Quantum Teleportation with a Quantum Dot Single Photon Source

D. Fattal, E. Diamanti, K. Inoue,* and Y. Yamamoto*
Quantum Entanglement Project, ICORP, JST, Ginzton Laboratory, Stanford University, Stanford California 94305, USA
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We report the experimental demonstration of a quantum teleportation protocol with a semiconductor single photon source. Two qubits, a target and an ancilla, each defined by a single photon occupying two optical modes (dual-rail qubit), were generated independently by the single photon source. Upon measurement of two modes from different qubits and postselection, the state of the two remaining modes was found to reproduce the state of the target qubit. In particular, the coherence between the target qubit modes was transferred to the output modes to a large extent. The observed fidelity is 80%, in agreement with the residual distinguishability between consecutive photons from the source. An improved version of this teleportation scheme using more ancillas is the building block of the recent Knill, Laflamme, and Milburn proposal for efficient linear optics quantum computation.

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Photons are almost ideal carriers of quantum information, since they have little interaction with their environment, and are easy to manipulate individually with linear optics. The main challenge of optical quantum information processing is the design of controlled interactions between photons, necessary for the realization of nonlinear quantum gates. Photons do not naturally "feel" the presence of other photons, unless they propagate in a medium with high optical nonlinearity. The amount of optical nonlinearity required to perform controlled operations between single photons is, however, prohibitively large.

Probabilistic gates can be implemented with linear optics only [1–3], but as such, they are not suitable for scalable quantum computation. In a seminal paper [4], Gottesman and Chuang suggested that quantum gates could be applied to photonic qubits through a generalization of quantum teleportation [5]. In such a scheme, the information about the gate is contained in the state of ancilla qubits. The implementation of a certain class of gates can then be reduced to the problem of preparing the ancilla qubits in some wisely chosen entangled state. Such a problem can be solved "off-line" with linear optics elements only, provided the photons used are quantum mechanically indistinguishable particles [6]. Following this idea, Knill, Laflamme, and Milburn (KLM) [1] proposed a scheme for efficient linear optics quantum computation (LOQC) based on the implementation of the controlled-sign gate (C-z gate) through teleportation. Since the C-z gate acts effectively on only one of the two modes composing the target qubit, a simplified procedure can be used where a single optical mode is teleported, instead of the two modes composing the qubit. This procedure will be referred to as *single mode teleportation* to distinguish it from the usual teleportation scheme. In its basic version using one ancilla qubit, it succeeds half of the time. In its improved version using an arbitrarily high number of ancillas, it can succeed with a probability arbitrarily close to 1 [1,7].

In this Letter, we report an experimental demonstration of the basic version of the single mode teleportation. We use quantum mechanically indistinguishable photons from a quantum dot single photon source [8], featuring high suppression of two-photon pulses. The fidelity of the teleportation depends critically on the quantum indistinguishability of two photons emitted independently by the single photon source, a feature that was experimentally verified in [9]. A similar experiment was done in the past using two photons emitted spontaneously by parametric down conversion (PDC) [10]. However, the efficiency of such a process is intrinsically limited by the presence of two photon pulses, which makes it unsuitable when more identical photons are needed, e.g., to implement the improved teleportation scheme. To date, the demonstration of the single mode teleportation with a single photon source remained a capital step to be achieved towards scalable LOQC.

