Demonstration of a Memory for Tightly Guided Light in an Optical Nanofiber

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(Dated: February 6, 2015)

We report the experimental observation of slow-light and coherent storage in a setting where light is tightly confined in the transverse directions. By interfacing a tapered optical nanofiber with a cold atomic ensemble, electromagnetically induced transparency is observed and light pulses at the single-photon level are stored in and retrieved from the atomic medium with an overall efficiency of $(10\pm0.5)\%$. Collapses and revivals can be additionally controlled by an applied magnetic field. Our results based on subdiffraction-limited optical mode interacting with atoms via the strong evanescent field demonstrate an alternative to free-space focusing and a novel capability for information storage in an all-fibered quantum network.

PACS numbers: 03.67.-a, 03.67.Hk, 42.50.Gy, 42.50.Ex, 42.81.Qb

Over the recent years, the physical implementation of quantum interfaces between light and matter has triggered a very active research, with unique applications to quantum optics and quantum information networks [1, 2]. Within this context, a promising approach consists in coupling light with atomic ensembles [3, 4]. Reversible quantum memories have been realized in a variety of ensemble-based systems, e.g. doped crystals and free-space collection of alkali atoms [5]. Significant advances have been made, including the demonstration of entanglement between remote memories and the development of first rudimentary capabilities for quantum repeater architectures [6–9]. However, free-space focusing as used in these seminal works is limiting the coupling one can obtain and the connectivity to fiber networks.

Interfacing guided light with atoms has therefore been foreseen as a promising alternative, enabling longer interaction length, large optical depth and potential non-linear interactions at very low power level [2]. A first possible implementation consists in encasing a vapor into the hollow core of a photonic-crystal fiber, confining thus atoms and photons in the waveguide. Slow-light, all-optical switching and few-photon modulation have been demonstrated [10–12]. Recently, single-photon-level memory based on Raman interaction has been realized with larger core fibers, with storage limited to the 10 ns time-scale [13]. Another approach can be based on an even tighter confinement of light in a nanoscale waveguide leading to a large evanescent field that can interact with atoms located in the vicinity. This situation can be ideally realized with optical nanofibers exhibiting sub-wavelength diameter [14]. Using a nanofiber suspended in a hot Rubidium vapor, nonlinear interactions and low-power saturation have been reported [15–17], albeit with very short transit time of hot atoms in the evanescent field and large broadening.

In this new avenue of research, the unique prospects of combining cold atoms with optical nanofibers have triggered vast theoretical and experimental efforts. Pioneering works investigated the interaction of a small number of atoms with the guided mode, including fluorescence coupling and surface interactions [18–20], and the dipole trapping of atom arrays in the evanescent field [21, 22]. Recent works have focused on the study of anisotropy in the scattering of light into the guided mode [23, 24] and demonstrated the possibility of chiral nanophotonics based on this promising platform for light-matter interfacing within a fiber network.

Here, we report the demonstration of an optical memory based on the interaction of cold cesium atoms with the evanescent field surrounding an optical nanofiber. By using electromagnetically induced transparency (EIT) and realizing the configuration initially proposed in 2002 by Hakuta and coworkers [25], slow-light and reversible storage at the single-photon level are demonstrated. With an additional external magnetic field, controlled collapses and revivals are obtained. More generally, this work provides the realization of a memory for light based on EIT in evanescent fields.

Our setup is illustrated in Fig. 1(a). A cloud of laser-cooled cesium atoms spatially overlaps with a nanofiber suspended in the ultra-high vacuum chamber and connected to the outside by two teflon feedthroughs. The nanofiber is fabricated from a non polarization-preserving (Thorlabs SM800-5.6-125) by the flame brushing technique [26–30]. It exhibits a $2r = 400 \pm 20$ nm diameter over a length of 9 mm, longer than the cesium cloud. It guides the hybrid fundamental mode $HE_{11}$ in the nanofiber waist and is adiabatically coupled via a tapered region on both sides.

