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Free-space photonic quantum memory

Nathan T. Arnold[1], Michelle Victora[4], Michael E. Goggin[2], and Paul G. Kwiat[1,3]

[1]Dept. of Physics, University of Illinois Urbana-Champaign
[2]Truman State University
[3]Illinois Quantum Information Science & Technology Center, University of Illinois Urbana-Champaign
[4]RightHand Robotics, Inc

ABSTRACT

Photonic quantum memories will play an essential role in several quantum information protocols, including distributed quantum computing, quantum sensing, and the synchronization of repeater nodes. Most photonic memories operate by storing the photon in matter-based systems, but those approaches have limitations. Namely, they are inherently narrow bandwidth, often require costly overhead in the form of cryogenics, and typically have low retrieval efficiency into single-mode fiber. In this work, we develop a photonic quantum memory that operates at room temperature in free space, allowing us to avoid the aforementioned drawbacks.

Keywords: Quantum Memory, Herriott Cell, Delay Line, Quantum Repeater, Quantum Buffer

1. INTRODUCTION

Several emerging quantum applications either require,[1] or heavily benefit from, the use of quantum memories in their operation[2].[3] Specifically, early-stage quantum networking protocols gain a large performance improvement when using photonic quantum memories. As such, many different technologies have been investigated for the development of a quantum memory that can store qubits encoded onto photons and reliably retrieve the information once the photon is released. These different technologies can be generally classified into memories that convert photons into a state of matter (matter memory), or memories that allow the photon to travel in a controlled way for a set amount of time (delay-line memory).

Matter memories typically involve the conversion of photons into electronic[4] or spin[5] states of a cloud or lattice of atoms. This type of memory offers deterministic storage and release of photons over a range of storage times and potential high fidelity. In practice the overall memory bandwidth is limited by the speed at which a control field can be applied by an external laser, and most matter memories have an inherently narrow range of optical wavelengths they can store,[6] as the photon being stored must have the exact energy of the excitation it's being stored in. In addition, matter memories often operate at extreme high or low temperatures, which necessitates costly overhead to operate them. Lastly, transferring the photon into and out of the atomic ensemble can add noise and/or loss that significantly reduce the retrieval efficiency of the photons into single-mode fiber[7] (SMF), and the fidelity of the quantum state carried by the photon.

Delay-line memories, contrary to matter memories, do not convert photons into a different state, rather they simply delay the arrival of the photon by an amount of time determined by the travel distance (and index of refraction of the delay line material). One method of creating a delay-line memory is to simply add an extra length of fiber-optic cable to the system in question. This approach is cheap and simple, offering a stable and cost-effective way to delay the arrival photons by a fixed time, but comes with very few features (e.g., one cannot change the delay time of fiber by any meaningful amount). Fiber delays avoid the costly overhead and

Further author information: (Send correspondence to N.T.A.)
N.T.A.: E-mail: narnold4@illinois.edu
M.V.: E-mail: michelle4654@gmail.com
M.E.G: E-mail: mgoggin@truman.edu
P.G.K.: kwiat@illinois.edu

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strict wavelength bandwidth of matter memories, but they still only have low loss in a specific wavelength band. Further, fiber-based memories offer very few available degrees of freedom (DOF), not allowing for encoding of more than a couple types of qubits on a single photon.

This work takes the delay-line approach, but rather than storing photons in a fiber, we store photons in a series of multiplexed free-space cavities. Like all delay-line memories, we must know the desired storage time prior to storage of the photon*, but for systems that operate on a synchronized clock this is not an issue. Our memory operates in free space at room temperature, allowing us to avoid the losses and DOF-limitations of fiber (in principle, we can store qubits encoded into OAM-modes and spatial modes, which a SMF can't operate with), as well as the costly overhead and severe bandwidth-limitations of matter memories (bulk optics operate well over a wide range of wavelengths, and can be tailored to virtually any situation).

