Light Storage in a Cold Atomic Ensemble with a High Optical Depth

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A quantum memory with a high storage efficiency and a long coherence time is an essential element in quantum information applications. Here, we report our recent development of an optical quantum memory with a rubidium-87 cold atom ensemble. By increasing the optical depth of the medium, we have achieved a storage efficiency of 65% and a coherence time of 51 μs for a weak laser pulse. The result of a numerical analysis based on the Maxwell-Bloch equations agrees well with the experimental results. Our result paves the way toward an efficient optical quantum memory and may find applications in photonic quantum information processing.

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I. INTRODUCTION

An optical quantum memory finds its importance in photonic quantum computation and long-distance quantum communication. In quantum computation, the quantum memories may be used to synchronize multi-photon events to enhance the success probabilities of linear optical quantum gates [1]. In quantum communication, the quantum memories are crucial parts of a quantum repeater for the distribution of entangled photons over a long-distance quantum channel which suffers from photon loss and decoherence [1–4].

A cold atomic ensemble prepared by a magneto-optical trap (MOT) has been an ideal platform for studying a quantum memory due to its strong interaction with single photons and negligible Doppler broadening effects [5–10]. In quantum memory applications based on cold atoms, one of the important parameters determining the memory efficiency is the optical depth (OD) $\mathcal{D}$, which is defined as $T = \exp(-\mathcal{D})$, where T is the light transmission through the medium [6,7]. The higher the OD, the stronger the absorption of light, increasing the memory efficiency. Because the OD is proportional to the atomic density and the sample length, there have been many approaches to increase the density or to make a bigger cold atom cloud [11–14].

The other important parameter of a quantum memory based on cold atoms is the coherence time of the medium, defined as the Gaussian decay time of the memory retrieval efficiency [7,10]. The two main factors that negatively affect the coherence time are the stray magnetic fields around the cold atoms and the atomic motions. Substantial efforts have been made to overcome these effects by eliminating the magnetic fields and suppressing the atomic motion with an optical dipole trap [5,7–10].

In this work, we report a high efficiency storage of 65% for a weak laser pulse in a rubidium-87 cold atom ensemble via the electromagnetically induced transparency (EIT) quantum memory protocol. For such a high retrieval efficiency, we prepared a medium with a high OD of $\mathcal{D} = 142$ by employing four-pair cooling beams, the temporal dark MOT technique, depumping, and magnetic field compression [13,14]. We simultaneously achieved a coherence time of 51 μs by quickly turning off the MOT coil and compensating the residual magnetic fields.

II. EXPERIMENT

The essential features of the experiment are depicted in Fig. 1(a). Rubidium-87 (Rb-87) cold atoms are pre-

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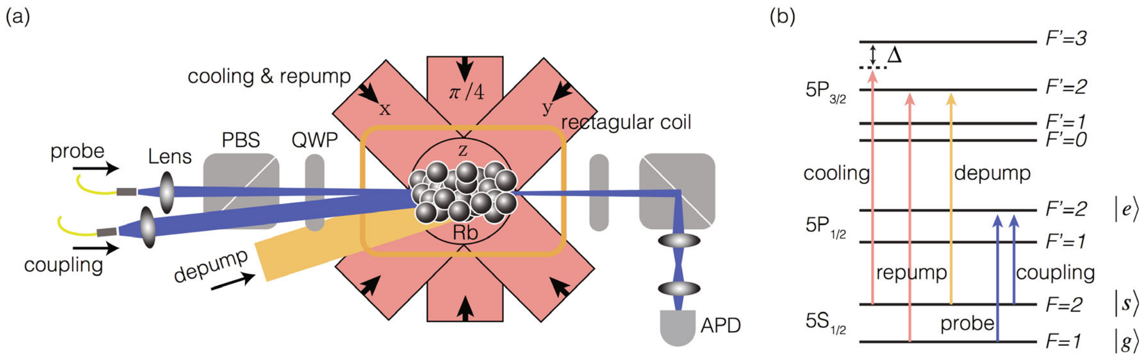

Fig. 1. (Color online) Experimental setup for the light slowing and storage experiment. (a) 87 Rb cold atoms are prepared in a 2D MOT with a rectangular coil. The cooling and the repump lasers are combined with a PBS, which is not shown here. The probe and coupling are circularly polarized in the frame of the atoms. The probe at the medium is 4f-imaged to the APD. All lasers are spatially filtered with single-mode fibers. (b) Energy level diagram. (PBS: polarizing beam splitter, QWP: quarter wave plate, APD: avalanche photodiode).

