Nonlocality test of energy-time entanglement via nonlocal dispersion cancellation with nonlocal detection

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The energy-time entangled biphoton source plays a great role in quantum communication, quantum metrology, and quantum cryptography due to its strong temporal correlation and capability of nonlocal dispersion cancellation. As a quantum effect, nonlocal dispersion cancellation is further proposed as an alternative way for nonlocality testing of continuous variable entanglement via the violation of the Bell-like inequality proposed by Wasak *et al.* [Phys. Rev. A **82**, 052120 (2010)]. However, to date there is no experimental report either on the inequality violation or on a nonlocal detection with single-photon detectors at a long-distance transmission channel, which is key for a true nonlocality test. In this paper, we report an experimental realization of a violation of the inequality after 62-km optical fiber transmission at telecom wavelengths with a nonlocal detection based on event timers and a cross-correlation algorithm, which indicates a successful nonlocal test of energy-time entanglement. This work provides feasibility for the strict test of the nonlocality for continuous variables in both long-distance communication fiber channel and free space.

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I. INTRODUCTION

Nonlocality is considered as a central feature of quantum entanglement, which cannot be explained by classical or any local hidden-variable theories [1,2]. Such nonlocality can be tested via a violation of Bell inequality in two different scenarios. The first scenario is to use discrete variables such as polarizations of the optical field. Due to its robustness to channel losses and noise, polarization entanglement has been applied for more than 36 years to the test of Bell inequality violation and such violation has been recently realized over free-space links of thousands of kilometers by satellite [3,4]. The second scenario is to use continuous variables such as amplitude and phase quadratures of the optical field, which recently has been demonstrated in Ref. [5]. However, such quadratures will experience unavoidably large loss and decoherence in the long-distance transmission, making it difficult to verify nonlocality over long distances.

The energy-time entangled photons (biphotons), which has both strong temporal correlation and frequency anticorrelation, is intrinsically robust against the loss and decoherence when propagating through long-distance fiber links [6]; it thus has found great applications in areas such as fiber-based quantum communication, quantum metrology [7–9], and quantum cryptography [10,11]. The nonlocality test of energy-time entanglement has been proposed by Franson with a Franson-type interferometer [12] and nonlocal dispersion cancellation (NDC) [13]. The NDC is a nonlocal quantum effect, in which a pair of energy-time biphotons propagates through two distant dispersive media with equal and opposite dispersion; the dispersion experienced by one photon can be canceled nonlocally by the other. Benefiting from the NDC effect, the energy-time biphotons will still remain tightly correlated in time after dispersion propagation. In contrast to another dispersion cancellation scenario [14,15], in which the time measurement is based on the *local* Hong-Ou-Mandel [16] interference and has been proven to have classical analogs [17–21], the NDC effect is fundamentally independent of the separation between the two photons and provides a further example of the nonlocal nature of the quantum theory [22–25]. To witness the presence of entanglement in NDC, a Bell-like inequality has been further proposed by Wasak *et al.* [25] for bounding the strength of temporal correlations in a pair of light beams after propagating through dispersive media with equal and opposite dispersion. The violation of the inequality can thus be used for identifying the nonlocal feature of energy-time entanglement.

Since it was first proposed, the NDC effect has been demonstrated successfully at nanosecond-level resolution with local observation such as time-correlated single-photon counting (TCSPC); (e.g., PicoHarp 300) [26–28]. A femtosecond-level NDC [29,30] has been achieved by up-

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conversion of the photon pairs [31,32], but is intrinsically local and can be mimicked using classical laser light [20], which limits its further application in a genuine quantum nonlocality test. Therefore, a *nonlocal detection* is particularly desired for a real test.

Recently, MacLean *et al.* [33] showed the violation of Wasak's inequality using optically gated single-photon detection technology in a nonlocal way, which enables one to directly observe the NDC on femtosecond timescales. However, due to relatively large timing jitter of the single-photon detectors, the experimental violation of the inequality with distinct single-photon detectors at long-distance transmission channel has been difficult to realize.

