

Towards high-speed optical quantum memories

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Quantum memories, capable of controllably storing and releasing a photon, are a crucial component for quantum computers¹ and quantum communications². To date, quantum memories^{3–6} have operated with bandwidths that limit data rates to megahertz. Here we report the coherent storage and retrieval of sub-nanosecond low-intensity light pulses with spectral bandwidths exceeding 1 GHz in caesium vapour. The novel memory interaction takes place through a far off-resonant two-photon transition in which the memory bandwidth is dynamically generated by a strong control field^{7,8}. This should allow data rates more than 100 times greater than those of existing quantum memories. The memory works with a total efficiency of 15%, and its coherence is demonstrated through direct interference of the stored and retrieved pulses. Coherence times in hot atomic vapours are on the order of microseconds⁹, the expected storage time limit for this memory.

Photons are ideal carriers of quantum information. They have a very large potential information capacity, and do not interact with one another, making encoded information robust. Recent developments in sources, detectors, gates and protocols have laid the basis for the construction of large-scale photonic quantum computers with unique capabilities^{1,10}, as well as inter-continental quantum networks that are immune to undetected eavesdropping¹¹. However, the effects of photon loss and the inherently probabilistic character of some of these components make photon storage desirable. The difficulty that many photonic networks successfully produce a result only rarely is overcome if photons can be stored, because this allows complex protocols to be orchestrated by holding the output of successful operations until all have been correctly executed¹. Quantum memories are therefore an active area of research, with much interest being focused on reversibly mapping photons into collective atomic excitations^{5,12}.

The key characteristics for quantum memories are long storage time, high memory efficiency, the ability to store multiple modes (multiple distinct photons)^{11,13} and high bandwidth. High bandwidth allows the storage of temporally short photons, enabling quantum information to be processed at a higher ‘clock rate’. This can be difficult to achieve with atomic memories, because photons must be stored in long-lived atomic states with narrow linewidths. Here we demonstrate the storage of signal pulses with a bandwidth 300 times larger than the natural width of the caesium $D2$ line that mediates the interaction.

Previously implemented memory protocols include electromagnetically induced transparency (EIT), controlled reversible inhomogeneous broadening (CRIB) and atomic frequency combs (AFCs). Memories based on measurement and feedback have also been developed^{14,15}. EIT-based memories^{16–18} use the extreme dispersion of an induced transparency window to modify the group velocity, and stop, store and retrieve light pulses in a controllable manner. CRIB^{19–21} is a photon echo technique that uses an artificial inhomogeneous broadening of the atomic resonance. Reversing this

broadening during the readout process causes the atomic spins to re-phase and collectively re-emit the original signal. In the AFC protocol^{4,22}, an artificially created AFC absorbs the incident signal, and the periodic structure of the absorption spectrum results in a subsequent re-phasing and re-emission of the stored signal. These protocols are resonant; off-resonant light storage has also been implemented by means of four-wave mixing⁹, stimulated Brillouin scattering²³ and through the gradient echo memory (GEM) protocol²⁴. For all these protocols, typical storage times range from microseconds to milliseconds, achieved efficiencies from 1 to 15% (although two experiments have reported higher values for either storage time or efficiency^{25,26}) and reported bandwidths from a few kilohertz to several megahertz.

In this Letter, we present the experimental demonstration of a coherent, efficient and broadband Raman memory for light. In a Raman memory, the bandwidth is generated dynamically by ancillary write/read pulses, which dress the narrow atomic resonances to produce a broad virtual state to which the signal field couples. The off-resonant nature of the scheme confers some appealing features^{7,8,27}. The first, as already mentioned, is the ability to store broadband pulses. The large detuning guarantees that the atomic polarization adiabatically follows the pulse envelopes, even when they are temporally short. The second feature is insensitivity to inhomogeneous broadening. The Raman transition is detuned far beyond the Doppler linewidth of the caesium vapour. Finally, the ‘failure mode’ of the memory is transmission. If storage is partial, the remaining signal passes through the memory without being absorbed resonantly in the atoms, thus entangling the memory with the transmitted optical mode. In other words, a Raman memory behaves like a beamsplitter, the transmissivity of which depends on the shape and energy of the write pulse⁸. Such light-matter entanglement operations are primitives for the construction of quantum repeaters^{2,11}. In our current experiment, we used signal pulses containing several thousand photons, but because the memory interaction is linear and coherent, the Raman protocol is a genuine quantum memory that would also be capable of single-photon operation. (A detailed discussion of the associated technical challenges can be found in the Supplementary Information.)

