Research Article | Vol. 28, No. 1 / 6 January 2020 / Optics Express 360

Optics EXPRESS

Cavity-enhanced and long-lived optical memories for two orthogonal polarizations in cold atoms

YAFEI WEN,[1,2] PAI ZHOU,[1,2] ZHONGXIAO XU,[1,2] LIANG YUAN,[1,2] MINJIE WANG,[1,2] SHENGZHI WANG,[1,2] LIRONG CHEN,[1,2] AND HAI WANG[1,2,*]

[1] *The State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China*
[2] *Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan 030006, China*
[*] *wanghai@sxu.edu.cn*

Abstract: The storage and retrieval efficiency (SRE) and lifetime of optical quantum memories are two key performance indicators for scaling up quantum information processing. Here, we experimentally demonstrate a cavity-enhanced long-lived optical memory for two polarizations in a cold atomic ensemble. Using electromagnetically induced-transparency (EIT) dynamics, we demonstrate the storages of left-circularly and right-circularly polarized signal light pulses in the atoms, respectively. By making the signal and control beams collinearly pass through the atoms and storing the two polarizations of the signal light as two magnetic-field-insensitive spin waves, we achieve a long-lived (3.5 ms) memory. By placing a low-finesse optical ring cavity around the cold atoms, the coupling between the signal light and the atoms is enhanced, which leads to an increase in SRE. The presented cavity-enhanced storage shows that the SRE is ~30%, corresponding to an intrinsic SRE of ~45%.

1. Introduction

Optical quantum memory, which can store an incoming input photon in a stationary device and then efficiently retrieve the photon after a given time, plays an important role in quantum information processing, such as scaling-up linear optical quantum computations [1], long-distance entanglement distribution [2,3], the quantum internet [4] and measurement-device-independent quantum key distribution [5]. In the last two decades, the storage of coherent light pulses and photonic quantum states has been experimentally demonstrated using various schemes, such as electromagnetically induced transparency (EIT) [6–10], off-resonant Raman interactions (ORRIs) [11–12], atomic frequency combs (AFCs) [13–15] and gradient echo memories (GEM) [16–18]. Efficiency and lifetime are two important performance indicators of the memory. According to theoretical estimations [3], a 1% increase in the retrieval efficiency will lead to a 10%–14% increase in the long-distance entanglement distribution rate. Moreover, lifetimes should be at least on the order of milliseconds [19]. In recent years, much effort has been devoted to improving the storage and retrieval efficiencies (SREs) and lifetimes of optical memories and significant progresses have been achieved. Theoretical analyses of the dependences of the SREs on optical depth [20–21] and cavity cooperativity [22] have been presented, respectively. By using a cold atomic ensemble with an ultrahigh optical depth (*OD*) of more than 100, highly efficient optical memories have been experimentally demonstrated with EIT [23–25]. These experiments include memories for optical pulses [23], photonic polarization qubits [24] and single-photon polarization qubits [25], whose SREs are 92%, 68% and 85%, respectively. However, the lifetimes in these experiments are in the range of 20–320 μs. Also, highly efficient memories for coherent optical pulses [26,27] have been demonstrated with solid-state atomic ensembles,

#376962 https://doi.org/10.1364/OE.376962
Journal © 2020 Received 3 Sep 2019; revised 18 Dec 2019; accepted 18 Dec 2019; published 2 Jan 2020

