Quantum teleportation is a cornerstone of quantum information science due to its essential role in important tasks such as the long-distance transmission of quantum information using quantum repeaters. This requires the efficient distribution of entanglement between remote nodes of a network. Here, we demonstrate quantum teleportation of the polarization state of a telecom-wavelength photon onto the state of a solid-state quantum memory. Entanglement is established between a rare-earth-ion-doped crystal storing a single photon that is polarization-entangled with a flying telecom-wavelength photon. The latter is jointly measured with another flying polarization qubit to be teleported, which heralds the teleportation. The fidelity of the qubit retrieved from the memory is shown to be greater than the maximum fidelity achievable without entanglement, even when the combined distances travelled by the two flying qubits is 25 km of standard optical fibre. Our results demonstrate the possibility of long-distance quantum networks with solid-state resources.

Quantum teleportation allows the transfer of a quantum state between remote physical systems through the use of quantum entanglement and classical communication. The combination of quantum teleportation with quantum memories can provide scalable schemes for quantum computation, quantum repeaters and quantum networks. Light-to-matter quantum teleportation has been demonstrated using quantum memories based on warm or cold atomic ensembles, single atoms or a quantum dot spin qubit. In these demonstrations, the memory emits a photonic qubit, with which it is entangled, and the photon is used to distribute the entanglement necessary to perform teleportation.

To achieve long-distance light-to-matter quantum teleportation, and more generally to exchange quantum information between distant nodes of a quantum network, we require an efficient method to distribute entanglement. Optical fibre is naturally suited to entanglement distribution, but it requires the flying qubits to have a suitable telecom wavelength. Satisfying this requirement using emissive quantum memories is difficult, because the relevant atomic transition is typically far away from the low-loss region of standard optical fibre. An approach based on practical sources of photon pairs combined with multimode quantum memories can overcome this limitation. The essential idea is that spontaneous parametric down-conversion (SPDC) sources create pairs comprised of one photon stored in a nearby quantum memory, while the other telecom-wavelength photon is used to distribute the entanglement to a remote node. For quantum repeaters, multimode storage with selective recall is essential to achieve practical rates. A promising candidate for the multimode quantum memories of this proposal are rare-earth-ion doped crystals, which offer a technologically simple way of trapping an atomic ensemble using a solid-state host. In recent years they have been used to demonstrate key properties such as high-efficiency storage, coherence times as long as one minute, multimode storage, on-demand readout at the single-photon level, gigahertz-wide storage bandwidth and storage of photonic entanglement. Here, we demonstrate quantum teleportation of the polarization state of a telecom-wavelength photon onto the state of a single collective excitation stored in a rare-earth-ion doped crystal. To achieve this, a pair of polarization-entangled photons is first generated from SPDC in nonlinear waveguides. One photon from the pair is then stored in a nearby rare-earth-ion doped crystal for a pre-determined storage time. The other telecom-wavelength photon from the entangled pair is sent to a Bell-state analyser, where it is jointly measured with a photon that is carrying the polarization qubit state to be teleported. The polarization state of the photon retrieved from the quantum memory is then analysed with quantum state tomography and the fidelity is shown to outperform the classical benchmark. We also performed teleportation in a configuration where the combined distance travelled by both telecom-wavelength photons was 25 km in standard optical fibre, demonstrating the long-distance capability of the approach.

The experiment set-up is presented in Fig. 1. A pair of entangled photons at 883 nm (the ‘signal’ photon) and 1,338 nm (the ‘idler’ photon) is created from SPDC. To achieve this, 532 nm light coherently pumps two nonlinear waveguides such that the photon pair is in a superposition of being created in a first waveguide (with horizontal polarizations $HH$) and in a second waveguide (with vertical polarizations $VV$). Recombining the output modes of the waveguides on two polarizing beam splitters (PBSs) yields two optical modes containing the signal and idler photons, respectively, prepared in an entangled state that is very close to $\frac{1}{2}(HH + ee|VV\rangle)$. The spectra of the idler photon (and consequently of the frequency-correlated signal photon of the pair) are subsequently filtered to a spectral width of $\sim 240$ MHz, corresponding to a coherence time of $\tau = 1.4$ ns. This spectral width is more than five times larger than in our previous experiments with the

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same type of quantum memory\textsuperscript{5}, and therefore increases the intrinsic repetition rate of our experiment by the same factor.

