Optical quantum memories are essential elements in quantum networks for long-distance distribution of quantum entanglement. Scalable development of quantum network nodes requires on-chip qubit storage functionality with control of the readout time. We demonstrate a high-fidelity nanophotonic quantum memory based on a mesoscopic neodymium ensemble coupled to a photonic crystal cavity. The nanocavity enables >95% spin polarization for efficient initialization of the atomic frequency comb memory and time-bin–selective readout through an enhanced optical Stark shift of the comb frequencies. Our solid-state memory is integrable with other chip-scale photon source and detector devices for multiplexed quantum and classical information processing at the network nodes.
The experimental magnetic field ($B = 540$ mT) configuration is illustrated in Fig. 3A. The misalignment of the magnet with respect to the sample caused a slight deviation $\theta$ of the field orientation from the $c$ axis (crystal symmetry axis). From the bulk optical pumping measurement [supplementary text (17)], we estimated this deviation to be $-8.2^\circ$. A representative spectrum for the four transitions is plotted next to the Zeeman-level splitting (24) in Fig. 3A. The spin-preserving transitions a and c overlapped, which favored higher optical depth and better impedance-matching when using their overlapped spectral region as a photon-atom interface. The b and d transitions had smaller branching ratios, but both were enhanced, similar to the a and c transitions in the cavity. Using the pulse modulation sequence shown in the inset of Fig. 3C, we verified that the Zeeman spin lifetime in the cavity, $T_1^\text{cav} = 12.5 \pm 1.0$ ms, was not degraded relative to the bulk, $T_1^\text{bulk} = 12.7 \pm 1.5$ ms (Fig. 3B). Figure 3C plots the spin population as a function of optical pumping time $t_p$. In the nanocavity, a maximum spin polarization of $P_\parallel = 20 (P_\perp < 5\%)$ was achieved with $t_p$ less than 1 ms, whereas in the bulk, it took more than 10 ms to reach $P_\parallel = 3$. This enhancement can be understood from a rate-equation model taking into account the field angle-dependent branching ratios given by the spin Hamiltonian (23-25) [supplementary text (17)].

To demonstrate storage of photonic qubits by means of the AFC protocol, we sent a sequence of 10-ns pulse pairs separated by a time interval $t = 1/\Delta$, where $\Delta$ is the frequency spacing of the
cavity for a photon sent into the cavity will be emitted back into the waveguide terminal (where $i > 5\%$ (blue), versus $-20\%$ (red) in the bulk). The inset shows the AOM modulation sequence. The bulk spin population was measured by the transmission of the probe pulse (red). The cavity was probed using photoluminescence counts after the probe excitation (blue). (D) An AFC with $F = 3.3$ and $\sim 400$ ions in each tooth. Gray, 100-kHz resolution; black, 500-kHz resolution. (E) Input (black line), reflected (blue area), and AFC echo signal of a coherent state (mean photon number $\alpha = 0.58$) time-bin mode $|+/-\rangle$ from the nanocavity. The inset shows the lower bounds on the qubit storage fidelity for a set of inputs, with an arithmetic mean fidelity of 96.8%. Error bars, standard deviation.

comb. The number of pulses in the sequence was optimized for the best echo efficiencies for a given $t_e$, which effectively controlled the finesse $F$ of the comb. Figure 3D shows an AFC with $F = 3.3$, $\Delta = 13.3$ MHz, and a vanishing absorption background. The peaks of the comb appeared to be slightly eroded because of power broadening of the burning pulses. The narrowest tooth width was 3.2 MHz full-width-at-half-maximum (FWHM), which was likely to be limited by the superhyperfine interactions in Nd:YVO and spectral diffusion during comb preparation.

Given the comb profile, we estimate an expected device storage efficiency $\eta_{\text{echo}}$, defined as the probability that an AFC echo photon will be emitted back into the waveguide terminating the cavity for a photon sent into the cavity—to be 4%, on the basis of $\eta_{\text{echo}} = \frac{4\kappa\Gamma_{\text{comb}}}{\kappa + \Gamma_{\text{comb}} + \Gamma_{\text{bg}}^2 + 2\kappa^2} [\text{supplementary methods (77)}]$, where $\Gamma_{\text{comb}}$ and $\Gamma_{\text{bg}}$ are the cavity-enhanced absorption rates for ions contributing to the comb and the background, respectively. The storage of a single coherent pulse was first measured to characterize the AFC efficiency and noise performance [supplementary text (77)]. Figure 3E plots the reflected input and AFC echo signal of coherent photons prepared in a time-bin state $|+\rangle$ (where $|e\rangle$ and $|l\rangle$ are early and late time-bin states, respectively) with a mean photon number of $\alpha = 0.58$. The input intensity was determined from a signal (black line) that was detuned 1 nm from the cavity resonance (i.e., 879 nm in Fig. 2A). The AFC device efficiency was 2.5% for a storage time of 75 ns. This efficiency was measured 200 $\mu$s ($\sim$40 times the $T_2^\text{cav}$ in the cavity) after the preparation sequence. The discrepancy from theory is likely due to an elevated background density in the comb at large detunings, which reduces the echo efficiency by not rephasing the input excitation. This effect is caused by the limited bandwidth of current AFC preparation pulses, which can be eliminated by shortening the pulses to 1 ns with a faster arbitrary-wave generator.

