Heralded atomic-ensemble quantum memory for photon polarization states

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Abstract
We describe the mapping of quantum states between single photons and an atomic ensemble.
In particular, we demonstrate a heralded quantum memory based on the mapping of a photon
polarization state onto a single collective-spin excitation (magnon) shared between two atomic
ensembles. The polarization fidelity above 90(2)% for any input polarization far exceeds the
classical limit of $\frac{2}{3}$. The process also constitutes a quantum non-destructive probe that detects
and regenerates a photon without measuring its polarization.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction: coherent mapping between single photons and single magnons

A quantum memory, i.e. a system that can receive and store quantum states that are ideally carried by photons, is a key element for quantum information processing [1–9]. The conceptually simplest quantum memory is a single two-level atom. Coherent mapping between a photon and the atom that is acting as a quantum memory requires the atom to appear opaque to the photon. This can be achieved by focusing the photon to a small area containing the atom, and passing it through this area many times using mirrors with very low loss [10]. In the optical domain an opacity (or resonant optical depth η) of ∼100 can be achieved in this way [10, 11].

An alternative method for increasing the optical depth is to use an ensemble [1–5], [12], rather than a single particle. It may seem that an ensemble of non-interacting two-level particles cannot be used as a memory for a quantum bit, as the Hilbert space of the ensemble is much larger than that of the photon, and most ensemble states do not couple strongly to the photon [13]. However, using a probabilistic but heralded process [1], it is possible to restrict the ensemble Hilbert space to just two states where the atoms couple cooperatively and strongly to the light field [13]. The effectiveness of this method has been proved by the efficient (∼90%) conversion of a single quantized spin-wave excitation of the ensemble (magnon) into a photon [12].

2. Optical transfer of single magnon between two atomic ensembles

If two ensembles are located inside an optical resonator, it is possible to transfer a single spin-wave quantum between them via the optical resonator while populating the resonator mode only virtually [14]. The method is akin to stimulated adiabatic rapid passage in a five-level system (see figure 1(b)), where the system is transferred from the initial quantum state ($|G_A\rangle$, magnon in ensemble A) to the final state ($|G_B\rangle$, magnon in ensemble B) through three unstable intermediate states ($|E_A\rangle, |E_A\rangle$, corresponding to an excited atom in ensembles A and B, respectively, and $|C\rangle$, corresponding to a photon in the resonator). In the ideal limit of large optical depth the unstable intermediate states are only virtually populated, and the magnon transfer efficiency from A to B can approach unity, in spite of resonator loss.

The transfer from A to B is accomplished by turning on the laser beam Ω_B, ramping up the beam Ω_A and subsequently ramping down Ω_B (see figure 1(a)). If both beams are extinguished simultaneously when the magnon is found with equal probability in either of the two ensembles
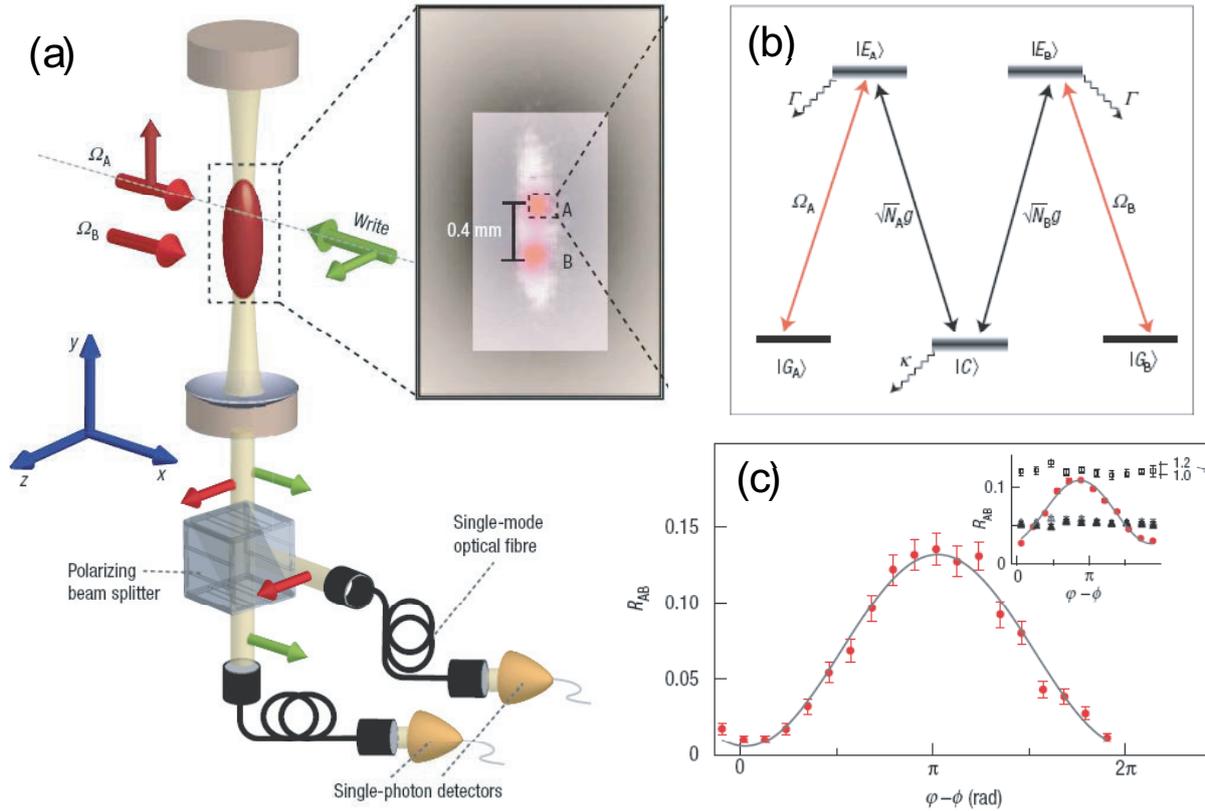
Figure 1. (a) Set-up for phase-coherent optical transfer of a single spin-wave quantum (magnon) between two ensembles and entanglement generation. Two ensembles, A and B, are defined within a cloud of laser-cooled cesium atoms by two laser beams. A single magnon generated in ensemble A by the detection of a single photon is transferred via a dark state of the resonator to ensemble B. (b) Adiabatic transfer in a five-level system. The magnon can be transferred between two ensembles by time-dependent control of the laser beams Ω_A, Ω_B addressing the two ensembles. (c) Verification of coherence between the two ensembles. When a single magnon is shared between the two ensembles, the emission into the optical resonator exhibits an interference fringe, in analogy to superradiant and subradiant emission states of two atoms [13].