where SREs are 69% [26] and 76% [27], respectively. A long-lived and efficient single-mode optical memory has been demonstrated with a GEM in atomic ensembles with a large *OD* [18], where the signal and control light beams are collinearly directed into the atoms; the SRE is 87% and the lifetime is 1 ms. However, quantum storage in cold atoms with an ultrahigh *OD* makes operations, such as optical pumping and photon noise filtering, complex and technically demanding. To improve the SRE, an alternative scheme is to use optical cavities to enhance the coupling between the atoms and the signal light field. By placing solid-state ensembles in optical cavities, cavity-enhanced AFC quantum memories have been theoretically proposed [28] and have been experimentally demonstrated [29–30]. In the experiments, the SREs are 56% [29] and 53% [30] respectively, for the coherent optical pulses. Although the storage times in the experiments were no more than 30 μs, it may be significantly increased by the radio-frequency sequence technique [31]. Long-lived storages of bright [32,33] and weak coherent laser pulses [31] have been experimentally demonstrated with solid-state atomic ensembles, respectively. The lifetimes in these experiments are 1 min in [32], 1s in [33] and 1 ms in [31], together with SREs of 0.4% [32], 1% [33] and 6.5% [31] respectively. In optical storages based on cold atoms, the decoherence, which results from inhomogeneous broadening of spin transitions induced by residual magnetic fields and atomic random motion, will limit the storage time [3]. By mapping coherent light pulses into magnetic-field-insensitive spin waves in ultra-cold atoms, Bloch [34] and Kuzmich [35] groups have experimentally demonstrated single-mode EIT storages, in which lifetimes are 240 ms [34] and 16s [35], respectively. The SREs for short storage times in these experiments are ~0.3% [34] and ~14% [35], respectively. Using the EIT dynamic, quantum storage for polarization quibits in a cold atomic ensemble with an *OD* of ~4 has been experimentally demonstrated [36]. In this experiment, the weak signal light (photonic qubit) and bright control light beams collinearly go through the atoms and the photonic qubits are stored as two magnetic-field-insensitive spin waves. In this way, the storage lifetime for the polarization fidelity is 4.5 ms. However, this long-lived storage relies on the application of a moderate magnetic field on the cold atoms, which in turn induce a ~10-MHz single-photon detuning in EIT systems and then reduce the coupling between the signal light and the atoms [36]. The measured SRE is ~8% in this experiment [36]. For improving this low efficiency, an approach is to apply an optical ring cavity into this experiment. We also noted that a Duan-Lukin-Cirac-Zoller (DLCZ) quantum memory that utilizes the collinear model, magnetic-field-insensitive spin waves and the optical ring cavities, has been demonstrated with cold atoms [37]. A long lifetime (~3 ms) and high retrieval efficiency (73%) has been achieved in this experiment. This DLCZ quantum memory, which relies on spontaneous Raman scattering of photons [4], is different from the read-write (in-out) EIT-based quantum memories [38]. So for, the EIT storage system that simultaneously contains the collinear model, magnetic-field-insensitive spin waves and the optical ring cavities have not been demonstrated.

In this article, we experimentally demonstrate a cavity-enhanced and long-lived optical memory for the two polarization modes of light in a cold atomic ensemble. Based on the EIT scheme, we store left-circularly and right-circularly polarized signal light pulses in an atomic ensemble. To achieve a long-lived memory, we make both the signal and control beams collinearly go through the atoms and store the two polarizations of the signal light as two magnetic-field-insensitive spin waves. The coupling between the signal light pulses and the atoms is enhanced by a low-finesse optical ring cavity around the cold atoms and then the SRE is increased. For the case that the atoms are placed inside the cavity, the SREs for the two polarizations as a function of storage time are measured. The results show that SRE at zero delay and the *1/e* lifetime are 30% and 3.5 ms, respectively. We want to emphases that the presented value of the SRE is limited by losses of optical elements inside the cavity. By using the optical elements with perfect anti-reflection coating, one may increase the SRE to its intrinsic value of $\eta_C^{inc} \simeq 45\%$.

2. Experimental setup

The illustration of the experiment is shown in Fig. 1(a). Our quantum memory is based on an ensemble of ^{87}Rb atoms trapped in a magneto-optical trap (MOT) with a maximum size of $\sim 5\,mm \times 5\,mm \times 10\,mm$. The involved atomic levels are shown in Figs. 1(b) and 1(c), where the atomic ground levels are $|a\rangle = |5^2S_{1/2}, F = 1\rangle$ and $|b\rangle = |5^2S_{1/2}, F = 2\rangle$, and the excited level is $|e\rangle = |5^2P_{1/2}, F' = 1\rangle$. After the atoms are released from the MOT, we prepared the atoms into their Zeeman levels $|a, m_{F_a}\rangle$ ($m_{F_a} = 0, \pm 1$) via optical pump. The frequencies of the signal and write (read) control light fields are tuned to the transition $|a\rangle \leftrightarrow |e\rangle$ and $|b\rangle \leftrightarrow |e\rangle$. Under the drives of the two light fields, the EIT occurs in the three-level system $|a\rangle \leftrightarrow |e\rangle \leftrightarrow |b\rangle$. In the presented experiment, we realize an EIT-based storage of the left-circularly or right-circularly polarized signal field. Considering the Zeeman degeneracy of the levels, the EIT system ($|a\rangle \leftrightarrow |e\rangle \leftrightarrow |b\rangle$) includes several EIT subsystems, such as, $|a, m_F = -1\rangle \leftrightarrow |e, m_F = 0\rangle \leftrightarrow |b, m_F = 1\rangle$ and $|a, m_F = 0\rangle \leftrightarrow |e, m_F = -1\rangle \leftrightarrow |b, m_F = -2\rangle$ for storing right-circularly polarized signal field, as well as $|a, m_F = 1\rangle \leftrightarrow |e, m_F = 0\rangle \leftrightarrow |b, m_F = -1\rangle$ and $|a, m_F = 0\rangle \leftrightarrow |e, m_F = 1\rangle \leftrightarrow |b, m_F = 2\rangle$ for storing left-circularly signal field, which are involved in magnetic-field-insensitive and magnetic-field-sensitive [36] spin transitions. We apply a moderate magnetic field (13.5 G) to the cold-atom ensemble to lift the Zeeman degeneracy of the levels of the atoms, which leads to a ~10-MHz frequency splitting between the two Zeeman sublevels with the difference of $\delta m_F = \pm 1$ in the levels $|a\rangle$ or $|b\rangle$ [see Figs. 1(b) and 1(c)]. Thus, the magnetic-field-sensitive transitions are removed from the EIT system, and the right-circularly and left-circularly polarized signal fields may be stored as magnetic-field-insensitive spin waves $|a, m_F = -1\rangle \leftrightarrow |b, m_F = 1\rangle$[see Fig. 1(b)] and $|a, m_F = 1\rangle \leftrightarrow |b, m_F = -1\rangle$ [see Fig. 1(c)], respectively, which enables us to suppress the decoherence induced by resident magnetic field [36].

