Long Distance Quantum Teleportation in a Quantum Relay Configuration

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A long distance quantum teleportation experiment with a fiber-delayed Bell state measurement (BSM) is reported. The source creating the qubits to be teleported and the source creating the necessary entangled state are connected to the beam splitter realizing the BSM by two 2 km long optical fibers. In addition, the teleported qubits are analyzed after 2.2 km of optical fiber, in another laboratory separated by 55 m. Time-bin qubits carried by photons at 1310 nm are teleported onto photons at 1550 nm. The fidelity is of 77%, above the maximal value obtainable without entanglement. This is the first realization of an elementary quantum relay over significant distances, which will allow an increase in the range of quantum communication and quantum key distribution.

Quantum teleportation (QT) is the transmission of the quantum state of a particle to another distant one, without the transmission of the particle itself. The QT channel consists of nonclassical Einstein-Podolski-Rosen (EPR) correlations between two particles supplemented by some bits of classical information. Since the theoretical proposal in 1993 [1], several experiments have demonstrated the principle of QT using different types of discrete and continuous variables [2–7]. QT could find applications in the context of quantum communication, where the goal is to distribute quantum states over large distances, e.g., for quantum key distribution [8] or for future quantum networks [9]. The simplest way to send a quantum state from a sender to a receiver, usually called Alice and Bob, is to send directly the particle carrying the state, e.g., using an optical fiber. However, as detectors are noisy and fibers lossy, the signal to noise ratio (and thus the fidelity) decreases with distance, and the maximal distance for a given fidelity is thus limited. Quantum repeaters [10] that rely on QT, entanglement purification [11], and quantum memories have been proposed to overcome this problem. However, a full quantum repeater is not realizable with present technology, due to the need for a quantum memory. Nevertheless, QT could still be useful in this context, even without quantum memory, by implementing a so-called quantum relay [8,12,13].

The basic idea is the following. Suppose that the qubit sent by Alice is teleported to Bob using the entangled state created by an EPR source, as in Fig. 1(a). To perform the teleportation, Charlie makes a joint measurement, called a Bell state measurement (BSM) between Alice's photon and one-half of the EPR pair, which projects Bob's photon into the state of Alice's photon, modulo a unitary transformation. A successful BSM implies, in particular, that a photon has left the EPR source towards Bob. This means that although the logical qubit travels an overall distance l from Alice to Bob, the effective distance covered by the photon to be detected by Bob is reduced to around $l/3$. This provides an increase in the maximal

distance for a given fidelity. Figure 1(b) shows the calculated qubit fidelity as a function of the distance for different configurations (see [13] for the details of the calculations). The price to pay is a reduction of the count rate. The first experiment in this direction has been reported recently, where the teleported qubit was analyzed after 2 km of optical fibers [7]. But this is not enough, as the source creating the qubit and the EPR source should be distant from each other. In this Letter, we present the first realization of an elementary quantum relay by implementing a long distance QT experiment with a fiber-delayed BSM in order to simulate distant sources.

Beyond experimental difficulties encountered in short distance QT experiments, the addition of distance implies two additional challenges. First, entanglement must be
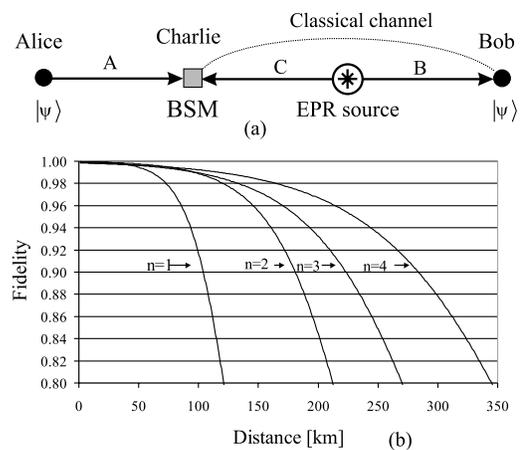

FIG. 1. (a) Quantum teleportation as a quantum relay. (b) Fidelity of the transmitted quantum state as a function of the distance for different configurations. Direct transmission ($n = 1$), with an EPR source in the middle ($n = 2$), teleportation ($n = 3$), and entanglement swapping ($n = 4$). We assume that the fidelity is affected only by the detectors noise. The curves are plotted for a realistic dark count probability $D = 10^{-4}$ per ns and a fiber attenuation of 0.25 dB/km.

