Phase coherence and control of stored photonic information

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We report the demonstration of phase coherence and control for the recently developed "light-storage" technique. Specifically, we employ a dynamic form of electromagnetically induced transparency to bring the group velocity of a light pulse to zero, thereby mapping the photonic information into an ensemble spin coherence in warm Rb vapor. We then apply a pulsed magnetic field to vary the phase of the atomic spin excitations and map the altered information back into light. We detect the resultant phase shift in an optical interferometric measurement, thus confirming that the storage process preserves phase coherence.

The coherent and reversible storage of photon states in matter is an outstanding problem for the practical realization of many basic concepts in quantum information processing. Photons are the fastest and simplest carriers of quantum information, but in general they are difficult to localize and store; for this reason matter (e.g., spins) will likely serve as quantum memory elements. A quantum carrier/memory interface is a key component in the realization of scalable quantum networks [1,2]. In contrast to ordinary techniques which, e.g., destructively convert light intensity into electrical signals by photoabsorption, or transfer angular momentum from polarized light into oriented atomic spins by dissipative optical pumping, a quantum carrier/memory interface would coherently, linearly, and reversibly convert *entire* excitations carried by light pulses into long-lived matter states with minimal dissipation.

Several theoretical proposals have addressed the transfer of quantum states from photons to matter excitations. Early work focused on the use of individual atoms as quantum memory elements [3], and active experimental efforts toward this goal are currently underway [4,5]. However, it was recently realized that quantum state transfer could be simplified by using atomic ensembles [6,7]. In particular, recent experiments employing cold Na atoms [8] and warm Rb vapor [9] demonstrated an important step in this direction: the "storage" of a classical light pulse in an atomic ensemble by the dynamic and reversible reduction of the light pulse group velocity to zero.

The light storage technique is based on a recently proposed [6], dynamic form of the phenomenon of electromagnetically induced transparency (EIT) [10]. In conventional EIT, an external optical field (the "control field") is used to make an otherwise opaque medium transparent near an atomic resonance. A second, weak optical field (the "signal field") at an appropriate frequency and polarization can then propagate without dissipation and loss but with a substantially reduced group velocity [11–13].

In contrast to conventional EIT, the light-storage technique involves the use of a *dynamic* control field. Theoretical work to date [6] indicates that "dynamic EIT" should allow the information in an input pulse of signal light to be linearly, coherently, and reversibly mapped with high efficiency into a collective atomic state without suffering the signal pulse bandwidth limitations imposed in conventional EIT by a static control field [14]. However, the two initial light-storage experiments [8,9] measured only the intensities of the output fields, not the phases. Thus these previous experiments did not show that the light-storage technique provides coherent writing and reading of the signal light pulse into and out of a collective atomic state.

Here we present experimental evidence that the light-storage technique is phase coherent. Although anticipated from theoretical predictions [6], this essential feature of dynamic EIT has not been verified experimentally. Specifically, we demonstrate that the phase of the stored coherence, after being manipulated during the storage interval using standard techniques, is mapped coherently onto the released light pulse. We also demonstrate that light storage is a linear optical process. These results indicate that the present technique should be suitable for applications in quantum information processing, although this remains to be demonstrated with nonclassical (e.g., single photon) states [6]. We note that the light storage technique is an essential component of a recently proposed "quantum repeater" protocol [15] to enable scalable quantum communication over very long distances [16]. Scalable quantum computation using atomic ensembles coupled by light has also been suggested [17].