In this paper, we report an experiment that violates the inequality for the NDC with a nonlocal temporal correlation identification of biphotons. The energy-time entangled signal and idler photons at telecom wavelengths are generated via the spontaneous parametric down-conversion (SPDC) from a cw pumped type-II PPKTP crystal [34]. Then the signal photons are transmitted through a 62-km-long single-mode fiber (SMF) while the idler photons are passed through a 7.47-km-long dispersion compensation fiber (DCF). To reduce the timing jitter of the detectors, self-developed superconducting nanowire single-photon detectors (SNSPDs) [35] are applied, and the registered arrival times of the detected signal and idler photons are recorded independently by two separate event timers (ETs). By applying a cross-correlation algorithm to these time sequences, the temporal correlation between the signal and idlers is then nonlocally identified [36]. In this way, we successfully demonstrate a NDC experiment which violates Wasak's inequality by about 14 standard deviations. This violation provides experimental proof for the quantum nonlocality feature of continuous variable entanglement and can be effectively extended to a long-distance transmission channel for further loophole-free testing [37–40].

II. THEORY

In this section, a review on the theory of the NDC and Wasak's inequality is briefly given. For a cw pumped type-II SPDC, when biphotons traveled through two dispersive media with dispersion coefficients of k_s'', k_i'' and lengths of l_1, l_2, the joint detection probability of the two detectors is proportional to the second-order Glauber correlation function [27]

$$G^{(2)}(t_1 - t_2) \propto e^{-\frac{[(t_1-t_2)+\bar{\tau}]^2}{2\sigma^2}}, \tag{1}$$

where $\sigma = \sqrt{\gamma D^2L^2 + [(k''_s l_1 + k''_i l_2)/2]^2/\gamma D^2L^2}$ and $\bar{\tau} = k_s' l_1 - k_i' l_2$ denote the width of the $G^{(2)}$ function and the overall time delay between signal and idler photons after propagating through the dispersion media, respectively. L is the crystal length; D is the inverse group velocity difference between signal and idler photons in the SPDC crystal, respectively. $\gamma = 0.048\,22$ is chosen for Gaussian approximation of the phase matching function. The full width at half maximum (FWHM) of the $G^{(2)}$ function is then given as $\Delta t = 2\sqrt{2\ln 2}\sigma$.

If k_s'' and k_i'' have opposite signs, $|k''_s l_1 + k''_i l_2| \to 0$ can be realized by adjusting the lengths of l_1 and l_2. In the case of ideal NDC, $k_s'' l_1 + k_i'' l_2 = 0$ and the FWHM of $G^{(2)}$ function remains as $\Delta t = 2\sqrt{2\ln 2\gamma}DL$, so the effect of NDC can be observed by measuring the width of $G^{(2)}$.

On the other hand, the quantum nonlocality feature of the NDC can be verified by violation of a Bell-like inequality. With regard to this, Wasak *et al.* [25] deduced the minimum broadening of temporal correlations between two classical light beams during propagation through dispersive media with equal and opposite dispersion, which can be expressed as an inequality,

$$\langle(\Delta\tau')^2\rangle \geqslant \langle(\Delta\tau)^2\rangle + \frac{(2\beta l)^2}{\langle(\Delta\tau)^2\rangle}, \tag{2}$$

where $\langle(\Delta\tau)^2\rangle$ and $\langle(\Delta\tau')^2\rangle$ are the time-difference variance before and after dispersive propagation, respectively. In our case, $2\beta l = |k''_s l_1| = |k''_i l_2|$. According to Ref. [25], a violation of this inequality is an unambiguous signature that the two beams are energy-time entangled. Thus, it can be used as a criterion for the test of the quantum nonlocal feature for continuous variable energy-time entanglement. In the following discussion, we will give our experimental results in a normalized form of Eq. (2); i.e.,

$$W = \frac{\langle(\Delta\tau')^2\rangle\langle(\Delta\tau)^2\rangle}{\langle(\Delta\tau)^2\rangle^2 + (2\beta l)^2} \geqslant 1. \tag{3}$$

As discussed in Ref. [25], the jitter of the single-photon detectors (approximately tens of picoseconds), which is much greater than the biphoton correlation time, must be considered in practical experiment. Thus $\langle(\Delta\tau)^2\rangle$ in Eq. (3) should be replaced by $\langle(\Delta\tau)^2\rangle_{\text{obs}} = \langle(\Delta\tau)^2\rangle_{\text{source}} + \langle(\Delta\tau)^2\rangle_{\text{jitter}}$. When $\langle(\Delta\tau)^2\rangle_{\text{jitter}} \gg \langle(\Delta\tau)^2\rangle_{\text{source}}$, $\langle(\Delta\tau)^2\rangle_{\text{jitter}}$ becomes the dominant contribution to the observed time-difference variance. Therefore, in order to violate the inequality, there are two ways that can be considered: one is to reduce the jitter time of the single-photon detector, and the other is to increase the magnitude of dispersion. In our experiment, we realized the goal by using self-developed SNSPDs with a FWHM jitter as low as 37 ps and introducing a large amount of dispersion with a 62-km-long SMF.