To increase the wavelength of the spin waves and suppress the decoherence arising from atomic random motions, the signal light and control light, which are combined in a 50/50 single-mode fiber beamsplitter (BS), collinearly pass through the atoms along the z axis [see Fig. 1(a)].

As shown in Figs. 1(b) and 1(c), when the moderate magnetic field is applied on the cold atoms, an about 10-MHz single-photon detuning in the two EIT storage systems are induced, which reduces the coupling between the signal light and the atoms. To enhance the coupling strength between the signal beam and the atoms and then improve the optical storage efficiency, we placed a ring cavity around the cold atoms. As shown in Fig. 1(a), the ring cavity consists of a partially reflecting mirror (PR), which has a typical reflectance of $R = 80\%$, two planoconvex lenses with the same focal length of 400 mm, and three highly reflecting mirrors HR_1, HR_2 and HR_3 (reflectance >99%). HR_3 is mounted on a piezoelectric transducer (PZT), which is used for actively locking the cavity length. The cavity has a round-trip length of 1.6 m and a free spectral range of 187.5 MHz. The optical loss of all the optical elements in the cavity is $L \approx 10\%$, which mainly includes an 8% loss from the two lenses and a 2% loss from the vacuum chamber of the MOT. The finesse (F) of the cavity with the cold atoms in the EIT condition is measured to be ~17. In cavity-enhanced EIT storage, we use a ring cavity instead of a stationary cavity. If a stationary cavity is used, the signal light will be reflected by the end mirror of the cavity and then pass back through the atoms (along the z axis). The storage of the backward signal light will generate a short-wavelength spin wave and then lead to a rapid decoherence of the memory. The coupling strength between the signal light and the atoms can be described by the cavity cooperativity (effective optical depth), which may be written as $Co \propto F \times OD$ [37], where OD is the optical depth, which corresponds to an intensity attenuation when the signal light beam with its frequency being resonant on the atomic transition $|a\rangle \leftrightarrow |e\rangle$ goes through the cold atoms. The intensity attenuation is calculated by $e^{-OD} = I/I_0$, where I_0 (I) is the input (transmission) intensity of the weak signal light beam.

