Article

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Abstract

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Reference

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Fidelity of an optical memory based on stimulated photon echoes

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We investigated the preservation of information encoded into the relative phase and amplitudes of optical pulses during storage and retrieval in an optical memory based on stimulated photon echo. By interfering photon echoes produced in a Ti-indiffused single-mode Er-doped LiNbO$_3$ waveguiding structure at telecom wavelength, we found that decoherence in the atomic medium translates only as losses (and not as degradation) of information, as long as the data pulse series is short compared to the atomic decoherence time. The experimentally measured value of the visibility for interfering echoes is close to 100 %. In addition to the expected three-pulse photon-echo interferences we also observed interference due to a four-pulse photon echo. Our findings are of particular interest for future long-distance quantum communication protocols, which rely on the reversible transfer of quantum states between light and atoms with high fidelity.

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Transfer of coherence properties between light and atoms can be investigated through interferometric and spectroscopic techniques. These studies are of fundamental interest, but also deliver important information for future applications in the field of quantum information science.

In quantum communication schemes, such as quantum cryptography, non-orthogonal states of light are used as information carrier. The encoding of information into the relative phase and amplitudes of a time-bin qubit has proven to be well suited for transmission over long distances, because this coding is robust to the decoherence mechanism in optical fibers [1, 2]. However, the extension of quantum communication to arbitrary distances relies on the availability of *quantum memories*, which are key to the building of a quantum repeater [3]. Although significant progress has recently been reported [4, 5, 6], coherent, reversible transfer of quantum information from photons to atoms with high fidelity and efficiency remains an important and open challenge.

From this perspective, it is important to understand *how the fidelity of a time-bin qubit evolves when the information is stored in a quantum memory*. It is the primary objectives of this Letter to address this issue. In particular, we show a case in which the decoherence in the atomic medium is a state-independent coupling with the environment: its effect on the retrieved signal is therefore only *losses*, i.e. a decrease of the retrieval probability. By post-selecting only cases when photons are actually emitted, one retrieves uncorrupted information, which does not require complicated classical or quantum error correction.

We work in the framework of a recent proposal [7], and of first experimental studies [8], for storage of time-bin qubits based on controlled, reversible, inhomogeneous broadening. This is a *photon-echo type approach* to quantum memories with a theoretical efficiency of 100 %. Photon-echoes are well known for storage of classical optical pulses [9, 10] as well as for being a phase-preserving process. However, the storage of information encoded in the amplitude and relative phase of subsequent optical pulses, crucial for the proposal under study, has received only limited attention so far [11, 12].

The photon echo experiments reported here were done using an Er^{3+} doped LiNbO$_3$ crystal with a waveguiding structure. To our knowledge, these are the first reported photon echo experiments in Er^{3+}:LiNbO$_3$ waveguides, LiNbO$_3$ being widely used as a non linear material in integrated optics. In the experimental set-up the light is guided entirely through standard telecommunication fibers, integrated intensity/phase modulators, polarization controllers and the Ti-indiffused Er^{3+}:LiNbO$_3$ waveguide in a mono-mode structure, thus the assumption of only one dimension, often used in theoretical calculations, is fully justified.

A common approach to storage and retrieval of light using photon echoes is based on *three-pulse photon echo (3PE)*, also known as stimulated photon echo [10]. In this process a first strong optical "write" pulse prepares the medium. The "data" pulses, a sequence of pulses encoding the information to be stored, are sent into the medium some time after the write pulse. In order to retrieve the information, a third strong "read pulse" is used, which causes a photon echo to be emitted afterwards. If certain conditions for excitation energy and absorption depths are met, the echo is to a high degree an amplitude and phase replica of the stored data pulses. A common physical picture used to explain the 3PE is that the write pulse creates an atomic coherence and the data pulses transfer the coherence into a frequency-dependent population grating in the ground and excited states. The read pulse scatters off the grating, forming echoes a time
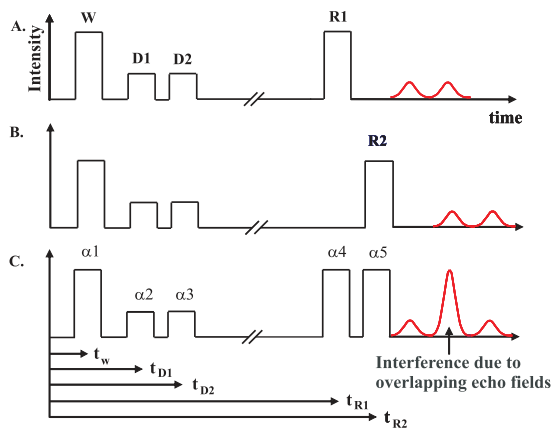
FIG. 1: Illustration of the sequence of pulses for the interference of photon echoes. The data is read out twice and the phase between data and read pulses is changed to produce interference in the central time bin (see text for details).

