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Phase-controlled light switching at low light levels

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We report experimental observations of interference between three-photon and one-photon excitations, and phase control of light attenuation and/or transmission in a four-level system. Either constructive or destructive interferences can be obtained by varying the phase and/or frequency of a weak control laser. The interference enables absorptive switching of one field by another field at different frequencies and ultralow light levels.

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Laser-induced interference plays an important role in interactions of radiation and matter, and has found numerous applications in optical physics. One such example is electromagnetically induced transparency (EIT) [1]. EIT has been used to obtain slow light speed in an absorbing medium [2] and to study nonlinear optics at low light levels down to single photons [3]. It has been shown that the EIT technique may be used to explore quantum information science [4].

Light switching light at low light levels based on quantum interference or other mechanisms has been studied in recent years and quantum light switching with single photons may have important applications in quantum electronics [5]. Here we present a scheme based on phase-controlled quantum interference that may be used to realize a single-photon light switch. We report experimental observations of interference between three-photon and one-photon excitations in a four-level system and the resulting phase switching of light absorption and/or transmission at low light powers ($<10^{-7}$ W). We show that the interference leads to interesting spectral and dynamic features, and one weak field can be used to control another weak field, and vice versa, at ultralow light levels.

Before proceeding further, we note that Georgiades *et al.* observed quantum interference of two-photon transitions in cold atoms [6]; Korsunsky *et al.* studied the phase-dependent coherent population trapping (CPT) [7]; Huss *et al.* reported correlation of the phase fluctuation in a double-Λ system [8]; Deng and Payne showed that EIT can be induced by destructive interference between three-photon and one-photon excitation channels, and, that a pair of matched light pulses can be generated in a three-level medium [9]. Also, a variety of other phenomena and applications involving three- or four-level EIT systems has been studied in recent years [10–21].

Consider a four-level system driven by two coupling fields (Fig. 1). The coupling field 1 (2) drives the transition $|2\rangle$-$|3\rangle$($|4\rangle$) with Rabi frequency $\Omega_1(\Omega_2)$. Two weak fields, one as a probe and another as a control, drive the transitions $|1\rangle$-$|3\rangle$ and $|1\rangle$-$|4\rangle$ with Rabi frequency Ω_p and Ω_c (the probe and control are interchangeable). Here $\Omega_i=|\Omega_i|e^{i\phi_i}$ ($i=1$, 2, p, and c) is characterized by the amplitude $|\Omega_i|$ and phase ϕ_i. The frequency detunings for the respective transitions are defined as $\Delta_p=\omega_p-\omega_{31}, \Delta_1=\omega_1-\omega_{32}, \Delta_c=\omega_c-\omega_{41}$, and $\Delta_2=\omega_2-\omega_{42}$ [ω_i ($i=p$, 1, c, 2) is the angular frequency of the laser field i]. For $|\Omega_1|\sim|\Omega_2|, |\Omega_p|\sim|\Omega_c|, |\Omega_{1(2)}|\gg|\Omega_{c(p)}|$, and $\Delta_i=0$ ($i=p$, 1, c, and 2), the adiabatic excited-state populations are

$$P_3=\left|\frac{\Omega_p(|\Omega_2|^2+\gamma_2\gamma_4)-\Omega_1\Omega_2^*\Omega_c}{\gamma_2\gamma_3\gamma_4+\gamma_3|\Omega_2|^2+\gamma_4|\Omega_1|^2}\right|^2 \quad (1a)$$

and

$$P_4=\left|\frac{\Omega_c(|\Omega_1|^2+\gamma_2\gamma_3)-\Omega_2\Omega_1^*\Omega_p}{\gamma_2\gamma_3\gamma_4+\gamma_3|\Omega_2|^2+\gamma_4|\Omega_1|^2}\right|^2, \quad (1b)$$