Optics EXPRESS

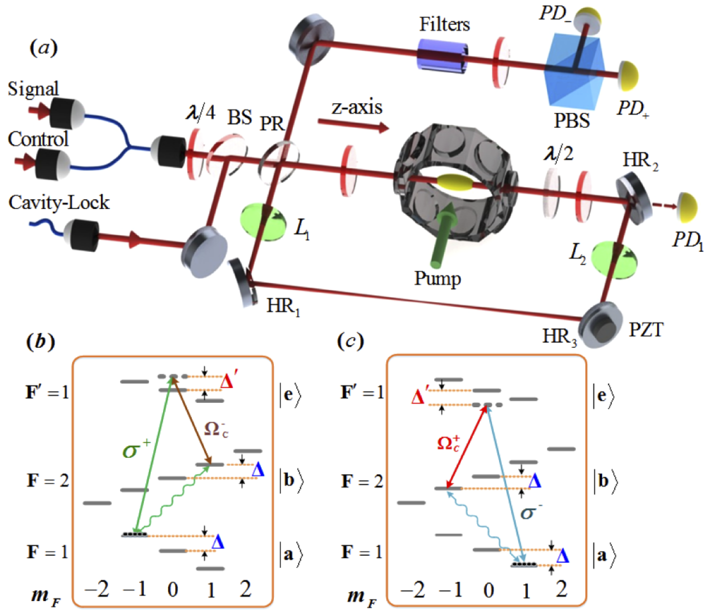

Fig. 1. Overview of the experiment. (a) Illustration of the experimental setup, where $PD_{\pm}$ and PD_1 are photodetectors, L_1 and L_2 are lenses with a focus length f specified in millimeters, HR_1 - HR_3 are highly reflecting mirrors, BS is a nonpolarizing beamsplitter, $\lambda/4$ and $\lambda/2$ are quarter- and half-wave plates, the filters are etalons, and PBS is a polarizing beamsplitter. (b) and (c) show the three-level Λ-type EIT systems for the storage of the signal light fields in a moderate magnetic field ($B_0 = 13.5G$). Ω_C^+ (σ^+) and Ω_C^- (σ^-) denote the right-circularly and left-circularly polarized control (signal) light fields, respectively. Δ denotes the frequency splitting between the two Zeeman levels with the difference of $\delta m_F = \pm 1$ in the levels $|a\rangle$ or $|b\rangle$. Δ' denotes the single-photon detuning of the EIT systems. In the presented system, we have $\Delta \approx \Delta'$.

A frequency-modulated locking light beam, which is red-detuned ~500 MHz relative to $5S_{1/2}, F = 1 \longrightarrow 5P_{1/2}, F' = 1$, is combined with the signal (control) light with a nonpolarizing BS with reflectance of 95%. To avoid degradation of the polarization of the signal light, a polarization compensation set containing $\lambda/4$, $\lambda/2$ and $\lambda/4$ waveplates is inserted into the cavity, which can generate any unitary transformation and then eliminate the phase shift between the horizontal and vertical polarizations of the signal light. The signal and control light beams are coupled into the cavity through the partially reflecting mirror PR. Before the mirror PR, the powers of the signal and control light beams are ~20 μW and 8 mW, respectively. At the center of the atoms, the diameter of the signal (control) beam is 1.4 mm. By using the Pound-Drever-Hall locking scheme, we actively stabilize the cavity length and make the signal and control light fields resonant with the cavity simultaneously. When we perform an EIT storage, the locking beam is blocked by an acousto-optic modulator (AOM). The leakage of the locking beam through HR_2 is detected by a photodiode (PD_1), which can generate an error signal for stabilizing the cavity length. The signal light pulse is stored in the atoms via EIT dynamics, i.e., switching off the write control light beam. After a storage time Δt, a read control pulse with a polarization orthogonal to that of the signal pulse is applied to retrieve the memory. The retrieved photons escape from the mirror PR and pass through three etalons. The etalons may significantly attenuate the power of the read laser pulse. The retrieved photons then are directed to the photodetectors $PD_{\pm}$.(Hamamatsu C5331) [see Fig. 1(a)].

For storage with the cavity, the SREs $\eta_C^{\pm}(\Delta t)$ for pulse signals of right (σ^+) and left (σ^-) circularly polarized light are defined as

$$\eta_C^{\pm}(\Delta t) = \int_{\Delta t}^{\Delta t+T} \left\langle |\varepsilon_C^{\pm out}(t)|^2 \right\rangle dt / \int_0^T \left\langle |\varepsilon_{in}^{\pm}(t)|^2 \right\rangle dt \quad (1)$$

where Δt is the storage time, T is the duration of the signal pulse, $|\varepsilon_C^{\pm out}(t)|^2$ are the intensities of the retrieved $\sigma^{\pm}$-polarized light signals, which escape from the mirror PR and are measured by the photondetectors $PD_{\pm}$ [see Fig. 1(a)], and $|\varepsilon_{in}^{\pm}(t)|^2$ denote the intensities of the $\sigma^{\pm}$-polarized light of the input signals. To show that the cavity enhances the storage, we should measure the SREs of the signal light storage without the cavity, which are express as

$$\eta_{NC}^{\pm}(\Delta t) = \int_{\Delta t}^{\Delta t+T} \left\langle |\varepsilon_{NC}^{\pm out}(t)| \right\rangle^2 dt / \int_0^T \left\langle |\varepsilon_{in}^{\pm}(t)| \right\rangle^2 dt \quad (2)$$

where $|\varepsilon_{NC}^{\pm out}(t)|^2$ are the retrieved $\sigma^{\pm}$-polarized signal light from the storage without the cavity. To measure the area $\int_{\tau}^{\tau+T} |\varepsilon_{NC}^{\pm out}(t)|^2 dt$, we remove the mirror PR and detect the retrieval signal directly after the atoms with the detectors $PD_{\pm}$. In EIT storage, the input (retrieved) pulse signal has a temporal Gaussian profile with a width of ~80 ns.

