Remote creation of hybrid entanglement between particle-like and wave-like optical qubits

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The wave–particle duality of light has led to two different encodings for optical quantum information processing. Several approaches have emerged based either on particle-like discrete-variable states (that is, finite-dimensional quantum systems) or on wave-like continuous-variable states (that is, infinite-dimensional systems). Here, we demonstrate the generation of entanglement between optical qubits of these different types, located at distant places and connected by a lossy channel. Such hybrid entanglement, which is a key resource for a variety of recently proposed schemes, including quantum cryptography and computing, enables information to be converted from one Hilbert space to the other via teleportation and therefore the connection of remote quantum processors based upon different encodings. Beyond its fundamental significance for the exploration of entanglement and its possible instantiations, our optical circuit holds promise for implementations of heterogeneous network, where discrete- and continuous-variable operations and techniques can be efficiently combined.

D iscrete1–3 and continuous4–6 variable approaches to linear optical quantum computing and quantum communication7–11 rely on different physical states for their implementation. The first involves single photons5, and the photonic qubits live in a two-dimensional space spanned, for example, by orthogonal polarizations or the absence or presence of a single photon, as expressed by $c_0|0\rangle + c_1|1\rangle$. In the continuous alternative, encoding is realized in the quadrature components of a light field, in an inherently infinite-dimensional space, and the qubits, also sometimes called qumodes6, can be implemented as arbitrary superpositions of classical light waves with opposite phases7–8, $c_0|\alpha\rangle + c_1|-\alpha\rangle$, where $|\alpha\rangle$ is a coherent state with mean photon number $|\alpha|^2$.

In recent years, in parallel with ground-breaking experiments with single photons, coherent state superpositions have also spurred considerable theoretical and experimental activity as reminiscent of the Schrödinger cat state but also as the main off-line resource for investigating continuous-variable-based protocols. Quantum repeater architectures using this paradigm have been proposed9,10, and there is now a variety of schemes for quantum computing using such a computational basis, including fault-tolerant operations with coherent states of moderate amplitude $|\alpha| \approx 1.2$ (ref. 11).

Both encodings have advantages and drawbacks11,12. Continuous variables can benefit from unconditional operations, high detection efficiencies, unambiguous state discrimination and more practical interfacing with conventional information technology. However, it is well known that they suffer from a strong sensitivity to losses and intrinsically limited fidelities. On the other hand, discrete-variable approaches can achieve fidelity close to unity, but usually at the expense of probabilistic implementations. Combining the two—that is, in hybrid architectures4–6—may offer serious advantages13,14. Some operations might better take advantage of the continuous-variable toolbox, while others might be more efficient within the discrete-variable framework. In this endeavour, transferring information between the two encodings is a crucial requirement.

One way to realize a mapping between the two encodings may be provided by teleportation using entanglement between particle-like and wave-like qubits, that is, hybrid entanglement of the form $|+\rangle|\alpha\rangle + |-\rangle|-\alpha\rangle$, where $|\pm\rangle$ refers to the two-level qubit system15. Such entanglement can also be useful for quantum key distribution protocols and security analysis16,17. Moreover, hybrid entanglement is the key resource for the elegant quantum bus approach in which direct qubit–qubit interactions are avoided via mediation by a common qumode18,19 (therefore an example of a scheme combining both encodings). It is also the main off-line state required for the recently proposed schemes of resource-efficient quantum computation with the promise of near-deterministic universal gate operations19.

Optical circuit for hybrid entanglement

In the present work, in contrast to proposals based on the daunting dispersive light–matter interaction20 or Kerr nonlinearities between single photon and coherent states (ref. 21 and references therein), we propose and implement a measurement-induced generation of such an entangled state at a distance. Similar to the Duan–Lukin–Cirac–Zoller protocol in the discrete-variable regime21, or the remote generation of quasi-Bell states in the continuous-variable regime22, our scheme relies on a probabilistic preparation heralded by the detection of a single photon in an indistinguishable fashion. The fragile components remain local, and only single photons propagate between the two distant nodes. In this way, a lossy channel affects the count rate but not the fidelity of the resulting state.