pared in a glass-cell ultra-high vacuum chamber ($\sim 10^{-9}$ Torr). Several methods are applied for increasing the OD of the medium. First of all, four pairs of cooling beams with diameters of 25 mm are applied instead of the widely used three pairs [14]. Without the additional pair, the atoms may leak from the center due to the imbalance of the power of each pair in the high OD MOT. The additional pair enhances the optical confinement force for stable trapping. The cooling beam, red-detuned by $\Delta/2\pi = 15$ MHz, has a total power of 70 mW. The experiment is repeated every 200 ms; after the 177-ms initial loading, compression techniques such as temporal dark MOT, depumping, and magnetic field compression are applied for 11.5 ms. Then, the EIT slowing and storage experiment is conducted during the next 11.5 ms. In the compression period, the cooling and the repump laser powers are modulated to achieve a temporal dark MOT [13–16]. The modulations help the already cooled atoms to accumulate into the dark state $5S_{1/2}$ $F = 1$. As the dark state does not interact with the intense cooling laser, the re-radiation is reduced and the atoms can accumulate in the state at a higher density. The cooling power is gradually reduced from 70 mW to 10.5 mW, and the repump power is gradually reduced from 0.8 mW to 0.091 mW [14–16]. To improve the performance of the temporal dark MOT, we apply a depump laser with a diameter of 15 mm and a power of 1.0 mW for the resonant pumping into the dark state. As the temporal modulations of the cooling and the repump are not sufficient for the atoms to be pumped into the dark state, the depump helps the atoms to be efficiently depumped into the dark state [16]. The depump is linearly polarized to perform the optical pumping of all the Zeeman states into the dark state. Furthermore, the magnetic field gradient of the MOT coil is gradually increased from 8 G/cm to 26 G/cm, which forces the atoms into a smaller trapping volume as increasing the density. The details of the timing sequence are shown in Fig. 2.

After the compression, the MOT coil and other lasers

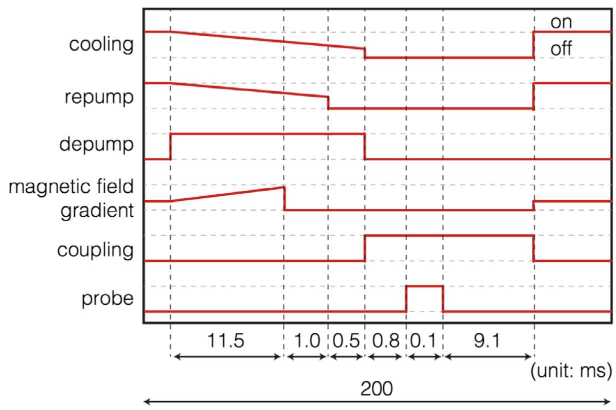

Fig. 2. (Color online) Timing diagram for the OD measurement.

are turned off for the main experiment. The MOT coil is turned off quickly by using a switching circuit made of an insulated-gate bipolar transistor (Fuji Electric 1MBI400V-120-50). After the repump has been fully turned off, the cooling and the depump are turned off as all the atoms have been prepared in the ground state $|g\rangle$. Then, the main experiments, such as OD measurement and light slowing and storage, are carried out.

For the coherent storage and retrieval of a weak laser pulse in a cold-atom ensemble, the EIT protocol is utilized in this experiment [17–22]. In the three-level lambda configuration composed of the coupling and the probe as shown in Fig. 1(b), all the atoms are initially prepared in the ground state $|g\rangle$ so that there is no population in the spin state $|s\rangle$. With the presence of a strong coupling field, the resonant probe laser is not absorbed by the EIT medium. Rather, it propagates through the medium without loss in the ideal case when the OD of the medium goes to infinity and the ground state dephasing rate approches zero [7,25]. If the coupling field is kept turned on, the probe pulse slowly propagates through the medium. If the coupling is turned off during the