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distributed over a large distance with a high quality. This is overcome by taking the profit of the robustness of time-bin entanglement when transmitted in optical fibers [14]. Moreover, the use of standard telecommunication fibers imposes the wavelength of the carrier photons, in order to minimize losses. Second, to achieve a successful BSM, the two photons involved must be indistinguishable, which is much more difficult to preserve when the photons travel long distances in two optical fibers. In the following, we first review the basic principles of quantum teleportation with time-bin qubits and then present the experiment, focusing mainly on the indistinguishability of the photons involved in the BSM.

The procedure of quantum teleportation using time-bin qubits is the following. Alice prepares a time-bin qubit, that is, a photon in a coherent superposition of two time bins, by passing a single photon through an unbalanced interferometer with path-length difference $\Delta\tau$. The time-bin qubit can be written as $|\psi\rangle_A = a_0|1,0\rangle_A + a_1 e^{i\alpha}|0,1\rangle_A$, where $|1,0\rangle_A$ represents the first time bin (i.e., a photon having passed through the short arm of the interferometer), $|0,1\rangle_A$ the second time bin (i.e., a photon having passed through the long arm), α a relative phase, and $a_0^2 + a_1^2 = 1$. Time-bin qubits can be conveniently represented on a Poincaré sphere [see Fig. 2(b)]. Alice sends the qubit to Charlie, who shares with Bob a classical communication channel and a pair of time-bin entangled qubits [15] in the state: $|\phi^+\rangle_{BC} = (1/\sqrt{2}) \times (|1,0\rangle_C|1,0\rangle_B + |0,1\rangle_C|0,1\rangle_B)$. Charlie now performs the BSM; i.e., he projects photons A and C onto one of the four Bell states, defined by $|\phi^\pm\rangle = (1/\sqrt{2})(|1,0\rangle|1,0\rangle \pm |0,1\rangle|0,1\rangle)$ and $|\psi^\pm\rangle = (1/\sqrt{2})(|1,0\rangle|0,1\rangle \pm |0,1\rangle|1,0\rangle)$. Depending on the result of the BSM (communicated by Charlie with two classical bits), Bob can now apply the appropriate transformation (i.e., bit flip and/or phase flip or identity) to recover the initial state. We perform an interferometric BSM, by mixing the two photons on a

beam splitter (one per input mode) that allows one, in principle, to discriminate two out of the four Bell states [16]. We select only projections onto the $|\psi^-\rangle$ singlet state. It can be shown that the detection of one photon in each output mode with a time difference $\Delta\tau$ realizes this projection. In this case, photon B is projected onto the state

$$|\psi\rangle_B = a_0|0,1\rangle_B - a_1 e^{i\alpha}|1,0\rangle_B = i\sigma_y|\psi\rangle_A, \qquad (1)$$

where σ_y is a Pauli matrix.

A schematic of the experiment is presented in Fig. 2(a) (see also [7] for a more detailed description). Ultrashort pulses from a mode-locked Ti-sapphire laser ($\Delta t = 150$ fs, $\lambda = 710$ nm, and $f_{\rm rep} = 75$ MHz) are split by a variable beam splitter made of a half-wave plate and a polarizing beam splitter (HWP + PBS). The transmitted beam is used to create entangled time-bin qubits in the state $|\phi^+\rangle_{BC}$ by passing it first through a bulk optical Michelson interferometer (pump interferometer) with path-length difference $\Delta\tau = 1.2$ ns, and then through a nonlinear lithium triborate (LBO) crystal, where entangled nondegenerate collinear time-bin qubits at telecom wavelength (1310 and 1550 nm) are created. The optical path-length difference of this interferometer defines a reference; therefore the phase φ is taken to be zero. The pump beam is removed with a silicon filter (SF) and the created photons are coupled into an optical fiber and separated using a wavelength division multiplexer (WDM). Photon C at 1310 nm is sent to Charlie and its twin photon B at 1550 nm to Bob [see Fig. 1(a)].