The optical circuit is illustrated in Fig. 1a. Alice and Bob (denoted A and B in the following), who are using discrete-variable and continuous-variable encodings for information processing, respectively, are willing to establish hybrid entanglement. To establish this internode connection, they locally prepare two non-classical light fields: a two-mode squeezed state in the very low gain limit on Alice’s side, $|\psi\rangle_{ab} = |0\rangle_0 |0\rangle_0 + \alpha |1\rangle_1 |1\rangle_1 + \mathcal{O}(\alpha^2)$, where ‘s’ and ‘i’ indicate the signal and idler modes, and a single-mode even cat state on Bob’s side given by $|\text{cat}\rangle = |\alpha\rangle + |-\alpha\rangle$. A small fraction of the cat state is then tapped off and transferred to a router station, where it can be superposed on a tunable beamsplitter, in an indistinguishable way, with the idler mode of Alice’s state. Conditioned...
on the detection of a single photon at the output, and with a beamsplitter ratio adjusted to balance the two contributions, the resulting state is a maximally entangled state for any values of $|\alpha|$, that is, containing 1 ebit. In the ideal case it can be written as (Supplementary Section I)

$$|\Psi_{AB}\rangle = |0\rangle_\text{A} |\text{cat}_\text{B}\rangle + e^{i\varphi} |1\rangle_\text{A} |\text{cat}_\text{B}\rangle$$

(1)

where $\varphi$ is the overall relative phase for the triggering modes, which can be controlled and adjusted, and $|\text{cat}_\text{B}\rangle = |\alpha\rangle - |\bar{\alpha}\rangle$ denotes an odd cat state.

This generation procedure can be understood in the following way. A detection event heralds either the subtraction of a single photon from the even cat state resulting in a parity change and leaving Alice’s signal mode in a thermal state very close to the vacuum state, or the detection of a single photon in the idler mode resulting in projection of the signal into a single-photon state and leaving the initial cat state unchanged.

The resulting entangled state can also be written using, for Alice, the rotated qubit basis $|\pm\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$, $|\mp\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$ as

$$|\Psi_{AB}\rangle = |+\rangle_\text{A} |\alpha\rangle_\text{B} + e^{i\varphi} |-\rangle_\text{A} |-\alpha\rangle_\text{B}$$

(2)

The normalizations are omitted here, and this rewriting from equation (1) is valid when the two coherent states are approximately orthogonal (Supplementary Section I). Let us note, however, that this approximation is already good for moderate values of $|\alpha|$ (refs 8,11). Indeed, an amplitude $|\alpha| = 1$ gives an overlap $|\langle \alpha | - \bar{\alpha} \rangle|^2 = e^{-2|\alpha|^2} \approx 0.02$.

This state directly enables the teleportation of a qubit encoded in the $|\pm\rangle, |\mp\rangle$ basis to the coherent state computational basis $|\pm\rangle, |-\rangle$. It also refers to the spirit of the Schrödinger Gedanken experiment where the two classical states are entangled with a microscopic degree of freedom. Let us note also that a Hadamard gate, which can be performed with non-Gaussian ancillas and projective measurements24, would enable the conversion of this state into state $|0\rangle_\text{A} |\alpha\rangle_\text{B} + |1\rangle_\text{A} |-\alpha\rangle_\text{B}$.

**Experimental implementation**

In the present work, the non-classical fields were generated at 1.064 nm with continuous-wave optical parametric oscillators (OPOs) operated below threshold (see Methods), as illustrated in Fig. 1b. Importantly, these sources enable the generation of quantum states in a very well-defined spatiotemporal mode due to the cavity25 (Supplementary Section II). On Bob’s side, a type I OPO is used to generate a single-mode squeezed vacuum with 3 dB noise reduction below the shot noise level. For $|\alpha|^2 \lesssim 1$, this state has a fidelity close to unity, with an even cat state $|\text{cat}_\text{A}\rangle$. A small fraction ($R = 3\%$) of the light is tapped off via a beamsplitter. Subtracting a single photon from this state results in the generation of an odd cat state26–29. On Alice’s side, the required two-mode squeezed vacuum is generated by a type II frequency-degenerate OPO. At the output, the orthogonally polarized signal and idler modes are spatially separated via a polarizing beamsplitter. The device is operated very far below threshold (around 100 times below) to limit the multiphoton component to a few percent30. The tapped mode and the idler mode are then brought to interfere.

