Fiber-Optic quantum two-way time transfer with frequency entangled pulses

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Abstract: High-precision time transfer is of fundamental interest in physics and metrology. Quantum time transfer technologies with frequency entangled pulses have been proposed for its potential enhancement of the precision and guaranteed security by the complementarity principle in quantum mechanics. However, the superiority of quantum time transfer is previously underappreciated due to the relatively low photon rate and decoherence effect of optical loss. Here we demonstrate that, with the unique property of quantum nonlocal dispersion cancellation associated with frequency entangled pulses, quantum time transfer through a dispersive channel can appreciably outperform the analogous classical scheme. A quantum two-way time transfer over a 20 km-long fiber link is experimentally demonstrated with a time transfer accuracy of 1.23 ps and a time deviation of 922 fs at 5 s and 45 fs at 40960 s. The femtosecond-scale time transfer capability of this two-way quantum time transfer, together with its inherent secure advantage, will be applicable to high-precision middle-haul synchronization systems.

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1. Introduction

The capability to precisely synchronize distant clocks have become increasingly important for contemporary space geodesy, high-resolution radio-astronomy, modern particle physics, navigation and positioning, and for almost every type of precision measurement. Among various kinds of time transfer techniques, the two-way time transfer (TWTT) provides a precise way since the common mode noise of the one-way transfer can be cancelled by symmetrical transport in both directions. For example, the two-way satellite time transfer (TWSTFT), as the primary method of atomic clock comparisons, has achieved nanosecond accuracy [1] and a timing stability of 200ps at most [2]. With a much higher frequency and bandwidth of laser pulses than radio radiations, the time transfer by laser link (T2L2) provides a high-quality time transfer technique with a time stability of 1 ps at 1000 s and 10 ps at 1 day [3], and an accuracy better than 100 ps [4]. Due to the advantages of low loss, high reliability, and high stability of optical fiber, fiber-optic TWTT becomes an alternative offering much better results than the satellite methods. Based on measuring times of arrival of pulses with direct detection and event timing systems, a time stability as low as 0.2 ps for averaging times of hours has been reported in several literatures whilst the accuracy remains leveling at tens of picoseconds [5, 6]. However, these techniques are yet far from enough to satisfy the growing requirement for comparison of the new generation of high-precision atomic clocks [7]. On the other hand, though the two-way transfer enables detecting man-in-the-middle (MITM) delay
attacks, these classical time synchronization techniques have been shown to be susceptible to interference by malicious parties, which can spoof the legitimate timing signal introducing unaccounted for delays, and adversely affect the overall functionality of applications depending on it [8]. Therefore, there is a compelling need for fundamentally new methods for efficiently and securely distributing high precision time information.

According to the quantum theory, the use of quantum optical source can break through the shot noise limit to the classical measurement precision [9], much better time stability is thus expected [10-16]. Furthermore, secure time synchronization can be guaranteed by the complementarity principle in quantum mechanics [17-19]. Despite its potential high precision and cryptographically secure fashion, the superiority of quantum time transfer is previously underappreciated due to the relatively low photon rate, decoherence effect of optical loss as well as the confined detection strategy to a local coincidence identification of the correlated photon pairs. Here we demonstrate that, with the unique property of quantum nonlocal dispersion cancellation associated with frequency entangled pulses, a fiber-optic quantum two-way time transfer scheme through a dispersive channel can outperform the analogous classical schemes.

In this paper, the performance of this scheme has been simulated based on the quantum model. Through theoretical analysis, we show that the achievable time stability is determined by the spectral bandwidth of the entangled photon pairs as well as the dispersive broadening induced by the fiber. Exploiting nonlocal dispersion compensation can thus improve the transfer stability. Furthermore, a two-way quantum time transfer experiment has been demonstrated on a 20-km-long fiber coiling, in which a dispersion compensation fiber with a length of 2.49 km has been inserted into the idler arm for the nonlocal dispersion cancellation. Experimental results show that the time transfer stabilities in terms of TDEV reach 920 fs at averaging time of 5s and 45 fs at 40960s, which is presently mainly restricted by the limited acquisition rate and timing jitter of the event timing system. Compared with the classical analogues, the time transfer stability has been improved for almost one magnitude.

