# Two-Way Time Transfer via a Common-Path Fiber Link

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**Abstract—In this paper, we present a preliminary experiment on two-way time transfer through a 25-km optical fiber link. The fiber link based on a common-path configuration can provide good reciprocity in both directions. Therefore, the propagation path delays in the fiber can be cancelled out almost entirely by employing the two-way method. The resulting data exhibit the time deviation of less than 7 ps for the averaging times from one second to one day. The frequency stability of $1\times10^{-16}$ at one day has been demonstrated.**

***Key words:* *time transfer, fiber, two-way***

## I. INTRODUCTION

The optical fiber has the characteristics of broad bandwidth and low transmission loss. Through a standard single mode fiber (SMF) [1], the light with 1550 nm wavelength has low dispersion and only the loss of 0.22 (dB/km), and the light with 1310 nm wavelength has zero dispersion and the loss less than 0.35 (dB/km). Then, the transmission distance can reach at least 50 km for an optical power budget of 20 dB. If employing optical amplifiers, one can extend the transmission distance to several thousand kilometers [2]. Therefore, the optical fiber is an ideal communication channel for the purpose of time and frequency transfer. During the most recent years, the ultra-stable frequency transmission over an optical fiber link has been developed in some major laboratories in USA, Europe and Japan. These links are: the Joint Institute for Laboratory Astrophysics (JILA) – National Institute of Standards and Technology (NIST) in USA, Physikalisch-Technische Bundesanstalt (PTB) – Max Planck Institute for Quantum Optics (MPQ) in Germany, Observatoire de Paris (SYRTE) – Laboratoire Parole et Langage (LPL) in France, and National Institution of Information and Communication Technology (NICT) –National Metrology Institute of Japan (NMIJ) – University of Tokyo (UT) in Japan. An RF transfer using amplitude modulation of the laser carrier has demonstrated the frequency stability of $10^{-15}$ level at 1-s averaging time and the range of $10^{-18}$ at one day [3-5]. An optical carrier transfer can reach stability below $10^{-18}$ after 1000 s [6-8]. In addition, the recorded distance for frequency transfer was extended from 251 km in 2007 [9] to 920 km in 2011 [10] with $10^{-19}$ relative accuracy. In China, there have already been regular frequency comparisons between the National Institute Metrology (NIM) and Tsinghua University (THU) via the 80 km urban telecommunication fiber network in the Beijing area. The frequency dissemination stability of $7\times10^{-15}$ at 1 s and $4.5\times10^{-19}$ at $10^5$ s has been demonstrated [11]. Although precision optical fiber frequency transfer links via an urban network setting have received a lot of interest recently, the methods require bidirectional access to the fiber. However, telecom fiber networks are inherently unidirectional. For the application purpose of the remote frequency users, a simple and economic frequency dissemination method by using the current synchronous optical fiber communication networks has been considered [12]. The method provides an uncertainty of less than $1 \times 10^{-12}$ at an averaging time of one day, which is suitable for most applications. On the other hand, a one-way two-color fiber link for frequency transfer has been introduced recently [13-14]. In this system, two separate wavelengths are sent one way along a fiber network. The work may be of benefit for future applications.

Unlike frequency transfer, the time transfer over fiber needs precise calibration on delays. Several laboratories have started the studies [15-19]. Almost of them employ the two-way method [15] to cancel the major delay and discuss the residual delay asymmetry, e.g., chromatic dispersion. The technique may replace the satellite link in the future. However, for a long-haul time transfer, the absolute delay calibration is very important for verifying some relativity effects, such as Sagnac effect. Currently, the GPS-based time calibration is still the best way to verify the absolute calibration of time transfer over fibers [20].

In Taiwan, the demands of precise time synchronization has been increasing recently, e.g., the next-generation telecommunication synchronization, the smart grid of electric power distribution systems, the time scale for financial networks, and the science study in some campuses. As the previous studies mentioned, due to the environmental sensitivity of the optical fiber, the variation of propagation delay would cause the time and frequency instability. The propagation delays, coming from both the electric and optical equipment, will also include the noise and unstable sources. These issues are important topics for future applications. Therefore, we have to evaluate these unstable sources and to study the effective method to cancel them.