Following the creation of a pair, the signal photon is directly sent to a 14-mm-long quantum memory consisting of two inline neodymium-doped yttrium orthosilicate crystals interspaced with a half-wave plate. This configuration compensates for the polarization-dependent absorption of a single crystal\textsuperscript{23–25}. The absorption bandwidth of the quantum memory is 600 MHz and stores photons for 50 ns with an overall efficiency of 5\% using the atomic frequency comb (AFC) storage protocol\textsuperscript{16}. The qubit state to teleport, hereon termed the ‘input state’, is encoded in the polarization of a photon from a weak coherent state (WCS) at 1,338 nm, which is created by means of difference-frequency generation in a separate nonlinear waveguide. This automatically yields the same central wavelength for the WCS and idler photons. The Bell-state measurement (BSM) between the idler photon and the input state is performed by sending them through a 50/50 beamsplitter, projecting their joint state onto the Bell state $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$ when they are detected in different output modes. The photons are then coupled in single-mode optical fibres and detected using tungsten-silicide superconducting nanowires (WSi) SNSPDs operated at 2.5 K in a closed-cycle cryocooler (D$_1$ and D$_2$) operated at 2.5 K in a closed-cycle cryocooler and entangled non-linear optical processes after the BSM (Fig. 1), and their detection occurred while the signal photon was stored in the quantum memory.

The system includes a source of polarization-entangled photons at 883 nm (the signal) and 1,338 nm (the idler) using filtered spontaneous parametric down-conversion from two nonlinear waveguides (PPLN and PPKTP) coherently pumped with 532 nm light. After the waveguides, the signal and idler modes are separated using dichroic mirrors (DM) and are then individually manipulated to obtain good overlap after recombination at two polarization beam splitters (PBS\textsubscript{2}), as well as high transmission through the filtering cavity and etalon. A single pair of energy-correlated spectral modes of the signal and idler photons are selected using volume Bragg gratings (VBG). The signal photon is sent to a neodymium-based polarization-preserving quantum memory that was previously prepared as an atomic frequency comb using 883 nm light (see Methods). A switch (Sw) selects either the preparation light or the signal photons. The weak coherent state (WCS) at 1,338 nm is created by means of difference-frequency generation from 532 and 883 nm light. The WCS is then selected using a grating (Gr) and coupled in an optical fibre. The input state to be teleported is prepared using wave plates and sent towards a 50/50 beamsplitter where it is mixed with the idler photon to perform the Bell-state measurement (BSM).

The output modes of the beamsplitter are polarization-filtered and sent towards two high-efficiency detectors based on WSi superconducting nanowires (D$_1$ and D$_2$) operated at 2.5 K in a closed-cycle cryocooler 10 m away from the quantum memory. A coincidence detection at D$_1$ and D$_2$ heralds a successful BSM. The signal photon retrieved from the quantum memory is sent to a polarization-state analyser where it is detected on D$_3$ or D$_4$. The idler and WCS photons are each transmitted either over a short distance or over 12.4 km of single-mode optical fibre. See Supplementary Information for details.

The results for the teleportation of the state $|\psi^+\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$ are shown as two-dimensional histograms in Fig. 2a (with D$_3$ projecting on $|\alpha\rangle$) and Fig. 2b (with D$_4$ projecting on $|\beta\rangle$). Offsets on the detection times are chosen such that events in the vicinity of the centre of the histograms (that is, for $\delta t_{\alpha1}, \delta t_{\alpha2} < \tau = 1.4$ ns) correspond to the actual teleportation. Figure 2a shows an increased number of counts at the centre, whereas Fig. 2b has a dip, which is expected if the retrieved state is close to input state $|\psi^+\rangle$. This is more easily visualized in Fig. 2c (or Fig. 2d), which shows a horizontal slice of Fig. 2a (or Fig. 2b) centred on $|\alpha\rangle = 0$ (or $|\beta\rangle = 0$).

