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Quantum interference of stored dual-channel spin-wave excitations in a single tripod system

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We present an experimental demonstration of dual-channel memory in a single tripod atomic system. The total readout signal exhibits either constructive or destructive interference when the dual-channel spin-wave excitations (SWEs) are retrieved by two reading beams with a controllable relative phase. When the two reading beams have opposite phases, the SWEs will remain in the medium, which can be retrieved later with two in-phase reading beams. Such a phase-sensitive storage and retrieval scheme can be used to measure and control the relative phase between the two SWEs in the memory medium, which may find applications in quantum-information processing.

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I. INTRODUCTION

The recently developed techniques of electromagnetically induced transparency (EIT) or Raman two-photon manipulation have allowed researchers to store photons in atomic ensembles and then retrieve them at a later time. Such techniques have been successfully applied in quantum memories, which are essential elements in long-distance quantum networks [1,2]. In a typical EIT three-level Λ-type atomic system, photons can be transferred into a single-channel collective spin-wave excitation (SWE) or atomic coherence (Zeeman coherence) by switching off the writing laser beam and retrieved by switching on a reading laser beam at a later time, which can be well described by the dark-state polariton (DSP) dynamics [3]. In the quantum or optical signal storage experiments with the atoms prepared into a three-level Λ-type system, one-channel spin coherence is involved and the retrieved signal exhibits a monotonic decay with a storage time in the milliseconds time scale in a cold atomic cloud [4,5], and in the second time scale in an atomic lattice [6] or Bose-Einstein condensate (BEC) [7]. In most atomic memory experiments [8,9], the atomic system includes multiple Λ-type subsystems and thus DSPs include many different Zeeman coherences. In the qubit memory, two collective SWEs are used for the two basis states [10,11], which typically include more than two Zeeman coherences. Since different Zeeman coherences have different Larmor precession periods, the DSPs will experience a "collapse and revival" phenomenon [12] due to the interference between the multiple SWEs. Such a phenomenon has been observed experimentally [12], which indicates that the stored signal may not be retrieved at the "collapse" period.

Recently, the schemes of dual-channel storage, i.e., storing an optical signal simultaneously into two adjacent SWEs in the four-level inverted-Y [13] or tripod [14] atomic configuration have been proposed, in which the manipulation of the storing and release of the optical signals can be well described by the generalized dark-state polariton (GDSP) dynamics [13,14]. An earlier experiment with one writing or reading beam and two signal beams in a tripod atomic system has shown resonant beating in the readout signal due to the lifted Zeeman sublevel degeneracy of the ground states in a magnetic field [15].

II. THEORETICAL MODEL

In this work, we experimentally demonstrate a dual-channel memory with the retrieval efficiency varying with the relative phase between the two reading light beams in a single four-level tripod system, as shown in Fig. 1. The weak signal beam (P) is simultaneously stored in the dual-channel coherent SWEs ($\tilde{\sigma}_{ca}$ and $\tilde{\sigma}_{ba}$) by switching off the two circularly polarized writing beams, and then read at a later time by switching on two circularly polarized beams (R^+, R^-) with a certain relative phase $\delta_R = \varphi_R^+ - \varphi_R^-$. Since quantum interference is induced by the light-matter interaction between the two stored collective SWEs, the total readout signal shows a maximum or minimum value depending on the relative phase δ_R between the two reading light beams. By varying δ_R, the total readout signal shows a sinusoidal interference pattern.

Before presenting the experimental results, we first give a simple theoretical description of the optical storage and retrieval processes in the tripod system using the generalized DSP concept [13], which is modified to fit the current experimental situation. The two quantum fields $\hat{\Psi}(z,t)$ and $\hat{\Phi}(z,t)$, defined as the superpositions of the quantized optical field $\hat{\varepsilon}_p(z,t)$ and the collective spin-wave component $\hat{S}(z,t)$, can be written as [3,13]

$$\hat{\Psi}(z,t) = \cos\theta(t)\hat{\varepsilon}_p(z,t) - \sin\theta(t)\sqrt{N}\hat{S}(z,t), \tag{1a}$$

$$\hat{\Phi}(z,t) = \sin\theta(t)\hat{\varepsilon}_p(z,t) + \cos\theta(t)\sqrt{N}\hat{S}(z,t). \tag{1b}$$

The mixing angle is defined as $\tan\theta(t) = g\sqrt{N} / \sqrt{|\Omega_C^+(t)|^2 + |\Omega_C^-(t)|^2}$; $|\Omega_C^+(t)|$ and $|\Omega_C^-(t)|$ (C denotes W or R) are the amplitudes of the Rabi frequencies for the right- and left-circularly-polarized writing (W^+ and W^-) or reading (R^+ and R^-) beams, respectively. $\hat{\Psi}(z,t)$ is immune to spontaneous emission and is called the GDSP [13], while $\hat{\Phi}(z,t)$ corresponds to the bright state and is called the generalized bright-state polariton (GBSP) [13]. Both generalized polaritons can be decomposed using the plane waves,

