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Long-distance entanglement swapping with photons from separated sources

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We report the experimental realization of entanglement swapping over long distances in optical fibers. Two photons separated by more than 2 km of optical fibers are entangled, although they never directly interacted. We use two pairs of time-bin entangled qubits created in spatially separated sources and carried by photons at telecommunication wavelengths. A partial Bell-state measurement is performed with one photon from each pair, which projects the two remaining photons, formerly independent onto an entangled state. A visibility high enough to infer a violation of a Bell inequality is reported, after both photons have each traveled through 1.1 km of optical fiber.

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Quantum theory is nonlocal in the sense that it predicts correlations between measurement outcomes that cannot be described by theories based solely on local variables. Many experiments confirmed that prediction using pairs of entangled particles produced by a common source. It is only in 1993 that Zukowski and colleagues [1] noticed that this "common source" is not necessary: nonlocality can manifest itself also when the measurements are carried out on particles that have no common past, but have been entangled via the process of entanglement swapping. It consists of preparing two independent pairs of entangled particles (see Fig. 1), and to subject one particle from each pair (B and C) to a joint measurement called Bell-state measurement (BSM). This BSM projects the two other particles (A and D), formerly independent, onto an entangled state that may exhibit nonlocal correlations. Let us emphasize that this kind of quantum nonlocality cannot be used to signal faster than light. There is thus no direct conflict with relativity. In the entanglement swapping process this aspect goes as follows. Initially, particles A and D have independent pasts, hence share no correlation (except possibly for some classical correlation). They share quantum nonlocal correlations only after their twins B and C have been jointly measured and only conditioned on the outcome of this measurement: without the conditioning they appear as independent. Hence, as long as the classical information about the joint measurement outcome is not available, no nonlocal correlation can be observed.

Besides its fascinating conceptual aspect, entanglement swapping also plays an essential role in the context of quantum information science. It is for instance the building block of protocols such as quantum repeaters [2,3] or quantum relays [4–6] proposed to increase the maximal distance of quantum key distribution and quantum communication. It also allows the implementation of a heralded source of entangled photon pairs [1]. Finally, it is a key element for the implementation of quantum networks [7] and of linear optics quantum computing [8]. More generally, coherent manipulations of several quantum systems, as in a BSM, are essential for all quantum computing and simulation processes.

Experimental demonstration of entanglement swapping has been reported in 1998, using two pairs of polarization entangled qubits encoded in photons around 800 nm created by two different parametric down conversion (PDC) events in the same nonlinear crystal [9]. The fidelity of this experiment was, however, insufficient to demonstrate nonlocal correlations. In 2002, an improved version allowed a violation of a Bell inequality [10], thus confirming the nonlocal character of this protocol. More recently, an experiment with qubits entangled in the Fock basis (one photon with the vacuum) has been reported [11]. However, it involves only two photons instead of four. All the experiments realized so far have demonstrated the principle of entanglement swapping over short distances (of the order of a meter). However, most applications in quantum communication require this process to happen over large distances. A promising approach for this purpose is to use the existing network of optical fibers. However, none of the previously demonstrated schemes was well adapted for this task.

In this paper, we present the experimental demonstration of entanglement swapping with a quantum architecture optimized for long-distance transmission in optical fibers. We use two pairs of time-bin entangled qubits encoded in photons at telecommunication wavelengths created by PDC. This type of encoding has been proven to be robust against decoherence in optical fibers [12] and has been used to achieve long-distance quantum teleportation in optical fibers [6,13]. Contrary to the previous swapping experiments involving four photons [9,10], the two pairs are created in spatially separated sources although pumped by the same laser. As a proof of principle of the robustness of this scheme, we demonstrate entanglement swapping over more than 2 km of

