Broadband waveguide quantum memory for entangled photons

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Quantum information processing and communication relies on the encoding of information into quantum states of physical system such as photons, which are extremely mobile and thus excellent for long distance quantum communication [1]. The resulting applications of fundamental properties of quantum physics offer secure encryption through quantum key distribution without relying on unproven mathematical assumptions [2] and, by means of quantum teleportation, allow for the disembodied transfer of quantum states between distant places [1].

The implementation of a quantum interface between light and matter is central to advanced applications of quantum information processing and communication. Notably, such an interface is a key ingredient in quantum repeaters, which are required in order to extend quantum communication channels over distances beyond around hundred kilometres [3]. While light is ideal for transmitting quantum information, matter serves to store quantum information for later recall. In quantum communication applications such as quantum repeaters [4] and quantum networks [5], the ability to store quantum information until needed enables synchronisation of the information flow through the communication channel or network. A key property of such a quantum interface is the ability to faithfully map entanglement between light and matter. In the case of an entangled photon pair the mapping of one of the two entangled photons into matter results in photon-matter entanglement. This again clears the path to build quantum repeaters and perform quantum teleportation experiments.

Theoretical and experimental efforts to uncover and characterise different physical systems for their fundamental or technological applicability to quantum information processing and communication have received much attention over the past decades. Experimental capabilities have advanced rapidly over the past years and quantum state transfer between light and atomic vapours, solid state ensembles, or single absorbers, as well as the generation of light-matter entanglement through the absorption of photons, or the emission of photons from atomic ensembles or single emitters has been reported. For a quantum memory to become practical, it is important to reduce the complexity of experimental implementations, and the recent addition of rare-earth-ion-doped (RE) crystals [6, 7] to the set of storage materials has been an important step towards this goal. RE crystals, beings solid state implementations, are attractive due to their resemblance with building blocks of current telecommunication devices and thus prospectively their ease of integration with existing information technology. Their promise is further enhanced through potentially long storage times. In addition, given the large inhomogeneous broadening of optical zero-phonon lines, up to 100 GHz, RE crystals in principle offer storage of photons with less than 100 ps duration when being used in conjunction with a suitable quantum memory protocol [6].

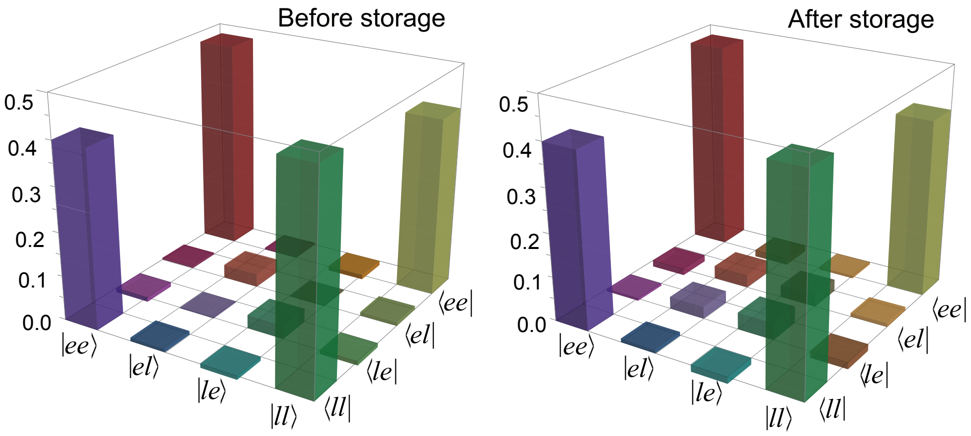

FIG. 1: Reconstructed density matrices calculated using a maximum likelihood estimation for the bi-photon state before and after storage. Only the real parts are shown – the absolute values of all imaginary components are below 0.04.

In this work we report the reversible transfer of photon-photon entanglement, generated by means of spontaneous parametric down-conversion, into entanglement between a photon and a collective atomic excitation in a thulium-doped lithium niobate waveguide cooled to 3 K [8] (This was simultaneously demonstrated in [9]). Towards this end we we narrow the bandwidths of our time-bin entangled photons to match the 5 GHz acceptance bandwidth of our storage device achieved by employing an Atomic Frequency Comb (AFC) memory protocol. The entanglement-preserving nature of our storage device is assessed by reconstructing the bi-photon quantum state before and after the reversible transfer as depicted in FIG. 1. This allows us to gauge the amount of entanglement contained in the detected photon pairs, showing, within statistical error, a perfect mapping process c.f. TABLE I. Additionally, we directly verify the sufficiency of the entanglement for quantum communication by violating the CHSH Bell inequality [1] before and after the storage process.

	Purity [%]	Entanglement of formation [%]	Fidelity with $\|\phi^+\rangle\langle\phi^+\|$ [%]	Input-Output Fidelity [%]	Expected $S_{\rm th}$	Measured S
ρ_{in}	75.7±2.4	64.4±4.2	86.2±1.5		2.235±0.085	2.379±0.034
ρ_{out}	76.3±5.9	65±11	86.6±3.9	95.4±2.9	2.2±0.22	2.25±0.06

TABLE I: Purity, concurrence, entanglement of formation (normalized with respect to the entanglement of formation of $|\phi^+\rangle$), and fidelity with the ideal state $|\phi^+\rangle$ for input and output density matrices ρ_{in} and ρ_{out}. The input-output fidelity refers to the fidelity of ρ_{out} with respect to ρ_{in}. Expected and measured Bell inequality violation for input and output state. Uncertainties indicate one-sigma standard deviations and are estimated using Monte Carlo simulation.

The transfer of entanglement between physical systems of different nature shown in our experiment, shows that this fundamental quantum property is not as fragile as is often perceived. In light of future applications, the broadband and integrated features of our device facilitates linking this promising quantum storage device with commonly used, efficient sources of photons in bi- and multi-partite entangled states [1]. Thus, our broadband integrated approach to quantum memory constitutes an important milestone on the path towards quantum repeaters and moves fundamental quantum memory research further towards application. In the quest to build future quantum networks, the demonstrated increase in storage bandwidth is a major benefit, as it simplifies the mutual frequency matching of photons with remote quantum memories. Again as a result of the large storage bandwidth it is possible to encode quantum information into short optical pulses that allows one to increase the number of temporal modes to be stored. This boosts the quantum information flow through a network and decreases the time it takes for entanglement to be established over a large distance using a quantum repeater [3, 4]. Despite the limitations of a pre-set storage time, and the necessity to increase the storage efficiency and storage time, this study paves the way to new explorations of fundamental and applied aspects of quantum physics.

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