The accounted accuracy in terms of the dependence on fiber length has been investigated by measuring the clock differences as a function of the fiber length varying from 15m to 20km, giving a variation of 1.23 ps in standard deviation. This also reveals that our system has superior time transfer symmetry than the classical systems whose variation is normally tens of picoseconds due to the inevitable Rayleigh backscattering. By using new event timers with sub-picosecond precision and single photon detectors with lower timing jitter, this result can be further improved. Together with its inherent secure advantage, the two-way quantum time transfer method can be very useful for highly accurate and secure time transfer through modest distances.

The rest of the paper is organized as follows. Section 2 is a brief description of the scheme. Section 3 gives the theoretical derivation. Section 4 is the experimental setups and results. Section 5 is the conclusion.

2. Schematic description

The scheme for realizing the quantum two-way time transfer between two clocks at separate sites A and B and interconnected via a fiber link is sketched in Fig. 1. Each site includes a frequency entangled photon pair source, a pair of single-photon detectors and an event timer which is referenced to its local time scale. The frequency entangled photon pair sources are used as the timing signals. Via optical circulators, the optical fiber transmission is connected to the timing signals and the inputs of the event timers in bidirectional way. For the entangled source generated at site A, the signal photons are traveled from A to B through a fiber with a length of $l$ while the idler photons are held at site A. To compensate for the dispersion experienced by signal photons in the fiber link, a piece of dispersion compensation fiber with a length of $l'$ is inserted into the path of idler photons. With the help of single-photon detectors and event timers, the arrival times of the signal and idler photons are recorded as
\[ \{ \ell^{(i)} \} \text{ and } \{ \ell'^{(i)} \}, \text{ where } j = 1..n \text{ denotes a series of time tagged sequences. By applying the cross-correlation algorithm on them [20], the coincidence histogram of the time difference between } t_2 \text{ and } t_1 \text{ can be built. Through Gaussian fitting of the coincidence distribution, the registration time difference } t_2 - t_1 \text{ with respect to the maximum “coincidences” is obtained. Assume the time difference between clock } A \text{ and clock } B \text{ is } t_{0B} = t_{0A} - t_{00}, \text{ it is estimated that } t_2 - t_1 = l / v_{s.a} - l' / v_{s.a} - t_0, \text{ where } v_{s.a} \text{ and } v'_{s.a} \text{ are the group velocities in the propagation path and dispersion compensation fiber. At site } B, \text{ similar manipulations are performed. The signal photons of the frequency entangled source } B \text{ are traveled from } B \text{ to } A \text{ through the same fiber link and the idler photons are held at site } B \text{ after travelling through the same type of dispersion compensation fiber with the same length as that in site } A. \text{ Then by recording the arrival times of the signal and idler photons as } \{ \ell^{(i)} \} \text{ and } \{ \ell'^{(i)} \}, \text{ the registered time difference } t_4 - t_3 \text{ can be obtained as } t_4 - t_3 = l / v_{s.b} - l' / v'_{s.b} + t_0. \text{ Assuming the two frequency entangled photon pair sources are produced perfectly the same, } v_{s.a} = v_{s.b} \text{ and } v'_{s.a} = v'_{s.b}. \text{ Then by comparison of the two measured time difference results, the time difference between the two clocks are then given as } t_0 = (t_2 - t_1) - (t_4 - t_3) / 2. \]

Fig. 1. Sketch of the quantum two-way time transfer between two clocks at separate sites A and B and connected via fiber link.

3. Theoretical analysis

In this section the detailed theoretical analysis of the above quantum two-way time transfer scheme is given. According to quantum field theory, the probability of coincidently detecting events at space-time points \((D_i,t_i),(D_{i'},t_{i'}),(D_j,t_j),(D_{j'},t_{j'})\), is proportional to the fourth-order correlation function of the fields [21]

\[
G^{(4)} = \langle \Psi | E^{(1)}_1 E^{(2)}_2 E^{(3)}_3 E^{(4)}_4 | \Psi \rangle. \tag{1}
\]

Where \( E^{(j)} \) refers to the negative and positive components of the electric field at the \( j \)-th detector, which is directly related to the annihilation (creation) operators \( \hat{a}_j, (\hat{a}_j^\dagger) \)

\[
E^{(j)}(D_j,t_j) = \hat{a}_j(D_j,t_j), \quad E^{(j)}_j = (E^{(j)}_j)^\dagger, j = 1,2,3,4. \tag{2}
\]

