

Long-Lived Telecom-Heralded Single-Photon Storage in an Absorptive Spin-Rephased Quantum Memory

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Long-lived storage of single photons under the form of atomic excitations is at the foundation of long-distance entanglement distribution in quantum networks. To mitigate decoherence effects induced by the environment, rephasing of the hyperfine coherences using microwave pulses have been implemented in a variety of single-emitter and ensemble-based solid-state systems. However, the demonstration of storage of single photons in an absorptive quantum memory including such a spin-rephasing mechanism remains elusive. In this Letter, we show nonclassical storage of telecom-heralded single photons in a $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ rare-earth ion doped crystal quantum memory using the atomic frequency comb spin-wave protocol combined with a XY4 spin-rephasing sequence. Long-lived atomic frequency comb photon echoes are first observed in the classical regime for storage times of up to approximately 3 ms. We then demonstrate nonclassical correlations between heralding photons and stored signal photons generated by a cavity-enhanced parametric photon-pair source for storage times of up to 180 μs and with measured cross-correlation values as high as 4.6(4). Together with the capacity of $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ quantum memories to support highly efficient and multiplexed storage, this result represents a significant step toward scalable long-distance quantum repeater links.

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The achievement of large-scale quantum networks is one of the most fascinating pathways of quantum technologies opening the door to exploiting the full potential of quantum computing, sensing, and secure communications in a distributed framework [1,2]. Most quantum network architectures rely on the creation of entanglement between stationary matter systems acting as quantum memories (QMs) heralded by single photons traveling across long-distance optical channels [3,4]. In such a heralded scheme, the stored atomic excitation has to be kept in the QM for at least the total communication round-trip time taken by the heralding photon to travel through the link segment and by the detection signal to travel back to the QM. In typical metropolitan fiber-optical links at telecom wavelengths,

this communication time is of the order of 125 μs for 25 km. However, in a multinode network, due to losses and the probabilistic nature of the establishment of entanglement, the required storage time for successful entanglement creation over several links is much higher, typically several tens of milliseconds, which poses stringent requirements on the coherence properties of atomic systems to allow for operation in a quantum network scenario. Additionally, to ensure compatibility with fiber architectures and guarantee high entanglement rates at long distance, heralding must be performed at telecom wavelengths.

Long storage times on the hundreds of microseconds to milliseconds scale have already been achieved in several types of emissive QMs and exploited in demonstrations of long-distance entanglement distribution. This includes solid-state color centers [5,6], single ions and atoms [7,8], and laser-cooled atomic ensembles [9]. Yet, the currently limited multiplexing capability and the need to frequency-convert the heralding photon to the telecom band hinder their potential use in a fully fledged quantum network link. Another promising system are absorptive rare-earth ion doped crystal (REIC) QMs coupled to narrow-band photon-pair sources [10]. Indeed, they benefit from massive multiplexing in several degrees of freedom [11–16], high storage efficiency [17], telecom heralding at high rates [18], and compatibility with photonic integration

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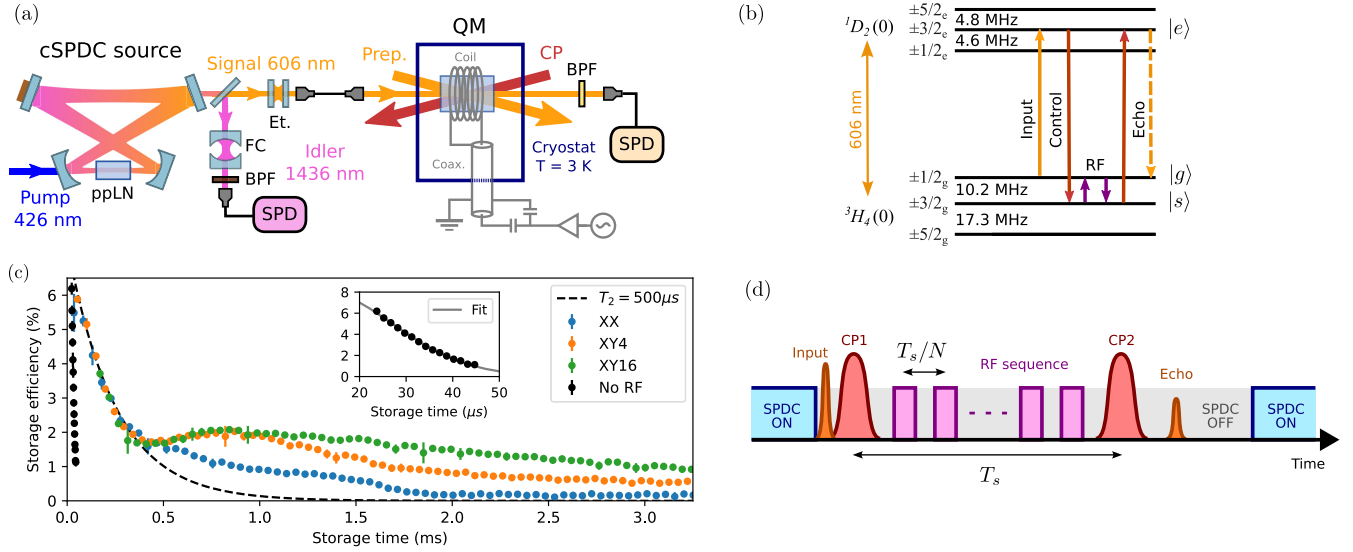


