Quantum teleportation with a quantum dot single photon source

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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%, a figure which can be explained quantitatively by 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 KLM proposal for efficient linear-optics quantum computation.

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 non-linear quantum gates. Photons do not naturally "feel" the presence of other photons, unless they propagate in a medium with high optical non-linearity. The amount of optical non-linearity required to perform controlled operations between single photons is however prohibitively large.

Probabilistic gates can be implemented with linear-optics only [1, 2, 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 [3]. 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 [5]. Following this idea, Knill, Laflamme and Milburn (KLM) [6] 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 (i.e. two ancilla modes), this procedure 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 one [6, 7].

In this paper, 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 (see fig. 1). The target qubit can a priori be in an arbitrary state $|0\rangle_L + \beta |1\rangle_L$ where the logical $|0\rangle_L$ and $|1\rangle_L$ states correspond to the physical states $|0\rangle_2 |0\rangle_2$ and $|0\rangle_3 |1\rangle_2$ respectively in a dual rail representation. The ancilla qubit is prepared with a beam-splitter (BS a) in the coherent superposition $\frac{1}{\sqrt{2}}(|0\rangle_L + |1\rangle_L) = \frac{1}{\sqrt{2}}(|1\rangle_3 |0\rangle_4 + |0\rangle_3 |1\rangle_4)$. One rail of the target (mode 2) is mixed with one rail of the ancilla (mode 3) with a beam-splitter (BS b), for subsequent detection in photon counters C and D. For a given realization of the procedure, if only one photon is detected at detector C, and none at detector D, then we can infer the resulting state for the output qubit - composed of mode (1) and (4) :

$$\psi_C = \alpha |0\rangle_L + \beta |1\rangle_L = \alpha |1\rangle_1 |0\rangle_4 + \beta |0\rangle_1 |1\rangle_4$$

which is the initial target qubit state. Similarly, if D
clicks and C does not, then the output state is inferred to be:

\[ \psi_D = \alpha |0\>_L - \beta |1\>_L = \alpha |1\>_1 |0\>_4 - \beta |0\>_1 |1\>_4 \]

which again is the target state up to an additional phase shift of \(\pi\), which can be actively corrected for \[1]\]. We did not implement this active feedforward here. Half of the time, either zero or two photons are present at counters C or D, and the teleportation procedure fails. 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 \(\alpha = \beta = \frac{1}{\sqrt{2}}\) 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 paper, 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 mainly on the transfer of coherence between the two modes of the target qubit. If the target qubit is initially in state \(|0\>_L = |1\>_1 |0\>_2\), then the ancilla photon cannot end up in mode \(4\) because of the postselection condition, so that the output state is always \(|1\>_1 |0\>_4\) as wanted. The same argument applies when the target qubit is in state \(|1\>_L\). However, when the target qubit is in a coherent superposition of \(|0\>_L\) and \(|1\>_L\), the output state might not retrieve the full initial coherence. We can test the transfer of coherence by preparing the target in a maximal superposition state:

\[ \psi_{\text{tar}} = \frac{1}{\sqrt{2}} \left( |0\>_L + e^{i\phi} |1\>_L \right) \]

where \(\phi\) is a phase that we can vary. If the initial coherence of the target qubit is not transferred to the output qubit, a change in \(\phi\) will not induce any measurable change in the output qubit. However, if changing \(\phi\) induces some measurable change in the output qubit, then we can prove that the initial coherence was indeed transferred, at least to some extent.

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 \(|0\>_L\), 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 (\(\sim 200\) ps or 6 cm in space). Note that the 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 microns [10].

The ancilla is prepared in the superposition state

\[
\psi_{\text{anc}} = \frac{1}{\sqrt{2}} (|0\rangle_L + |1\rangle_L)
\]

with a beam-splitter 'BS a'. The target qubit is prepared in a similar superposition state, with in addition a variable phase between the two modes, so that

\[
\psi_{\text{tar}} = \frac{1}{\sqrt{2}} (|0\rangle_L + e^{i\phi} |1\rangle_L).
\]

The phase shift is applied by changing the path length on mode (1) with a piezo-actuated 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. Modulating the phase \(\phi\) of the target qubit should result in the modulation of the count rate in detector A and B (conditioned on a click at detector C), with a contrast related to the degree of coherence between the output modes (1) and (4).

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 post-selects 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 photon can reach detector D. 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 post-selection 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 phases \(\phi\) of the target qubit. The result of the experiment is shown in fig 3. The number of counts recorded in the post-selected 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.

If the initial coherence was fully conserved during the single mode transfer, the state of the output qubit would truly be \(\alpha |0\rangle_L + \beta e^{i\phi} |1\rangle_L\), and the single count rate at detector A (resp. B) would be proportional to \(\cos^2(\frac{\phi}{2})\) (resp. \(\sin^2(\frac{\phi}{2})\)), giving a perfect contrast as the target phase \(\phi\) is varied. More realistically, part of the coherence can be lost in the transfer, resulting in a degradation of the contrast. Such a degradation is visible on fig 3. 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 \(V = \int |\psi_{\text{tar}}\rangle |\psi_{\text{anc}}\rangle\) between target and ancilla wave-packets [3], the two-photon pulses suppression factor \(g^{(2)}\) [3], as well as the non-ideal 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 [3]), \(g^{(2)}(0) \sim 2\%\), \(V_1 \sim 0.92\) and \(V_2 \sim 0.91\). The contrast \(C\) in counts at detector A or B when we vary the phase \(\phi\) should be:

\[
C = \frac{V \cdot V_1 \cdot V_2}{1 + g^{(2)} / 2} \sim 0.62
\]

This predicted value compares well with the experimental

![FIG. 3: typical correlation histograms taken simultaneously between detectors A/C and B/C. The central region indicated by the dashed lines correspond 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 phase \(\phi\) varies, so does the relative size of the central peaks for detector A and B. The sum of count rates for the central peaks of detector A and B was 800 /s, independently of \(\phi\) as shown in fig 3.](image-url)
value of \( C_{\text{exp}} \sim 0.60 \).

The fidelity of teleportation is \( F = \frac{1+C}{2} \sim 0.8 \). 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, current 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 such techniques on single quantum dots.

Using more ancillas in a scheme first proposed in \[1\] and significantly improved in \[2\], the single mode teleportation can be made nearly deterministic. This would allow the replacement of deterministic non-linear 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 were 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 \( \left( \frac{2}{3} \right)^2 \sim 0.73 \) \[7\].

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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