Experimental Synchronization of Independent Entangled Photon Sources

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We report the generation of independent entangled photon pairs from two synchronized but mutually incoherent laser sources. 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 are not only important for realistic linear optical quantum-information processing, but also enable new tests of local realism.

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Entangled photon pairs are essential for linear optics quantum-information processing (LOQIP) [1,2]. For example, using linear optical elements one can combine entanglement swapping and entanglement purification to efficiently generate highly entangled states between two distant locations [2,3]. Moreover, one can exploit linear optics and entangled photon pairs to achieve logic operations between single photons [4]. On this basis, one can further prepare cluster states to perform one-way quantum computation [5,6]. 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 [7], entanglement purification [8], and photonic logic operation [9–11]. However, in reality scalable LOQIP necessitates the ability to synchronously generate entangled photon pairs either at the same or at distant locations [1,2].

To have a better understanding on this requirement, let us give a brief introduction on entanglement swapping. Entanglement swapping [12] 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 is in long-distance quantum communication [13]. Because of the absorption and decoherence of the 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 [3]: first, 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 achieved entanglement swapping with synchronized entangled photon sources among all distributed segments.

Nowadays, entangled photon pairs are usually created via spontaneous parametric down-conversion (SPDC) from a pump laser pulse. In this case, the pump laser pulses in each distributed segment must be synchronized. One natural solution is to split a single pump laser pulse into N beams and distribute them to each segment [14]. 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 [proportional to $(1/N)^N$] will thus exponentially decrease with the number of segments. To solve the scalability problem, a practical solution is to synchronize a number of independent pump lasers with sufficient output power and then distribute them to each segment. In this way, we can prepare synchronized entangled pairs in each segment without the problem of low pump power. Thereafter we connect these pairs via entanglement swapping.

On the other hand, although significant experimental advances have been achieved both in proof-in-principle demonstration of entanglement swapping [7] and in the test of quantum nonlocality for photons that never interacted [15], a more strict experiment with independent entangled photon sources is still necessary to fully demonstrate the quantum nature of entanglement swapping. This is because in all previous experiments the two entangled photon pairs are generated via SPDC from one and the same uv laser pulse—they thus have a fixed phase relation [2,8]; this leaves some ambiguousness in explanation of the experimental phenomena. In other words, it is not clear to what extent the previous experiments constituted a full demonstration of entanglement swapping—entangling particles that never interacted. In addition, a recent theoretical proposal on the test of local realism by Greenberger, Horne, and Zeilinger [16] also calls for such independent but synchronized entangled photon sources.

Here, we report the experimental generation of independent entangled photon pairs from two synchronized but mutually incoherent femtosecond lasers. The quality of synchronization is confirmed by observing a violation of

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Bell's inequality with 3.2 standard deviations in an entanglement swapping experiment.

Consider 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

$$|\Psi\rangle_{\rm total} = \tfrac{1}{2}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2) \otimes (|H\rangle_3|V\rangle_4 - |V\rangle_3|H\rangle_4). \qquad (1)$$

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. [7]. 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 expressed as

$$|\Psi\rangle_{\rm total} = \tfrac{1}{2}(|\Psi^+\rangle_{14}|\Psi^+\rangle_{23} + |\Psi^-\rangle_{14}|\Psi^-\rangle_{23} + |\Phi^+\rangle_{14}|\Phi^+\rangle_{23} + |\Phi^-\rangle_{14}|\Phi^-\rangle_{23}). \qquad (2)$$

Equation (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 that they are produced separately and never interacted with one another. Because of the limitation of the linear optics element, only two of the four Bell states can be analyzed. In our experiment we decide to analyze only the case that photons 2 and 3 are projected to the $|\Psi^-\rangle_{23}$ state and interfering photons 2 and 3 at a 50:50 beam splitter is able to identify the $|\Psi^-\rangle_{23}$ 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 the $|\Psi^-\rangle_{23}$ state, and then photons 1 and 4 will be in the entangled state $|\Psi^-\rangle_{14}$.

Note that, since the Bell-state analysis relies on the interference of photons 2 and 3, one has to guarantee that 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 SPDC 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 SPDC 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 lasers use either active synchronization with an electrical feedback device [18], or passive synchronization by nonlinear coupling mechanism [19]. In our experiment, we implement the 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; this will result in a very small timing jitter [20]. Considering the two lasers before they are synchronized, operating at repetition frequencies of f_1 and f_2, respectively, they cross a common Kerr medium (KM in Fig. 1) at a repetition rate of $|f_1 - f_2|$ and suffer a frequency shift according to their temporal overlap in KM; for example, the slower pulse shifts to blue, and the faster one shifts to red. Considering if the pulses start to cross inside the KM, due to the negative group dispersions in the laser cavities, the crossing of the two pulses will be enhanced after they take one round trip in their cavities, when both cavities are adjusted to be nearly equal. Therefore, the leading pulse will be slowed down and the sluggish one will be fastened, until they overlap maximally in time domain. The common KM does not contribute to mode locking or the short pulse formation of each cavity. It is worth noting that the two femtosecond lasers are independent in two senses: First, the two lasers are mutually incoherent, i.e., have no fixed phase relation. Second, the two lasers could have completely different wavelengths; for example, one emits green light and the other emits red light [20].

