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.

Quantum memories for light play a vital role in optical quantum networks (1) for long-distance secure communications and interconnecting future quantum computers. Although optical quantum memories—devices that faithfully store input photonic qubits—have already been implemented in macroscopic systems such as atomic ensembles (2), solid-state crystals (3–5), and waveguides (6–8), realizing scalable networks requires integration of micro- or nanoscale memories with other guided-wave components for on-chip quantum information routing and processing. Crystals doped with rare-earth ions (REIs) are appealing solid-state materials for quantum storage because of their highly coherent optical transitions between four levels, which are further split into Zeeman and hyperfine levels with coherent transitions in the microwave regime (4, 9, 10). So far, memories based on macroscopic rare-earth crystals have been realized with electromagnetically induced transparency (11), gradient echo, controlled reversible inhomogeneous broadening (CRIB) (12), and atomic frequency comb (AFC) protocols (3, 13). REI-doped waveguide quantum memories have also been developed (6–8), but the macroscopic lengths of these devices are not ideal for on-chip integration. Coherent coupling of a mesoscopic REI ensemble to a nanophotonic cavity has been achieved recently (14, 15). To show the versatile functionality of this nanoscale platform, we demonstrate storage of photonic quantum bits with high fidelity, fast memory initialization, and a method for dynamically controlling the storage time.

Our optical quantum memory is based on a triangular nanobeam photonic crystal resonator (16, 10) fabricated in a Nd:YVO crystal nominally doped at 100 parts per million [materials and methods (17)]. Figure 1. The device is a one-sided cavity; the input mirror (left side in Fig. 1, B and C) was fabricated using a smaller number of photonic crystal lattice periods and thus has a lower reflectivity. The optical coupling in and out of the device was implemented by means of a 45°-angled coupler at one end of the nanobeam that totally internally reflects light into the device. An aspheric doublet lens matched the mode of the single-mode fiber to the mode of the nanocavity resonance, the strong Purcell enhancement modified the emission of the cavity so near resonance, the strong Purcell enhancement increases the branching ratio of the $Y_1$ to $Z_1$ transition from initially 27% (22) to ~97%, which facilitates an efficient system for optical pumping experiments. The optical coherence time $T_2$ from two-photon photo echo measurements was $3.1 \pm 0.3 \mu s$ ($\Gamma = 1/\pi T_2 = 100 \text{ kHz}$) for cavity-coupled ions when the cavity was detuned from the ensemble resonance by ~50 GHz (blue curve in Fig. 2C), which is close to the $3.2 \pm 0.2 \mu s$ found for the bulk crystal. When the cavity was on resonance, the strong Purcell enhancement modified the $T_2$ to $T_2^{\text{on}} = 2.3 \pm 0.3 \mu s$. With an inhomogeneous broadening of ~2 GHz, our nanocavity contained a total of $4 \times 10^5$ ions, with a peak spectral density of $N \sim 20$ ions per $\Gamma$, estimated from the cooperativity and a maximum single-photon Rabi frequency $\Omega_{\text{max}} = 2 \pi \times 30 \text{ MHz}$ (23).

Ensemble-based optical quantum memory protocols such as AFC and CRIB require preparing high-contrast spectral features within the inhomogeneous profile by means of persistent hole-burning. In REI-doped crystals, this preparation step is typically slow because of the long excited-state optical lifetimes $T_1$. Additionally, the resultant spin polarization, measured by the ratio of two spin-ground-state populations, can be poor for Kramers ions that, compared with non-Kramers ions, have shorter Zeeman lifetimes $T_2$ relative to optical $T_1$ (e.g., erbium) (29). Here we show that the nanocavity increases the optical pumping efficiency and spin polarization by enhancing the spontaneous decay rate from excited states to the Zeeman level.
The experimental magnetic field ($B = 340\, \text{mT}$) 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 $\sim 8.2^\circ$. 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, $T_{1,\text{cav}} = 12.5 \pm 1.0\, \text{ms}$, was not degraded relative to the bulk, $T_{1,\text{bulk}} = 12.7 \pm 1.5\, \text{ms}$ (Fig. 3B). Figure 3C plots the spin population as a function of optical pumping time $t_{\text{pump}}$. In the nanocavity, a maximum spin polarization of $\rho_d/\rho_0 = 20$ ($\rho_0 < 5\%$) was achieved with $t_{\text{pump}}$ less than 1 ms, whereas in the bulk, it took more than 10 ms to reach $\rho_d/\rho_0 = 3$. 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, 24) [supplementary text (17)].

To demonstrate storage of photonic qubits by means of the AFC protocol, we sent a sequence of 10-nsec pulse pairs separated by a time interval $t = 1/\Delta$, where $\Delta$ is the frequency spacing of the...
comb. The number of pulses in the sequence was optimized for the best echo efficiencies for a given $t$, which effectively controlled the Finesse $F$ of the comb. Figure 3D shows an AFC with $F = 3.3$ and $3\times10^4$ 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 $\bar{n} = 0.58$) 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.

To assess the performance of this nanophotonic memory at the single-photon level, we measured the recalled state fidelity for test input qubit states $|\phi\rangle$, $|\phi^+\rangle$, $|\phi^-\rangle$, and $|\phi^+\rangle$ [supplementary text (17)] at two mean photon numbers $\alpha_0 = 0.58$ and $\alpha_2 = 0.26$. 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 (17)]. 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 50% for a single-qubit system. 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 $\pm 10$ GHz ($\Delta_{\text{at}} > \Delta$) from the center of the AFC [supplementary methods (17)] uniformly compressed the comb spacing by $\delta\Delta = \Delta_{\text{at}} (\Delta_{\text{at}}^2 / \Delta^2)$ (27) (Fig. 4A) over the Stark pulse duration of $\tau_{\text{st}} = 16$ ns (where $\bar{n}_{\text{at}}$ is the average number of photons in the cavity while the Stark pulse passes through it, and $\bar{g}_{\text{at}}$ is the Stark Rabi frequency per single photon in the cavity). This comb compression resulted in an additional delay of the echo by $\delta\Delta / \Delta$. Figure 4C plots the measured echo retrieval time with increasing Stark pulse intensities from $\bar{n}_{\text{at}} = 0$ to $\sim 170$ photons per pulse. The relative timing of the echo peaks is plotted against the Stark pulse 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
Stark shifts in the nanocavity.

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 additional delay in echo retrieval times. (Zhong will require the incorporation of the spin-wave preparation. An on-demand quantum memory

light-matter interface and offers the distinctive

enables versatile engineering of the quantum

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—instance by adding micro-wave striplines or microelectrodes 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).

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
Figs. 51 to 54
Table S1
References (33–35)
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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 Δt = 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.

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 anodes by site-controlled implantation (28). Alternatively, isolating subensembles with more homogeneous Rabi frequencies could be possible by optical pumping with repeated 2γ 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
Nanophotonic rare-earth quantum memory with optically controlled retrieval


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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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