In this paper, we present a preliminary experiment on two-way time transfer through a common-path optical fiber link. The common-path optical link can provide good reciprocity in both directions. Therefore, the propagation path delay in the fiber can be cancelled out almost entirely by employing the two-way method. More detailed experimental results are described in the following section. In addition, some brief discussions on calibration and unstable sources are also provided.

## II. COMMON-PATH OPTICAL LINK

We employ two optical circulators and two pairs of optical transceivers (i.e., E/O and O/E) to construct a common-path optical link. The RF signals are modulated to optical signals on the same light wavelength, and are transmitted bi-directionally along a single fiber. Thus, the common-path link can avoid the non-reciprocity of path.

Figure 1 shows the block diagram of a common-path optical link [21]. It is composed of 1310 nm directly modulated lasers, photodetectors, optical circulators, and single mode fibers. The key component is optical circulators, which are passive, multi-port, and non-reciprocal optical devices. The circulators utilize the Faraday effect to route light from port 1 to port 2, port 2 to port 3 and are used here for bi-directional transmission. They also have the characteristics of low insertion loss and high isolation. So the signal to noise ratio will be kept high and the reflected signal will be isolated to a large extent.

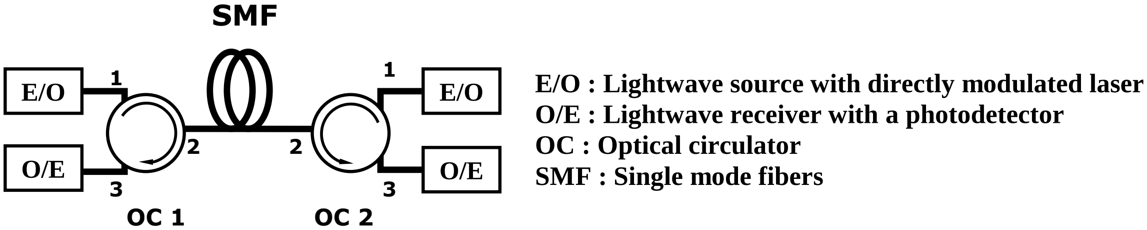


Figure 1. Block diagram of a common-path optical link.

A 70 MHz signal from a modem is converted to an optical signal by the directly modulated laser, and then is transmitted to the remote side through optical links. In the receiver side, a photodetector converts the optical signal to the 70 MHz signal. The same procedure is also operated in the reverse direction through the same fiber with the same light wavelength. Therefore, the reciprocity of the optical link is ensured.

## III. MEASUREMENTS

### *A. Experimental Setup*

Figure 2 shows the experiment configuration. We used two-way time transfer modems (Timetech SATRE, [22]) that are driven from a common clock to conduct a two-way test. The propagation delays through the common-path optical link are also investigated. In the measurement, we employed 20 MHz chip rate coded signals and added 3 Hz and 7 Hz offsets to the 70 MHz carrier frequency at both sites respectively to avoid the possible beat note with the modem reference frequency [23]. The coaxial cables, which connected the modem and optical transmitter/receiver, were chosen as short as possible. The experiment was set in a temperature-controlled room and the temperature was about 24.5±1.5°C. The length of the single mode fiber used here was 25 km and the temperature coefficient of the fiber was about 38 ps/(km·°C).