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. 1, respectively. The symmetry of

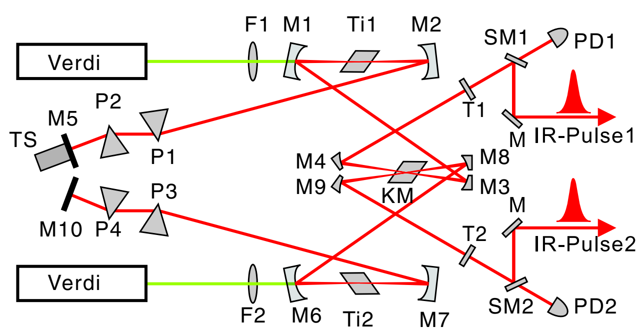

FIG. 1 (color online). Experimental setup of synchronized femtosecond pulse lasers. F1 and F2 are lens to focus the pumping 532 nm laser from two Verdi laser systems; Ti1 and Ti2 are Ti:sapphire crystals; M5 and M10 are high reflection flat mirrors; M1-M4 and M6-M9 are concave mirrors of 10 cm radius of curvature; P1-P4 are prisms; T1 and T2 are 20% output couplers. On the top of the figure, Ti1, M1-M5, P1, P2, and T1 constitute the first mode-lock femtosecond laser cavity. An analogous mode-lock femtosecond laser cavity shown at the bottom of the drawing is constituted of Ti2, M6-M10, P3, P4, and T2. KM is a Ti:sapphire crystal for synchronization. One end mirror M5 is driven by a translation stage (TS) to match the two laser cavity lengths. Both 788 nm infrared laser pulses are detected by fast photodiodes (PD1 and PD2) behind beam samplers (SM1 and SM2). Hence we can monitor the synchronization between two laser pulses on an oscilloscope.

two cavities ensures that both cavities length are approximately the same, and both laser pulses work at the repetition rate of about 81 MHz, which provides the basic condition of synchronization. To fine-tune the match of cavities, a translation stage 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 and 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 laser (Verdi-V10). Under the pump power of 8 W for each, each Ti:sapphire femtosecond provides 700 mW power at synchronized mode locked status, and the central wave lengths of the lasers are 788 nm. Thereafter, we measure the pulse durations by an autocorrelator. The laser pulse durations (FWHM) are 60 and 70 fs, respectively. Furthermore, we measure the crossing correlation of the synchronized lasers with a homemade cross correlator. After passing one laser beam through the variable delay line with a motor-driven roof reflector, both laser beams are focused in a nonlinear crystal BBO (β-BaB_2O_4) 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 individual pulse durations, we can deduce that the two lasers are synchronized with a timing jitter less than 2 fs [20]. We observed an ultralong cavity length mismatch tolerance of more than 10 μm, which ensures the two lasers can keep on synchronizing over 24 h, which indicates 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. We should note that system with more lasers can be synchronized by a similar method. For a system consisted of N independent lasers, every two adjacent lasers can be synchronized by coupling them to a common Kerr medium. Thus, only the $N - 1$ Kerr medium is required to synchronize the N 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 (LiB_3O_5) crystal. For the first uv pulse we obtained an average uv power of 250 mW, and for the second uv pulse, 300 mW. Passing the first uv pulses through a 2-mm-thick BBO crystal creates a pair of photons 1 and 2 in the entangled state $|\Psi^-\rangle_{12}$, via type-II SPDC [21]. The registered event rate of photon pairs was about 2000 counts 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, we obtained 2500 counts per second. The observed visibility in the 45° polarization basis is about 90% for both photon pairs.