The present communication can be understood by considering a Λ configuration of atomic states coupled by two optical fields [see Fig. 1(a)]. Here, the control field (Rabi-frequency Ω_c) and signal field (Ω_s) are left and right circularly polarized light (σ^+ and σ^-). Via Raman transitions, these light fields create in the atomic ensemble a coherent antisymmetric superposition of a pair of ground-state Zeeman sublevels ($|-\rangle, |+\rangle$) which have magnetic quantum numbers differing by two. Associated with the reduced group velocity of the signal field is a considerable spatial compression which allows a signal pulse to be almost completely localized in the atomic medium. Inside the medium the light pulse propagates together with the ensemble Zeeman coherence, like a wave of flipped spins. The propagation of the coupled light and spin excitations can be efficiently described in terms of a quasiparticle, the "dark-state polariton" [6], which is a coherent superposition of photonic and spin-wave contributions. In order to store the state of a pulse of signal light, one smoothly turns off the control field, causing
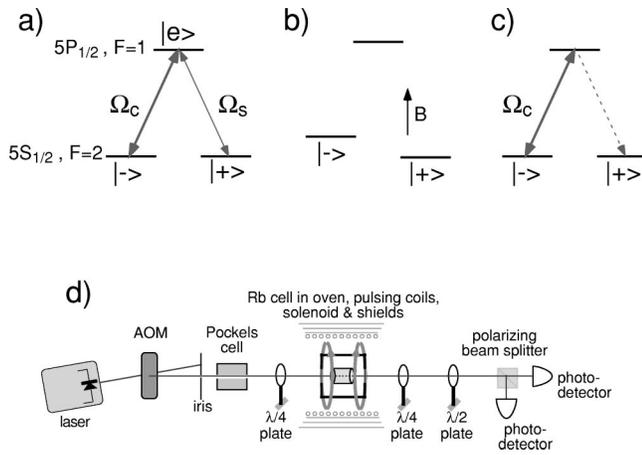
FIG. 1. Schematic of system for "light storage" and phase manipulation. (a) Λ-type configuration of ^{87}Rb atomic states resonantly coupled to a control field (Ω_c) and a signal field (Ω_s). (b) Phase manipulation of Zeeman coherence using a magnetic field. (c) Retrieval of stored photonic excitation using a control field. (d) Schematic of the experimental setup. Approximately 5 torr of helium buffer gas was used to keep Rb atoms in the laser beam for approximately 200 μs and thus to maintain long storage times. Note the addition since our previous experiment [9] of Helmholtz coils to pulse the magnetic field at the Rb cell.

the dark-state polariton to be adiabatically converted into a purely atomic spin excitation which is confined in the vapor cell.

The phase of an atomic Zeeman coherence can be easily manipulated using an external magnetic field. If a pulsed magnetic field $B_z(t)$ is applied in a direction parallel to that of the light propagation (the quantization or $\hat{z}$ axis), then the Zeeman sublevels are differentially shifted in energy [see Fig. 1(b)], producing a phase shift in the Zeeman coherence given by

$$\Phi = (g_+ - g_-)\frac{\mu_B}{\hbar}\int_0^T B(t')dt'. \tag{1}$$

Here $g_\pm$ are Landé-factors corresponding to the Zeeman states $|\pm\rangle$ and T is the time during which the magnetic field is applied. Once the magnetic field is removed, the dark-state polariton can be adiabatically restored to a photonic excitation by turning the control field (Ω_c) back on [see Fig. 1(c)]. The phase-shift Φ of the atomic coherence is thus transfered to a phase difference between the control field and the reconstituted signal pulse emitted from the sample.

Similar to our previous work [9] we performed light-storage experiments in atomic Rb vapor at temperatures of $\sim70-90°$ C, corresponding to atomic densities of $\sim10^{11}-10^{12}$ cm^{-3}. Under these conditions the 4-cm-long sample cell was normally opaque for a single, weak optical field near the Rb D_1 resonance ($\simeq795$ nm). To create the conditions for EIT, we derived control and signal beams from the output of the same extended cavity diode laser by carefully controlling the light polarization as illustrated in the experimental schematic shown in Fig. 1(d). For the data presented here we employed the $5^2S_{1/2}, F=2 \rightarrow 5^2P_{1/2}, F=1$ (i.e., D_1) transi-

tion in ^{87}Rb. The control field (σ^+ polarization light) was always much stronger than the σ^- signal field ($\Omega_c \gg \Omega_s$); hence, most of the relevant atoms were in the ground-state sublevel with the largest projection of angular momentum along the quantization axis. In this case the states $|-\rangle, |+\rangle$ of the simplified three-level model correspond, respectively, to $|F=2, M_F=0\rangle$ and $|F=2, M_F=+2\rangle$. We circularly polarized the input laser beam to create the σ^+ control field, and then collimated and focused the beam to a diameter of about 1 mm as it passed through the Rb vapor cell. By using a Pockels cell we slightly rotated the polarization of the input light to create a weak pulse of σ^- light, which served as the signal field [13]. Input peak powers were about 1 mW and 100 μW for the σ^+ and σ^- components. Peak power in the control field provided a transparency bandwidth for the signal pulse [18] of approximately 40 kHz.

Additional polarizing optics after the atomic vapor cell allowed us to monitor the output signal light pulse [see Fig. 1(d)]. A $\lambda/4$ waveplate converted the two circular polarizations into linear polarizations, followed by a $\lambda/2$ wave plate, a polarizing beam splitter, and two photodetectors to provide two detection channels–nominally for the control and signal fields. To form an interferometer for the two fields, we adjusted the $\lambda/2$ plate such that a small fraction ($<10\%$) of the control field was mixed into the signal detection channel with approximately the same steady-state magnitude as the peak of the released signal pulse.

