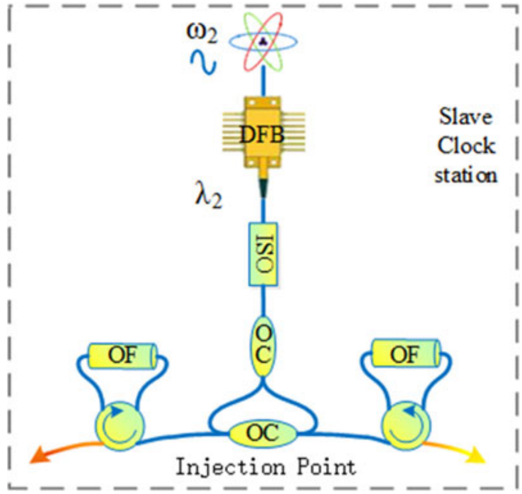

Fig. 3. Schematic diagram of the slave clock injection station. OC: optical coupler, OF: optical filter, ISO: isolator

They are then mixed by a balanced frequency mixer and filtered by a 2 GHz bandpass filter to remove the direct current out. A 2 GHz ($2\omega_1$) up-converted frequency signal is obtained as

$$V_{2\omega 1} = \cos\left(2\omega_1 t + 2\varphi_1 + \Delta\varphi_a + \Delta\varphi_b + \Delta\varphi_c + \Delta\varphi_d + \Delta\varphi_{ODL}\right). \tag{7}$$

According to (4), all of the phase fluctuation terms are cancelled out. In order to keep the same radio frequency with the master clock, a divider is used to achieve a stable frequency

$$V_{\omega 1} = \cos\left(\omega_1 t + \varphi_1 + \xi_1\right) \tag{8}$$

where ξ_1 is the intrinsic phase shift induced by the frequency divider. Thus, the frequency reference of the master clock is duplicated in the recovery station.

The key advantage of the scheme is that it allows to inject other clock reference into the stabilized fiber optic link. The structure of a slave clock injection station is shown in Fig. 3. Theoretically, it can also be placed at arbitrary node along the ring-like network. As an experimental test, a 2 km fiber spool is adopted between the master station and the slave station (at point A in Fig. 2). We use another wavelength of 1549.3 nm (marked as λ_2) to carry the frequency $\omega_2(\omega_2 = \omega_1)$ of the slave clock. The original signal can be written as

$$V_{\lambda 2} = \cos\left(\omega_2 t + \varphi_2\right). \tag{9}$$

Similar to the master clock station, the light carrying the ultra-stable frequency is transmitted into the fiber link in two directions. The signals pass through one round of the fiber link and then come back to the slave station. They will no longer enter the link once again because the two optical filters are used to stop the wavelength of λ_2 passing through. This design prevents the light reinjectinginto the fiber link, otherwise it may seriously degrade the signal-to-noise ratio upon photo-detector.

Thanks to the ring-like injection structure we proposed, the light of λ_2 passes through the common segments of the fiber link, suffering almost the same impact of vibration and temperature changing as light of λ_1. So anoptical noise suppression actuator can jointly compensate the phase noise imposed on them. That is to say the optical delay line in master clock station is still effective for the slave clock signal. Ignoring noise within a clock station, the total phase drifting of the slave clock reference after one circle propagation is equal to that of (4).

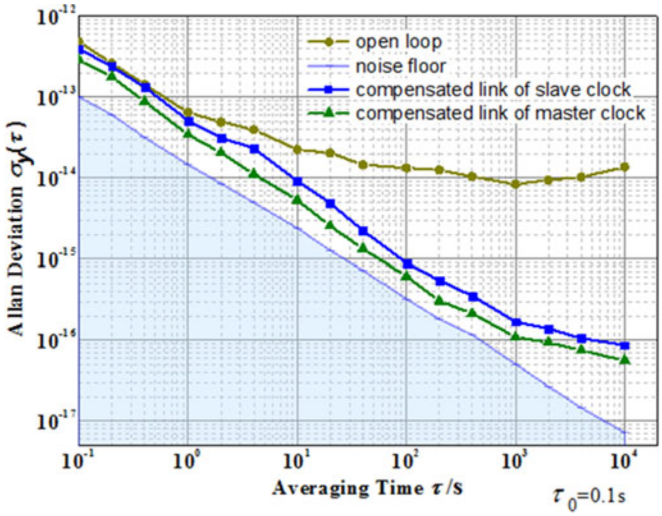

Fig. 4. Relative stabilities of frequency references for different clock stations.

In the recovery station, the 1549.3 nm channel of WDM (green line) is coming in handy. The slave clock frequency signal from two directions are

$$V_{\lambda 2+} = \cos(\omega_2 t + \varphi_2 + \Delta\varphi_b + \Delta\varphi_c) \quad (10)$$

$$V_{\lambda 2-} = \cos(\omega_2 t + \varphi_2 + \Delta\varphi_a + \Delta\varphi_d + \Delta\varphi_{ODL}). \quad (11)$$

Even though each of them is unstable and their phase fluctuation term are different from $V_{\lambda 1+}$ and $V_{\lambda 1-}$, the mixed signal $V_{2\omega 2}$ is analogous to (7):

$$V_{2\omega 2} = \cos(2\omega_2 t + 2\varphi_2 + \Delta\varphi_a + \Delta\varphi_b + \Delta\varphi_c + \Delta\varphi_d + \Delta\varphi_{ODL}). \quad (12)$$

In fact, the phase drifting terms also sum to be zero. After the frequency divider, the recovered output frequency is stabilized and obtained as

$$V_{\omega 2} = \cos(\omega_2 t + \varphi_2 + \xi_2) \quad (13)$$

where ξ_2 is the corresponding intrinsic phase shift induced by the divider. Finally all the recovered frequency references thus click the same as they are in the clock stations.

