Experimental Synchronization of Independent Entangled Photon Sources

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Realistic linear quantum information processing necessitates the ability to synchronously generate entangled photon pairs either at the same or at distant locations. Here, we report the experimental realization of synchronized generation of independent entangled photon pairs. The quality of synchronization is confirmed by observing a violation of Bell’s inequality with 3.2 standard deviations in an entanglement swapping experiment. The techniques developed in our experiment will be of great importance for future linear optical realization of quantum repeaters and quantum computation.

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Entangled photon pairs are an essential resource for linear optics quantum information processing (LOQIP) †, ‡. For example, using linear optical elements one can combine entanglement swapping ‡ and entanglement purification ‡ to efficiently generate highly entangled states between two distant locations ‡. Moreover, one can exploit linear optics and entangled photon pairs to achieve logic operations between single photons ‡. On this basis, one can further prepare cluster states to perform one-way quantum computation ‡, ‡. Recently, using entangled photon pairs created by one and the same laser pulse significant progress has been made in proof-in-principle demonstration of entanglement swapping ‡, entanglement purification ‡ and photonic logic operation ‡, ‡, ‡. However, in reality scalable LOQIP necessitates the ability to synchronously generate entangled photon pairs either at the same or at distant locations †, ‡. Here, we report experimental realization of synchronized generation of independent entangled photon pairs. The quality of synchronization is confirmed by observing a violation of Bell’s inequality with 3.2 standard deviations in an entanglement swapping experiment.

Entanglement swapping, i.e., teleportation of entanglement †, ‡, is a way to project the state of two particles onto an entangled state while no direct interaction between the two particles is required. During entanglement swapping, if each of the two particles is originally entangled with one other partner particle, a Bell-state measurement of the partner particles would thus collapse the state of the two particles into an entangled state, even though they are far apart.

One important application of entanglement swapping, probably also the most important application, is in long-distance quantum communication ‡. Due to the absorption and decoherence of quantum channel, the cost for communication between two distant parties increases exponentially with the channel length. One excellent solution is to connect distant communicating parties with quantum repeaters ‡: firstly dividing the whole quantum channel into several segments, and then performing entanglement swapping and entanglement purification. Therefore, in realistic realization of quantum repeaters one has to achieve entanglement swapping with synchronized entangled photon sources among all distributed segments.

Nowadays, entangled photon pairs are usually created via parametric down-conversion from a UV laser pulse. In this case, the UV laser pulses in each distributed segment must be synchronized. One natural solution is to split a single UV laser pulse into N beams and then distribute them to each segment †, ‡. However, such a naive solution is not a scalable scheme. This is because the maximal output power of a single laser is technically limited and the efficiency of the scheme will thus exponentially decrease with the number of segments. A practical solution is to utilize synchronized pump lasers to prepare entangled pairs in each segment. Thereafter we connect these pairs via entanglement swapping. Here, we are going to report the first experimental realization of this kind, i.e., entanglement swapping with independent entangled photon pairs that are created by two synchronized femto-second lasers.

Considering two independent EPR sources, each emitting a pair of polarization entangled photons synchronously. The expected state of the system consisting of two independent pairs can be written as:

$$|\Psi\rangle_{\text{total}} = \frac{1}{2}(|H_1\rangle_1|V_2\rangle_4 - |V_1\rangle_1|H_2\rangle_4) \otimes (|H_3\rangle_3|V_4\rangle_4 - |V_3\rangle_3|H_4\rangle_4).$$

(1)

Here photons 1 and 2 (3 and 4) are entangled in the antisymmetric polarization state $$|\Psi^-\rangle$$. Note that, hereafter we exactly follow the notations as used in ref. ‡. From Eq. (1), one can easily see there is no any entanglement of any of photon 1 or 2 with any of the photon 3 and 4.