To manipulate the phase of the atomic Zeeman coherence, we carefully controlled the magnetic field at the Rb cell. To this end, we employed three layers of high permeability magnetic shields to screen out external magnetic fields. Additionally, we used two separate coils to generate homogeneous magnetic fields along the propagation direction of the optical beam. First, a precision solenoid produced a static magnetic field of less than 1 mG to offset the remnant field unscreened by the shields. Second, a Helmholtz coil pair generated the pulsed field to manipulate the Rb Zeeman coherence, thereby inducing phase shifts in the stored light. We typically applied current pulses to the Helmholtz pair of 10 to 30 μs duration, with peak magnetic fields as large as 100 mG [19].

Figure 2(a) shows an example of stored light observed with an applied magnetic-field pulse which created an approximately $\Phi=4\pi$ phase shift between the signal pulse and the control field. With the σ^+ control field dressing the atoms, we measured a small background signal due to the control field being slightly mixed into the signal detection channel via the slightly rotated $\lambda/2$ plate [region I of Fig. 2(a)]. We then applied a σ^- signal pulse of duration ~20 μs. Upon entrance into the sample cell the signal pulse was spatially compressed by more than five orders of magnitude in the Rb vapor due to the reduction in group velocity, as estimated from the observed delay in pulse propagation. With the peak amplitude of the signal pulse inside the cell, we ramped down the control field, effectively storing the pulse in an ensemble Zeeman coherence in the Rb vapor. Note that approximately half the signal pulse had already left the cell before the beginning of the storage procedure (region II) [20]. This front part of the signal pulse was not affected by
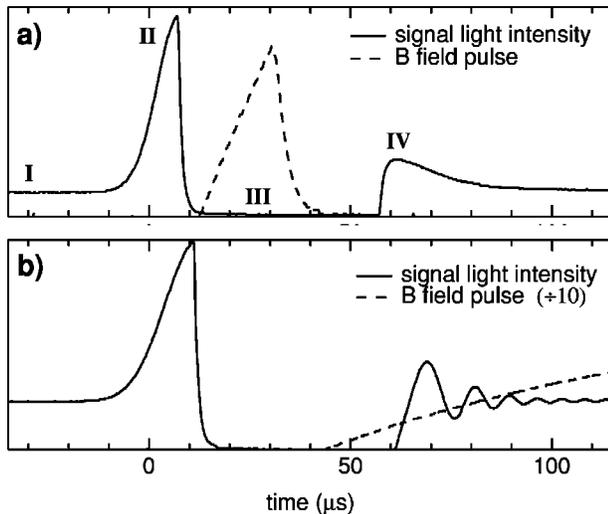
FIG. 2. Examples of "stored light" with interferometric detection and a pulsed magnetic field. The dashed line indicates the pulsed magnetic field; the solid line is the measured signal field. A small portion of the control field (σ^+) was mixed into the signal field (σ^-) detection channel by a slight rotation of the $\lambda/2$ wave plate after the Rb cell. Thus the relative phase Φ between the outgoing control field and the released signal pulse could be determined from the degree of constructive and/or destructive interference between these two fields. (a) Magnetic-field pulse is applied during the storage interval. In the example shown here, $\Phi \approx 4\pi$, leading to constructive interference at the region marked IV. (The significance of the other three regions is explained in the main text.) (b) Magnetic-field pulse is on during the retrieval procedure. The frequency of the output signal pulse shifts, resulting in interferometric beating with the control field.

the phase manipulations and was used as a reference in the experiment. With the remainder of the signal pulse stored in the vapor cell, we applied a pulsed current to the Helmholtz coils to induce a controllable phase shift in the ^{87}Rb ensemble Zeeman coherence (region III). After the pulsed magnetic field, we turned the control field back on and the signal light pulse was reconstituted, emitted from the sample, and observed interferometrically (region IV). The integrated magnetic-field pulse in the example shown in Fig. 2(a) was 1.5 G μs, producing a signal/control field phase shift of about 4π: i.e., constructive interference between the two optical fields.

Note that for the accurate, coherent control of the phase it is essential to apply the magnetic field only during the storage interval. For example, the peak magnetic field in Fig. 2(a) corresponds to a Zeeman frequency shift which is at least four times larger than the EIT transparency window. If such a field is applied before the storage is complete, the medium becomes completely opaque and no signal pulse is recovered. Alternatively, if the magnetic field is left on during the retrieval procedure, the light is retrieved at a different frequency resulting in a modulated interferometric signal [Fig. 2(b)]. (Only the control field is applied to the atoms during release of the stored signal pulse, which obviates the need for degenerate Zeeman levels to maintain EIT.)