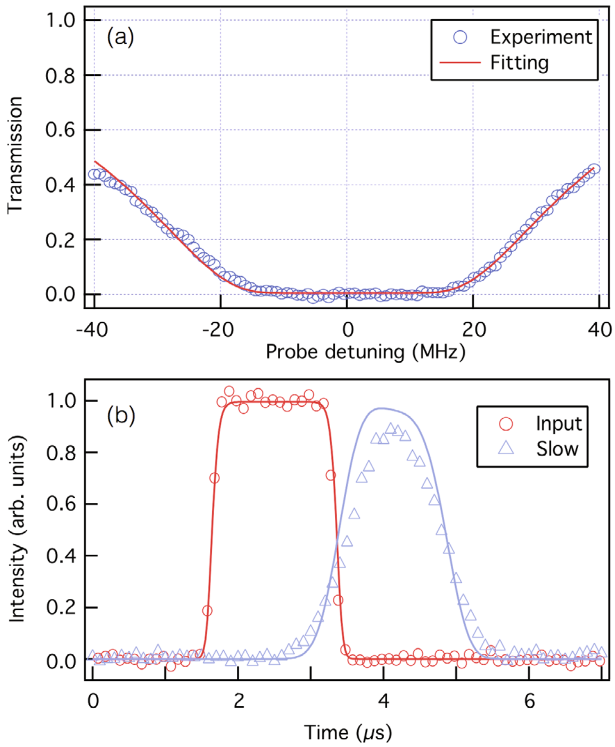

Fig. 3. (Color online) (a) Two-level transmission curve of the probe. The fitting value of the OD is 142. (b) Slow light in the EIT medium. The red open circles represent the input probe pulse and the blue open triangles represent the delayed probe pulse. The superimposed solid lines are due to the numerical simulation.

slow propagation of the probe, the probe is coherently mapped into the spin state of the atomic ensemble as a form of spinwave, which is the principle of EIT light storage [17–22].

As the storage time of a light pulse mainly depends on the ground-state dephasing rate γ_{gs} between $|g\rangle$ and $|s\rangle$, reducing the dephasing rate by removing the inhomogeneous magnetic fields and compensating the residual magnetic fields is crucial. The experiment is started at 2.3 ms, as shown in Fig. 2, after the coil turn-off when the inhomogeneous magnetic field generated by the MOT coil is almost negligible. The residual stray fields are well compensated by using three pairs of Helmholtz coils not shown in Fig. 1(a).

First, the OD of this medium, which is defined as

$$T(\delta) = \exp\left(-\frac{\mathcal{D}}{1+(\delta/\gamma_{ge})^2}\right), \tag{1}$$

where δ is the probe detuning and γ_{ge} is the relaxation rate between $|e\rangle$ and $|g\rangle$, was determined from the two-level transmission T shown in Fig. 3(a). The measured OD in the D1 transition is 142 ± 2.1. Because the storage efficiency saturates at ODs larger than 100, our high OD medium is good enough for high efficiency retrieval [6,7]. For the EIT light slowing and storage experiment, the

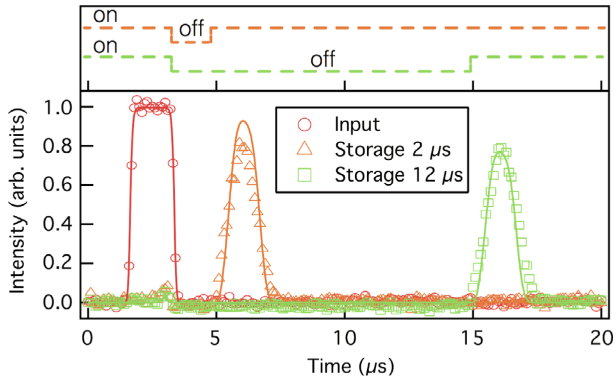

Fig. 4. (Color online) Storage results. The input pulse (red open circles) is stored in the EIT medium by turning off the coupling (dashed lines). The open orange triangles (open green squares) represent the retrieved probe pulse with a storage time of 2 μs (12 μs) controlled by the orange (green) dashed line. The superimposed solid lines are due to the numerical simulation.

