An efficient quantum light–matter interface with sub-second lifetime

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Quantum repeaters1 hold promise for scalable long-distance quantum communication. The basic building block is a quantum light–matter interface that generates non-classical correlations between light and a quantum memory2. Significant progress has been made in improving the performance of this interface3,4, but further development of quantum repeater is hindered by the difficulty of integrating the key capabilities into a single system4. Here we report a high-performance interface with an efficiency and lifetime that fulfill the requirement of a quantum repeater. By confining cold atoms with a three-dimensional optical lattice and enhancing the atom-photon coupling with a ring cavity, we observe an initial retrieval efficiency of 76 ± 5% together with a 1/e lifetime of 0.22 ± 0.01 s, which supports a sub-Hz entanglement distribution at 1,000 km through the Duan-Lukin-Cirac-Zoller (DLCZ) protocol2. Together with an efficient telecom interface5,6 and moderate multiplexing7, our result may enable a quantum repeater system that beats direct transmission in the near future8.

Quantum communication9,10 relies on photon transmission over long distances. Direct transmission is limited to moderate distances (less than 300 km9,10) due to the exponential decay of photons. The quantum repeater1 is one solution to this limitation. Many quantum repeater schemes have been proposed11–13, but with current experimental capabilities memory-based schemes4 are much more feasible than the error correction-based schemes11–12. In a memory-based quantum repeater, the building blocks are a pair of non-classically correlated photon–memory pairs that can be generated either through direct Raman scattering2 or storing one photon in a quantum memory (see Methods for more discussion). Significant progress has been made in improving the performances of these building blocks9, but further advances are hindered by the difficulty of integrating key capabilities such as long storage times14–16 and memory efficiency17–20 into a single system. So far the storage lifetime has been improved to the sub-second regime for single excitations in an atomic ensemble5,15 and to the sub-minute regime for classical light storage16; nevertheless, storage efficiency in these experiments is typically very low (~16%). If we define a threshold of 50% for the memory efficiency, the longest storage time is limited to 1.2 ms21, which is far removed from the second regime requirement4 of a quantum repeater. Memory efficiency is critical as it intervenes in every entanglement swapping operation between adjacent quantum repeater nodes. According to theoretical estimations4, a 1% increase in the retrieval efficiency can improve the long-distance entanglement distribution rate by 10%–14%.

In this Letter we report an efficient quantum memory with a sub-second lifetime by making use of a three-dimensional (3D) optical lattice to confine an atomic ensemble inside a ring cavity. The quantum memory is non-classically correlated with a single photon, thus forms a light–matter interface for quantum repeaters2,4. The optical lattice limits atomic motion in all direction and thus suppresses all motion-induced decoherence. The ring cavity enhances atom–photon coupling, thereby improving the retrieval efficiency. We further use the magic trap technique22,23 to compensate for the lattice-induced differential light shift. To be compatible with sub-second regime storage, the ring cavity is stabilized with a large-detuned reference beam. By taking all of these measures, we finally realize a light–matter interface with an initial efficiency of 76 ± 5% and a 1/e lifetime of 0.22 ± 0.01 s.

The experimental set-up is shown in Fig. 1. An ensemble of 87Rb atoms is first prepared through magneto-optical trapping (MOT) and cooled down to about 12 µK via optical molasses. The atoms are finally loaded into a 3D optical lattice by interfering four 1064-nm laser beams at the set-up centre and optically pumping to the ground state (F = 2, mF = 0). Lattice periods are 5.9 µm, 2.8 µm and 0.54 µm for the x, y and z directions, respectively. The lattice-trapped ensemble is 0.2 mm wide in the x–y plane and 0.8 mm long in the z direction. The optical depth is about 1.6 in the z direction. A temporal gap of 90 ms is left in the lattice phase to allow the unbound atoms to escape (see Methods for more technical details). Confinement of the atom motion with a 3D optical lattice suppresses all motion-induced decoherence24, but gives rise to a new decoherence—a differential light shift. By adding an appropriate bias magnetic field B, the differential light shift from the vector polarizability compensates that from the scalar part25. Without the ring cavity, we first calibrate the magic condition via electromagnetically induced transparency (EIT)25. The single-photon-level probe pulse to be stored is resonant with the D1 line (F = 2 → F′ = 1) and transmits in the write-out direction in Fig. 1. The control pulse is resonant with the transition (F = 1 → F′ = 2) and transmits in the write-out direction. The probe and control pulses are controlled to enable a stopped-light configuration25. By optimizing the retrieval amplitude at t = 0.5 s, we find the best magic compensating field to be 4.56 gauss. With a lattice potential of U0 = 146 µK, we measure the retrieval signal decay as a function of storage time in Fig. 2a. The 1/e time constant is fitted to be 0.51 ± 0.03 s. As the lattice laser power U0 is varied, the storage lifetimes are more or less the same with an average value of 0.53 s (Fig. 2b). This indicates that the differential light shift has been successfully eliminated.