The fidelity of the retrieved state $\rho$ with respect to the input state $|\psi\rangle$ (which here is effectively pure) is $F = (|\rho|^{1/2} |\psi\rangle |\psi^{*}\rangle)$. For teleportation of state $|\psi^+\rangle$, the fidelity of the retrieved state can be estimated from the number of events observed at the centre of Fig. 2c ($\delta t_{\alpha2} = 0$) and at the minimum of Fig. 2d ($\delta t_{\beta2} = 0$). The measured fidelity is 92 ± 4\%. To obtain complete information about state $\rho$, we performed quantum state tomography. With this information, we can assess if the reduced fidelity is due to an undesired unitary rotation.

![Figure 1 | Experimental set-up.](image-url)
on the Bloch sphere, or due to depolarization, which leads to a reduction in the purity $P = \text{Tr}(\rho^2)$ of the retrieved state. The undesired rotation can stem from drifts of the phase $\varphi$ and/or of the amplitude of the $|HH\rangle$ and $|VV\rangle$ terms of the entangled state, while the main cause of the depolarization is noise arising from multi-pair emission of the source and/or of multiple photons in the WCS. The measured purity with input state $|–\rangle$ is $94 \pm 6\%$. This value allows us to find an upper bound $F_{\text{max}} = \frac{1}{2}(1 + \sqrt{2P - 1}) = 97 \pm 3\%$ on the observable fidelity. See Supplementary Information for details.

The tomography was repeated for other input states, and the results are listed in Table 1. The expected fidelity of an arbitrary state is $F = \frac{1}{2}F_s + F_p$, where $F_s$ and $F_p$ are the average fidelities measured on the equator and the pole, respectively. We find $F = 89 \pm 4\%$, which is larger than the maximum fidelity of 66.7% achievable with a prepare-and-measure strategy that does not use entanglement. Most of the obtained fidelities are very close to $F_{\text{max}}$ and are therefore limited by depolarization. For the teleportation of $|+\rangle$, the measurements around the equator of the Bloch sphere shown in Fig. 2e reveal an additional rotation of the Bloch vector that further reduces the observed fidelity below the $F_{\text{max}}$ upper bound (see Supplementary Information for details).

We also performed a teleportation of the $|+\rangle$ state in a configuration where the WCS photon and the idler photon each travel through 12.4 km of standard single-mode optical fibre before the BSM. This distance exceeds the previous record of 6 km for a fibre-based (and quantum memory-less) quantum teleportation. The histograms show a dip (Fig. 2f) and a peak (Fig. 2g), which are indicative of the teleportation. The fidelity of this measurement is $81 \pm 4\%$. We note that in this configuration, the signal photon was retrieved after 50 ns, that is, before the idler photon reached the BSM. The realization of a complete teleportation with feed-forward over this distance requires a storage time of at least 120 µs. A promising approach towards this goal is to combine spin-wave storage with dynamical decoupling.

Our experiment demonstrates the feasibility of long-distance teleportation of single quanta of light onto a solid-state quantum memory. The fundamentals of our experiment could be used in future demonstrations of a small-scale network of remote quantum memories, or ultimately in a real-world quantum repeater based on an optical-fibre architecture. In a broader context, our experiment could be useful for transferring quantum information between remote quantum network nodes made of rare-earth crystals coupled to superconducting qubits, which could ultimately lead to the realization of deterministic Bell-state measurements on photon qubits.

**Methods**

**Source of polarization-entangled photons.** Details about the source are provided in the Supplementary Information. In brief, it uses two periodically poled (PP) nonlinear waveguides (Fig. 1). One is a 1.3-cm-long waveguide embedded in potassium titanyl phosphate (PPKTP) and the other is a 6-cm-long titanium-indiffused waveguide based in lithium niobate (PPLN). Several procedures were implemented to monitor and stabilize the properties of the source. First, the pump light at 532 nm was continuously frequency-stabilized using a feedback mechanism based on difference-frequency generation of light at 1,338 nm from mixing the residual 532 nm light present in the unused output ports of the two PPKTs located just before the cavity and the etalon was used to continuously lock the phase $\varphi$ of the entangled state. To achieve this, an error signal was derived from the 532 nm light and feedback was applied on two piezo-mounted mirrors (one for the signal photon and one for the idler photons) located immediately after the dichroic mirrors. Fast

| Input state | Fidelity (%) | Purity (%) | $F_{\text{max}}$ (%) |
|-------------|--------------|------------|----------------------|
| $|–\rangle$  | 94 ± 3       | 93 ± 3     | 96 ± 3               |
| $|\pm\rangle$ | 92 ± 4       | 94 ± 6     | 97 ± 3               |
| $|+\rangle$  | 82 ± 4       | 83 ± 9     | 91 ± 6               |

