Broad-Bandwidth Photonic Quantum Memory

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Abstract: Photonic quantum memories will play an essential role in synchronizing nodes of quantum networks. Here we present a system that can store polarization and time-bin qubits for up to 12.5 μs over a THz bandwidth. © 2022 The Author(s)

1. INTRODUCTION

Quantum networks promise to provide secure long-distance communication links, as well as distributed quantum computing and sensing [1]. These networks will require high-performance photonic quantum memories for the synchronization of optical signals from multiple emitters that are spread apart. Most current proposed photonic memories have the drawback that they store the photon in an atomic ensemble or rare-earth-ion doped crystals, which have a severely limited bandwidth and require cryogenic freezing [2]. Another issue with the matter-based memory approach is that photon retrieval is a difficult task, resulting in a low efficiency [3]. This work circumvents these issues by taking an all-optical approach to storing photonic qubits [4]. By multiplexing three free-space storage loops we achieve competitive storage times with high collection efficiencies in single-mode fiber and a bandwidth that is orders of magnitude greater than schemes that use atomic ensembles.

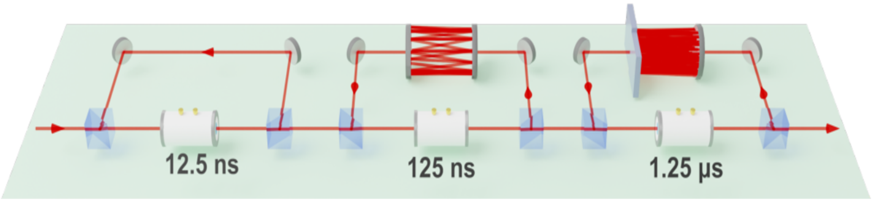

Fig. 1. Simplified diagram of the layout of the quantum memory.

2. METHODS

2.1. *Optical Delay Line*

The primary technology of our memory is a series of free-space optical delay lines with varying storage times that we can switch light into and out of as desired. Horizontally polarized photons at 705 nm enter each delay via a low-loss polarizing beam splitter (PBS); a Pockels Cell (PC) can change the polarization to either keep a photon in the current loop of the memory or output the photon to the next loop of the memory. The PC's and accompanying drivers we employ can achieve a 5-ns rise and fall time, but the repetition rate is currently limited to 40 kHz; improved drivers are available and can achieve repetition rates exceeding 1 MHz. The optical switch (PBS + PC) has a transmission of 97.5% and is the dominating loss in the short storage loop. For the longer storage loops the loss largely stems from the reflectivity of the mirrors we employ (R $\sim$ 99.93%).

2.2. *Digital Quantum Memory*

Whereas some matter-based quantum memories can emit stored photons on-demand, we are required to wait until our photon has traversed the full length of the loop it is actively stored in. To combat this drawback and to achieve an optimal balance of storage time and efficiency, our memory was built with three optical delay lines with varying storage times. By multiplexing these storage loops we can map our analog optical delays into "digital" storage times, or time-bin qubits. The storage times of the short, medium and long loops are 12.5 ns, 125 ns and 1.25 μs respectively – as shown in Fig. 1 – and translate to path lengths of 3.7 m, 37 m and 370 m. Because we can switch between the storage loops, we are able to store photons for any multiple of 12.5 ns – currently up to 12.5 μs.

3. Performance

3.1. *Efficiency*

Our long path lengths are achieved by using Herriott Cells – multi-pass reflection cavities – in both the 125-ns and 1.25-μs storage loops (a modified HC for the latter [5]). The mirrors we use in these cavities have high-reflectivity coatings ($R > 99.95\%$ at 705 nm), so even with several hundred reflections in the longest loop, we still have high efficiency. The efficiency per cycle of the 12.5-ns, 125-ns and 1.25-μs loops are 97.3%, 93.1% and 72%, respectively. These efficiencies can be improved significantly, as the mirrors were coated over 10 years ago and have since degraded somewhat. Current state-of-the-art mirror coatings can offer $>99.999\%$ reflectivity; with this high of a reflectivity our system would be efficiency-limited only by the optical switch, which can be improved to 98.5%, allowing us to achieve storage times exceeding 100 μs, and over 10^4 addressable time bins.

3.2. *Time-Bandwidth*

As mentioned previously, one large benefit of our technology is that we are not bandwidth-limited by atomic transitions; rather, we are limited by bandwidth of the optics we employ and the effective bandwidth of the PC[1]. Combining the large bandwidth (>1 THz) of our system with its considerably long storage time provides us with the best Time-Bandwidth product for a photonic quantum memory ($\sim 6\times10^6$) by several orders of magnitude – an advantage that will only improve as we improve the optics.

3.3. *Qubit State Fidelity*

Along with having impressive storage and retrieval efficiency and a large bandwidth, it is important for a quantum memory to preserve the state of the qubit being stored. A process tomography of each storage loop shows an average χ-fidelity of 97.5(2)%, 99.8(1)% and 97.8(2)% for the 12.5-ns, 125-ns and 1.25-μs loops respectively.

4. Conclusion

The ability to store and synchronize signals from multiple spatially disparate emitters will be essential for the development of quantum networks. Many current technologies with this goal have the drawbacks of offering low bandwidth and poor retrieval efficiency. We present an alternative method that avoids these drawbacks, while simultaneously being able to reliably store time-bin qubits, in addition to polarization qubits (after they are first converted to time bins). Our memory should also be compatible with hybrid photonic states encoded in *multiple* degrees of freedom – including frequency and possibly even spatial mode. These high-dimensional quantum states may lead to new capabilities for quantum networking, including more efficient quantum error correction [6].

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[1] High-reflectivity mirrors can operate well with a wavelength range of several nanometers, allowing us to theoretically store frequency-bin qubits as well. For the PC, the ability to apply the correct phase shift for switching requires knowledge of the wavelength of light being stored. If the wavelength is known, the proper voltage can be applied; otherwise, the switching efficiency will decrease slightly, e.g., a 180° phase for 700nm light corresponds to a switch-out efficiency of 99.2% at 720nm.