Rearranging the terms by expressing photon 2 and photon 3 in the basis of Bell state, Eq. (1) can be ex-
pressed as
\[ |\Psi\rangle_{total} = \frac{1}{2}(|\Psi^+\rangle_{14}|\Psi^+\rangle_{23} + |\Psi^-\rangle_{14}|\Psi^-\rangle_{23} + |\Phi^+\rangle_{14}|\Phi^+\rangle_{23} + |\Phi^-\rangle_{14}|\Phi^-\rangle_{23}). \tag{2} \]

Eq. (2) implies that projecting photons 2 and 3 in one of the four Bell-states will lead the remaining photons 1 and 4 entangled in the corresponding Bell-state, despite they are produced separately and never interacted with one another. Due to the limitation of the linear optics element, only 50% Bell-state can be analyzed. In our experiment we decide to analyze only the case that photons 2 and 3 are projected in |Ψ−⟩23 state and interfering photons 2 and 3 at a 50 : 50 beam splitter is able to identify the |Ψ−⟩23 state. When detecting a coincident count between the two detectors at the output ports of the beam splitter, photons 2 and 3 are projected to |Ψ−⟩23 state, and then photons 1 and 4 will be in the entangled state |Ψ−⟩14.

Note that, since the Bell-state analysis relies on the interference of photons 2 and 3 one has to guarantee the photons 2 and 3 have good spatial and temporal overlap at the beam splitter. In previous experiments where the two photon pairs are created by parametric down-conversion from the same laser pulse, the interference of photons is guaranteed by making the coherence times of interfering photons much longer than the pump pulse duration [17]. However, since in our experiment the two photon pair are created by parametric down-conversion from two independent pump lasers, besides increasing the coherence times of the interfering photons by inserting narrow bandwidth filters in front of the detectors registering photons 2 and 3, one has to further ensure that the two independent laser pulses are synchronized perfectly and the timing jitter of synchronization is much smaller than the coherence times. This is experimentally very challenging.

Usually, femtosecond laser uses either active synchronization with an electrical feedback device [18], or passive synchronization by nonlinear coupling mechanism [19]. In our experiment, we implement passive technique to synchronize two Ti:Sapphire lasers, because the passive technique is stimulated by cross-phase modulation and should be capable of operating at lower fluctuation. An analogous mode-lock femtosecond laser cavity shown at the bottom of the drawing is constituted of Ti2, M6-M10, P3, P4 and T2. The two laser pulses are synchronized by coupling both lasers in the Ti: Sapphire crystal Kerr medium (KM). In order to induce stronger cross-phase modulation effect for synchronization, we focus the beams in the Kerr medium and make the two beams cross in the Kerr medium with a narrow angle. Considering the crucial condition of synchronizing lasers, One end mirror M5 is driven by a translation stage to match the two laser cavity lengths. Both 780nm Infrared laser pulses are detected by fast photodiodes (PD1 and PD2) behind beam samplers (BS1 and BS2). Hence we can monitor the synchronization between two laser pulses on an oscilloscope.

In the experiment we synchronize two Ti:Sapphire femtosecond lasers by coupling both laser pulses in an additional Ti:sapphire crystal. Figure 1 is the schematic of the experimental setup of laser synchronization. It consists of two Ti:Sapphire femtosecond lasers located at the top and bottom corners in Fig. respectively. The symmetry of two cavities ensures that both cavities length are the same, and both laser pulses work at the same repetition rate of 81MHz, which provides the basic condition of synchronization. To fine tune the match of cavities, a translation stage (TS) is also used to drive the end mirror M5 of the first Ti:Sapphire laser. Both laser pulses are coupled into a Ti:Sapphire crystal KM to synchronize with each other. To enhance the cross-phase modulation, focus mirrors M3 and M4 are inserted into the first laser cavity, and M8, M9 are inserted into the second laser cavity for introducing additional focal point inside the KM.

We pump each Ti:Sapphire femtosecond laser with a solid-state diode-pumped 532-nm laser (Verdi-V10). Under the pump power of 8W for each, each Ti:Sapphire femtosecond provides 700mW power at synchronized