where γ_2 is the decay rate of the ground-state coherence ρ_{12}. The first term in Eqs. (1a) and (1b) represents the one-photon excitation $|1\rangle$- $|3\rangle$ ($|1\rangle$-$|4\rangle$) while the second term represents the three-photon excitation $|1\rangle$-$|4\rangle$-$|2\rangle$-$|3\rangle$ ($|1\rangle$-$|3\rangle$-$|2\rangle$-$|4\rangle$). The two excitation paths interfere with each other, and can be manipulated by varying the phases and amplitudes of the laser fields. When $\Omega_1\Omega_c=\Omega_2\Omega_p$ [neglecting γ_2, which is justified due to $|\Omega_{1(2)}|\gg\gamma_2$ and $\gamma_{3(4)}\gg\gamma_2$], the interference is destructive: P_3 and P_4 vanish, and the probe and control fields propagate in the medium without attenuation. When $\Omega_1\Omega_c=-\Omega_2\Omega_p$, the interference is constructive: P_3 and P_4 are maximized, and the probe and control fields are attenuated in the medium. The four-level system can be used for absorptive switching of one weak field by another weak field. To discuss the interference switching, we consider propagation of the probe and control fields in the four-level medium of length ℓ. For $\Omega_1\sim\Omega_2, \Omega_p\sim\Omega_c, \Omega_{1(2)}\gg\Omega_{c(p)}, \Delta_c=\Delta_p$, and the four laser fields propagate in the z direction (neglecting depletion of the two coupling fields), the Maxwell equations for the two weak fields are

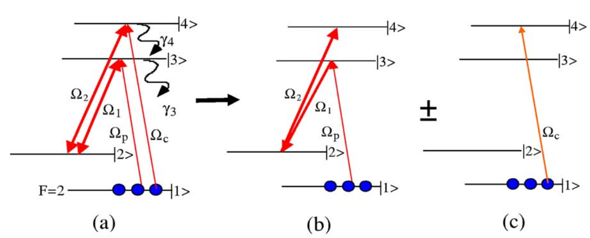

FIG. 1. (Color online) (a) Four-level system. $\gamma_3(\gamma_4)$ is the spontaneous decay rate ($\gamma_3\approx\gamma_4=2\pi\times5.4\times10^6$ s^{-1}). Interference occurs between (b) three-photon excitation $|1\rangle$-$|3\rangle$-$|2\rangle$-$|4\rangle$ and (c) one-photon excitation $|1\rangle$-$|4\rangle$. The interference between three-photon excitation $|1\rangle$-$|4\rangle$-$|2\rangle$-$|3\rangle$ and one-photon excitation $|1\rangle$-$|3\rangle$ is not drawn here.

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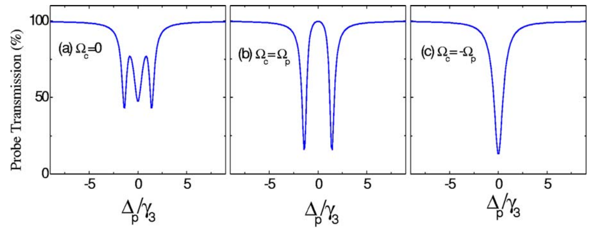

FIG. 2. (Color online) (a) Calculated probe transmission vs Δ_p without the control laser. (b) Calculated probe transmission vs $\Delta_p=\Delta_c$ with $\Omega_c(0)=\Omega_p(0)$. The absorption is suppressed by destructive interference at $\Delta_p=0$ and enhanced by constructive interference at $\Delta_p=\pm\Omega$. (c) Calculated probe absorption vs $\Delta_p=\Delta_c$ with $\Omega_c(0)=-\Omega_p(0)$. The absorption is enhanced by constructive interference at $\Delta_p=0$ and suppressed by destructive interference at $\Delta_p=\pm\Omega$. The parameters are $\Omega_1=\Omega_2=\gamma_3, \gamma_3=\gamma_4, \gamma_2=0.02\gamma_3, \Delta_1=\Delta_2=0$, and $K_{13}\ell/\gamma_3=K_{14}\ell/\gamma_4=1$.

$$\frac{d\Omega_p}{dz}=\frac{iK_{13}(|\Omega_1|^2-\delta_1\delta_c)}{\Lambda}\Omega_p-\frac{iK_{13}\Omega_1\Omega_2^*}{\Lambda}\Omega_c, \tag{2a}$$

$$\frac{d\Omega_c}{dz}=\frac{iK_{14}(|\Omega_2|^2-\delta_1\delta_p)}{\Lambda}\Omega_c-\frac{iK_{14}\Omega_1^*\Omega_2}{\Lambda}\Omega_p. \tag{2b}$$

Here $\delta_p=\Delta_p+i\gamma_3, \delta_1=\Delta_p-\Delta_1+i\gamma_2, \delta_c=\Delta_c+i\gamma_4$, and $\Lambda=\delta_1\delta_2\delta_p-\delta_p|\Omega_2|^2-\delta_2|\Omega_1|^2$, and $K_{ij}=2\pi N\omega_{ij}|\mu_{ij}|^2/\hbar c$ (N is the atomic density).