after the read pulse, which is equal to the time separation between write and data pulse.

Now, consider a data field consisting of two pulses (D1 and D2) with a amplitude ratio R and phase relation φ (see Fig. 1 a.). The 3PEs appears at times $t_e = t_r + t_{Di} - t_w$ $(i = 1, 2)$, where t_r is the time of readout, t_{Di} the time of data pulse Di $(i = 1, 2)$ and t_w the arrival time of the write pulse. The echoes will thus be $dt = t_{D2} - t_{D1}$ apart.

Because the efficiency of the 3PE is at best a few percent [14], much of the frequency-dependent population grating is preserved in the atomic ensemble after the read pulse. Therefore more echoes can be produced by sending in several read pulses. In our experiment, two subsequent read pulses were used to produce two copies of the data pulse. If we chose the distance between the read pulses to be dt, the same as the distance between the two data pulses D1 and D2, the echo of the second data pulse read out by the first read pulse (D2|R1), and the echo of the first data pulse read out by the second read pulse (D1|R2), will be indistinguishable and thus interfere (Fig. 1 c.). The phase of a 3PE is controlled by the relative phase of the write, the data and the read pulse. The write pulse has a phase $\alpha 1$, the data pulses a phase $\alpha 2/3$, and the read pulses a phase $\alpha 4/5$. Thus one can obtain constructive or destructive interferences by carefully choosing the different phases of the input pulses [13]. This is true provided that the phase or amplitude coherence is not lost partially or totally during storage and retrieval.

The data pulse above is related to what is known in quantum communication as a time-bin qubit. A *time-bin qubit* [1] is a coherent superposition of a photon being in two time-bins, separated by a time difference long compared to the coherence time of the photon. It can be written in

the form:

$$|\psi\rangle = c_0|1,0\rangle + c_1 e^{i\varphi}|0,1\rangle \qquad (1)$$

where $|1,0\rangle$ $(|0,1\rangle)$ stands for a photon being in the first (respectively the second) time-bin and $\varphi = \alpha 2 - \alpha 3$ for the relative phase.

In the present experiment classical coherent pulses were used (see Fig. 1 c.). These *time-bin pulses* are two coherent pulses such that the width of each pulse is much smaller than the temporal spacing dt between the two pulses; the state of light is a Poisson distribution of photons $(n \sim 10^8)$, each of which is in the state described by Eq. (1).

The output field amplitude of a 3PE, taking $t_w{=}0$ and assuming that the whole storage process takes place on a time scale small compared to the radiative lifetime, will be reduced by a factor of e^{-2t_{Dj}/T_2}, where T_2 is the *atomic* decoherence time. Therefore a time-bin qubit absorbed by a photon echo material will be emitted as follows, assuming that the photon echo amplitude is linear compared to that of the input field:

$$|\Psi\rangle \sim [e^{-2t_{D1}/T_2}c_0|1,0\rangle + e^{-2t_{D2}/T_2}c_1 e^{i\varphi}|0,1\rangle]|\mathcal{E}_0\rangle$$
$$+\lambda|0,0\rangle\mathcal{E}_1 \quad (2)$$

