Manipulating the retrieved width of stored light pulses

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(Received 1 August 2005; published 2 November 2005)

We have systematically studied the method proposed by Patnaik *et al.* [Phys. Rev. A **69**, 035803 (2004)] that manipulates the retrieval of stored light pulses. The measured probe pulse width of the retrieval is inversely proportional to the intensity of the reading field. We also show that the method does not introduce any phase shift or jump into the retrieved pulses. Our study demonstrates that the distortion at the output of the light storage can be corrected by manipulating the retrieval process and the phase information of the stored pulses can remain intact during the process.

DOI: 10.1103/PhysRevA.72.053803 PACS number(s): 42.50.Gy, 32.80.Qk

Light is often used as a carrier of information in human communications, because it hardly interacts with the environment and possesses a fast propagation speed. Consequently, the ability to manipulate the behavior of light becomes very important in optical communications. In recent years, many interesting experiments have shown that light pulses can be greatly slowed down and even stored under the effect of electromagnetically induced transparency (EIT) [1–7]. The light-storage technique is based on the quantum state transfer between light and matter [8–13], and may have important applications in a quantum network [14–20]. On the other hand, the light-storage technique also has potential applications in classical optical communications, such as the all-optical pulse delay device to control the release time of each pulse, all-optical frequency or wavelength shifter, all-optical phase controller, and so on [21–25]. In this paper, we demonstrate a simple method for manipulating the retrieved width of stored light pulses and show that the method does not introduce any phase shift or jump into the retrieved pulses.

Although the light-storage technique has potential applications in both quantum and classical communications, the narrow bandwidth of EIT transparency window will distort the shape of short light pulses. Due to the pulse shape preserved in the process of light storage, the distortion also appears in the retrieved light pulses. Patnaik *et al.* recently obtained an analytical solution for the retrieved process of stored light pulses and found the width of retrieved light pulses is related to the intensity of the coupling field during the retrieval (i.e., the reading field). In addition, they derived a condition to correct the shape distortion of retrieved light pulses by using a linearly ramped reading field [26]. The ability to manipulate the width of light pulses and correct the shape distortion of light pulses provides more freedom in expanding applications of the light-storage technique to other practical systems, such as optical fiber [24,25].

We experimentally studied the process of light storage and retrieval in cold ^{87}Rb atoms produced by a vapor-cell magneto-optical trap (MOT). We trapped around 10^9 atoms in the MOT, as measured by the optical-pumping method [27]. In the EIT experiment, we employed the weak probe and strong coupling fields to drive the D_2 transitions of $|F=1\rangle \rightarrow |F'=2\rangle$ and $|F=2\rangle \rightarrow |F'=2\rangle$, respectively (see Fig. 1). Here the probe and coupling fields were circularly polarized with σ_+ polarization and propagated in nearly the same direction. They formed the three-level Λ-type configuration of EIT. The relaxation rate of the ground-state coherence was about 0.002Γ, as estimated from the EIT spectrum, where $\Gamma = 2\pi \times 5.9$ MHz is the spontaneous decay rate of the excited states. Details of the measured EIT spectrum can be found in Ref. [28].

The scheme of experimental setup is shown in Fig. 2. The probe and coupling fields came from two different diode lasers (DLs). The two lasers were injection locked by the same external cavity diode laser (ECDL). Each of the probe and coupling fields passed through an acousto-optic modulator (AOM) before interacting with the atoms. We controlled the rf power of the AOMs to produce the Gaussian probe pulses and to set the various intensities of the coupling field. Furthermore, we employed the method of the beat-note interferometer to directly and dynamically measure the phase variations in the process of light storage and retrieval. In the system of the beat-note interferometer, we spatially recombined the zeroth-order (continuous wave) and first-order (Gaussian pulse) beams of the probe AOM by a 50/50 beam splitter (BS) cube. Coming out of the BS, beam 1 was directly received by a photodetector (PD1) and beam 2 was

