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AFZELIUS, Mikael, et al.

Abstract

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Reference


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Demonstration of Atomic Frequency Comb Memory for Light with Spin-Wave Storage

Mikael Afzelius,1,* Imam Usmani,1 Atia Amari,2 Björn Lauritzen,1 Andreas Walther,2 Christoph Simon,1 Nicolas Sangouard,1 Jiří Minař,1 Hugo de Riedmatten,1 Nicolas Gisin,1 and Stefan Kröll2

1Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland
2Department of Physics, Lund University, Box 118, SE-22100 Lund, Sweden

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We present a light-storage experiment in a praseodymium-doped crystal where the light is mapped onto an inhomogeneously broadened optical transition shaped into an atomic frequency comb. After absorption of the light, the optical excitation is converted into a spin-wave excitation by a control pulse. A second control pulse reads the memory (on-demand) by reconverting the spin-wave excitation to an optical one, where the comb structure causes a photon-echo-type rephasing of the dipole moments and directional retrieval of the light. This combination of photon-echo and spin-wave storage allows us to store submicrosecond (450 ns) pulses for up to 20 μs. The scheme has a high potential for storing multiple temporal modes in the single-photon regime, which is an important resource for future long-distance quantum communication based on quantum repeaters.

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A quantum memory (QM) for photons is a light-matter interface that can achieve a coherent and reversible transfer of quantum information between a light field and a material system [1]. A QM should enable efficient, high-fidelity storage of nonclassical states of light, which is a key resource for future quantum networks, particularly in quantum repeaters [2–6]. In order to achieve reasonable entanglement distribution rates, it has been shown that some type of multiplexing is required [4,5], using for instance independent frequency, spatial or temporal modes (multimode QM).

Several types of light-matter interactions have been proposed for building a QM, for instance electromagnetically induced transparency [7–10], Raman interactions [11–14], or photon-echo techniques [15–21]. Photon-echo techniques in rare-earth-ion doped crystals have an especially high multimode capacity for storing classical light [22]. Classical photon echoes are not useful, however, for single-photon storage due to inherent noise problems [23]. The photon-echo QM based on controlled reversible inhomogeneous broadening [15–18] is free of these noise problems. But this technique has a lower time-multiplexing capacity than classical photon echoes, for a given optical depth, due to loss of storage efficiency as the controlled frequency bandwidth is increased [19,24]. Some of us recently proposed a photon-echo type QM based on an atomic frequency comb (AFC) [19] that has a storage efficiency independent of the bandwidth, allowing optimal use of the inhomogeneous broadening of rare-earth-doped crystals. An AFC memory has the potential for providing multimode storage capacity [19,24] crucial to quantum repeaters. The few reported AFC experiments [20,21] have been investigating the physics of the optical AFC echo, where the memory storage time is predetermined by the periodicity of the comb. For quantum repeaters it is crucial to be able to choose the time of the memory readout (on-demand readout). Here we present the first light-storage experiment where an AFC is used in combination with reversible transfer of the excitation to a spin state [19], resulting in on-demand readout and storage times longer than 20 μs.

The underlying idea of the AFC QM is to shape an inhomogeneously broadened optical transition |g⟩→|e⟩ into a periodic series of narrow and highly absorbing peaks with periodicity Δ, see Fig. 1. A photon with a bandwidth that is matched to the width of the AFC structure is then stored as an optical excitation delocalized over the peaks, which we can write as |


\[ \psi = \sum_{j=1}^{N} c_j e^{i\delta_j} e^{-ikz_j}|g_1 \cdots e_j \cdots g_N\] where N is the number of atoms in the AFC, δ_j is the detuning of atom j with respect to the laser frequency, z_j is the position, k is the wave number of the light field, and the amplitudes c_j depend on the frequency and on the spatial position of the particular atom j. The terms in this large superposition state accumulate different phases due to the inhomogeneous distribution of atomic resonance frequencies, resulting in a loss of the initially strong collective coupling to the light mode. But the periodic AFC peak separation Δ leads to a rephasing of the terms after a time 1/Δ, which restores the strong collective coupling, leading to a photon-echo type reemission [25], the AFC echo. The narrow and highly absorbing peaks can theoretically absorb all the light and completely emit the energy in the AFC echo [19]. A large number of peaks leads to a high multimode capacity [19,24].

In the original proposal [19] on-demand readout and longer storage times rely on reversible transfer of the optical excitation to a long-lived spin state by strong control pulses (see Fig. 1). If we imagine a perfect π pulse applied at time T', each term in the superposition state becomes |g_1 \cdots s_j \cdots g_N\); thus, we have a single collec-
can be unambiguously excited. This distillation technique, which we will summarize here, has been the subject of several papers [27–29]. A laser beam whose frequency is swept pumps atoms from ground levels $|g\rangle$ and $|s\rangle$ to the auxiliary storage level $|aux\rangle$; see Fig. 1, which creates a wide transmission window within the inhomogeneous profile. In the next step a narrow absorption peak is created in the hole by coherently transferring back atoms, within a narrow frequency range, from $|aux\rangle$ to $|g\rangle$ [28]. In this experiment we extended this method by transferring back atoms at different frequencies to create a frequency comb. In Fig. 1(b) we show the absorption spectrum recorded after the preparation sequence. The AFC created on the $|g\rangle \leftrightarrow |e\rangle$ transition is clearly visible. The $|s\rangle$ level is used for the spin-wave storage, which means that the control pulses will be applied on the $|s\rangle \leftrightarrow |e\rangle$ transition displaced by 10.2 MHz with respect to the $|g\rangle \leftrightarrow |e\rangle$ transition. Note that the absorption spectrum in Fig. 1(b) is shown only for visualization purposes, since the fast frequency scan method [29] we used leads to distortions for absorption depths $d \geq 2$. The experimental setup is shown in Fig. 2. The control pulses were both counterpropagating with respect to the input pulse. By phase matching condition the output pulse then copropagates with the input signal [19]. Using this configuration we could reduce noise due to off-resonant free-induction decay emission produced by the strong control pulses.