\[ |\Psi\rangle_{total} = \frac{1}{2}(|\Psi^+\rangle_{14}|\Psi^+\rangle_{23} + |\Psi^-\rangle_{14}|\Psi^-\rangle_{23} + |\Phi^+\rangle_{14}|\Phi^+\rangle_{23} + |\Phi^-\rangle_{14}|\Phi^-\rangle_{23}). \tag{2} \]
mode locked status, and the central wave lengths of the lasers are 788nm. Thereafter, we measure the pulse durations by auto correlator. The laser pulse durations (FWHM) are 60 fs and 70fs respectively. Further more, we measure the crossing correlation of the synchronized lasers with a homemade cross correlator. After passing one laser beam through variable delay line with a motor-driven roof reflector, both laser beams are focused in a nonlinear crystal BBO to generate the sum-frequency signal (SFG). Measuring the SFG signal while scanning the delay line, we observe the cross-correlation curve. The FWHM of the cross-correlation curve is about 90 fs. Subtracting the contributions of pulse duration, we can deduce that the two lasers are synchronized with a timing jitter less than 2 femtoseconds. We also observe that the two lasers are able to keep on synchronizing over 24 hours, which indicate that the laser system is stable for our further implementation. The short pulse duration and little timing jitter are sufficient to ensure the perfect interference of two independent photons produced by synchronized laser pulses.

Figure 2 is the schematic of the experimental setup of entanglement swapping. Two 394 nm UV pulses are produced by frequency doubling the 788 nm pulses of the synchronized lasers using two nonlinear LBO(LiB3O5) crystals. For the first UV pulse we obtained an average UV power of 250 mW, and for the second UV pulse, 300mW. Passing the first UV pulses through a 2-mm thick BBO (β−BaB2O4) crystal creates a pair of photons 1 and 2 in the entangled state |Ψ−⟩12, via type-II parametric down conversion 21. For the 2-mm thick BBO crystal, using filters with ΔλHMFW = 2.8nm, the registered event rate of photon pairs was about 2000 count per second. In the same way, another pair of photons 3 and 4 is created by the second UV pulse in a different BBO crystal. For the second pair of photons, again using filters with ΔλHMFW = 2.8nm, we obtained 2500 count per second. The observed visibility in the 45 degree polarization basis is about 90% for both photon pairs.

According to the entanglement swapping scheme, upon projection of photons 2 and 3 into the |Ψ−⟩23 state, photon 1 and 4 should be projected into |Ψ−⟩14 state. To verify that this entangled state is obtained, we have to analyze the polarization correlation between photons 1 and 4 conditioned on coincidences between the detectors (D2 and D3) of the Bell-state analyzer. We utilize a half wave plate and two detectors (D∥1 and D⊥1) behind a polarizing beam splitter to analyze the polarizations of photon 1. For example, we can choose to analyze the polarization of photon 1 along the +45◦ and −45◦ by rotating the half wave plate 22.5◦. Photon 4 is analyzed by detector D4 behind a polarizer with a variable polarization direction θ4.

If entanglement swapping happens, then the twofold coincident between D∥1 and D4, and D⊥1 and D4, conditioned on the |Ψ−⟩23 detection, show two sine curves as a function of θ4 which are 90◦ out of phase. Figure 4 shows the experimental one of our result for the coincidences between D∥1 and D4, and D⊥1 and D4, given that photons 2 and 3 have been registered by the two detectors in the Bell-state analyzer, where we rotate the half wave plate 22.5◦ to make D∥1 to register photon 1 with +45◦ polarization, and D⊥1 to register photon 1 with −45◦ polarization. The experimentally obtained four-fold coincidences shown in figure 4 have been fitted by a joint sine function with the same amplitude for both curves. The observed visibility of 82% clearly surpasses the 0.71 limit of Bell’s inequalities, which indicates the entanglement swapping do has been happened.

The high-visibility sinusoidal coincident curves in the experiment imply a violation of a suitable Bell’s inequality 22, S ≤ 2 for any local realistic theory, where

\[ S = |E(\theta_1, \theta_4) - E(\theta_1, \theta'_4) - E(\theta'_1, \theta_4) - E(\theta'_1, \theta'_4)| (3) \]

and the E(θ1, θ4) is the coefficient for measurement where
and 4 gave the following results:

\[ S^{QM} = 2 \] 

resulting from twofold coincidence conditions on the twofold coincidences of the Bell-state measurement. When varying the polarizer angle \( \theta_1 \), the two complementary sine curves with a visibility of 82% demonstrate that photons 1 and 4 are polarization entangled.