The beam reflected at the variable coupler is used to create the qubits to be teleported. To do so, the 1310 nm photon (A) from a pair produced in a similar LBO crystal passes through a fiber Michelson interferometer with relative phase α generating a superposition between two time bins. To create the two time-bin states $|1,0\rangle_A$ and $|0,1\rangle_A$, fibers of appropriate length are employed instead of the interferometer. The retroreflector R is used to adjust the qubit arrival time at the BSM. The two 1310 nm photons (A and C) travel to Charlie, who performs the BSM with a 50/50 fiber beam splitter (BS), through 2 km of standard optical fibers. In order to avoid spurious coincidences that would limit the teleportation fidelity, one has to postselect only events where one pair is created in each crystal. This is done by decreasing the probability of creating a pair in the EPR source, relative to the qubit source by a factor of 7 using the variable coupler [7].

Bob is located in another laboratory, separated by 55 m, and connected by 2.2 km of dispersion-shifted optical fiber. The qubit is analyzed with a fiber interferometer similar to the one used for the creation, but adapted for the wavelength of 1550 nm or by a fiber (see below). All photons are detected with avalanche photodiodes (APD). Detector C_1 is a passively quenched Ge APD (quantum efficiency $\eta = 10\%$ and dark count rate dc = 40 kHz),
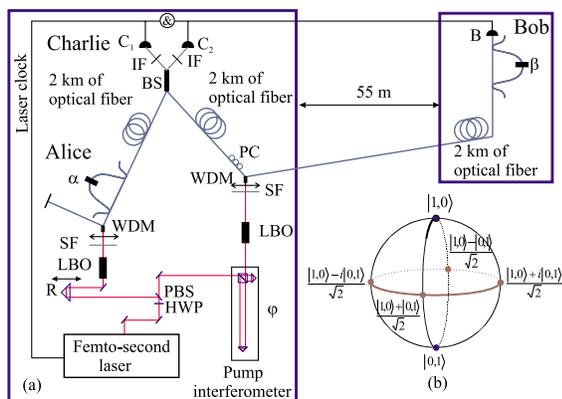

FIG. 2 (color online). (a) Long distance quantum teleportation experiment, with 2 km of optical fibers inserted between each source and the BSM. (b) Poincaré sphere representing the qubit states.

and detectors C_2 and B are Peltier cooled InGaAs APDs operating in gated mode ($\eta = 30\%$ and $dc = 10^{-4}$ per ns) [17]. To reduce the dark count rate, the trigger signal for the latter is given only by a coincidence between detector C_1 and the laser clock (t_0). The BSM (coincidence $C_1 + C_2 + t_0$) is realized using a fast (i.e., <1 ns) coincidence electronics. To verify the teleportation process, fourfold coincidences ($C_1 + C_2 + B + t_0$) are monitored with a time-to-digital converter, where the start is given by a successful BSM and the stop by Bob's detector B.

To verify that the entanglement of the EPR pair is preserved after the transmission over 2×2 km of optical fibers, we perform a Franson-type two photon interference experiment with the same three interferometers used for the teleportation. The method is described in detail in [15]. We observe interference fringes with a high net visibility of $(96 \pm 1)\%$ (see Fig. 3), showing that there is no degradation of the entanglement during the transmission. This measurement also allows us to ensure that the three interferometers have the same optical path-length difference, which is also required for the teleportation experiment.

