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Antariksha Das[a], Mohsen F. Askarani[a], Jacob H. Davidson[a], Gustavo C. Amaral[a], Neil Sinclair[b,c], Joshua A. Slater[d], Sara Marzban[a], Daniel Oblak[e], Charles W. Thiel[f], Rufus L. Cone[f], and Wolfgang Tittel[a,g,h]

[a]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, 2628 CJ Delft, The Netherlands
[b]John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
[c]Division of Physics, Mathematics and Astronomy, and Alliance for Quantum Technologies (AQT), California Institute of Technology, Pasadena, California 91125, US
[d]QuTech, Delft University of Technology, 2628 CJ Delft, The Netherlands
[e]Institute for Quantum Science and Technology, and Department of Physics & Astronomy, University of Calgary, Calgary, Alberta, T2N 1N4, Canada
[f]Department of Physics, Montana State University, Bozeman, Montana 59717, USA
[g]Department of Applied Physics, University of Geneva, 1211 Geneva 4, Switzerland
[h]Schaffhausen Institute of Technology - SIT in Geneva, 1211 Geneva 4, Switzerland

ABSTRACT

Long optical storage times are an essential requirement to establish high-rate entanglement distribution over large distances using memory-based quantum repeaters. Rare earth ion-doped crystals are arguably well-suited candidates for building such quantum memories. Toward this end, we investigate the 795.32 nm $^3H_6 \leftrightarrow {}^3H_4$ transition of 1% thulium-doped yttrium gallium garnet crystal (Tm^{3+}:$Y_3Ga_5O_{12}$: Tm^{3+}:YGG). Most essentially, we find that the optical coherence time can reach 1.1 ms, and, using laser pulses, we demonstrate optical storage based on the atomic frequency comb (AFC) protocol up to 100 μs. In addition, we demonstrate multiplexed storage, including feed-forward selection, shifting, and filtering of spectral modes, as well as quantum state storage using members of non-classical photon pairs. Our results show that Tm:YGG can be a potential candidate for creating multiplexed quantum memories with long optical storage times.

Keywords: Quantum Repeater, Quantum Memory, Rare-earth-ion-doped Crystal

1. INTRODUCTION

The realization of quantum networks will enable the distribution of entanglement over long distances and will open the path to the next generation of advanced quantum technology applications, from secure communication to distributed quantum computing.[1] Quantum repeaters promise the possibility to perform quantum communications over large distances.[2] This can be achieved through (i) the heralded distribution of entanglement across the subsections (known as elementary link) of the total communication link, (ii) storage of entanglement at the end-nodes of each elementary link, and (iii) swapping of entanglement established in neighboring elementary links to the end-points of the total channel.

Quantum memories are an essential requirement in order to distribute quantum information in certain quantum repeater protocols. Highly multimode quantum memories are necessary to construct a multiplexed quantum repeater to achieve useful communication rates. Memories that are able to store many photons simultaneously

Further author information: (Send correspondence to Antariksha Das)
Antariksha Das: E-mail: a.das-1@tudelft.nl

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in different degrees of freedom (temporal, spectral, and spatial), allow increasing the entanglement distribution rate of repeater-based quantum communication channel.[3] It is possible to employ spectrally-multiplexed states together with memories with fixed storage time, supplemented with feed-forward selection, shifting, and filtering of spectral modes[4] to achieve this goal.

Ensemble-based systems are very promising candidates than single absorbers for developing multiplexed quantum memories. Among possible candidates, rare-earth-doped crystals[5] are particularly attractive solid-state platform as optical quantum memories as they offer excellent coherence properties.[6–8] Storage time of a quantum memory is an important figure of merit. Long optical storage times are always required regardless of the degree of freedom used for multiplexing. It allows extending the elementary link lengths in quantum repeater architectures that do not employ mapping between optical and spin coherence.[9] In turn, this leads to higher entanglement distribution rates as it effectively reduces the number of probabilistic Bell state measurements that are required to connect neighboring links.

In this article, we investigate a thulium-doped yttrium gallium garnet crystal (Tm^{3+}:$Y_3Ga_5O_{12}$ or Tm^{3+}:YGG) whose promising spectroscopic properties has been pointed out before,[10,11] as a potential photonic quantum memory. We show that its optical coherence time T_2 can reach upto 1.1 ms, which is one of the longest times reported for any rare-earth-doped systems.[6,8] We show the storage of classical optical pulses up to 100 μs of optical storage time,[12] using the two-level atomic frequency comb (AFC) protocol[13] where the optical excitation is stored in Tm^{3+} ions as a collective delocalized atomic excitation. We Find that the memory decay time T_m is around 13 μs which is 20 times smaller than the T_2-imposed maximum of 275 μs. To demonstrate the multiplexing capability of our system, we individually store 10 temporal modes and 3 spectral modes. Finally, to evaluate the potential of our system as quantum memory, we implement storage of heralded single photons. We confirm the quantum nature of our memory by showing quantum correlations between members of spontaneous parametric down-conversion photon-pairs throughout storage.