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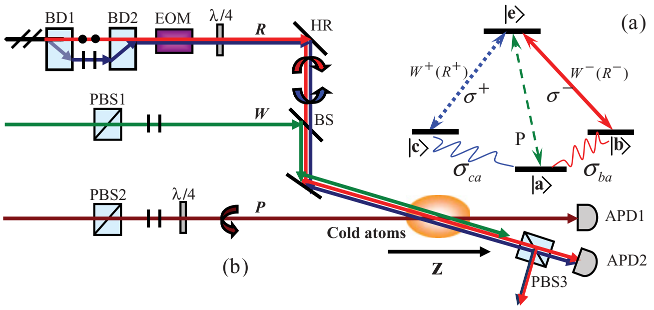

FIG. 1. (Color online) (a) Experimental setup. EOM: electronic optical modulator. BD1 and BD2: beam displacing polarizers. PBS1–PBS3: polarization beam splitters, the angle of the orientation of PBS3 from the horizontal (p) direction (same as the orientation of PBS1 and PBS2) is 45°; APD1 and APD2: avalanche photodetectors. The symbols "$\ldots$," "$\|$," "$//$," "↶," and "↷" denote the vertical, horizontal, 45°-angle-to-horizontal, left- and right-circular polarizations, respectively. The polarization of PBS3 is along the orientation with (or at) 45° angle to the horizontal polarization. (b) The scheme of a four-level tripod system of ^{87}Rb atom. $|a\rangle$ is the $|5S_{1/2},F=1,m=+1\rangle$ state; $|b\rangle$ and $|c\rangle$ are the $|5S_{1/2},F=2,m=+1\rangle$ and $|5S_{1/2},F=2,m=-1\rangle$ states, respectively; and $|e\rangle$ is the $|5P_{1/2},F'=1,m=0\rangle$ state.

i.e., $\hat\Psi(z,t)=\sum_k \hat\Psi_k(t)e^{ikz}$ and $\hat\Phi(z,t)=\sum_k \hat\Phi_k(t)e^{ikz}$. In the limit of photon number density that is much smaller than the atomic density, i.e., $\hat\sigma_{aa}\approx 1$, $\hat\sigma_{cc}\approx 0$, $\hat\sigma_{bb}\approx 0$, and $\hat\sigma_{cb}\approx 0$, $\hat\Psi(z,t)$ and $\hat\Phi(z,t)$ obey the following bosonic commutation relations [13]:

$$[\psi_k,\psi_{k'}^\dagger]\approx[\Phi_k,\Phi_{k'}^\dagger]\approx\delta_{k,k'},\quad [\psi_k,\Phi_{k'}^\dagger]\approx 0. \tag{2}$$

The spin wave $\hat S(z,t)$ is the superposition of the two SWEs, and is defined as

$$\hat S(z,t)=\cos\Theta e^{-i\varphi_C^+}\tilde\sigma_{ca}(z,t)+\sin\Theta e^{-i\varphi_C^-}\tilde\sigma_{ba}(z,t). \tag{3}$$

Another composite spin wave $D(z,t)$, as introduced in Ref. [14], is orthogonal to $\hat S(z,t)$and given by

$$\hat D(z,t)=\sin\Theta e^{-i\varphi_C^+}\tilde\sigma_{ca}(z,t)-\cos\Theta e^{-i\varphi_C^-}\tilde\sigma_{ba}(z,t), \tag{4}$$

where φ_C^+ and φ_C^- are the phases of the writing (W^+ and W^-) or reading (R^+ and R^-) fields. $\tilde\sigma_{\beta\alpha}$ ($\beta=b$ or c, $\alpha=a$) is the collective atomic spin operator [12], defined as $\tilde\sigma_{\beta\alpha}(z,t)=\frac{1}{N_z}\sum_{z_j\in N_z}\tilde\sigma_{\beta\alpha}^j(t)$ ($\tilde\sigma_{\beta\alpha}^j=\hat\sigma_{\beta\alpha}^j\exp[i(\omega_{\alpha\beta}/c)(z-ct)]$ with $\hat\sigma_{\beta\alpha}^j=|\beta_j\rangle\langle\alpha_j|$ being the spin flip operator); $N_z(\gg 1)$ is the number of atoms in an interval Δz along the propagation direction. The interval Δz is assumed to be small enough, so that the (slowly varying) amplitude of the quantized (signal) light field does not significantly change in it [3,13]. The mixing angle Θ is defined as $\tan\Theta=\Omega_C^-(t)/\Omega_C^+(t)$. We assume that the ratio $\Omega_C^-(t)/\Omega_C^+(t)$ (i.e., Θ) is kept constant during the storage and release processes. In the first-order approximation, the operators $\hat\Psi(z,t)$, $\hat S(z,t)$,and $\hat D(z,t)$ obey the following bosonic commutation relations [14]:

$$\begin{aligned}[\psi(z,t),\psi^\dagger(z',t)]&=[D(z,t),D^\dagger(z',t)]\\&=[S(z,t),S^\dagger(z',t)]=g^2L\delta(z-z'),\end{aligned} \tag{5a}$$

$$[\psi(z,t),D^\dagger(z',t)]=0,\quad [S(z,t),D^\dagger(z',t)]=0. \tag{5b}$$

When the two writing (W^+ and W^-) beams [with $|\Omega_W^+(t)|=|\Omega_W^-(t)|$] are adiabatically turned off over the time interval $[t_{0,}t_1]$, the mixing angle$\theta\rightarrow\pi/2$ and the input signal field $\hat\varepsilon_P^{\text{in}}(z,t)$ is mapped onto $\hat S(z,t)$, i.e., simultaneously stored in the dual-channel collective SWEs ($\tilde\sigma_{ca}$ and $\tilde\sigma_{ba}$) with the relative phase information ($\delta_w=\varphi_w^+-\varphi_w^-$) imprinted into the atomic ensemble. Ŝ(z,t) in the writing stage can be written as

$$\hat S_w(z,t_1)=\cos\Theta_w\tilde\sigma_{ca}(z,t_1)e^{-i\varphi_w^+}+\sin\Theta_w\tilde\sigma_{ba}(z,t_1)e^{-i\varphi_w^-}. \tag{6}$$

The ratio of $\tilde\sigma_{ca}/\tilde\sigma_{ba}$ can be solved in the lowest nonvanishing order from the Heisenberg-Langevin equations for the four-level system to be

$$\tilde\sigma_{ca}^{(1)}/\tilde\sigma_{ba}^{(1)}=\Omega_C^{+^*}/\Omega_C^{-^*}. \tag{7}$$

Using the GDSP dynamical relation $\hat\varepsilon_P^{\text{in}}\rightarrow\hat S_w$ and the above equation (7), we obtain

$$\tilde\sigma_{ca}(z,t_1)\propto\cos\Theta_w\varepsilon_P^{\text{in}}(z-z_{01},t_0)\,e^{i\varphi_W^+}, \tag{8a}$$

$$\tilde\sigma_{ba}(z,t_1)\propto\sin\Theta_w\varepsilon_P^{\text{in}}(z-z_{01},t_0)\,e^{i\varphi_W^-}, \tag{8b}$$

where $\varepsilon_P^{\text{in}}(z-z_{01},t_0)$ is the slowly-varying amplitude of the input signal field at $z-z_{01}$ $[z_{01}=\int_{t_0}^{t_1}dt'v_g(t')]$ and time $t=t_0$. In the writing stage, $\hat{\text{D}}_w(z,t)$ can be calculated by introducing the expressions of $\tilde\sigma_{ba}(z,t_1)$ and $\tilde\sigma_{ca}(z,t_1)$ [Eq. (8)] into Eq. (4), and is found to be zero, which means that the GDSP $\hat\Psi(z,t)$ cannot be converted into $\hat D(z,t)$ in the writing stage.

In a finite magnetic field, the atomic spin coherences $\tilde\sigma_{ba}(z,t_1)$ and $\tilde\sigma_{ca}(z,t_1)$ experience a Larmor precession, and after a storage time interval of $\tau=t_2-t_1$, they then become

$$\tilde\sigma_{ca}(z,t_2)\propto\cos\Theta_w\varepsilon_P^{\text{in}}(z-z_{01},t_0)e^{i\varphi_W^+}, \tag{9a}$$

$$\tilde\sigma_{ba}(z,t_2)\propto\sin\Theta_w\varepsilon_P^{\text{in}}(z-z_{01},t_0)e^{i\varphi_W^-+i2\Omega_L\tau}. \tag{9b}$$

$\Omega_L=g_F\mu_BB/\hbar$ is the Larmor precession frequency. At the time t_2, if two reading beams are switched on to read the dual-channel SWEs stored in the tripod atomic medium, $\hat S(z,t)$ and $D(z,t)$ become

$$\hat S_R(z,t_2)=\cos\Theta_R\tilde\sigma_{ca}(z,t_2)e^{-i\varphi_R^+}+\sin\Theta_R\tilde\sigma_{ba}(z,t_2)e^{-i\varphi_R^-}, \tag{10a}$$

$$\hat D_R(z,t_2)=\sin\Theta_R\tilde\sigma_{ca}(z,t_2)e^{-i\varphi_R^+}-\cos\Theta_R\tilde\sigma_{ba}(z,t_2)e^{-i\varphi_R^-}. \tag{10b}$$

According to the GDSP dynamics, in the reading stage $[\cos\theta(t)\rightarrow 1]$, $\hat S_R(z,t_2)$ will be turned into the released optical signal, while$\hat D_R(z,t_2)$ will still remain in the atomic ensemble [14]. For this reason, we call $\hat S_R(z,t_2)$ the "active spin-wave polariton" and $\hat D_R(z,t_2)$ the "dormant spin-wave polariton."