In the experiment, a strong write pulse and a weak signal pulse, both broadband, are spatially and temporally overlapped and sent together into a caesium vapour cell, the storage medium in which the Raman interaction takes place (Fig. 1a). The signal pulse is mapped via a two-photon transition with the write pulse into a collective atomic excitation called a spin wave. At a later time, a strong read pulse is sent into the vapour cell and converts the spin wave into an optical output signal that is measured by a fast detector. The $F = 3, 4$ ‘clock states’ of the $6^2S_{1/2}$ ground-level hyperfine manifold serve as the states $|1\rangle$ and $|3\rangle$, which are connected to the excited state $|2\rangle$ (the $6^2P_{3/2}$ manifold) via the $D2$ line at 852 nm (Fig. 1b). The caesium is heated to 62.5 °C, so that the $D2$ -line optical depth $d \approx 1,800$ is high.

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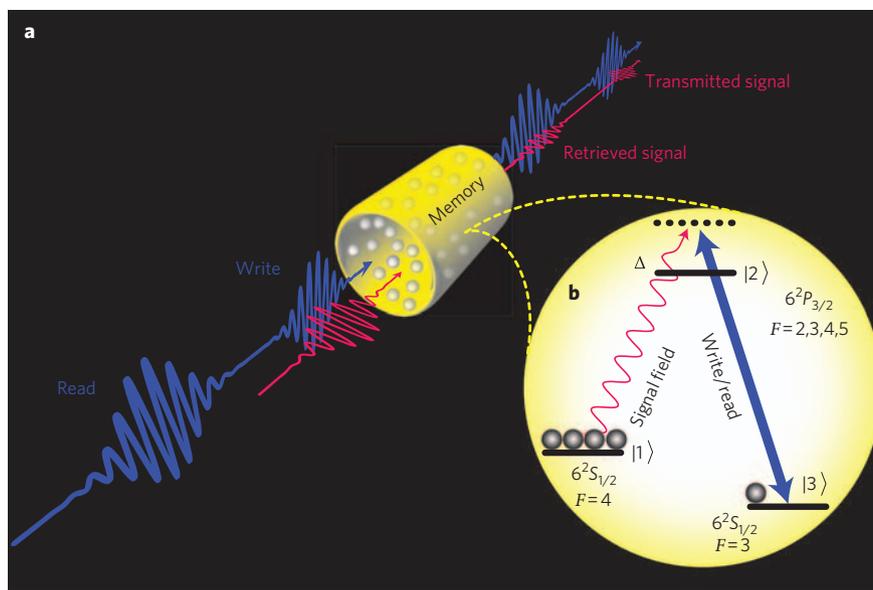


Figure 1 | Raman memory. **a**, The signal is directed into the memory together with a bright write pulse and is stored. If the storage is partial, any unstored signal is transmitted through the memory. A subsequent bright read pulse extracts the stored excitation, which emerges along with the transmitted read pulse. **b**, The Λ -level structure of the atoms in the memory. The atoms are prepared in the ground state $|1\rangle$ by optical pumping. The signal is tuned into two-photon resonance with the write field; both are detuned Δ from the excited state $|2\rangle$. Absorption of a signal photon transfers an atom from $|1\rangle$ into the storage state $|3\rangle$ via Raman scattering stimulated by the write field. Upon retrieval, the interaction is reversed.