($\Omega_A = \Omega_B$), the transfer is interrupted and the system is left in an entangled state $|G_A\rangle + e^{i\phi}|G_B\rangle = |1\rangle_A|0\rangle_B + e^{i\phi}|0\rangle_A|1\rangle_B$, where $|n\rangle_S$ denotes n magnons in ensemble S = A, B. The existence of a definite quantum phase ϕ between the components $|1\rangle_A|0\rangle_B$ and $|0\rangle_A|1\rangle_B$ can be tested by coupling both ensembles simultaneously to the resonator in an attempt to convert the magnon into a photon that can be measured directly. As the phase ϕ between the ensembles is varied, the emission into the resonator exhibits interference fringes (figure 1(c)) that can be understood as constructive and destructive interference (superradiance and subradiance) between the emission processes by the two ensembles [13]. In combination with the sub-Poissonian character of the stored single excitations, this interference implies entanglement between the two ensembles [14].

3. Heralded storage of photon polarization states

For the transport of quantum states between remote locations, the state stored in one ensemble can be converted into a photon that is transported via an optical fiber to a distant location, where it is mapped onto another ensemble. The transmission will, in practice, be subject to loss, be it due to fiber losses or to imperfect mapping between the photon and the quantum memory. To a certain extent, such a loss

can be remedied by a heralding feature where successful storage is announced without giving away the incoming quantum state (figure 2(b)). In the case discussed here, a single photon of fixed polarization announces the successful storage of a photon of unknown, or even potentially undetermined, polarization. Such a heralded storage is achieved by means of a spontaneous Raman process that simultaneously creates a photon of fixed polarization that serves as the herald, and a magnon that is a copy of the input-beam polarization (figure 2(c)). To store an arbitrary polarization state $|\psi\rangle = \cos\theta|R\rangle + e^{i\phi}\sin\theta|L\rangle$, written as a superposition of right/left circularly polarized states $|R\rangle$, $|L\rangle$ with two arbitrary angles θ, ϕ, we use two spatially overlapping atomic ensembles A, B inside an optical resonator. The atomic levels are chosen such that ensemble A (B) absorbs only $|R\rangle$ ($|L\rangle$) polarized light, while both can emit a photon of the same polarization (π) into the resonator on the Raman transition of interest (figure 2(c)). The detection of the emitted π photon heralds the mapping of the input polarization state onto a magnon, $|\psi\rangle \rightarrow |\Psi\rangle = \cos\theta|1\rangle_A|0\rangle_B + e^{i\phi}\sin\theta|0\rangle_A|1\rangle_B$, but does not provide 'which-path' information to distinguish between A and B. The heralding also ensures that, even if the input is a coherent beam, only one magnon is generated between the two ensembles in the limit of small Raman scattering probability. At a later time, the stored state can be retrieved