Afterwards, we set up a ring cavity around the lattice-trapped atoms to enhance the atom–photon coupling strength and carry out DLCZ2 memory with single photons. The orthogonal linearly polarized write and read pulses counterpropagate through the atoms (Fig. 1). The write and read beams are red detuned by 40 MHz to the D1 transitions. The write-out and read-out photons are configured to be resonant with the ring cavity. The
cavity has a finesse of $\mathcal{F} = 52$ and a linewidth of 9.2 MHz. To optimize the cavity enhancement during retrieval, the cavity is stabilized with a large-detuned reference beam during storage (see Methods for details). By applying a write pulse, a write-out photon is detected with an overall probability of $p_w \approx 10^{-3}$ and heralds the creation of a collective excitation in the atomic ensemble. As $p_w$ is low, we repeat the write trials until a write-out signal photon is detected. The retrieval process with an adjustable delay only starts after a successful write-out event. The retrieval efficiency is measured as $R = p_{bw}/p_w$, where $p_{bw}$ ($p_w$) refers to the conditional (unconditional) detection probability of a read-out photon. Unexpectedly, we observe a significant efficiency decay within the initial sub-millisecond regime, as shown in Fig. 3 in black. We suspect that this is due to imperfect lattice potentials that result in some free atoms not confined within single lattice sites. Thus we make the same measurement for the angled case\textsuperscript{24} ($\theta = 0$), with the result shown in Fig. 3 in red. The retrieval efficiency drops by about 50\% in both measurements but with different timescales. The retrieval efficiency of the angled case drops faster as the phase grating is distorted by transverse movement of a half spin-wave wavelength ($\lambda_{sw}/2 = 7.6 \mu m$). In the collinear case, however, as the spin-wave wavelength is increased to 4 cm, transverse motion influences the retrieval efficiency by distorting the transverse mode of the read-out photon, which is sensitive to the movement scale of the cavity mode waist ($w_{cav} = 60 \mu m$). Considering an atom temperature of 12 $\mu K$, the time required for movement over $\lambda_{sw}/2$ or for $w_{cav}$ coincides with the decay time observed in Fig. 3. To minimize these free atoms, we dynamically increase $U_0$ from 70 $\mu K$ to 180 $\mu K$ after all the unloaded atoms escape the lattice region. By doing this, the rate of reduction in the retrieval efficiency decreases remarkably to $1 - R(10 ms)/R(0 ms) \approx 20\%$, which is a significant improvement compared with previous experiments with a 1D lattice\textsuperscript{3, 15, 26} and a hollow beam dipole trap\textsuperscript{27}. In Fig. 4 we show the final result of the retrieval efficiency measurements in the range of 0–500 ms. The intrinsic retrieval efficiency $\chi$ is obtained through $\chi = R/(n_{cav} \eta \eta_{pd})$, where $n_{cav} = 68 \pm 3$ $\%$ refers to the photon emanation rate from the ring cavity, $\eta = 55 \pm 2$ $\%$ refers to the propagation efficiency from the cavity to the detectors and $\eta_{pd} = 63 \pm 2$ $\%$ refers to the detection efficiency for the single-photon detectors. We fit the data with a double-exponential decay function $\chi(t) = \chi_1 \exp(-t/\tau_1) + \chi_2 \exp(-t/\tau_2)$, where $\tau_1$ and $\tau_2$ are the two characteristic decay parameters. The fit parameters are $\tau_1 = 0.13 \pm 0.04$ ms, $\tau_2 = 285 \pm 12$ ms, $\chi_1 = 15.8 \pm 1.8$ $\%$ and $\chi_2 = 59.8 \pm 4.0$ $\%$ respectively. The initial intrinsic retrieval efficiency is $\chi(0) = 76 \pm 5$ $\%$, which is comparable with the best previous results on efficiency in the single-quanta regime\textsuperscript{17, 21}. The 1/e decay time for

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### Figure 1: Experimental set-up and atomic levels.

