Storage and retrieval of time-bin qubits with photon-echo-based quantum memories

Nicolas Gisin,[1] Sergey A. Moiseev,[2] and Christoph Simon[1]
[1]*Group of Applied Physics, University of Geneva, Geneva, Switzerland*
[2]*Kazan Physical-Technical Institute of the Russian Academy of Sciences, Kazan, Russia*
(Received 16 April 2007; published 9 July 2007)

Quantum memories based on the photon-echo principle (with controlled reversible inhomogeneous broadening) allow in principle perfect reconstruction of the stored light. In the retrieval process, the envelope of the absorbed wave packet is reversed in time, but the evolution of the phase of the carrier wave is unchanged. We discuss the consequences of this fact for the relative phase of pulses with a certain time delay, and thus for the storage of time-bin qubits. As an illustration, we show that the combination of photon-based memories and unbalanced interferometers leads to a counterintuitive interference effect, allowing one to measure a path length difference ΔL using pulses that are much shorter than ΔL.

DOI: 10.1103/PhysRevA.76.014302 PACS number(s): 03.67.Hk

The realization of quantum memories for photons is an important goal in quantum-information processing. In particular, such memories are a basic ingredient for quantum repeaters [1]. Various approaches to quantum memories are currently being pursued [2]. Here we focus on a particular approach based on the principle of photon echo [3]. In Ref. [4] it was shown that highly efficient photon echoes can be generated in a gas of atoms by exploiting the fact that the Doppler shift changes sign if the propagation direction of the light is reversed. References [5] proposed a realization of the same principle using controlled reversible inhomogeneous broadening (CRIB). This method allows in principle perfect reconstruction of the stored light. It is well adapted to atomic ensembles in solids, e.g., crystals doped with rare-earth ions.

To implement such a memory, one has to prepare a narrow absorption line inside a wide spectral hole, using optical pumping techniques [6]. The line is artificially inhomogeneously broadened, e.g., by applying an electric field gradient. Then the light can be absorbed, e.g., a train of pulses as described above. After the absorption the electric field is turned off, and atoms in the excited state are transferred by a π pulse to a second low-lying state, e.g., a different hyperfine state. For recall, the population is transferred back to the excited state by a counterpropagating π pulse, and the electric field is turned back on with the opposite sign, thereby inverting the inhomogeneous broadening. This leads to a *time reversal* of the absorption. The pulse train is reemitted in inverted order, with a retrieval efficiency that is not limited by reabsorption [5]. The described protocol has recently been studied in some detail both theoretically [7,8] and experimentally [9].

In this Brief Report we discuss the storage and retrieval of time-bin qubits [10] with such memories. The Hilbert space of a time-bin qubit is defined by two single-photon wave packets that have the same shape but a certain time delay that is larger than the duration of the wave packets. Time bins are a good implementation of qubits, in particular for quantum communication using optical fibers, because they are not sensitive to depolarization effects. We describe what happens to an arbitrary time-bin qubit state if it is stored and recalled using a photon-echo-based memory in a straightforward way. It is clear that the order of the two pulses defining the basis of the Hilbert space will be inverted in the photon-echo process. It is less clear intuitively what will happen to the relative phase of the two time bins. This is the key point of our present note. In order to clarify this question it is essential to realize that the time reversal mentioned above in our description of the storage and recall process applies only to the slowly varying envelope of the photon wave packets. It is indeed possible to invert the coupled time evolution of the slowly varying envelopes of the light field and of the atomic coherence [7,8]. In contrast, the evolution of the carrier wave phase factor $e^{-i\omega_0 t}$, where $\hbar\omega_0$ corresponds to the energy of the photons, is unaffected by the storage and retrieval. This simple fact can have somewhat counterintuitive consequences. In particular, we show that by using a photon-echo-based memory one can (interferometrically) determine the path length difference of an interferometer in an experiment with pulses that are much shorter than this path length difference.