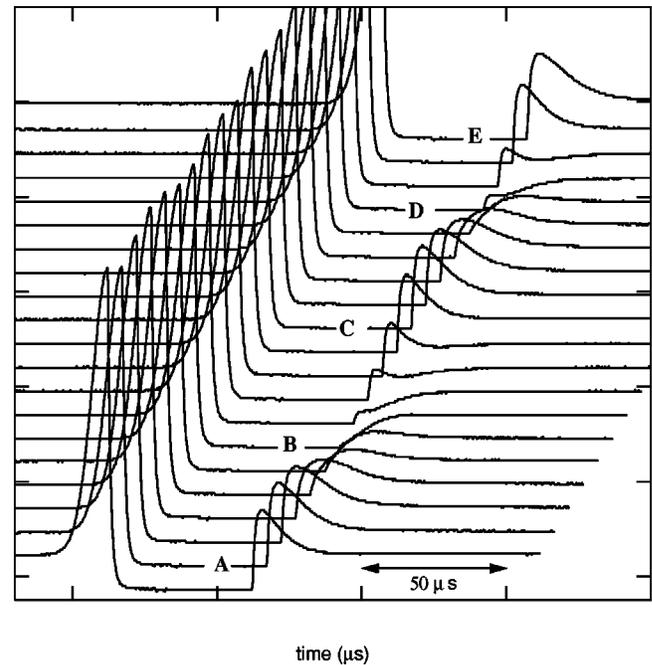By adjusting the applied magnetic-field pulse during the

FIG. 3. Results of interferometric measurements of released photonic excitations: 20 light storage experiments similar to that shown in Fig. 2. The magnetic field was pulsed during the storage interval with increasing strength from trace A to E such that the accumulated phase difference between the output signal pulse and the control field varied from approximately 0 to 4π. Note: there is a small phase offset at zero pulsed magnetic field, caused by the Pockels cell.

storage, we could easily modify the phase Φ of the coherent excitation. Figure 3 shows 20 stored light experiments for which we increased the Zeeman phase shift by approximately 0.2π for each successive run. Trace A in Fig. 3 shows the result for $\Phi \simeq 0$ and hence, maximum constructive interference between the output signal light and the control field. As we increased the pulsed magnetic field to change the phase by π, we observed destructive interference (e.g., trace B). As we increased the pulsed magnetic field still further, we alternatively observed constructive and destructive interference as expected at $\Phi \simeq 2\pi$, 3π, 4π, etc. (traces C-E in Fig. 3). (Note: Fig. 2(a) and trace E in Fig. 3 show the same data.) We observed up to ten periods of phase accumulation (i.e., $\Phi \simeq 20\pi$) without loss of coherence, limited by the strength of our pulsed magnetic-field power supply rather than nonlinear shifts in the Rb Zeeman levels at higher fields [19] or magnetic-field inhomogeneity. We obtained similar results for various intensities of the signal light as long as the peak value was much smaller than the initial intensity of the control field, thus showing that the light-storage technique is a linear optical process.

These dynamic EIT results should also be compared with analogous phase manipulation experiments using conventional (i.e., static control field) EIT [21]. With conventional EIT and a degenerate Λ configuration, an applied magnetic field induces a phase shift corresponding to a rotation of the signal light's polarization; this is a particular form of the nonlinear Faraday effect [13,18]. However, the magnitude of

the phase shift achieved in such conventional EIT experiments is much smaller than π [13,21] even if a high-density medium is used [18], a consequence of the finite bandwidth of the EIT transparency window [22]. As shown in the above data, the dynamic EIT approach easily allowed us to increase the phase shift by more than two orders of magnitude.

In conclusion, we have demonstrated that the recently developed ''light-storage'' technique [9] is phase coherent. In so doing we have performed accurate, coherent manipulation of information that is stored in an ensemble atomic spin coherence and then transferred back into a pulse of signal light and released using a dynamic form of electromagnetically induced transparency (EIT). We have also shown that light storage is a linear optical process. These results suggest that this technique should be effective for the storage of nonclassical states, although this important characteristic remains to be demonstrated. In future work, the light-storage technique may aid the realization of quantum information processing applications such as a scalable quantum repeater protocol [15] and new techniques for quantum computation [17].

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