3. Experimental results

First, we demonstrate a cavity-assisted EIT storage of the σ^+-polarized signal light for a storage time $\Delta t = 0.4\ \mu s$ and an OD of 12. For this OD value and the cavity finesse F ~17 mentioned above, we evaluated the cavity cooperativity to be $Co = F \times OD \approx 200$. As shown in Fig. 2, the red dotted line denotes the input signal pulse. The pulse at $t = 0.4\ \mu s$ (the black solid line) represents the retrieved light signal that is transmitted from the mirror PR and detected by the photodetector PD_-. The black solid line pulse at $t = 0\ \mu s$ is the light signal that is reflected by the mirror PR during the storage. The input signal pulse is a reference that is measured by a detector (C5331) before the mirror PR. The detector is mounted on a flipped mirror and removed when we perform the storage and retrieval experiments. The pulses of the black solid line are detected by PD_-. The ratio between the areas of the input and retrieved pulse signals gives a SRE of ~30% for the σ^+-polarization mode.

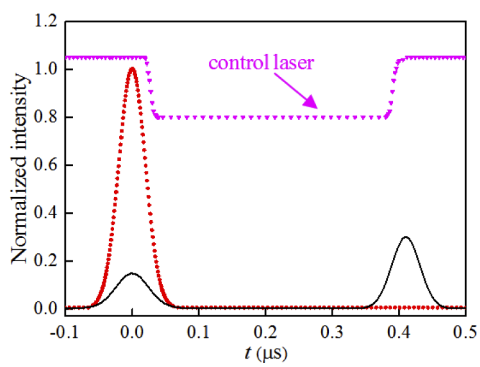

Fig. 2. EIT optical storage measurement at an OD of 12. The red dotted curve represents the input signal pulse, the black solid curve at $t = 0.4\ \mu s$ denotes the retrieved signal light pulse, and the black solid line at $t = 0\ \mu s$ is the light signal that is reflected by the mirror PR during the storage. The SRE is 30%.

We next demonstrate the storages of the $\sigma^{\pm}$- polarized pulse signal with and without the cavity, respectively. The two pulse signals come from a diagonal-line-polarization pulse signal.

Optics EXPRESS

The measured η_C^+ (η_C^-) and η_{NC}^+ (η_{NC}^-) are plotted as a function of OD [see Fig. 3(a)], by the red triangle (purple diamond) dots and blue rectangle (green circle) dots. From which we can see that the SREs $\eta_C^\pm$ ($\eta_{NC}^\pm$) are basically symmetric. In this case, we have $\eta_C^+ \approx \eta_C^- \approx \eta_C$ and $\eta_{NC}^+ \approx \eta_{NC}^- \approx \eta_{NC}$, where $\eta_C = (\eta_C^+ + \eta_C^-)/2$ and $\eta_{NC} = (\eta_{NC}^+ + \eta_{NC}^-)/2$ are the average SREs between the two polarizations. The two curves are fits to the measured results of η_C and η_{NC}, respectively, based on exponential growth functions. We can see that the SREs increase with increasing OD. The SRE η_{NC} is approximately ∼22% at an OD of 12, which is close to that reported in [39]. For storage using the cavity, the SRE η_C (purple curve) is obviously larger than η_{NC} (green curve), which shows that the cavity enhances storage. To appropriately describe such an enhancement, we calculate the cavity-enhanced factor, which is defined as the ratio $r = \eta_C/\eta_{NC}$ between the SREs with and without the cavity. Figure 3(b) plots r as a function of the OD. There is an obvious cavity enhancement when $OD < 2$, for example, $r \approx 3.1$ for $OD = 1$.

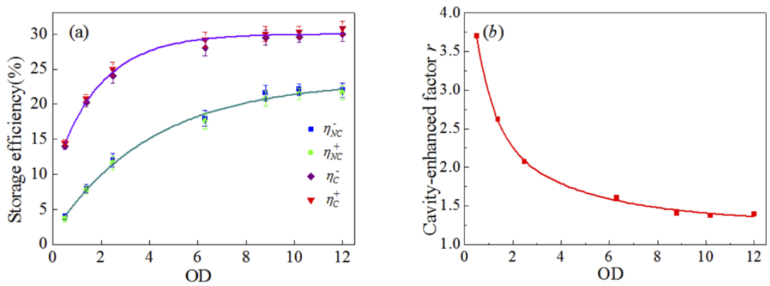

Fig. 3. (a) Measured SREs η_C^+ (η_C^-) and η_{NC}^+ (η_{NC}^-) as a function of the OD for storage with and without the cavity. η_C^+ (η_C^-) marked by red triangles (purple diamonds), η_{NC}^+ (η_{NC}^-) by blue rectangles (green circles). (b) Cavity-enhanced factor as a function of OD.