The two basis states $|0\rangle$ and $|1\rangle$ of a single time-bin qubit correspond to the single-photon wave packets

$$\psi^{(0)} = f(t)e^{-i\omega_0 t} \quad (1)$$

and

$$\psi^{(1)} = f(t-\tau)e^{-i\omega_0 t}, \quad (2)$$

respectively. Here $f(t)$ is an arbitrary slowly varying envelope function, $e^{-i\omega_0 t}$ is the phase factor corresponding to the carrier frequency, and τ is the delay between the two time bins. By convention the first (in time) time bin is associated with the basic quantum ket $|0\rangle$ and the later time bin to $|1\rangle$. A general qubit state has the form

$$|\psi\rangle = r|0\rangle + \sqrt{1-r^2}e^{i\phi}|1\rangle. \quad (3)$$

If the state is prepared by introducing a delay between two parts of an original single wave packet, then the relative phase satisfies $\phi=\omega_0\tau$. However, by using intensity and phase modulators in combination with a cw laser beam to generate the time-bin states, one can in principle control the delay and the relative phase independently. The intensity modulator allows one to cut envelopes of arbitrary shape out of the continuous wave, while the phase modulator allows one to change the phase of the continuous wave between successive pulses. This way of preparing time bins makes it clear that the delay τ and the relative phase ϕ are indeed independent parameters.

Storage and retrieval with a CRIB-based quantum memory will transform the wave packet $\psi^{(0)}$ into $f(-t)e^{-i\omega_0 t}$ and the wave packet $\psi^{(1)}$ into $f(-t-\tau)e^{-i\omega_0 t}$. The envelope functions are inverted in time while the carrier wave phase factors continue to evolve unchanged [7,8]. This is a consequence of the fact that the photon is stored as a coherent excitation of the medium without changing its energy. Therefore the phase continues to evolve with the same optical frequency for the whole time that the photon is stored in the memory. The photon is stopped, but the phase of the corresponding atomic excitations continues to "keep the time." Since the time order of the reemitted wave packets is changed, their labels 0 and 1 are exchanged according to the above mentioned convention. However, if the input envelope function $f(t-\tau)$ was associated with a phase factor $e^{i\phi}$ (corresponding to a carrier wave that is shifted by ϕ), then the corresponding output envelope will still be associated with this phase factor. The overall quantum state after the memory is therefore given by

$$r|1\rangle + \sqrt{1-r^2}e^{i\phi}|0\rangle. \quad (4)$$

Note that this form of the final state is valid for any memory protocol where the pulses are re-emitted in inverted order.

Let us apply the above discussion to the example illustrated in Fig. 1. A short pulse arrives from the left and passes through an imbalanced interferometer with path length difference ΔL, and the two time bins are stored in a quantum memory of the photon-echo type considered here. At a later time the time bins are released, they propagate now from right to left and pass a second time through the same imbalanced interferometer. At the left we have three pulses; we shall concentrate on the central one, as only this one exhibits interesting interferences. The pulse that propagates through the short arm on its way to the quantum memory (QM) (i.e., the early incoming time bin, denoted s in Fig. 1) remains stored longer than the pulse that propagates through the long arm (l in Fig. 1), because the early incoming time bin corresponds to the delayed outcoming time bin. Consequently, the three pulses propagating back toward the left correspond to the following paths in the interferometer: "long-short" (ls), "long-long and short-short" (ll and ss), and "short-long" (sl). According to our discussion above, the pulse l, which acquires a phase $\alpha=\omega_0\Delta L/c$ (relative to s) on its first pass through the interferometer, still has this phase after retrieval from the quantum memory. As a consequence, the pulse ll has a phase 2α relative to ss, leading to interference fringes (as a function of ΔL) in the central time bin after the second pass, cf. Fig. 1.

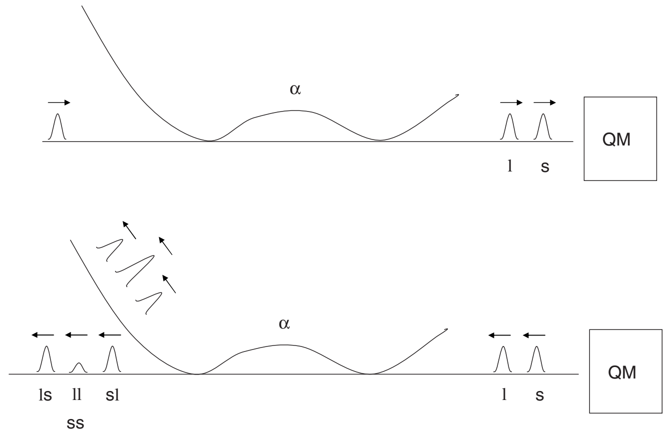

FIG. 1. A short pulse is sent into an unbalanced interferometer. At each exit there are two components, depending on whether the pulse has taken the long (l) or the short (s) arm. Storage and retrieval with a photon-echo-based quantum memory inverts the order of the pulses, but the pulse l keeps the phase α it has acquired on the first pass through the interferometer (see text). As a consequence, after the second pass there is interference with a phase difference 2α between the pulse that took the long arm twice (ll) and the pulse that took the short arm twice (ss).

