Quantum teleportation on a photonic chip

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Quantum teleportation is a fundamental concept in quantum physics1 that now finds important applications at the heart of quantum technology, including quantum relays2, quantum repeaters3 and linear optics quantum computing4,5. Photonic implementations have largely focused on achieving long-distance teleportation for decoherence-free quantum communication4-6. Teleportation also plays a vital role in photonic quantum computing4,5, for which large linear optical networks will probably require an integrated architecture. Here, we report a fully integrated implementation of quantum teleportation in which all key parts of the circuit—entangled state preparation, Bell-state analysis and tomographic state measurement—are performed on a reconfigurable photonic chip. We also show that a novel element-wise characterization method is critical to the mitigation of component errors, a key technique that will become increasingly important as integrated circuits reach the higher complexities necessary for quantum enhanced operation.

Quantum teleportation is essential to many schemes for universal fault-tolerant quantum computation, making it an important protocol for any physical implementation of a quantum information processor5,10. In their seminal work, Knill, Laflamme and Milburn showed that such a quantum processor could be constructed using only linear optical elements, at the expense of rendering each quantum logic gate probabilistic4. Adapting the teleportation scheme of Gottesman and Chuang2, they then showed that this protocol could be efficiently scaled to a large number of concatenated gates, motivating a renewed interest in building more complex linear optical circuits for quantum information processing10. Realizing such a scheme requires building large, sophisticated networks of nested optical interferometers. This motivates the use of waveguides integrated onto compact and inherently stable photonic waveguide architectures, as well as a careful element-wise characterization of the fabricated device are key to successful operation.

In this Letter, we demonstrate teleportation of a photonic qubit on an integrated waveguide device. We use a reconfigurable photonic chip to perform the teleportation protocol with state encoding, entanglement preparation, Bell-state analysis and state tomography, all carried out on chip. We develop a theoretical model to account for all sources of possible error in the circuit and find good agreement with the measured teleported state fidelities, which exceed the average teleportation fidelity possible with a classical device. We identify the elements of this error budget relevant to scaling and find that improvements to chip characterization and fabrication will be required to achieve high-fidelity operation. The combination of high-heralding-efficiency single-photon sources, a low-loss silica waveguide architecture, as well as a careful element-wise characterization of the fabricated device are key to successful operation.

The quantum teleportation circuit, shown in Fig. 1a, aims to transfer the quantum state of an input qubit Q1 to the target qubit Q3. The protocol begins by generating a maximally entangled photonic resource, a Bell state, encoded on qubits Q2 and Q3. A two-qubit Bell state measurement (BSM) is then performed on input Q1 and one half of the entangled state (Q2). This measurement projects the target qubit Q3 onto the original input state via a final feed-forward operation. The combination of high-heralding-efficiency single-photon sources, a low-loss silica waveguide architecture, as well as a careful element-wise characterization of the fabricated device are key to successful operation.

In the present experiment, although the final feed-forward rotation could in principle be implemented using the on-chip phase shifters φ2 and θ2, in reality these shifters do not have sufficiently rapid response to make this feasible. Instead, we use these phase shifters to perform quantum state tomography (QST) of the teleported qubit Q3 and replace the final physical rotation by an entirely equivalent numerical rotation in post-processing. Directly implementing feed-forward in standard integrated optics chips is a major open challenge requiring ultrafast on-chip photon detection, classical electronics, feed-forward and phase modulation, all operating at terahertz bandwidths. Recently, progress towards integrated high-speed photon detectors22, fast phase control based on...
strain-optic\textsuperscript{23} and electro-optic\textsuperscript{24} effects, and efficient on-chip delays\textsuperscript{25} has been demonstrated.

The waveguide circuit encodes three qubits using a dual-rail scheme, as shown in Fig. 1c. In this scheme, a single photon in the top rail represents the logical state $|0\rangle = \hat{a}^\dagger |\text{vac}\rangle = |10\rangle_{x,y}$ whereas one photon in the lower mode represents the logical state $|1\rangle = \hat{b}^\dagger |\text{vac}\rangle = |01\rangle_{x,y}$. Deterministic single-qubit operations are realized using linear beamsplitters\textsuperscript{26} and thermo-optic phase shifters\textsuperscript{27} and allow us to implement reconfigurable single qubit unitary rotations, $\hat{U}(\theta, \phi) = e^{-i\phi \sigma_y/2} e^{-i\theta \sigma_z/2}$ (see Methods).