The $^{87}$Rb atoms are trapped with a 3D optical lattice by interfering four circularly polarized 1,064 nm laser beams ($L_i = (1,2,3,4)$). The atoms are initially prepared in the ground state ($|F = 2, m_F = 0\rangle$). Another ground state of ($|F = 1, m_F = 0\rangle$) is employed for storage. The ring cavity in the horizontal plane (the $y$-$z$ plane) consists of an elliptical mirror (PM) of 92.0 $\pm$ 0.3 $\%$ reflection rate and cavities of $|F = 2, m_F = 0\rangle$ and $|F = 1, m_F = 0\rangle$ are combined into the read-out channel with a polarized beam splitter. The write-out and read-out photons are cavity-enhanced through the atoms with a separation angle of $\theta = 3^\circ$, whereas red dots indicate the collinear case $\theta = 0^\circ$. For a reference of $R_{sw} = 0.5e^{-t/1} + 0.5$ (grey dashed line), the decay time is 0.23 ms for the angled case and 2.52 ms for the collinear case. $U_0$ has a fixed value of 70 $\mu K$. Error bars indicate ±1 s.d.

### Figure 2: Lifetime measurement of the optical lattice-trapped EIT memory without a cavity.

**a.** Retrieval amplitude normalized to the time point $t = 10$ ms. Fitting with an exponential function (grey dashed line), we get a 1/e lifetime of $\tau = 0.51 \pm 0.03$. The lattice potential is set to $U_0 = 146$ $\mu K$ for this measurement. **b.** Lifetime measured for different trap potentials. The average value is $\tau = 0.53$ s (grey dashed line). In both plots the error bars indicate ±1 s.d.

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### Figure 3: Millisecond-regime decay of the retrieval efficiency with DLCZ storage. $R$ is normalized to the initial value at $t = 0$. Black squares refer to data points for $\theta = 3^\circ$, whereas red dots indicate the collinear case $\theta = 0^\circ$. For a reference of $R_{sw} = 0.5e^{-t/1} + 0.5$ (grey dashed line), the decay time is 0.23 ms for the angled case and 2.52 ms for the collinear case. $U_0$ has a fixed value of 70 $\mu K$. Error bars indicate ±1 s.d.
the retrieval efficiency is 0.02 ± 0.01 s, which is also comparable with the best previous results on lifetime in the single-quanta regime. For an threshold of χ ≥ 50%, our memory can persist until 51 ms, whereas the best previous result is merely 1.2 ms. We would like to stress that efficient storage far beyond the millisecond regime is critical for quantum repeaters. To further identify that our experiment genuinely operates in the single-quanta regime, we measure the anticorrelation parameter D for different storage times, with the results shown in Table 1. The write-out photon is detected with D, whereas the read-out photon is 50:50 split and detected with two separate detectors D2 and D3. The parameter is defined as

\[ \alpha = \frac{p_{123}/(p_{21} \cdot p_{31})}{1} \] (1)

where \( p_{ijk} \) is the conditional single (twofold coincidence) detection probability. The measured \( \alpha \) parameter at \( t = 0 \) s and \( t = 0.5 \) s are 0.11 ± 0.05 and 0.30 ± 0.21 respectively, both of which are well below the classical threshold of \( \alpha \geq 1 \), implying the non-classical behaviour of our memory and safely precluding any interpretation of the efficient retrieval as a nonlinear amplification process.

Realization of a light–matter interface with high efficiency and sub-second lifetime has significant applications in long-distance quantum communication. If we consider a DLCZ quantum repeater with multiplexing, our current efficiency and lifetime results already support sub-Hz entanglement distribution up to 1,000 km (see the Supplementary Information for detailed calculations), assuming a channel loss of 0.16 dB/km (ref. 10), perfect telecom interface, single-photon detectors with 100% efficiency and moderate multiplexing. A higher intrinsic retrieval efficiency will be possible by using a cavity with higher finesse. Longer storage times will be possible through dynamical decoupling, employing a solid-state ensemble or both. As the optical lattice tightly confines atoms in all directions, our system has a feasible spatial multiplexing capacity with a long lifetime. To realize a practical quantum repeater, coupling losses have to be minimized and a telecom interface with high efficiency should be integrated. Our result will also be very useful for creating large-scale cluster states for one-way quantum computing.

### Methods

Methods and any associated references are available in the online version of the paper.