3. Experimental Result

To demonstrate the idea of "N" to "N" dissemination scheme, we insert another identical recovery station in point B which is 20 km away from point A and 5 km away from point C. All the fibersfor the link are spooled. Like some of our previous work [14], the fibers that contribute to phase fluctuations in each station is set as short as possible and put into a case that full of spongesto reduce the residual phase noise induced by them. The relative frequency stabilities of both recovered signals are measured by comparing them with their original signals. For example, we measure the relative frequency stability by comparing $V_{\omega 1}$ with $V_{\lambda 1}$ (with 5 Hz effective measurement bandwidth) to evaluate the performance of master clock dissemination(as shown in Fig. 2, the green line means $V_{\lambda 1}$&$V_{\omega 1}$ compared by phase discriminator), where both remote sites are located within the same laboratory. Both recovery stations play a very similar behavior of the overlapping Allan deviation (ADEV). To be clear, here we only demonstrate the stability curves of the recovery station at point C as an illustration. The results are shown in Fig. 4. Short-time instability can reach 3.4×10^{-14}@ 1 s for the master clock dissemination and 5.1×10^{-14}@1 s for the slave clock dissemination, while long-time performance extends to 5.5×10^{-17}@10^4 s and 8.6×10^{-17} @10^4 s, respectively. The curve of open loop is the relative frequency stability of $V_{\omega 1}$ compared to $V_{\lambda 1}$ that the servo loop is not motivated. The curve of noise floor shows the optical background noise of our system mainly introduced by electro-opticandphoto-electricconversion.

Compared with free-running state, both of them improve a lot, especially at long averaging time. In general, the trends of two curves are similar to each other but the slave one is a little worse for the whole time. That is reasonable mainly for two reasons: a) Even though the optical path for the two modulated lights are almost the same, they still have some uncompensated parts, such as the fiber in each stations and the noise induced by electro-optic conversion process. These parts are out of the servo loop, which will introduce additional noise. b) As long as the dispersion exists, the error signal which is used to drive the optical delay line corresponding to λ_1 cannot be completely equal to that of the light of λ_2. Indeed, the thermal sensitivity of the phase-delay deviation with respect to dispersion is different. A simple solution can be to add a dispersion compensation fiber of adequate length into the ring-like link. Apart from the holistic behavior between two curves, the slope turns to be slow after 100 s. It is principally because the mixers we used are nonlinear and sensitive to temperature changing. Nevertheless, the performance of the compensated state proves the scheme to be effective.

4. Discussion

First, for network design, the other advantage of this scheme is that a recovery terminal can be set in the same lab of master clock station, since the recovery station is not sensitive to locations. It is helpful for an administrator to monitor all the performance of clocks existed in the network. Through this monitor we can know which atomic clock runs best. Then, users do not have to recover all the clock references. As the performance is known, it is convenient for users to choose the best one to be recovered by using a wavelength selective switch (WSS) instead of the WDM in the recovery stations.

Second, in some particular applicationssuch as clock comparison, we only need to obtain the frequency (or phase) difference between different clocks. The proposed scheme can also be effective, even though the optical fiber path is time-varying. If these two clocks are in one laboratory, the phase of (1) can be directly compared with the phase of (9):

$$\Delta\varphi = (\omega_1 t - \omega_2 t) + (\varphi_1 - \varphi_2)\,. \tag{14}$$

However, in reality, high precision atomic clocks run in different institutions. We can apply the clock injection structure as we proposed above, but turn off the noise suppression servo in the master clock station. At the recovery station the output frequency of each clock should be modified to

$$V'_{\omega 1} = \cos\left(\omega_1 t + \varphi_1 + \frac{\Delta\varphi_a + \Delta\varphi_b + \Delta\varphi_c + \Delta\varphi_d + \Delta\varphi_{ODL}}{2}\right) \tag{15}$$

$$V'_{\omega 2} = \cos\left(\omega_2 t + \varphi_2 + \frac{\Delta\varphi_a + \Delta\varphi_b + \Delta\varphi_c + \Delta\varphi_d + \Delta\varphi_{ODL}}{2}\right). \tag{16}$$

Even if the phase fluctuation term doesn't sum to zero this time, the phase difference of these two signals is the same as (14). If there are only two clocks, it is similar to TWTFT strategy [18], [19], but it can be exciting when facing a multi-clock situation. All the clocks can be compared with each other at the same time without considering the common phase noise imposed by the fiber as if they are at the same place.

5. Conclusion

We propose a novel "N" to "N" ultrastable radio-frequency dissemination scheme. It is fantastic that frequency references from different clock stations are allowed to inject anywhere along a ring-like fiber link and can be jointly recovered without using any extra noise suppression actuator. It dramatically simplifies the complexity of a multi-clock dissemination network. The ability of network management can be enhanced by monitoring the performance of all the atomic clocks hanging upon the link. As a proof-of-principle experimental test, two clock signals are injected into a stabilized fiber optic link. Instabilities of 3.4×10^{-14}@1 s and 5.5×10^{-17}@10^4 s for the master clock and 5.1×10^{-14}@1 s and 8.6×10^{-17}@10^4 s for the slave clock are obtained for point C, which is 27 km away from the master station. The basic idea may be extended to optical frequency delivery and pulse transmission. In addition, we introduce a special application for multi-clock comparison via a time-varying fiber path. We expect this scheme to be applicable for the time and frequency synchronization network which is currently under construction.

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