here $|\mathcal{E}_0\rangle$ and $|\mathcal{E}_1\rangle$ are the states of the environment to which the memory couples. The information encoded in the time-bin is preserved provided $dt = t_{D2} - t_{D1} \ll T_2$ and provided the process has not modified the pulse in such a way, that the width of the echo is $\sim dt$. Indeed in this case Eq. (2) can be simplified to $|\Psi\rangle \sim e^{-2t_{D1}/T_2}|\psi\rangle|\mathcal{E}_0\rangle + \lambda|0,0\rangle|\mathcal{E}_1\rangle$. It follows that even if atomic decoherence has acted during a long time ($t_{D1} \sim T_2$) it does not influence the amplitude ratio or phase difference of the time-bin information. By means of postselecting the cases where a detection is obtained one can thus reach a very high fidelity, however at the expense of a smaller retrieval probability as compared to simply detecting the vacuum component. A memory having these characteristics can be, depending on the application, advantageous compared to one with high retrieval probability and low fidelity.

The retrieved time-bin pulses (photon echoes) shown schematically in Fig. 1 c. interfere constructively or destructively depending on the phase difference φ and the phases of the read pulses. The visibility V of the interference should only be a function of the relative amplitudes of the *incoming* time-bin pulses:

$$V = 2\frac{\sqrt{R}}{1 + R}, \qquad (3)$$

with ratio $R = c_0^2/c_1^2$.
Note that one could also describe our experiment as a setup containing two interferometers, as used for phase-

coding quantum cryptography [2]: One interferometer prepares the time-bin qubits, i.e. here our two data pulses, while the second allows the projection measurement, i.e. our two read pulses.

Now we describe the experimental setup, which is similar to the one used in [15]. The output from an external-cavity cw diode laser (Nettest Tunics Plus) was gated by a combined phase and intensity modulator and followed by an intensity modulator, both fiber-optic produced by Avanex. The first modulator created the five excitation pulses and applied phase shifts to some of the pulses, depending on the particular experiment, the second modulator was synchronized to the first one and used to improve the peak-to-background intensity ratio. The pulses had durations of t_{pulse}=15 ns, with a clock frequency of 30 Hz. The first data pulse was created at $t_{D1} = 0.6$ μs and the time between the data pulses was typically $dt = 60ns$ and the read-out pulses were delayed with regard to the data pulses by 1 to 2 μs. The pulses were then amplified by an EDFA (Erbium Doped Fiber Amplifier). In order to obtain a good background suppression (> 70 dB) and to avoid spectral holeburning by the EDFA, we placed an additional acousto-optical modulator between the optical amplifier and the input of the pulse-tube cooler, which opened only for the series of pulses and suppressed light for all other times. The light was then coupled into the Er^{3+}-doped $LiNbO_3$ crystal inside the pulse tube cooler (Vericold), where the crystal was cooled to about 3.4 K. The resulting peak powers were in the range of 5 mW for the write pulses at the refrigerator input (and on the order of 1 mW for the other pulses). The photon echo was detected by a fast detector (1611v, New Focus) after the pulse-tube cooler.

The z-cut $LiNbO_3$ was Erbium doped over a length of 10 mm by indiffusion of an evaporated 8 μm thick Er-layer at 1130 ^0C for 150 h, leading to a Gaussian concentration profile of 8.2 μm 1/e penetration depth and 3.6×10^{19} cm^{-3} surface concentration. The guiding channel was fabricated by indiffusion of a 7 μm wide, 98 nm thick Ti-stripe at 1060 ^0C for 8.5 h, leading to a monomode guide with a mode size of $4.5\times 3\mu m$ FWHM intensity distribution [16]. The light was injected and collected with standard optical fibers into a waveguide of a diameter of 9 μm. A magnetic field of about 0.2 Tesla was applied parallel to the C_3 axis. This reduces decoherence due to spectral diffusion [17], resulting in a decoherence time of about $T_2 \sim 6\mu s$.

Fig. 2 shows typical interference patterns for constructive and destructive interference. Here the input data pulses had the same amplitude, thus R=1. We scanned the phase difference between the two interfering photon echoes continuously by varying phase $\alpha2$ using the intensity/phase modulator and obtained a clear modulation of the photon echo interference signal (see Fig. 2).