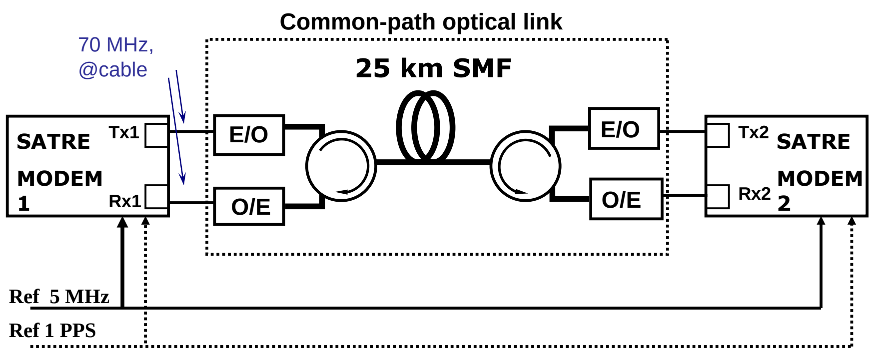


Figure 2. Block diagram of the two-way time transfer experiment via a 25-km fiber.

### *B. Calibration : Comparison between a short fiber and a 25-km fiber*

For the purpose of time calibration, we need to determine the internal delays of modems, delays of the connected coaxial cables, fiber pigtails, and other optical components. Since the system was placed at the same location at the beginning, we can replace the 25-km fiber with a 10-m fiber pigtail, and then initial differential delays can be measured. The differential delay was 13.444 ns for the system with the short fiber pigtail. When the two nodes were separated by the 25 km fiber (connected to a 25-km long spool of fiber), the measured differential delay was 13.375 ns. This value differs from that of 10-m fiber pigtail by only 69 ps.

We may consider the difference is caused by the non-reciprocity of the 25-km SMF fiber. One of the non-reciprocity sources may be due to the chromatic dispersion. Nevertheless, the effect should be relatively small for the light sources around 1310 nm (zero dispersion for fibers). Due to the Sagnac effect induced by the earth rotation [24-25], the time difference between the forward and backward fiber paths may be

$$\Delta t = \frac{4NA_E\Omega}{c^2}, \tag{1}$$

where the fiber is wound onto a circular coil with $N$ turns, $A_E$ is the perpendicular projection of the area of the fiber coil onto the equatorial plane, $\Omega$ is the rotation rate of the Earth, and c is the speed of light. In our experiment, the 25-km spool of fiber with an average 20-cm coil diameter was placed on a table top located at latitude of 24.95° N. Then, ($N A_E$) is about 1133 m$^2$, and the time difference induced by the Sagnac effect is about $9.2\times10^{-19}$ s. This non-reciprocity term is negligible in the common clock test.

Because the laser sources we used had slightly different optical powers, and the absorption, reflection and scattering in bi-directions of the fiber were different, the revived RF power levels consequently differed by 6 dB between both sides. Moreover, the different levels will lead to slightly variant results for delay measurements in modems [17]. If the revived power is kept constant, the non-reciprocity of the 25-km fiber can be smaller than 69 ps.

### *C. Results of Two-Way Time Difference*

Figure 3 shows the path delay data measured by the internal counter of the SATRE modems. The trends of the two curves are similar, and the variation during the period of 16 days (in December 2011) is up to 2 ns. The two-way time difference (i.e., a half of the time difference between the forward and backward delays) is shown in the same plot, and its variation range becomes only 83 ps. This result indicates that the delay variation can be cancelled out to a certain extent.