Before detection, frequency filtering elements are needed to remove the non-degenerate modes emitted by the OPOs. Finally, the filtered mode is detected by a superconducting single-photon detector (SSPD, Scontel) working at cryogenic temperature. The very low dark noise (below 1 Hz) avoids false detection events, a crucial feature in achieving high fidelity in state generation31,32.
Figure 2 | Experimental quantum state tomography. The relative phase is set to \( \phi = \pi \) and the beamsplitter ratio in the central station is adjusted to generate a maximally entangled state, that is, with equal weights. a, Wigner functions associated with the reduced density matrices \((k|\hat{p}|l)\) for the odd cat state \((\eta = 85\%)\), one on each node. A total of 200,000 data points were recorded with an equally distributed choice of quadratures (Supplementary Section IV). The two-mode density matrix of the state was then reconstructed via a maximum likelihood algorithm34. This new kind of hybrid state, which is composed of a discrete mode and a continuous one, raises the question of how to represent it in a visual and illustrative manner. We have chosen as a convenient representation to display in a matrix form the Wigner functions (well adapted to continuous-variable states) associated with the reduced density matrices \((k|\hat{p}|l)\), where \(k\) and \(l\) indicate discrete-qubit states.

The experimental results are given in Fig. 2a without and with correction for detection losses, for a phase set to \( \phi = \pi \) and a beamsplitter ratio tuned to balance the detection probability from each node. This figure confirms that the discrete mode is contained in the qubit subspace spanned by \(|0\rangle, |1\rangle\). Higher-photon-number components are indeed limited to 2%. In this subspace the two first diagonal elements, namely projections \(|0\rangle|\hat{p}|0\rangle\) and \(|1\rangle|\hat{p}|1\rangle\), correspond respectively to a photon-subtracted squeezed state and to a squeezed state. The non-zero off-diagonal terms demonstrate the coherence of the superposition. The generated state can also be represented using as another projection basis the rotated one, \(|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}, |−\rangle = (|0\rangle − |1\rangle)/\sqrt{2}\) (Fig. 2b). As can be clearly seen from the contour plots, the two projections \(|+\rangle\) and \(|−\rangle\) exhibit an opposite displacement in phase space, corresponding with large fidelity to the two states \(|\alpha\rangle\) and \(|−\alpha\rangle\). Corrected for detection losses, we obtain a fidelity of 77 ± 3% with the targeted state with \( \phi = \pi \) and \(|\alpha| = 0.9\). The demonstrated size is already compatible with the value \(|\alpha| \approx 1\) shown as the optimal value in recent proposals of resource-efficient operations with hybrid qubits13.

To quantitatively assess the generated entanglement, we also computed the negativity35 given by \(N = \langle|\rho^{AB}||1, −1\rangle/2\), where \(\rho^{AB}\) stands for the partial transpose of the two-mode density matrix \(\rho\) with respect to mode A. This quantity reaches 0.5 for the ideal maximally entangled state. Experimentally, \(N = 0.26 ± 0.01\) is obtained without correction for detection losses and \(N = 0.37 ± 0.01\) when corrected, demonstrating that the hybrid entanglement is remotely prepared and showing its suitability for hybrid teleportation25. The heralding rate is equal to 30 kHz, limited by an overall loss in the conditioning path equal to 97% (ref. 30). This lossy channel would be equivalent to 75 km of fibre at telecom wavelengths. This value confirms the reliability of our method to establish entanglement connection over long distances.