2. METHODS

2.1 Multiplexed Storage Loops

Our memory was built with three multiplexed optical delay lines that we can sequentially switch between (Fig. 1) with varying storage times – 12.5 ns, 125 ns and 1.25 μs – to achieve an optimal balance of storage time and efficiency. The shortest loop offers us a fine time resolution, at the expense of low efficiency for long storage times, while the longest loop offers high-efficiency storage for long times with low time resolution. We can control the number of times a photon is stored in each of the three storage loops by making use of an intra-loop polarizing beam-splitter (PBS) and Pockels Cell (PC) to act as an active switch. This allows for storage of photons for an arbitrary number of cycles in each loop, but because the storage times of the three loops differ by a factor of 10 it is only effective to store the photons up to 9 times in the 12.5-ns and 125-ns loops. By multiplexing the three loops we achieve a "digital" memory that can store photons for any number of 12.5-ns increments with an exponentially enhanced efficiency falloff compared to using a single storage loop†.

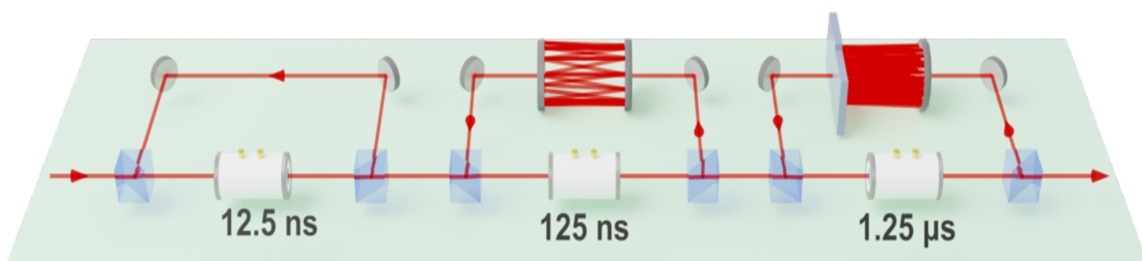


Figure 1. Simplified diagram of the layout of the quantum memory.[8] Each delay line has a PBS at the entrance/exit, as well as a PC inside of the loop to switch polarization. The 125-ns and 1.25-μs delay lines use Herriott cells (or modified Herriott cells) to achieve long storage times.

2.2 Herriott Cell Design

In order to obtain such long free-space storage times on a 4ft x 6ft optical table, we make use of Herriott cells (Fig 2) – multi-pass reflection cavities – in both the 125-ns and 1.25-μs delays (a modified Herriott cell for the latter[9]). Often used for absorption spectroscopy, Herriott cells are compact cavities that provide optical path lengths orders of magnitude greater than the length of the cavity itself. Traditionally, a Herriott cell, such as the one in our 125-ns loop, is comprised of two spherical mirrors facing each other, with a hole drilled into one or both mirrors for entry/exit after traversing the cell. Our regular Herriott cell provides a total path length that is 37 times the length of the cavity itself. Our 1.25-μs storage loop makes use of a modified Herriott cell in which

*Strictly speaking, our switchable delays *do* permit some flexibility in choosing the release time, even after the photon has entered the memory.

†For a free-space memory based on reflective cavities to be competitive, it is essential that the optics used have very low loss: in particular, the improved efficiency falloff described above only occurs in the limit that the mirrors loss (<0.05% in our present system) is less than the loss of the switching optics (PBS + PC).

one of the spherical mirrors has been replaced by two square, flat mirrors, with a slight but specific relative tilt between them. Unlike the regular Herriott cell, there are no entry/exit holes drilled into the mirrors; rather, one of the square mirrors is vertically offset from the other, and the light enters below/exits above the mirror. The modified Herriott cell provides a total path length that is 340 times the length of the cavity itself.