probe pulse is applied along with the coupling field which is slightly tilted from the probe by 0.3°. The coupling beam is well collimated, and the diameter of the beam is 1.8 mm. The probe is focused with a diameter of 250 μm. In the case of the always-on coupling, the probe propagates through the medium with a reduced speed, which results in a delay of 1.6 μs as shown in Fig. 3(b). The solid lines are the results from numerical simulations of the Maxwell-Bloch equations [23–25],

$$\begin{aligned}(\partial_t + c\partial_z)\Omega_p(z,t) &= i\frac{\mathcal{D}\gamma_{ge}c}{L}\rho_{eg}(z,t),\\ \partial_t\rho_{eg}(z,t) &= -\gamma_{ge}\rho_{eg}(z,t)\\ &\quad +\frac{i}{2}(\Omega_p(z,t)+\Omega_c(z,t)\rho_{sg}(z,t)),\\ \partial_t\rho_{sg}(z,t) &= -\gamma_{gs}\rho_{sg}(z,t)+\frac{i}{2}\Omega_c^*(z,t)\rho_{eg}(z,t),\end{aligned} \tag{2}$$

where $\Omega_p(\Omega_c)$ is the probe (coupling) Rabi frequency, L is the length of the medium, and c is the vacuum speed of light. The rest of the parameters are OD = 142, $\gamma_{gs}/2\pi$ = 1.5 kHz, and $\Omega_c/2\pi$ = 9.0 MHz. Because the group delay τ_g depends on the coupling Rabi frequency, which is given as

$$\tau_g = \frac{2\gamma_{ge}\mathcal{D}}{|\Omega_c|^2 + 4\gamma_{ge}\gamma_{gs}}, \tag{3}$$

the slowed light can be explicitly separated from the input by simply reducing the coupling power at the expense of reduced transmission.

Next, the probe pulse is stored as a spinwave in the atomic ensemble by turning off the coupling field, as shown in Fig. 4. Each dashed line represents the variation in the coupling power corresponding to each storage trace. After a programmable storage time, the coupling field is turned back on, and the stored spinwave is retrieved back to the photonic excitation. As in the slow-

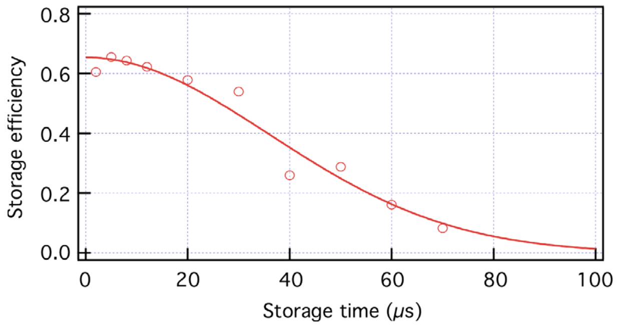

Fig. 5. (Color online) Storage efficiency as a function of the storage time. The fitting gives a max efficiency of 65.4% and a coherence time of 50.9 μs.

ing experiment, the solid lines are the results of numerical simulations, which matched the experimental results well. We measured the variation of the storage efficiency by changing the storage time, as shown in Fig. 5. A Gaussian decay time constant τ_c of 50.9 $\pm$ 3.0 μs and a max storage efficiency E of 0.654 $\pm$ 0.024 are extracted from the fitting function $E\exp[-(t/\tau_c)^2]$.

III. CONCLUSIONS

We achieved an optical quantum memory with an efficiency of 65% and a coherence time of 51 μs in rubidium-87 cold atoms. The high efficiency is obtained from the high OD of 142 by applying a number of techniques such as four-pair cooling beams, magnetic field compression, temporal dark MOT, and depumping. The long coherence time is achieved by reducing the ground-state dephasing rate mostly coming from the inhomogeneous magnetic fields. Furthermore, the numerical simulations have well retrieved all the experimental results. Our development of this optical quantum memory with a high efficiency storage and a long coherence time may help the realization of quantum information protocols.

We note that a number of other techniques for enhancing the efficiency and the coherence time are possible. As to the higher efficiency, it is reported recently that the OD up to 1000 is feasible in cold atoms by making the size of the medium bigger and further cooling the medium along with our methods [13, 14]. Another way is to apply the time-reversal method, where the temporal waveform of a light pulse is shaped in a time-reversal manner and is retrieved in the backward direction [7, 26, 27]. A longer coherence time requires the atomic motion, *i.e.*, the spinwave motional dephasing rate, to be reduced. A huge improvement up to the order of seconds can be achieved by suppressing the motion of the spinwave via optical dipole trapping [5,8,9].

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