Our demonstrations thus show that Tm^{3+}:YGG can be a suitable candidate for realizing highly multiplexed quantum memories with long optical storage times for practical quantum repeater applications. We anticipate that our results will accelerate the development of quantum repeaters and advanced quantum optics experiments.

2. MEMORY DEADTIME AND REPEATER-BASED ENTANGLEMENT DISTRIBUTION RATE

A high rate of entanglement distribution is necessary for a quantum repeater to be practical, thus requiring the use of a highly multiplexed quantum memory. To maximize the entanglement distribution rate qubits should be added incessantly to the memory. Any memory-specific control operation, triggered by the absorption of a newly arriving qubits should not introduce deadtime that prevents the memory from accepting additional qubits. This would cause a reduction in the entanglement distribution rate which can be at odds with a high repetition rate. For an example, the temporal multiplexing and the read-out on demand procedure from the spin-wave atomic frequency comb (AFC) quantum memory,[9] which requires one to temporarily map qubit states between optical and spin coherence. Thus it is very important to optimize the *optical storage time*, i.e. the time during which qubits are stored as optical coherence. It is important to note that this conclusion holds in the case of entirely optical storage where no spin mapping procedure is involved.

To understand the impact of a memory with dead-time (which imposes a delay time) on repeater performance, more precisely the impact on the entanglement distribution rate, we focus on the quantum repeater protocol that are described and analyzed in.[4,14] See Figure 1 for an illustration.

In this approach, a definite number of qubits in n distinct spectral modes is generated at each node and sent towards the central Bell-state measurement station of the elementary link that connects to the neighboring node. Each qubit is entangled with a second qubit, also in one of n different spectral modes, whose states are mapped into a quantum memory where they are stored as *optical coherence* (not spin coherence). At the central location, a Bell-state measurement projects the transmitted qubits pairwise in a spectrally-resolved manner onto a maximally entangled state. This entangles qubits in the two memories–one on either end of the elementary link. After feed-forwarding the information about the channel(s) in which entanglement has been generated back to the two nodes, each node recalls all qubits from its memory and selects, out of the block of n, one (now