The uncertainties are obtained from Monte Carlo simulations assuming a Poisson distribution of the number of threefold events. Also shown is the upper bound on the fidelity $F_{\text{max}}$, that is obtained from the measured purity.
fluctuations were compensated for, but ψ could still slowly drift by a few degrees per hour, at most. Third, a characterization of the properties of the source was performed every 30 min with a completely automated procedure. For this, the teleportation was stopped for a few minutes by switching off the WCS. Then, by measuring twofold coincidences between the idler photon and the transmitted signal photon, the visibility of the source was measured, and the value of phase ψ was extracted (see Supplementary Information). The measured average visibility was 93%. From these measurements, the second-order cross-correlation function between the idler and the signal photons was estimated and used to monitor the probability $P$ of emitting a pair of photons in a time window of ~500 ps. We measured $P \approx 10^{-7}$. The monitoring and stabilization yielded stability for periods as long as 24 h. We note that the 532 nm light was pulsed in 25-ns-long Gaussian pulses with 100 ns between successive pulses (which is twice the storage time) to improve the signal-to-noise ratio of the teleportation experiment (see Supplementary Information for details).

Polarization-preserving quantum memory. The compact, broadband and polarization-preserving quantum memory was achieved by placing two 5.8-mm-long Nd$^{3+}$:Y$_2$SiO$_5$ crystals around a 2-mm-thick half-wave plate, resulting in a total device length of 14 mm. Anti-reflective coatings were added on all surfaces (crystal, windows, crystals and half-wave plate). The resulting off-resonance transmission coefficient was 95%. To obtain short crystals with sufficient absorption we grew Nd$^{3+}$:Y$_2$SiO$_5$ crystals using the Czochralski process, with a neodymium concentration estimated to be 75 ppm. These crystals have an absorption coefficient of $\alpha = 3.7 \text{ cm}^{-1}$ (with an applied magnetic field of 300 mT, as in ref. 21). The resulting optical depth of the polarization-preserving memory device was $d = 2.3 \times 10^4$. The AFC was prepared using an acousto-optic modulator (AOM), used in a double-pass configuration, which modulates the intensity and frequency of the light from an external cavity diode laser at 883 nm (centred on the absorption line of the $\text{J}_{43/2} \rightarrow \text{J}_{9/2}$ transition) in order to pump some of the atoms to the other Zeeman level (see ref. 21). This was used to create a 120 MHz comb with a spacing of 20 MHz between peaks. To increase the memory bandwidth beyond 120 MHz, the light at the output of the AOM was sent into a phase modulator that creates a 20 MHz between peaks. To increase the memory bandwidth beyond 120 MHz, the light at the output of the AOM was sent into a phase modulator that creates a 20 MHz between peaks. To increase the memory bandwidth beyond 120 MHz, the light at the output of the AOM was sent into a phase modulator that creates a 20 MHz between peaks. To increase the memory bandwidth beyond 120 MHz, the light at the output of the AOM was sent into a phase modulator that creates a 20 MHz between peaks. To increase the memory bandwidth beyond 120 MHz, the light at the output of the AOM was sent into a phase modulator that creates a 20 MHz between peaks. To increase the memory bandwidth beyond 120 MHz, the light at the output of the AOM was sent into a phase modulator that creates a 20 MHz between peaks.

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Author contributions

The experiment was conceived by F.B., C.C., M.A. and N.G. The superconducting detectors were fabricated by V.B.V., S.W.N. and F.M. and characterized by V.B.V., B.K. and F.B. The rare-earth ion doped crystals were grown by A.F. and P.G. and characterized by A.T. and F.B. The lithium niobate waveguide was fabricated by H.H., C.S. and W.S. and characterized by C.C. The measurements and data analysis were done by C.C., A.T. and F.B. The manuscript was written by F.B., A.T. and C.C., with contributions from all authors.

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 F.B.

Competing financial interests

The authors declare no competing financial interests.