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### Table 1 | Measurement of the α parameter.

| t (ms) | α | \( n_{123} \) | \( n_{231} \) | R (%) | χ (%) | \( T_m (h) \) |
|-------|---|--------|--------|------|------|----------|
| 0     | 0.11(5) | 6 | 55 | 17.1(5) | 73(5) | 1.4 |
| 10    | 0.16(7) | 6 | 37 | 12.4(4) | 53(4) | 5.3 |
| 100   | 0.28(11) | 7 | 25 | 9.7(3) | 41(3) | 6.1 |
| 300   | 0.09(9) | 1 | 11 | 5.0(2) | 23(2) | 5.6 |
| 500   | 0.30(21) | 2 | 7 | 2.6(1) | 24(1) | 24.7 |

\( n_{123} \) number of triple coincidence events of the detectors D1, D2 and D3 \( (n_{231}) \), theoretical expected triple coincidence events when α = 1, \( T_m \) measurement duration.
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Author contributions
S.-J.Y., X.-H.B. and J.-W.P. conceived and designed the experiment. S.-J.Y., X.-J.W. and X.-H.B. carried out the experiment. All authors analysed the data. S.-J.Y., X.-H.B. and J.-W.P. wrote the paper. X.-H.B. and J.-W.P. supervised the whole 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 X.H.B. and J.W.P.

Competing financial interests
The authors declare no competing financial interests.
Methods
Comparison between the different types of memory. For application in quantum repeaters, optical quantum memories can be categorized into two classes. Class 1 emits one photon first and emits another photon later on demand, which is the case with our memory. Class 2 is the in-and-out quantum memory, which can store an arbitrary state of a single photon and release it later on demand, such as memories based on EIT or the atomic frequency comb (AFC). A class 1 memory can be used directly to build a quantum repeater. A class 2 memory can be used together with a suitable photon pair source to form an equivalent class 1 memory by storing one photon from a photon pair with a class 2 memory. In this sense, the two types of memories can be compared. Memory efficiency in class 1 refers to the heralded retrieval efficiency for a read-out photon conditioned on a detected write-out photon, which compares with the overall (storage and retrieval) efficiency of a class 2 memory. The write-out photon detection probability for a class 1 memory corresponds to the idler-photon detection probability (with the signal photon stored in a class 2 memory). In general, we think both classes have merits and drawbacks. For class 2, it is easy to incorporate a telecom interface by making use of a frequency non-degenerate photon pair that has one photon of a telecom wavelength and the other of a wavelength for storage. A key difficulty with class 2 is making an efficient connection between a photon pair source and the memory. For class 1, its simplicity is a major advantage due to the built-in photon source, nevertheless high-demanding technique of single-photon frequency conversion has to be used to interface with telecom fibres.

Technical details. The optical lattice is formed by four circularly polarized laser beams $L_i$ ($i = \{1,2,3,4\}$), with the same waist diameter of 500 $\mu m$ overlapping through the atoms, axisymmetrically angled at 12° to the bias magnetic field $B$. The 1,064 nm laser output is split 50:50 into two beams $L_1$ and $L_2$, then reflected backwards and used as the beams $L_3$ and $L_4$, respectively. As the vacuum glass cell does not have an anti-reflective coating for 1,064 nm, the power of $L_3$ ($L_4$) is 19% lower than $L_1$ ($L_2$). The write pulse is vertically polarized, with a pulse width of 120 ns and a beam power of 3.8 $\mu W$; whereas the read pulse is horizontally polarized, with a pulse width of 240 ns and a beam power of 330 $\mu W$. The write-out photons are collected by a single-mode fibre, and measured by single-photon detector $D_1$ after a Fabry–Perot cavity filter; the read-out photons are collected and sent through a vapour cell atomic filter and then measured by single-photon detectors $D_2$ and $D_3$ after 50:50 splitting. To suppress the beam leakages and their influences on the stored single excitations in the ensemble, most of the laser beams are controlled by double-passed acousto-optic modulators and the laser beams for the MOT are blocked with a mechanical chopper during memory operations.

Cavity stabilization during storage. In our previous experiments, the cavity was intermittently stabilized to avoid influences from the locking beam on the memory. To obtain a high retrieval efficiency for long storage durations, we have developed a cavity stabilization technique with large detuning of the atomic transitions. The cavity locking beam is from a reference laser of $\lambda = 800$ nm 5 nm detuned to the D1 line transition, and is stabilized with an ultra-stable cavity due to the unavailability of atomic lines. The cavity locking beam has a power of 1 $\mu W$, which introduces a differential light shift of 0.3 Hz inside the cavity. In our experiment, we turn on the locking beam for 10 ms to pull back the cavity resonance before applying the read pulse.