Long distance quantum teleportation of qubits from photons at 1.3 $\mu$m to photons at 1.55 $\mu$m wavelength

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Elementary 2-dimensional quantum states (qubits) encoded in 1.3 $\mu$m wavelength photons are teleported onto 1.55 $\mu$m photons. The use of telecommunication wavelengths enables to take advantage of standard optical fibre and permits to teleport from one lab to a distant one, 55 m away, connected by 2 km of fibre. A teleportation fidelity of 81.2% is reported. This is large enough to demonstrate the principles of quantum teleportation, in particular that entanglement is exploited. This experiment constitutes a first step towards a quantum repeater.

I. INTRODUCTION

According to Aristotle, objects are constituted of matter and form. Today one would say energy and structure. For quantum physicists objects are constituted by elementary particles and quantum states. Matter and energy can not be teleported: they can not be transferred from one place to another without passing through intermediate locations. However, in 1993 it was discovered\footnote{\textsuperscript{1}} that quantum states (i.e. the ultimate structure of objects) can be teleported: this is quantum teleportation. Accordingly, objects can be transferred from one place to another without ever existing anywhere in between! But only the structure is teleported, the matter stays at the source side and has to be already present at the final location. Moreover, the matter at the final location has to be entangled (i.e. form an EPR state\footnote{\textsuperscript{2}}) with yet another piece of matter, located near the original object. The original object and the nearby half EPR state undergo then a joint measurement, i.e. a so-called Bell state measurement, whose result is communicated to the distant final location where it determines a simple transformation to be applied to the second half of the EPR-state. This second half carries now precisely the quantum state of the original object. Note that the Bell state measurement destroys the quantum state of the initial object and that no information about which state is teleported is acquired because its final state is completely mixed. The first, and with foreseeable technologies the only, application of quantum teleportation is in quantum communication where it helps to extend quantum cryptography to larger distances\footnote{\textsuperscript{3}}.

Since the familiar article by Bennett and five colleagues presenting the concept\footnote{\textsuperscript{1}} quantum teleportation received a lot of attention. On the conceptual side, it has been proven that it is a universal gate for quantum computing\footnote{\textsuperscript{4}}. In particular, together with quantum memories, it offers the possibility to realize quantum repeaters with unlimited range\footnote{\textsuperscript{2}}. But it is fair to say that its fundamental meaning for our understanding of quantum nonlocality and of the structure of space and time may still awaiting discovery. On the experimental side, progress in demonstrations of the concept has been surprisingly fast\footnote{\textsuperscript{5,6,8,10,11,12,13,14}}. Already in 1997, only 4 years after Bennett et al.’s landmark publication, two groups, one in Rome, one in Innsbruck, presented first results of quantum teleportation employing qubits (i.e. two dimensional quantum states). The Italian group, led by Prof. de Martini$^6$, exploited an idea by Prof. Popescu to teleport a qubit carried by one of the photons of the EPR pair. However, this nice trick prevents the possibility to concatenate this teleportation scheme. The Austrian group, led by Prof. Zeilinger$^7$ (now in Vienna), used a more complete scheme, where only one qubit is carried per photon. Hence, soon after their initial experiment they could also demonstrate entanglement swapping\footnote{\textsuperscript{15,16}}, i.e. the teleportation of an entangled qubit. However, this scheme was also incomplete since it used what is called a partial Bell state measurement which implies that even in principle the teleportation succeeds only in 25% of cases. A few years later, Prof. Shih and his group\footnote{\textsuperscript{10}} at Baltimore University reported on a teleportation experiment with complete Bell state measurements, but the efficiency of the measurement was only of the order $10^{-7}$\textsuperscript{10}. The difficulty is, as proven by Lütkenhaus et al.\footnote{\textsuperscript{17}}, that a complete Bell state measurement for qubits requires non-linear optics. Hence, either one stays with linear optics and admits incomplete measurements (as Zeilinger’s group and the result presented in this article); or one goes for non-linear optics and admits very inefficient measurements; or one does not use qubits, nor finite dimensional Hilbert spaces. Indeed, it has been shown, first theoretically\footnote{\textsuperscript{18}}, then experimentally\footnote{\textsuperscript{8}}, that the teleportation of continuous variables can, in principle, be fully achieved using linear optics. However, the difficulty is then to produce close to maximally entangled EPR states. This difficulty is even more significant when the distance is increased, because squeezed states of light beams (i.e. EPR states for continuous variables) are very vulnerable to losses.