Let us now analyze in more detail the indistinguishability criteria for the BSM: photons A and C must be described by identical spatial, spectral, polarization, and temporal modes. Spatial and spectral indistinguishability is ensured by using a fiber beam splitter and identical interference filters (IF) for both photons, respectively. A polarization controller (PC) inserted before the BSM beam splitter allows us to equalize the polarization for the two photons. For temporal indistinguishability, two points must be considered. First, the photons must be created at well-defined times, which means that their coherence time must be larger than the pump pulse duration [18]. This is achieved by using ultrashort pulses (150 fs) and narrow IF (10 nm) to increase the coherence time of the photons to about 250 fs. Second, the two photons must arrive at the same time at the BSM beam splitter, within their coherence time. This implies, in particular, that the length difference of the two fibers

must remain constant within a few tenth of microns for several hours. Thermally induced fiber length variations are of the order of 8 mm/K for a 2 km long fiber. The temperature of the two fiber spools should thus be constant within the mK range. Even in a well controlled laboratory environment, this proved to be a very stringent condition. We finally placed both fibers together on the same spool. In this case, local temperature variations act in the same way on the two fibers. With this method, we obtained length difference variations of around 3 μm/h, an acceptable value for a teleportation experiment. Finally, the two fibers must have the same chromatic dispersion in order to avoid "which path" information. Indeed, contrary to Ref. [19], the dispersion is not canceled since the two photons are not frequency correlated.

We perform a Hong-Ou-Mandel (HOM) quantum interference experiment to verify the indistinguishability of photons A and C [20]. Figure 4 shows the coincidence count rate of the two detectors placed at the outputs of the BSM beam splitter plus the laser clock ($C_1 + C_2 + t_0$) as a function of the delay of Alice's photon, when the pump intensity is equal for the two sources. The maximum visibility of the interference is limited to 33% in this case, due to the impossibility to discard the (noninterfering) events where two pairs are created in the same source [21]. We observe a raw visibility of $(17 \pm 2)\%$ and a net visibility of $(28 \pm 2)\%$. Interestingly, this interference occurs even if the photons are actually no more Fourier transform limited but still indistinguishable when they arrive at the beam splitter. The effective length of the wave packets (≈ 40 ps) is indeed much longer than the coherence length given by the IF, due to chromatic dispersion in the fibers. The observed width of the dip (≈ 140 μm) corresponds roughly to the width expected from the IF, and not to the effective length. An intuitive way to understand this is to note that chromatic dispersion could, in principle, be compensated after the BS. Which path information could then be gained, except within the coherence length of the photons.

To demonstrate the teleportation process, we teleport two classes of qubit states: one class contains qubits that
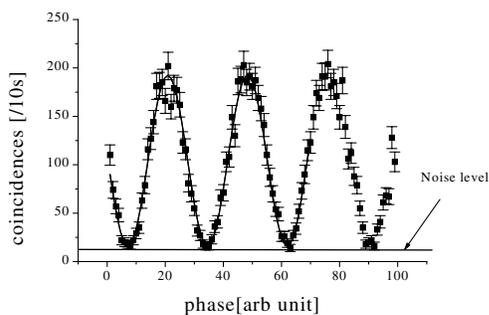

FIG. 3. Two photon interference after two times 2 km of optical fibers. The solid line is a sinusoidal fit from which we can infer a net visibility of $(96 \pm 1)\%$.
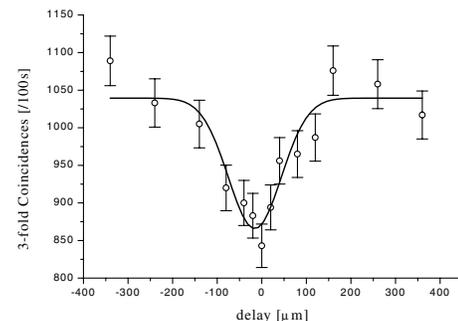

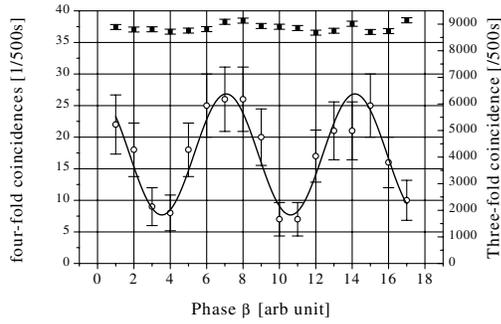FIG. 4. HOM interference after 2×2 km of optical fibers. See the text for details.