FIG. 1. (a) Experimental setup. In single-photon storage experiments, a second $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ crystal is used for spectral filtering before detection (not shown). ppLN, periodically poled lithium niobate; FC, filter cavity; BPF, bandpass filter; SPD, single-photon detector; Et., etalon; Prep., preparation beam; CP, control pulse beam; Coax, coaxial cable. (b) Energy levels for the ${}^3H_4(0) \leftrightarrow {}^1D_2(0)$ transition of $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ showing the optical and hyperfine transitions used in the spin-wave AFC storage protocol. (c) Storage efficiency for classical light as a function of total storage time. Black dots: without rf rephasing pulses. Color symbols: single XX, XY4, or XY16 pulse sequence. Black dashed line: calculated decay for XX assuming zero applied magnetic field and a spin coherence time $T_2 = 500 \mu\text{s}$. (d) Schematic representation of the conditional spin-wave AFC storage sequence with spin rephasing (N : number of applied rf π pulses).

[19–22]. In addition, long-lived storage in the hyperfine nuclear spin state of REICs can be performed by mitigating decoherence effects via spin-rephasing sequences applied to the spin transitions [23]. Using this technique, ultralong spin coherence times have been observed in multiple REIC species ranging from hundreds of milliseconds to several hours [24–27]. This, in turn, enabled the demonstration of storage of classical light for up to 1 h [28], single-photon-level pulses for up to 42 s [29,30], and nonclassical correlations between collective spin excitations and single photons for 1 ms, albeit in an emissive scheme and without quantum frequency conversion [31].

Despite all of these achievements, to date no spin-rephased storage of single photons in an absorptive quantum memory with telecom heralding has been reported. Indeed, previous demonstrations featured reduced storage bandwidth, which implies the use of sub-MHz spectrally narrow photons that are typically difficult to generate using deterministic or parametric sources. In addition, the significant added noise imparted by the multiple rephasing pulses and the reduced count rate when operating with external quantum frequency conversion also make the observation of nonclassical storage challenging.

In this Letter, we fill this gap by demonstrating storage of telecom-heralded single photons from a narrowband nondegenerate parametric photon-pair source in a $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ QM using the atomic frequency comb (AFC) protocol and a XY4 spin-rephasing sequence.

In the classical regime, storage of bright pulses for several milliseconds is achieved, the longest reported to date for spin-wave AFC in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$. Furthermore, we witness nonclassical correlation between signal and idler photons at the memory output for storage times of up to $180 \mu\text{s}$, corresponding to an equivalent fiber-link distance of more than 30 km. We emphasize that our scheme does not require a quantum frequency conversion stage and supports the use of moderate photon bandwidth (2.5 MHz). This result sets the current state of the art for single-photon storage in spin-rephased absorptive solid-state quantum memories and represents a milestone toward the accomplishment of long-distance quantum network links.

The experimental setup is sketched in Fig. 1(a), showing the cavity-enhanced spontaneous parametric down-conversion (cSPDC) photon-pair source and the $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ quantum memory located in a 3 K closed-cycle cryostat. The relevant energy level scheme is depicted in Fig. 1(b). A coil made of copper wire thermally connected to the 3K stage of the cryostat is wrapped around the memory crystal in order to address the $|g\rangle \leftrightarrow |s\rangle$ transition at 10.2 MHz via rf pulses to perform spin rephasing (see Appendix A).

