High-fidelity entanglement between a trapped ion and a telecom photon via quantum frequency conversion

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Quantum repeaters that establish long-distance entanglement are essential tools in the emerging field of quantum communication technologies [1]. Important building blocks for these repeaters are quantum nodes, i.e. efficient, low-noise quantum memories, and photonic channels to distribute quantum information among the nodes. A promising candidate for quantum nodes are, among others, single trapped ions providing a very high level of control over their photonic interaction, large coherence times and high-fidelity quantum gates [2, 3]. However, their optical transitions are located outside the wavelength regime between 1260 nm and 1625 nm where telecom fibres afford low-loss transmission. Thus, there is a demand for interfaces connecting the telecom-wavelength regime and the visible/NIR range in a coherent way, i.e., preserving quantum information encoded in a degree of freedom of a single photon, e.g. its polarization.

Here we present a complete device generating entangled states between a trapped $^{40}\mathrm{Ca}^+$ ion and the polarization state of a telecom photon utilizing a solid-state quantum frequency converter (QFC) connecting 854 nm to the telecom O-band at 1310 nm [4] (see Fig. 1). The first part of the device is a trapped-ion node, generating atom-photon entanglement between a Zeeman qubit in the $D_{5/2}$-manifold of the ion and the polarization state of a single photon at 854 nm with a fidelity of 98.3 ± 0.3%.

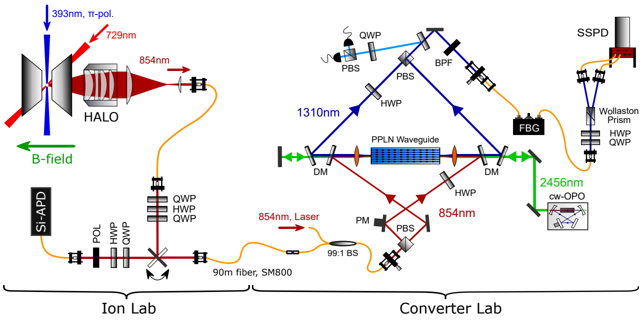

Figure 1: Experimental setup.

The second part is a solid-state QFC device based on a χ^2-nonlinear interaction. This technique has been established as a proven tool to connect quantum nodes with system wavelengths in the visible/NIR to the telecom bands [5]. However, the strong polarization dependence of the χ^2-process and the high demands on efficiency and noise properties hindered so far the entanglement of a stationary qubit with the polarization state of a telecom photon via solid-state QFC. Our approach to overcome the polarization dependency utilizes a polarization Mach-Zehnder interferometer with a single nonlinear crystal, i.e. both interferometer arms pass through the same crystal in a counter-propagating way (see Fig. 1). The use of nonlinear waveguides together with strong spectral filtering ensures a highly efficient low-noise operation of the device. All in all, we achieve a process fidelity in the polarization-state conversion of 99.75 ± 0.18%, an external frequency conversion efficiency of 26.5% and a conversion-induced ungated background of 11.4 photons/s.

The complete ion-telecom-photon quantum interface is established by combining both parts. We achieve ion-telecom-photon entanglement with a fidelity of 97.7 ± 0.2%, which proves that the converter leaves the input state almost unaltered (Fig. 2a). Moreover, the converter renders possible the generation of maximally entangled states with a fidelity of 98.2 ± 0.2% (Fig. 2b).

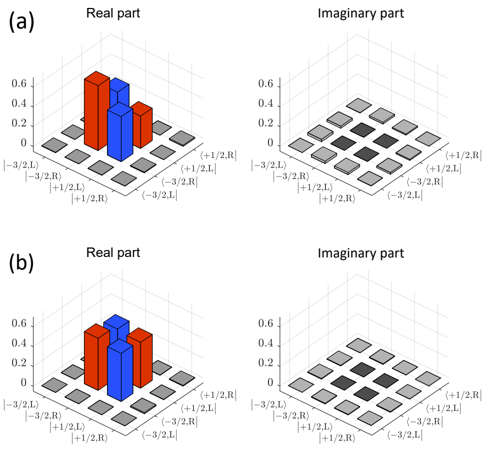

Figure 2: Quantum state tomography of the ion-telecom-photon entangled states.

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