Demonstration of an atomic frequency comb quantum memory using velocity-selective pumping in warm alkali vapour

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Abstract: We present the first demonstration of velocity selective pumping in a warm atomic vapour as a means to preserve light matter coherence. We illustrate this control with a subsequent demonstration of creating an atomic frequency comb in the vapour and using it as a multi-mode quantum memory.

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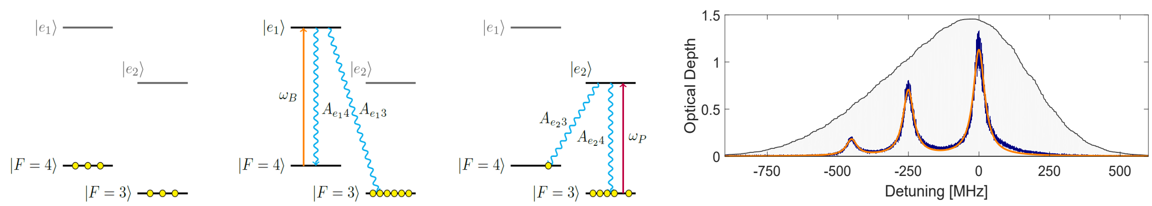
Quantum memories are a crucial technology for enabling large-scale photonic quantum networks through the synchronisation of probabilistic operations. Such networks impose strict requirements on the properties of a quantum memory, such as storage time, retrieval efficiency, bandwidth, and scalability. On- and off-resonant ladder protocols in warm atomic vapour platforms are promising candidates, combining efficient high-bandwidth operation with low-noise on-demand retrieval. However, their storage time is severely limited by motion-induced dephasing arising due to the broad velocity distribution of atoms comprising the vapour. Here, we demonstrate velocity selective optical pumping as a technique to overcome this decoherence mechanism, decreasing the dephasing rate well below the storage state lifetime limit in a room temperature caesium vapour. This property can be further utilised to create arbitrarily shaped absorption profiles necessary for the atomic frequency comb (AFC) quantum memory protocol, which we experimentally demonstrate.

1. Velocity Selective Pumping

Creating local photonic quantum networks with a high clock requires quantum memories with broadband acceptance. On- and off-resonant Λ and ladder protocols in warm alkali vapour platforms are a promising candidate, in particular, the off-resonant cascaded absorption (ORCA) memory [1] and the fast ladder memory (FLAME) [2]. These inherently noise-free protocols involve the mapping of a weak signal field into an atomic coherence between two states via a two-photon absorption process in an atomic ensemble, mediated by a strong control field. Kaczmarek et al. used the ORCA memory to store and recall heralded single photons, preserving quantum correlations upon read-out, demonstrating unequivocally that the protocol is noise free.



(a) Initial population (b) Burn (c) Velocity Selective Pump d) Optical Depth of D2 F=4 transition

Fig. 1. Outline of the velocity selective pumping: (a) initial population in thermal equilibrium, (b) burn stage in which all population in the $F = 4$ hyperfine level is transferred to the $F = 3$ level, (c) velocity-selective pumping re-pumps a velocity class back into the $F = 4$ hyperfine level for participation in the memory protocol d) Optical depth of the D2 transition from the $F = 4$ state with (blue & orange) and without (grey) velocity-selective pumping.

The major performance limitation with this platform is the motion-induced dephasing, which restricts the storage time to 5.4 ns in [1], well below the storage state spontaneous emission lifetime limit (60 ns) [3]. Motion-induced dephasing is an inhomogeneous broadening mechanism that arises as a result of the Doppler effect and the thermal motion of atoms comprising the vapour.

A common approaches to negate Doppler dephasing is to reduce the spread of velocities in the distribution. Typically this involves atom trapping techniques which results in added experimental complexity compared to vapour cells. Velocity selective optical pumping is a technique that allows preparation of atoms in a warm vapour such that only atoms of a specific velocity class are in the memory ground state $|g\rangle$ and the rest of the atoms are populating an auxiliary state $|aux\rangle$ that does not take part in the memory protocol. This results in a much narrower velocity distribution of atoms participating in the protocol, thereby increasing the dephasing time whilst still being implemented in a warm vapour cell.