Light storage is performed using the spin-wave AFC protocol (see Appendix B). Extensive descriptions of AFC preparation can be found in Refs. [18,32,33]. A comb-shaped absorption profile of periodicity Δ is prepared into the inhomogeneously broadened $|g\rangle \leftrightarrow |e\rangle$ optical transition by spectral hole burning allowing for storage at a

predetermined time of $\tau_{\text{AFC}} = 1/\Delta$. To perform on-demand retrieval of the excitation, a pair of bright control pulses (CPs) is used to map the optical excitation in and out of the long-lived hyperfine state $|s\rangle$, as depicted in Fig. 1(b). By adjusting the time T_s between the two CPs, the recall time $\tau_{\text{AFC}} + T_s$ can be chosen while the photon is inside the QM, an essential feature for the synchronization of quantum network links. In this configuration, the storage time is limited by spin dephasing caused by the inhomogeneous broadening of the $|g\rangle \leftrightarrow |s\rangle$ transition. In Fig. 1(c), we plot in black the storage efficiency as a function of time for a 400 ns-long classical input pulse tailored to the spatio-temporal profile of signal photons emitted by the photon-pair source. From the decay, we extract a value of 15.8(1) kHz for the spin inhomogeneous broadening, on par with previously reported values in the literature [18,34]. We observe that spin dephasing prevents the observation of significant photon echoes at storage times larger than 35 μs , thus severely limiting the use of this method for long-distance quantum networks.

Fortunately, the effect of spin inhomogeneous broadening can be canceled by inserting between the two CPs a pair of identical π pulses at the frequency of the $|g\rangle \leftrightarrow |s\rangle$ spin transition with a center-to-center temporal separation of $T_s/2$, as sketched in Fig. 1(d). Analogously to a Hahn echo, the spin population is being refocused by the microwave pulses, allowing for the observation of AFC echoes at much longer times, as shown in the blue curve of Fig. 1(c). The storage time under this so-called XX sequence is ultimately limited by the spin coherence time, which in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ was measured to be $T_2 = 500 \mu\text{s}$ at zero magnetic field [35]. In the case of a T_2 -limited spin rephasing, the efficiency scales as $\exp(-2T_s/T_2)$ as illustrated by the black dashed line. However, we see that, in our case, the XX sequence allows for echoes at delays greater than nominal T_2 . This is likely an indicator of the presence, despite a magnetic shielding layer around the QM, of a small external residual magnetic field inducing Zeeman splitting of the Pr^{3+} and host yttrium ions hyperfine ground states. This phenomenon translates into an effective decoupling of the rare-earth ion spin from the surrounding yttrium bath, therefore increasing the spin coherence time [36]. In this situation, due to the beating of the coherence created between the different spin sublevels, the efficiency decay deviates from a purely exponential law [36,37]. In specific field configurations, such as the one observed in our experiment, this can lead to an increase of spin coherence, while in others, it can cause the complete suppression of photon echoes [37,38]. We observe a very slight modulation pattern, with a period of approximately 600 μs , hinting at Zeeman splitting of the Pr^{3+} hyperfine ground state of a few kHz.

More complex sequences with specific phase relationships between the rf π pulses allow for an even greater increase of the spin coherence [39]. In Fig. 1(c), we show the result of

storage under a four-pulse XY4 sequence with phases $\{0, \pi/2, 0, \pi/2\}$ and a sixteen-pulse XY16 sequence with phases $\{0, \pi/2, 0, \pi/2, 0, \pi/2, 0, \pi/2, 0, \pi/2, 0, \pi/2, 0, \pi/2, 0, \pi/2\} \times 2$. Compared to a simple XX, these sequences benefit from robustness to pulse area errors, meaning the spin coherence can be successfully maintained even in the presence of imperfect rf pulses [40,41]. We see that storage time is indeed notably extended with measurable photon echoes beyond 3 ms, which represents an increase of nearly 2 orders of magnitude compared to previous work on spin-wave AFC storage in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ without spin rephasing [34]. The efficiency decay with XY4 and XY16 also exhibit nonexponential features that stem from the interplay between the Pr^{3+} -Y magnetic dipole coupling under small external magnetic field and the rf pulses position [42]. We also emphasize that for storage times above 500 μs , the coherence time increases with the number of applied rf pulses, a signature of dynamical decoupling [23,39]. In addition, we point out that the sequence supports on-demand retrieval, similarly to ordinary spin-wave AFC, by delaying the last pulse of the rf sequence while keeping its delay to CP2 fixed.

