Low-Light-Level Cross-Phase-Modulation Based on Stored Light Pulses

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We experimentally demonstrate a low-light-level cross-phase-modulation (XPM) scheme based on the light-storage technique in laser-cooled ^{87}Rb atoms. The proposed scheme can achieve a similar phase shift and has the same figure of merit as one using static electromagnetically induced transparency under the constant coupling field. Nevertheless, the phase shift and the energy loss of a probe pulse induced by a signal pulse are neither influenced by the coupling intensity nor by the atomic optical density in the light-storage XPM scheme. This scheme enhances the flexibility of the experiment and makes possible conditional phase shifts on the order of π with single photons.

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The recent development of slow light arising from electromagnetically induced transparency (EIT) has made storage and retrieval of quantum information carried by photon pulses feasible. In the three-level Λ-type EIT system [1], a weak probe pulse can be completely halted in the atoms by adiabatically switching off the control field, and can be subsequently released intact by the reverse process [2–6]. It has been shown that such reversible storage of the photonic information is coherent and there is no phase jump or shift caused by the switching process [7–9]. This "light-storage" technique using EIT is able to coherently transfer quantum states between photons and atoms [10–15], and has potential applications in quantum networks or quantum communication.

The cross-phase-modulation (XPM) refers to the phase of a photon pulse (probe pulse) modulated by another pulse (signal pulse). It can be employed in the applications of quantum nondemolition measurements and quantum phase gates, and the manipulation of quantum information [16,17]. If large Kerr nonlinearity is attainable in the XPM, the phase shift of the probe pulse will detect the photon number of the signal pulse in the quantum nondemolition measurement. Suppose that phase shifts of the order of π with single-photon pulses can be achieved in the XPM. One can utilize the signal and probe pulses as the control and target qubits to realize the controlled phase gate which is the basic and essential element in the quantum computation. It is also possible to generate entangled photon pairs from the outcomes of the XPM for quantum cryptograph and quantum teleportation. Schmidt and Imamoğlu have proposed a XPM scheme based on the static EIT under the constant coupling field in a four-level system [18]. Their four-level XPM can reach the similar phase shift as the conventional three-level XPM but with much lower light level. Kang and Zhu have measured the spectrum of the probe phase shift in the four-level XPM scheme [19]. They achieved a phase shift of 7.5° by employing the static signal field of the Rabi frequency of about 1.0Γ, where Γ is the spontaneous decay rate of the excited state. In this Letter, we propose and experimentally demonstrate a new XPM scheme based on the light-storage technique. With this light-storage XPM, we obtained a phase shift of 44° of the probe pulse by employing a 2 μs square signal pulse of the Rabi frequency of 0.32Γ. To achieve such a phase shift, the energy transmission of the probe pulse due to the presence of the signal pulse is about 65% or the energy loss is less than e^{-1}.

The light-storage XPM scheme is described below. Figure 1(a) shows the probe and coupling fields form the three-level Λ-type configuration that gives rise to the EIT effect. $|1\rangle$ and $|2\rangle$ are the ground states and $|3\rangle$ is the excited state. A weak probe pulse was stored in a sample by adiabatically switching off the coupling field. During the storage, the ground-state coherence or the atomic spin excitation inherited the information of phase and amplitude of the probe pulse [2]. A signal pulse was applied to affect the phase evolution of the atomic spin excitation as shown