To show that the cavity-enhanced polarization storage has a long memory lifetime, we demonstrate the storages of the $\sigma^\pm$ polarizations of the signal pulses with the cavity and measure the SREs $\eta_C^\pm$ as a function of the storage time t. The measured results $\eta_C^+(\Delta t)$ and $\eta_C^-(\Delta t)$ are shown in Fig. 4 by the red square and blue circle dots, respectively. The SREs $\eta_C^+(\Delta t)$ and $\eta_C^-(\Delta t)$ are basically symmetric and approximately equal to the average SRE $\eta_C(\Delta t)$. The red solid and blue dashed lines in the figure are fits to the data $\eta_C^\pm$ using an exponential function

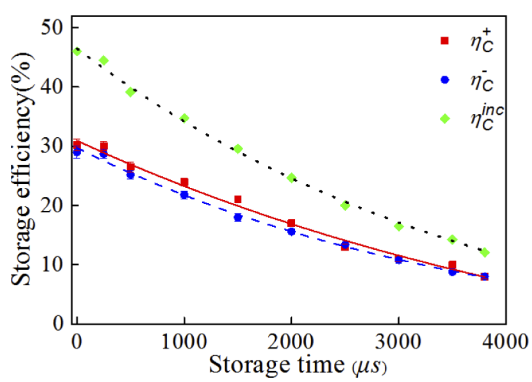

Fig. 4. SREs $\eta_C^\pm$ and the intrinsic SRE η_C^{inc} as a function of the storage time Δt. The red square and blue circle dots denote the measured η_C^+ and η_C^-, respectively. The green diamonds represent the intrinsic η_C^{inc}. The red solid, blue dashed and black dot lines indicate fits to the SREs η_C^+, η_C^- and η_C^{inc} based on the exponential function $\eta(\Delta t) = \eta_0 e^{-\Delta t/\tau}$.

$\eta_C(\Delta t) = \eta_0 e^{-\Delta t/\tau}$, which yields a coherence time $\tau = 3.5ms$. Considering that the optical loss L of the cavity will lead to additional leakages of the retrieved signal, the measured SRE η_C will be smaller than the intrinsic SRE. The intrinsic SRE is defined as $\eta_C^{inc} = \eta_C/C$ [37], where C is the output efficiency of the cavity, which equals to the fraction of the retrieved signal light that escape from the PR mirror and can be written as $C = T_{PR}/(L + T_{PR} + L_{PR})$, T_{PR} and L_{PR} are the transmission and the loss of the PR mirror. The relation of T_{PR}, L_{PR} and R is $T_{PR} + L_{PR} = 1 - R$. In the presented experiment, $L_{PR} \approx 0.3\%$, $T_{PR} \approx 1 - R - L_{PR} = 19.7\%$ and $L = 10\%$. Based on these parameters and the measured SRE $\eta_0 \approx 30\%$ at zero delay ($\Delta t \approx 0$), we calculate the output efficiency, which is $C \approx 0.66$. So, the intrinsic SRE at $\Delta t = 0$ is $\eta_C^{inc} = \eta_0/C \approx 45\%$. The green diamond dots are the intrinsic SRE (calibrated by the expression $\eta_C^{inc} = \eta_C/C$) as a function of the storage time.

4. Conclusion

By integrating the collinear model, magnetic-field-insensitive spin waves and the optical ring cavities into a single EIT storage system, we demonstrate efficient and long-lived optical memories for two orthogonal polarizations in cold atoms. The SREs for the two polarizations reach ~30% for $OD \approx 10$, which is ~ 3.7 times larger than that in the previous work [36]. The lifetime reaches 3.5 ms in the presented work, which is comparable with that in the previous work [36]. The measured SREs for two polarization modes are basically symmetric, which is important for realizing high-fidelity storage of a polarization qubit [36]. If the cavity loss $L = 10\%$ is decreased to 1%, the SRE value may be increased to its intrinsic value of $\eta_C^{inc} \simeq 45\%$. The presented memory system allows one to independently store two orthogonal polarization modes, which enable an efficient and long-lived quantum storage of polarization qubits. Also, the presented results [see Fig. 3(b)] show that the SRE may be obviously increased when the atomic OD is relative low (OD ~1), which provides an effective approach to improving the SRE for EIT storage in low-OD ensembles, such as in Rydberg atoms [40], where the SRE is ~4%. The presented work represents a key step toward the realization of an efficient and long-lived optical memory for polarization entangled photons and may find applications in scale-up quantum information networks.

Funding

Ministry of Science and Technology of the People's Republic of China (No. 2016YFA0301402); National Natural Science Foundation of China (11274211, 1147510, 11604191, 61805133); Shanxi "1331 Project" Key Subjects Construction and Innovation Team.