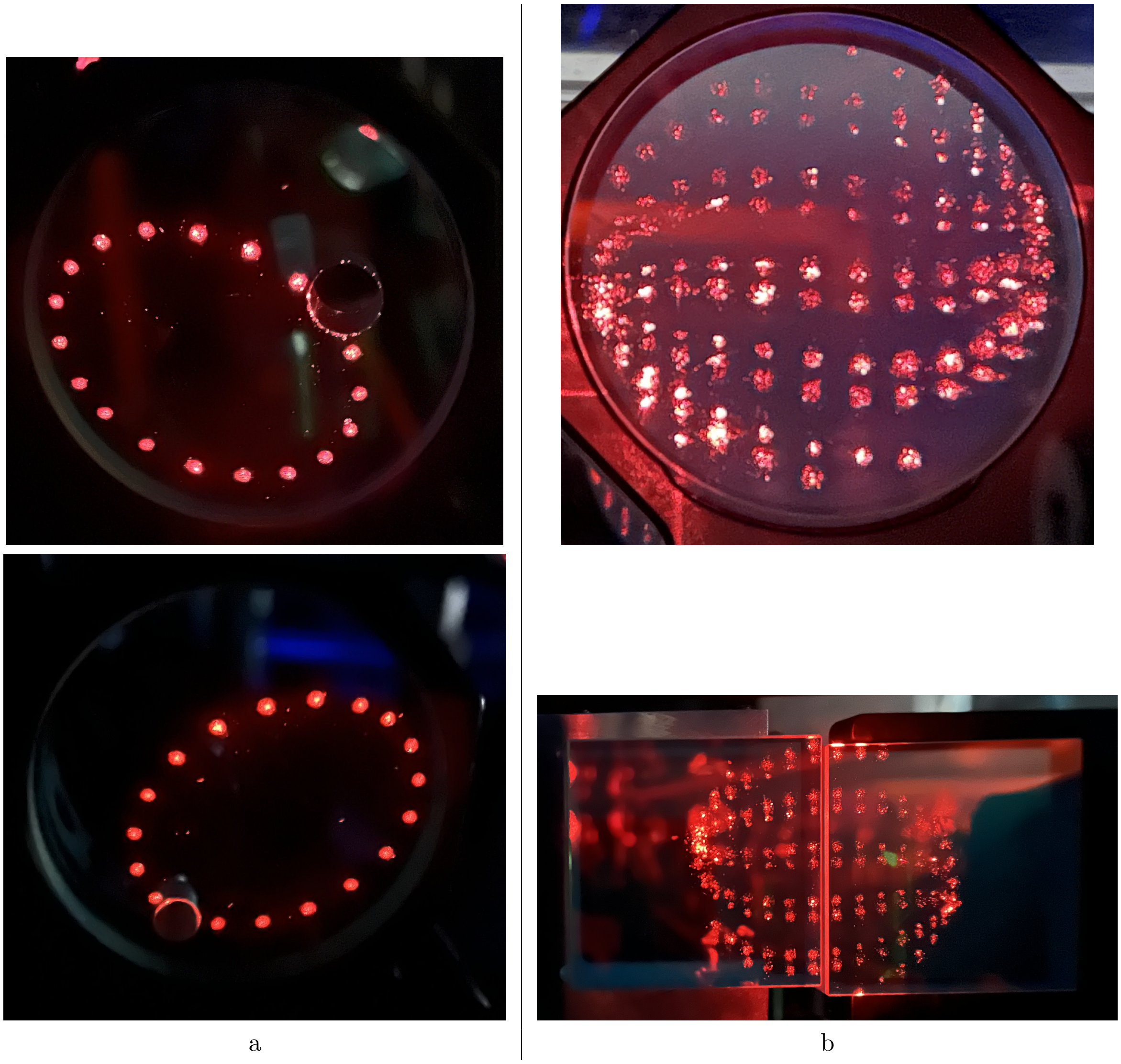


Figure 2. Reflection patterns of the regular (a) and modified Herriott cell (b). For the regular Herriott cell, each spherical mirror has a 1-m radius of curvature with mirror separation of 0.9 m. Each mirror has light reflect off them 18 times during one storage cycle. The light traces out a single elliptical pattern on each mirror before exiting through one of the holes, with a total storage time of ~117 ns. The spherical mirror (b top) has a 3-m radius of curvature and a 3" diameter with a mirror separation of 1.1 m. There are a total of 170 reflection spots on the spherical mirror. The two square flat mirrors (b bottom) are 2" x 2", each with 85 reflection spots. The two mirrors are offset vertically and are both slightly tilted inward to prevent the light from exiting the cell. Light enters the modified Herriott cell by passing under the right square mirror and exits by exiting above the same. The unique geometry of the modified Herriott cell allows for the reflection spots to fill virtually the entire surface area of the mirrors (instead of only an ellipse as in the regular Herriott cell). The total storage time of our modified Herriott cell is 1.25 μs.

2.3 Transducer

In the previous sections we have discussed the general methods for storing photons in a multiplexed delay-line memory, but in practice our goal is to faithfully store and emit photonic *qubits* – typically in the form of a polarization qubit, but possibly with qubtis encoded into other DOF's – with high efficiency and fidelity. Our goal is made difficult by the fact that our memory can only operate with a single input polarization (because of the polarization-dependent switching mechanisms we employ). To fix this issue, the photonic qubit to be stored first goes through polarization-to-time-bin transducer (Fig. 3), which converts an arbitrary polarization state into a time-bin qubit with a single polarization. The two temporal qubits exit the transducer, are stored by the memory, and then propagate backwards through the transducer to re-combine, restoring the initial polarization state.