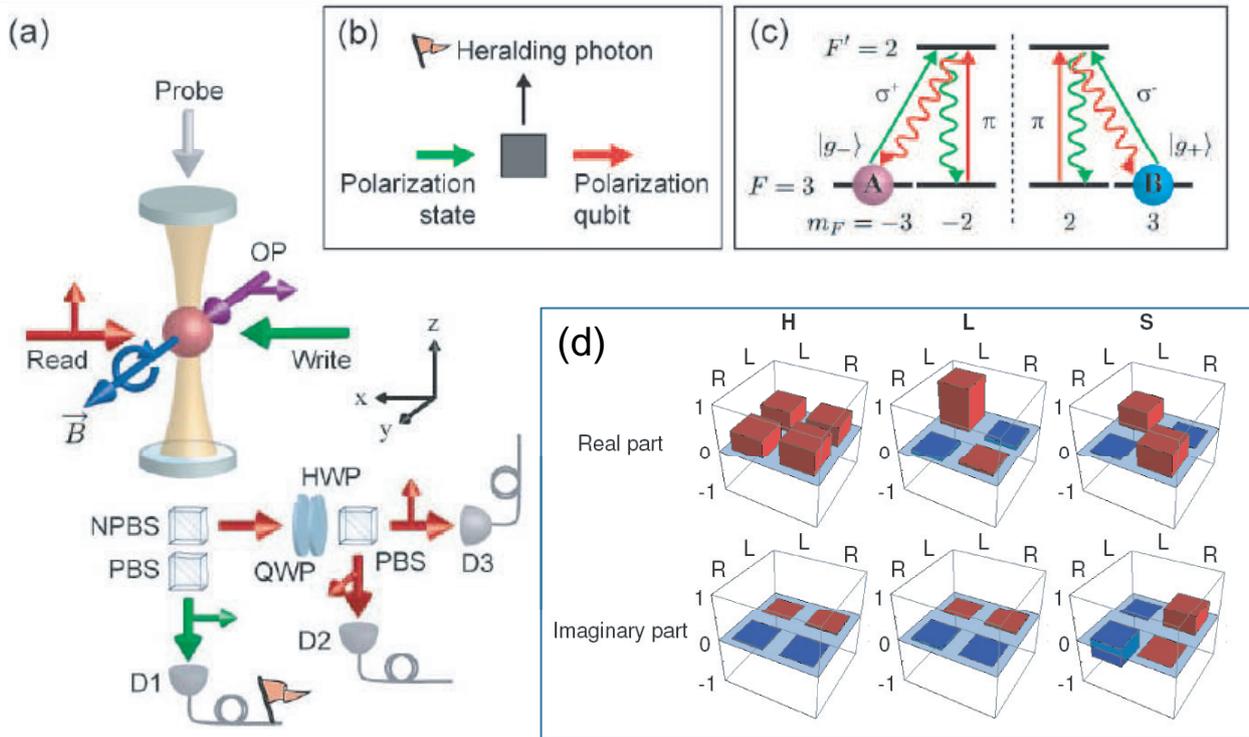
Figure 2. (a) Set-up. The storage of a photon of arbitrary polarization from the write beam is heralded by a photon detected on single-photon counter D1. Small arrows indicate beam polarization and OP is the optical pumping beam. NPBS, PBS, QWP and HWP denote a non-polarizing beamsplitter, a polarizing beamsplitter, a quarter-waveplate and a half waveplate, respectively. D2 and D3 are single-photon counting modules used for polarization analysis of the stored photon. A static magnetic field induces magnon precession. (b) Principle of heralded polarization storage. A heralding photon of fixed polarization announces the storage of a photon of unknown, and potentially undetermined, polarization. (c) Energy levels. Ensembles A and B are initially prepared in hyperfine and magnetic sublevels $|g_{\mp}\rangle \equiv |F = 3, m_F = \mp 3\rangle$. The write (green) and the read (red) processes are $\sigma^{\pm}$–π and π–$\sigma^{\pm}$ spontaneous Raman transitions, respectively. Detection of the π-polarized photon announces storage. (d) Quantum state tomography of the stored photon. Measured density matrix elements for different photon polarization states. The polarization fidelity for all of the stored states exceeds 90%.

on demand as a single photon by utilizing the strong coupling of the magnon to the resonator mode [1, 12].

The heralded storage occurs rarely ($p \sim 10^{-6}$ per incident photon in our non-optimized set-up), but when it does, the incident photon is stored and can later be recreated with good efficiency ($\varepsilon \sim 50\%$) and sub-Poissonian statistics ($g_2 \approx 0.24$), while its polarization state is restored with very high fidelity ($\mathcal{F} > 90\%$). The fidelity of the stored state is measured by converting the stored magnon into a photon, and performing quantum state tomography. Figure 2(d) shows the reconstructed density matrix for three different input polarizations [15].

It should be possible to significantly increase the storage probability to a few percent by increasing the resonator finesse from the current low value $F \sim 300$ to $F \sim 10^4$. Then it would be possible to use the current system for the storage of incoming single photons or entangled photon pairs, as, for example, produced by a parametric downconverter. The storage of such pairs would then enable the heralded or deterministic generation of entangled photon pairs.

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