Experimental data for the storage and retrieval processes are displayed in Fig. 2, showing retrieval of the stored information 12.5 ns after storage of the signal pulse ($t=0$). The storage and retrieval efficiencies depend on the write and read pulse energy. When this energy is zero, 100% of the incident signal field is transmitted, which contrasts with resonant storage protocols, in which the memory becomes absorbing when ‘inactive’. As the energy increases, the transmitted fraction of the incident signal decreases and the retrieved signal increases. The inset in Fig. 2 shows the short pulse duration of the retrieved signal. The measurement is

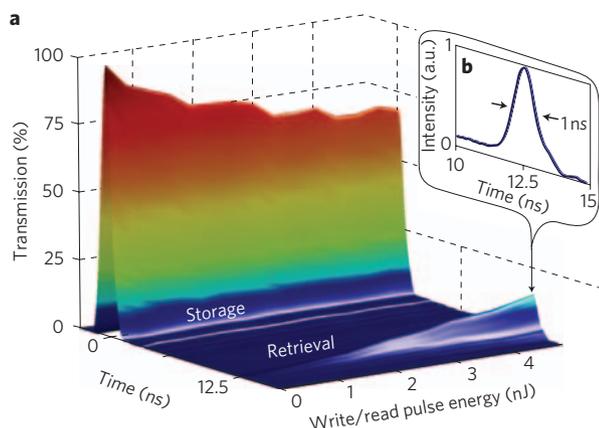


Figure 2 | Experimental data for storage and retrieval processes. **a**, Storage ($t=0$ ns) and retrieval ($t=12.5$ ns) of light pulses plotted versus write/read pulse energy. With no write pulse present (0 nJ), there is 100% transmission. With the highest write/read pulse energies (4.8 nJ) the transmission drops to 70%, indicating that 30% of the incident signal is stored. At $t=12.5$ ns, 50% of the stored information is retrieved, giving a total memory efficiency of 15%. **b**, Detail of the retrieved signal field showing the measured full-width at half-maximum (FWHM) temporal duration of 1 ns, limited by the detector response time. This shows that the bandwidth of the retrieved signal exceeds 1 GHz.

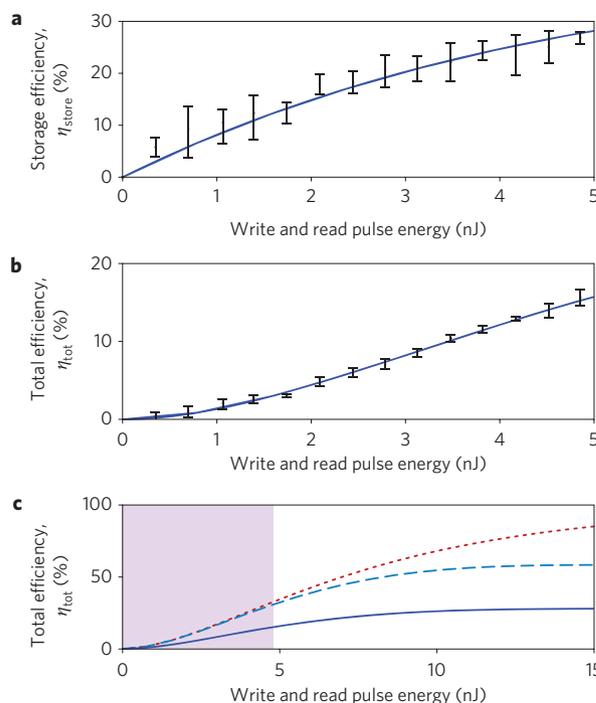


Figure 3 | Dependence of memory efficiency on write/read pulse energy.

a, Storage efficiency. **b**, Total efficiency. Dots and error bars represent experimental data; solid lines represent predicted theory. Error bars indicate the standard deviation derived from several data sets, each averaged over 100 samples per point. **c**, Theoretical predictions for total efficiency extrapolated to higher pulse energies, using the same experimental optical depth d . Solid line: efficiency for current experimental configuration (forward readout). Dashed line: optimal efficiency using forward retrieval, limited by re-absorption^{7,28}. Dotted line: optimal efficiency using phase-matched backward retrieval. The shaded area denotes the range of pulse energies accessible in the present experiment.

limited by the 1 ns response time of the detector, corresponding to a bandwidth of 1 GHz. Theoretically, the Raman memory is also capable of larger bandwidths (see Supplementary Information).

