Frequency-multiplexed photon storage and read-out on demand using an atomic frequency comb-based quantum memory

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The ability to send quantum information encoded in photons over large distances is hampered by the unavoidable loss in the communication channel. In classical communication, channel-loss is alleviated by amplifying the information carrier, however due to the no-cloning theorem for quantum states this approach is not viable for quantum communication channels. Instead long-distance quantum communication can be enabled by quantum-repeaters, which serve to distribute entanglement over the entire channel by means of entanglement swapping between subdivision of the channel[1]. In order to synchronize the process of entanglement swapping between adjacent subdivisions, quantum repeaters must incorporate quantum memories[2]. A quantum memory is a device that has the ability to (reversibly) map quantum states between photons and atoms[3]. In most of the quantum repeater architectures proposed to date, it is required that quantum memories feature recall on demand. Other desirable attributes of a quantum memory are high fidelity and efficiency, long storage times, and the possibility to simultaneously store multiple carriers of quantum information, i.e. record multiple photonic modes. The combination of a quantum state storage protocol based on an atomic frequency comb (AFC)[4] with rare-earth-ion doped crystals cooled to cryogenic temperatures as storage materials[5] has been shown to meet many of these requirements. In particular, it is well suited for storage of temporally multiplexed photons[6,7]. Yet, despite first proof-of-principle demonstrations[8], recalling the quantum information at a desired time (i.e. read-out on demand) with broadband, single-photon-level pulses remains an outstanding challenge. Fortunately, the AFC protocol allows not only for multi-mode storage in the time domain, but also in the frequency domain.

Here, we will present the first experimental demonstration of frequency-multiplexed storage of attenuated laser pulses followed by read-out on demand in the frequency domain, pointing to a quantum repeater architecture based on frequency multiplexing. Our work is based on the AFC protocol and employs a Tm-doped $LiNbO_3$ waveguide cooled to 4 K[9,10]. Using a serrodyne sideband chirping technique we prepare several frequency-combs in the atomic absorption spectrum. Each section of AFC is a few 100 MHz wide and since we vary the comb-tooth spacing in each section we prepare them with different storage times on the order of 20-150 ns. After the AFC preparation, we send a probe pulse, which is modulated to contain several frequency components that correspond to the centre frequencies of the AFC sections. The mean photon number in each mode is set to be around one. As the probe pulse is mapped to our quantum memory the different frequency modes are mapped to different sections of the AFC and thus recalled at different times. The recalled pulses pass through a frequency filter with a band-width matching a single frequency mode. Before frequency filtering we are able to impart again a frequency shift on the recalled pulses, which can hence be set to pass the spectral filter. This constitutes recall on demand of a particular frequency mode. Our multi-mode quantum memory is highly flexible and can be set to recall all modes at the same time, and adapted to broader or narrower frequency modes. In addition it has been shown to faithfully store time bin qubits in pure and entangled states and preserve all degrees of freedom of the photonic wavefunction[9,11].

Finally, we will argue that, in view of a quantum repeater, our approach based on a multimode memory with read-out on demand in the frequency domain is equivalent to temporal multiplexing and read-out on demand in the temporal domain. This overcomes one further obstacle to building quantum repeaters using rare-earth-ion doped crystals as memory devices.

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