Note that the shape of $G^{(2)}$ cannot generally be directly measured instead of the coincidence counting rate within a certain time window [41]. When the width of $G^{(2)}$ is much greater than the time window, the shape of $G^{(2)}$ can be observed by the distributions of coincidence counting from a time-to-amplitude converter-multi-channel analyzer system [41] or TCSPC [27]. In our experiment, we will reconstruct the shape of $G^{(2)}$ using the distributions of coincidence counting from the cross-correlation algorithm on time sequences tagged by ETs. Additionally, consider that only one dispersive medium is connected into the channel, i.e., only the SMF in the signal arm or the DCF in the idler arm; then the FWHM of $G^{(2)}$ in the far-field regime can be approximated as $\Delta t_{s(i)} = \eta k''_{s(i)} l_{1(2)}$ with $\eta = \sqrt{2\ln 2/\gamma D^2L^2}$. For a fixed biphoton source and dispersion coefficient of k_s'' or k_i'', $\Delta t_{s(i)}$ increases linearly with the length of SMF or DCF. Therefore, one can check whether there is a change of bandwidth of biphotons induced by the propagation channel loss by measuring the linear dependence of $\Delta t_{s(i)}$ on $l_{1(2)}$.

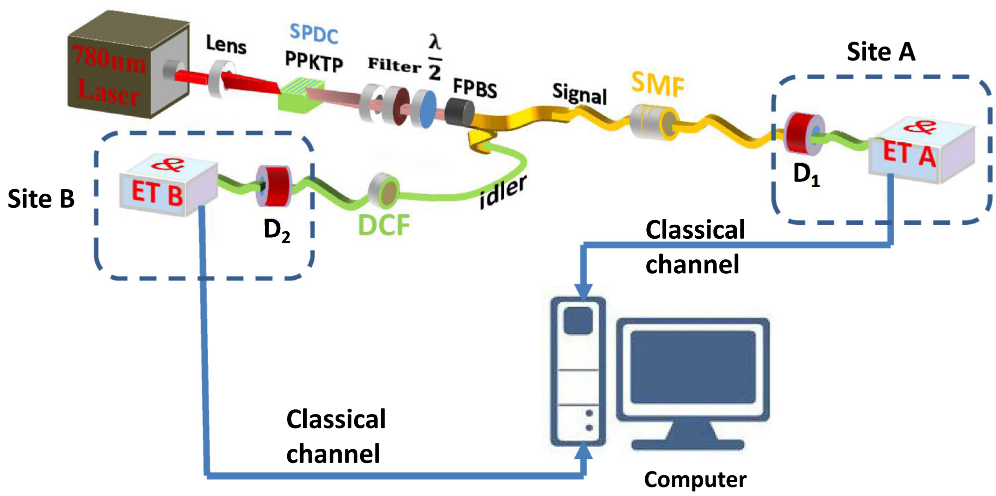

FIG. 1. The experimental setup.

III. EXPERIMENTAL RESULTS

A. Experimental setup

The experimental setup is shown as Fig. 1. The energy-time entangled signal and idler photons are generated via SPDC within a piece of type-II PPKTP crystal (Raicol Ltd.; $L = 1\,\text{cm}$, a poling period of $46.146\,\mu\text{m}$, and $D = 2.96\,\text{ps/cm}$) pumped by a 780-nm laser which is frequency doubled from a 1560-nm cw fiber laser (NKT photonics, Koheras BoostiK C15). Detailed information about the frequency doubling cavity can be found in Ref. [34]. The spectra of the signal and idler photons are centered at 1560.23 and 1560.04 nm while their 3-dB bandwidths are both 3.22 nm. After filtering out the residual pump, the output orthogonally polarized biphotons were coupled into the fiber polarization beam splitters (FPBS). With the help of a half-wave plate (HWP) before the FPBS, the signal and idler photons were spatially separated for subsequent fiber transmission. Afterward, the signal photons traveled through a SMF with $k_s'' = -2.26 \times 10^{-26}\,\text{s}^2/\text{m}$ to site A and were detected by detector D_1. The idler photons traveled to site B through a DCF with $k_i'' = 1.95 \times 10^{-25}\,\text{s}^2/\text{m}$ and were detected by detector D_2. D_1 and D_2 are SNSPDs with an efficiency of 50%. The arrival times of the signal and idler photons to the detectors were recorded independently by ET A and ET B (Eventech Ltd, A033-ET) as time tag sequences $\{t_A^{(j)}\}$ and $\{t_B^{(j)}\}$, which were transmitted through a classical communication channel to the same terminal for data processing. In our experiment, the input time tag rate of each input was set around 12 kHz and a data acquisition time of 5 s was applied. Thus both sequences for the signal and idler number about 60 000. By applying a cross-correlation algorithm on the acquired time sequences [36], the $G^{(2)}$ can then be constructed.