The single mode teleportation in its simplest form involves two qubits, a target and an ancilla, each defined by a single photon occupying two optical modes (Fig. 1). The target qubit can *a priori* be in an arbitrary state

$$|\psi_t\rangle = \alpha|0\rangle_L + \beta|1\rangle_L,$$

where the logical $|0\rangle_L$ and $|1\rangle_L$ states correspond to the physical states $|1\rangle_1|0\rangle_2$ and $|0\rangle_1|1\rangle_2$, respectively, in a dual-rail representation. The ancilla qubit is prepared with a beam splitter (BS a) in the coherent superposition

$$|\psi_a\rangle = \frac{1}{\sqrt{2}}(|0\rangle_L + |1\rangle_L) = \frac{1}{\sqrt{2}}(|1\rangle_3|0\rangle_4 + |0\rangle_3|1\rangle_4).$$

One rail of the target is mixed with one rail of the ancilla with a beam splitter (BS 1), for subsequent detection in photon counters C and D. The state after mixing can be

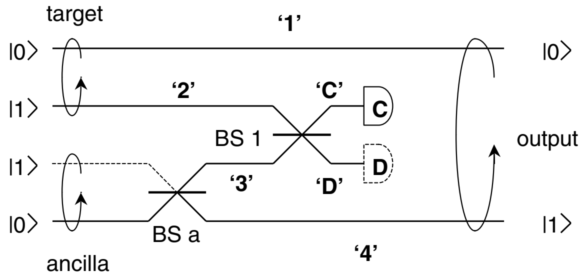

FIG. 1. Schematic of single mode teleportation. Target and ancilla qubits are each defined by a single photon occupying two optical modes (1-2 and 3-4). When detector C records a single photon, the state in modes 1-4 reproduces the initial state of the target. In particular, the coherence between modes 1-2 of the target can be transferred to a coherence between modes 1-4.

written in terms of modes C, D, 1, and 4 as

$$|\psi_t\rangle_{12}|\psi_a\rangle_{34} = \frac{1}{2}|10\rangle_{\rm CD}|\psi_t\rangle_{14} + \frac{1}{2}|01\rangle_{\rm CD}(Z|\psi_t\rangle_{14}) + \frac{\alpha}{\sqrt{2}}|00\rangle_{\rm CD}|11\rangle_{14} + \frac{\beta}{2}(|02\rangle + |20\rangle)_{\rm CD}|00\rangle_{14}.$$

For a given realization of the procedure, if only one photon is detected at detector C, then the state of the output qubit (modes 1 and 4) is $|\psi_t\rangle$, so the teleportation was successful. Similarly, if only one photon is detected at detector D, then the output state is $Z|\psi_t\rangle$, so in this case we have to apply the Pauli operator Z (phase shift of π) to the output modes to retrieve the initial state $|\psi_t\rangle$ [11]. We did not implement this active feedforward here, to simplify the experiment. For this reason, our teleportation procedure succeeds with probability $\frac{1}{4}$ (as compared to $\frac{1}{2}$ had we used feedforward).

It is interesting and somewhat enlightening to describe the same procedure in the framework of *single rail logic*. In this framework, each optical mode supports a whole qubit, encoded in the presence or absence of a photon, and the single mode teleportation can be viewed as entanglement swapping. Indeed, for the particular values $\alpha = \beta = (1/\sqrt{2})$ modes 1 and 2 find themselves initially in the Bell state $|\psi^+\rangle_{12}$, while modes 3 and 4 are in a similar state $|\psi^+\rangle_{34}$. A partial Bell measurement takes place using BS 1 and counters C/D, which if it succeeds leaves the system in the entangled state $|\psi^+\rangle_{14}$, so that entanglement swapping occurs. In the rest of the Letter, we choose to consider the scheme in the dual-rail picture, since it is a more robust, hence realistic way of storing quantum information (at the expense of using two modes per qubit).

The success of the teleportation depends mostly on the transfer of coherence between the pair of modes 1-2 and 1-4. If the target qubit is initially in state $|0\rangle_L = |1\rangle_1|0\rangle_2$, then the ancilla photon cannot end up in mode 4 because of the postselection condition, so that the output state is always $|1\rangle_1|0\rangle_4$ as wanted. The same argument applies when the target qubit is in state $|1\rangle_L$. Hence the success of the teleportation is granted when the target qubit is not in a superposition state. However, when the target qubit is in a coherent superposition of $|0\rangle_L$ and $|1\rangle_L$, the output state might not retrieve the full initial coherence. A good way to test the coherence transfer is by changing the optical path length Δ on mode 1. If the teleportation procedure does not randomize the phase between mode 1 and mode 4, then changing Δ in a controlled manner changes the well-defined phase between modes 1-4, which can be observed by interfering modes 1 and 4 in an auxiliary setup. If, however, the teleportation randomizes the phase between modes 1-4, then changing the path length Δ will not have any effect on the interferometric signal.