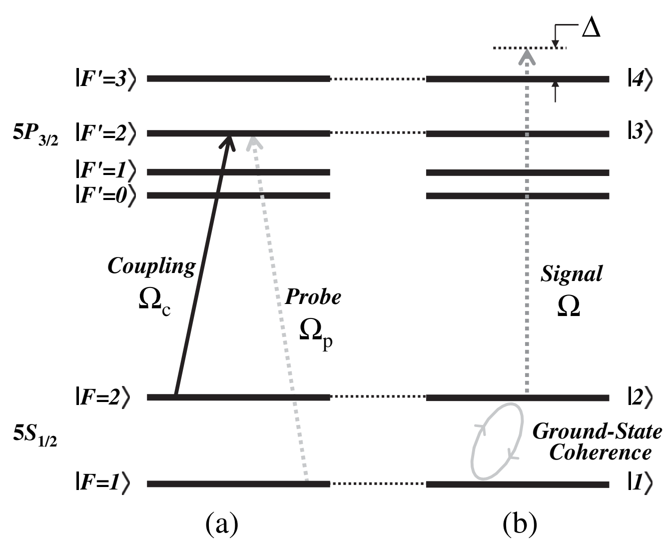

FIG. 1. Relevant energy levels of ^{87}Rb atoms and laser excitations in the experiment. (a) The coupling and probe fields form the Λ-type EIT configuration. (b) The detuned signal field drives the cycling transition during the light storage.

in Fig. 1(b). This pulse drove the cycling transition from $|2\rangle$ to $|4\rangle$ with a detuning of Δ and the Rabi frequency of Ω. After the signal pulse was completed, we coherently converted the atomic spin excitation back to the light by adiabatically switching on the coupling field. The probe pulse acquired a phase shift which was induced by the signal pulse. We analyzed the amounts of phase shift and energy loss of the probe pulse by solving the optical Bloch equation of the density-matrix operator in the system of Fig. 1(b). The relevant equations are given by

$$\frac{d\rho_{21}}{dt} = -i\omega_0\rho_{21} + i\frac{\Omega}{2}e^{i\omega t}\rho_{41} - \gamma\rho_{21}, \quad (1)$$

$$\frac{d\rho_{41}}{dt} = -i\omega_0'\rho_{41} + i\frac{\Omega}{2}e^{-i\omega t}\rho_{21} - \frac{\Gamma'}{2}\rho_{41}, \quad (2)$$

where ω_0 and ω_0' are the $|1\rangle \rightarrow |2\rangle$ and $|1\rangle \rightarrow |4\rangle$ transition frequencies, ω is the frequency of the signal pulse, γ is the ground-state decoherence rate, and Γ' is the angular linewidth of the one-photon transition. The spontaneous decay rate of the excited state, laser linewidth, and others contribute Γ'. We assume that γ is negligible with respect to Γ' as well as Δ, and the change rate of the amplitude of ρ_{21} is small compared to Γ'. For the constant Ω, the solution of ρ_{21} is

$$\rho_{21}(t) = \rho_{21}(0)e^{-i\omega_0 t}\exp\left(-\frac{\Omega^2/4}{\Gamma'/2 - i\Delta}t\right). \quad (3)$$

The phase of ρ_{21} in the second exponential determines the phase shift of the retrieved probe pulse and is given by

$$\phi = -\frac{\Omega^2\Delta}{\Gamma'^2 + 4\Delta^2}\tau, \quad (4)$$

where τ is the presence time of the signal pulse. The ratio of the output and input probe energies is determined by the square of the ρ_{21} amplitude attenuation or $e^{-\alpha}$, where

$$\alpha = \frac{\Omega^2\Gamma'}{\Gamma'^2 + 4\Delta^2}\tau. \quad (5)$$

The figure of merit is defined as ϕ/α ($= \Delta/\Gamma'$). The ϕ/α of the two XPM schemes based on the static EIT [18] and the light storage are the same.