Equation (10) shows the relations among $\hat S_R(z,t_2)$, $\hat D_R(z,t_2)$, $\tilde\sigma_{\text{ba}}(z,t_1)$, and $\tilde\sigma_{\text{ca}}(z,t_1)$ in the retrieval process of the dual-channel SWEs. The behavior described in Eq. (10) can be considered as an analog of splitting light beams. We define $\langle N_S\rangle=\int_0^l|\hat S_R(z-z_{02},t_2)|^2dz$ and $\langle N_D\rangle=\int_0^l|\hat D_R(z-z_{02},t_2)|^2dz$ (where l is the length of the atomic ensemble), which correspond to the number of the "active spin-wave polariton" and the number of the "dormant spin-wave polariton," respectively. From Eq. (10), we can easily obtain the following relation:

$$\langle N_S\rangle + \langle N_D\rangle = \langle|\tilde{\sigma}_{ca}(t_2)|^2\rangle + \langle|\tilde{\sigma}_{ba}(t_2)|^2\rangle, \tag{11}$$

where $\langle|\hat{\sigma}_{ba}(t_2)|^2\rangle = \int_0^l |\tilde{\sigma}_{ba}(z,t_2)|^2 dz$ and $\langle|\hat{\sigma}_{ca}(t_2)|^2\rangle = \int_0^l |\tilde{\sigma}_{ca}(z,t_2)|^2 dz$. In the case of $\sigma_{aa} \approx 1$, $\langle|\hat{\sigma}_{ba}(t_2)|^2\rangle$ $[\langle|\hat{\sigma}_{ca}(t_2)|^2\rangle]$ can be viewed as the number of the excitations in the state $|b\rangle$ ($|c\rangle$). The above relation shows that the sum of the photon number in the released optical signal and the number of collective excitations still remaining in the atomic ensemble is equal to the total number of collective excitations originally stored in the atomic ensemble.

Under the current situation, we calculate the total signal retrieved from the dual-channel SWEs. With experimental parameters $\Omega_w^-(t) = \Omega_w^+(t)$, $\Omega_R^-(t) = \Omega_R^+(t)$, and $\cos\Theta_w = \sin\Theta_w = \cos\Theta_R = \sin\Theta_R = 1/\sqrt{2}$, $\hat{S}_R(z,t)$ can be calculated from Eqs. (9) and (10) as

$$\tilde{S}_R(z - z_{02},t_2) \propto \tfrac{1}{2}\varepsilon_P^{\text{in}}(z - z_0,t_0)\,(e^{-i\delta_R + i\delta_W - i2\Omega_L\tau} + 1). \tag{12}$$

At the reading stage ($\theta \approx 0$) and according to the GDSP dynamics of $\hat{S}(z,t) \rightarrow \varepsilon_P^{\text{out}}(z,t)$, the total retrieved signal field can be expressed as

$$\begin{aligned}\varepsilon_P^{\text{out}}(z,t) &\propto \tilde{S}_R(z - z_{02},t_2)\\ &\propto \tfrac{1}{2}\varepsilon_P^{\text{in}}(z - z_0,t_0)\,(e^{-i\delta_R + i\delta_W - i2\Omega_L\tau} + 1),\end{aligned} \tag{13}$$

where $z_{02} = \int_{t_2}^{t} v_g(t')dt'$, $z_0 = z_{01} + z_{02}$, $\delta_R = \varphi_R^+ - \varphi_R^-$, and $\delta_w = \varphi_w^+ - \varphi_w^-$.

The individual signal $\varepsilon_{P+}^{\text{out}}$ or $\varepsilon_{P-}^{\text{out}}$ corresponds to the optical field retrieved separately from each of the dual memory channels ($\tilde{\sigma}_{ca}$ and $\tilde{\sigma}_{ba}$) with only one reading beam (R^+ or R^-). Under the conditions of $\theta \approx 0$, $\Omega_w^-(t) = \Omega_w^+(t)$, and $\Omega_R^-(t) = 0$ or $\Omega_R^+(t) = 0$, the retrieved signals can be calculated according to the GDSP dynamics as

$$\varepsilon_{P+}^{\text{out}}(z,t) \propto \frac{1}{\sqrt{2}}\varepsilon_P^{\text{in}}(z - z_0,t_0)\,, \tag{14a}$$

or

$$\varepsilon_{P-}^{\text{out}}(z,t) \propto \frac{1}{\sqrt{2}}\varepsilon_P^{\text{in}}(z - z_0,t_0)\,. \tag{14b}$$