FIG. 5. Teleportation of equatorial states. The open circles are raw fourfold coincidences and the solid squares are threefold coincidences. The integration time for one point is 500 s.

lie on the equator of the Poincaré sphere [see Fig. 2(b), coherent superpositions of $|1,0\rangle_A$ and $|0,1\rangle_A$ with equal amplitudes] and the other class contains the two poles of the Poincaré sphere (the two time bins themselves). For the equatorial states, a successful teleportation implies Bob's photon to be in a superposition state [see Eq. (1)]. Thus, the coincidence count rate of detector B, conditioned on a successful BSM (fourfold coincidence $C_1 + C_2 + B + t_0$) is expected to vary as $R_c = \frac{1 + V\cos(\alpha + \beta)}{2}$, where V is the visibility of the interference fringes, that can reach theoretically the value of 1. From the measured visibility, we can compute the fidelity for the equatorial states $F_{equator} = \frac{1+V}{2}$. If there is no information about the BSM, Bob's photon will be in a mixed state and no interference is expected. This can be visualized by recording threefold coincidences ($C_1 + B + t_0$).

Figure 5 shows a typical teleportation result for equatorial states. Fourfold and threefold coincidence count rates are plotted as a function of the phase β of Bob's interferometer. Fourfold coincidences are clearly oscillating and a sinusoidal fit gives a raw visibility of $(55 \pm 5)\%$, leading to a fidelity of $F_{equator} = (77 \pm 2.5)\%$. Various measurements for different values of α have been performed, leading to similar fidelities.

The analysis of the two other states represented by the north and south poles of the Poincaré sphere is made by replacing the interferometer by one fiber by looking for detections at appropriate times. The fidelity F_{poles} is the probability of detecting the right state when measuring in the north-south basis, $F_{poles} = \frac{R_{correct}}{R_{correct} + R_{wrong}}$. The measured fidelity for the $|1,0\rangle$ input state is $(77 \pm 3)\%$, and the measured fidelity for the $|0,1\rangle$ input state is $(78 \pm 3)\%$, leading to a mean value of $F_{poles} = 77.5\%$. Consequently, the total fidelity is $\frac{1}{3}F_{poles} + \frac{2}{3}F_{equator} = (77.5 \pm 3)\%$ higher than the maximum value obtainable without entanglement (66.7%).

The fidelity depends both on the quality of the BSM and on the visibility of the interferometers V_{int}, as

$$F = V_{BSM}\frac{1 + V_{int}}{2} + (1 - V_{BSM})\frac{1}{2}, \qquad (2)$$

where V_{BSM} is the probability of a successful BSM. As the visibility of the interferometers is close to 1, the teleportation fidelity is mainly limited by the quality of the BSM, which could be improved by using narrower interference filters and by detecting the fourth photon as a trigger. This would, however, result in lower count rates and require an improvement of the setup stability.

In conclusion, we reported a long distance quantum teleportation experiment with a fiber-delayed BSM, where Alice and Bob were separated by 6.2 km of optical fibers and where the photon to be detected by Bob covers an effective distance of 2.2 km. This constitutes the first experimental realization of an elementary quantum relay over significant distances. The main experimental difficulty of such a configuration is to preserve the necessary indistinguishability of the two photons involved in the BSM. For an implementation outside the laboratory, the coherence length of these photons should be dramatically increased in order to tolerate more fiber length fluctuations. This can be done, e.g., by placing the nonlinear crystals in cavities or by using bright photon pair sources [22] together with narrower filters.

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