Experimental imperfections can be summarized on both nodes via an effective local efficiency (\(\eta_A\) and \(\eta_B\), which here arises predominantly from transmission losses, finite detection efficiency and the escape efficiency of the OPO (given by \(T(T + L)\) where \(T\) is the transmission of the output coupler and \(L\) is the intracavity losses). Dark counts are negligible in our experiment. By using the value of the Wigner function at the origin for the states generated independently, these efficiencies are estimated to be \(\eta_A = 76 ± 2\%\) and \(\eta_B = 71 ± 2\%\). These values are in agreement with the observed negative value at the origin of the Wigner function for the odd cat state \((0|\hat{p}|0)\) given in Fig. 2a, \(W_0 = −0.14 ± 0.01\) (not corrected, ideally −1). Note that both local efficiencies contribute to this value. Indeed, projecting on Alice’s side translates into adding an extra vacuum contribution on Bob’s side resulting from her non-uniqueness of the efficiency. Achieving negativity without correction is thus a difficult task here and is a notable feature of our work.

The accurate control of the experimental parameters achieved in our implementation also enables complete engineering of the hybrid state by choosing the relative phase \( \phi \) and the superposition weights. Figure 3 presents an example of states with \( \phi = 0\), that is, opposite to that in Fig. 2, and with a different ratio of the beamsplitter used for mixing. The two extreme states indeed result from heralding events coming only from Alice’s node or Bob’s node. The figure in the middle provides the balanced case, which is very similar to the one shown in Fig. 2a but with opposite phase, as

To achieve entanglement, various parameters must be strictly controlled. First, the superposed beams must be indistinguishable. In particular, this stringent condition requires the bandwidth of the two OPOs to be matched. Starting with similarly constructed OPOs, fine tuning of the cavity lengths is performed by adjusting the temporal modes in which the conditional states are emitted when operated separately. Second, the relative phase \( \phi \) has to be kept constant12. The different phases in the experiment are therefore controlled and actively stabilized by using auxiliary weak beams injected into both OPOs (see Methods). For this reason, the experiment was conducted in a cyclic fashion: 50 ms were used for phase locking, and data acquisition began in the next 50 ms with seed beams off (Supplementary Section III).

Characterization of the hybrid state

The heralded state \(\hat{p}\) is characterized by a two-mode quantum tomography performed with two high-efficiency homodyne detections \((\eta = 85\%)\), one on each node. A total of 200,000 data points were recorded with an equally distributed choice of quadratures (Supplementary Section IV). The two-mode density matrix of the state was then reconstructed via a maximum likelihood algorithm34.

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can be seen in the off-diagonal terms. The two other blocks give examples of intermediate ratios, showing the build-up of the coherences. Negativity is provided in each case, showing the transition from separability to entanglement and back.

**Discussion**

As can be seen in Fig. 2b in the rotated basis, the projected states are not completely round as is expected for coherent states. This feature arises from the initial approximation, which consists of starting with a squeezed vacuum in the experimental protocol. The maximum achievable fidelity with the targeted hybrid state is therefore 94% in this case. To go beyond this demonstrated result in future extensions, Bob can perform a local single-photon subtraction to initially prepare an odd cat state. This preparation will directly allow $|\alpha| \rightarrow |\alpha|$ to increase above 1, as well as an achievable fidelity close to unity (Supplementary Section V and Supplementary Fig. 6). Higher amplitudes can be obtained by means of additional photon subtractions. Our optical circuit is well suited for these operations and provides a platform for future experiments. Higher values of squeezing with high purity will be necessary, and are readily available given our OPO escape efficiency. Efficient photon detectors are also required for these cascaded detections and can be provided by the new generation of superconducting devices working in the near-infrared. In a different framework, these future works will also enable the study of squeezing-induced micro–macro states (as recently proposed in ref. 40) where the phase-space distance can be varied, in contrast to recently reported results based on displaced squeezed vacuum state by higher terms when the detected photon originated from the other OPO. In both cases, the ratio was the same, given by the parametric gain.