To assess the performance of this nanophotonic memory at the single-photon level, we measured the recalled state fidelity for test input qubit states $|e\rangle$, $|l\rangle$, $|+\rangle$, and $|-\rangle$ [supplementary text (77)] at two mean photon numbers $\alpha_e = 0.58$ and $\alpha_l = 0.26$. We then calculated the lower bounds on the qubit storage fidelity, following a decoy-state strategy in quantum key distribution that was recently adopted to gauge the quantum storage process (25) [supplementary text (77)]. The results of this analysis are plotted in the inset of Fig. 3E, in which the mean fidelity of a time-bin qubit is 96.8%, considerably above the classical limit of two-thirds and on par with the state-of-the-art bulk AFC memories (3, 26).

The ability to store photons in multiple time bins and to retrieve one at an arbitrary bin is a key functionality in proposed multiplexed quantum repeater networks (25). Upon successful Bell-state measurement, a feedforward signal will be sent to retrieve the stored photon at a desired time bin for subsequent entanglement swap. Here we demonstrate time bin–selective readout of a coherent pulse, using the cavity-enhanced ac Stark shift. Two Stark pulses detuned at $\pm \Delta_{\text{st}} = 1$ GHz ($\Delta_{\text{st}} > \Delta$) from the center of the AFC [supplementary methods (77)] uniformly compressed the comb spacing by $\delta \Delta = 4\Delta_{\text{st}}(\delta \lambda_{\text{st}}/\lambda_{\text{st}}^2)$ 13 (27) (Fig. 4A) over the Stark pulse duration of $t_{\text{st}} = 16$ ns (where $n_{\text{st}}$ is the average number of photons in the cavity while the Stark pulse passes through it, and $g_{\text{st}}$ is the Stark Rabi frequency per single photon in the cavity). This comb compression resulted in an additional delay of the echo by $\delta \Delta_{\text{st}}/\Delta$. Figure 4C plots the measured echo retrieval time with increasing Stark pulse intensities from $n_{\text{st}} = 0$ to 170 photons per pulse. The relative timing of the echo peaks is plotted against the Stark pulse photon number in Fig. 4D, with a linear fit of $\sim 50$ ps per photon (red dashed line). As the Stark pulse intensity increased, the echo efficiency gradually dropped (Fig. 4E), owing to broadening and distortion of the AFC teeth as a result of inhomogeneous ac Stark frequency shifts produced by random locations of ions in the cavity. Nevertheless, the echo signal (Fig. 4C) was still 12.3 dB above the background at the highest Stark pulse intensity. The maximum delay of the measured echo
efficiency with Stark pulse intensity, caused by AFC distortion resulting from inhomogeneous far-detuned Stark pulses induce uniform compression of the AFC. (spectral configuration of two Stark pulses with respect to the AFC comb. The symmetric, number in 16-ns Stark pulses. Here the echo envelope with no Stark pulses. (D) AFC echo delay against Stark pulse intensity. A linear fit (red dashed line) corresponds to 50 ps per photon. (E) Decrease of AFC echo efficiency with Stark pulse intensity, caused by AFC distortion resulting from inhomogeneous Stark shifts in the nanocavity.

was 10 ± 1 ns, which is comparable to the FWHM of the echo pulse—that is, a time bin. In the current device, inhomogeneous Rabi frequencies cause a smearing of the comb teeth while the Stark pulses are applied. This results in a weaker echo, thus limiting the maximum time shift without severely attenuating the echo intensity. Such limitations can be lifted if ions are selectively doped at the cavity antinodes by site-controlled implantation (29). Alternatively, isolating subensembles with more homogeneous Rabi frequencies could be possible by optical pumping with repeated 2π pulses, as demonstrated in (29).

The nanocavity scheme demonstrated here enables versatile engineering of the quantum light-matter interface and offers the distinctive advantage of faster and more efficient memory preparation. An on-demand quantum memory will require the incorporation of the spin-wave storage in long-lived hyperfine levels of REIs (30) or the use of controlled reversible inhomogeneous broadening. Both of these can benefit from the nanoscale platform—for instance, by adding micro-wave striplines or microelectodes in proximity to the nanocavity device for control of the rare-earth spins. With advances in nanofabrication of the REI host crystals, medium- to large-scale quantum memory arrays can be envisioned, which would enable highly multiplexed repeater schemes. Furthermore, our platform also allows direct integration with single rare-earth qubits (31) and interfacing to superconducting quantum devices (32).

Fig. 4. Temporal-mode selective pulse retrieval using ac Stark pulses. (A) Schematic spectral configuration of two Stark pulses with respect to the AFC comb. The symmetric, far-detuned Stark pulses induce uniform compression of the AFC. (B) Stark pulses cause an additional delay in echo retrieval times. (C) Measured AFC echoes with increasing photon number in 16-ns Stark pulses. Here Δ\text{int} = 1 GHz and Δ = 13.3 MHz. The blue shaded area overlays the echo envelope with no Stark pulses. (D) AFC echo delay against Stark pulse intensity. A linear fit (red dashed line) corresponds to 50 ps per photon. (E) Decrease of AFC echo efficiency with Stark pulse intensity, caused by AFC distortion resulting from inhomogeneous Stark shifts in the nanocavity.

REFERENCES AND NOTES

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17. See the supplementary materials.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/357/6358/1392/suppl/DC1
Materials and Methods
Supplementary Text
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A rare-earth quantum memory

The development of global quantum networks will require chip-scale optically addressable quantum memories for quantum state storage, manipulation, and state swapping. Zhong et al. fabricated a nanostructured photonic crystal cavity in a rare-earth-doped material to form a high-fidelity quantum memory (see the Perspective by Waks and Goldschmidt). The cavity enhanced the light-matter interaction, allowing quantum states to be stored and retrieved from the memory on demand. The high fidelity and small footprint of the device offer a powerful building block for a quantum information platform.

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