Where \( \hat{a}_j \) denotes the annihilation operators at the \( j \)-th detector.

\[ |\Psi\rangle \text{ is the state of the input field. Consider the states of the two frequency-entangled sources at } A \text{ and } B \text{ are given by } |\Phi_A\rangle \text{ and } |\Theta_A\rangle. \text{ } |\Psi\rangle \text{ can then be given by the direct product } |\Psi\rangle = |\Phi_A\rangle \otimes |\Theta_A\rangle. \text{ Assume they are generated through the same degenerate type II SPDC process via a monochromatic pump, the state functions can be written as} \]


\[ |\Phi_s\rangle = \int d\omega f(\omega)\hat{a}_{s,\omega}(\omega_0 + \omega)\hat{a}_{s,\omega}^+(\omega_0 - \omega)|0\rangle, \]
\[ |\Theta_q\rangle = \int d\omega g(\omega)\hat{a}_{q,\omega}(\omega_0 + \omega)\hat{a}_{q,\omega}^+(\omega_0 - \omega)|0\rangle. \]

(3)

Where \( \hat{a}_{s,\omega} \) and \( \hat{a}_{q,\omega} \) are the creation operators for the signal and idler photons of the frequency entangled source generated at site A (B). \( |0\rangle \) represents the vacuum state. The signal and idler are ideally frequency anticorrelated with their spectra centered around \( \omega_0 \), and \( f(\omega) = g(\omega) = \text{sinc}\left(\frac{DL\omega}{2}\right) \) denote the joint spectral amplitude functions of the frequency entangled states respectively. Here \( L \) is the crystal length and \( D \) is the inverse group velocity difference for signal and idler photons. To simplify the deduction, the above expression can be approximated as a Gaussian function \( f(\omega) \approx e^{-\gamma(\omega)^2} \) with \( \gamma = 0.04822 \).

In terms of the annihilation operators of the signal and idler, those \( \hat{a}_j \) at the \( j \)-th detector are given by

\[ \hat{a}_s(l',t_0) = \int d\omega \hat{a}_{s,\omega}(\omega) e^{-i\omega(l'-t_0)} e^{ik(\omega)t_0}, \]
\[ \hat{a}_i(l,t_0) = \int d\omega \hat{a}_{i,\omega}(\omega) e^{-i\omega(l-t_0)} e^{ik(\omega)t_0}, \]
\[ \hat{a}_s(l,t_0) = \int d\omega \hat{a}_{s,\omega}(\omega) e^{-i\omega(l-t_0)} e^{ik(\omega)t_0}. \]

(4)

Where \( t_{40} \) and \( t_{90} \) refer to the time at which clock A and clock B start, thus the time difference between the two clocks is denoted as \( t_0 = t_{40} - t_{90} \). \( k(\omega) \) and \( k'(\omega) \) describe the propagation constant during the transmission fiber with length \( l \) and the dispersion compensation fiber with length \( l' \), respectively. Their Taylor expansion around the center frequency \( \omega_0 \) can be given by

\[ k(\omega) = \frac{n(\omega)\omega}{c} = k_0 + k_1(\omega - \omega_0) + \frac{1}{2!}k_2(\omega - \omega_0)^2, \]
\[ k'(\omega) = \frac{n'(\omega)\omega}{c} = k'_0 + k'_1(\omega - \omega_0) + \frac{1}{2!}k'_2(\omega - \omega_0)^2. \]

(5)

Substituting eqns. (2)-(5) into eqn. (1), we can rewrite the fourth-order correlation function as

\[ G^{(4)}(\tau,\tau') = G^{(2)}(\tau)G^{(2)}(\tau') \approx e^{\left(\frac{\tau^2 + \tau'^2}{2\sigma^2}\right)}. \]

(6)

Where \( \tau = t_4 - t_1 - t_0 - k_l + k'_l \) and \( \tau' = t_2 - t_1 + t_0 - k_l + k'_l \). The standard deviations of the two \( G^{(2)} \) functions after propagation can be denoted as \( \sigma = \sqrt{\gamma D^2l + \frac{1}{\gamma D^2l} \left(\frac{k_l + k'_l}{2}\right)^2} \).