The total photon number in the retrieved signal from the dual-channel SWEs is proportional to $\langle|\varepsilon_P^{\text{out}}(t)|^2\rangle$, which can be expressed as

$$\begin{aligned}\left\langle\left|\varepsilon_P^{\text{out}}(t)\right|^2\right\rangle &= \int \left|\varepsilon_P^{\text{out}}(z,t)\right|^2 dz\\ &\propto \frac{[1 + \cos(\delta_R - \delta_w + \Omega_L\tau)]}{2}\left\langle\left|\varepsilon_P^{\text{in}}(t_0)\right|^2\right\rangle\\ &= [1 + \cos(\delta_R - \delta_w + \Omega_L\tau)]\left\langle\left|\varepsilon_{\text{single}}^{\text{out}}(t)\right|^2\right\rangle,\end{aligned} \tag{15}$$

where $\langle|\varepsilon_P^{\text{in}}(t_0)|^2\rangle = \int |\varepsilon_P^{\text{in}}(z - z_0,t_0)|^2 dz$ corresponds to the photon number of the input signal pulse and $\langle|\varepsilon_{\text{single}}^{\text{out}}(t)|^2\rangle = \langle|\varepsilon_{P\pm}^{\text{out}}(t)|^2\rangle = \int |\varepsilon_{P\pm}^{\text{out}}(z,t)|^2 dz$ corresponds to the photon number of the individual signal $\varepsilon_{P+}^{\text{out}}$ or $\varepsilon_{P-}^{\text{out}}$. From the above equation, it is easily seen that when $\Delta = \delta_R - \delta_{\text{W}} + 2\Omega_L\tau = 0$ and π, the retrieved photon number reaches its maximum ($\langle|\varepsilon_P^{\text{out}}|^2\rangle \approx 2\langle|\varepsilon_{\text{single}}^{\text{out}}|^2\rangle$) and minimum ($\langle|\varepsilon_P^{\text{out}}|^2\rangle = 0$) values, respectively, which show the constructive and destructive interferences at the total optical readout signal. Such an effect results from the interference between the two stored internal atomic states, which can be viewed as super- and subradiant states for the atomic excitations, or is simply referred to as "quantum interference." As the retrieved photon number from the "active spin-wave polariton" changes with the relative phase between the two reading beams, the number of the remaining (unread) excitations $\langle|\hat{D}(z,t)|^2\rangle$ in the atomic ensemble also changes. Since the sum of the numbers of $\langle|\hat{S}(z,t)|^2\rangle$ and $\langle|\hat{D}(z,t)|^2\rangle$ is a constant [see Eq. (11)], the number of the remaining excitations in the atomic ensemble reaches minimum (maximum) when the retrieved photon number reaches maximum (minimum).

III. EXPERIMENTAL SETUP

The experimental setup and the tripod atomic system are shown in Fig. 1. All the laser beams are split from the same grating feedback diode laser. The p-(horizontally) polarized writing beam W (about 1.2 mW) provides the left- and right-circularly-polarized writing beam components (W^- and W^+, about 0.6 mW each), which interact with the transitions $|b\rangle$ to $|e\rangle$ and $|c\rangle$ to $|e\rangle$, respectively. The left- and right-circularly-polarized reading beams (R^- and R^+, about 1.4 mW each) also couple to the transitions $|b\rangle$ to $|e\rangle$ and $|c\rangle$ to $|e\rangle$, respectively, whose relative phase δ_R can be varied by the electro-optic modulator (EOM) and measured by optical interference with signal outputs from PBS3. The probe beam (about 55 μW) is left-circularly-polarized with a frequency shift of about 6.8 GHz upward from the writing or reading beams by two acousto-optic modulators (AOMs). It couples to the transition $|a\rangle$ to $|e\rangle$ and goes through the cold atomic sample with a small angle (~0.4°) from the writing or reading beams. The measured optical depth of the cold ^{87}Rb atoms in the magneto-optical trap (MOT) is about 1.5 and the trap temperature can reach ~200 μK. In the experiment, the MOT (including cooling and repumping lasers, as well as the trapping magnetic field) is switched off, and, at the same time, a bias magnetic field of 300 mG along the z axis is applied, so the z-direction quantization axis is well defined. Then a 780-nm, right-circularly-polarized pumping laser beam (coupling to the transition from $|a\rangle$ to $|5\,^2P_{3/2}, F' = 1\rangle$) and the p-polarized writing laser beam (with two circularly polarized components in the atomic medium) are turned on, so most of the atoms (>90%) are prepared into a single Zeeman ($|a\rangle$) state [16]. After 300 μs, the probe pulse (with a pulse length of 100 ns) enters into the atomic medium. The pumping and writing laser beams are then successively switched off quickly, thus the signal pulse is adiabatically mapped onto the cold atoms as two collective SWEs in the tripod system. After waiting for a time duration of $\tau = 380$ ns, the reading beams are first turned on to read the stored spin coherences. Next, the p-polarized writing beams are turned on again at $\tau = 3.4$ μs to read the remaining SWEs in the atomic ensemble.