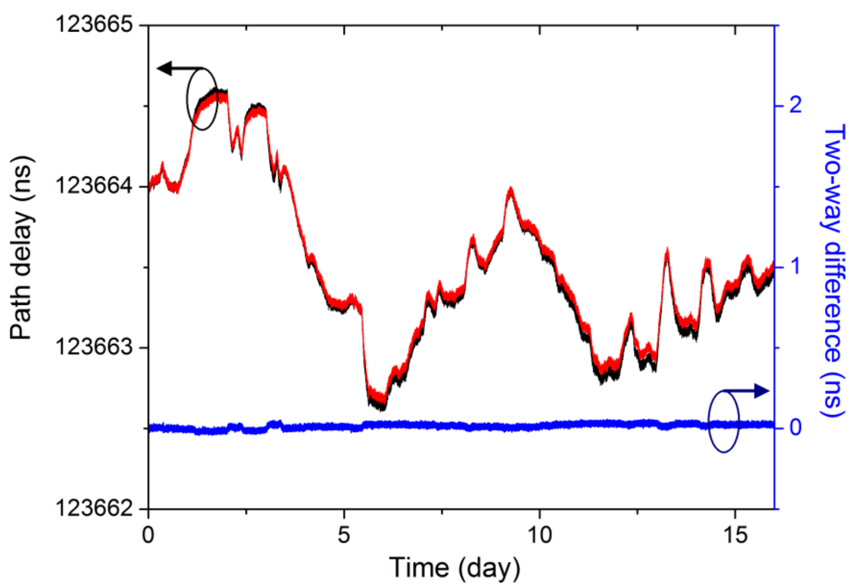


Figure 3. Forward and backward path delays via a common-path optical link and their two-way time difference. The delay 1 (backward, red line) and delay 2 (forward, black line) were measured by SATRE 1 and SATRE 2, respectively.

Figure 4 shows the time stability of the bi-direction delays and their two-way time difference. The curves of delays represent time transfer results through the one-way fiber link. The time instability is below 1 ns at the averaging times around $10^5$ s. After employing the two-way method to cancel out the delay variation, the time instability can be below 7 ps at the $10^5$ s averaging time. Figure 5 shows the corresponding frequency instability of the one-way delays and their two-way difference. At the one-day averaging time, the modified Allan deviation of the one-way delay is $3.0\times10^{-15}$, while that of the two-way difference is $1\times10^{-16}$.

In the short-term ($\tau$<10 s), the performance of the optical link is limited by the resolution of the measurement method. When using the 20 Mcps PRN coded signals, the resolution is about several ps. The actual resolution value is also related to the $C/N_0$ ratio. The overall time deviation of the transfer via common-path optical link can be under 7 ps for the averaging times from one second to one day. Then, the time transfer over fiber is a very potential method for next-generation applications.

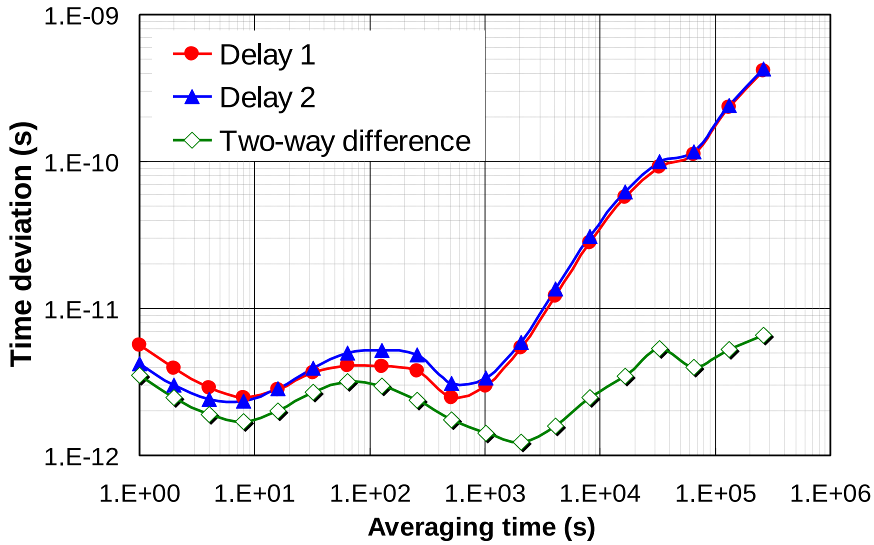


Figure 4. Time stabilities of the delay 1, delay 2 and their two-way time difference.

