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Coherent optical memory with GHz bandwidth

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We demonstrate the coherent storage and retrieval of sub-nanosecond low-intensity light pulses with spectral bandwidths exceeding 1 GHz in cesium vapor, using the novel, far off-resonant two-photon Raman memory protocol.

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1 Introduction

Quantum memories, capable of temporarily 'freezing' a pulse of light, are a crucial component for quantum computers [1] and quantum communications [2]. So far, quantum memories — either ensemble based [3–5] or single absorbers [6] — have operated with bandwidths of kHz or MHz and have been very sensitive to the experimental environment. Robust, higher bandwidth (faster) quantum memories operating with very short laser pulses are a prerequisite for reliable and broadband quantum technology devices that allow for high-speed quantum processing and high data transfer rates in completely secure quantum networks. Here we report the storage and retrieval of sub-nanosecond low intensity light pulses consisting of several thousand photons with spectral bandwidths exceeding 1 GHz in cesium vapor. The novel memory interaction takes place via a far off-resonant two-photon transition in which the memory bandwidth is dynamically generated by the strong control field [7,8]. This makes the memory robust to environmental noise and allows an increase of speed by a factor of almost 1000 compared to existing quantum memories. The memory works with a total efficiency of 15% and its coherence is demonstrated by directly interfering the stored and retrieved pulses.

2 Method

The off-resonant two-photon Raman memory interaction and the atomic states of cesium involved in the Raman protocol are shown in Figure 1(b). The read, write and signal pulses are derived from a Ti:Sapph oscillator and have a FWHM duration of 300 ps. The fundamental Ti:Sapph laser frequency is tuned 18.4 GHz to the blue of the $|3\rangle$-$|2\rangle$ transition. A Pockels cell selects two consecutive pulses, separated by 12.5 ns. The laser beam is split into a strong control arm with vertical polarization(write & read) and a very weak signal arm with horizontal polarization . The control arm is delayed by 12.5 ns with respect to the signal arm such that the first pulse in the control arm overlaps in time with the last pulse in the signal arm. An electro-optic modulator is used in the signal arm to generate sidebands 9.2 GHz shifted from the fundamental laser frequency. After spectral filtering only the 9.2 GHz red-shifted sideband corresponding to the $|1\rangle$-$|2\rangle$ transition remains and forms the signal field. The control and the signal beam, spectrally separated by 9.2 GHz, are recombined and made collinear. Together (see Fig.1(a)), they are focussed into a 7 cm long vapor cell filled with cesium atoms and neon buffer gas. After the cell polarization and spectral filtering allow for the detection of the signal field only. A high-speed avalanche photo detector (APD) with a bandwidth of 1 GHz detects the very weak signal pulse. The atomic ensemble is initially prepared in the ground state $|1\rangle$ by optical pumping using an external cavity diode laser tuned to resonance with the $|3\rangle$-$|2\rangle$ transition.

3 Results and discussion

Figure 2(a) illustrates the storage and retrieval process with the short pulse durations clearly visible. The storage of the signal pulse takes place at time $t = 0$ and the retrieval of the stored information is carried out 12.5 ns later. When the write and read pulse are switched off nothing of the incident signal is stored and 100% are transmitted (solid line). Switching on the write and read field turns on the memory and 30% of the incident signal field are mapped into an atomic spin-wave excitation inside the cesium ensemble (dashed line). 50% of the stored information is read out and reconverted into a retrieved signal. The temporal shape

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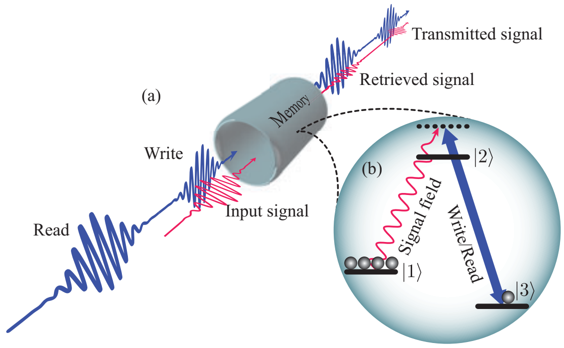

Figure 1: (a) Raman memory. The signal is sent into the memory along with a strong write pulse and gets stored. If the storage is partial, any unstored signal is transmitted through the memory. A subsequent read pulse reconverts the stored excitation and the retrieved signal emerges along with the transmitted read pulse. (b) Atomic Λ-level structure. The two photon memory interaction takes place over the cesium D_2-line at 852 nm. The ground state $|1\rangle$ and storage state $|3\rangle$ are the $6S_{1/2}$ hyperfine split states and the excited state $|2\rangle$ consists of the $6P_{3/2}$ hyperfine manifold.

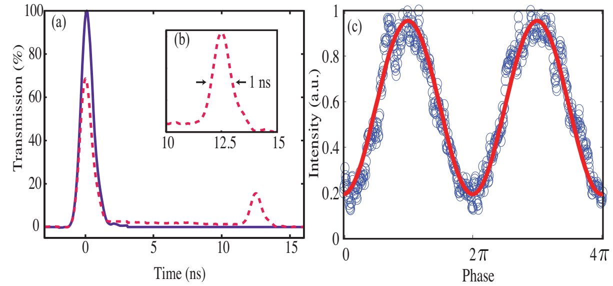

Figure 2: (a) Solid line: Transmission of incident signal field without the presence of write/read field – No storage/ no retrieval. Dashed line: Transmission of incident signal and retrieved signal in presence of write/read field – 30% storage/15% retrieval (b) Retrieved signal field – FWHM = 1 ns corresponding to a bandwidth of 1 GHz. (c) Combined intensity of stored and retrieved signal. Circles indicate experimental data, the red curve is a least square fit. A linear scan of the path length difference in the interferometer results in sinusoidal fluctuations of the total intensity. This indicates constructive and destructive interference and demonstrates the coherence of the memory. The visibility is $67 \pm 5\%$.

of the retrieved signal pulse can be viewed in Figure 2(b). Its FWHM duration is 1 ns; limited by the response time of the APD. To investigate the coherence properties of the memory, a copy of the incident signal field is attenuated, delayed and overlapped with the retrieved signal in a Mach-Zehnder configuration. After matching the intensities of the two interfering pulses, fringes are observed in the detected signal (Fig. 2(c)), by scanning the phase in the interferometer. This proves the coherence of the demonstrated memory.

4 Conclusion

In summary, we have demonstrated the coherent storage and retrieval of signal pulses with bandwidths greater than 1 GHz using the Raman memory protocol. This is an increase of almost a factor of 1000 compared to existing quantum memories. Storage efficiencies up to 30% and retrieval efficiencies as high as 50% were observed. The coherence of the memory was directly verified by interfering the stored and the retrieved pulses. We are optimistic that this and similar protocols will form the basis of fast, controllable and robust photonic quantum information processors in the near-future.

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