Disclosures

The authors declare that there are no conflicts of interest related to this article.

References

1. D. E. Browne and T. Rudolph, "Resource-efficient linear optical quantum computation," Phys. Rev. Lett. **95**(1), 010501 (2005).
2. N. Sangouard, C. Simon, J. Minář, H. Zbinden, H. de Riedmatten, and N. Gisin, "Long-distance entanglement distribution with single-photon sources," Phys. Rev. A **76**(5), 050301 (2007).
3. N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, "Quantum repeaters based on atomic ensembles and linear optics," Rev. Mod. Phys. **83**(1), 33–80 (2011).
4. H. J. Kimble, "The quantum internet," Nature **453**(7198), 1023–1030 (2008).
5. S. Abruzzo, H. Kampermann, and D. Bruß, "Measurement-device-independent quantum key distribution with quantum memories," Phys. Rev. A **89**(1), 012301 (2014).
6. M. Fleischhauer and M. D. Lukin, "Dark-state polaritons in electromagnetically induced transparency," Phys. Rev. Lett. **84**(22), 5094–5097 (2000).
7. C. Liu, Z. Dutton, C. H. Behroozi, and L. V. Hau, "Observation of coherent optical information storage in an atomic medium using halted light pulses," Nature **409**(6819), 490–493 (2001).

