Towards a Memory-Assisted Bell State Measurement Between Two Independent Entanglement Sources

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Abstract: We report on progress towards achieving entanglement swapping between independent cavity-enhanced entanglement sources that are tuned for quantum memory operation. Together with quantum memories, we envision the demonstration of a Type II quantum repeater.

1. Introduction

Quantum networks have the potential to improve the security and information capacity of optical communication systems. State-of-the-art quantum networks can now distribute entanglement over long distances. However, these elementary quantum networks are still loss-limited and are based on the probabilistic nature of entanglement creation and detection. To overcome these challenges, a new generation of quantum networks is required, where light-matter interfaces are used to synchronize streams of entangled photons [1], thus increasing the probability of distributing entanglement across the network [2]. These quantum repeater networks, assisted by non-linear atomic systems will be the backbone of an entanglement-based quantum internet [3].

Two of the main requirements for creating a Type II quantum repeater using in-out quantum memories are: 1) the creation of a-priori entanglement that is tuned to atomic transitions and 2) the demonstration of coherent control in quantum memory systems (e.g. storage and heralding) using independently created streams of photons. In this work, we will describe the development of two independent sources of entanglement with MHz-bandwidths that are compatible with atomic quantum memories. As it is paramount that the entanglement sources be identical in their quantum properties, our experiments will be dedicated to show indistinguishability between these two independent sources through Hong-Ou-Mandel interference measurements. We will also discuss the operation of the sources when they are tuned to operate on resonance with the D_1 line of rubidium and show the results of their interaction with rubidium atomic ensembles.

2. Experimental results

2.1. Cavity enhanced sources of photon pairs

EIT-based memories put a constraint on the bandwidth of the photons that can be stored. Typical single photon sources using nonlinear crystals, generate photons that are much broader in bandwidth. Placing the non-linear crystal in a cavity with narrow linewidth, assists in creating photons suitable for storage in these memories. We have developed a pair source using a 20mm long type I PPKTP crystal placed inside an optical cavity with a 5 MHz linewidth. The cavity is pumped with light at 397.5nm and the down-converted photon pairs in the cavity mode (at 795nm) are coupled into a fiber. We employ two consecutive Fabry Perot etalons having slightly different FSRs of 13 and 23 GHz to filter out extra frequencies that are resonant with the cavity, retaining only the frequency resonant to the atomic transitions of interest in rubidium. Within these conditions, we have measured a spectral brightness of approx. 4000 photons/MHz/mW after filtering out the unwanted SPDC peaks transmitted by the cavity at other FSR resonances.

Additionally, we show our developments regarding a second pair source, where we have extended the optical parametric amplifier (OPA) concept to the generation of entangled photon pairs. In this source, we used two nonlinear PPKTP crystals producing photon pairs states of either HH or VV depending on the orientation of its optic axis and the pump field's polarization. We exploit this to generate polarization-entangled states of the form $\frac{1}{\sqrt{2}}(HH + e^{i\phi}VV)$ by placing the crystals back-to-back with their optic axes orthogonal to one another inside the cavity. Additionally, we will report on the indistinguishability of the photons produced by the two photon-pair sources through the demonstration of robust Hong-Ou-Mandel interference between the photons created by the independent sources.

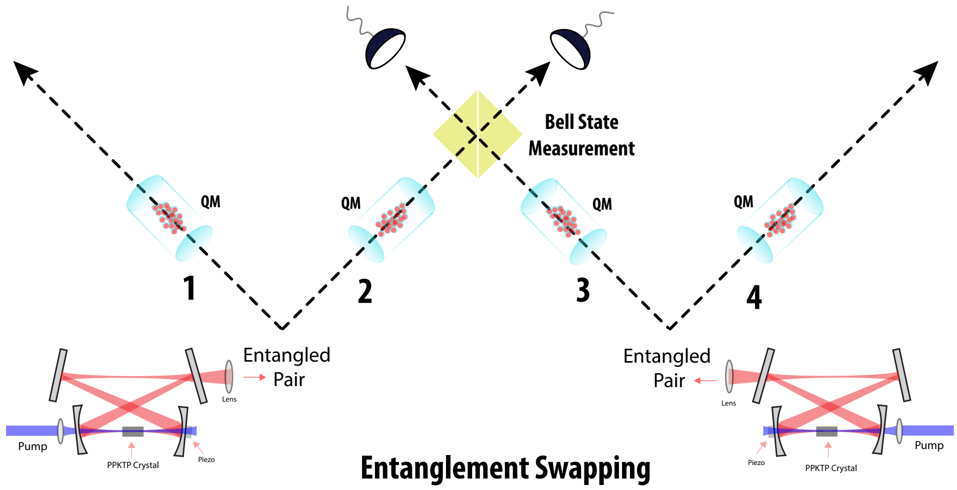

Fig. 1. **HOM interference with memory-tuned independent entanglement sources.** Quantum repeaters rely on memory-assisted entanglement swapping between independent entangled photon streams. In our experiments, we show HOM indistinguishability between independent entangled sources. Additionally, we also show experiments interfacing the cavity-enhanced photons with room-temperature rubidium quantum memories.

2.2. *Integration of cavity-enhanced sources with quantum memories*

Within the context of creating entanglement-based quantum repeater networks, the next natural step is to store the cavity-enhanced single photons in rubidium-vapor-based, room-temperature quantum memories. We will also report on our current experiments towards storing our cavity-enhanced photons with signal-to-background ratios (SBR) higher than 10. In order to reduce the limiting four-wave mixing (FWM) noise we plan on implementing a re-pumping scheme [4] using 780 nm lasers resonant to the $5S_{\frac{1}{2}} \rightarrow 5P_{\frac{3}{2}}$ transition. These beams optically pump the atoms to the Zeeman level $F = 2, m_F = +2$ where fewer FWM noise channels can be generated, generating the necessary higher SBR to store photons from the OPA source.

3. Near Term Outlook

The implementation of a quantum repeater protocol using memory-assisted entanglement swapping first requires the demonstration of the following experiments: Storage of OPA-produced and heralded storage of photons [5]. The latter, we plan on achieving by utilizing one photon in the pair as a heralding signal for memory preparation. We also plan to perform quantum state tomography of the retrieved single photons from the memory. Once the storage of OPA-produced photons has been realized, we will be poised to perform a Bell-state measurement between two OPA-produced photons that had been stored in our quantum memories.

References

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