IV. RESULTS AND DISCUSSION

Figure 2(a) shows the storage and retrieval of the signal from a single (left) channel (blocking the right writing or

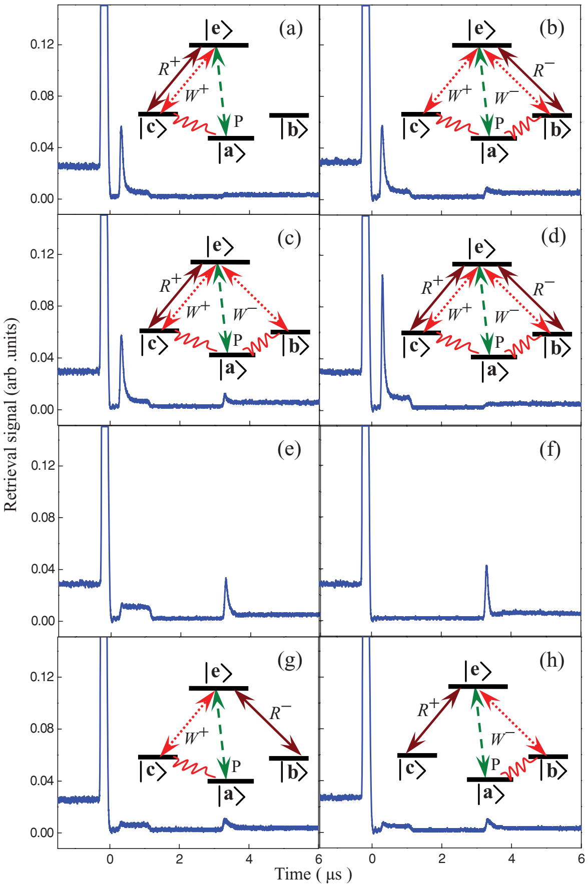

FIG. 2. (Color online) Retrieval signal for different storage and retrieval configurations. (a) One-channel storage and retrieval. The stored SWE (σ_{ca}) in one (left) channel has been retrieved by the reading beam $R+$ at 380 ns, and no clear signal is retrieved again by the p-polarized writing beam at 3.4 μs. (b) Dual-channel storage and only one (right) channel (σ_{ba}) retrieval. The stored SWE in the right channel (σ_{ba}) was first retrieved by the reading beam R^- at 380 ns. At 3.4 μs, a small optical signal [with ~13% of the full-scale readout in Fig. 2(f)] is retrieved by the p-polarized writing beam from the remaining SWE (σ_{ca}). (c) Dual-channel storage and only one- (left-) channel retrieval. The stored SWE in the left channel (σ_{ca}) was first retrieved by the reading beam R^+ at 380 ns. At 3.4 μs, a small optical signal [with ~20% of the full-scale readout in Fig. 2(f)] is retrieved by the p-polarized writing beam from the remaining SWE (σ_{ba}). (d) Dual-channel storage and dual-channel retrieval with in-phase reading beams at 380 ns. There is no retrieved signal by the p-polarized writing beam at 3.4 μs. (e) Dual-channel storage and dual-channel retrieval with out-of-phase reading beams at 380 ns, and reading again at 3.4 μs with the writing beams. (f) Dual-channel storage and retrieval by reading with two writing beams at 3.4 μs only. (g) Left-channel storage and right-channel retrieval. At 380 ns, only a small optical signal [about 7% of the full-scale readout in Fig. 2(f)] is retrieved by the R^- reading beam. At 3.4 μs, an optical signal [about 21% of the full-scale readout in Fig. 2(f)] is retrieved by the p-polarized writing beam. (h) Right-channel storage and left-channel retrieval. At 380 ns, only a small optical signal [about 9% of the full-scale readout in Fig. 2(f)] is retrieved by the R^+ reading beam. At 3.4 μs, an optical signal [about 20% of the full-scale readout in Fig. 2(f)] is retrieved by the p-polarized writing beam. In Figs. 2(a)–2(h), the retrieved signals at 380 ns have a broad offset background, which comes from the leakage of the reading beams.