The experimental setup is shown in Fig. 2. Two photons emitted consecutively by the single quantum dot photon source [8,9] are captured in a single mode fiber. In the dual-rail representation, we refer to the first photon as the ancilla, and to the second photon as the target (see Fig. 1). The ancilla qubit, initially in state $|0\rangle_L$, is delayed in free space to match the target qubit temporally at BS 1. The delay must be adjusted to within a fraction of the photons temporal width (~200 ps or 6 cm in space). Note that the

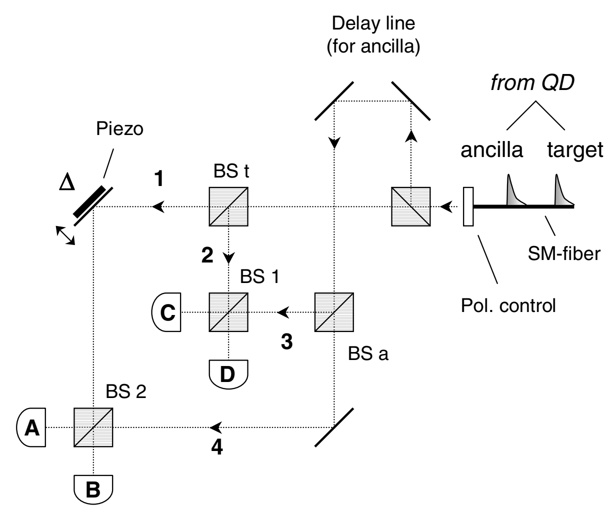

FIG. 2. Experimental setup. All the beam splitters (BS) shown are 50-50 nonpolarizing BS. The teleportation procedure works when the ancilla photon is delayed, but the target is not. After preparation, the target photon occupies modes 1 and 2, and the ancilla occupies modes 3 and 4. Modes 2 and 3 are mixed at BS 1 and subsequently measured by detectors C and D, this step being the heart of the teleportation. When C records a single photon, another single photon occupies modes 1-4 (output qubit). The phase coherence between modes 1-4 in the output state is measured by mixing those modes at BS 2 and recording single counts at detector A or B. Note that since an event is recorded only if A *and* C or B *and* C clicked, more than one photon could not have reached detector C.

mode matching is significantly easier here than in similar experiments using photons from PDC, where the optical path length have to be adjusted with a tolerance of only a few μm [10].

The ancilla is prepared in the superposition state $\psi_{anc} = (1/\sqrt{2})(|0\rangle_L + |1\rangle_L)$ with a beam splitter "BS a." The target qubit is prepared in a similar maximum superposition state (with "BS t"). The path length Δ of mode 1 is changed in a controlled manner with a piezoactuated mirror. The "partial Bell measurement" responsible for the teleportation is done at BS 1 by mixing the optical modes 2 of the target qubit and (3) of the ancilla qubit, with subsequent detection in counter C. A Mach-Zehnder type setup is used to measure the coherence between the two modes 1 and 4 of the output qubit. It is composed of a 50-50 beam splitter BS 2 mixing modes 1 and 4, with subsequent detection in counters A and/or B. The phase coherence of the teleportation is proven if modulating the path length on mode 1 results in the modulation of the count rate in detector A and B (conditioned on a click at detector C). Moreover, the degree of phase coherence between modes 1-4 can be quantified by the contrast (or visibility) of the count rate modulation.

