We report the demonstration of phase coherence and control for the recently developed “light storage” technique. Specifically, we use a pulsed magnetic field to vary the phase of atomic spin excitations which result from the deceleration and storing of a light pulse in warm Rb vapor. We then convert the spin excitations back into light and detect the resultant phase shift in an optical interferometric measurement. The coherent storage of photon states in matter is essential for the practical realization of many basic concepts in quantum information processing.

The realization of scalable quantum networks for long-distance quantum communication and quantum computation requires the use of photons as quantum information carriers and matter (e.g., spins) as quantum memory elements [1]. For example, intermediate memory nodes will be essential for quantum communication over lossy photonic channels [2,3]. When successfully implemented, such a technique will facilitate secure transmission of secret messages over long distances [4,5]. Likewise, quantum memory elements linked by light are desirable for scalable quantum computation [6].

The quantum carrier/memory interface is a key component that should be capable of reversibly transferring quantum states between light pulses and long-lived matter states. In contrast to ordinary “destructive” techniques which convert light into, e.g., electrical signals by photoabsorption, a quantum memory should be free from dissipation and, most importantly, should preserve phase coherence in the process of information transfer to and from the carrier.

Recently, proposals have been made to accomplish the quantum transfer of photon states to individual atoms [7] and atomic ensembles [8,9]. Active experimental efforts toward the realization of these ideas are currently under way [10,11]. In particular, recent experiments employing cold Na atoms [12] and warm Rb vapor [13] demonstrated the basic principle of the “storage of light” in atomic ensembles by the dynamic and reversible reduction of the light pulse group velocity to zero.

In this Letter we present the first experimental evidence that this light storage technique is phase coherent. Although anticipated from theoretical predictions [8,9], this essential feature of a quantum memory for light has not been verified experimentally up to now. In addition, we demonstrate that the phase of the stored coherence can be accurately manipulated during the storage interval and then mapped coherently onto the released light pulse. These results show that the present technique should be suitable for applications in quantum information processing. For example, a specific “quantum repeater” protocol, which allows for scalable quantum communication over very long distances using this technique, has already been proposed [14]. Scalable quantum computation using atomic ensembles coupled by light has also been suggested [15].

The light storage technique is based on the phenomenon of Electromagnetically Induced Transparency (EIT) [16], in which 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 [17–19]. The present experiment can be understood by considering a Λ configuration of atomic states coupled by two optical fields (see Fig. 1a). Here, the control field (Rabi-frequency \( \Omega_c \)) and signal field (\( \Omega_s \)) are left and right circularly polarized light (\( \sigma^+ \) and \( \sigma^- \)). Via Raman transitions, these light fields create in the atomic ensemble a coherent antisymmetric superposition of a pair of ground-state Zeeman sublevels (|−⟩, |+⟩) 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 quasi-particle, the “dark-state polariton” [9], 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 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, \( B_y(t) \), 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. 1b), producing a phase shift in the Zeeman

\[
\begin{align*}
|−\rangle & \rightarrow |−\rangle + \text{phase shift} \\
|+\rangle & \rightarrow |+\rangle - \text{phase shift}
\end{align*}
\]

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coherence given by:
\[ \Phi = (g_+ - g_-) \frac{\mu_B B}{\hbar} \int_{0}^{T} B(t') dt'. \]

Here \( g_{\pm} \) are Lande 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 \((\Omega_c)\) back on (see Fig. 1c). The phase-shift \( \Phi \) of the atomic coherence is thus transferred to a phase difference between the control field and the reconstituted signal pulse emitted from the sample.