Equations (2a) and (2b) can be solved analytically. Figure 2 plots the calculated probe transmission versus Δ_p in the four-level system. Without the control field [Fig. 2(a)], the probe field is attenuated in the medium with peak absorptions at $\Delta_p\sim\pm\Omega=\pm\sqrt{\Omega_1^2+\Omega_2^2}$ and $\Delta_p=0$ (EIT enhanced nonlinear absorption [5]). When the control field is present and $\Omega_p(0)\Omega_2=\Omega_c(0)\Omega_1$ [$\Omega_{p(c)}(0)$ is the incident probe (control) Rabi frequency at $z=0$], the absorption for the probe and the control at $\Delta_p=\Delta_c=0$ are suppressed (destructive interference) while the absorption for the probe and the control at $\Delta_p=\Delta_c\approx\pm\Omega$ are enhanced (constructive interference) [Fig. 2(b)]. That is, EIT is induced simultaneously for both the probe and control fields at $\Delta_p=\Delta_c=0$. The group velocity of the two weak fields are given by

$$V_{g(p)}=c/\left(1+\frac{\omega_p}{2}\frac{\gamma_4K_{13}}{\gamma_3|\Omega_2|^2+\gamma_4|\Omega_1|^2}\right)$$

and

$$V_{g(c)}=c/\left(1+\frac{\omega_c}{2}\frac{\gamma_3K_{14}}{\gamma_3|\Omega_2|^2+\gamma_4|\Omega_1|^2}\right).$$

Matching of the slow group velocities, $V_{g(p)}\approx V_{g(c)}$, is possible for atomic systems in which $\omega_p\gamma_4K_{13}\approx\omega_c\gamma_3K_{14}$ (such as the Rb system of Fig. 3), and the four-level system may be used to produce a pair of matched light pulses [9]. On the other hand, when the four laser fields satisfy the condition $\Omega_p(0)\Omega_2=-\Omega_c(0)\Omega_1$, the probe and control absorptions at $\Delta_p=\Delta_c=0$ are enhanced (constructive interference) while the probe and control absorptions at $\Delta_p=\Delta_c\approx\pm\Omega$ are suppressed (destructive interference) [Fig. 2(c)]. We note that the calculations are valid for arbitrarily weak probe and control fields. The interference requires the control Rabi frequency satisfying $|\Omega_c(0)|=|\Omega_p(0)\Omega_2/\Omega_1|$. With $|\Omega_c(0)|=\sqrt{n_c}g_c$ and $|\Omega_p(0)|=\sqrt{n_p}g_c$ [$n_{c(p)}$ is the average number (expectation value) of the control (probe) photons and $g_{c(p)}$ is the coupling coefficient], the amplitude condition becomes $n_c=|\Omega_2g_p/(\Omega_1g_c)|^2n_p=\alpha n_p$ (α can be $\geqslant 1$ or <1).Thus the phase-controlled interference may be implemented near single-photon levels ($n_c\sim n_p\sim 1$) and the four-level system may be used as an absorptive quantum switch, which turns on or off single probe photons by single control photons at different frequencies. We note that when the photon number approaches one, the quantum fluctuation is important, and understanding of the statistical properties of the photon switching requires calculations of the second-order noise correlations in the four-level system.

The dressed state picture provides a simple explanation for the interference of the two weak fields in the four-level system. The two resonant coupling fields create a manifold of three dressed states, the semiclassical representation of which is given by