Coincidences between counters A-C and B-C were simultaneously recorded, by using a start-stop configuration (each electronic "start" pulse generated by counter C was doubled for this purpose). This detection method naturally postselects events where one photon went through BS 1, and the other went through BS 2, as required by the teleportation scheme. Since no more than one photon is emitted by the single photon source, no more than one photon can reach detector C if detector A or B is to click. Typical correlation histograms are shown in Fig. 3. The integration time was 2 min, short enough to keep the relative optical path length between different arms 1-4 of the interferometer stable. The whole setup was made compact for that purpose, and stability over time periods as long as 10 min was observed. A second postselection was made, depending on the timing between target and ancilla photons, which is adequate only one time out of four - the ancilla taking the long path and the target the short path. The resulting coincidence counts were recorded for different path length Δ of mode 1. The result of the experiment is shown in Fig. 4. The number of counts recorded in the postselected window (-1 ns $< \tau <$ 1 ns) was normalized by the total number of counts recorded in detectors A and B in the broader window -5 ns $< \tau <$ 5 ns, corresponding to all events where one photon went through BS 1 and the other through BS 2 (but only one quarter of the time with right timing). Complementary oscillations are clearly observed at counter A and at counter B, indicating that the initial coherence was indeed transferred to the output qubit. In other words, mode 2 of the target qubit was "replaced" by mode 4 of the ancilla without a major loss of coherence.

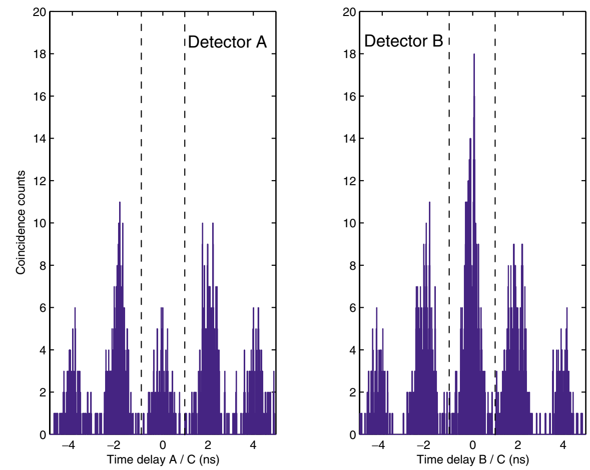

FIG. 3 (color online). Typical correlation histograms taken simultaneously between detectors A/C and B/C. The central region indicated by the dashed lines corresponds to the postselected events, when target and ancilla photons had such a timing that it is impossible to distinguish between them based on the time of detection. As the path length Δ varies, so does the relative size of the central peaks for detectors A and B. The sum of count rates for the central peaks of detector A and B was 800/s, independently of ϕ as shown in Fig. 4.

If the initial coherence was fully conserved during the single mode transfer, the count rate at detector A (respectively B) would be proportional to $\cos^2(\pi\Delta/\lambda)$ [respectively $\sin^2(\pi\Delta/\lambda)$, λ being the single photon wavelength], giving a perfect contrast as the path length Δ is varied. More realistically, part of the coherence can be lost in the