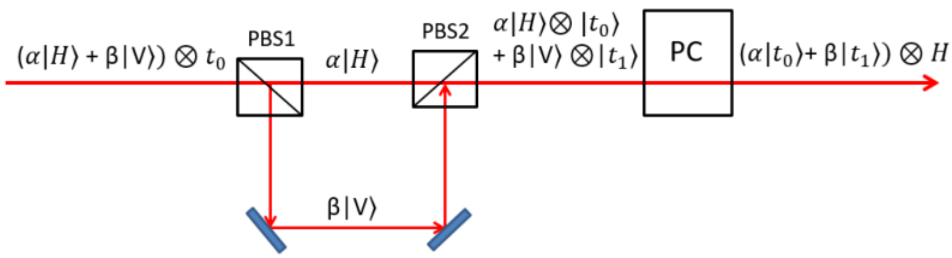
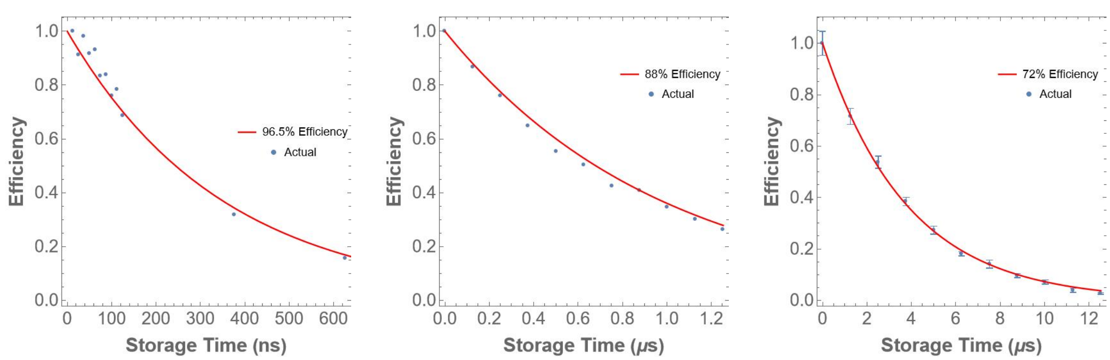


Figure 3. Diagram of the transducer as well as the decomposition of the input state into two time-bin states of a single polarization (the PC only rotates the polarization of the second time-bin).

3. PERFORMANCE

3.1 Efficiency

As mentioned in section 2.1, it is imperative that the losses be minimal to achieve enhanced efficiency scaling from multiplexing. To this end, we have sourced mirrors for the Herriott cells and lenses that have received state-of-the art coatings at the time of creation. The mirrors(lenses) used initially had a reflectivity(transmission) of $\geq$99.95%, but as they are over a decade old their performance has degraded somewhat: Currently, the 12.5-ns, 125-ns and 1.25-μs storage loops respectively have efficiencies of 96.5%, 88% and 72% per cycle into SMF(Fig 4). We have demonstrated storage of light for up to 12.5 μs with end-to-end efficiency of 5% (Figure 5).



a b c

Figure 4. Transmission efficiency vs. storage time for the (a) 12.5-ns, (b) 125-ns and (c) 1.25-μs storage loops. All plots show the predicted exponential decay of their efficiency (red line), and the actual data (blue dots). Note that the 12.5-ns loop has efficiency data taken out to over 600 ns of storage time (50 cycles in the loop).

