

Fidelity of light storage in warm atomic gases at different storage time

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The fidelity of light with arbitrary polarizations stored in a warm ⁸⁷Rb atomic vapor at different storage time is studied. The exponential decay of regeneration efficiency with the storage time is observed and a detectable signal at 300- μ s storage time is still existed. The storage fidelity at different storage time is well maintained in our experiment.

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Light storage and recovery in an atomic ensemble are very promising ways for the development of the future quantum memory^[1]. Recently, mapping a polarization state of light onto an atomic spin state via electromagnetically induced transparency (EIT)^[2] has been proposed^[3–6] and demonstrated^[7–9]. A photon polarization state is a physical realization of a quantum bit (qubit). The general description of a qubit, $\alpha|1\rangle + \beta|0\rangle$, can be mapped onto the Bloch sphere, which covers all possible completely polarized states.

Light storage combines the technique of ultraslow light group velocity^[10] and EIT effect, which are both caused by the resonant or near resonant interaction between light and a Λ -type atom (Fig. 1 (a)). Typically, we use a control light to make an opaque medium become transparent near atomic resonance. Then an orthogonal polarized weak optical field (signal field) can propagate without much absorption but with a substantially reduced group velocity. In the same time a mixture of light field and collective atomic excitation of spin transitions, known as dark-state polariton, can be generated. Turn off the control field smoothly, the signal field is converted to a purely atomic spin-wave polariton and the quantum state of the signal field is then transferred to the atoms. We turn on the control field again after a time interval, the stored signal field then can be released out.

The storage of arbitrary polarized lights with a good fidelity in the atomic ensembles has also been demonstrated recently^[11]. This leads to a possible way to expand current technologies to apply in photonic quantum memory or quantum repeater. However, for any quantum memory, the stored signal amplitude and phase will suffer from atomic depolarization and decoherence processes^[1,12]. Depolarization deteriorates the atomic spin state hence affects the regenerate signal efficiency. Depolarization is caused by the collisions of the target atoms with the cell walls or with other atoms and by external fields such as the leakage of the Earth's magnetic field. Decoherence destroys the phase relation of atomic coherent spin state and hence affects the re-

generate signal fidelity. Decoherence is caused by the aforementioned effects as well as additional ones, including Doppler broadening and inhomogeneous magnetic fields^[13,14]. So it is important to know that how the stored signal amplitude and fidelity change during the depolarization and decoherence processes in the light storage experiment.

Since atom keeps colliding with glass cell, clearly both the atomic depolarization and decoherence are affected with the storage time. In this letter, we report an experimental study on the regeneration signal efficiency and the fidelity of polarized light stored in a warm ⁸⁷Rb atomic ensemble at different storage times. We find the regeneration efficiency of light storage is exponential decay with the increasing storage time, however the fidelity can still be well maintained as long as one has detectable storage signal.

The experimental setup is similar to the one in Ref. [11], as shown in Fig. 1(b) for convenience. An extended cavity diode laser with linewidth less than 300 kHz is used as a source. An acoustic-optical modulator (AOM) and an iris allow for rapid switching of this source. The linearly polarized laser light can be slightly rotated by a fast Pockel's cell to create a weak pulse, which is the signal field (I_s , y -direction). The polarization of the weak pulse is perpendicular to that of the remaining light, which serves as the control field (I_c , x -direction). Two polarizing beam splitters (PBS) are used to comprise a Mach-Zender interferometer, and separate the control and signal beams, make them pass different paths, and recombine them. A piezo-electric transducer (PZT) is connected to the reflector in the signal path giving a phase shift between the two paths. The cell temperature is maintained at about 80 °C, corresponding to an atomic density of $\sim 10^{12}$ /cm³. In order to avoid the magnetic field caused by heater cable, we use a AerObiax heater cable, which is wired the forward and backward line together. The residual earth magnetic field inside magnetic shielding is about 2 mG. We do not find any obvious magnetic field generated from the heater. More detailed description of experimental setup can also be

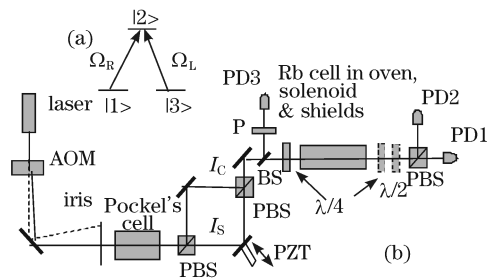


Fig. 1. (a) Schematic of a Λ -system of ^{87}Rb atomic states resonantly coupled to a right circularly polarized light (Ω_R) and left circularly polarized light (Ω_L). (b) Schematic of the experimental setup. BS: beam splitter; P: polarizer.