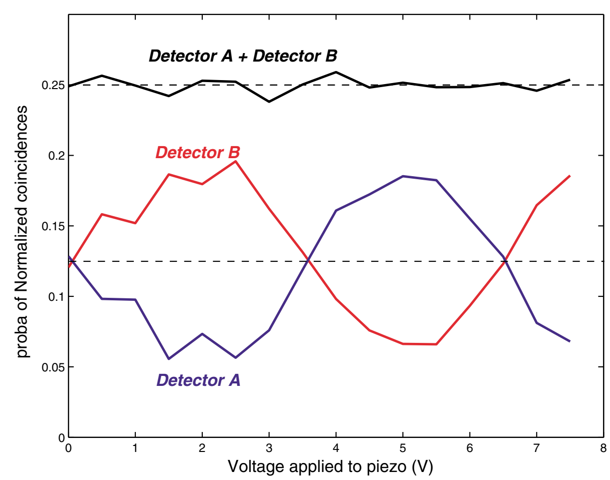

FIG. 4 (color online). Verification of single mode teleportation. Coincidence counts between detector A/C and B/C are plotted for different voltages applied to the piezo transducer, i.e., for different path length Δ of mode 1. The observed modulation of the counts implies that the initial coherence contained in the target qubit was transferred to a large extent to the output qubit. The reduced contrast (~60%) is principally due to imperfect indistinguishability between the target and ancilla photons.

transfer, resulting in a degradation of the contrast. Such a degradation is visible on Fig. 4. It arises mainly due to a residual distinguishability between ancilla and target photons. Slight misalignments and imperfections in the optics also result in an imperfect mode matching at BS 1 and BS 2, reducing the contrast further. Finally, the residual presence of two-photon among pulses can reduce the contrast even more, although this effect is negligible here. The overlap $V = |\langle\psi_t|\psi_{\rm anc}\rangle|^2$ between target and ancilla wave packet [9], the two-photon pulses suppression factor $g^{(2)}$ [8], as well as the nonideal mode matching at BS 1 and BS 2 — characterized by the first-order interference visibilities V_1, V_2—were all measured independently. The results are $V \sim 0.75$ (measured with the setup described in [9]), $g^{(2)}(0) \sim 2\%$, $V_1 \sim 0.92$, and $V_2 \sim 0.91$. The contrast C in counts at detector A or B when we vary the phase ϕ should be

$$C = \frac{VV_1V_2}{1 + g^{(2)}/2} \sim 0.62.$$

This predicted value compares well with the experimental value of $C_{\rm exp} \sim 0.60$.

The fidelity of teleportation is $F = [(1 + C)/2] \sim 0.8$. This high value is still not enough to meet the requirements of efficient LOQC [1]. In particular, the quantum indistinguishability of the photons must be increased further to meet these requirements. In our single photon source, a dephasing mechanism acting on a time scale of a few nanoseconds [12] is responsible for the loss of indistinguishability. Using the Purcell effect [13], one can reduce the quantum dot radiative lifetime well below this dephasing time. However, jitter in the photon emission time will eventually prevent any further reduction of the quantum dot lifetime. Time jitter happens as a consequence of the incoherent character of our method to excite the quantum dot [8]. It is currently of order 10 ps. Time jitter can be completely suppressed using a coherent excitation technique (see, e.g., [14] for such a scheme with single atoms). It therefore seems important to develop similar techniques with single quantum dots.

Using more ancillas in a scheme first proposed in [1] and significantly improved in [7], the single mode teleportation can be made nearly deterministic. This would allow the replacement of deterministic nonlinear gates necessary for scalable quantum computation with probabilistic ones, recently demonstrated experimentally with linear optics [3]. This generalized teleportation procedure requires more indistinguishable ancilla photons, produced no more than one at a time, a feature absent in [10] but present in our implementation of the teleportation. We also point out that the generalized scheme requires the discrimination of different photon numbers. Progress in this direction was reported in [15], in which photon numbers up to six could be discriminated. This would in principle allow the implementation of a linear optics C-z gate with a success probability of $(\frac{6}{7})^2 \sim 0.73$ [7].

In conclusion, we have demonstrated the basic version of the single mode teleportation procedure described in the KLM scheme with independent single photons and linear optics. LOQC has emerged in recent years as an appealing alternative to previous quantum computation schemes, and to date there had been no experimental proof of principle except for those based on parametric down conversion, a technique that sets limits to the scalability of the system. Our experiment suggests that it is possible to build an efficient QIP unit using single photon sources and linear optics, provided the photons generated are indistinguishable.

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*Also with: NTT Basic Research Laboratories, Atsugishi, Kanagawa, Japan.

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