The time–bandwidth product N of a memory quantifies the number of distinct time bins available for computational operations in a hypothetical quantum processor using the memory. Assuming that the storage time of the memory is limited to several hundred microseconds—typical of warm alkali vapours⁹—time–bandwidth products as high as $N \approx 1 \times 10^5$ should be achievable. Another useful figure of merit is the multimode capacity: the number of modes that can be stored simultaneously (in a single storage/retrieval cycle)^{11,13}. Multimode memories have applications in multiplexed quantum repeater protocols¹¹. Although the Raman memory is essentially a single-mode memory in the current collinear configuration¹³, multiple modes can be stored by using either angular multiplexing²⁸ or multiple memories²⁹.

Figure 3a,b shows a comparison of the measured storage and retrieval efficiencies with the predictions of a theoretical model⁸ (see Supplementary Information). The experimental observations agree well with this model.

The retrieval efficiency $\eta_{\text{ret}} = \eta_{\text{tot}}/\eta_{\text{store}}$ is significantly larger than the storage efficiency η_{store} , because the total efficiency η_{tot} exceeds η_{store}^2 , indicating that the signal pulse shape is not optimal, (an ideal memory has equal storage and retrieval efficiencies)⁷.

Figure 3c shows a theoretical extrapolation for η_{tot} to larger control pulse energies. In the present configuration, using forward retrieval, $\eta_{\text{tot}} \approx 30\%$ is achievable for pulse energies of ~ 15 nJ. Also plotted is the optimal attainable efficiency for this case, along with the optimal efficiency for backward retrieval^{7,28}. Achieving these bounds requires appropriate shaping of the signal field to compensate for distortion introduced by the etalons and for the dynamic Stark shift from the strong write field. This, however, may not be straightforward, because pulse shaping in the sub-nanosecond regime is an emerging technology and an active research area in itself. Re-absorption of the signal limits the efficiency to $\sim 60\%$ for forward retrieval, but efficiencies above 90% can be reached using phase-matched backward retrieval²⁸.

Because we retrieve the stored signal after just 12.5 ns, the observed efficiency is not affected by decoherence, which is only significant over much longer timescales. Instead, it is a direct probe of the intrinsic efficiency of the Raman memory interaction (see Supplementary Information). In addition, with this configuration it is easy to delay a copy of the signal pulse and interfere it directly with the retrieved pulse, to demonstrate the coherence of the interaction (Fig. 4). The fringe visibility of $82.7 \pm 0.9\%$ indicates that the memory is highly coherent. This matches well with the model,

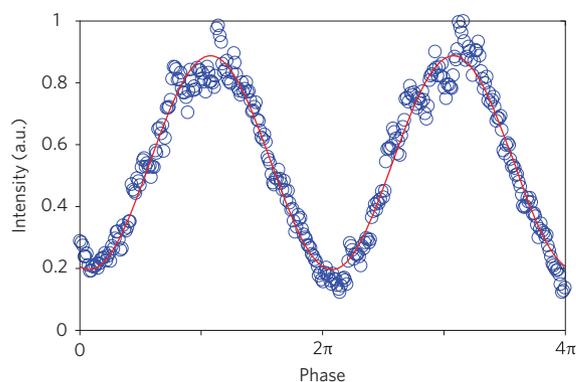


Figure 4 | Raw interference of stored and retrieved signals. Circles indicate experimental data, and the solid curve is a least-squares fit. A linear scan of the path length difference in the interferometer results in sinusoidal oscillations of the total intensity. This shows a high visibility of $82.7 \pm 0.9\%$ (normalized for interferometer instability).

which predicts some distortion due to dispersion and Stark shifts (see Supplementary Information), suggesting that the memory interaction itself is perfectly coherent.

In summary, we have demonstrated a broadband quantum-capable memory by coherently storing and retrieving signal pulses with bandwidths greater than 1 GHz. This is an increase of a factor of more than 100 compared to existing quantum memories. We observed storage efficiencies up to 30% and retrieval efficiencies as high as 50%, and increasing the power of the control pulses should allow further improvements. The excellent coherence of the memory was directly verified by interfering the stored and retrieved pulses. This Raman memory scheme is broadly applicable and not constrained only to hot atomic vapours; other possible interaction media include cold gases and solid-state systems. Such high-speed memories will form the basis of fast, controllable and robust photonic quantum information processors in the near future.