The concatenated C-PHASE gates in the circuit are implemented using the probabilistic scheme proposed by Ralph\textsuperscript{27}. In this scheme, effective two-photon interactions are induced via post-selection of one photon being detected in each of the three qubit modes. This occurs with probability 1/27, which sets the overall success probability of the circuit.

We now describe the main experiment showing on-chip quantum teleportation. Three single photons generated by two parametric downconversion sources are coupled into the ultraviolet (UV)-written, silica-on-silicon photonic chip (see Supplementary Sections I and V, Fig. 4). An array of six avalanche photodiodes (APDs) monitor all output modes. We identify successful teleportation events as runs in which one photon is detected for each of the three qubits, as well as in an ancillary heralding arm. Fourfold detection coincidences are registered using a field-programmable gate array (FPGA). Data are collected for three linearly independent input states, $|\psi_i\rangle = \hat{U}_i |\psi_{in}\rangle$, coded on Q1 by appropriately setting $\theta_1$ and $\phi_1$. For each input state, $\theta_3$ and $\phi_3$ are adjusted to perform projective measurements of Q3 in three different bases, allowing us to reconstruct the teleported state via maximum-likelihood tomography.

Each input state is teleported to one of four possible output states depending on the outcome of the BSM: $|\psi_{out}\rangle = \hat{U}_i |\psi_{in}\rangle$, where the rotation $\hat{U}_i$ is uniquely determined by the BSM outcome. For an ideal circuit, $\hat{U}_i$ corresponds to an element of $\{\hat{\sigma}_x, i\hat{\sigma}_y, \hat{\sigma}_z\}$. A realistic circuit deviates from the ideal case due to fabrication imperfections. In general, the rotations that optimize the teleportation fidelity must be found by characterizing the actual device. To do so, we use a numerical model to simulate the teleported output state at the point immediately prior to the QST stage on Q3. The simulation uses ideal indistinguishable Fock-state inputs and critically relies on being able to perform an element-wise characterization of our circuit in order to remove the effects of the on-chip state encoding and tomography stages from this analysis (see Methods). We then numerically find the unitary rotations, $\hat{U}_i$, which maximize the average output state fidelity over 10,000 randomly chosen input states. We note that the resulting rotations are found independently of the primary experimental data and depend only on the classical circuit characterization. To verify successful teleportation, we numerically apply these predetermined rotations to the reconstructed state of Q3, $\hat{\rho}_{\text{out}}$, and calculate the fidelity to the input states, $F = \langle \psi_i | \hat{U}_i^\dagger \hat{\rho}_{\text{out}} \hat{U}_i^\dagger |\psi_i\rangle$. Although it is not possible to achieve high-efficiency teleportation without fast feed-forward, using this post-selective approach allows us to easily confirm the success of our experiment for each classical BSM outcome.

The teleportation results for the BSM outcome $|\psi'\rangle$ are summarized in Fig. 2. The experiment was performed using three linearly independent input states close to the three orthogonal axes of the Bloch sphere (see Supplementary Section III). We label them $|V\rangle$, $|D\rangle$ and $|L\rangle$, according to the closest lying axis state (Fig. 2a–c). Fourfold coincidences were registered in a specific BSM outcome at $\sim 5 \text{ mHz}$ and around 100 coincidence counts were collected for each measurement setting and BSM outcome. The initial input states are recovered with an average fidelity of 89 $\pm$ 3%, which exceeds the classical limit of 2/3 by more than six standard deviations$^{21}$. Because any state on the Bloch sphere is a linear combination of these three states, the results are sufficient to conclude that this chip is capable of teleporting general quantum states with high fidelity. The results from all four BSM outcomes are
The initial qubit states on Q1 for each of three trials are depicted on the Bloch sphere (top) and as real and imaginary parts of a density matrix (black wire frames, middle and bottom, respectively). The final teleported states on Q3 are reconstructed using on-chip quantum state tomography and then transformed by optimal state-independent rotations in post-processing (coloured bars). The fidelity $F$ between the initial and final state is calculated (bottom). Representative data here are for experiments with a $|\Psi^+\rangle$ Bell state measurement outcome. Similar reconstructed states for all four Bell state measurement outcomes are found in Supplementary Figs 1 and 2.