In a preliminary experiment we investigate the AFC echo on the $|g\rangle \leftrightarrow |e\rangle$ transition without applying the control pulses, see inset in Fig. 3. This allows us to optimize the relevant comb parameters in order to obtain a strong echo. The input pulse duration was set to 450 ns so that the bandwidth is entirely contained in the 2 MHz wide AFC. The efficiency of this AFC echo, which we define as the
ratio of the AFC echo area to the input pulse area, depend on the shape of the AFC [19]. Two critical parameters are the peak absorption depth $d$ and the finesse defined as $F = \Delta / \gamma$ where $\gamma$ is the full-width at half maximum of a peak. For instance, a high finesse leads to low decoherence during the storage time $1/\Delta$, but also to a lower effective absorption $\sim d / F$ of the input pulse [19]. The peak absorption $d$ could be controlled by the power of the laser beam creating the peaks in the transmission hole, but a high power also had an impact on the finesse by causing power broadening of the peaks. The peak width was also limited by laser frequency stability, resulting in typical widths of $\gamma = 100$ kHz. For a periodicity of $\Delta = 1$ MHz, the optimized efficiency was about 15%. The delay of 1 $\mu$s was not sufficiently long, however, for applying the control pulses before the emission of the AFC echo. We therefore set the periodicity to $\Delta = 250$ kHz giving us 4 $\mu$s to apply the control pulses. The closer spacing of the peaks lowered the finesse of the comb, thus lowering the efficiency to $\sim 5\%$ (see inset in Fig. 3). This efficiency is in reasonable agreement with numerical simulations using the experimentally estimated peak absorption depth and finesse of the comb.

In Fig. 3 we show the main result where two control pulses are applied on $|s\rangle \rightarrow |e\rangle$ to transfer the excitation to the $|s\rangle$ hyperfine level. The retrieved pulse is clearly observed above the noise level. This realizes a true storage of the input pulses, with on-demand readout. Thus, the control pulses provide a mechanism for momentarily interrupting the predetermined AFC evolution [19]. We tested this mechanism in detail by varying the time at which the first control pulse was applied $T' = (1.17, 1.63, 2.23) \mu$s [cf. Fig. 1(c) for notation]. This resulted in different measured durations $T'' = (2.84, 2.41, 1.85) \mu$s. The total time spent in the excited state $|e\rangle$, however, is constant (within the measurement error), $T' + T'' = (4.01, 4.04, 4.08) \mu$s, corresponding to the expected $1/\Delta$.

In Fig. 4 we show storage experiments where the spinwave storage time $T_s$ is varied. The output signal is clearly visible up to $20 \mu$s of total storage time ($1/\Delta + T_s$). The exponential decay of the output signal as a function of $T_s$ can be attributed to inhomogeneous spin dephasing, corresponding to an inhomogeneous broadening of 26 kHz consistent with previous measurements [30]. We point out that this can be compensated for by spin echo techniques. With such techniques Longdell et al. [31] stopped light during $>1$ sec in a Pr$^{3+}$:Y$_2$SiO$_5$ crystal using electromagnetically induced transparency.

We now discuss the total storage efficiency $\eta$. Clearly $\eta$ is bounded by the AFC echo efficiency $\eta_e = 4\%\sim5\%$ for $1/\Delta = 4 \mu$s (cf. Fig. 3 inset). This can be improved by increasing the finesse and optical depth (see discussion above). The spin-wave storage further decreases the efficiency. By extrapolating the experimentally measured $\eta$ to the limit $T_s \rightarrow 0$ we find that $\eta = 0.5\%\sim1\%$, which is a value independent of spin dephasing. The effect of the control pulses can now be understood by a simple model. We assume that one pulse has a single-atom $|s\rangle \rightarrow |e\rangle$ transfer efficiency $\eta_T$, which is constant as a function of detuning. Then the application of the two control pulses reduce the efficiency to $\eta = \eta_e \eta_T$. Numerical simulations using 3-level Maxwell-Bloch equations show that this simple model is correct if the control pulses do not induce any additional phase decoherence. From the experimental values given above we thus find $\eta_T = 0.30\sim0.45$.

To better understand this value we have performed numerical calculations. The control pulses were two identical complex hyperbolic secant pulses, which can achieve...
We finally show an example of storage of two temporal input modes. The normalized input modes shown here (dashed line) are recorded before the crystal using a reference detector. The AFC was prepared with a periodicity of $T_s = 200$ kHz, corresponding to $5 \mu s$ storage time on the optical transition. The spin-storage time was set to $T_s = 7.6 \mu s$, resulting in a total storage time of $1/\Delta + T_s = 12.6 \mu s$.

FIG. 5 (color online). Storage of two temporal input modes. The normalized input modes (solid line) are recorded before the crystal using a reference detector. The AFC was prepared with a periodicity of $T_s = 200$ kHz, corresponding to $5 \mu s$ storage time on the optical transition. The spin-storage time was set to $T_s = 7.6 \mu s$, resulting in a total storage time of $1/\Delta + T_s = 12.6 \mu s$.

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*afzelius@unige.ch