Methods

The experimental layout is described in Fig. 5. The read, write and signal pulses are obtained from a Ti:sapphire oscillator with a FWHM of 300 ps (1.5 GHz bandwidth). The fundamental Ti:sapphire laser frequency is tuned 18.4 GHz to the blue of the $|2\rangle$ – $|3\rangle$ transition in Fig. 1b. A Pockels cell selects two consecutive pulses separated by 12.5 ns. The laser beam is split into a strong control arm with vertical polarization (\updownarrow) and a very weak signal arm with horizontal polarization (\leftrightarrow). The control arm is delayed by 12.5 ns with respect to the signal arm such that the first pulse in the control arm overlaps in time with the last pulse in the signal arm. An electro-optic modulator (EOM) is used in the signal arm to generate sidebands 9.2 GHz shifted from the fundamental laser frequency. After spectral filtering with

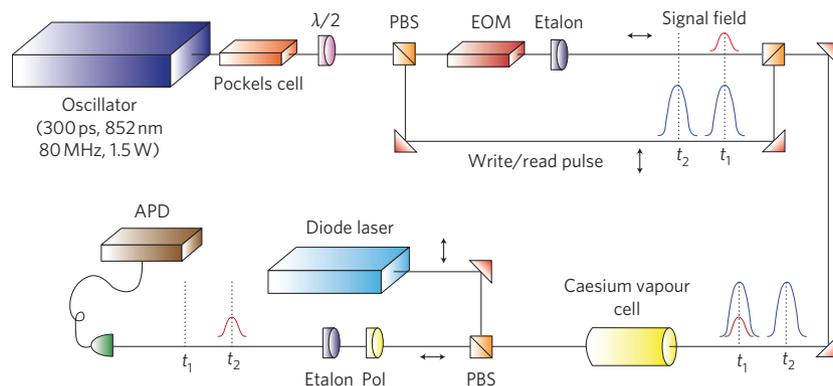


Figure 5 | Experimental set-up. A caesium vapour cell is optically prepared with a diode laser. In time bin t_1 , an incoming signal pulse is mapped by a strong write pulse into a spin wave excitation in the atomic ensemble. At t_2 , a strong read pulse reconverts the excitation into a light pulse. After polarization filtering (Pol), the retrieved signal is detected by a high-speed avalanche photo detector (APD). Vertical polarization is indicated as ' \updownarrow ' and horizontal polarization as ' \leftrightarrow '. EOM, electro-optic modulator; PBS, polarizing beamsplitter.

Fabry–Perot etalons, only the 9.2 GHz redshifted sideband corresponding to the $|1\rangle$ – $|2\rangle$ transition is transmitted and used as the signal field (see Supplementary Section). The control and the signal beam, spectrally separated by 9.2 GHz, are recombined and made collinear. They are focused with a beam waist of 350 μm into the 7-cm-long vapour cell filled with caesium and 20 torr of neon buffer gas. Polarization and spectral filtering are used after the cell to reject the strong write and read pulses and transmit only the signal field. A high-speed avalanche photodetector (APD) with a bandwidth of 1 GHz detects the very weak signal pulse. The atomic ensemble is initially prepared in the ground state $|1\rangle$ by optical pumping using an external cavity diode laser tuned to resonance with the $|2\rangle$ – $|3\rangle$ transition.

To investigate the coherence properties of the memory, a copy of the incident signal field is attenuated, delayed and overlapped with the retrieved signal in a Mach–Zehnder configuration. We correct for imperfections in the interferometer by simultaneously interfering the signal and a replica as a benchmark (see Supplementary Information); this yields a visibility of $82.7\pm 0.9\%$ for the memory.

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Author contributions

K.F.R. built the experiment, with initial assistance from V.O.L., and collected the data. K.F.R., J.N. and B.J.S. contributed to the theoretical analysis. N.K.L. assisted with design and analysis of the coherence measurements. K.C.L., N.K.L. and D.J. added useful insights, and I.A.W. conceived the experiment. The manuscript was written by K.F.R. with input from B.J.S., J.N., N.K.L. and I.A.W.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper at www.nature.com/naturephotonics. Reprints and permission information is available online at <http://npg.nature.com/reprintsandpermissions/>. Correspondence and requests for materials should be addressed to I.A.W.