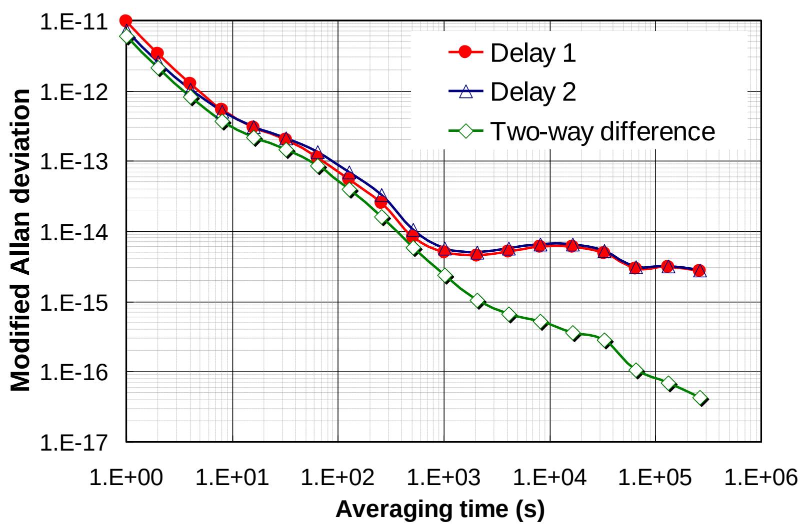


Figure 5. Frequency stability of the delay 1, delay 2 and their two-way time difference.

### *D. A Comparative Experiment*

Although our experiment was carried out by the common clock (the same reference source for two nodes), the clock noise may still come from the imperfection of the phase lock loop (PLL) in the modem. For understanding this influence, we performed a comparative test by using an additional time interval counter (TIC, SR 620) to directly measure the timing difference between the 1 PPS (pulse per second) outputs of two modems. Figure 6 shows the comparison of the two-way difference over the 25-km common-path optical link and the TIC measurement for the timing difference between two modems. The two curves in the plot show a high correlation. This result presents the basic limit of accuracy in this time transfer experiment. Although the two modems were connected with the same reference signal, there were still slight variations (up to 81 ps) between their timing systems. The variation, possibly caused by the imperfection of PLL in time transfer equipments, resulted in the residual instabilities. If the variation cannot be cancelled, it will affect the time comparison results of two remote clocks.

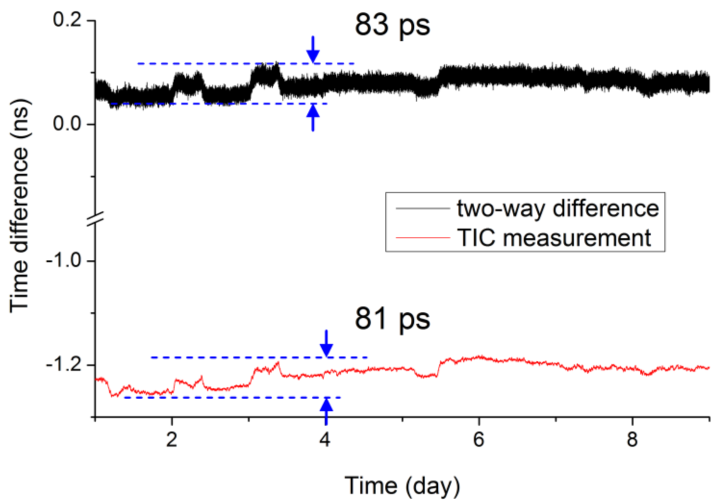


Figure 6.

Figure 7. Comparison between the two-way difference over the 25-km common-path optical link and the TIC measurement for timing difference between two modems.

## IV. CONCLUSION

We have conducted a two-way time transfer experiment by employing a common-path optical link. The experiment over a 25-km fiber shows a promising result that the time deviations were below 7 ps for the averaging times from one second to one day. Therefore, the time transfer over fiber is a potential method for the next-generation applications. However, our experiment was only performed in an indoor environment. If a dark fiber or a dark channel is available, we hope to extend the time transfer experiment to other remote laboratories in Taiwan. The study on remote two-way time transfer experiments with the common-path optical links will be carried out in the near future.

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