In this article we report the first experimental long distance demonstration of this fascinating aspect of quantum mechanics. Qubits carried by photons of 1.3 $\mu$m wavelength are teleported onto photons of 1.55 $\mu$m wavelength from one lab to another one, 55 m away in bee line and connected by 2 km of standard telecommunication fi-
II. TIME-BIN QUBIT

Qubits can be realized in an unlimited number of ways. A well-known one uses photon polarization, but this is not the optimal choice for long distance quantum communication. Another implementation of qubits in photons, more robust against unavoidable polarization fluctuations in fibres, consists in using time-bins \([19, 20, 21]\). Figure 1b presents the preparation of an arbitrary qubit state as superposition of two time-bins \(|1, 0\rangle + c_1 e^{i\phi} |0, 1\rangle\). This state corresponds to the input photon passing through the short arm \(|1, 0\rangle\) of an unbalanced interferometer, with probability amplitude \(c_0\), and through the long arm \(|0, 1\rangle\), with probability amplitude \(c_1\). The phase \(\phi\) characterizes the imbalancement of the interferometer with respect to a reference optical path length difference. Alice’s variable coupler allows one to choose the value of the two amplitudes, and the switch enables to superpose them without losses.

Figure 1 also shows how arbitrary (projective) measurements can be implemented. Bob’s switch is used to send the first time-bin through the long arm, and the second time-bin through the short arm such that they arrive simultaneously at the beam-splitter. With the phase shifter and the variable coupler we can choose to measure the state in any basis \([10]\).

In the experiment, instead of using a true variable coupler, we use 3 different settings with coupling ratio of 0\% , 100\% and 50\%. These settings correspond to preparation of and projections onto the states represented on the north pole, south pole and on the equator of the generalized Poincar sphere (see \(\text{Fig. 1}\)). We did also replace the switches by passive fibre couplers. This implies a 50\% loss, both for the preparation and the measurement apparatuses. But since fast switches have even larger losses, our choice is the most practical one and does not affect the principle of the experiment. The result of the measurement for each basis can then be found by looking at the appropriate detection times \([22]\). Note that the concept of time-bins, contrary to polarization, can easily be generalized to higher dimensions \([23]\). Time-bins are sensitive to chromatic dispersion, but this phenomenon can be passively compensated using linear optics \([24]\), on the contrary to polarization mode dispersion \([25]\).

III. EXPERIMENTAL REALIZATION

Let us recall the quantum teleportation scenario and define the terminology. Suppose that Alice wants to transmit an unknown quantum state of her qubit to Bob. However, she cannot send the particle directly, for instance due to a lossy transmission channel. But she has the possibility to send her qubit to Charlie who shares a pair of entangled qubits and a classical communication channel with Bob (see Fig. 2). Charlie now entangles Alice’s qubit with his part of the shared pair by means of a so-called Bell state measurement \([26]\) and then communicates the result, i.e. the Bell state he projected onto, to Bob. Performing now an unitary transformation - a bit flip, a phase flip, or both, or the identity operation -, depending on Charlie’s result, Bob’s photon ends up in the initial state of Alice’s photon, although the state
remains unknown.

Our experimental set-up is presented in fig. 3. A mode locked Ti:Sapphire laser (Coherent Mira 900) produces 150 fs pulses at \( \lambda_p = 710 \text{ nm} \) with a repetition rate of 76 MHz. To remove all unwanted infrared light the beam passes through a series of dichroic mirrors, reflecting only wavelengths centred around 710 nm. The laser beam is then split into two parts using a variable beam-splitter made of a half wave plate (HWP) and a polarizing beam splitter (PBS).