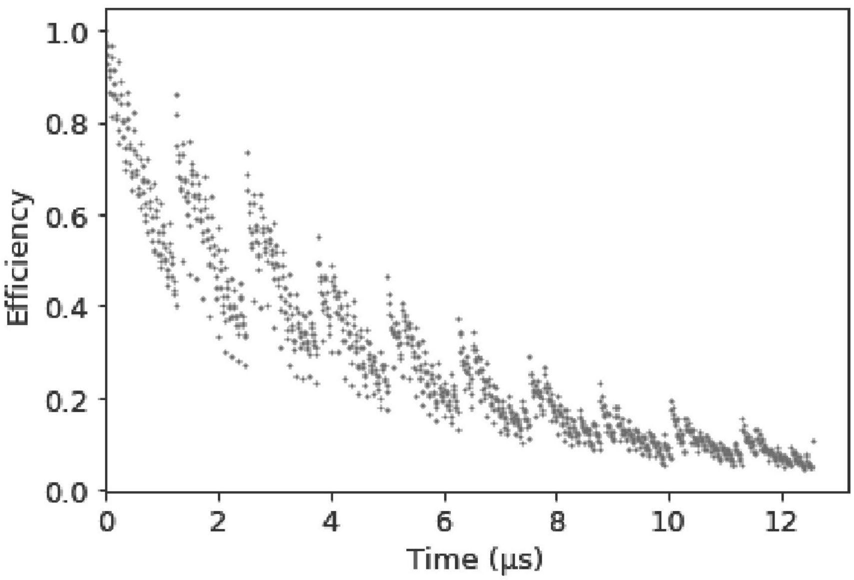


Figure 5. Transmission efficiency vs. storage time for the entire memory. The plot shows the total memory storage time of every permutation of number of storage cycles in each of the three loops with the number of cycles in each loop ranging from 0 to 10 (e.g., the furthest right data point represents 10 cycles in the longest storage loop (12.5 μs) and 0 in the shortest and middle).

3.2 Bandwidth and Time-Bandwidth

One primary benefit of our free-space system is that there is no light-matter interaction, so the wavelength bandwidth is only limited by the bandwidth of the optics used and the effective bandwidth of the PC. Current high-reflectivity mirror coatings operate well over a wavelength range of tens of nanometers. Also noteworthy is that the PC's we use are wavelength-dependent in their operation, which can limit the effective bandwidth of our memory. The largest impact that PC's have on our performance is their imperfect transmission and relatively low intrinsic extinction ratio (<1000:1 in our case). Along with this large bandwidth, our system also has considerably long storage times in the longer loops. With the pulse duration of the light we store being 5 ps, we obtain Time-Bandwidth products of 2.5×10^3, 2.5×10^4 and 2.5×10^5 for our 12.5-ns, 125-ns and 1.25-μs storage loops respectively. However, the Time-Bandwidth product of our memory as a whole is limited by the rep rate of our PC's, which cannot operate above a rep rate of 2 MHz. There is promising research suggesting near-term optical switches can operate well into the GHz regime.[10]

3.3 Qubit State Fidelity

Along with the other metrics mentioned above, it is essential that a quantum memory has high fidelity, the ability to preserve the quantum information encoded onto the photons it stores. By performing polarization-state process tomographies of the transducer and all three storage loops in the memory, we have determined the average χ-fidelity of the transducer to be 99.12(4)%, and of the 12.5-ns, 125-ns and 1.25-μs loops to be 99.35(25)%, 99.0(1)% and 97.8(2)%, respectively. The fidelity of the polarization qubits is mostly limited by the extinction ratio of the polarizing optics we employ (e.g., PC's and PBS's).

3.4 Stability

One major benefit to our free-space scheme is that there is no need for cryogenic cooling or an oven for our operation. Although our system works at room temperature, due to the long path lengths it is somewhat susceptible to instability in the alignment caused by temperature variations. To reduce the impact of these fluctuations we have surrounded the system in an enclosure and implemented two active stabilization systems inside the memory. The enclosure prevents turbulent air from entering system, which reduces drift in the alignment. In addition to this reduction in drift, our two active stabilization systems use a combination of an ancillary laser with piezoelectric-controlled mirrors and a quadrant cell photo-receiver (or quad-cell) to adjust the alignment of the system when drifting does occur.

4. CONCLUSION

The development of more robust high-performance quantum memories will enable several quantum communication protocols, and will be a cornerstone of quantum repeater nodes in near-term quantum networks. Scalable, high-efficiency and high-fidelity memories will be essential for these applications, and our memory is well suited to take this role for many protocols. Our memory boasts an impressive Time-Bandwidth, competitive storage times, scalability and a large range of operational wavelengths (a useful characteristic for early-stage networks, which might use various wavelengths of light). As active polarization-switching optics and optic-coating technologies improve, the methods presented in this work will also continue to improve.

ACKNOWLEDGMENTS

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