**Frequency filtering in the conditioning path.** To remove the non-degenerate modes emitted by the OPOs and consequently only detect heralding single photons at the carrier frequency, two-stage filtering was applied. An interferential filter (Barr Associates) with a bandwidth of 0.5 nm was associated with a home-made linear Fabry–Pérot cavity (length of 0.45 mm and finesse of 1,000) with a free spectral range of 330 GHz and a bandwidth of 320 MHz (six times larger than that of the OPOs). The unwanted modes were rejected below 0.3%.

**Control of phases.** The relative phase $\varphi$ in the generated state, which critically has to be kept constant to achieve entanglement, was determined by the optical paths after the OPOs and also by the phases of each OPO pump field. To control these phases, a very weak seed beam was injected into each OPO. These beams were amplified or de-amplified depending on the relative phase between the seed and the pump. To set this phase, a small part of each beam was measured (photodiodes P1 and P2 in Fig. 1) and the intensity locked at a constant level. The second step consisted of locking the relative phase where the tapped modes were combined (photodiode P3). The interference between the seed and the local oscillator on each site also gave access to the phase of the measured quadrature for the subsequent quantum state tomography. Further details are provided in the Supplementary Information, including experimental timings.

**References**

1. Kok, P. et al. Continuous linear optical quantum computing with photonic qubits. Rev. Mod. Phys. 79, 135–174 (2007).
2. Braunstein, S. L. & Pati, A. (eds) Continuous Variable Quantum Information (Kluwer Academic, 2003).
3. Ralph, T. C. & Pryde, G. J. Optical quantum computation. Prog. Opt. 54, 209–269 (2010).
4. O’Brien, J. L., Furusawa, A. & Vuckovic, J. Photonic quantum technologies. Nature Photon. 3, 687–695 (2009).
5. Knill, E., Laflamme, R. & Milburn G. J. A scheme for efficient quantum computation with linear optics. Nature 409, 46–52 (2001).
6. Van Loock, P. Optical hybrid approaches to quantum information. Laser Photon. Rev. 5, 167–200 (2011).
7. Jeong, H. & Kim, M. S. Efficient quantum computation using coherent states. Phys. Rev. A 65, 042305 (2002).
8. Ralph, T. C., Gilchrist, A., Milburn, G. J., Munro, W. J. & Glancy, S. Quantum computation with optical coherent states. Phys. Rev. A 68, 042319 (2003).
9. Sangouard, N. et al. Quantum repeaters with entangled coherent states. J. Opt. Soc. Am. B 27, 137–145 (2010).
10. Brask, J. B. et al. A hybrid long-distance entanglement distribution protocol. Phys. Rev. Lett. 105, 160501 (2010).
11. Lund, A. P., Ralph, T. C. & Haselgrove, H. L. Fault-tolerant optical quantum computing with small-amplitude coherent states. Phys. Rev. Lett. 100, 030503 (2008).
12. Park, K. & Jeong, H. Entangled coherent states versus entangled photon pairs for practical quantum-information processing. Phys. Rev. A 82, 062325 (2010).
13. Lee, S.-W. & Jeong, H. Near-deterministic quantum teleportation and resource-efficient quantum computation using linear optics and hybrid qubits. Phys. Rev. A 87, 022326 (2013).
14. Morin, O. et al. Witnessing trustworthy single-photon entanglement with local homodyne measurements. Phys. Rev. Lett. 110, 130401 (2013).
15. Kreis, K. & van Loock, P. Classifying, quantifying, and witnessing qudit–quomode hybrid entanglement. Phys. Rev. A 85, 032307 (2012).
16. Rigas, J., Gühne, O. & Lütkenhaus, N. Entanglement verification for quantum-key-distribution systems with an underlying bipartite qubit-mode structure. Phys. Rev. A 73, 012341 (2006).
17. Wittmann, C. et al. Witnessing effective entanglement over a 2 km fiber channel. Opt. Express 18, 4499–4509 (2010).