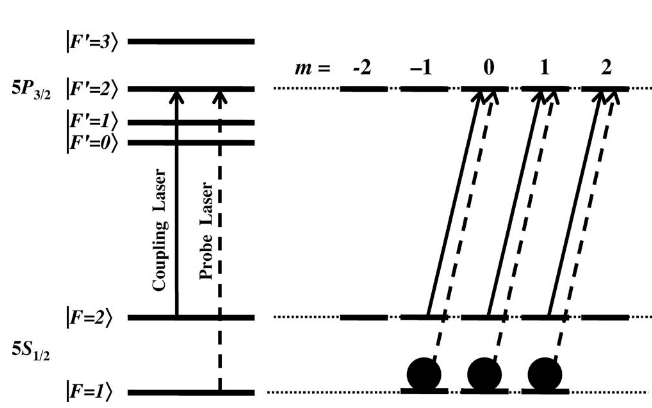

FIG. 1. Relevant energy levels of ^{87}Rb atoms and laser excitations in the experiment.

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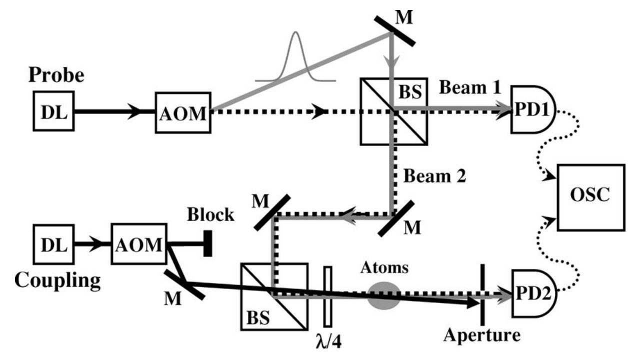

FIG. 2. Scheme of the experiment. DL, diode laser; PD, photodetector; BS, beam splitter cube; λ/4, quarter waveplate; M, mirror; OSC, oscilloscope.

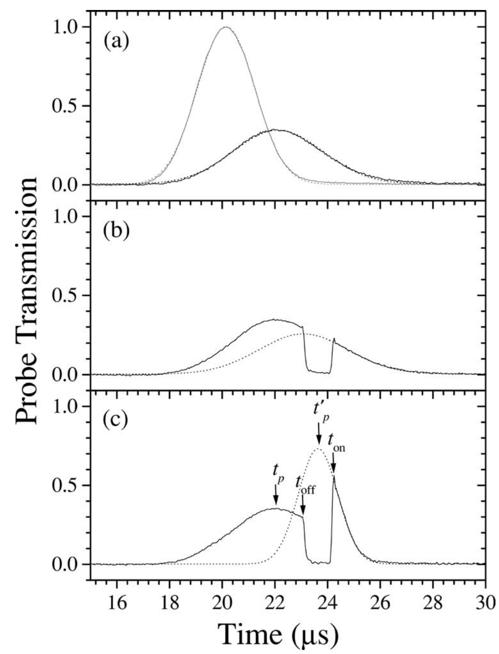

FIG. 3. Typical data of the slow light and the retrieval of the stored light pulse for $\Omega_c^W=0.3\Gamma$. Gray and black solid lines are the input and output probe pulses, respectively; dotted lines are the best fits. (a) The widths of the best fits of input and output pulses are 3.0 and 4.9 μs, respectively. (b) The width of the best fit of retrieved pulse τ' is 5.0 μs and the Rabi frequency of the reading field, Ω_c^R, is 0.3Γ. (c) $\tau'=2.1$ μs and $\Omega_c^R=0.45\Gamma$. t_p, t_p', $t_{\rm off}$, and $t_{\rm on}$, used in Eqs. (2) and (3), are illustrated in the figure.

received by another photodetector (PD2) after propagating through the sample (see Fig. 2). The driving frequency, ω_a, of the AOM in our experiment was 80 MHz, which is sufficiently large that the interaction between the zeroth-order beam and the sample is negligible. Both beams 1 and 2 carry beat notes at the frequency of ω_a. We measure the phase evolution of the probe pulse by directly comparing the two beat notes in the oscilloscope. Details of the above method can be found in Ref. [29].