Similar to our previous work \[13\] we performed light-storage experiments in atomic Rb vapor at temperatures of \( \sim 70 - 90 \) °C, corresponding to atomic densities of \( \sim 10^{11} - 10^{12} \) 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 (\( \sim 795 \) 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. 1d. For the data presented here we employed the \( ^5S_{1/2}, F = 2 \rightarrow ^5P_{1/2}, F = 1 \) (i.e., \( D_1 \)) transition in \( ^{87}\text{Rb} \). The control field \((\sigma^+)\) polarization light) was always much stronger than the \( \sigma^- \) signal field \((\Omega_c \gg \Omega_s)\); hence most of the relevant atoms were in the highest angular momentum ground-state sublevel. In this case the states \(|-,+\rangle\) of the simplified 3-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 \( \sigma^+ \) 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 \( \sigma^- \) light, which served as the signal field. Input peak powers were about 1 mW and 100 \( \mu \)W for the \( \sigma^+ \) and \( \sigma^- \) components. Peak power in the control field provided a transparency bandwidth for the signal pulse \[20\] of approximately 40 kHz.

Additional polarizing optics after the atomic vapor cell allowed us to monitor the output signal light pulse (see Fig. 1d). A \( \lambda/4 \) waveplate converted the two circular polarizations into linear polarizations, followed by a \( \lambda/2 \) waveplate, 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 \( \mu \)s duration, with peak magnetic fields as large as 100 mG \[21\].

Fig. 2a 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 \( \sigma^+ \) 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. 2a). We then applied a \( \sigma^- \) signal pulse of duration \( \sim 20 \) \( \mu \)s. 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) \[22\]. This front part of the signal pulse was not affected by 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 \( ^{87}\text{Rb} \) ensemble Zeeman coherence. 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. 2a was 1.5 gauss \( \mu \)s, producing a signal/control field phase shift of about 4 \( \pi \): 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. 2a 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. 2b). (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 storage, we could easily modify the phase $\Phi$ of the coherent excitation. Figure 3 shows twenty stored light experiments for which we increased the Zeeman phase shift by approximately $0.2\pi$ for each successive run. Trace A in Fig. 3 shows the result for $\Phi \approx 0$ 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 $\pi$, 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 $\Phi \approx 2\pi, 3\pi, 4\pi$, etc. (traces C-E in Fig. 3). (Note: Fig. 2a and trace E in Fig. 3 show the same data.) We observed up to 10 periods of phase accumulation (i.e., $\Phi \approx 20\pi$) without loss of coherence, limited by the strength of our pulsed magnetic field power supply rather than non-linear shifts in the Rb Zeeman levels at higher fields or magnetic field inhomogeneity.

In conclusion, we have demonstrated that the recently developed “light storage” technique [13] is phase coherent. In so doing we have performed accurate, coherent manipulation of information that is stored in an atomic spin coherence and then transferred back into light and released. The present work may facilitate the practical implementation of scalable quantum repeater protocols [14] and new techniques for quantum computation [15]. It is a pleasure to thank M. Fleischhauer and S. Yelin for many fruitful ideas and collaboration on theoretical aspects of this work. We also thank M. O. Scully for many stimulating discussions. This work was partially supported by the National Science Foundation through the grant to ITAMP, the Office of Naval Research, and NASA.

[21] At fields of 100 mG, differential shifts in the Zeeman frequencies between different levels and deviations from the linear approximation are < 2 Hz and $3 \times 10^{-6}$, respectively, which is negligible in the present experiment.
[22] We estimate that a signal pulse storage efficiency of better than 90% should be possible in warm vapor with an optimized system.
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 ($\Omega_c$) and a signal field ($\Omega_s$). (b) Phase manipulation of Zeeman coherence using magnetic field. (c) Retrieval of stored photonic excitation using 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 [13] of Helmholtz coils to pulse the magnetic field at the Rb cell.

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 ($\sigma^+$) was mixed into the signal field ($\sigma^-$) detection channel by a slight rotation of the $\lambda/2$ waveplate after the Rb cell. Thus the relative phase $\Phi$ 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) 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) Pulse is on during the retrieval procedure. The frequency of the output signal pulse becomes shifted, resulting in interferometric beating in the measurement.
FIG. 3. Results of interferometric measurements of released photonic excitations: twenty light storage experiments similar to that shown in Figure 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 $4\pi$. Note: there is a small phase offset at zero pulsed magnetic field, caused by the Pockels cell.