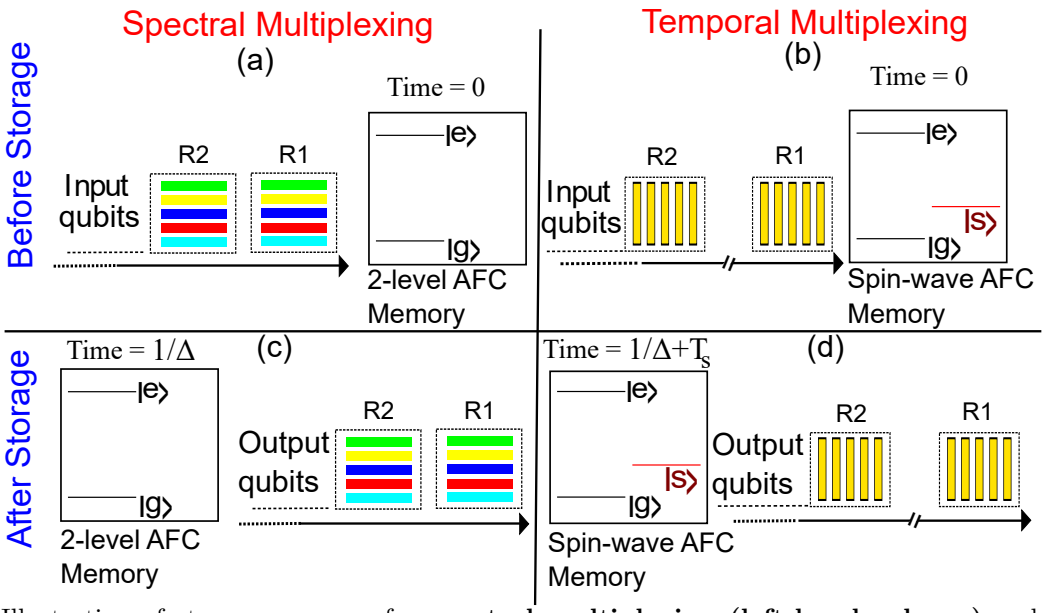

Figure 1: Illustration of storage sequence for **spectral multiplexing (left-hand column)** and **temporal multiplexing (right-hand column)**. **(a)** and **(b)** represent the moment **before storage**, and **(c)** and **(d)** **after storage**. Two subsequent trains (or blocks) of qubits are labelled R1, R2. In (a) and (c), different colours represent different spectral modes. The three-level lambda system needed for read-out on demand is formed by spin states $|g\rangle$ and $|s\rangle$, and by excited state $|e\rangle$. Note how the dead-time of the spin-wave memory imposes a delay time between qubit trains R1 and R2 (in b and d).

entangled) qubit whose mode is subsequently frequency-shifted to allow for a Bell-state measurement with a qubit from the neighboring elementary link. Given the multi-mode capacity of the assumed memory as well as no dead-time, the next set of qubits can be generated by the source and stored in the memory as soon as the creation of the previous set has been terminated.

Generalizing this approach to temporal modes, we arrive at the following: First, n qubits belonging to n entangled pairs in n subsequent temporal modes are generated and sent to the central Bell-state measurement station of the elementary link. The other qubits of the n pairs are stored one after the other in optical coherence, and once the whole train of qubits has been mapped into the memory, it is transferred "en bloc" onto spin coherence. The outcome of a temporally-resolved Bell-state measurement at the central node then affects when the train of stored qubits is read out in each memory, ensuring that qubits from neighboring elementary links become indistinguishable in the temporal domain and can be subjected to another Bell-state measurement. Unfortunately, the use of spin-states (or spin coherence) for photon storage implies that the memory is dead after absorption (and spin-transfer) of the n qubits. And hence, we encounter the problem that the entanglement distribution rate is reduced by the ratio between optical storage time and total storage time.

3. RESULTS

Long-lived storage of optical pulses – By means of two-pulse photon echo technique, we find the optical coherence time T_2 — an important key feature for achieving long optical storage times and hence a large temporal multimode capability — can exceed 1 ms.[12] This makes the $^3H_6 \leftrightarrow {}^3H_4$ 795.32 nm transition almost radiatively limited.[10] We exploit such exceptional coherence property to demonstrate the long-lived storage capability of our system. For this purpose, the crystal is cooled to 500 mK and we implement the two-level atomic frequency comb (AFC) quantum memory protocol[13] to store the optical pulses in the 1% thulium-doped YGG crystal. We demonstrate storage of 1μs-long laser pulses up to 100 μsec of optical storage time.[12] Because of the limited optical depth of the crystal (≈ 1), the storage efficiency is very small (e.g: $\approx 1\%$ for 5μs of storage time). We find that the memory decay lifetime (T_m: the time after which the memory efficiency drops by $1/e$ of its initial

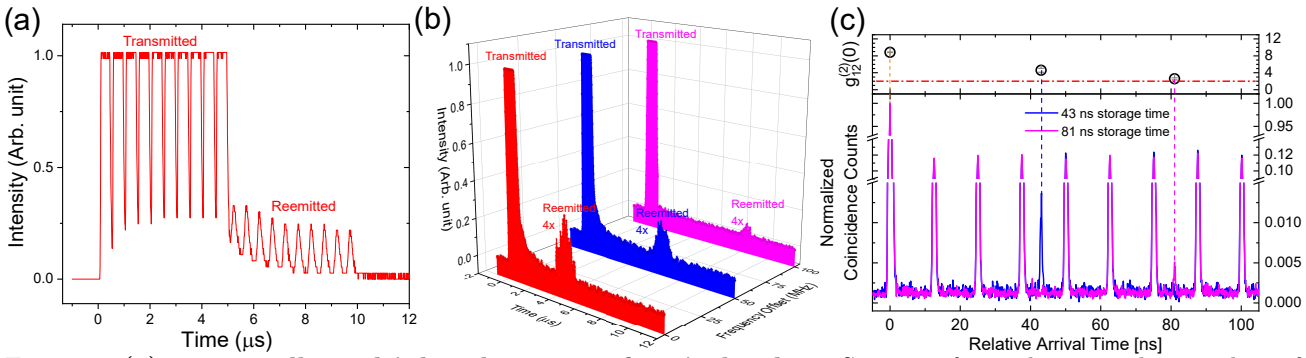

Figure 2: **(a) Temporally multiplexed storage of optical pulses:** Storage of 10 subsequent laser pulses of 200 ns duration for 5 μs of storage time. The re-emitted train of pulses can be observed from 5 μs to 10 μs. **(b) Frequency multiplexed storage of optical pulses:** Frequency-multiplexed AFC quantum memory used to simultaneously store optical pulses of 1 μs duration in 3 spectral modes (in different colours) for 4 μs, 6 μs, and 8 μs storage time respectively. **(c) Single photon storage:** The lower and upper panels show, respectively, the coincidence-detection histogram and the 2nd order cross correlation coefficients $g_{12}^{(2)}$ for transmitted as well as stored and subsequently re-emitted single-photons at 43 ns and 81 ns storage time.