The timing sequence in the experiment is described below. We first turned off the magnetic field of MOT. After a 1.45-ms delay, we shut off the repumping field, turned on the coupling field, and switched off the trapping beams. The entire population was optically pumped to the $|F=1\rangle$ ground state. When all the fields of the MOT were turned off, the probe Gaussian pulse was turned on. We turned off the coupling field for about 1.0 μs to store part of the probe pulse in the atoms and then turned on the coupling field again to release the stored pulse. A 125-MHz photodiode (New Focus 1801) detected the signal of the probe pulse and its output was directly sent to a digital oscilloscope. After the measurement was complete, the coupling field was turned off and the MOT was turned back on again. The above sequence was repeated at a period of 100 ms; the data as averaged 256 times by the oscilloscope before being transferred to the computer. When we measure the amplitude of the probe pulse only, the zeroth-order beam of the probe AOM is blocked. When we measure the phase evolution of a light pulse, the zeroth-order beam is unblocked and, together with the first-order beam, forms the beat-note interferometer.

A weak probe pulse can be slowed down by interacting with a strong coupling field in a three-level Λ-type EIT system as shown in Fig. 3(a). The Rabi frequency of the coupling field, Ω_c, was 0.3Γ and that of the peak of the probe pulse, $\Omega_{p,max}$, was 0.1Γ. Gray and black solid lines are the input and output probe pulses, respectively. The delay time of the probe pulse was about 2.0 μs. Figure 3(a) also shows the broadening effect of the pulse width in the EIT condition; the best fits (dotted lines) show the $1/e$ full widths of the input and output pulses are 3.0 and 4.9 μs, respectively. Figure 3(b) shows the typical data of the light-storage experiment. The Rabi frequencies of both the coupling field before the storage (the writing field), Ω_c^W, and the coupling field after the storage (the reading field), Ω_c^R, were 0.3Γ. The left part of the signal shows the portion of the probe pulse had left the EIT sample before the coupling field was turned off. The gap in the signal is due to the storage. The right part of the signal shows the portion of the probe pulse that was stored in and then released from the EIT sample. Figure 3(c) shows the typical data of manipulating the retrieved width of a light pulse by changing the intensity of the reading field. All the conditions were the same as those in Fig. 3(b) except Ω_c^R was 0.45Γ.

We determine the widths of retrieved probe pulses by fitting experimental data with a Gaussian function, which is given by

$$y(x) = h \exp\left\{\left[\frac{x-t_p'}{(\tau'/2)}\right]^2\right\}, \quad (1)$$

where $y(x)$ is the detector signal of the retrieved pulse, x is the time that the signal arrives at the detector, h is the pulse amplitude, t_p' and τ' represent the peak and $1/e$ full width of retrieved pulses, respectively. We only store part of the probe pulse in the atoms. In the fitting, the percentage of this part should not be changed. Therefore, the relationship between the input pulses and the retrieved pulses follows the equation below.

$$\frac{t_p'-t_{\rm on}}{\tau'} = \frac{t_p - t_{\rm off}}{\tau}, \quad (2)$$

where t_p and τ are the peak and $1/e$ full width of the probe pulse passing through the EIT medium without storage. $t_{\rm off}$

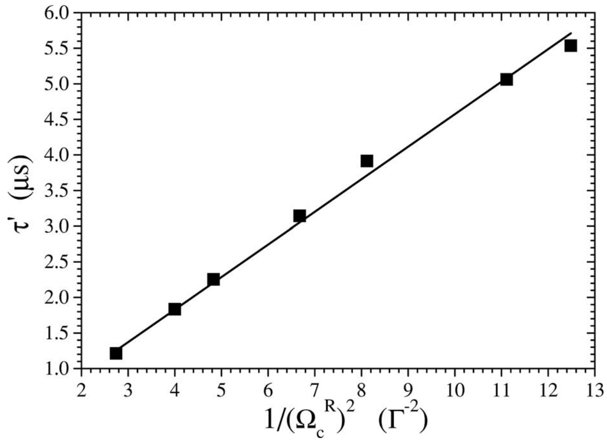

FIG. 4. The width of the retrieved pulse versus the reciprocal of the reading field intensity. The $1/e$ full width of input probe pulse is 3.0 μs; $\Omega_c^W=0.3\Gamma$. The error bar is about the size of the data points.