We systematically studied the light-storage XPM in cold ^{87}Rb atoms produced by a magneto-optical trap (MOT). The cold atom cloud was optically thick such that the probe pulse is absorbed to about e^{-7} when propagating alone [20]. The coupling, probe, and signal fields came from three diode lasers, all of which were injection-locked by the same master laser. One beam from the master laser was sent through a 6.8 GHz electro-optic modulator (EOM) (New Focus 4853). The high-frequency sideband of the EOM seeded the probe laser. The coupling field and the probe pulse resonantly drove the $|5S_{1/2}, F = 2\rangle \rightarrow |5P_{3/2}, F' = 2\rangle$ and $|5S_{1/2}, F = 1\rangle \rightarrow |5P_{3/2}, F' = 2\rangle$ transitions. They were circularly polarized with the right helicity. The signal pulse drove the $|5S_{1/2}, F = 2\rangle \rightarrow |5P_{3/2}, F' = 3\rangle$ transition and was circularly polarized with the left helicity. Each of them passed through a distinct acousto-optic modulator (AOM) that could be switched on or off individually. The driving frequencies of these three AOMs were maintained constant throughout the experiment. All three laser fields propagated in nearly the same direction. The diagram of the experimental setup is shown in Fig. 2. The timing sequence of the measurement is very similar to the one described in Ref. [21]. All the laser and magnetic fields of the MOT were turned off during the measurement. A 125 MHz photodiode (New Focus 1801) detected the probe transmission and its output was directly sent to a digital oscilloscope. Data were averaged 256 times by the oscilloscope before being transferred to the computer.

The blue line in Fig. 3(a) shows typical data of the storage and retrieval of the probe pulse. 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. In the caption, Ω_c denotes the Rabi frequency of the coupling field and $\Omega_{p,\max}$ denotes that of the peak of the input Gaussian probe pulse. By employing the beat-note interferometer, we measured the phase shift of the retrieved probe pulse. 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 received by another photodetector (PD2) after propagating through the sample as shown in Fig. 2. The rf frequency of the AOM, ω_a, was 80 MHz, which is sufficiently large that the interaction between the zeroth-order beam and the atoms is negligible. Both beams 1 and 2 carry

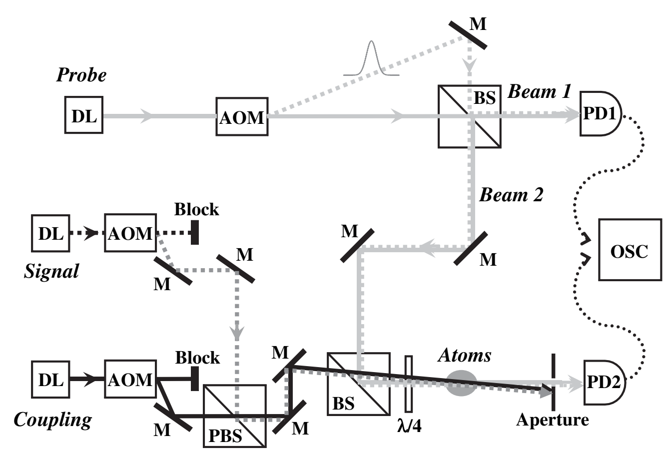

FIG. 2. The experimental setup. DL: diode laser, PD: photodetector, BS: beam splitter cube, PBS: polarizing beam splitter cube, $\lambda/4$: quarter wave plate, M: mirror, OSC: oscilloscope.