The transmitted (horizontally polarized) beam is used to create entangled time-bin qubits (EPR source) by passing the beam first through an unbalanced bulk Michelson interferometer (referred to as the pump interferometer) with optical path-length difference \( \Delta r = 1.2 \text{ ns} \). The beam is then directed onto a type I non-linear crystal (Lithium triborate, LBO, from Crystal Laser) where entangled non-degenerate collinear time-bin qubits at telecom wavelengths (1310 and 1550 nm) are created. The pump light is removed with a silicon filter (SF) and the twin photons are collimated into an optical fibre and separated by a wavelength-division-multiplexer (WDM). The 1310 nm photon is then sent to Charlie and its twin 1550 nm photon to Bob. The entangled state is described by:

\[
|\Phi\rangle = \frac{1}{\sqrt{2}} |1,0\rangle_{\text{Charlie}} |1,0\rangle_{\text{Bob}} + e^{i\varphi} |0,1\rangle_{\text{Charlie}} |0,1\rangle_{\text{Bob}}
\]

(1)

where \(|1,0\rangle\) represents the first time-bin and \(|0,1\rangle\) the second one. The imbalancement of this interferometer defines the reference time difference between the first and the second time-bin, thus the phase \( \varphi \) is taken to be zero. As described in [27] we observed two-photon fringe visibilities up to 95 % when testing the source, showing that the purity and the degree of entanglement is high enough for the use in quantum communication protocols.

The reflected (vertically polarized) beam is used to create the qubits to be teleported. Similar to the creation of the entangled pairs, the beam is focussed into a LBO crystal creating pairs of photons at 1310 nm and 1550 nm wavelengths, however, without passing first through an interferometer. After blocking the pump light and coupling the photon pairs into an optical fibre, the 1550 nm photon is removed using a WDM. Alice passes the 1310 nm photon through an unbalanced fibre Michelson interferometer, thereby creating a time bin qubit:

\[
|\Phi\rangle_{\text{Alice}} = \frac{1}{\sqrt{2}} (a_0 |1,0\rangle_{\text{Alice}} + a_1 e^{i\alpha} |0,1\rangle_{\text{Alice}}) \quad (2)
\]

where 0, 1 or \( \frac{1}{\sqrt{2}} \) depending on the discrete variable coupler setting, and \( a_1 = \sqrt{1 - a_0^2} \). The phase \( \alpha \) is defined relatively to the reference phase \( \varphi \). Alice’s qubit is finally sent to Charlie. Charlie performs the joint Bell-state measurement between the qubit sent by Alice and his part of the pair, with the 50/50 fibre coupler BS. As
proven by Lütkenhaus et al. 17, only two out of four different results can be discriminated using linear optics. We choose to select only the one which projects the two particles onto the singlet entangled state

\[ |\Phi^-\rangle = \frac{1}{\sqrt{2}} (|1,0\rangle_{\text{Alice}} |0,1\rangle_{\text{Charlie}} - |0,1\rangle_{\text{Alice}} |1,0\rangle_{\text{Charlie}}) \]

(3)