From this expression, by making \( k'_l \) and \( k_l \) have opposite signs \([22, 23, 24]\), \( |k_l + k'_l| \to 0 \) can be approached. The full width at half maximum (FWHM) of the two \( G^{(2)} \) functions is then given by \( \Delta_{\text{FWHM}} = \Delta_{\text{FWHM}} = \sigma = 2.355 \sigma \). By taking the integration of \( \int dt \int d\tau (\tau - \tau')G^{(4)}(\tau,\tau') \), \( \langle \tau - \tau' \rangle = 0 \) is derived. Thus we can get \( \langle t_0 \rangle = \frac{(t_4 - t_1) - (t_2 - t_1)}{2} \), which is exactly the same with the classical conclusion given in the above section. The standard deviation of \( t_0 \) is then determined by variance of \( \tau - \tau' \)
\[ \Delta_0 = \Delta \left( \frac{\tau - \tau'}{2} \right) = \frac{1}{2} \left( \int \int d\tau d\tau' \left[ \left( \frac{\tau - \tau'}{2} \right) - \left( \frac{\tau - \tau'}{2} \right) \right] ^2 G^{(4)}(\tau, \tau') \right)^{1/2}. \]  

(7)

Substituting eqn. (6) into (7), \( \Delta_0 = \sigma \) is deduced. For detectors with perfect time resolution, given a large number \( N \) of detected photon pairs, the deviation should be given by

\[ \langle \Delta_0 \rangle_N = \frac{1}{\sqrt{2N}} \langle \Delta_0 \rangle = \frac{1}{\sqrt{2N}} \sqrt{\gamma D^2 L^2 + \frac{1}{\gamma D^2 L^2} \left( k_2 l + k_2' l' \right)^2}. \]  

(8)

Consider the type-II PPKTP crystals with a length of 10mm and a poling period of 46.146\( \mu \)m are used to generate the frequency entangled sources at 1560nm, thus \( DL = 2.96 \text{ ps} \). In the experiment, the fiber coil with \( l = 20\text{ km} \) has a \( k_2 \) value of \(-2.14 \times 10^{-6} \text{s}^2/\text{m} \); while the dispersion of dispersion compensation fiber with \( l' = 2.49\text{ km} \) was measured to be \( k_2' = 4.78 \times 10^{-3} \text{s}^{-1} \). Then the FWHM widths \( \Delta_{\text{FWHM}} \) for the cases with and without the dispersion compensation can be estimated to be 89ps and 777ps, respectively. Their corresponding standard deviations \( \langle \Delta_0 \rangle_N \) are then derived to \( 3.78 \times 10^{-10}/\sqrt{N} \) and \( 3.30 \times 10^{-10}/\sqrt{N} \).

4. Experimental setup

The experimental setup for implementing the quantum two-way time transfer over fiber is shown in Fig. 2. To generate the frequency entangled photon-pair sources, the quasi-monochromatic 780 nm laser was produced by the cavity-based frequency doubling process [25] and then splitted into two beams by a 50:50 beam splitter (BS). Each beam was focused into a type-II PPKTP crystal with a length of 10mm and a poling period of 46.146\( \mu \)m. After filtering out the residual 780nm pump, the output orthogonally polarized frequency entangled photon pairs were coupled into the fiber polarization beam splitters (FPBS) for spatial separation and subsequent fiber transmission. The superconducting nanowire single photon detectors (SNSPDs) with a detection efficiency of 50% and a timing jitter of 70ps, were used to detect the travelled frequency entangled photons. The time tags of them were provided by the commercial event timers (Eventech Ltd, A033-ET). There are two input ports A and B for each event Timer. Port A of event timer A records time tag sequences \( \{ t_1^{(i)} \} \) and port B records \( \{ t_2^{(i)} \} \). For event timer B, Port A records \( \{ t_2^{(i)} \} \) and port B records \( \{ t_1^{(i)} \} \). Due to the data rate limitation of the event timers, the input signal rate of each port was set around 6kHz. As the data acquisition time is 5s, each sequence contains 30000 time tags.

To evaluate the time transfer performance of the experimental setup, both event timers were referenced to a common time scale based on the lab-owned H-maser frequency standard. A fiber coiling with a length of 20km was used as the fiber link. Meanwhile, a dispersion compensation fiber with a length of 2.49km was inserted into the idler arm to nonlocally cancel the dispersion experienced by the signal photons. To further investigate the transfer accuracy in terms of the dependence on fiber length, the absolute time difference between two sites as a function of the fiber length ranging from 15m to 20km was measured.
Fig. 2. The experimental setup of the proof-of-principle experiment of the fiber-based two-way quantum time transfer.