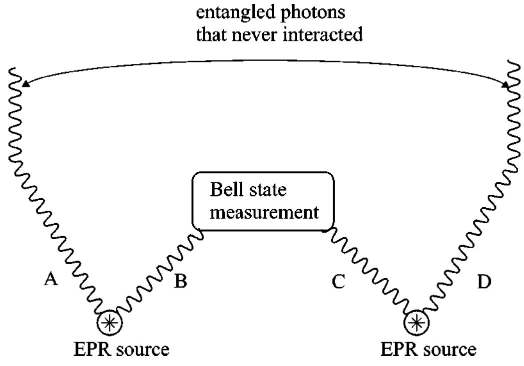

FIG. 1. Scheme of principle of entanglement swapping.

optical fiber. For this purpose, a partial BSM is performed onto one photon from each pair, entangling the two remaining photons which have each traveled over separated 1.1 km spools of optical fiber. Entanglement is verified using a two-photon quantum interference conditioned on a successful BSM.

Time-bin entangled qubits can be seen as photon pairs created in a coherent superposition of two emission times with a well-defined relative phase [14]. They are created first by splitting a laser pulse into two subsequent pulses using an unbalanced interferometer called a pump interferometer. One photon pair is then created by PDC. The down converted photons originate from the two pulses with a relative phase δ, hence the photon pair quantum state is $|\phi^{+}(\delta)\rangle = c_0|0,0\rangle + e^{i\delta}c_1|1,1\rangle$, where $|0,0\rangle$ corresponds to a photon pair created in the early time bin and $|1,1\rangle$ to a photon pair created in the delayed time bin, with $c_0^2+c_1^2=1$. In our experiment, we employ two spatially separated sources of entangled photons. In one of these sources, we create a state $|\phi^{+}(\delta)\rangle_{A,B}$, while in the other one we create a state $|\phi^{-}(\delta)\rangle_{C,D} = |\phi^{+}(\delta+\pi)\rangle_{C,D}$. Initially, the two photon pairs are independent and the total state can be written as the tensor product: $|\Psi_{ABCD}\rangle = |\phi^{+}(\delta)\rangle_{AB} \otimes |\phi^{-}(\delta)\rangle_{CD}$ This state can be rewritten in the form.

$$|\Psi_{ABCD}\rangle = \frac{1}{2}[|\phi^{+}\rangle_{BC} \otimes |\phi^{-}(2\delta)\rangle_{AD} + |\phi^{-}\rangle_{BC} \otimes |\phi^{+}(2\delta)\rangle_{AD} + |\psi^{+}\rangle_{BC} \otimes e^{i\delta}|\psi^{-}\rangle_{AD} + |\psi^{-}\rangle_{BC} \otimes e^{i\delta}|\psi^{+}\rangle_{AD}], \quad (1)$$

where the four Bell states are $|\phi^{\pm}(\delta)\rangle = 1/\sqrt{2}(|0,0\rangle \pm e^{i\delta}|1,1\rangle)$ and $|\psi^{(\pm)}\rangle = 1/\sqrt{2}(|1,0\rangle \pm |0,1\rangle)$. When photons B and C are measured in the Bell basis, i.e., projected onto one of the four Bell states, photons A and D are projected onto the corresponding entangled state. Note that when photons B and C are projected onto the state $|\psi^{+}\rangle$ or $|\psi^{-}\rangle$, the state of photons A and D is independent of the phase δ, which appears only as a global factor. This means that in this case, the creation process is robust against phase fluctuations in the pump interferometer and pump-laser wavelength drifts [15]. Hence, this experiment can also be considered as a (postselected) heralded source of entangled photon pairs robust against phase fluctuation in the preparation stage [16]. If, however, photons B and C are projected onto the state $|\phi^{+}\rangle$ or $|\phi^{-}\rangle$ the state of photons A and D depends on twice the phase δ. In our experiment, we make a partial BSM, looking only at projections of photons B and C onto the $|\psi^{-}\rangle$ Bell state. Another interesting feature to note is that all the four Bell states are involved in the experiment, since we start from $|\phi^{+}\rangle$ and $|\phi^{-}\rangle$ states, and make a projection onto the $|\psi^{-}\rangle$ state, which projects the two remaining photons onto the $|\psi^{+}\rangle$ state.