B. Results

To determine the jitter contribution from the SNSPDs and the ETs, we firstly measured the coincidence distribution $G^{(2)}$ between the biphotons before fiber propagations. As shown in Fig. 2(a), a FWHM width of about 37.6 ps was obtained. In order to verify the validity of our nonlocal coincidence detection method, we also measured directly the coincidence distributions with an integrated coincidence device, PicoHarp 300, as shown in the inset of Fig. 2(a). The very good agreement between the two results shows that the nonlocal detection method is highly suitable for the coincidence distribution measurement.

Figures 2(b)–2(d) show the results of coincidence counts with only SMF (l_1 correspondingly chosen as 10, 20, and 62 km) in the signal arm (blue triangles) or DCF (l_2 correspondingly chosen as 1.245, 2.49, and 7.47 km) in the idler arm (blue circles), both SMF and DCF connected (red squares). It can be seen that $G^{(2)}$'s are broadened due to the fiber dispersion in one arm. By comparing the broadening amounts caused by SMF and DCF for all three cases, $|k''_s l_1| \approx |k''_i l_2|$ is roughly satisfied. The FWHMs of $G^{(2)}$ (Δt) (red squares) in Figs. 2(b)–2(d) were narrowed to 89.3, 105.14, and 107.0 ps due to the NDC effect using both SMF and DCF in two arms (i.e., $k_s'' l_1 + k_i'' l_2 \approx 0$). The observed reduction of the coincidence counts from Figs. 2(a)–2(d) can be attributed to the channel loss as the length of the fiber increases. The corresponding theoretical simulations are also given by solid lines in Figs. 2(b)–2(d), which are in good agreement with the experimental results. Therefore, it can be concluded that the nonlocal coincidence measurement as well as the NDC have been successfully achieved.

Now we turn to whether the inequality given by Eq. (3) can be violated in our experiment. The inequality cannot be violated due to insufficient dispersion in Figs. 2(b) and 2(c). To violate the inequality, we introduce a large amount of dispersion with a 62-km-long SMF in Fig. 2(d). From Fig. 2(a), we achieve the time-difference variance before dispersive propagation is $\langle(\Delta\tau)^2\rangle_{\text{obs}} = (15.982 \pm 0.150\,\text{ps})^2$. From Fig. 2(d), we achieve the time-difference variance after dispersive propagation through both 62-km SMF and 7.47-km DCF is $\langle(\Delta\tau')^2\rangle_{\text{obs}} = (45.676 \pm 4.565\,\text{ps})^2$. Using the average magnitude of the applied dispersions on both channels $2\beta l = 1428.92\,\text{ps}^2$, we obtain a value of $W = 0.253 \pm 0.052$. Therefore, the inequality given by Eq. (3) is obviously violated by about 14 standard deviations. Analogous to the Bell

