Bell State Measurement Between Photonic Qubits Stored in Two Independent Room Temperature Quantum Memories

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Abstract: We demonstrate the feasibility of entanglement swapping after storage by performing Bell-state measurements on polarization qubits stored in two independent room-temperature quantum memories, a crucial step in developing a quantum repeater. © 2023 The Author(s)

1. Introduction

Quantum technologies have promised many advantages in the fields of computation, metrology, and security, as well as a plethora of fundamental scientific endeavors. Recently it has become clear that in order to achieve quantum advantage in all of these fields, the development of a large-scale interconnected set of quantum networks, a quantum internet, is a necessity [1]. Elementary versions of these networks have already been developed and can distribute engagement over hundreds of kilometers [2]. A new kind of network that has the ability to distribute entanglement over long distances through entanglement swapping, is now needed. Towards this end, a mechanism of controlled storage, retrieval, and heralding is necessary [3]. Warm atomic vapor quantum memories have repeatedly been shown to be a promising candidate for such a mechanism [4].

In this work, we describe our efforts to develop a warm Rb vapor memory-assisted Bell-state measurement station that can be used to facilitate the swapping of entanglement in a type-II quantum repeater. We show our recent experimental progress in the storage, subsequent interference, and Bell-state projection of single photon-level coherent phase-randomized qubits stored in two independent quantum memories, we have recently shown this for uni-polarization qubits [5]. We also discuss the physical limitations of such a system as well as the memory specifications needed in order to achieve quantum advantage.

2. Experiments

We investigated indistinguishability, and distinguishability, of polarization qubits that were stored in room-temperature ^{87}Rb vapor quantum memories. This configuration of a basic quantum network requires the use of two independent qubit memories (four light-matter interfaces), a source of phase-randomized polarization qubits, and a Bell-state measurement device (Fig. 1a). Our polarization qubits are attenuated coherent states, 400 MHz red detuned from the $1 \leftrightarrow 1$ ^{87}Rb D$_1$ transition, whose amplitudes are modulated by independent but synchronized acousto-optic modulators (AOMs) to achieve, on average, one photon per pulse. One qubit's phase is then randomized with an electro-optical modulator (EOM), and then both qubits are sent to wave plates to assign a polarization before being sent into our quantum memories.

In each memory, individual qubits are separated into their $|H\rangle$ and $|V\rangle$ components and are combined with a strong control field, 400 MHz red detuned from the $2 \leftrightarrow 1$ ^{87}Rb D$_1$ transition [6]. We use EIT to store the qubits for a short time, $\mathscr{O}(\mu s)$, before retrieval. The signal is then sent through polarization and etalon filtering which reduces the background signal from the control field to mostly four-wave-mixing photons, with a frequency similar to that of the qubit. Their polarizations are then individually corrected to have the same basis as their creation, before being sent to the Bell-state measurement station.

In our first experiments [5] we investigated the indistinguishability of single-photon level, vertical polarization qubits that were stored in a single rail of our quantum memories. This was accomplished using a Hong-Ou-Mandel (HOM) measurement between the retrieved qubits with the $g^{(2)}$ correlation measured as a function of differences in storage times between the two memories, $\Delta\tau$, with the input time of the qubits being the same (Fig. 1b). The resulting interference was analyzed for various regions of interest resulting in data sets with different signal-to-background ratios (SBRs), a maximum visibility of $43.0 \pm 1.6\%$ was measured as compared to a measurement of

48.5 ± 0.5% without memories (Fig. 1c). The relationship between the HOM visibility versus the SBR was investigated and a heuristic model was used to fit the data (Fig. 1d). From this, it is clear that a high SBR is a necessary requirement for a high-visibility memory HOM measurement, and thus a high-fidelity Bell-state measurement.