The sources responsible for the reduction in fidelity were investigated using a full theoretical model taking into account the experimentally characterized beamsplitter ratios and interferometer phases, higher-order photon emission, photon distinguishability and propagation losses (see Supplementary Section VIII). This model was used to calculate the expected click statistics on Q3 for given BSM outcomes and phase-shifter settings. These simulated clicks were substituted into our data analysis routine, including the appropriate unitary rotation, to predict the expected teleportation fidelity for different input states. This analysis reveals that the imperfect beamsplitting ratios decrease the degree of entanglement in the circuit, causing a reduction in the achievable fidelity to ~90% that depends on the input state (see Supplementary Section VII). Non-ideal aspects of the photon source cause the remaining error. The predicted teleportation fidelities averaged over all input states are summarized in Fig. 3 as shaded blue boxes.

This error analysis highlights three key impediments to future scaling: photon sources, imperfect photonic chips and loss. Although the success of this experiment relies on our development of a high-quality single photon source, the absence of a true, high-purity, single-photon source continues to limit the achievable fidelity. This ubiquitous problem in quantum optics experiments is being addressed by the recent development of low-loss waveguided sources. Also, moving to larger on-chip experiments will place stringent demands on photonic circuit performance. Fabricated beamsplitters and phase shifters will inevitably show some deviation from their designed parameters. Recent progress demonstrating...
tighter control of fabricated optical components is promising. However, as more components are integrated onto circuits, robust characterization methods together with active circuit control will be required to identify, and then correct, remaining deviations from design.

In conclusion, we present the on-chip implementation of a three-qubit quantum circuit, successfully teleporting three linearly independent quantum states. We have modelled sources of error and their effect on the teleportation fidelity. This work shows that continuing advances in waveguide and photonic source technology will be critical in addressing the challenges in achieving larger-scale linear-optical quantum computing—cooping with the increased loss and identifying and correcting component errors.

Methods

Device fabrication. The waveguide circuit used in this work was fabricated by the direct UV-writing technique utilizing silica slab waveguides deposited on a silicon substrate. The individual waveguides were written by focusing a continuous-wave UV laser (wavelength, 244 nm) onto the germanium-doped silica photosensitive waveguide core and translating the laser beam transversely to the surface normal with computer-controlled two-dimensional motion. Waveguides (typically 4.5 μm × 4.5 μm) were formed as a result of UV-induced permanent refractive index change inside the photosensitive waveguide core layer. The UV-writing process is the creation of optical networks using commercial X-couplers, the splitting ratio of which can be selected by adjusting the waveguide crossing angle during the UV-writing process. Compact X-couplers have a number of advantages over more traditional directional couplers, that is, compact footprint, low guidance loss and more stable coupling ratio.

The thermo-optic phase shifters utilize a small NiCr electrode (0.35 μm × 50 μm × 2.5 mm, electrical resistance = 0.85 kΩ) deposited directly over one of the waveguides through which a current can be passed. The passive stability of the interferometers with the phase shifters set to a constant voltage was measured to be less than 1° over 24 h and achieved a repeatability error of less than 3° when the voltage settings were changed.

Circuit characterization. The beamsplitter reflectivities and behaviour of the phase shifters were characterized to determine the unitary rotations and to correctly simulate the performance of the experiment. Recent proposals to characterize the behaviour of linear optical circuits have treated the devices as a ‘black box’, returning the overall transfer matrix of the network without reference to any information about the geometry of the underlying circuit. For experiments using a reprogrammable circuit, however, it is critical to be able to characterize the individual linear optical elements so that it is not necessary to perform a full characterization for every configuration of the circuit. A full loss-tolerant characterization of the twelve beamsplitters was performed making use of transversely scattered light from the waveguide.