After characterizing the memory using classical pulses, we perform storage of heralded single photons generated by cSPDC. The source consists of a periodically poled lithium niobate crystal inserted inside a doubly resonant bowtie cavity, as depicted in Fig. 1(a) [43]. We employ a widely nondegenerate phase matching with a pump field at 426 nm, allowing for the creation of a signal photon resonant with the $|g\rangle \leftrightarrow |e\rangle$ transition of $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ at 606 nm correlated to an idler photon in the telecom band at 1436 nm. This ensures direct compatibility of the heralding photon with telecom fiber infrastructure without the need to resort to quantum frequency conversion, unlike previously demonstrated emissive memory schemes [5,6,9]. Furthermore, the photons are generated inside the narrow spectral modes of the cavity resulting in a biphoton linewidth of 2.5 MHz that complies with the 4.6 MHz bandwidth of AFC storage in this REIC. We restrict the generated state to a single frequency mode by filtering the idler field with a narrowband filter cavity. Storage is performed in a conditional manner: upon detection of an idler, the SPDC pump is turned off to avoid excess noise in the echo temporal window and the optical CP and rf decoupling pulses are sent to the memory. The storage sequence operates at a repetition rate of 55 attempts per second. A detailed breakdown of all the timing overheads is provided in Appendix C. After retrieval from the QM, the output field is filtered using a second $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ crystal, located in the same cryostat, into which we prepare a narrow 3 MHz-wide transparency window around the single-photon frequency.

We start by certifying the single-photon nature of the input light by performing a heralded autocorrelation measurement. Here, the signal photons are not stored in the QM but instead are sent through a broad 16 MHz-wide transparency window prepared inside both memory and filter

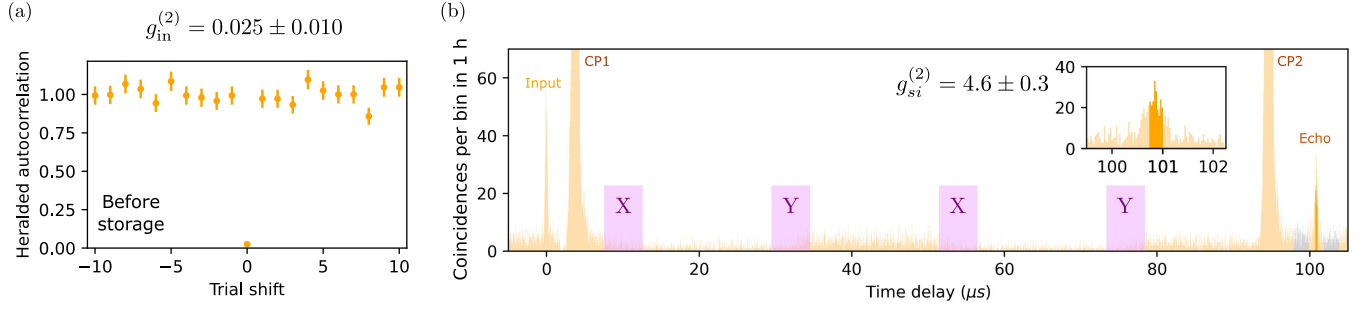


FIG. 2. (a) Heralded autocorrelation of signal photons without storage. The signal mode goes through a broad transparency window prepared in both the QM and the filter crystal. (b) Time-correlation histogram between the detection of idler and signal photons after storage in the QM with a single XY4 sequence for 100.9 μs . The temporal envelope of the rf pulses is depicted in light pink. The inset shows a zoom on the region of the photon echo. Bin size: 20 ns.

crystals then directed to a fiber 50/50 beam splitter and detected by superconducting single-photon detectors (IDQuantique ID281). The result of the measurement is featured in Fig. 2(a), where we plot the value of the heralded autocorrelation function of the signal field for different delays between subsequent heralding signals [44]. We see a strong suppression of triple coincidence events at zero delay with a value of $g_{\text{in}}^{(2)} = 0.025 \pm 0.010$ showing that the cSPDC source emits high-purity heralded single photons.