This takes place when the two photons trigger the detectors labelled \( C_1 \) and \( C_2 \) on fig. 4 at times that differ precisely by the time difference \( \Delta \tau \) between two timebins. Indeed, each of the two terms in Eq. 3 may produce this detection result, either with each photon remaining in their fibre or both coupling to the other (hence the \( \pi \) phase shift which corresponds to the minus sign in Eq. 3). To achieve this projection the two photons have to be indistinguishable when they emerge from the beam-splitter 25, i.e.: (i) They have to be localised in the same two spatial output modes. This condition is easily met using a single mode fibre beam-splitter. (ii) The two photons must arrive at the beam splitter at the same time, within their coherence time \( \tau_c \). This means that the pump pulses have to be better localised than the created photons. This condition is fulfilled by using 150 fs pump pulses together with 10 nm filters (IF) centred at 1310 nm to increase the coherence time of the created photons to about \( \tau_c = 250 \) f.s. The arrival time of Alice’s qubit is controlled by a retroreflector (R) mounted on a micrometric translation stage. (iii) The time separation \( \Delta \tau \) between two time bins for Alice’s qubit and the entangled qubit must be the same, again within \( \tau_c \). Thus, the optical path length difference of the pump and Alice’s interferometer have to be precisely aligned. This is achieved using white light interferometry and then, for the fine alignment, by maximizing the visibility of the two photon interference 27. (iv) The spectra of the two photons must be equal. This is insured by using the same PDC process and by the IF. (v) The polarisation of the two photons have to be the same when they arrive at the beam-splitter. This is done with the polarisation controller (PC), aligned with a LED and a classical polarimeter. Photon \( C_1 \) is detected by a passively quenched Germanium avalanche photo diode (APD) working at liquid nitrogen temperature in so called Geiger mode 24, 34 (quantum efficiency \( \eta = 10\% \), dark count rate \( dc=35 \) KHz, from NEC). To reduce the noise we make a coincidence between the Germanium APD and a trigger from the laser pulses. Photon \( C_2 \) is detected with a Peltier cooled InGaAs APD working in the so called Gated mode 31 \((\eta = 30\%, dc=10^{-4}\) per ns, from id Quantique). This means that the APD is only active during a short time gate \((\sim 100\) ns) when a photon is expected. The trigger is given by the coincidence between the Germanium APD and the laser pulse. Fast electronics provides information about the arrival time with an accuracy of 600 ps. Finally the signals of the APDs are sent to a fast coincidence electronics to achieve the Bell state measurement.

As we reported in 25 the production of multi-photon pairs by the EPR source should be avoided in many quantum communication protocols. If the probability of creating a photon pair is the same in both crystals, then, due to stimulated emission, the probability of creating two pairs in one crystal is the same as the probability of creating one pair in each crystal 32. Thus, two times over three Charlie detects a wrong event 25. In order to detect only the desired events, we decrease the probability of creating entangled qubits relative to the probability of creating the qubit to be teleported. The wrong events are thus reduced to only the cases where two entangled pairs are created, which can be made arbitrary small. The ratio of probabilities is controlled by the variable coupler HWP+BPS. Eventually we chose the ratio of 8 with the probability of creating Alice’s qubit per laser pulse of around 10%. Bob is situated in another lab, 55 m away from Charlie in bee line. To simulate a longer distance we added 2 km of dispersion shifted optical fibre before the teleported photon reaches Bob’s analyser. Once Charlie has the information that the (partial) Bell state measurement was successful, he informs Bob by the classical channel. This operation projects Bob’s photon onto the state:

\[ |\Phi\rangle_{Bob} = \frac{1}{\sqrt{2}} (a_1 e^{i\alpha} |1,0\rangle_{Bob} - a_0 |0,1\rangle_{Bob}) \]

(4)

In order to recover Alice’s qubit state (Eq 2) Bob should apply the \( \sigma_y \) unitary transformation consisting in a bit flip \(|1,0\rangle \leftrightarrow |0,1\rangle \) and a phase flip (a relative phase \( \pi \)). However these unitary operations are not necessary to prove that teleportation takes place. To show that our teleportation set-up operates correctly, Bob analyses the received photon with an analyser adapted for the wavelength of 1550 nm 27 (see Fig 11). The analysis basis thus contains the vector:

\[ k_0 |1,0\rangle + k_1 e^{i\beta} |0,1\rangle \]

(5)

where 0, 1 or \( \frac{1}{\sqrt{2}} \), depending on the variable coupler setting, and \( k_1 = \sqrt{1-k_0^2} \).