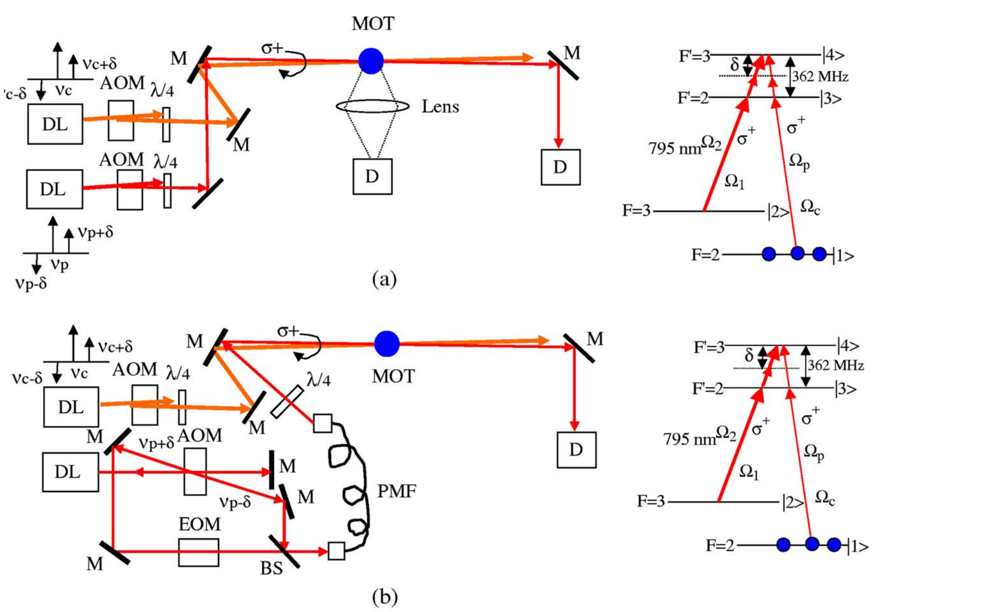

FIG. 3. (Color online) (a) Simplified diagram of the experimental setup with two frequency modulated lasers and the coupled four-level ^{85}Rb system. (b) Simplified diagram of the experimental setup used for measurements of the light transmission vs the phase variation of the control field. AOM: acousto-optic modulator; EOM: electro-optic modulator; PMF: polarization maintaining fiber; $\lambda/4$: quarter-wave plate; DL: extended-cavity diode laser; M: mirror; D: photodetector.

$$|+\rangle = \frac{1}{\sqrt{2}}\left\{|1\rangle - \frac{\Omega_1}{\Omega}|3\rangle - \frac{\Omega_2}{\Omega}|4\rangle\right\},$$

$$|0\rangle = \frac{\Omega_2}{\Omega}|3\rangle - \frac{\Omega_1}{\Omega}|4\rangle,$$

and

$$|-\rangle = \frac{1}{\sqrt{2}}\left\{|1\rangle + \frac{\Omega_1}{\Omega}|3\rangle + \frac{\Omega_2}{\Omega}|4\rangle\right\}\left(\Omega = \sqrt{\Omega_1^2 + \Omega_2^2}\right).$$

The corresponding level shifts are Ω, 0, and $-\Omega$ respectively. With two weak fields Ω_c and Ω_p, the transition probability from the state $|1\rangle$ to the dressed states $|+\rangle$ and $|-\rangle$ is $P_{1\pm} \propto |\Omega_p\Omega_1 + \Omega_c\Omega_2|^2 = |\Omega_p|^2|\Omega_1|^2 + |\Omega_c|^2|\Omega_2|^2 + 2|\Omega_p||\Omega_1||\Omega_c||\Omega_2|\cos(\Phi_2 + \Phi_c - \Phi_1 - \Phi_p)$, and the transition probability from the state $|1\rangle$ to the dressed state $|0\rangle$ is $P_{10} \propto |\Omega_p\Omega_2 - \Omega_c\Omega_1|^2 = |\Omega_p|^2|\Omega_2|^2 + |\Omega_c|^2|\Omega_1|^2 - 2|\Omega_p||\Omega_1||\Omega_c||\Omega_2|\cos(\Phi_2 + \Phi_c - \Phi_1 - \Phi_p)$. Φ_i (i=1, 2. c, and p) is the phase of the laser field. The interference between the two excitation paths can be manipulated by varying the amplitudes and phases of the four laser fields. For example, when $\Omega_1 = \Omega_2$ and $\Omega_c = \Omega_p$, complete destructive interference occurs for the transitions $|1\rangle$-$|0\rangle$ while complete constructive interference occurs for the transitions $|1\rangle$-$|\pm\rangle$.