We then demonstrate the quantum character of the output state by recording temporal correlations between idler and signal detections after spin-wave storage with a single XY4 block (see Appendix D). The measured time-correlation histogram for a total storage time of 100.9 μs is displayed in Fig. 2(b). We calculate the signal-idler cross-correlation as $g_{\text{si}}^{(2)} = p_{\text{si}}/p_s p_i$, where p_{si} is the probability of detecting a coincidence within the 280 ns detection window (orange area), while p_s and p_i are the probabilities of single signal and idler clicks. Experimentally, the term $p_s p_i$ corresponds to the noise background of uncorrelated counts and is obtained by integrating coincidence events over two noise windows located before and after the photon detection window (gray areas). The experimental value of the cross-correlation for this storage time is $g_{\text{si}}^{(2)} = 4.6 \pm 0.3$, which is well above the nonclassical bound of 2 for the Cauchy-Schwarz inequality violation, assuming thermal statistics for the signal and idler fields [45]. Furthermore, based on the measured values of $g_{\text{si}}^{(2)}$ and $g_{\text{in}}^{(2)}$, we extrapolate the heralded autocorrelation at the memory output as [46] $g_{\text{out}}^{(2)} = (g_{\text{in}}^{(2)} + 2/s + 1/s^2)/(1 + 2/s + 1/s^2)$, with $s = g_{\text{si}}^{(2)} - 1$ the signal-to-noise ratio of the storage in the QM. We infer a value of $g_{\text{out}}^{(2)} = 0.397 \pm 0.026$ at 100.9 μs , which is below the threshold of 0.5 by 3.9 standard deviations, indicating that single photons are retrieved from the memory after storage.

Lastly, we show that spin rephasing allows for successful storage of single photons at longer storage times in the

$\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ QM. To do so, we repeat the previous measurement for different values of the total storage time. The results are displayed in Fig. 3. As shown in Fig. 3(a) a value of $g_{\text{si}}^{(2)}$ above 2 is obtained for up to 180 μs , corresponding to an equivalent fiber-link distance of around 36 km. In addition, the estimated output autocorrelation $g_{\text{out}}^{(2)}$, plotted in Fig. 3(b) is below the single-photon bound of 0.5 for storage times under 150 μs and reaches the

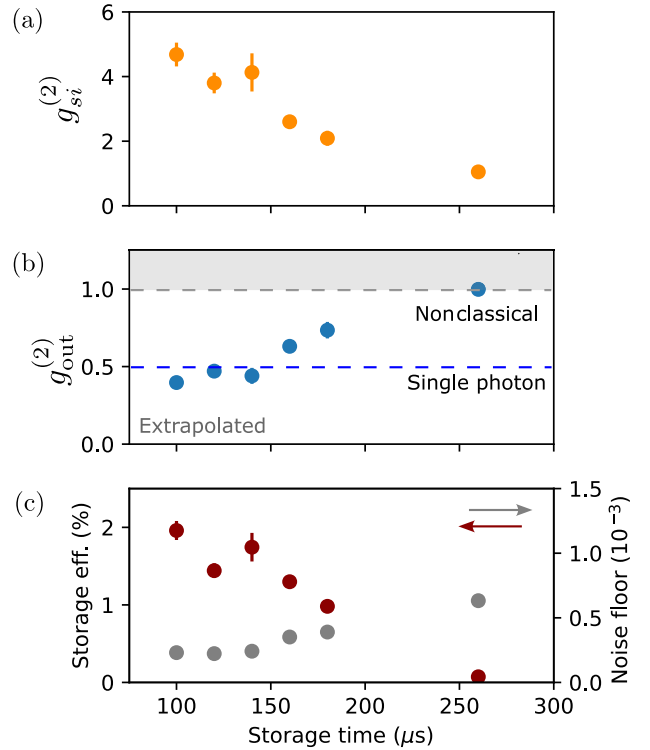


FIG. 3. Long-lived storage of heralded single photons with a XY4 sequence. (a) Signal-idler cross-correlation $g_{\text{si}}^{(2)}$, (b) extrapolated output autocorrelation $g_{\text{out}}^{(2)}$, and (c) storage efficiency and noise floor as a function of total storage time. The noise floor here is defined as the probability per herald of detecting a noise photon backpropagated to after the QM.

classical threshold of 1 at 260 μ s. This demonstrates the ability of our system to maintain the quantum character of input single photons at storage times that are relevant for metropolitan-scale fiber links and, as such, represents an important step toward the implementation of realistic quantum networks.

