Temporal-mode selection with a Raman quantum memory

J. H. D. Munns[1], S. E. Thomas[1], K. T. Kaczmarek[1], P. M. Ledingham[1], D. J. Saunders[1], J. Nunn[2], B. Brecht[1], and I. A. Walmsley[1]

[1] *Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU, UK*

[2] *Centre for Photonics and Photonic Materials, Department of Physics, University of Bath, North Road, Bath, BA2 7AY, UK*

benjamin.brecht@physics.ox.ac.uk

Abstract: Temporal modes (TMs) of pulsed single-photon states have been identified as appealing basis states for quantum information science. Recent work has seen progress towards TM-selective operations based on nonlinear optics. Here, we demonstrate for the first time a linear TM-selective device, namely a Raman quantum memory in warm atomic Caesium vapour. We achieve switching fidelities of 86.5% when operating the memory with ns-duration pulses. These results pave the way towards new quantum information applications, where TM-selection, TM-reshaping, and network synchronisation are achieved with one single device.

OCIS codes: 270.0270, 270.5585.

Temporal modes (TMs) of quantum pulses are field-orthogonal modes which span an infinitely dimensional Hilbert space and are compatible with integrated fibre networks. Recently, they have been identified as an appealing basis for quantum information science [1]. To date, approaches towards operating on a basis of TMs are based on nonlinear optical interactions. In fact, a quantum pulse gate based on dispersion-engineered sum-frequency generation in lithium niobate waveguides has been realised [2] and recent results put forward ways of addressing single TMs with high fidelities [3]. In such a device the addressed TM is converted to a different wavelength and can be subsequently separated with standard optical components.

On the other hand, quantum memories are considered crucial elements for building scalable photonic quantum networks. Different memory protocols have been studied in different material systems, including electromagnetically induced transparency, atomic frequency combs, and Raman memories (see e.g. [4]). The latter combines operation at ambient conditions, good storage efficiencies, broadband operation, and sufficient storage times. In addition, as opposed to other protocols which are inherently multimode, the Raman interaction can be described as a special, time non-stationary quantum mechanical beam splitter that acts on a single TM [5]. In this case, the shapes of the stored and retrieved TM are defined by the temporal amplitudes of the strong control pulses used to drive the memory. This enables storage, delay and re-shaping of a user-defined TM in one single device.

In a proof-of-concept experiment we demonstrate TM-selective storage of weak coherent pulses with mean photon number of $\langle\hat{n}\rangle \approx 10$ in a Raman quantum memory in warm atomic Caesium vapour [6]. We use the $6S_{1/2}(F=3)$ and $(F=4)$ hyperfine states as ground and storage state, respectively. The memory interaction is mediated by strong control pulses which drive a two-photon Raman transition from ground to storage state via the $6P_{3/2}$ manifold. We use a fibre-integrated electro-optic modulator to carve pulses from a continuous wave laser which is locked to two-photon resonance. The modulator features two electrodes which are driven by arbitrary waveform generators with a sampling rate of 6.4 Gs/s and which facilitate phase and amplitude control. The shaped pulses serve as input signal for the memory. The strong control pulses are generated with an actively mode-locked Titanium Sapphire oscillator and filtered to a duration of around 1 ns. We send both control and signal pulses to the memory, after which we filter remaining control light with a succession of polarizers and Fabry-Perot filters. The transmitted and retrieved signal is detected with a standard fibre-coupled single-photon avalanche photo diode and a time-to-digital converter.

The measurement results for a 0th-order Hermite-Gaussian signal are shown in Figure 1a. The blue trace is the temporal envelope of the signal that is recorded when no memory operation takes place and the signal is merely transmitted. Aside from a slight asymmetry which is caused by the response of the radio frequency amplifiers of the modulator, the signal matches the control pulse (gray-shaded region) well and we find an intensity overlap of

