# Engineering a Noiseless and Broadband Raman Quantum Memory for Temporal Mode Manipulation

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**Abstract:** The Raman quantum memory can manipulate temporal modes of light - a promising high-dimensional basis for quantum information processing. We demonstrate both temporal mode manipulation and a novel suppression scheme for four-wave mixing noise. 

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Single-mode broadband quantum memories provide unique capabilities that can enhance and expand the performance of future quantum networks. On the one hand, they facilitate the temporally multiplexed generation of pure single photons at high clock rates, which can dramatically increase photon generation rates [1]. On the other hand, their single mode nature allows for operation as a broadband beam splitter that can operate on novel bases for information encoding. Their usefullness within quantum architectures hinges on the ability to preserve and retrieve the non-classicality of the input quantum state, thus requiring low-noise operation for any quantum applications.

Such broadband and single-mode quantum memories are compatible with temporal modes (TM) - complex temporal amplitudes of pulsed single photons - which have been identified as an appealing basis states for integrated quantum networks [2]. Information is encoded onto the complex temporal amplitude of pulsed single photons which are compatible with single-mode fibres. This allows for quantum networks using temporal modes as a high dimensional encoding alphabet to realise fibre-compatible qudits.

Our quantum memory system of choice operates using warm atomic caesium vapour, based on an off-resonant Raman scattering protocol [3], which combines operation at ambient conditions, high storage efficiencies, GHz bandwidth storage, and single-mode operation. The Raman interaction can be described as a time non-stationary light-matter beamsplitter that acts on a single temporal mode [4], and therefore the shapes of the stored and retrieved TM are defined by the temporal amplitudes of the strong control pulses used to drive the memory. All other modes are then transmitted, enabling storage, delay and re-shaping of a user-defined TM in one single device.

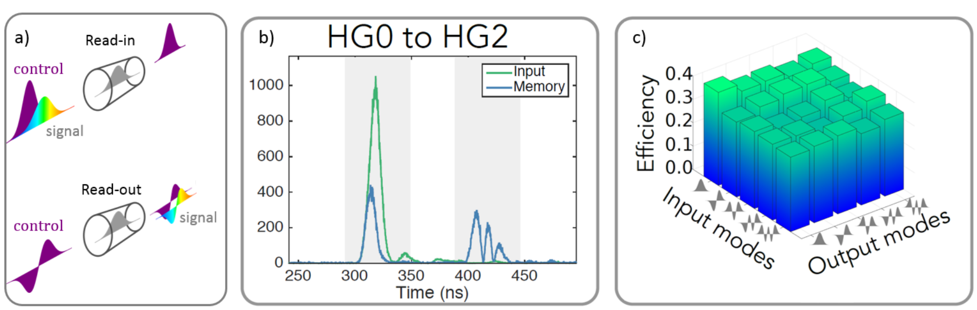


Fig. 1. a) Read-in and storage of a zeroth order Hermite-Gaussian (HG0) followed by read-out as a first order (HG1), acheived by tailoring the control field. b) Input (green) and output (blue) of Raman memory demonstrating conversion from the zeroth order Hermite-Gaussian (HG0) to the second order (HG2). c) Conversion efficiency (read-in as input, read-out as output) between the first five Hermite Gaussian modes.

Here we demonstrate TM manipulation of weak coherent pulses in our Raman memory system. We show conversion between different Hermite-Gaussian modes (Figures 1a,1b), and Figure 1c shows that we can fully convert between the first five basis states. The effciency of the conversion (storage and retrieval) is around 35% for all state transformations, showing that the Raman memory is a versatile device for temporal mode manipulation in this qudit basis ($d \geq 5$).

Of utmost importance to any memory protocol is the requirement of noise-free operation. Previous implementations of the Raman memory have suffered from four-wave mixing noise (Figure 2a) where the control couples to the populated state to produce a noise photon by anti-Stokes scattering. This noise contaminates the retrieved fields with thermal noise, destroying the non-classical statistics of stored quantum states. This has been identified as the key limiting factor in reaching quantum level operation [5].

In the past, the inclusion of a cavity around the memory [6] (which suffers from intra-cavity loss), or a weak two-photon absorption process to another isotope [7], have been used to achieve noise-suppression. Here, we engineer the Raman memory interaction such that the noise photon is resonant with the populated transition ($|g\rangle \rightarrow |e\rangle$ in Figure 2a) of the same caesium isotope, thereby undergoing strong absorption and dispersion, and thus suppressing the noise. Initial results show a different scaling of the noise as a function of control pulse power (Figure 2b), and significantly less noise - close to an order of magnitude - for the maximum control power tested. This result outperforms and is technically simpler than our previous cavity-enhanced Raman protocol [6].

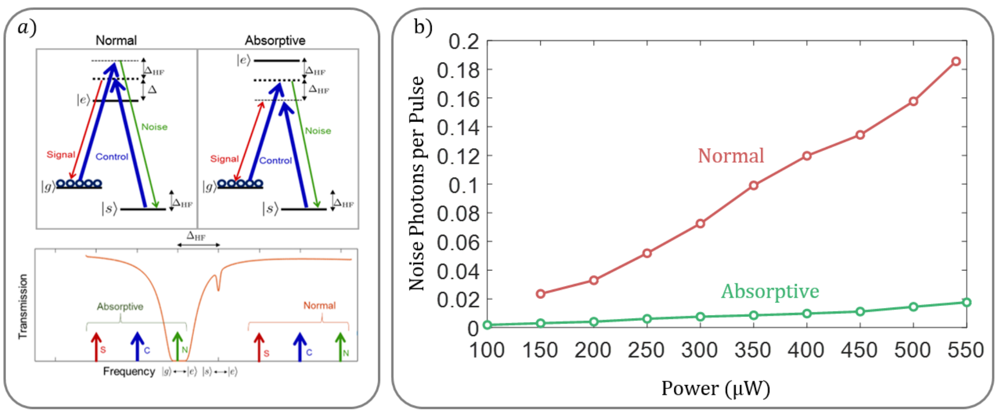


Fig. 2. a) (upper) Energy level diagram showing the fields involved in the Raman memory, including the four-wave mixing process. (lower) Transmission spectra of caesium showing the position of the fields in the normal operation of the Raman memory and when in the absorptive suppression scheme. b) Noise photons produced per pulse in the two regimes as a function of control field power (memory interaction strength).

With the potential elimination of this noise pathway, the Raman memory is a technically simple broadband and single mode memory capable of manipulating and storing an arbitrary and user-chosen quantum state in the temporal mode basis. This has many future applications including the re-shaping of the temporal wavepacket from solid state systems, such as atoms and quantum dots, for more efficient interfacing in hybrid quantum architectures. Therefore, with further engineering, the Raman memory is a promising candidate for room-temperature temporal-mode manipulation and multiplexed photon generation in quantum networks.

## References

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