In the present experiment, the maximum storage time of single photons is limited by the reduced efficiency compared to the classical case together with an increase of the noise background, as can be seen from Fig. 3(c). On the one hand, the lower efficiency stems for the fact that the single-photon-storage memory preparation sequence has been optimized to minimize the CP noise in order to reach the highest cross-correlations $g_{\text{si}}^{(2)}$, which, in general comes at the expense of storage efficiency. Nevertheless, by embedding the QM inside an impedance-matched cavity, single-photon storage efficiencies in spin-wave AFC of up to 18% have been demonstrated, therefore providing a favorable solution to this shortcoming [17]. On the other hand, the measured increase of noise floor is likely caused by the incapacity of the XY4 sequence to perform perfect rephasing of the spin population in the presence of Zeeman splittings induced by the residual background magnetic field, in spite of the increased spin coherence that was observed in the classical data of Fig. 1(c) [40–42]. Indeed, in this regime of small fields (< 1 mT) where Zeeman splittings are typically smaller than the Rabi frequency of the $|g\rangle \leftrightarrow |s\rangle$ transition, the application of an rf pulse leads to a mixing of the Zeeman sublevel populations, as discussed extensively in [42]. This mixing introduces interference between the rephasing contributions from different Zeeman sublevels. As the spacing between rf pulses increases, the dephasing between these quantum trajectories grows, causing destructive interference. In this situation, efficient spin rephasing requires both a well-chosen magnetic field orientation thanks to the use of a Helmholtz coil assembly and specifically tailored adiabatic rf pulses [42]. An increasing level of noise with storage time was also observed in early experiments without external field in $^{151}\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$ [47] but has been successfully overcome in later studies allowing for an improvement of an order of magnitude in storage time at the single-photon level [48]. This shows that the limitation to the storage time in the present work is not fundamental and can be resolved by implementing similar techniques.

Looking ahead, the use of a well-controlled external magnetic field opens the way to further increasing spin coherence time (see Appendix E). This will be instrumental in the synchronized entanglement swapping operation over several long-distance quantum repeater segments previously limited by the short storage time in the excited state and the lack of on-demand retrieval [49,50]. Indeed, under moderate magnetic fields (< 10 mT) the predicted $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ single ion spin coherence time can reach up to 5 ms without dynamical decoupling [36], while at

higher field amplitudes (up to 100 mT) the QM can be operated in a zero first-order-Zeeman (ZEFOZ) configuration allowing for second-scale storage [29,30].

In summary, we demonstrated in this Letter long-lived storage of single photons using spin rephasing in an absorptive QM. Storage has been achieved for up to 3 ms with classical pulses and up to 180 μ s with heralded single photons. This result shows the feasibility of storing single photons using spin-rephasing sequences, opening the door to ultralong storage times relevant for long-distance quantum network links. Lastly, the possibility to incorporate high-efficiency and multiplexed storage to our scheme establishes $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ quantum memories as a major candidate for the implementation of scalable quantum network links.

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Data availability—The data that support the findings of this article are openly available [51].

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End Matter

Appendix A: Details on the experimental setup—The QM consists of a 0.05%-doped $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ crystal with dimensions $2\times 3\times 5$ mm cut along the (D_1, D_2, b) crystallographic axes. Input light propagates along the b axis. The crystal is cooled down to a temperature of 3K using a closed cycle helium cryostat (MyCryoFirm). The crystal is shielded from parasitic external magnetic fields by covering the inner walls of the cryostat radiation shield with high-permeability metallic sheets (μ metal). Impedance matching of the rf line to the coil surrounding the QM is accomplished using an external circuit of adjustable capacitors. In this configuration we achieve a Rabi frequency of $2\pi \times 19$ kHz for the $|g\rangle \leftrightarrow |s\rangle$ transition at 10.2 MHz with an average rf power of 15 W. In all measurements featured in this Letter, we use rf square pulses of 5 μs duration without frequency chirp, leading to a FWHM frequency bandwidth of 31.8 kHz.