Bob’s photon is also detected with a InGaAs APD, as photon \( C_2 \). The trigger is again given by the coincidence between the Germanium APD and the laser pulse, but delayed by 10 \( \mu s \) which correspond to the time that the photon needs to propagate down the 2 km of fibre and arrive at Bob’s detector. The detection of Bob’s photon triggers a 1310 nm laser pulse. This pulse is sent back to the primary lab through another fibre and detected with a standard PIN diode. This detection is reported to the coincidence electronics as the detection of photon \( B \). Finally we monitor four-fold coincidences with a time to amplitude converter (TAC), where the start is given by a successful Bell state measurement (detectors \( C_1 \) and \( C_2 + \) laser pulse) and the stop by detector \( B \). The start plays the role of the classical information that Charlie sends to Bob. We choose to record only the events when
the photon in output $C_2$ arrives with a time difference $\Delta \tau$ after the photon in output $C_1$. We also record the coincidence between detectors $C_1$ and $B$. The rate should remain constant, as it contains no information about the Bell state measurement result. This provides a control of the stability of the entire set-up.

IV. RESULTS

In order to show that our teleportation set-up is universal we report the teleportation of two different classes of states. The first one is composed of superpositions of two time-bins, hence corresponds to states represented by points on the equator of the Poincaré sphere (see Fig.4). The second class consists of the two time-bins themselves, represented by the north and south poles of the sphere. The quality of the teleportation is usually reported in terms of fidelity $F$, i.e. the probability that Bob’s qubit successfully passes an analyzer testing that it is indeed in the state $\Psi_{Alice}$ prepared by Alice, averaged over all possible $\Psi_{Alice}$:

$$F = \int \langle \Psi_{Alice} | \rho_{out} | \Psi_{Alice} \rangle d\psi_{Alice}$$

(6)

The linearity of quantum mechanics implies

$$F = \frac{2}{3} F_{equator} + \frac{1}{3} F_{poles}$$

(7)

where $F_{equator}$ and $F_{poles}$ are the averaged fidelities for the equatorial and pole states, respectively. To measure the teleportation fidelity $F_{equator}$ of the equatorial states we scanned the phase $\beta$ in Bob’s interferometer (with both discrete variable couplers at setting 50%). This results in the normalized coincidence count rate:

$$R_C = \frac{1 - V \cos(\alpha + \beta)}{2}$$

(8)

corresponding to Bob’s state $\rho_{out} = V |\Psi_{Alice}\rangle \langle \Psi_{Alice}| + (1 - V)\frac{1}{2}$, where $V$ is the visibility which can theoretically reach the value of 1. Accordingly, the fidelity equals 1 with probability $V$ and equals $\frac{1}{2}$ with probability 1-$V$, hence $F_{equator} = \frac{1+V}{2}$. Figure 4a shows a nice result leading to a fidelity of $(85 \pm 2.5)\%$. By performing repeated many experiments over a few weeks with different phases $\alpha$ we typically obtained fidelities around $(80.5 \pm 2.5)\%$.

The preparation of the two other states, represented by the north and south poles, corresponds to the variable coupler at settings 0% and 100%, respectively. That was realized by using two different fibres of appropriate lengths. For the measurement, Bob uses only one fibre and looks for detections at appropriate times. As reported in Eq.3 when Alice sends such a state, Bob receives the orthogonal state, i.e. he should bit flip his qubit to recover Alice’s state. The corresponding fidelity is the probability of detecting the right state when measuring in the north-south basis, $F_{poles} = \frac{R_{correct}}{R_{wrong} + R_{correct}}$, see Fig.4b. The measured fidelity for the $|1,0\rangle$ input state is $(77 \pm 3)\%$ and for the $|0, 1\rangle$ input state $(88 \pm 3)\%$. Accordingly, the mean value is $F_{poles} = (82.5 \pm 3)\%$. The different results for the two input states is due to the fact

![Graph](image-url)
that in our experimental set-up the detection of the first photon, in mode $C_1$, triggers the two other detectors $C_2$ and $B$. When we prepare the state $|1,0\rangle$ the first detection is mostly due to Alice’s photon since, as explained above, we produce 8 times more qubits to be teleported than entangled pairs. Hence, the two detectors $C_2$ and $B$ are often triggered without any photon present, leading to an increasing number of accidental coincidences, i.e. wrong events. When preparing the other state $|0,1\rangle$ the first detection in mode $C_1$ can only be due to a photon coming from the EPR source or to a dark count. Since these events occur much less frequently than in the first mentioned case, the corresponding teleportation fidelity is less affected by accidental coincidences.