To extract the visibility we measured the background-subtracted area under the echo interference, and plot-
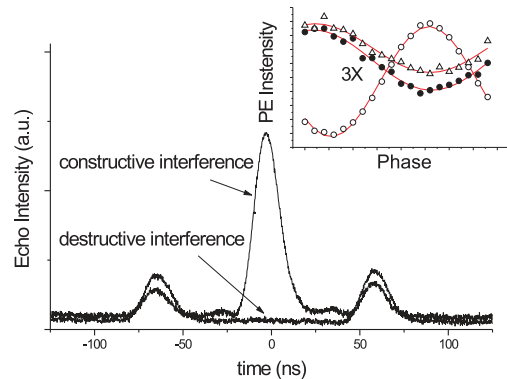

FIG. 2: Photon echo signals for constructive and destructive interference. Inset: Central echo peak intensity ∘, left ● and right △ side peak intensity as a function of phase. The phase modulation of both side peaks is synchronized and is opposite to the principle peak (Note that the amplitude of the side peaks was multiplied with a factor of 3). This is due to an interference with four-pulse photon echo (4PE) as described in more detail in the text.

ted the area as a function of the applied phase. The background was obtained by fitting the signal on either side of the side peaks. We have verified by several measurements, that the detection background was of purely electronic origin and that no coherent or incoherent background light was interfering with the echoes.

The large number of echoes produced by our pulse sequence (which is reduced to the echoes of interest in Fig. 1 c.) can easily lead to interference with subsidiary echoes, which has to be avoided by carefully choosing the time delays between pulses. Yet, as can be seen in Fig. 2 the side peaks also show a modulation, which we found to be due to an interference with higher-order echoes produced by four excitation pulses (4PE) [18]. The 4PE detected is much smaller than the 3PE, which results into a smaller visibility as compared to pure 3PE interference (see inset in Fig. 2). These higher-order types of echoes have been observed previously and have been denoted virtual echoes [19].

In order to demonstrate that our PE based measurement setup is analogous to an interferometer for analyzing the time-bin pulses, we also performed visibility measurements using time-bin pulses having different relative amplitudes. As expected, the extracted visibility increases with amplitude ratio and it follows, within the experimental error, the theoretical curve calculated using Eq. (3). Perfect visibility was reached in the case of equal amplitudes (see Fig. 3). Note that the experimental error is in principal larger for equal time-bin amplitudes, as the method of background subtraction is more sensitive to noise when the photon echo signal is small, i.e.
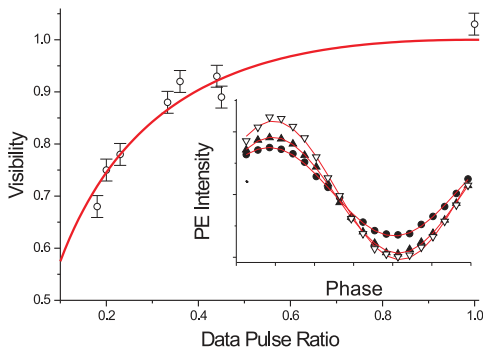
FIG. 3: The visibility as a function of the ratio between the two time-bin pulses is shown. Experimental points ○ are in good agreement with Eq. (3), which contains no free parameter. Inset: The area under the interfering photon echoes is plotted as a function of the phase for different incoming time-bin amplitude ratios (● V=0.68, ▲ V=0.93, ▽ V=1.04). The interference visibility (V) is extracted from a sinusoidal fit.
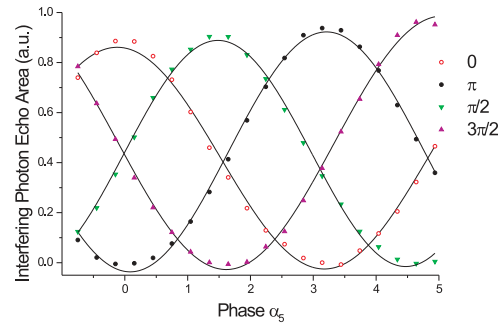

FIG. 4: Area under the echo as function of the phase of the second read-out pulse. All four classical states, analogous to the quantum states used in four-state quantum cryptography protocols, are stored, retrieved and analyzed with close to 100 % fidelity. This is possible even though the probability of retrieval from the memory is only a few percent, limited by the efficiency of the photon echo process and by decoherence processes in the storage material.

at the point of destructive interference. The error bars for all depicted data points in Fig. 3 are calculated from standard deviations of a large number of measurements for $R = 1$, setting thus an upper limit.