5. Results and analysis

The recovered temporal coincidence distribution histograms from the 30000 tagged time sequences \( \{ z_{1}^{(j)} \} \) and \( \{ z_{2}^{(j)} \} \) are shown in Fig. 3. With the dispersion compensation fiber in the idler arm (blue up-triangles), the FWHM width was narrowed to 88 ps with a total coincidence of about 1468. While without the dispersion compensation fiber in, the histogram (purple down-triangles) gives a Gaussian-fitted width of about 789 ps and total coincidence about 430. Based on the experimental parameters, the theoretical \( G^{(2)} \) distributions for the two cases are shown as well with the black and red dash curves respectively. One can see a very good agreement between experiments and theory. Therefore, both the nonlocal coincidence measurement and the nonlocal dispersion cancellation have been successfully achieved. Based on eqn. (8) the standard deviations of \( t_{0} \) can be estimated to be about 1.0 ps and 15.9 ps for the two cases.

Fig. 3 The experimentally recovered coincidence distributions from the 30000 tagged time sequences \( \{ z_{1}^{(j)} \} \) and \( \{ z_{2}^{(j)} \} \), and the theoretically simulated \( G^{(2)} \) functions under the conditions of with and without dispersion compensation fiber in the idler arm.
From the recovered temporal coincidence distributions, the averaged time differences \( t_2 - t_1 \), \( t_4 - t_3 \), and \( t_0 \) on an interval of 5s can then be extracted. With the dispersion compensation fiber in, the measured results for more than 72 hours have been shown in Fig. 4 in terms of TDEV. As can be seen by black squares and red dots, \( t_2 - t_1 \) and \( t_4 - t_3 \) fluctuate significantly with the same trend. By subtraction between \( t_2 - t_1 \) and \( t_4 - t_3 \), the transmission fluctuations can be cancelled out and the TDEV of \( t_0 \) gives 922 fs at 5-s averaging and a minimum 45 fs at 40960-s averaging. With the dispersion compensation fiber removed, the corresponding TDEV of \( t_0 \) is shown by purple down-triangles. At averaging time of 5s, the TDEV is 15.6±0.16ps. At 5120s, the TDEV reaches a minimum 3.77 ps. The standard deviations of \( t_0 \) for both cases were measured to be 1.15 ps and 17.35 ps respectively, which agree well the predicted values from theoretical simulation. One can see that, the nonlocal dispersion cancellation improves the time stability for one magnitude.

![Fig. 4 The measured TDEV of \( t_2 - t_1 \), \( t_4 - t_3 \) and \( t_0 \) between two clocks under the conditions that the 2.49-km dispersion compensation fiber were inserted, removed, and both the fiber coiling and the dispersion compensation fiber were removed.](image)

By shortcutting the 20-km fiber coiling with a 15-m-long fiber, the stability performance of the system itself was tested and the results are shown by green diamonds, which sets the lower limit for the achievable system stability. At averaging time of 5s, the TDEV is 450 fs; when the averaging time is extended to 40960s, the TDEV degrades to 30 fs.

To investigate the accuracy of the setup in terms of its dependence on the length of the used fiber, we measured the mean time difference as a function of the fiber length from 15m to 20km. The obtained results are shown in Fig. 5, giving a variation of 1.23 ps.
6. Conclusion

In summary, we have quantified and experimentally demonstrated a fiber-based two-way quantum time transfer by using frequency entangled pulses. Based on the successful nonlocal time correlation measurement and nonlocal dispersion cancellation, a highly precise time transfer on a 20-km fiber coiling with a stability of 922 fs at 5s and 45 fs at 40960s has been achieved. The lower limit for this achievable system stability was measured to be 450 fs at 5s and 30 fs at 40960s. By using new event timers with sub-picosecond precision [26] and higher acquisition rate, and applying new SNSPDs with lower timing jitter [27], the results can be further improved. The absolute time transfer accuracy as a function of the fiber length is evaluated, and shows an uncertainty of 1.23 ps in standard deviation. Besides the prospective improved time transfer stability over their classical counterparts, such quantum two-way time transfer system can also provide a secure distribution of timing information.

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