Quantum storage of entangled telecom-wavelength photons in an erbium-doped optical fibre

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The realization of a future quantum Internet requires the processing and storage of quantum information at local nodes and interconnecting distant nodes using free-space and fibre-optic links. Quantum memories for light are key elements of such quantum networks. However, to date, neither an atomic quantum memory for non-classical states of light operating at a wavelength compatible with standard telecom fibre infrastructure, nor a fibre-based implementation of a quantum memory, has been reported. Here, we demonstrate the storage and faithful recall of the state of a 1,532 nm wavelength photon entangled with a 795 nm photon, in an ensemble of cryogenically cooled erbium ions doped into a 20-m-long silica fibre, using a photon-echo quantum memory protocol. Despite its currently limited efficiency and storage time, our broadband light–matter interface brings fibre-based quantum networks one step closer to reality.

The end of the last century saw the discovery and to some extent the realization of several paradigm-shifting applications of quantum information science, including computers with unprecedented computational power, unconquerable secret key distribution, and measurement devices with ultimate precision (reviewed in refs 3–5, respectively). Combining these applications in the so-called quantum Internet1 requires transmitting quantum states encoded into photons between nodes of the network, as well as storage of the quantum states in the nodes. Although the quantum Internet can leverage existing telecom fibre networks, standard (classical) repeater technology cannot be used to build large-scale networks due to a fundamental restriction of quantum mechanics known as the ‘no-cloning theorem’8. Hence, classical repeaters, generally comprising erbium-doped fibre amplifiers, must be replaced with quantum repeaters, which include pairs of entangled photons, entanglement swapping and light–matter interfaces that allow the storage and processing of quantum states of light6.

Despite enormous success in developing suitable light–matter interfaces during the past decade (for recent reviews see refs 2, 6 and 7), the storage of non-classical states of light encoded into telecom-wavelength photons (that is, at ~1,550 nm and the most natural choice for a quantum network) remains to be demonstrated. Considering the most popular quantum memory materials —alkali atoms (particularly Cs and Rb) and rare-earth-ion-doped crystals—the reasons for this challenge are twofold. First, Cs and Rb lack easily accessible atomic transitions, that is, transitions starting at an electronic ground state, at ~1,550 nm wavelength. Second, the rare-earth element erbium (a seemingly obvious choice due to its telecom-wavelength transition and extensive use in fibre amplifiers) has so far eluded all attempts to store non-classical states of light with a fidelity above the classical limit due to improper relaxation dynamics for efficient optical pumping8 or noise issues9. This has prompted efforts towards finding indirect solutions such as the use of quantum state teleportation10 and wavelength conversion techniques11.

As well as telecom-wavelength storage, another milestone that would significantly benefit fibre-based quantum communication networks is the storage of non-classical states by means of light–atom interactions in optical fibres. This promises a simplified and robust set-up, comparable to the use of an erbium fibre amplifier in standard telecom networks. Cs-filled hollow-core photonic-crystal fibre shows promise in this regard12.

Here, we demonstrate that the obstacles to using erbium for optical quantum memory can be overcome and, furthermore, that quantum states of light can indeed be stored in impurities doped into an optical fibre. More precisely, through the use of commercially available erbium-doped fibre cooled to ~1 K and exposed to a suitably chosen magnetic field, the atomic frequency comb (AFC) quantum memory protocol13,14 can be implemented for the storage and faithful recall of 1,532 nm photons entangled with 795 nm photons.

Our experimental set-up (sketched and further explained in Fig. 1 and the Methods) is composed of three parts: a source of time-bin entangled photon pairs, a quantum memory for photons, and analysers that allow projection measurements with each member of the entangled photon pair. First, using spontaneous parametric downconversion (SPDC) of short laser pulses, we generate photon pairs with members at 795 nm and 1,532 nm wavelengths in a time-bin entangled biphoton state given by

$$|\phi'\rangle = \frac{1}{\sqrt{2}}(|e, e\rangle + |l, l\rangle)$$

(1)

Here, |i, j⟩ denotes a quantum state in which the 795 nm photon has been created in temporal mode i and the 1,532 nm photon in mode j. Furthermore, i, j ∈ |e, l⟩, and |e⟩ and |l⟩ label early and late temporal modes, respectively. The spectra of the 795 nm photon and the telecom photon are filtered to 6 GHz and 10 GHz, respectively, to allow subsequent storage of the 1,532 nm photon in the erbium-doped fibre.