In Fig. 4 the area under the echo is plotted as a function of the phase $\alpha 5$ that is applied to the second of the *read* pulses. While this phase is scanned, the phase $\alpha 3$ of the time-bin pulse is kept constant at: 0, $\pi/2$, π, and $3\pi/2$ and all other phases are kept at zero. This is conceptually analogous to preparing four different time-bin qubits states of two conjugate basis on the equator of the Poincaré sphere, as it is widely used in quantum cryptography in the so-called BB84 [20] or four state protocol. While in quantum cryptography setups the projection measurement is done with an interferometer [2], we project the state with photon echoes using two read pulses. Note that the photon echo process thus serves two purposes, *storage/retrieval and analysis* of the state.

Our results show that the relative phase and amplitude ratio of time-bin pulses can be preserved during storage in the optical memory. Apart from the variation of the visibility due to the change of ratio between the two time-bins, no further reduction is observed, despite the fact that the atomic coherence time is such that a significant part of the atomic coherence is lost during the storage time. This can be interpreted in the following way: external perturbation of the atomic coherence in the Erbium ions reduces the macroscopic dipole moment, representing a loss of coherent ions, which reduces the size of the coherent emission. The ions that have undergone no or small decoherence, however, still retain the phase and amplitude information of the incoming excita-

tion fields, which make it possible to store and retrieve information with high fidelity despite the decoherence in the photon echo material. This is true as long as the time separations between the time bins is comparable to or larger than the decoherence time, as discussed in connection to Eq. (2). Due to the possibility of post-selection a nearly perfect fidelity can be obtained being promising for a future CRIB based quantum memory [7].

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[1] J. Brendel et al., Phys. Rev. Lett. **82**, 2594, 1999
[2] N. Gisin et al. Rev. Mod. Phys. **74**, 145 (2002)
[3] H. J. Briegel et al., Phys. Rev. Lett. **81**, 5932 (1998)
[4] B. Julsgard et al., Nature **432**, 482 (2004)
[5] T. Chanelière et al., Nature **438**, 833 (2005)
[6] M. D. Eisaman et al., Nature **438**, 837 (2005)
[7] B. Kraus et al., Phys. Rev. A **73** 020302(R) (2006)
[8] A. L. Alexander et al., Phys. Rev. Lett. **96**, 043602 (2006)
[9] T. W. Mossberg, Opt. Lett. **7**, 77 (1982)
[10] M. Mitsunaga, Optical and Quantum Electronics **24**, 1137 (1992)
[11] M. Arend et al., Opt. Lett. **18**, 1789 (1993)
[12] U. Elman et al., J. Opt. Soc. Am. B. **13**, 1905 (1996)

[13] In the case of a simple 3PE, where the excitation pulses have the phase α_i, $i = 1, 2, 3$, the echo will have the phase: $\alpha_e = \alpha_1 - \alpha_2 - \alpha_3$.

[14] T. Wang et al., Phys. Rev. A **60** 757(R) (1999)

[15] M. U. Staudt et al. Optics Communn. in press

[16] I. Baumann et al., Applied Phys. A **164**, 33 (1997)

[17] Y. Sun et al., J. Lumin. **98**,281, 2002

[18] The 4PE phase Θ depends on the contributing pulse phases for our configuration for the left and right side peak as follows: $\Theta_1 = \alpha_1 - 2\alpha_2 + \alpha_3 - \alpha_5 + \pi$ and $\Theta_2 = \alpha_1 - \alpha_2 + \alpha_4 - 2\alpha_5 + \pi$. As can be seen in Fig. 2 the dependency of the phase of the side peaks is displaced by π from the principal peak leading into a flip of maximum and minimum.

[19] Z. Cole, master thesis, Montana State University, Montana, USA, 2000

[20] C. H. Bennett, G. Brassard, in Proceedings of the IEEE International Conference on Computers, Systems and Signal Processing, Bangalore, India (IEEE, New York,1984), p. 175