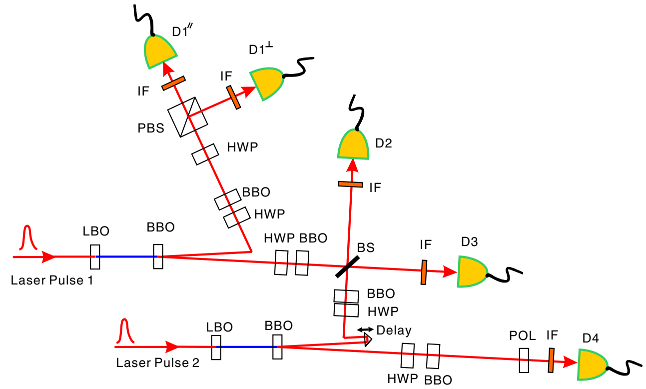

FIG. 2 (color online). The schematic drawing of experimental setup of quantum entanglement swapping. The two synchronized lasers produce two pairs of polarization entangled photons, respectively, by up-conversion and type-II SPDC. In order to compensate the birefringence of the BBO crystals, we place a half wave plate (HWP) and a compensating 1 mm BBO crystal on each path of the four photons. Interference filters (IF) with $\Delta\lambda_{\mathrm{FWHM}} = 2.8$ nm are place before each single photon detector (D_1–D_4). The beam splitter (BS) performs as a Bell-state measurement here. To meet the condition of temporal overlap, we used a step motor which minimum step is 0.1 μm to search for the position where the two photons arrived in the BS at the same time.

In the entanglement swapping scheme, upon projection of photons 2 and 3 into the $|\Psi^-\rangle_{23}$ state, photon 1 and 4 will be projected into $|\Psi^-\rangle_{14}$ 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 (D_2 and D_3) of the Bell-state analyzer. We utilize a half wave plate and two detectors ($D_1^{\parallel}$ and $D_1^{\perp}$) behind a polarizing beam splitter to analyze the polarization 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 D_4 behind a polarizer with a variable polarization direction θ_4.

If entanglement swapping happens, then the twofold coincidence between $D_1^{\parallel}$ and D_4, and $D_1^{\perp}$ and D_4, conditioned on the $|\Psi^-\rangle_{23}$ detection, should show two sine curves as a function of θ_4 which are 90° out of phase. Figure 3 shows the experimental one of our result for the coincidences between $D_1^{\parallel}$ and D_4, and $D_1^{\perp}$ and D_4, 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 $D_1^{\parallel}$ to register photon 1 with $+45°$ polarization, and $D_1^{\perp}$ to register photon 1 with $-45°$ polarization. The experimentally obtained fourfold coincidences shown in Fig. 3 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

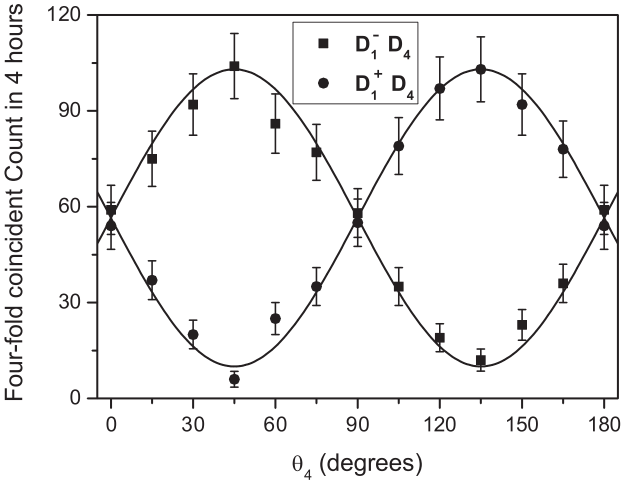

FIG. 3. Entanglement verification. Fourfold coincidences, resulting from twofold $D_1^+D_4$ and $D_1^-D_4$ coincidences conditioned on the twofold coincidences of the Bell-state measurement. When varying the polarizer angle θ_4, the two complimentary sine curve with a visibility of 82% demonstrate that photons 1 and 4 are polarization entangled.

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. In particular, according to the Clauser-Horne-Shimony-Holt (CHSH) inequality [22], $S \leq 2$ for any local realistic theory, where

$$S = |E(\theta_1, \theta_4) - E(\theta_1, \theta_4') - E(\theta_1', \theta_4) - E(\theta_1', \theta_4')|, \quad (3)$$

and the $E(\theta_1, \theta_4)$ is the coefficient for measurement where θ_1 (or θ_1') is the polarizer setting for photon 1, and θ_4 (or θ_4') is the setting for photon 4. In our experiment we set $\theta_1 = -22.5°$, $\theta_1' = -67.5°$, $\theta_4 = 0°$, and $\theta_4' = 45°$, which maximizes the quantum mechanics's prediction of S to $S^{\mathrm{QM}} = 2\sqrt{2}$ 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: $E(-22.5°, 0°) = -0.570 \pm 0.049$, $E(-22.5°, 45°) = 0.583 \pm 0.046$, $E(-67.5°, 0°) = 0.600 \pm 0.049$, and $E(-67.5°, 45°) = 0.554 \pm 0.046$. Hence, $S = 2.308 \pm 0.095$, 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 and enables new tests of local realism, the techniques developed in the experiment can be readily used to generate synchronized entangled photon pairs in all segments, hence taking a significant step towards realistic linear optical realization of quantum repeaters and quantum computation.

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