Second, to store the 1,532 nm photons, a cryogenically cooled, commercially available erbium-doped fibre (Supplementary Section 2) is used in conjunction with the AFC quantum memory protocol13,14. AFC-based storage relies on tailoring an

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inherently broadened atomic transition (in our case the \( {^4}I_{11/2} \leftrightarrow {^4}I_{13/2} \) transition in Er\(^{3+}\) ions) into a series of absorption lines that are equally spaced by frequency \( \Delta \), forming an AFC (Fig. 2a,b). Spectral tailoring is performed by frequency-selective optical pumping of the ions into long-lived auxiliary levels. After preparation, a photon absorbed by the comb creates a collective atomic excitation described by

\[
|\Psi\rangle_A = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} c_j e^{i 2 \pi \phi_j} e^{-i \phi_j} |g_1, \ldots, e_j, \ldots, g_N\rangle
\]

where \( N \) is the number of atoms in the ensemble and \( \delta_j \) is the frequency detuning of the \( j \)-th atom’s transition with respect to the input photon’s carrier frequency. \( e_j \) and \( c_j \) denote the position within the medium and the excitation probability amplitude of the \( j \)-th atom, respectively. Following excitation, the terms in equation (2) start to accumulate different phases due to different detunings \( \delta_j \) of the excited ions. However, due to the discrete and periodic nature of the possible atomic transition frequencies in the AFC, \( \delta_j = m\Delta \) \( m \in \mathbb{Z} \), all phases align at time \( \tau = 1/\Delta \), resulting in the re-emission of the photon in its original quantum state (Fig. 2c). Under certain circumstances, the retrieval process has
been predicted to approach unit efficiency. The AFC protocol has been successfully implemented in several rare-earth-ion-doped crystals and has shown promise for creating workable quantum memory for light. However, in erbium-doped crystals, the implementation of an AFC is very challenging due to insufficient lifetime of the auxiliary spin (electronic Zeeman) level compared to that of the excited level, resulting in inefficient optical pumping. Erbium-doped silica fibres show great promise in overcoming this limitation. On the other hand, the disorder of the amorphous host reduces the coherence time, as discussed in the following.

Finally, to demonstrate experimentally our memory’s ability to store entanglement, individual projection measurements were performed on each member of the photon pairs onto time-bin qubit states

\[ |\psi\rangle = e^{\theta} |e\rangle + e^{\phi} |l\rangle, \quad \alpha^2 + \beta^2 = 1 \]

before and after storage of the 1,532 nm photon (see Methods). From the measurement outcomes we reconstruct the joint quantum state of the photon pairs in terms of its density matrix before and after storage of the 1,532 nm photon, as shown in Fig. 3.

From the reconstructed density matrices we compute parameters, listed in Table 1, that quantify relevant properties of the two-photon system. First, the fidelity quantifies the overlap of two quantum states. The fidelities of the photon pair states before and after storage with the maximally entangled \( |\phi^+\rangle \)-state given in equation (1) are 0.825 ± 0.004 and 0.808 ± 0.048, respectively. The deviation from the optimum value of 1 for the fidelity and purity (Table 1) is due to SPDC not creating individual photon pairs, but rather a distribution over even numbers of photons. However, the two measured fidelities and purities are equal (within statistical uncertainty), suggesting that the state is not altered during storage. This conjecture is verified by the input–output fidelity \( F_{\text{in/out}} = 0.971 ± 0.049 \) of the quantum state after storage with respect to the state before storage.

Another important parameter is the entanglement of formation \( E_{\text{f}} \), which gauges the amount of entanglement in our photon pairs. Values for \( E_{\text{f}} \) range from 0 for a separable state to 1 for a maximally entangled state. We find \( E_{\text{f}} = 0.531 ± 0.011 \) before storage and \( 0.499 ± 0.105 \) after storage, which shows that it is—and remains—entangled.

As a final entanglement witness, we performed a Clauser–Horne–Shimony–Holt (CHSH) Bell-inequality test. Before storage, we find the Bell-inequality parameter (see Methods) \( S_{\text{in}} = 2.38 ± 0.05 \) and, crucially, \( S_{\text{out}} = 2.33 ± 0.22 \) after storage (Table 1). This means that we find a violation of the maximum value of 2 allowed in local realistic theories by 7.5 and 1.5 standard deviations (s.d.), respectively. For more details see Methods and Supplementary Section 5.

Despite these important results, several parameters of our memory need to be improved for it to become useful for a future quantum Internet. First, the memory efficiency is currently limited by imperfect optical pumping to ~1% for 5 ns storage time. However, additional spectroscopic studies have indicated that under optimal conditions it is possible to substantially improve the optical pumping, and hence approach unity efficiency (see Supplementary Section 3 for details).