The on-chip state preparation and tomography elements each consist of two thermo-optic phase shifters embedded in a Mach–Zehnder interferometer. The phase shifters are situated close enough to one another that residual heat from one can slightly affect the other by as much as 0.03%. The effect of this crosstalk must be characterized to accurately determine the behaviour of the circuit at different phase settings. Bright light was alternately coupled into the two input modes of Q1 while the power on the two output modes was monitored using photodiodes. The voltages applied to θ1 and θ2 were both varied to map out the two-dimensional response of the shifters on the effective phase change within their respective interferometers (see Supplementary Section VI and Fig. 7). A similar two-dimensional response was measured for the two phase shifters on Q3, and the zero-phase offset of the central interferometer on Q2 was also calculated. We found a small amount of crosstalk at the upper ranges of applied heater power, and account for this in our analysis.

Programmable unitary rotations. Generating and measuring arbitrary dual-rail qubit states requires control over only two parameters—a phase shift and a tunable beamsplitter, $U_{\text{beam}}(\phi, \theta) = e^{i\phi} e^{-i\theta/2} e^{i\theta/2}$ and $U_{\text{inter}}(\phi, \theta) = e^{i\phi} e^{-i\theta}$ —where $\phi_2, \phi_1$, and $\phi$ are the Pauli matrices. A tunable beamsplitter may be realized by embedding a phase shifter within a Mach–Zehnder interferometer (see Supplementary Section VII and III). In the ideal case, the MZI is composed of two $\eta = 1/2$ beamsplitters. As the beamsplitter reflectivity deviates away from this ideal, we no longer implement a perfect tunable beamsplitter, restricting the range of accessible input states and measurement operators (see Supplementary Section III). The limited tunability (see Supplementary Section IIIH) of our non-ideal beamsplitters restrict us to preparing and measuring quantum states over only one octant of the Bloch sphere.

Simulating teleportation fidelities. The expected click statistics of the photonic circuit were simulated by propagating input Fock states through a linear transfer matrix generated using the measured beamsplitter ratios and interferometer phase offsets. For a given input of $N$ photons distributed across the three input modes, the output probability distribution of clicks was obtained by calculating the permanents of specific $N \times N$ submatrices of the transfer matrix (see Supplementary Section VIII). However, the photon sources used in this work generate two-mode squeezed states, $|\Psi_{\text{S}}\rangle = \sqrt{\frac{1}{12}} \sum_{i=1}^{12} \lambda_{i} |i\rangle |i\rangle$. We thus model the input state as a mixture of the ideal three-photon Fock state input $(1,1,1)$ and the first set of higher-order terms $(1,2,2), (2,1,1)$, weighted by the squeezing parameter of the photon sources measured via the conditional second-order correlation function $g^{(2)} = 0.03$. The output probability distribution when one photon is distinguishable from the others is given by the incoherent sum of a single and an $N−1$ photon input (see Supplementary Section VIII). These output photon distributions are weighted by the distinguishability of our photon source through the measured reduction in expected Hong–Ou–Mandel dip visibility (see Supplementary Section VIII).