reading beams), which corresponds to the typical three-level Λ-type system [3]. The right channel alone shows the same behavior. When the p-polarized writing beam [with two components W^+ and W^- having equal power $|\Omega_W^+(t)| = |\Omega_W^-(t)|$] is turned on, the optical signal is stored simultaneously into the dual-channel SWEs ($\tilde{\sigma}_{ca}$ and $\tilde{\sigma}_{ba}$). If only one reading beam (either R^+ or R^-) is used to read them at 380 ns, the readout signal is about the same as in the single-channel case. Figures 2(b) and 2(c) present the readout signals from individual $\tilde{\sigma}_{ba}$ and $\tilde{\sigma}_{ca}$ (with only one reading beam on), respectively. It is noted that there are small retrieved signals [~13% and ~20% of the full-scale readout in Fig. 2(f)] at 3.4 μs in Figs. 2(b) and 2(c), which are retrieved by the writing beam when it is used to read the SWEs remaining in the atomic medium. For the presented experimental case, the Larmor precession is given by $2\Omega_L\tau \approx 0.3\pi$ for the Larmor frequency of $\Omega_L \approx 2\pi \times 0.21$ MHz and $\tau = 380$ ns. The p-polarized writing beam has a relative phase of $\delta_w = \pi/2$ for its W^+ and W^- components. If the relative phase δ_R (between the R^+ and R^- reading beams) is tuned to 0.2π, the total relative phase $\Delta = 0$. In this case, when both reading beams R^+ and R^- are turned on at the same time, a maximal readout signal is obtained [Fig. 2(d)]. The retrieved signal intensity is twice that of the single-channel case at the same storage time of $\tau = 380$ ns. When the total phase difference Δ is adjusted to be π by tuning δ_R, no optical signal is retrieved from the atomic medium even though both reading beams are turned on at 380 ns. After a delay time of 3.4 μs, the atomic medium is read again with the p-(horizontally) polarized writing beam, as shown in Fig. 2(e). For comparison, Fig. 2(f) presents the readout result when the stored spin coherences were not perturbed before the system is read at a storage time of 3.4 μs with the p-polarized writing beam. These results indicate that although the stored two-channel SWEs have been read with two reading beams at 380 ns for $\Delta = \pi$, they have not been converted into the optical signal due to destructive quantum interference between the two SWEs and remain in the atomic medium until they are read again with other laser beams at a later time. Such results clearly show that the observed interference originates from the interference of the two internal spin coherences in the tripod system.

Figures 2(g) and 2(h) shows that if an optical signal is stored in only one-channel SWE $\tilde{\sigma}_{ca}$ ($\tilde{\sigma}_{ba}$) and read by one reading beam at a later time from another channel $\tilde{\sigma}_{ba}$ ($\tilde{\sigma}_{ca}$), the retrieved signal is very small [about 7% (9%) of the full-scale readout in Fig. 2(f)]. Such a small signal mainly results from the poor polarizing beam splitters PBS1 and PBS2 (with an extinction ratio of 1:100) used to polarize the writing and probe beams, and indicates that there is a very small energy exchange between the two channels in the single tripod system with a well-defined direction of the magnetic field, which can largely prevent spin coherence from escaping from one channel to another (i.e., decoherence for the memory). This will greatly benefit potential applications of such dual-channel memory in quantum-information processing. In the previous experiment with a very weak magnetic field, the quantization axis for determining the interaction between the photon polarization and the internal atomic states is not well defined due to the magnetic-field fluctuations in different directions, which can make qubit memory leakage and cause decoherence [17]. It is

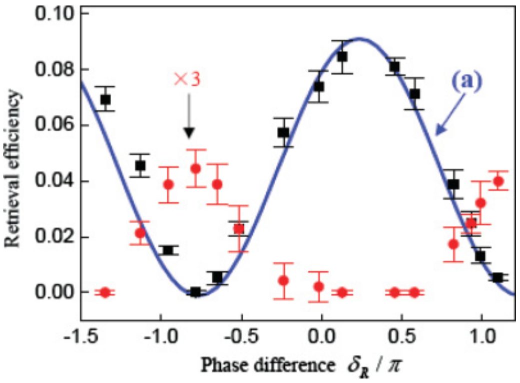

FIG. 3. (Color online) Retrieval efficiency as a function of the relative phase δ_R. Blue square points are the total retrieved efficiency at 380 ns storage time for different Δ. The solid blue line is the fit to the data. The red circular points are the retrieved efficiency at 3.4 μs storage time after the system has been first read at 380 ns with a pair of reading beams.

noted that, in Figs. 2(g) and 2(h), at 3.4 μs, an optical signal [about 21% (20%) of the full-scale readout in Fig. 2(f)] is retrieved by the p-polarized writing beam from the remaining SWE $\tilde{\sigma}_{ca}$ ($\tilde{\sigma}_{ba}$).