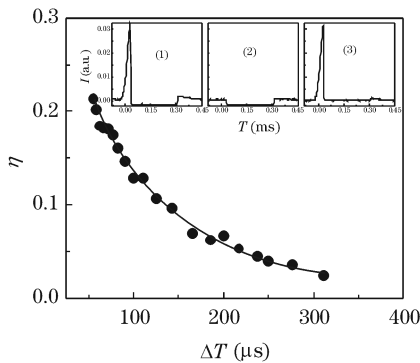


Fig. 2. Light storage regeneration efficiency as a function of storage time. Insets show a typical sequence of light storage experiment at storage time about 300 μs : (1) a combined detected signal with control and signal beams; (2) a control beam leakage to the detector; (3) the light storage signal obtained by subtracting (2) from (1).

found in Refs. [11, 15].

A PBS and two photodiodes (PD) comprise the detection system. To create the EIT effect, the laser frequency is adjusted to the D1 transition of ^{87}Rb ($\lambda \cong 795 \text{ nm}$), i.e., $5S_{1/2}$, $F = 2 \rightarrow 5P_{1/2}$, and $F = 1$, which is checked by observing the fluorescence spectrum. We can observe the EIT effect when the signal light is totally absorbed by blocking the control light. The maximum EIT transition in our experiment is about 70%. For the light storage experiment, the time sequence of the control and signal fields is the same as the one in Refs. [7, 11, 15].

We first study the dependence of the light regeneration efficiency on the storage time. Light storage efficiency (η) is defined as the ratio of the maximum light intensity between post- and pre-storage (output and input) after subtracting the leakage from the control beam. The leakage from the control beam is obtained by blocking the signal beam. This experiment is done using the linearly polarized control and signal light, which is produced after a commercial PBS (Extinction ratio $> 500:1$). The experimental results at different storage times are shown in Fig. 2. It can be seen that the efficiency exponentially decays due to the atomic depolarization process. We find there is still a detectable regenerated signal after 300- μs storage time. The solid line in Fig. 2 is the exponential decay fitting to the experimental data and it gives the storage time about 100 μs . The insets show a typical sequence to get the light storage signal at storage time of $\sim 300 \mu\text{s}$.

We then perform to store some elliptical polarized lights and measure their fidelities. A certain elliptical polarized light can be generated by using a $\lambda/4$ -plate. We modulate the PZT to find the maximum and minimum interference intensities of regenerated signal, which are measured by PD1. By placing a $\lambda/2$ -plate before PD1 at 0° and 45° , we can determine both field components of the regenerated signal light on knowing the control light intensity of each component. These components can be determined by blocking the signal field.

We can determine the relative phase between the regenerated signal field and the control field by adjusting the PZT induced phase shift to zero, as determined from an interference pattern observed before the first $\lambda/4$ -plate (at PD3). We can also obtain the relative phase between the control light components by blocking the signal light and adding the second $\lambda/4$ -plate and $\lambda/2$ -plate to the system, just before the PBS and detectors. Each of the Stokes parameters of the control light can be directly determined from the detected light intensity, simply by rotating the $\lambda/4$ and $\lambda/2$ -plates. The relative phase of the two control field components can then be calculated from these Stokes parameters. Thus the relative phase of the two regenerated signal field components can finally be determined.

The normalized regenerated signal field components and their relative phase are shown in Fig. 3. The solid lines are the theoretical prediction by considering the effect of paramagnetic Faraday rotation effect^[16,17] due to the population asymmetry in the magnetic sub-state of Λ -systems at different $\lambda/4$ -plate rotation angles. This effect is estimated by calculating the populations from rate equations at different $\lambda/4$ -plate rotation angles, and described as

$$\begin{aligned} \dot{n}_1 &= \Omega_R(n_2 - n_1) + \frac{\Gamma}{2}n_2, \\ \dot{n}_2 &= \Omega_R(n_1 - n_2) + \Omega_L(n_3 - n_2) - \Gamma n_2, \\ \dot{n}_3 &= \Omega_L(n_2 - n_3) + \frac{\Gamma}{2}n_2, \end{aligned} \quad (1)$$

where Ω_R and Ω_L are the Rabi frequency of right and left circularly polarized signal light, n_i is the atomic relative population of i level, Γ is the natural line width of upper level. The initial conditions for solving the equations are $n_1 = n_3 = 0.5$ and $n_2 = 0.0$. Equation (1) are solved when relative population approaches steady state. The time length is found usually about 1 μs which is much shorter than the signal pulse duration ($> 10 \mu\text{s}$). Since the cell is shield by the magnetic field, the optical rotation is dominated by the paramagnetic Faraday effect, and yields the Rb polarization as^[16]