A scheme of our experiment is presented in Fig. 2. Femtosecond pump pulses are sent to an unbalanced bulk Michelson interferometer with a travel time difference of $\tau = 1.2$ ns. Thanks to the use of retroreflectors, we can utilize both outputs of the interferometer, which are directed to spatially separated lithium triborate (LBO) nonlinear crystals. Collinear nondegenerate time-bin entangled photons at tele-

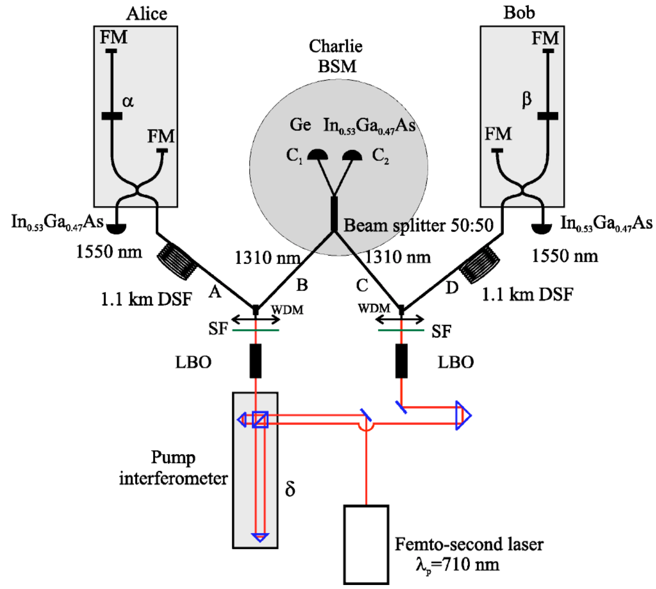

FIG. 2. Experimental setup. The pump laser is a mode-locked femtosecond Ti-sapphire laser producing 200 fs pulses at a wavelength of 710 nm with a repetition rate of 75 MHz. After the crystals, the pump beams are blocked with silicon filters (SF). The Faraday mirrors (FM) are used to compensate polarization fluctuations in the fiber interferometers.

communication wavelengths (1310 and 1550 nm) are eventually created by PDC in each crystal. Because of the phase acquired at the beam splitter in the pump interferometer there is an additional relative phase of π between the terms $|0,0\rangle$ and $|1,1\rangle$ in the second output of the interferometer. This explains why a state $|\phi^{+}(\delta)\rangle$ is created in one crystal while a state $|\phi^{-}(\delta)\rangle$ is created in the other one.

The created photons are coupled into single-mode optical fibers and deterministically separated with a wavelength-division multiplexer (WDM). The two photons at 1310 nm (B and C) are subject to a partial BSM using a standard 50-50 fiber beam splitter [17]. It can be shown that whenever photons B and C are detected in different output modes and different time bins, the desired projection onto $|\psi^{(-)}\rangle_{BC}$ is achieved [18]. For this kind of measurement, the two incoming photons must be completely indistinguishable in their spatial, temporal, spectral, and polarization mode. The indistinguishability is verified by a Hong-Ou-Mandel experiment [19,20]. The two photons at 1310 nm are filtered with 5 nm bandwidth interference filters (IF) in order to increase their coherence time to 500 fs, larger than the pump pulse's duration (200 fs), which is necessary in order to make the photons temporally indistinguishable [21].

The two photons at 1550 nm, filtered to 18 nm bandwidth (A and D), each travel over 1.1 km of dispersion shifted fiber (DSF). Their entanglement is then analyzed with two fiber Michelson interferometers with the same travel time difference as the pump one. The phase of each interferometer can be varied with a piezoactuator (PZA). Since the demonstration of entanglement swapping necessitates the detection of four photons, the coincidence count rate is very low. This requires the ability to perform interferometric measurements over an extended period of time and thus asks for a drastic improvement in the setup stability, compared to our previous experiments [6,13]. In order to control the phase, and to obtain a sufficient long-term stability, the fiber interferometers are actively controlled using a frequency stabilized laser (Dicos) and a feedback loop on the PZA. The phase of each fiber interferometer is probed periodically and is locked to a user-defined value [12]. This technique allowed us to obtain excellent stability tested over up to 96 h. Note that the pump interferometer requires no active phase stabilization.