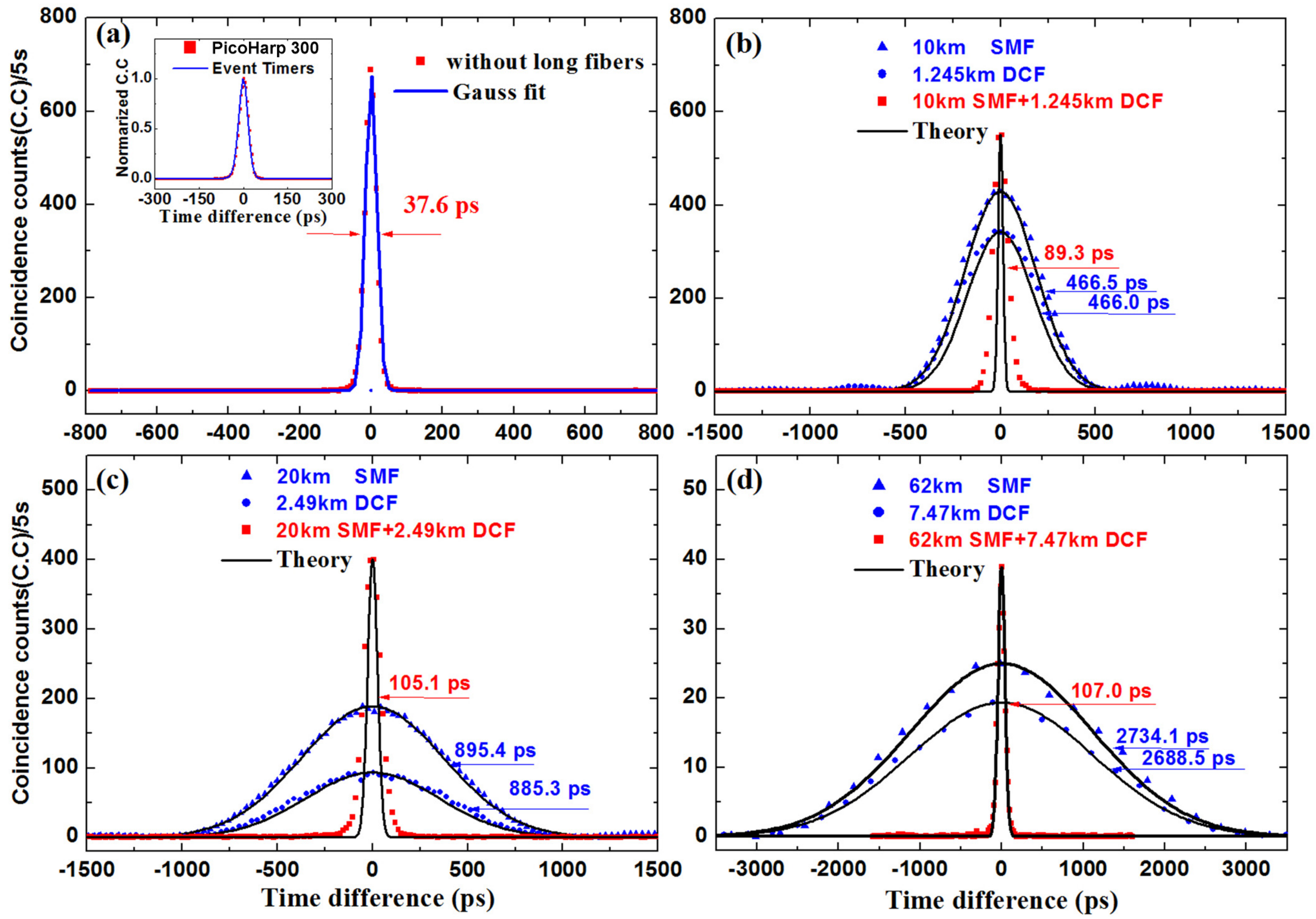

FIG. 2. The reconstructed coincidence distributions from two ETs for (a) without long fibers, (b,c) with only SMF in the signal arm (blue triangles) or DCF in the idler arm (blue circles), both SMF and DCF connected (red squares). The lengths of SMF (DCF) were chosen as (b) 10 km (1.245 km), (c) 20 km (2.49 km), and (d) 62 km (7.47 km), respectively. The solid lines in (b–d) correspond to the theoretical results, while that in (a) is the Gauss fit. The inset in (a) gives the comparison of the normalized coincidence distributions obtained by PicoHarp 300 and ETs, respectively.

test for discrete variables, such violation indicates deterministically the nonlocal feature of the energy-time entanglement after propagating through 62-km-long fibers.

IV. DISCUSSION

In our experiment, we utilized two individual ETs to tag the arrival times of the signal and idler photons. Since the time correlation between the propagated signal and idler photons is achieved via separate event timing systems instead of local coincidence hardware (e.g., PicoHarp 300), such detection method is eventually nonlocal and is desired for the real-field quantum nonlocality test. As mentioned above, the amount of time sequences is limited by the ETs. By manipulating the pump power of the SPDC and adding appropriate loss in the idler arm, we fixed all the detected single count rates as about 60 000 per 5 s.