Our experiment is done with cold ^{85}Rb atoms confined in a magneto-optical trap (MOT) described in our earlier studies [11]. A simplified experimental setup with two frequency modulated lasers for the spectral measurements is depicted in Fig. 3(a). An extended-cavity diode laser with a beam diameter ~3 mm and output power ~50 mW is used as the coupling laser. The driving electric current to the diode laser is modulated at δ=181 MHz with a modulation index ~0.5, which produces two first-order frequency sidebands separated by 362 MHz. The two sidebands are tuned to the ^{85}Rb$D_1 F=3 \rightarrow F'=2$ and $F=3 \rightarrow F'=3$ transitions, respectively, and serve as the two coupling fields ($\Omega_1 \approx -\Omega_2$ due to a π phase difference between the two sidebands). Another extended-cavity diode laser with a beam diameter ~0.4 mm and output power attenuated to ~0.1 mW is also current modulated at 181 MHz and the two first-order sidebands are tuned to the $D_1 F=2 \rightarrow F'=2$ and $F=2 \rightarrow F'=3$ transitions, serving as the probe field, and control field, respectively ($\Omega_c \approx -\Omega_p$). The carrier and the higher-order sidebands of the coupling and weak lasers are detuned from the atomic transitions by at least 181 MHz and their effects on the four-level system can be neglected at the laser intensity levels used in the experiment. The coupling and weak lasers are circularly polarized (σ^+) and interact with the Rb transitions to form four separate sets of the double-Λ-type four-level system among the magnetic sublevels. The two lasers propagate in the same direction separated by a small angle (~1°) and overlapped inside the MOT. The transmitted beam of the weak laser (both the probe and the control) is collected by a photodetector, and the fluorescence photons from spontaneous emissions of the atoms in the excited states $|3\rangle$ and $|4\rangle$ are collected by another photodetector after the imaging optics.

The experiment is run in a sequential mode with a repetition rate of 5 Hz. All lasers are turned on or off by acousto-optic modulators (AOM) according to the time sequence described below. For each period of 200 ms, ~198 ms is used for cooling and trapping of the ^{85}Rb atoms, during which the trapping and repump lasers are turned on by two AOMs while the coupling and weak lasers are off. The time for the data collection lasts ~2 ms, during which the trapping and repump lasers are turned off as well as the current to the anti-Helmholtz coils of the MOT, and the coupling and weak lasers are turned on. For the spectral measurements, the weak laser frequency is scanned across the ^{85}Rb$D_1 F=2 \rightarrow F'$ transitions after a 0.1-ms delay and the transmission of the weak laser and the fluorescent photons (proportional to the excited-state population) are then recorded.

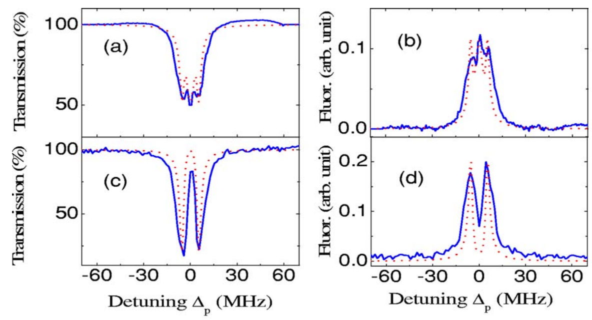

FIG. 4. (Color online) Measured probe transmission [(a) and (c)] and measured fluorescence intensity [(b) and (d)] vs the detuning $\Delta_c = \Delta_p$. The solid (dashed) lines are experimental data (calculations). In (a) and (b), the weak laser is not frequency modulated (no control field component). In (c) and (d), the weak laser is frequency modulated to produce two sidebands used as the probe and control fields, and the absorption peaks at Δ_p=0 in (a) and (b) are suppressed by the destructive interference. The experimental parameters are $\Omega_1/(2\pi) \approx \Omega_2/(2\pi) \approx 4$ MHz, $\Omega_p/(2\pi) \approx \Omega_c/(2\pi) \approx 0.2$ MHz, and $\Delta_1 = \Delta_2 = 0$. The fitting parameters are $\gamma_2 \approx 0.02\gamma_3, K_{13}\ell/\gamma_3 = K_{14}\ell/\gamma_4 = 0.8$.

The light transmission and the fluorescence intensity versus the weak laser detuning ($\Delta_c = \Delta_p$) are plotted in Fig. 4. Figures 4(a) and 4(b) show the measurements without the control field (the weak laser is not frequency modulated) and represents the EIT manifested absorption spectra in the four-level system observed before [5]. The light transmission spectrum with both the probe and control fields present (the weak laser is frequency modulated) is plotted in Fig. 4(c), and shows that the absorption at the resonance ($\Delta_p = \Delta_c = 0$) is suppressed by the destructive interference, which results in simultaneous EIT for both the probe and control fields. Correspondingly, the measured fluorescence intensity is suppressed at $\Delta_p = \Delta_c = 0$ [Fig. 4(d)], which demonstrates the suppression of the excited-state population by the destructive interference between three- and one-photon excitations.