The cesium cloud is released from a magneto-optical trap (MOT) cigar-shaped along the fiber direction by using rectangular coils. The experiment is conducted in a cyclic fashion. First, the current in the MOT coils is switched off, then, after a 4.4 ms decay of eddy currents, the trapping beams are also turned off. Measurements are performed during 1 ms, while the cloud expands freely. After this stage, the trap is reloaded for...
FIG. 1. (color online). Experimental setup. (a) A 400-nm diameter nanofiber is overlapped with a large ensemble of cold cesium atoms. The signal to be stored is guided inside the nanofiber while the control propagates at the outside, with an angle $\alpha \sim 13^\circ$. The inset shows the energy levels for EIT, with the ground state $|g\rangle = \{6S_{1/2}, F = 4\}$ and the excited state $|e\rangle = \{6P_{3/2}, F = 4\}$ transition. The low saturation power results from the confined geometry over the cloud length. (c) Transmission profile for a signal pulse at the single-photon level as a function of the detuning $\delta$ from the $|g\rangle \rightarrow |e\rangle = \{6P_{3/2}, F = 4\}$ transition.

The relative polarisation of the signal and control beams must be chosen properly. For the Cs levels used here, without optical pumping, EIT is efficient for orthogonal polarisations [31]. However, light guided through the nanofiber has a complex polarisation pattern, including a significant non-transverse component [32]. Controlling this polarisation is therefore crucial. This can be done by using the method described in Refs. [22, 32] based on Rayleigh scattering. When a 0.5 mW continuous laser beam is sent through the fiber, the guided light partly scattered by inhomogeneities and surface impurities can indeed be detected from the side by a camera equipped with a polarization filter to suppress the non-transverse component. By adjusting the polarization at the input, it is therefore possible to obtain a polarization pattern in the transverse plane with a quasi-linear orientation over the nanofiber waist. In our setup, this polarization is aligned horizontally and stable over many hours.

As a preliminary characterization, we monitor the absorption of a light pulse propagating through the fiber. This measurement is first used to optimise the overlap of the cloud with the nanofiber waist: the cloud position is adjusted for maximal absorption by slightly misaligning the trapping beams. The resulting optical depth (OD - negative logarithm of the transmission) is typically 6 when the signal is tuned on resonance with the cycling $|g\rangle \rightarrow \{6P_{3/2}, F = 5\}$ transition and between 2 and 3 for the $|g\rangle \rightarrow |e\rangle$ transition.

Transmission for a probe at resonance with the cycling transition is reported on Fig. 1(b) as a function of its power. This measurement is used to determine the saturation power, which is expected to be very low due to the tight confinement. The shape is fitted accordingly to the empirical nonlinear model $T = e^{-\alpha L}$ with $\alpha = \alpha_0/(1 + P/P_{sat})^k$, which has been shown to be well adapted to the nanofiber case with $k = 1$ [17].

This fit yields a saturation power $P_{sat} = 1.3 \pm 0.2$ nW and an absorbed power in the saturated regime $P_{abs} = \alpha_0 L P_{sat} = 8 \pm 2$ nW. $P_{abs}$ enables to estimate an effective number $N$ of atoms involved in the interaction region. By considering the nominal power radiated by a saturated single Cs atom $p = 3.8$ pW, $N$ can be inferred as $N = P_{abs}/p = 2000 \pm 500$ atoms. This value is compatible with an independent estimate taking into account the spatial dependence of the atomic density in the vicinity of the fiber [19, 33]. Indeed, due to van der Walls interaction, atoms are repelled from the surface. The radial dependence of the density can be explicitly calculated, as given in [33]. By considering an interaction length $L = 5$ mm, a typical MOT density of $10^{11}$ atoms/cm$^3$ and by integrating over a distance from the surface equal to 4$r$, this estimation leads to 1500 atoms.

Figure 1(c) then shows the transmission profile for a signal pulse as a function of the detuning $\delta$ from the $|g\rangle \rightarrow |e\rangle$ transition. The fitted line profile, $\exp[-OD/(1 + (2\delta/\Gamma)^2)]$, yields OD = 3 and $\Gamma/2\pi = 6.8 \pm 0.5$ MHz. This value is 30% larger than the natural linewidth of Cs atoms in free space, $\Gamma_0/2\pi = 5.2$ MHz, resulting from the finite temperature, surface interactions and modification of the spontaneous emission rate in the vicinity of the fiber [19].