Furthermore, our memory provides a preprogrammed delay set by the AFC peak spacing. To convert it to a quantum memory with on-demand recall, one may utilize the inhomogeneous d.c. Stark shift to realize the controlled reversible inhomogeneous broadening (CRIB) protocol, or a hybrid AFC–CRIB memory protocol. Another approach is to reversibly map the optical coherence onto a long-lived spin level. However, the complex and largely unknown properties of these levels are likely to make such spin–wave mapping challenging, and further detailed studies are required. Having said this, we emphasize that recall on demand is not required for quantum memory to be useful for a practical quantum repeater. Instead, storage must be multimode in some degree of freedom and be susceptible to feedforward control of the recall in that same degree of freedom. On-demand recall corresponds to feedforward in the temporal degree of freedom, but spatial routing or frequency shifting are equally viable solutions for repeater architectures based on spatial and spectral multiplexing.
respective\textsuperscript{25}. It is worth noting that any repeater architecture requires ideal photon-pair sources\textsuperscript{27}, which seem particularly challenging to realize for spatial or spectral multiplexing approaches. See Supplementary Section 3 for further discussions.

Finally, the storage time (at most 35 ns in our demonstration) is limited mainly by the coupling of erbium ions to two-level systems, which are inherent in amorphous materials (Supplementary Section 3). Although it is conceivable that coherence times increase in lightly doped fibres, millisecond-long coherence times, as required for quantum repeaters, remain elusive given the current knowledge of the interaction of rare-earth ions in glassy hosts. Nevertheless, even if only short storage times are attainable, the large time–bandwidth product and multimode storage capacity of our light–matter interface is attractive for building on-demand single-photon sources\textsuperscript{27} or programmable atomic processors\textsuperscript{28}. These will probably find applications in a future quantum Internet, for example, in linear optics quantum computers and photonic quantum state processing. Moreover, erbium-based memories serving as short-lived interfaces may allow the conversion of quantum information between telecommunication photons and superconducting circuits\textsuperscript{29}.

To conclude, our results show that photon–photon entanglement can be reversibly mapped onto entanglement between a photon and a collective atomic excitation delocalized over a 20-m-long sample of $\sim 1 \times 10^{13}$ erbium atoms. Being based on the same material as a classical erbium fibre amplifier, our memory is the first to store non-classical states of light at telecom wavelength and, furthermore, it is the first quantum memory to use light–atom interaction in an optical fibre. We anticipate our proof-of-principle investigation to benefit the realization of quantum networks, and spur fundamental research towards an improved understanding of light–matter interaction in glassy hosts and collective atomic effects in unconventional materials.

**Methods**

Photon pair source. A mode-locked laser emitted, with 80 MHz repetition rate, 6-ps-long pulses at 1,047 nm wavelength. The pulses were frequency doubled by means of second harmonic generation (SHG) in a periodically poled lithium niobate (PPLN) crystal and directed to an imbalanced Mach–Zehnder interferometer (MZI) that split each pulse into two, separated by 1.4 ns. The interferometer phase was locked using a frequency-stabilized laser (not shown in Fig. 1) and adjusted using a procedure described previously\textsuperscript{46}. SPDC in a PPLN crystal yielded time-bin entangled photon pairs with centres at 795 nm and 1,532 nm wavelength. Filters (not shown) removed the remaining 523 nm light, after which a dichroic mirror separated the two photons in each pair. Finally, a Fabry–Perot cavity reduced the bandwidth of the 795 nm photon to $\sim 6$ GHz and a fibre Bragg grating reduced the bandwidth of the 1.532 nm photon to $\sim 10$ GHz, to allow it to be stored in the erbium-doped fibre. In addition, we note that the filtering creates entangled pairs suitable for quantum teleportation and, furthermore, allows the 795 nm photon to be stored in the Tm:LiNbO$_3$ quantum memory\textsuperscript{34} (see also Fig. 1b).

**Analysers.** The quantum states of the 795 and 1,532 nm photons were projected onto time-bin qubit states spanned by two, 1.4-ns-separated temporal modes. To this end, MZIs featuring path-length differences corresponding to 1.4 ns delay were used, followed by single photon detectors (SPDs), allowing projections onto $|\psi\rangle = (|e\rangle + e^{i\phi}|f\rangle)\sqrt{2}$ where the phase $\phi$ of the MZI was stabilized in the same manner as that of the photon pair source. Projections onto $|e\rangle$ and $|f\rangle$ were performed with a delay line (not shown) followed by an SPD. These projection measurements are henceforth also referred to as projections onto eigenstates and superpositions of the Pauli operators $\sigma_x$, $\sigma_y$, and $\sigma_z$ (corresponding to projections onto $1/\sqrt{2}(|e\rangle + |f\rangle)$, $1/\sqrt{2}(|e\rangle - |f\rangle)$, and $|l\rangle$, respectively). The SPDs for the 795 nm photons were based on silicon avalanche photodiodes and had detection efficiencies of $\sim 60\%$ and dark counts of $\sim 100$ Hz. The 1,532 nm photons were detected using superconducting nanowire single-photon detectors (SNSPDs) with a system efficiency of $\sim 60\%$ and dark counts of $\sim 10$ Hz (ref. 30; see Supplementary Section 1 for more details). A coincidence unit and a PC allowed the rates with which certain combinations of projections occurred to be assessed (for example, the rate at which the 795 nm photon was projected onto $|e\rangle$ and the 1,532 nm photon was projected onto $|e\rangle + |f\rangle)/\sqrt{2}$). The typical measured coincidence rates after storage were 0.06 Hz for projections onto $|\psi\rangle = (|e\rangle + e^{i\phi}|f\rangle)/\sqrt{2}$ and 1.4 Hz for projections onto $|e\rangle$ and $|f\rangle$ for the settings yielding maximum correlations (Fig. 1c).