According to Eq. (2), the width of $G^{(2)}$ with perfect NDC should be equivalent to the coherence width of the generated biphotons, which is about 2.96 ps in our case [34]. However, due to the inherent time jitter of single-photon detectors, the minimum width of $G^{(2)}$ that can be achieved is limited to about dozens of picoseconds (37.6 ps in our experiment). By looking at the results shown in Figs. 2(d) and 3, both the measured and simulated $G^{(2)}$'s indicate the incompleteness of NDC; that is, there is residual uncompensated dispersion resulting in broadening of the $G^{(2)}$ wave packet. To achieve perfect dispersion cancellation, a dispersion-adjustable component such as chirped fiber Bragg gratings [42] should be desired to overcome undercompensation or overcompensation for satisfying the compensation condition as much as possible.

Another issue to be considered is that the reduction of bandwidth of biphotons may also lead to the broadening of $G^{(2)}$ [27], so, is it due to the dispersion of fibers or the reduction of bandwidth of biphotons? In order to answer this question, we give an experimental result of Δt versus the length of SMF and DCF in one arm as shown in Fig. 3. We can see that Δt increases linearly with the length of SMF and DCF, which agrees well with the theoretical prediction. From the linear fits, we obtained a slope of 42.96 and 359.63 ps/km, and derived the dispersion coefficient being $k_s'' = -2.37 \times 10^{-26}\,\mathrm{s}^2/\mathrm{m}$ and $k'' = 1.99 \times 10^{-25}\,\mathrm{s}^2/\mathrm{m}$, which are also in good agreement with the experimental parameters. Thus, we give proof that the broadening of $G^{(2)}$ in the single arm is

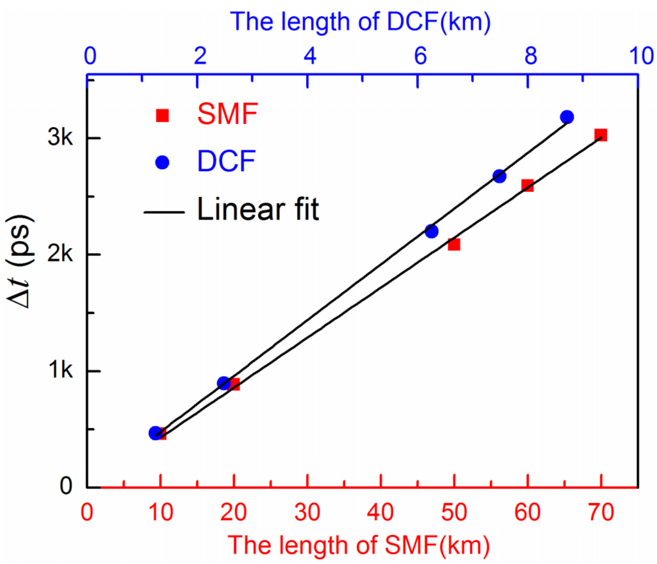

FIG. 3. The reconstructed FWHM of $G^{(2)}$ (Δt) versus the length of SMF and DCF in one arm.

only attributed to the length of optical fibers instead of the reduction of bandwidth of biphotons in spite of channel loss.

Note that when the signal or idler photons propagate through a dispersive channel, random noise associated with the dispersion adds to the registered time sequences, and decreases the photon pair collection efficiency. However, benefiting from the NDC effect, the narrowed $G^{(2)}$ was observed. Therefore, the NDC enables arrival times of the signal and idlers remaining tightly bunched after long-distance transmission, thus recovering the efficient signal from the noise and improving the signal-to-noise ratio.

Our NDC is implemented at telecom wavelengths, which is robust in transmission through both fiber and free-space links, and is compatible with wavelength-division multiplexing. Although our result is merely a proof-of-principle experiment on the nonlocality test, it demonstrates the feasibility for the strict test of nonlocal features of continuous variable entanglement with the energy-time entangled photons over a long distance. Furthermore, the NDC can also be applied to enhance the stability of quantum time transfer [43].

V. CONCLUSION

In summary, we reported a picosecond-level NDC and demonstrated a violation of Wasak's inequality for determining the nonlocal feature of energy-time entanglement with a nonlocal detection method over 60-km fibers at telecom wavelengths. According to the violation criterion given by Eq. (3), we obtained a value of $W = 0.253 \pm 0.052 < 1$, which violates the inequality obviously by about 14 standard deviations. We believe our work is a significant step toward the future strict testing of nonlocality for continuous variable entanglement after a long-distance fiber or free-space transmission.

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