8. D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, "Storage of light in atomic vapor," Phys. Rev. Lett. **86**(5), 783–786 (2001).
9. A. Kuzmich, W. P. Bowen, A. D. Boozer, A. Boca, C. W. Chou, L.-M. Duan, and H. J. Kimble, "Generation of nonclassical photon pairs for scalable quantum communication with atomic ensembles," Nature **423**(6941), 731–734 (2003).
10. K. S. Choi, H. Deng, J. Laurat, and H. J. Kimble, "Mapping photonic entanglement into and out of a quantum memory," Nature **452**(7183), 67–71 (2008).
11. K. F. Reim, J. Nunn, V. O. Lorenz, B. J. Sussman, K. C. Lee, N. K. Langford, D. Jaksch, and I. A. Walmsley, "Towards high-speed optical quantum memories," Nat. Photonics **4**(4), 218–221 (2010).
12. K. F. Reim, P. Michelberger, K. C. Lee, J. Nunn, N. K. Langford, and I. A. Walmsley, "Single-photon-level quantum memory at room temperature," Phys. Rev. Lett. **107**(5), 053603 (2011).
13. H. de Riedmatten, M. Afzelius, M. U. Staudt, C. Simon, and N. Gisin, "A solid state light-matter interface at the single photon level," Nature **456**(7223), 773–777 (2008).
14. C. Clausen, I. Usmani, F. Bussières, N. Sangouard, M. Afzelius, H. de Riedmatten, and N. Gisin, "Quantum storage of photonic entanglement in a crystal," Nature **469**(7331), 508–511 (2011).
15. E. Saglamyurek, N. Sinclair, J. Jin, J. A. Slater, D. Oblak, F. Bussières, M. George, R. Ricken, W. Sohler, and W. Tittel, "Conditional detection of pure quantum states of light after storage in a tm-doped waveguide," Phys. Rev. Lett. **108**(8), 083602 (2012).
16. G. Hétet, M. Hosseini, B. M. Sparkes, D. Oblak, P. K. Lam, and B. C. Buchler, "Photon echoes generated by reversing magnetic field gradients in a rubidium vapor," Opt. Lett. **33**(20), 2323–2325 (2008).
17. M. Hosseini, G. Campbell, B. M. Sparkes, P. K. Lam, and B. C. Buchler, "Unconditional room-temperature quantum memory," Nat. Phys. **7**(10), 794–798 (2011).
18. Y. W. Cho, G. T. Campbell, J. L. Everett, J. Bernu, D. B. Higginbottom, M. T. Cao, J. Geng, N. P. Robins, P. K. Lam, and B. C. Buchler, "Highly efficient optical quantum memory with long coherence time in cold atoms," Optica **3**(1), 100 (2016).
19. C. Simon, "Towards a global quantum network," Nat. Photonics **11**(11), 678–680 (2017).
20. A. V. Gorshkov, A. André, M. D. Lukin, and A. S. Sørensen, "Photon storage in -type optically dense atomic media. II. Free-space model," Phys. Rev. A **76**(3), 033805 (2007).
21. R. Zhang and X. B. Wang, "Storage efficiency of probe pulses in an electromagnetically-induced-transparency medium," Phys. Rev. A **94**(6), 063856 (2016).
22. A. V. Gorshkov, A. André, M. D. Lukin, and A. S. Sørensen, "Photon storage in -type optically dense atomic media. I. Cavity model," Phys. Rev. A **76**(3), 033804 (2007).
23. Y. F. Hsiao, P. J. Tsai, H. S. Chen, S. X. Lin, C. C. Hung, C. H. Lee, Y. H. Chen, Y. F. Chen, I. A. Yu, and Y. C. Chen, "Highly efficient coherent optical memory based on electromagnetically induced transparency," Phys. Rev. Lett. **120**(18), 183602 (2018).
24. P. V. Gris, K. Huang, M. Cao, A. S. Sheremet, and J. Laurat, "Highly-efficient quantum memory for polarization qubits in a spatially-multiplexed cold atomic ensemble," Nat. Commun. **9**(1), 363 (2018).
25. Y. F. Wang, J. F. Li, S. C. Zhang, K. Y. Su, Y. R. Zhou, K. Y. Liao, S. W. Du, H. Yan, and S. L. Zhu, "Efficient quantum memory for single-photonpolarization qubits," Nat. Photonics **13**(5), 346–351 (2019).
26. M. P. Hedges, J. J. Longdell, Y. Li, and M. J. Sellars, "Efficient quantum memory for light," Nature **465**(7301), 1052–1056 (2010).
27. D. Schraft, M. Hain, N. Lorenz, and T. Halfmann, "Stopped light at high storage efficiency in a Pr3+:Y2SiO5 crystal," Phys. Rev. Lett. **116**(7), 073602 (2016).
28. M. Afzelius and C. Simon, "Impedance-matched cavity quantum memory," Phys. Rev. A **82**(2), 022310 (2010).
29. M. Sabooni, Q. Li, S. Kröll, and L. Rippe, "Efficient quantum memory using a weakly absorbing sample," Phys. Rev. Lett. **110**(13), 133604 (2013).
30. P. Jobez, I. Usmani, N. Timoney, C. Laplane, N. Gisin, and M. Afzelius, "Cavity-enhanced storage in an optical spin-wave memory," New J. Phys. **16**(8), 083005 (2014).
31. P. Jobez, C. Laplane, N. Timoney, N. Gisin, A. Ferrier, P. Goldner, and M. Afzelius, "Coherent spin control at the quantum level in an ensemble-based optical memory," Phys. Rev. Lett. **114**(23), 230502 (2015).
32. G. Heinze, C. Hubrich, and T. Halfmann, "Stopped light and image storage by electromagnetically induced transparency up to the regime of one minute," Phys. Rev. Lett. **111**(3), 033601 (2013).
33. J. J. Longdell, E. Fraval, M. J. Sellars, and N. B. Manson, "Stopped light with storage times greater than one second using electromagnetically induced transparency in a solid," Phys. Rev. Lett. **95**(6), 063601 (2005).
34. U. Schnorrberger, J. D. Thompson, S. Trotzky, R. Pugatch, N. Davidson, S. Kuhr, and I. Bloch, "Electromagnetically induced transparency and light storage in an atomic mott insulator," Phys. Rev. Lett. **103**(3), 033003 (2009).
35. R. Zhang, S. R. Garner, and L. V. Hau, "Creation of long-term coherent optical memory via controlled nonlinear interactions in Bose-Einstein condensates," Phys. Rev. Lett. **103**(23), 233602 (2009).
36. Z. Xu, Y. Wu, L. Tian, L. Chen, Z. Zhang, Z. Yan, S. Li, H. Wang, C. Xie, and K. Peng, "Long lifetime and high-fidelity quantum memory of photonic polarization qubit by lifting zeeman degeneracy," Phys. Rev. Lett. **111**(24), 240503 (2013).
37. X.-H. Bao, A. Reingruber, P. Dietrich, J. Rui, A. Dück, T. Strassel, L. Li, N.-L. Liu, B. Zhao, and J.-W. Pan, "Efficient and long-lived quantum memory with cold atoms inside a ring cavity," Nat. Phys. **8**(7), 517–521 (2012).

Optics EXPRESS

38. M. Afzelius, N. Gisin, and H. de Riedmatten, "Quantum memory for photons," Phys. Today **68**(12), 42–47 (2015).
39. Y. H. Chen, M. J. Lee, I. C. Wang, S. W. Du, Y. F. Chen, Y. C. Chen, and I. A. Yu, "Coherent optical memory with high storage efficiency and large fractional delay," Phys. Rev. Lett. **110**(8), 083601 (2013).
40. D. Maxwell, D. J. Szwer, D. P. Barato, H. Busche, J. D. Pritchard, A. Gauguet, K. J. Weatherill, M. P. A. Jones, and C. S. Adams, "Storage and control of optical photons using Rydberg polaritons," Phys. Rev. Lett. **110**(10), 103001 (2013).