value $\approx$ 13 μs) is significantly shorter than the optical coherence time ($T_2 \approx 1.1$ ms). Possible reasons include magnetic field instabilities, spectral diffusion (e.g. neighboring gallium spin flips), vibrations of the crystal inside the pulse-tube cooler, and laser-line jitter, etc.

Multimode storage of optical pulses – A demonstration of temporal and frequency multiplexed storage of optical pulses are presented in Figure 2(a) and Figure 2(b) respectively. As the atomic frequency comb (AFC) protocol[9,13] is inherently multimode in time, it allows us to store optical pulses in different temporal modes. For this demonstration, We prepare a 10 MHz AFC for 5 μsec storage time. 10 consecutive laser pulses of 200 nsec duration are directed into, stored in, and subsequently re-emitted after 5 μsec from the Tm:YGG memory (see Figure 2(a)).

To realize frequency multiplexing, it is required to store the distinct spectral modes simultaneously. For this purpose, we create 3 different memory channels, each of 1 MHz bandwidth and spaced by 50 MHz within the inhomogeneous absorption linewidth of the thulium ions. Spectrally matched laser pulses of 1 μsec duration are stored and reemitted after 4 μsec, 6 μsec, and 8 μsec storage time respectively (Figure 2(b)). Our results show the multimode capability of our memory can extend over the spectral and temporal degrees of freedom. To realize the feed-forward-based mode mapping, imposed by the targeted use of a spectrally multiplexed memory in a quantum repeater, we furthermore demonstrate frequency shifting and filtering of the recalled optical pulses such that only the desired frequency mode can be retrieved.

Storage of heralded single photons – To confirm that our memory can operate in the quantum regime, we measure the non-classical correlations between photon pairs at 795 nm and 1532 nm wavelength, created by means of spontaneous parametric down-conversion (SPDC). The detection of a 1532 nm photon using a superconducting nanowire single-photon detector heralded the presence of a 795 nm photon, which is directed into, stored in, and released after a desired storage time from the Tm:YGG memory. To store classical optical pulses, we create AFCs with a bandwidth of around 1 MHz. But since the spectrum of the 795 nm photons extends after filtering over 10 GHz, we increase the AFC bandwidth to 4 GHz. This resulted in a reduced recall efficiency, even for a storage time of only 43 ns.

The second-order cross correlation function is defined as $g_{12}^{(2)}(t) = P_{12}(t)/P_1P_2$, where P_1 and P_2 denote the individual detection probabilities for the two photons per photon pair, and $P_{12}(t)$ is the joint detection probability (coincidence) occurring with time difference t. We measure the 2nd order cross-correlation coefficient $g_{12}^{(2)}(t)$ between the stored (and subsequently reemitted) 795 nm photon and 1532 nm photon of a pair using time-resolved coincidence detection. We note that the repetition period of our pump laser is 12.5 ns, giving rise to "accidental" coincidences at integer multiples of 12.5 ns (see Figure 2(c)). Since these coincidences are

proportional to $P_1 P_2$ in the case of spontaneous parametric downconversion, the cross correlation coefficient can be calculated by taking the ratio of "desired" coincidence detections—in our case for t=0 ns and t = 43 ns & 81 ns—and accidental detections: $g_{12}^{(2)}(t) = \mathrm{R}(t)/\langle \mathrm{R}(t + 12.5\mathrm{ns})\rangle_{\mathrm{n}}$ where "$\langle..\rangle_{\mathrm{n}}$" denotes averaging over several repetition periods n.

We obtain $g_{12}^{(2)}(0\,ns) = 18 \pm 0.02$, before storage, and $g_{12}^{(2)}(43\,ns) = 4.58 \pm 0.46$, after 43 ns of storage time. Both values surpass the classical upper bound of 2 (see Figure 2(c)), which proves the quantum nature of the photon source as well as the memory.

Most of the results reported above are thoroughly discussed in[12]

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