PhD THESIS DEFENSE: Light-matter entanglement between telecom photons and solid-state quantum memories

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Future networks for quantum communication will require a new form of technology in order to operate over long distances. The no-cloning theorem precludes the use of amplification, so quantum repeater schemes have been proposed to achieve long-distance quantum communication through the distribution of entanglement. A key device for this setup is a quantum memory, which is required in order to store entanglement and synchronise its distribution.

Among the many physical systems than can be used as a quantum memory, rare-earth ion-doped crystals stand out due to their long coherence times and potential for multiplexing and integration. This thesis reports the use of one such system, Pr3+:Y2SiO5, as a quantum memory using the atomic frequency comb (AFC) protocol. Building on previous work, we improved the performance of the memory to be able to demonstrate light-matter entanglement with a telecommunications wavelength photon and the quantum memory, for both a bulk memory and an integrated version.

To measure light-matter entanglement, we use photon pairs generated through cavity-enhanced spontaneous parametric down conversion, where one photon (the signal) is stored in the memory and the other (the idler) is at a telecommunications wavelength. These photon pairs exhibit energy-time entanglement, which we analyse in the time basis using fibre- and AFC-based Mach-Zehnder interferometers.

In the first experiment, we demonstrate light-matter entanglement where the bulk quantum memory is used with on-demand retrieval via storage in a spin-wave. We measure interference fringes with average visibilities of 89(2)% for AFC storage, and 70(3)% for spin-wave storage, sufficient to demonstrate entanglement. This is the first such demonstration using an on-demand multimode solid-state memory and telecom photon. We show that entanglement is maintained for up to 47.7 ?s of storage. These results were made possible through improvements in the AFC efficiency and the noise filtering. Furthermore, we perform on-demand storage and retrieval of up to 30 temporal modes.

We take the next step towards implementing our system in a real world scenario by measuring entanglement over a distance. To do so, we send the idler photons through both optical fibre spools and deployed fibre in the metropolitan area of Barcelona, Spain, while the photon detection still occurs in the same lab. The resulting visibilities (80% or higher) demonstrate that the photonic qubit does not decohere during transmission through the optical fibre. We then decouple the photon creation and detection by measuring non-classical correlations between signal photons detected in the lab, and idler photons detected 16 km away (44 km in fibre) in a different location.

The final experiment uses a fibre-integrated memory for light-matter entanglement. We use a Pr3+:Y2SiO5 crystal containing a Type I laser-written waveguide, interfaced directly with optical fibre. The fibre-integration allows for improved transmission and AFC efficiency compared to a free-space coupled waveguide memory. To analyse the performance of the memory, we demonstrate non-classical correlations for storage times up to 28 ?s. We perform qubit tomography in the time basis for storage times of 3 and 10 ?s, measuring two-qubit fidelities of 86(2)% and 86(4)%, respectively, demonstrating storage of entanglement.

These experiments demonstrate the potential of our system for use as part of a quantum repeater, with many opportunities for further improvement to the storage time, efficiency, and multiplexing capability.