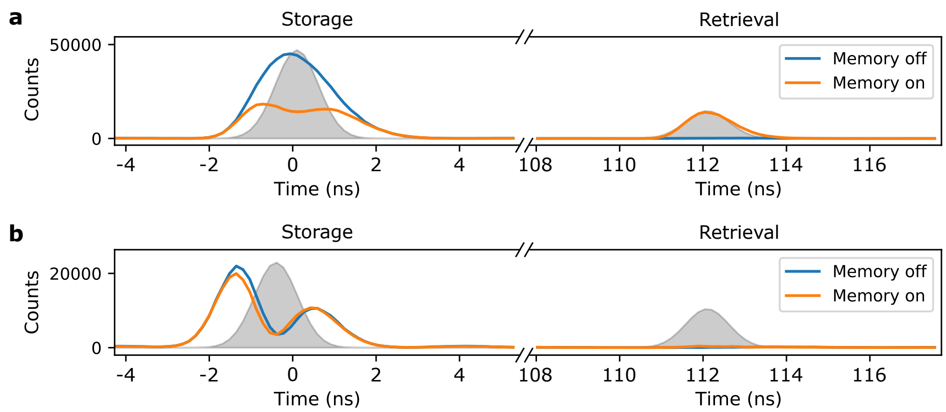

Fig. 1. TM-selective storage in a Raman memory. **a** When an input signal in a 0th-order Hermite-Gaussian TM (blue) is combined with the Gaussian control field (gray-shaded region), we see both significant storage and retrieval (orange). We have rescaled the control intensity to match the maxima of input and retrieved signal, for better comparability. **b** In contrast, when a signal in a 1st-order Hermite-Gaussian TM is used, neither storage nor retrieval are observed although signal and control have a significant temporal overlap, which demonstrates the TM-selectivity of the Raman memory.

73%. When we turn the memory on, we observe both storage and retrieval in the orange trace. We extract a storage efficiency of 47.5% and an overall memory efficiency of 20% which are typical values for the Raman memory. We also see that the retrieved light almost perfectly matches the control field amplitude, which highlights the possibility to reshape upon retrieval (see also [7]). Figure 1b shows the same for a 1st-order Hermite-Gaussian signal. In this case the storage and total efficiencies drop to 6% and 2.7%, respectively, corresponding to an 86.5% reduction compared to the 0th order signal. The sharp drop in memory efficiency clearly demonstrates TM-selective operation. The reduced intensity overlap of 51% between signal and control which we calculate from the measurement trace would only support a 30% drop in efficiency, which is incompatible with the observed result.

In conclusion we have demonstrated TM-selective operation of a Raman quantum memory in warm atomic Caesium vapour. We stored and retrieved 0th-order Hermite-Gaussian pulses with an efficiency of 20%. Upon switching to 1st-order Hermite-Gaussian pulses, the efficiency dropped to 2.7%, demonstrating a reduction of 86.5%. This number is comparable to values achieved with the quantum pulse gate [2], but our memory additionally allows for a user-chosen delay and TM-reshaping upon retrieval. This paves a route towards synchronised, scalable photonic quantum networks based on TMs of pulsed quantum light.

References

1. B. Brecht, D. V. Reddy, C. Silberhorn, and M. G. Raymer, “Photon temporal modes: A complete framework for quantum information science,” Physical Review X **5**, 041017 (2015).
2. B. Brecht, A. Eckstein, R. Ricken, V. Quiring, H. Suche, L. Sansoni, and C. Silberhorn, “Demonstration of coherent time-frequency Schmidt mode selection using dispersion-engineered frequency conversion,” Physical Review A **90**, 030302 (2014).
3. D. V. Reddy, M. G. Raymer, and C. J. McKinstrie, “Sorting photon wave packets using temporal-mode interferometry based on multiple-stage quantum frequency conversion,” Physical Review A **91**, 012323 (2015).
4. K. Heshami, D. G. England, P. C. Humphreys, P. J. Bustard, V. M. Acosta, J. Nunn, and B. J. Sussman, “Quantum memories: emerging applications and recent advances,” Journal of Modern Optics **63**, 2005–2028 (2015).
5. J. Nunn, I. A. Walmsley, M. G. Raymer, K. Surmacz, F. C. Waldermann, Z. Wang, and D. Jaksch, “Mapping broadband single-photon wave packets into an atomic memory,” Physical Review A **75**, 011401 (2007).
6. K. F. Reim, P. Michelberger, K. C. Lee, J. Nunn, N. K. Langford, and I. A. Walmsley, “Single-photon-level quantum memory at room temperature,” Physical Review Letters **107**, 053603 (2011).
7. K. A. G. Fisher, D. G. England, J.-P. W. MacLean, P. J. Bustard, K. J. Resch, and B. J. Sussman, “Frequency and bandwidth conversion of single photons in a room-temperature diamond quantum memory.” Nature communications **7**, 11200 (2016).