The photons are detected with avalanche photodiode (APD) single-photon detectors. One of the 1310 nm photons (detector C_1) is detected with a liquid-nitrogen-cooled Ge APD (NEC), with an efficiency of around 10% for 40 kHz of dark counts. The three other photons are detected with $In_xGa_{1-x}As$ APDs (id-Quantique) with an efficiency of 30% for a dark count probability of around 10^{-4} per ns. The trigger signal for those detectors is given by a coincidence between the Ge APD and the emission time of the pump pulses. The coincidence events between different detectors are recorded with a multistop time-to-digital converter (TDC). The coincidence between the Ge APD and the emission time of the laser is used as "Start" while the other APDs are used as "Stops." Note that the classical information about the BSM is delayed electronically by roughly 5 μs, corresponding to the travel time of the 1550-nm photons inside optical fibers. Hence, the swapping process is completed only when the photons are already 2 km apart. A homemade program allows us to register any combination of coincidence count rate between the four detectors, which is useful to characterize the stability of the whole setup during the measurement process. In our experiment, the average pump power for each source was about 80 mW, leading to a probability of creating an entangled pair per laser pulse of around 6%.

If entanglement swapping is successful, the two photons A and D at 1550 nm should be in the entangled state $|\psi^{(+)}\rangle$, conditioned on a projection on the $|\psi^{(-)}\rangle$ Bell state. However, as real measurements are imperfect, there will be some noise that we suppose will be equally distributed between all possible outcomes. Hence, the created state can be written as

$$\rho = F_2|\psi^{(+)}\rangle\langle\psi^{(+)}| + \frac{1-F_2}{3}(|\psi^{(-)}\rangle\langle\psi^{(-)}| + |\phi^{(+)}\rangle\langle\phi^{(+)}| + |\phi^{(-)}\rangle \times\langle\phi^{(-)}|) = V|\psi^{(+)}\rangle\langle\psi^{(+)}| + \frac{(1-V)}{4}\mathbb{1}, \quad (2)$$

where V is the visibility and F_2 the two-qubit fidelity defined as $F_2=\langle\psi^{(+)}|\rho|\psi^{(+)}\rangle$. V is related to F_2 as

$$V = \frac{4F_2 - 1}{3}. \quad (3)$$

The Peres criteria [22] shows that the two photons are entangled (i.e., in a nonseparable state) if $V>1/3$, and consequently if $F_2>1/2$. It can also be shown that the Clauser-Horne-Shimony-Holt Bell inequality can be in principle violated if $V>1/\sqrt{2}$ [23] (see also [12] for an experimental demonstration with time-bin entangled qubits).

To verify the entanglement swapping process we perform a two-photon interference experiment with the two photons at 1550 nm, conditioned on a successful BSM. This is done by sending photons A and D to two interferometers. The evolution of $|\psi^{(+)}\rangle$ in the interferometers is

$$|\psi^{(+)}\rangle \rightarrow |0_A,1_D\rangle + e^{i\alpha}|1_A,1_D\rangle + e^{i\beta}|0_A,2_D\rangle + e^{i(\alpha+\beta)}|1_A,2_D\rangle + |1_A,0_D\rangle + e^{i\alpha}|2_A,0_D\rangle + e^{i\beta}|1_A,1_D\rangle + e^{i(\alpha+\beta)}|2_A,1_D\rangle, \quad (4)$$

where $|i_A,j_D\rangle$ corresponds to an event where the photon A is in time bin i and the photon D is in time bin j. A photon traveling through the long arm of an interferometer passes from time bin i to time bin $i+1$. If the arrival time difference between photons A and D are recorded, Eq. (4) shows that there are five different time windows, with $\Delta\tau=t_A-t_B=\{0,\pm\tau,\pm2\tau\}$. This is in contrast with previous experiments using time-bin entangled qubits in the state $|\phi^{(\pm)}\rangle$, where only three time windows were present (see, e.g., [12]). If only the event with $\Delta\tau=0$ is selected, there are two indistinguishable events leading to a coincident count rate,