and $t_{\rm on}$ represent the times of switching off and on the coupling field. We obtain $t_p'=t_{\rm on}+(t_p-t_{\rm off})(\tau'/\tau)$ from the above equation, and the fitting function becomes

$$y(x) = h \exp\left\{\left[\frac{x - t_{\rm on} - (t_p - t_{\rm off})(\tau'/\tau)}{(\tau'/2)}\right]^2\right\}. \qquad (3)$$

The values of $t_{\rm off}$, $t_{\rm on}$, t_p, and τ are determined experimentally. Only h and τ' are the fitting parameters. The dotted lines in Figs. 3(b) and 3(c) are the examples of the best fits. This fitting technique applied to all the data of the retrieved pulses and the consistency between the experimental data and the best fits is as good as that shown in Figs. 3(b) and 3(c). The $1/e$ full widths of the retrieved probe pulses at different intensities of the reading field are plotted in Fig. 4.

The analytical solution of the retrieved pulses described by Eq. (14) in the paper of Patnaik *et al.* is squared to express the intensity below.

$$[\Omega_p^R(z,t')]^2 = \left[\frac{\Omega_{p0}^W\Omega_c^R}{p(t')\Omega_c^W}\right]^2 \exp\left\{\frac{-2(t'-q)^2}{[p(t')T_p(\Omega_c^W/\Omega_c^R)^2]^2}\right\}, \qquad (4)$$

with $[p(t')]^2=1+[8\gamma(\Omega_c^R)^2/(\Omega_c^W)^4T_p^2][t'+\gamma/4(\Omega_c^R)^2]$, where z and t' are the space and time variables, q is the function of z describing the peak position of the retrieved pulse, $\gamma=\Gamma$, and Ω_{p0}^W and T_p are the amplitude and $1/e$ half width of the Rabi frequency of the input Gaussian probe pulse. From Eq. (4), $\sqrt{2}p(t')T_p(\Omega_c^W/\Omega_c^R)^2$ is the $1/e$ full width of the retrieved pulse. It is obvious that $p(t')$ describes the shape distortion of the retrieved pulse in the EIT medium. Now, we consider the $p(t'=T_d)$ of our experimental condition where T_d is the propagation time that the retrieved probe pulse takes to leave the atoms. T_d is the order of μs for the Ω_c^R used in the experiment. Since $\Gamma/4(\Omega_c^R)^2$ (=0.075 μs at $\Omega_c^R=0.3\Gamma$) is much less than T_d, $[p(T_d)]^2\approx 1+[8\Gamma(\Omega_c^R)^2/(\Omega_c^W)^4T_p^2]T_d$. Furthermore, the propagation time of the EIT medium is inversely proportional to the square of the Rabi frequency of the coupling field, i.e., $T_d\propto 1/(\Omega_c^R)^2$. We use the relationship between T_d and Ω_c^R and find $p(T_d)$ is independent of Ω_c^R in our experiment. The measured width of the retrieved probe pulse, τ', is equal to $\sqrt{2}p(T_d)T_p(\Omega_c^W/\Omega_c^R)^2$ and, thus, is proportional to $1/(\Omega_c^R)^2$.

The width of the retrieved probe pulse is measured as a function of the Rabi frequency of the reading field. In the measurement, the Rabi frequency of the writing field and the width of the input probe pulse are kept constant. We have shown in the previous paragraph that the width of the retrieved probe pulse is inversely proportional to the square of the Rabi frequency of the reading field. Figure 4 plots the τ' versus $1/(\Omega_c^R)^2$. The squares are the experimental data. We fit the data with a straight line that passes through the origin. The solid line in the figure is the best fit. It is demonstrated that $\tau'\propto 1/(\Omega_c^R)^2$ and the consistency between the experimental data and the theoretical prediction is satisfactory. According to Eq. (4), the slope of the straight line should be $\sqrt{2}p(T_d)T_p(\Omega_c^W)^2$. We estimate $p(T_d)$ from the slope of the best fit and find it is 1.69. By setting $\Omega_c^W=\Omega_c^R$, Eq. (4) also describes a probe pulse propagating through the EIT medium without the storage. The $1/e$ full width of the output pulse is $\sqrt{2}p(T_d)T_p$. From the data shown in Fig. 3(a), we find the width of the best fit of the output pulse is 4.9 μs and, thus, $p(T_d)$ is 1.63. The two experimentally determined $p(T_d)$'s are in good agreement.