Appendix B: Details on the AFC preparation—Through optical pumping, the atomic population of a

single class of ions within the 10 GHz homogeneously broadened absorption line is polarized in the hyperfine state $|g\rangle$ while leaving the state $|s\rangle$ empty. Then, by spectral hole burning, a comb-shaped absorption profile of periodicity Δ is imprinted onto the $|g\rangle \leftrightarrow |e\rangle$ optical transition over a spectral window of 4.6 MHz, limited by the excited state hyperfine splitting. When an incoming light field is resonant with this transition, a collective excitation is created in the excited state of the atomic ensemble and undergoes dephasing before producing a photon echo in the forward direction after a predetermined storage time of $\tau_{\text{AFC}} = 1/\Delta$ [32,33].

Appendix C: Details on the single-photon storage experimental sequence—AFC preparation lasts around 400 ms and is synchronized to the cycles of the pulse tube of the cryostat (period of 700 ms) to be able to perform storage in the part of the cycle exhibiting the lowest level of mechanical vibrations. Discarding high vibration time windows, the remaining allowed time for

single photon storage is 200 ms. For all single-photon measurements, the cSPDC source is operated at a pump power of 1.9 mW, with a heralding efficiency of 20% and 1500 cps raw heralding rate. Details on the source locking scheme can be found in the appendix of Ref. [18]. By taking into account the source locking (54%) and AFC preparation (57%) duty cycles as well as the 2 ms memory dead time to avoid heating by rf pulses, the rate of storage attempts is on average 55 per second. As an illustration, for the data displayed in Fig. 2(b), the measured coincidence rate for a 280 ns-long detection window is 0.057 cps and the number of noise photons per herald backpropagated at the memory (noise floor) is 0.23×10^{-3} .

This unprecedented low level of noise compared to previous work in $^{151}\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$ can be explained by the lower rf power required for the rephasing pulses (limiting heating of the sample) as well as a careful optimization of all pulse durations and chirps with respect to noise in single-photon-level measurements. As pointed out in the main text, this emphasis on low noise explains the comparatively low storage efficiency, since sequence optimization was carried out to favor the former figure of merit.

We finally point out that the present experiment is performed conditionally with a single stored temporal mode but can nevertheless be extended to support temporal multiplexing using an unconditional storage sequence similar to the one described in Ref. [18].

Appendix D: Choice of rephasing sequence for single-photon storage—Aside from XY4, XX and XY8 sequences have been tested in single-photon-level storage experiments but the very high measured noise floor hindered the observation of echoes at low input photon number. We believe this stems from the imperfect rf pulses that prevent operation both with XX and XY8. Under current conditions, from classical data we estimate the single rf pulse transfer efficiency to be 85%. In the case of XY8, the potential improvement provided by the pulse error resilience of the sequence is counterbalanced by the increased amount of noise when doubling the number of rf pulses. In the future, thorough

optimization of the rf pulse temporal and spectral properties under controlled B field should allow reaching a near-ideal rf transfer efficiency that may allow working at higher number of rf pulses.

Furthermore, we estimate that the increase in spin coherence under moderate B fields, or later at a ZEFOZ point, will be sufficient to eventually reach relevant time-scales for metropolitan quantum communications (milli-second time scale) using only a reduced number of rf pulses [29,36] (see Appendix E below). As a consequence, the favorable tradeoff between efficiency and noise of XY4 makes it a good candidate sequence for storage in long-distance quantum network links.

Appendix E: Magnetic field regimes for further extension of storage time—Different regimes of magnetic field amplitude can be leveraged in order to extend the spin coherence time of the $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ quantum memory. Using low magnetic fields (< 10 mT), interaction between the Pr^{3+} rare-earth ions and the spin environment of the host crystal can be further mitigated with predicted single-ion spin coherence times of up to 5 ms without dynamical decoupling, at optimal field orientations in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ [36] and measured single-photon level storage for 20 ms in $^{151}\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$ [48]. Related to the noise floor increase with storage time discussed in the main text, this field regime should allow suppressing this phenomenon both by eliminating several Y-mediated decoherence mechanisms and by enabling optimal spin population transfer [42]. At intermediate field magnitudes (10–50 mT), the Zeeman splitting can be large enough such that individual sublevels are addressable individually, allowing for efficient spin rephasing [52]. Eventually, ultralong storage times can be achieved with magnetic fields of the order of 100 mT by operating at ZEFOZ configuration and with dynamical decoupling [53], a technique that enabled the recent demonstration of few-photon-level storage on a second timescale in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ [29] and over 40s in $^{151}\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$ [30], albeit with ultranarrow input pulses (3 to 7.5 μs duration).