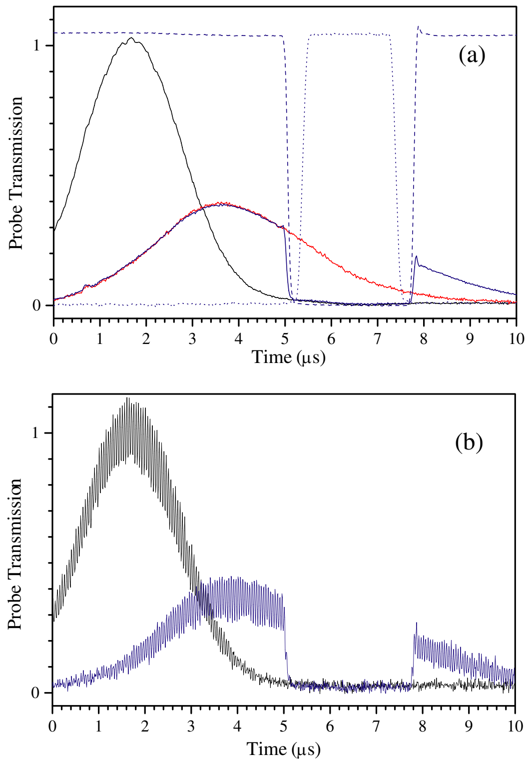

FIG. 3 (color online). $\Omega_{p,\max} = 0.1\Gamma$, $\Omega_c = 0.3\Gamma$, $\Omega = (0.32 \pm 0.02)\Gamma$, and $\Delta = (-4.8 \pm 0.3)\Gamma$. (a) Black and red lines (or black and gray lines in the printed journal) are the probe signals in the absence of the atoms and in the EIT condition. The blue line (or dark gray line with two separated parts) is the probe signal under the condition that the coupling field is switched off momentarily (dashed line) and the signal pulse is applied (dotted line). (b) Black and blue (dark gray) lines are the same as those in (a) except carrying the beat notes.

beat notes at the AOM frequency. The beat-note signals from PD1 and PD2 are proportional to $\cos(\omega_a t + \phi_1)$ and $\cos(\omega_a t + \phi_2 + \phi)$, where ϕ_1 and ϕ_2 are the phases resulting from the optical paths and ϕ is the phase shift due to the atoms. Although ϕ_1 and ϕ_2 fluctuate due to variation of the two optical paths from the AOM to the BS, their difference is always fixed because of the cancellation of the phase fluctuation. By directly comparing the two beat notes in the oscilloscope, we measured the phase shifts in different parts of the pulse that propagates through the atoms. In the absence of the signal pulse, the relative phase of the two beat notes is constant everywhere. There is no observable phase shift due to the storage. In the presence of the signal pulse, we observed a phase shift of ϕ in the retrieved part of the probe pulse but not in the part without the storage. Figure 3(b) demonstrates the data of the phase measurement. The high-frequency signal is the beat note. Details of the phase measurement can be found in Refs. [9,22].

In our experimental system, Γ' is about 1.3Γ determined by the spectral width of the one-photon absorption as well as by considering the laser linewidth and fluctuation of the laser center frequency. The ground-state decoherence rate is approximately 0.002Γ determined by the degree of transparency in the EIT spectrum [20,21]. We used the moderate intensity of the signal pulse in the study or $\Omega^2/(\Gamma'^2 + 4\Delta^2) \ll 1$. Therefore, the assumptions used in the derivation of Eqs. (4) and (5) should be valid for our measurements. Figures 4(a) and 4(b) show the phase shift of the retrieved probe pulse versus the detuning and the Rabi frequency of the signal pulse. Figures 4(c) and 4(d) show the energy transmission (i.e., $e^{-\alpha}$) versus the detuning and the Rabi frequency of the signal pulse. In the four figures, squares are the experimental data and solid lines are the best fits. We fit the experimental data with the functions in Eqs. (4) and (5). In the fitting, Γ' is set to 1.3Γ. For the data in Figs. 4(a) and 4(c), Ω is the fitting parameter. For the data in Figs. 4(b) and 4(d), Δ is the fitting parameter. The Ω and Δ of the best fits are reasonable for the day-to-day fluctuation of the experimental conditions. We notice that ϕ depends on both $1/\Delta$ and Ω^2 linearly at large Δ. This is the expected consequence of the ac Stark shift induced by the signal pulse. We also measured the effects of the blue- and red-detuned signal pulses. The results are in agreement with the predictions of Eqs. (4) and (5). We further verified that the Rabi frequency of the coupling field and the optical density of the atoms do not affect the phase shift and the energy loss. In all the measurements, the storage time of the probe pulse is 2.6 μs and the presence time of the square signal pulse is 2.0 μs.