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References

1. Bennett, C. et al. Teleporting an unknown quantum state via dual classical and Einstein–Podolsky–Rosen channels. Phys. Rev. Lett. 70, 1895–1899 (1993).
2. Jacobs, B., Pittman, T. & Franson, J. Quantum relays and noise suppression using linear optics. Phys. Rev. A 66, 052307 (2002).
3. Briegel, H.-J., Dür, W., Cirac, J. & Zoller, P. Quantum repeaters: the role of imperfect local operations in quantum communication. Phys. Rev. Lett. 81, 5932–5935 (1998).
4. Knill, E., Laflamme, R. & Milburn, G. A scheme for efficient quantum computation with linear optics. Nature 409, 46–52 (2001).
5. Gottesman, D. & Chuang, I. L. Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. Nature 402, 390–393 (1999).
6. Jin, X.-M. et al. Experimental free-space quantum teleportation. Nature Photon. 7, 381–386 (2013).
7. Marqüés, I., de Riedmatten, H., Tittel, W., Zbinden, H. & Gisin, N. Long-distance teleportation of qubits at telecommunication wavelengths. Nature 421, 509–513 (2003).
8. Ma, X.-S. et al. Quantum teleportation over 143 kilometres using active feed-forward. Nature 489, 269–273 (2012).
9. Childs, A., Leung, D. & Nielsen, M. Unified derivations of measurement-based schemes for quantum computation. Phys. Rev. A 71, 032318 (2005).
10. Kok, P., Nemoto, K., Ralph, T. C., Dowling, J. P. & Milburn, G. J. Linear optical quantum computing with photonic qubits. Rev. Mod. Phys. 79, 135–174 (2007).
11. Bienfang, P. J. et al. Generating, manipulating and measuring entanglement and mixture with a reconﬁgurable photonic circuit. Nature Photon. 6, 45–49 (2011).
12. Smith, B. J., Kundys, D., Thomas-Peter, N., Smith, P. G. R. & Walmsley, I. A. Phase-controlled integrated photonic quantum circuits. Opt. Express 17, 13516–13525 (2009).
13. Crespi, A. et al. Integrated photonic quantum gates for polarization qubits. Nature Commun. 2, 566 (2011).
14. Metcalfe, B. J. et al. Multiphoton quantum interference in a multipart quantum photonic device. Nature Commun. 4, 1356 (2013).
15. Spring, J. B. et al. Boson sampling on a photonic chip. Science 339, 798–801 (2013).
16. Crespi, A. et al. Integrated multimode interferometers with arbitrary designs for photonic boson sampling. Nature Photon. 7, 545–549 (2013).
17. Bouwmeester, D. et al. Experimental quantum teleportation. Nature 390, 575–579 (1997).
18. Boschi, D., Branca, S., Martini, F. D. & Hardy, L. Experimental realization of teleporting an unknown pure quantum state via dual classical and Einstein–Podolsky–Rosen channels. Phys. Rev. Lett. 80, 1121–1125 (1998).
19. Nilsson, J. Q. Quantum teleportation using a light-emitting diode. Nature Photon. 7, 311–315 (2013).
20. Martin, A., Allburt, O., Micheli, M. P. D., Ostrovsky, D. B. & Tanizaki, S. A quantum relay chip based on telecommunication integrated optics technology. New J. Phys. 14, 025002 (2012).
21. Massar, S. & Popescu, S. Optimal extraction of information from finite quantum ensembles. Phys. Rev. Lett. 74, 1259–1263 (1995).
22. Perarnau, N. H. P. et al. High-speed and high-efficiency travelling wave single-photon detectors embedded in nanophotonic circuits. Nature Commun. 3, 1325 (2012).
23. Humphreys, P. C. et al. Train-optic active control for quantum integrated photonic preprint. Preprint at arXiv.org/abs/1405.1594 (2014).
24. Bourennane, D. et al. Fast path and polarization manipulation of telecom wavelength single photons in lithium niobate waveguide devices. Phys. Rev. Lett. 108, 053601 (2012).
25. Lee, H., Chen, T., Li, J., Painter, O. & Vahala, K. I. Ultra-low-loss optical delay line on a silicon chip. Nature Commun. 3, 867 (2012).
26. Kundys, D. O., Gates, J. C., Dasgupta, S., Gawith, C. B. E. & Smith, P. G. R. Use of cross-couplers to decrease size of UV written photonic circuits. IEEE Photon. Technol. Lett. 21, 947–949 (2009).
27. Ralph, T. Scaling of multiple postselected quantum gates in optics. Phys. Rev. A 76, 012312 (2004).
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Author contributions

B.J.M., J.B.S., P.C.H., N.T.-P., N.K.L. and I.A.W. all contributed to designing and setting up the experiment. B.J.M. performed the experiment. J.B.S. designed the FPGA electronics and helped with data taking. D.K. and J.C.G. fabricated the waveguide device. X.-M.J., W.S.K., M.B., P.C.H., J.B.S. and B.J.M. all contributed to analysis of the data. B.J.M wrote the manuscript with input from all authors. B.J.S., P.G.R.S. and I.A.W. conceived the work and supervised the project.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.J.M.

Competing financial interests

The authors declare no competing financial interests.