The setup of Fig. 1 makes it possible to measure the path length difference ΔL using pulses much shorter than ΔL. In order to achieve this task with a subwavelength resolution one usually uses a continuous-wave laser with a coherence length longer than ΔL. At first sight it may seem impossible to achieve the same measurement using laser pulses shorter than ΔL. But this is not so if one uses, for example, our quantum memory. Indeed, as explained in the previous paragraph, the central pulse coming out of the interferometer is modulated with a phase 2α, providing thus a direct measurement of the path difference, with even a twofold increased resolution. Where is the necessary coherence of our measuring device? Clearly, it is still necessary to have a reference length or clock whose stability is larger than the measured quantity. However, the usual "continuous-wave laser clock" is replaced by the coherent excitations in the quantum memory: the quantum memory coherence time must be longer than the path length difference of the investigated interferometer divided by c.

This work was supported by the European Integrated Project QAP (IST-015848) and by the Russian Foundation of Basic Research (Grant No. 06-02-16822).

[1] H.-J. Briegel W. Dur, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **81**, 5932 (1998); L.-M. Duan *et al.*, Nature (London) **414**, 413 (2001); C. Simon, H. de Riedmatten, M. Afzelius, N. Sangouard, H. Zbinden, and N. Gisin, Phys. Rev. Lett. **98**, 190503 (2007).

[2] J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi, Phys. Rev. Lett. **78**, 3221 (1997); L.-M. Duan, J. I. Cirac, P. Zoller, and E. S. Polzik, *ibid.* **85**, 5643 (2000); A. Kuzmich and E. S. Polzik, *ibid.* **85**, 5639 (2000); M. Fleischhauer and M. D. Lukin, *ibid.* **84**, 5094 (2001); C. Liu *et al.*, Nature (London) **409**, 490

(2001); D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, Phys. Rev. Lett. **86**, 783 (2001); B. Julsgaard *et al.*, Nature (London) **432**, 482 (2004); T. Chanelière *et al.*, *ibid.* **438**, 833 (2005); M. A. Eisaman *et al.*, *ibid.* **438**, 837 (2005).

[3] N. Abella, I. D. Kurnit, and S. R. Hartmann, Phys. Rev. Lett. **13**, 567 (1964); T. W. Mossberg, Opt. Lett. **7**, 77 (1982); H. Lin, T. Wang, and T. W. Mossberg, *ibid.* **20**, 1658 (1995).

[4] S. A. Moiseev and S. Kröll, Phys. Rev. Lett. **87**, 173601 (2001).

[5] M. Nilsson and S. Kröll, Opt. Commun. **247**, 393 (2005); B. Kraus *et al.*, Phys. Rev. A **73**, 020302(R) (2006).

[6] G. J. Pryde, M. J. Sellars, and N. B. Manson, Phys. Rev. Lett. **84**, 1152 (2000); M. Nilsson, L. Rippe, S. Kroll, R. Klieber, and D. Suter, Phys. Rev. B **70**, 214116 (2004).

[7] S. A. Moiseev and M. I. Noskov, Laser Phys. Lett. **1**, 303 (2004); S. A. Moiseev, C. Simon, and N. Gisin, e-print arXiv:quant-ph/0609173(2006).

[8] N. Sangouard, C. Simon, M. Afzelius, and N. Gisin, Phys. Rev. A **75**, 032327 (2007).

[9] A. L. Alexander J. J. Longdell, M. J. Sellars, and N. B. Manson, Phys. Rev. Lett. **96**, 043602 (2006); G. Hétet *et al.*, e-print arXiv:quant-ph/0612169; M. U. Staudt *et al.*, Phys. Rev. Lett. **98**, 113601 (2007); S. R. Hastings-Simon *et al.*, Opt. Commun. **266**, 716 (2006); M. U. Staudt *et al.*, *ibid.* **266**, 720 (2006).

[10] J. Brendel, N. Gisin, W. Tittel, and H. Zbinden, Phys. Rev. Lett. **82**, 2594 (1999).