Here we implement the velocity selective pumping scheme in warm Ceasium vapour as shown in Figure 1; initially pumping all of the population to the $|F=3\rangle$ hyperfine state before transferring a single velocity class to the $|F=4\rangle$ state for use in a quantum memory. In this system we demonstrate an increase in the dephasing time to as long as 450 ns, offering the potential to significantly increase memory lifetime.

2. Atomic Frequency Memory

Atomic frequency combs (AFC) are spectral distributions consisting of equally spaced narrow absorption features separated from one-another by a detuning Δ. Typically realised in rare-earth systems, AFCs are created using optical pumping to generate the narrow features in an inhomogeneously broadened spectral distribution. They may be used in quantum memories whereby a broadband photon is absorbed by the comb and mapped into a collective excitation over the atoms comprising the comb [4, 5].

Using the above velocity selection scheme, and the Doppler broadening as the inhomogeneous broadening we have demonstrated coherent light storage using the AFC protocol in warm vapour. This is to our knowledge the first demonstration of this scheme in this medium. This is achieved by adding sidebands to the *pump-back* laser (Figure 1c) to transfer not just one but three velocity classes. This, combined with Caesium's hyperfine transitions produces the absorption spectrums shown in Figure 2a.

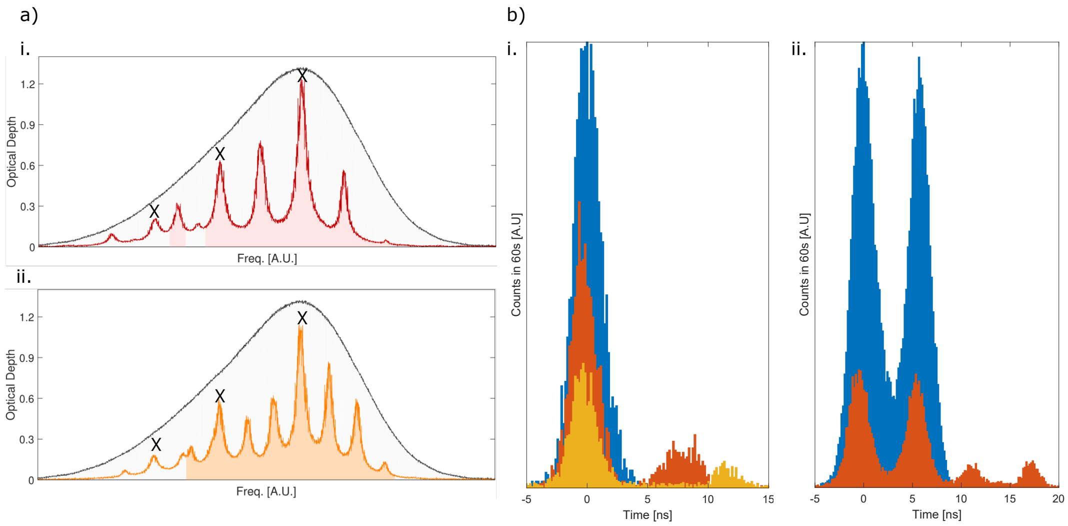


Fig. 2. a) Optical depth as a function of frequency of the velocity selected AFC. The 3 hyperfine D2 transitions of Cs corresponding to a single velocity class are marked with X's, with additional velocity classes making up the other teeth in the comb. i) Comb spacing $\Delta = 125.5$ MHz. ii) $\Delta = 125.5$ MHz. b) Storage and retrieval of an incident pulses (blue) using the AFc protocol on the velocity selected vapours shown in a). ii) Multi-mode storage and retrieval of two consecutive pulses.

Figure 2b shows the storage and retrieval of a 5 ns pulse stored in the vapour using the combs shown in Figure 2a. This debut use of the AFC protocol in atomic vapour yielded a efficiency of 6.9% and 3.2% with the time for an echo (9.79 ns and 11.95ns) dictated by the average splitting in the comb (Δ).

Conclusion

In conclusion velocity selective optical pumping has been demonstrated as a potential candidate for overcoming motion-induced de-phasing in warm vapour memories as a mechanism to extend the storage lifetime. Furthermore this pumping has been used to realise a AFC in warm vapour and produce the first recorded usage of a multi-mode AFC quantum memory protocol in atomic vapour.

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