Figure 3 (square points) shows the total retrieved signal as a function of δ_R at $\tau = 380$ ns for fixed $\delta_w = \pi/2$ and $2\Omega_L\tau \approx 0.3\pi$. The retrieval efficiency R_e ($R_e = \langle|\varepsilon_P^{\text{out}}|^2\rangle/\langle|\varepsilon_P^{\text{in}}|^2\rangle$) shows a sinusoidal interference pattern as Δ (δ_R) is varied. After the stored dual-channel collective SWEs $\tilde{\sigma}_{ba}$ and $\tilde{\sigma}_{ca}$ are first read by a pair of reading beams (at 380 ns), the atomic medium is read again by the p-polarized writing beam at 3.4 μs. Curve a is the fitting to the function $R_e = A\,[1 + \cos(\varphi_0 - \delta_R)]$, where $\varphi_0 = 2\Omega_l\tau - \delta_w = 0.2\pi$. It is clearly seen that the measured data of the retrieved signal at 380 ns are in good agreement with the fitting curve a. The retrieved signal intensities at 3.4 μs are also shown in Fig. 3 (circular points) as a function of δ_R (for the first pair of reading beams). It is clear that when one curve becomes larger, another gets smaller, which means that by tuning δ_R, the stored signals can be partly read with the remaining SWEs still stored in the medium and can be read at a later time. The error bars in the measured data in Fig. 3 are due to fluctuations of the number of cold atoms and/or the frequencies of the laser beams.

In the tripod atomic system with a small magnetic field ($\sim$300 mG), the Zeeman sublevels $|b\rangle$ and $|c\rangle$ are split, which causes Larmor precession for the stored collective SWEs [10]. With the phase difference between the two reading beams optimized for readout at 380 ns storage time, the retrieval efficiency as a function of storage time shows a sinusoidal behavior, as shown in Fig. 4 [circular points and curve (a)]. Such oscillatory behavior in the readout intensity can severely limit the ability to access the optimal retrieval efficiency at any desired times. In the current phase-sensitive storage and retrieval scheme, such oscillation in the readout signal intensity can be eliminated by adjusting δ_R to compensate the phase shift $2\Omega_L\tau$ due to Larmor precession in the total phase difference Δ. The square points [curve (b)] in Fig. 4 are the measured results, which show that the maximal readout signal intensity can be accessed at any storage time. The error bars in the measured data in Fig. 4 are also due to fluctuations of the number of cold atoms and/or the frequencies of the laser beams.

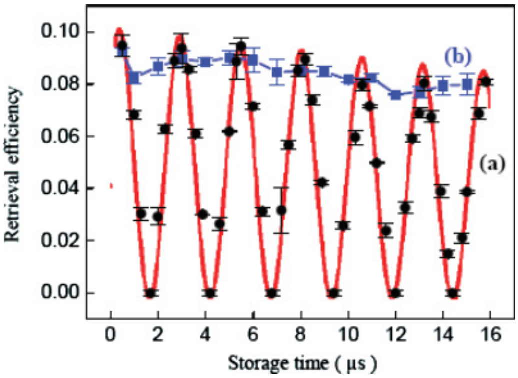

FIG. 4. (Color online) Retrieval efficiency and compensation of Larmor precession. Black circular points: retrieval efficiency as a function of storage time. Curve (a) (red curve): fitting to the function $R_e = A\cos^2(\Omega_L t - \phi/2)e^{-t/t_0}$, where the fitting parameters are $A = 0.1$, $\Omega_L = 2\pi \times 0.21$ MHz, $\phi = 0.3\pi$(initial phase), and the lifetime $t_0 \approx 90$ μs. Curve (b) (with blue squares): the results with compensated Larmor precession by adjusting the relative phase δ_R.

V. CONCLUSION

The ability to prepare this single four-level tripod system for dual-channel memory allows us to isolate contributions from the interested coherent atomic states and to demonstrate the quantum interference between the dual-channel internal SWEs. Although, in the present experiment, the dual-channel SWEs are generated by storing only one polarization component of the probe light and read with two orthogonally polarized reading beams, this method of measuring and manipulating the relative phase between the two internal atomic states $\tilde{\sigma}_{ba}$ and $\tilde{\sigma}_{ca}$ may be easily extended to the case with two SWEs in qubit memory with two polarization components. Besides, by compensating the Larmor precession via adjusting the relative phase between the two reading beams, the oscillation of the retrieved signal can be eliminated, so the total readout signal can be kept at its maximum. We expect that the Larmor precession in the qubit memory experiments [9,10] can also be compensated by changing the relative phase between the two orthogonal polarization components of the retrieved photons if the atoms are prepared into a single Zeeman level and the unwanted spin coherences are eliminated. In such a case, the memory lifetime for qubits would be significantly increased, which is essential for quantum-information processing and a quantum network.

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