$$R_c \sim 1 + V\cos(\alpha-\beta), \quad (5)$$

where V is the visibility of the interference which can in principle attain the value of 1, but is in practice lower than 1 due to various experimental imperfections. Figure 3 shows a measurement of two-photon interference. The plain squares represent coincidences between photons A and D, without conditioning on a BSM as a function of the phase of one interferometer. The fact that the coincidence count rate does not vary significantly with the phase is a confirmation that the two photons are completely independent in this case. However, if we now condition on a successful BSM (open circles), we see a sinusoidal variation with a fitted raw (i.e., without noise subtraction) visibility of $(80\pm4\%)$, leading to a fidelity F_2 of $(85\pm3.25\%)$, high enough to demonstrate teleportation of entanglement and to infer a violation of a Bell inequality with the swapped photons by more than two standard deviations. Note that the visibility obtained here is

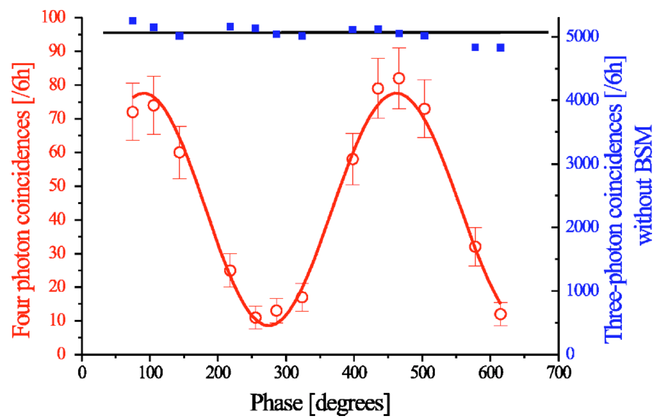

FIG. 3. Two-photon interferences for swapped photons, as a function of the phase of one interferometer. The plain squares represent the detection between photons A and D, without conditioning on the BSM. The errors bars are too small to be represented. The open circles represent four-photon coincidences, i.e., two-photon interference conditioned on a BSM.

significantly higher than the one obtained in previous demonstrations of long-distance quantum teleportation [6,13]. Hence, in this case the teleported entanglement can be used directly for quantum communication purposes, without further purifying. The whole measurement lasted 78 h, which demonstrates the robust character of our scheme. The nonperfect visibility of the interference fringe is attributed mainly to the limited fidelity of the BSM. The main limiting factor is the nonvanishing probability of creating multiple photon pairs in one laser pulse, due to the probabilistic nature of PDC [20,24]. The visibility could be improved by reducing the pump power but this would reduce the four-photon coincidence count rate. Note that the key parameters in order to increase the four-photon coincidence count rate without degrading the correlations are the quantum efficiencies of detectors and the coupling efficiencies into the single-mode fibers.

In summary, we have reported the demonstration of entanglement swapping over long distance in optical fibers. We used two pairs of time-bin entangled qubits encoded into photons at telecommunications wavelengths and created in spatially separated sources. The visibility obtained after the swapping process was high enough to demonstrate a teleportation of entanglement and to infer a violation of Bell inequalities with photons separated by more than 2 km of optical fibers that have never directly interacted. This constitutes a promising approach to push quantum teleportation and entanglement swapping experiments out of the laboratory, using the existing optical-fiber network.

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[15] Note that this is valid only if the laser used is the same for both sources. In case of distant sources pumped by independent lasers, the pump interferometer phases should be stabilized.
[16] Because of the probabilistic nature of PDC, the probability to create two photon pairs in one source is the same as the probability of creating one pair in each source. Hence, the four photons need to be detected in order to postselect the cases where (at least) one pair is created in each source, which are the events we are interested in.
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