We studied the phase switching of the probe absorption and/or transmission in the four-level system with an experimental setup shown in Fig. 3(b). With an AOM, we obtain two first-order beams of the weak laser: one as the probe (the frequency shifted down by δ) and another as the control (the frequency shifted up by δ). The upshifted control beam is then passed through an electro-optic modulator (EOM, New Focus 4002) and its phase is varied by a voltage applied to the EOM. The two beams with about equal powers are combined in a beam combiner and then are coupled into a

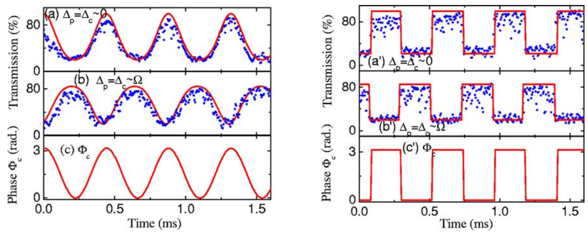

FIG. 5. (Color online) Transmission of the control and the probe fields vs the phase variation of the control field. The dots are experimental data and the solid lines are calculations with the adiabatic phase change. Left panel: $\Phi_c = \pi \cos(2\pi f t) + \varphi_0$ (f=2.3 KHz and φ_0 is set by the dc offset voltage). Right panel: square-wave shift of Φ_c (between 0 and π) at f=2.3 KHz. (a) and (a′): the light transmission at $\Delta_c = \Delta_p \approx 0$; (b) and (b′): the light transmission at $\Delta_c = \Delta_p \approx \Omega$; (c) and (c′): the control-laser phase ϕ_c vs time. $\Omega_1/(2\pi) \approx \Omega_2/(2\pi) \approx 4.5$ MHz, and the other parameters are the same as those in Fig. 4.

polarization-maintaining single-mode fiber, the output of which is collimated, attenuated to a power level of $<10^{-7}$ W (the intensity $\sim$0.1mW/cm^2), and directed to be overlapped with the frequency modulated coupling laser in the MOT. The transmission of the combined probe and control beams is collected by a photodetector. The left panel of Figs. 5(a) and 5(b) plots the transmitted probe and control beams versus the control laser phase Φ_c as Φ_c is varied by a sinusoidal voltage applied to the EOM [Fig. 5(c)]. Figure 5(a) plots the light transmission versus Φ_c at $\Delta_p = \Delta_c \approx 0$ and Fig. 5(b) plots the light transmission versus Φ_c at $\Delta_p = \Delta_c \approx \Omega$. The data show that there is a π phase difference in the interference pattern between the two cases, illustrating the phase and frequency control of the light transmission by the quantum interference. The right panel of Figs. 5(a) and 5(b) plots the transmitted light intensity versus time when a square-wave voltage is applied to the EOM to switch Φ_c from 0 to π. The data show the periodic switching of the light transmission versus Φ_c and the switching pattern is reversed through the π phase reversal at different frequencies. The switching efficiency may be defined as $\eta = (I_{close} - I_{open})/I_{in}$. Here I_{in} is the incident light intensity, I_{close} is the transmitted intensity when the switch is closed, and I_{open} is the transmitted intensity when the switch is open. For perfect switching, $\eta = 100\%$ ($I_{close} = I_{in}$ and $I_{open} = 0$). In our experiments, when the switch is open, the light transmission is $\approx$20%, which is limited by the optical depth of the cold atomic cloud; when the switch is closed, the light transmission is $\approx$80%, which is limited by the absorption loss due to the laser frequency drifts, the Zeeman broadening from the residual magnetic field, and the decay rate γ_2 of the ground-state coherence. The observed switching efficiency is $\eta \approx 60\%$ for $\Delta_p = \Delta_c \approx 0$ and $\eta \approx 55\%$ for $\Delta_p = \Delta_c \approx \Omega$.

In conclusion, we have observed interference of three- and one-photon excitations in a four-level system, and demonstrated the phase and frequency control of the absorptive switching at low light levels ($\sim$0.1mW/cm^2). The four-level phase control scheme can be used to produce matched slow light pulses and may lead to realistic implementation of a quantum switch in which the attenuation and/or transmission of single photons is controlled by single photons at different frequencies.