We now turn to the study of EIT, where a control field can change the transmission characteristics of the probe [34]. A large control beam propagating in free space is shined on the cloud, with a 400 $\mu$m waist and an angle $\alpha \sim 13^\circ$ with the nanofiber. This angle has been minimized given the technical constraints in the apparatus. The control is produced by an extended-cavity laser diode and is frequency-locked at the 9.2 GHz hyperfine frequency with the signal generated from a Ti:Sa laser.

The measurements are performed at the single-photon level. Reaching this regime requires to filter out the con-
tamination from the control that couples from freespace into the nanofiber guided mode. This coupling is on the order of $10^{-3}$. For this purpose, we use polarization filtering at the fiber output, taking advantage of the experimental fact that the control beam couples into the nanofiber with a quasi-linear vertical polarisation, thus orthogonal to the signal polarisation. Additional frequency filtering is obtained from a paraffin-coated Cs cell pumped in $|s\rangle$. With this two-step filtering, the remaining control light at the detection stage is $10^{14}$ times smaller than the initial control power. Measurements are done at the fiber output using a single-photon counting module (SPCM-AQR-14-FC) and reconstructing the histogram of arrival times with a 10-ns resolution.

Figure 2 gives the transmission profiles of the signal as a function of its detuning $\delta$ from resonance, for different values of the control power. When the control field is applied, a transparency window appears at resonance, providing a first signature of EIT in this evanescent-field configuration. Transparency close to 75% is measured for a control power of 1.6 mW. The finite contrast is primarily due to a non-negligible ground-state decoherence, which arises from three main concurrent mechanisms that will be detailed later. We note that a full model of the system should include the complexity of the guided light polarization and its evanescent nature, as first done in [34], but also importantly the complex level structure of atomic Cs, including Zeeman levels and other excited levels of the $6P_{3/2}$ manifold, as testified by the observed damping and asymmetries of the resonances [35].

After having observed induced transparency, we measure the delay, i.e. slow-light effect, resulting from pulse propagation under EIT condition. As a signal, we use attenuated laser pulses at the single-photon level. Results are displayed in Fig. 3(a). When the control power is decreased, smaller transparency but larger delays are obtained due to the narrower transparency window. For a 0.5 mW control pulse, close to the value used in the subsequent experiments, we achieve a delay equal to 60 ns. This value corresponds to a 2000-fold reduction in group velocity.

Next, we demonstrate the storage of the guided light by the dynamic EIT protocol [36]. While the light is slowed down, the control is ramped down to zero and the light signal is converted into a collective excitation. Later, the control is switched on again and the light can be retrieved back in a well-defined spatio-temporal mode due to the collective enhancement provided by the ensemble. Figure 3(b) provides the storage and retrieval results for a signal with a mean photon-number per pulse equal to 0.6±0.1. The pulses have been temporally shaped [37] to an exponentially-rising profile with a full width at half-maximum of 60 ns. Efficiency of the storage and retrieval processes is defined as the ratio of the photodetection event probability in the read-out to the one in the reference. After optimisation of the control power for a trade-off between transparency and delay, a storage and retrieval efficiency $\eta = 10 \pm 0.5 \%$ is obtained, therefore realizing an optical memory at the single-photon level in this novel fibered setting. The normalized efficiency as a function of the control polarization is provided in Fig. 3(c). This result shows the good control over the polarization in the nanofiber waist. We also note that the achieved efficiency is compatible with the limited OD used here. Remarkably, the single-photon signal-to-noise ratio in the retrieved pulse is already equal to 20.

![Graph showing transmission as a function of detuning](image1)

**FIG. 2.** (color online). Electromagnetically-induced transparency for the guided light. The control is on resonance on the $|s\rangle \rightarrow |e\rangle$ transition while the signal can be detuned by $\delta$ from the $|g\rangle \rightarrow |e\rangle$ resonance. Profiles are displayed as a function of $\delta$, for four values of the control power. The green line is a guide for the eye.