18. Spiller, T. P. et al. Quantum computation by communication. New J. Phys. 8, 30 (2006).
19. Van Loock, P. et al. Hybrid quantum computation in quantum optics. Phys. Rev. A 78, 022303 (2008).
20. Van Loock, P. et al. Hybrid quantum repeater using bright coherent light. Phys. Rev. Lett. 96, 240501 (2006).
21. Jeong, H. Using weak nonlinearity under decoherence for macroscopic entanglement generation and quantum computation. Phys. Rev. A 72, 034305 (2005).
22. Duan, L.-M., Lukin, M. D., Cirac, J. I. & Zoller, P. Long-distance quantum communication with atomic ensembles and linear optics. Nature 414, 413–418 (2001).
23. Ourjoumtsev, A., Ferreyrol, F., Tualle-Brouri, R. & Grangier, P. Preparation of amplitude coherent-state superposition. Phys. Rev. A 78, 022303 (2008).
24. Marek, P. & Fiurášek, J. Elementary gates for quantum information with Schroedinger kittens for quantum information processing. Science 312, 83–86 (2006).
25. Neergaard-Nielsen, J. S., Nielsen, B. M., Hettich, C., Molmer, K. & Polzik, E. S. Generation of a superposition of odd photon number states for quantum information networks. Phys. Rev. Lett. 97, 083604 (2006).
26. Wakui, K., Takahashi, H., Furusawa, A. & Sasaki, M. Controllable generation of highly nonclassical states from nearly pure squeezed vacua. Opt. Express 15, 3568–3574 (2007).
27. Lee, N. et al. Teleportation of nonclassical wave packets of light. Science 322, 330–333 (2011).
28. Morin, O., D’Auria, V., Fabre C. & Laurat, J. High-fidelity single-photon source based on a type-II optical parametric oscillator. Opt. Lett. 37, 3738–3740 (2012).
29. D’Auria, V., Lee, N., Amri, T., Fabre, C. & Laurat, J. Quantum decoherence of single-photon counters. Phys. Rev. Lett. 107, 050504 (2011).
30. D’Auria, V., Morin, O., Fabre, C. & Laurat, J. Effect of the heralding detector properties on the conditional generation of single-photon states. Eur. Phys. J. D 66, 249 (2012).
31. Van Enk, S. J., Lütkenhaus, N. & Kimble, H. J. Experimental procedures for entanglement verification. Phys. Rev. A 75, 052318 (2007).
32. Lvovsky, A. I. & Raymer, M. G. Continuous-variable optical quantum-state tomography. Rev. Mod. Phys. 81, 299–332 (2009).
33. Vidal, G. & Werner, R. F. A computable measure of entanglement. Phys. Rev. A 65, 032314 (2002).
34. Park, K., Lee, S.-W. & Jeong, H. Quantum teleportation between particlelike and fieldlike qubits using hybrid entanglement under decoherence effects. Phys. Rev. A 86, 062301 (2012).
35. Nielsen, A. E. B. & Molmer, K. Transforming squeezed light into a large-amplitude coherent-state superposition. Phys. Rev. A 76, 043840 (2007).
36. Morin, O. et al. Quantum state engineering of light with continuous-wave optical parametric oscillators. J. Visualized Experiments 87, e51224 (2014).
37. Marsili, F. et al. Detecting single infrared photons with 93% system efficiency. Nature Photon. 7, 210–214 (2013).
38. Andersen, U. L. & Neergaard-Nielsen, J. S. Heralded generation of a micro–macro entangled state. Phys. Rev. A 88, 022337 (2013).
39. Lvovsky, A. I., Gobadi, R., Chandra, A., Prasad, A. S. & Simon, C. Observation of micro–macro entanglement of light. Nature Phys. 9, 541–544 (2013).
40. Bruno, N. et al. Displacement of entanglement back and forth between the micro and macro domains. Nature Phys. 9, 545–548 (2013).

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Author contributions
J.L. and O.M. conceived the experiment. O.M., K.H. and J.L. carried out the experiment and analysed the data, under the supervision of J.L. O.M., K.H., H.L.J., C.F. and J.L. contributed to discussing the implementation and the results. O.M., K.H. and J.L. wrote the manuscript.

Additional information
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Competing financial interests
The authors declare no competing financial interests.