$$P_{\text{Rb}} = \frac{56\pi\Delta\phi\delta}{3NLF\lambda^2}, \quad (2)$$

where P_{Rb} is defined as

$$P_{\text{Rb}} = \frac{n_3 - n_1}{n_3 + n_1}, \quad (3)$$

δ is the signal light detuning, L and N are the glass cell length and total atomic number, respectively. Since the laser is unlocked with the hyperfine splitting of $5P_{1/2}$, $F = 1$ and $F = 2$ can not be identified from

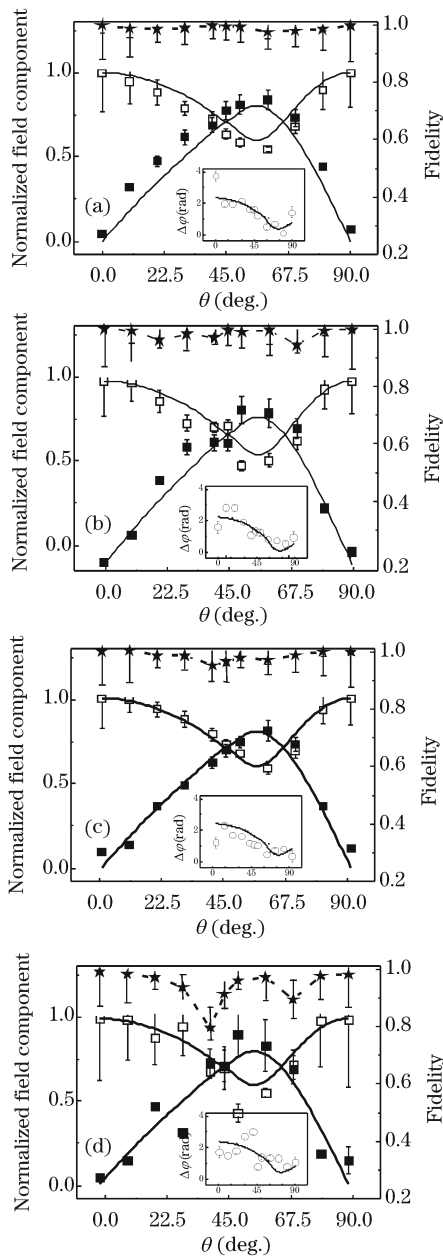


Fig. 3. Dependence of the regenerated signal field components E_x (\square) and E_y (\blacksquare), and their relative phase $\Delta\varphi$ (\circ) on the input polarizations ranging from linear ($\theta = 0^\circ$), through elliptical and circular ($\theta = 45^\circ$), and back to linear ($\theta = 90^\circ$). θ is the rotation angle of the $\lambda/4$ -plate. Storage times are (a) 55, (b) 100, (c) 150, and (d) 200 μs . The fidelity (\star) is calculated and the dashed line is a guide to the eye.

the Doppler broaden fluorescence spectrum, we estimate δ is about 800 MHz. The optical rotation angle $\Delta\phi$ can be determined by solving Eqs. (1)-(3). The regenerated signal field components and their relative phase can then be recalculated.

The comparison of the theoretical calculation results with the experimental data points and the calculated fidelity^[1] are also shown in Fig. 3. The fidelity is defined as usual as $F = |\langle\psi_{\text{out}}|\psi_{\text{in}}\rangle|$ for a pure state, or more specifically for our system as $F = |\mathbf{E}_{\text{out}}^* \cdot \mathbf{E}_{\text{in}}|$. Faraday

rotation also causes the data to be asymmetric around the $\lambda/4$ 45° setting. We find that all the polarization states are well maintained within a longer storage time although the regenerated signal efficiency decays exponentially. This property makes sense since the fidelity is not governed by signal amplitude. The fidelity begins to decrease after 200 μs mostly due to the small signal-to-noise ratio.

In conclusion, we demonstrate the fidelity can be maintained for an arbitrary polarized light stored in a warm ^{87}Rb atomic vapor with the increasing storage time. The properties guarantee that the fidelity of stored light polarized state is not strongly affected by its amplitude decay, which is important for its future applications. In addition, as mentioned in Ref. [11], by noticing the highly symmetric nature of our storage system (cylindrically symmetric, and parity transformation), our data for rotating the $\lambda/4$ -plate from 0° to 45° are equivalent for any other polarized lights. Thus all other polarized lights have the same properties.

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