**Quantum memory.** The light from an extended-cavity continuous-wave (c.w.) laser at 1,532 nm wavelength was frequency- and intensity-modulated using a phase modulator and acousto-optic modulator (AOM), respectively. After passing a switch and a circulator, it was sent into the erbium-doped fibre, which was exposed to a $\sim 600$ G magnetic field to split the erbium energy levels into magnetic sub-levels (Fig. 2a). Erbium–light interaction then led to frequency-selective persistent spectral hole burning with hole lifetimes of up to tens of seconds (more information will be published elsewhere) and, after repetition of the burning sequence for 400 ms, to an 8-GHz-wide AFC (Fig. 2b; for additional details see Supplementary Section 3). After spectral tailoring, we waited 300 ms in order to allow excited atoms to decay, that is, to ensure that recalled photons are not masked by spontaneous recommissioned photons. Finally, during 700 ms we sent entangled photons into the memory to be stored and recalled. To remove the light used for spectral hole burning during waiting and photon storage, the position of the switch was toggled (Fig. 1d).

**Density matrices.** By suitably adjusting the qubit analysers we could perform various joint projection measurements on the 795 nm and 1,532 nm photons onto time-bin qubit states, which we label $a$ and $b$, respectively, where $a, b \in \{\pm \sigma_x, \pm \sigma_y, \pm \sigma_z\}$. This yields coincidence count $C(a, b)$ rates of detected photon pairs. From two joint projection measurements, we calculate the normalized joint detection probability

$$P(a, b) = \frac{C(a, b)}{C(a, b) + C(a, -b)}$$

where $b$ and $-b$ refer to projections onto orthogonal states. The values of nine different joint detection probabilities (stemming from all combinations of $a, b \in \{\pm \sigma_x, \pm \sigma_y, \pm \sigma_z\}$) allow construction of the density matrices for our bipartite quantum system using a maximum likelihood method\textsuperscript{47} (Fig. 3).

**Bell inequality.** To test the CHSH Bell inequality we performed four sets of measurements, each consisting of four joint measurements with projections onto any combination of $ax$ (measured on one particle) and $xb$ (measured on the other particle), respectively, where $a \otimes b \in \{\sigma_x \otimes \sigma_x, \sigma_y \otimes \sigma_y, \sigma_z \otimes \sigma_z\}$. The chosen settings allow violation of the CHSH Bell inequality maximally. For each set, we calculate the correlation coefficient

$$E(a, b) = C(a, b) - C(-a, b) - C(a, -b) + C(-a, -b)$$

which, in turn, allows $S$ to be calculated as

$$S = |E(a, b) - E(a, b') + E(a', b) - E(a', b')|$$

Received 18 June 2014; accepted 27 November 2014; published online 12 January 2015

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Acknowledgements
E.S., J.J., D.O. and W.T. thank C. Thiel, N. Sinclair, M. Hedges, T. Lutz, K. Heshami, 
M. Grimau Puigiber, L. Giner, A. Croteau, C. La Mela and V. Kiselyov for technical help 
and/or discussions, and acknowledge funding through Alberta Innovates Technology Futures (AITF) 
and the National Science and Engineering Research Council of Canada (NSERC). W.T. is a senior fellow of the Canadian Institute for Advanced Research (CIFAR). 
V.B.V. and S.W.N acknowledge partial funding for detector development from the Defense 
Advanced Research Projects Agency (DARPA) Information in a Photon (InPho) 
programme. Part of the research was carried out at the Jet Propulsion Laboratory, California 
Institute of Technology, under a contract with the National Aeronautics and 
Space Administration.

Author contributions
The SNSPDs were fabricated and tested by V.B.V., M.D.S., F.M. and S.W.N. at the National 
Institute of Standards and Technology and Jet Propulsion Laboratory. All measurements 
were performed by E.S. and J.J., with help from D.O. The manuscript was written by W.T., 
E.S. and D.O.

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