We turn our attention to phase coherence in the process of manipulating the retrieval of stored light pulses [30]. We employed the beat-note interferometer to measure the phase shift as a function of Ω_c^R for the light pulse under the process of storage and retrieval. We first measured the phase difference before the storage, ϕ_1, between the reference signal (received by PD1 in Fig. 2) and the part of the probe pulse (received by PD2) that leaves the atoms before the coupling field is switched off. We then measured the phase difference after the retrieval, ϕ_2, between the same reference signal and the retrieved part of the same probe pulse. The two measurements were taken in different shots. Since the reference signal and the probe pulse come from the same light source and the beat-note interferometer is rather insensitive to fluctuation of the optical path, ϕ_1 and ϕ_2 are always constant from shot to shot within the experimental noise. The phase shift induced by the process of storage and retrieval is $\Delta\phi=\phi_2-\phi_1$.

Figure 5 shows $\Delta\phi$ versus Ω_c^R. The squares are the experimental data measured at the condition that the center frequency of the probe pulse and the coupling frequency satisfy the two-photon resonance or $\Delta_p-\Delta_c=0$. The result shows that the manipulation of the retrieved pulse width does not induce any phase shift. This implies that such method of manipulating the pulse width can be employed in the applications of quantum information, in which preservation or controllable manipulation of the phase is essential. We noticed that the probe frequency slightly detuned from the two-photon resonance can result in the Ω_c^R-dependent phase shift. Circles in the figure are the example of this Ω_c^R-dependent phase shift at $\Delta_p-\Delta_c=-80$ kHz or -0.013Γ. Therefore, it is necessary to carefully maintain the two-photon resonance in the manipulation of the retrieval.

In conclusion, we have systematically studied the method of manipulating the retrieved pulse width of light storage.

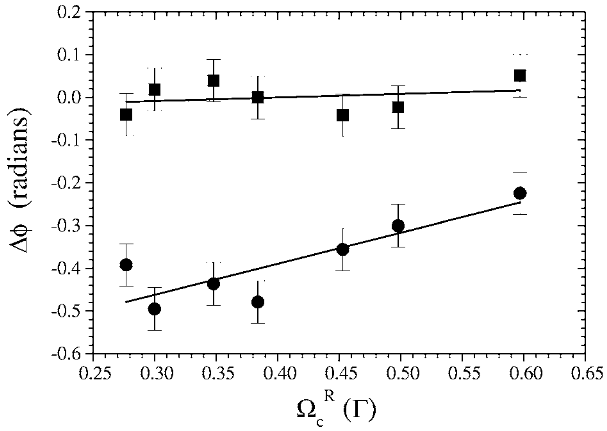

FIG. 5. The phase shift induced by the process of storage and retrieval versus the Rabi frequency of the reading field. The data are fitted with a straight line to guide the eye. The slopes of the best fits are 0.08 and 0.73 for $\Delta_p - \Delta_c = 0$ and -80 kHz, respectively.

The experimental data show that the measured width of the retrieved pulse is inversely proportional to the intensity of the reading field and are in agreement with the theoretical prediction. This implies that the distortion of the pulse shape can be corrected by manipulating the retrieval process. In addition, we show that there is no phase shift induced by the process of manipulating the retrieval as long as the two-photon resonance of the coupling and probe frequencies is satisfied. The phase information of the stored pulses can remain intact during the manipulation process. This method provides more freedom in applications of the light-storage technique. The demonstration of the method suggests that the reversible storage of light pulses using EIT is a suitable technique for coherent transfer of quantum states in the quantum network.

This work was supported by the National Science Council of Taiwan under Grant No. 93-2112-M-007-013.

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