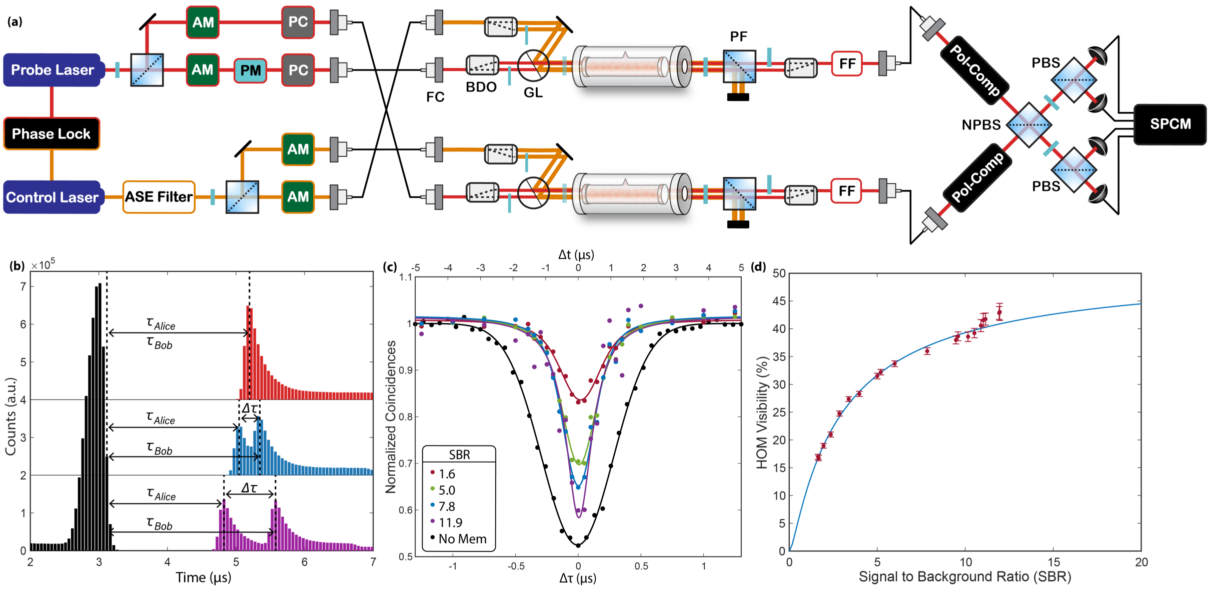

Fig. 1. **(a)** A schematic of the memory Bell-state measurement experiment **(b)** Histograms of single-photon detection events from pulses, $\langle n \rangle \approx 1.6$, stored in two independent single-rail room temperature quantum memories. Black: proportion of unstored events, Purple: storage time difference $\Delta\tau = 0.75\,\mu s$, Blue: storage time difference $\Delta\tau = 0.3\,\mu s$, Red: storage time of both memories $\tau = 2\,\mu s$. **(c)** $g^{(2)}(\Delta\tau)$ of HOM interference between two independent single-rail room temperature quantum memories for different estimated signal-to-background ratios (SBR), as compared to the visibility without memories (top x-axis), error bars not shown for clarity. **(d)** HOM visibility versus the signal-to-background ratio with a heuristic fit. [5]

3. Outlook: Memory Assisted Measurement Device Independent Quantum Key Distribution

One of the first applications of our system is the implementation of a memory-assisted measurement device independent quantum key distribution (MA-MDI-QKD) protocol. Having demonstrated the feasibility of polarization qubit retention in our memories in the few photon level regime [5], we plan to implement such a protocol under the same experimental framework. The primary technical challenge of such a system is the real-time generation and tracking of random polarization qubits. We will accomplish this using a white-rabbit-compatible, FPGA-controlled EOM system that will assign a polarization to the qubit based on input from a quantum random number generator (QRNG). These qubits will then be stored and projected into a Bell-state, the results of which will then be used to generate keys. Using decoy state methods we believe we will be able to achieve a positive key rate.

References

1. Stephanie Wehner, David Elkouss, and Ronald Hanson. Quantum internet: A vision for the road ahead. *Science*, 362(6412):eaam9288, 2018.
2. Sebastian Philipp Neumann, Alexander Buchner, Lukas Bulla, Martin Bohmann, and Rupert Ursin. Continuous entanglement distribution over a transnational 248 km fiber link. *Nature Communications*, 13(1), October 2022.
3. Nicolas Sangouard, Christoph Simon, Hugues de Riedmatten, and Nicolas Gisin. Quantum repeaters based on atomic ensembles and linear optics. *Rev. Mod. Phys.*, 83:33–80, Mar 2011.
4. I. Novikova, R.L. Walsworth, and Y. Xiao. Electromagnetically induced transparency-based slow and stored light in warm atoms. *Laser &amp Photonics Reviews*, 6(3):333–353, September 2011.
5. Sonali Gera, Chase Wallace, Mael Flament, Youngshin Kim, Alessia Scriminich, Mehdi Namazi, Steven Sagona-Stophel, Giuseppe Vallone, Paolo Villoresi, and Eden Figueroa. Hong-ou-mandel interference of polarization qubits stored in independent room-temperature quantum memories. (*In Preparation*).
6. Mehdi Namazi, Connor Kupchak, Bertus Jordaan, Reihaneh Shahrokhshahi, and Eden Figueroa. Ultralow-noise room-temperature quantum memory for polarization qubits. *Phys. Rev. Appl.*, 8:034023, Sep 2017.