From these results, we conclude that the overall mean fidelity is $\bar{F} = (81.2 \pm 2.5)\%$ (Eq.7). This value is six standard deviations above the maximum fidelity of 66.7% achievable with the best protocol using no entanglement. Note that the above reported result takes into account noise produced by Bob’s analyzer. Strictly speaking, this noise should not be attributed to the teleportation scheme. Hence, the achieved teleportation fidelity is actually higher, about $\frac{4}{5}0.86 + \frac{1}{5}0.83 = 0.85$. However, for practical applications, the significant value is $\bar{F}$.

The difference between the experimental results and the ideal theoretical case can be due to various imperfections: (i) Our Bell state measurement is not perfect; although we tried to detect only the events when there is only one photon in each mode, there is still 11% of chances that we make a spurious coincidence. This value can be found in the noise of the teleportation of the $|0,1\rangle$ input state, which is essentially due to the creation of double entangled pairs. Further reduction of the fidelity might be due to different polarization or spectra of the two photons when arriving at the beam splitter or to remaining temporal distinguishability. (ii) The creation and analysis of the qubits is not perfect, e.g. the two qubits entanglement leads to a fringe visibility limited to 95% [27]. (iii) Detector dark counts also reduce the measured fidelity. Finally, note that the fact that a) the teleportation occurs only when there is a projection onto the state $|\Psi^-\rangle$ and that b) only one eighth of the qubits sent by Alice are teleported renders our realization probabilistic, even assuming perfect detectors. This is a drawback from a fundamental point of view. However, if quantum teleportation is used as quantum relay (see next chapter and fig.5) in quantum cryptography, then the probabilistic nature of our teleportation scheme will only affect the count rate but not the quality of the quantum relay. For this application our scheme is useful.

V. QUANTUM RELAYs

Presently, the only potential application of quantum teleportation is as quantum repeaters for quantum cryptography [28]. Actually, a fully developed quantum repeater would also require quantum memories [29], but we shall see that quantum teleportation without quantum memory (so called quantum relay) can already extend the range of quantum cryptography from tens of km to hundreds, though not to unlimited ranges. The basic idea is as follows [28, 31, 33]. In quantum cryptography, the noise is dominated by the detector dark counts; hence the noise is almost independent of the distance. The signal, however, decreases exponentially with distance because of the attenuation. With realistic numbers, this sets a limit close to 80 km. But, if one could check at some points along the quantum channel whether or not the photon is still there, one could refrain from opening the detector when there is no photon. This simple idea is unpractical because it requires (presently unrealistic) photon number quantum non demolition measurements [30]. However, consider a channel divided into sections, e.g. 3 sections as shown in Fig.5. Assume that the photon sent by Alice down the first section is teleported to Bob using the EPR photon pair generated in-between sections 2 and 3. Two photons travel towards Bob, but one towards Alice. But, since the time ordering of the measurements is irrelevant [14], one may consider that the logical qubit propagates all the way from Alice to Bob. Accordingly, the Bell state measurement and the 2-photon source act on this logical qubit as a non demolition measurement!

VI. CONCLUSION

Quantum teleportation is a fascinating prediction of quantum mechanics which shakes basic concepts like object, information, space-time. We have reported the first long distance demonstration of this protocol. Using 2 km of standard telecom optical fibres, we teleported a qubit carried by a photon of 1.3 $\mu$m wavelength to a qubit in another lab carried by a photon of 1.5 $\mu$m wavelength. The photon to be teleported and the necessary entangled photon pairs were created in two different non-linear crystals. The measured mean fidelity of 81.2% is sufficient to demonstrate the basic principle. However, admittedly, work towards useful teleportation set-ups, e.g. as quantum relays as explained above, still requires a lot of effort and ideas, mainly to improve the stability of the experiment.
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