![Graph showing transmission profiles](image2)

**FIG. 3.** (color online). Observation of slow-light and reversible storage at the single-photon level for the guided light. (a) Transmitted pulses for different control powers. The control is overlapped in time with the signal. (b) Storage and retrieval. In the absence of control, the blue and purple points give the transmitted pulse without and with atoms respectively. The OD is equal here to 2. The red data corresponds to the memory sequence, showing leakage and retrieval. The black line indicates the control timing. The mean photon-number per pulse is 0.6 and the storage and retrieval efficiency is $10 \pm 0.5 \%$. (c) Efficiency as a function of the control linear polarisation angle. The zero angle corresponds to a vertical polarisation.
We finally investigate the memory lifetime. Figure 4(a) gives the retrieval efficiency as a function of the storage duration. Three concurrent decoherence mechanisms are involved and can be evaluated independently. The atomic motion related to the finite temperature first results in a possible loss of the atoms from the tiny evanescent field area. By denoting \( v = \sqrt{k_B T/m} \) the thermal velocity of an atom of mass \( m \) at a temperature \( T \), the transit time can be estimated by \( \tau_1 = 2r/v \). For a 200 \( \mu \text{K} \) temperature, this expression provides \( \tau_1 = 3.6 \mu \text{s} \). A second contribution, also related to the temperature, is the motional dephasing due to the strong angular dependence of EIT [38, 39]. The atomic motion related to the finite temperature first results in a possible loss of the atoms from the tiny evanescent field area. By denoting \( \alpha \sim 13^\circ \), the calculated time constant is \( \tau_2 = 5.3 \mu \text{s} \). Finally, the last decoherence process is caused by the residual magnetic field. It leads to a measured inhomogeneous broadening of 100 kHz and an associated lifetime \( \tau_3 = 10 \mu \text{s} \) [40]. The combination of the processes related to dephasing on one hand and loss of the atoms on the other gives a decay of the retrieval efficiency of the form

\[
\exp \left[ -\frac{(t/\tau_D)^3(1 + (t/\tau_T)^3)}{(1 + (t/\tau_T)^3)^2} \right],
\]

with \( \tau_T = \tau_1 \) and \( 1/\tau_D^2 = 1/\tau_2^2 + 1/\tau_3^2 \). The fit in Fig. 4(a) yields \( \tau_D = 5.5 \pm 1 \mu \text{s} \) and \( \tau_T = 3.7 \pm 0.2 \mu \text{s} \). These values are in good agreement with the evaluated time scales and thereby confirm that the main decoherence mechanisms are well identified.

Applying an additional DC magnetic field can also enable to control the time evolution of the stored collective excitation and to demonstrate collapses and revivals in the retrieval efficiency as a function of the storage time, as observed in free-space implementations [42]. Figure 4(b) and 4(c) correspond to this configuration, with a uniform magnetic field aligned along the nanofiber axis. The applied field is calibrated by measuring the Zeeman shifts. Revivals are observed at multiples of the half Larmor period, equal to 3.5 \( \mu \text{s} \) for a field of 0.4 G and 2.35 \( \mu \text{s} \) for 0.6 G.

In conclusion, we have reported the realization of EIT and storage of light at the single-photon level in a nanofiber-based interface. This novel capability based on the interaction of the evanescent part of the tightly guided mode with the surrounding atoms provides an intrinsically-fibered memory. The reported results, which are obtained with low optical depth relative to previous free-focusing and hollow-core fiber memory demonstrations, are promising given the possible improvements. Larger optical depth, retrieval efficiency and coherence time are expected by combining the present protocol with the recently achieved dipole trapping of atom arrays close to the nanofiber surface [21, 22]. Copropagating the control field in the guided mode would also enable a better matching of the involved light polarizations, a reduced decoherence rate and a control field at an ultra-low power level. However, theoretical and experimental challenges remain. In particular, very efficient frequency filtering will be required to distinguish between the copropagating trapping light at the milliwatt level and signal pulses and to finally reach large single-photon signal-to-noise ratio in this configuration. Finally, the present demonstration opens up the possibility to implement the seminal Duan-Lukin-Cirac-Zoller protocol [3] in this specific setting, with the unique prospects of efficient generation of intrinsically fibered single photons and the remote entanglement of all-fibered ensembles.

This work is supported by the ERA-Net CHISTERA (QScale), the European Research Council (Starting Grant HybridNet), the Emergence program from Ville de Paris and the IFRAF DIM Nano-K from Région Ile-de-France. The authors also acknowledge interesting discussions within the CAPES-COFECUB project Ph 740-12. A.N. acknowledges support from the Direction Générale de l’Armement (DGA). J.L. is a member of the Institut Universitaire de France.

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