\[ \theta_1 \text{ (or } \theta'_1) \text{ is the polarizer setting for photon 1, and } \theta_4 \text{ (or } \theta'_4) \text{ is the setting for photon 4. In our experiment we set } \theta_1 = -22.5^\circ, \theta'_1 = -67.5^\circ, \theta_4 = 0^\circ, \theta'_4 = 45^\circ, \text{ which maximizes the quantum mechanics’ prediction of } S \text{ to } S^{QM} = 2\sqrt{2} \text{ and leads to a contradiction between local realistic theory and quantum mechanics. In our experiment, the four correlation coefficients between photons 1 and 4 gave the follow results: } E(-22.5^\circ, 0^\circ) = -0.570 \pm 0.049, E(-22.5^\circ, 45^\circ) = 0.583 \pm 0.046, E(-67.5^\circ, 0^\circ) = 0.600 \pm 0.049, E(-67.5^\circ, 45^\circ) = 0.554 \pm 0.046. \text{ Hence, } S = 2.308 \pm 0.095 \text{ which violates the classical limit of 2 by 3.2 standard deviations. This clearly confirm the quantum nature of entanglement swapping.}

In summary, in the experiment we have exploited two synchronized femtosecond lasers to report for the first time an experimental demonstration of entanglement swapping with independent entangled photon pairs. Whereas our experiment presents a strict experimental realization of entangling photons that never interacted, the techniques developed in the experiment can be readily used to generate synchronized entangled photon pairs in all segments by cascading the coupling between the lasers, hence taking a significant step towards realistic linear optical realization of quantum repeaters and quantum computation.

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[1] E. Knill and R. Laflamme and G. J. Milburn, Nature (London), 409, 46 (2001).
[2] J.-W. Pan, C. Simon, C. Brukner, and A. Zeilinger, Nature (London), 410, 1067 (2001).
[3] M. Zukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert, Phys. Rev. Lett. 71, 4287 (1993).
[4] C. H. Bennett, G. Brassard, S. Popescu, B. Schumacher, J. A. Smolin, and W. K. Wootters, Phys. Rev. Lett. 76, 722 (1996).
[5] H.-J. Briegel, W. Dur, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. 81, 5932 (1998).
[6] T. B. Pittman, M. J. Fitch, B. C. Jacobs, and J. D. Franson, Phys. Rev. A 68, 032316 (2003).
[7] R. Rausendorf and H. J. Briegel, Phys. Rev. Lett. 86, 5188 (2001).
[8] M. A. Nielsen, Phys. Rev. Lett. 93, 040503 (2004).
[9] J.-W. Pan, D. Bouwmeester, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. 80, 3891 (1998).
[10] J.-W. Pan, S. Gasparoni, R. Ursin, G. Weihs, and A. Zeilinger, Nature (London) 423, 417 (2003).
[11] K. Sanaka, T. Jennewein, J.-W. Pan, K. Resch, and A. Zeilinger, Phys. Rev. Lett. 92, 017902 (2004).
[12] S. Gasparoni, J.-W. Pan, P. Walther, T. Rudolph, and A. Zeilinger, Phys. Rev. Lett. 93, 020504 (2004).
[13] Z. Zhao, A.-N. Zhang, Y.-A. Chen, H. Zhang, J.-F. Du, T. Yang, and J.-W. Pan, Phys. Rev. Lett. 94, 030501 (2005).
[14] C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. 70, 1895 (1993).
[15] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, Rev. Mod. Phys. 74, 145 (2002).
[16] H. de Riedmatten, I. Marcikic, J. van Houwelingen, W. Tittel, H. Zbinden, and N. Gisin, quant-ph/0406093.
[17] M. Zukowski, A. Zeilinger, and H. Weinfurter, Ann. NY Acad. Sci. 755, 91 (1995).
[18] L.-S. Ma, R. K. Shetlon, H. C. Kapteyn, M. M. Murnane, and J. Ye, Phys. Rev. A 64, 021802 (2001).
[19] M. R. X. D. Barros and P. C. Becker, Opt. Lett. 18, 631 (1993).
[20] Z. Wei, Y. Kobayashi, and K. Torizuka, Appl. Phys. B 74[Suppl.], S171 (2002).
[21] P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, and Y. Shih, Phys. Rev. Lett. 75, 4337 (1995).
[22] J. F. Clauser, M. Horne, A. Shimony, and R. A. Holt, Phys. Rev. Lett. 23, 880 (1969).