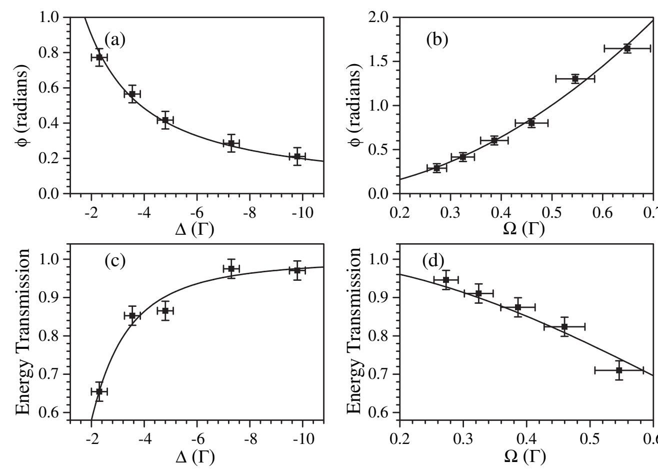

FIG. 4. $\Omega_{p,\max} = 0.1\Gamma$, $\Omega_c = 0.3\Gamma$, and $\tau = 2.0$ μs. The phase shift versus the detuning in (a) and versus the Rabi frequency in (b). The energy transmission versus the detuning in (c) and versus the Rabi frequency in (d). Squares are the experimental data measured at $\Omega = (0.32 \pm 0.02)\Gamma$ for (a) and (c) and at $\Delta = (-4.8 \pm 0.3)\Gamma$ for (b) and (d). Solid lines are the best fits with $\Omega = 0.33\Gamma$ in (a), $\Delta = -4.5\Gamma$ in (b), $\Omega = 0.32\Gamma$ in (c), and $\Delta = -4.8\Gamma$ in (d).

The light-storage XPM scheme is a robust method. The amounts of the phase shift and the energy loss caused by the signal pulse neither depend on the intensity of the coupling field nor the optical density of the medium. We can freely control the coupling intensity and the optical density such that a desired probe pulse is able to satisfy the EIT transparency bandwidth and be completely stored in the medium. As shown in Eq. (4), only the energy per unit area or $\Omega^2\tau$ of the signal pulse affects the phase shift at a fixed detuning. For a slowly-varying signal pulse, this energy per unit area is just proportional to $\int[\Omega(t)]^2 dt$. Since the probe pulse is stored in the medium, we can use not only a stronger and shorter signal pulse but also a weaker and longer one to achieve the desired phase shift as long as the decay of the ground-state coherence is mainly due to the signal pulse. The light-storage XPM scheme can greatly enhance the flexibility of the experiment. This flexibility can be a very useful merit in the applications of manipulation of quantum information.

We now consider the feasibility of achieving phase shifts of the order of π with single signal photons. Suppose that the coupling intensity and the optical density are suitable such that a probe pulse is completely stored in the medium with little energy loss. Both the probe and signal pulses are tightly focused to an area of about $\lambda^2/2\pi$. Since the amount of the phase shift is determined by the energy per unit area according to Eq. (4), the signal pulse width is not critical. One can focus a single-photon signal pulse to an area of $\lambda^2/2\pi$ to obtain $\Omega^2\tau$ of 3Γ. The signal pulse will be detuned 3.2Γ in order to maintain a good figure of merit. Under the above conditions, a phase shift of about $13°$ and an energy loss of about 7% for the probe pulse can be achieved. Furthermore, if an optical cavity or other method is employed to increase the interaction time between the pulse and the sample 14-fold, a phase shift of π and an energy transmission of e^{-1} for the probe pulse will be expected. Larger energy transmission at the phase shift of π can be obtained by increasing the detuning and the interaction time together.

In conclusion, we have proposed and systematically studied the light-storage XPM scheme. The experimental data are in agreement with the theoretical predictions. This XPM scheme is a robust method and enhances the flexibility of the experiment. With the method, a phase shift of π of a single-photon pulse induced by another is feasible.

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