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[1] S. E. Harris, Phys. Today **50**, 36 (1997).
[2] L. V. Hau *et al.*, Nature (London) **397**, 594 (1997); M. M. Kash *et al.*, Phys. Rev. Lett. **82**, 5229 (1999); D. Budker *et al.*, *ibid.* **83**, 1767 (1999).
[3] S. E. Harris and L. V. Hau, Phys. Rev. Lett. **82**, 4611 (1999).
[4] M. D. Lukin and A. Imamoglu, Phys. Rev. Lett. **84**, 1419 (2000); Nature (London) **413**, 273 (2001).
[5] S. E. Harris and Y. Yamamoto, Phys. Rev. Lett. **81**, 3611 (1998); B. S. Ham and P. R. Hemmer, *ibid.* **84**, 4080 (2000); K. J. Resch, *et al.*, *ibid.* **87**, 123603 (2001); K. J. Resch *et al.*, *ibid.* **89**, 037904 (2002); H. Schmidt and R. J. Ram, Appl. Phys. Lett. **76**, 3173 (2000); M. Yan *et al.*, Phys. Rev. A **64**, 041801(R) (2001); D. A. Braje *et al.*, *ibid.* **68**, 041801(R) (2003); Y. F. Chen *et al.*, *ibid.* **69**, 063801 (2004); H. Wang, *et al.*, Opt. Lett. **27**, 1354 (2002); A. Dawes, *et al.*, Science **29**, 672 (2005).
[6] N. Georgiades, *et al.*, Opt. Lett. **21**, 1688 (1996).
[7] E. A. Korsunsky *et al.*, Phys. Rev. A **59**, 2302 (1999).
[8] A. F. Huss *et al.*, Phys. Rev. Lett. **93**, 223601 (2004).
[9] L. Deng and M. G. Payne, Phys. Rev. A **71**, 011803(R) (2005).
[10] H. Schmidt and A. Imamoglu, Opt. Lett. **21**, 1936 (1996); A. B. Matsko *et al.*, *ibid.* **28**, 96 (2003).
[11] H. Kang and Y. Zhu, Phys. Rev. Lett. **91**, 093601 (2003); H. Kang, *et al.*, *ibid.* **93**, 073601 (2004).
[12] A. J. Merriam *et al.*, Phys. Rev. Lett. **84**, 5308 (2000); D. A. Braje *et al.*, *ibid.* **93**, 183601 (2004).
[13] P. R. Hemmer *et al.*, Opt. Lett. **20**, 982 (1995); Y. Li and M. Xiao, *ibid.* **21**, 1064 (1996); B. L. Lu, *et al.*, *ibid.* **23**, 804 (1998); B. S. Ham, *et al.*, *ibid.* **24**, 86 (1999).
[14] M. D. Lukin *et al.*, Phys. Rev. Lett. **82**, 1847 (1999); M. D. Lukin, *et al.*, Adv. At., Mol., Opt. Phys. **42**, 347 (2000); S. F. Yelin *et al.*, Phys. Rev. A **68**, 063801 (2003); A. S. Zibrov *et al.*, *ibid.* **65**, 051801(R) (2002).
[15] W. Harshawardhan and G. S. Agarwal, Phys. Rev. A **58**, 598 (1998); G. S. Agarwal and S. Dasgupta, *ibid.* **65**, 053811 (2002).
[16] J. C. Petch *et al.*, Phys. Rev. A **53**, 543 (1996); C. Dorman, *et al.*, *ibid.* **61**, 013802 (2000).
[17] M. T. Johnsson and M. Fleischhauer, Phys. Rev. A **66**, 043808 (2002); H. Shpaisman, *et al.*, *ibid.* **70**, 063814 (2005).
[18] M. G. Payne and L. Deng, Phys. Rev. Lett. **91**, 123602 (2003); T. Hong, *ibid.* **90**, 183901 (2003); Y. Wu and L. Deng, *ibid.* **93**, 143904 (2004).
[19] K. Hakuta *et al.*, Phys. Rev. Lett. **79**, 209 (1997); Q. Liang *et al.*, *ibid.* **85**, 2474 (2000).
[20] D. Vitali, *et al.*, Phys. Rev. Lett. **85**, 445 (2000); C. Ottaviani *et al.*, *ibid.* **90**, 197902 (2003); D. Petrosyan and G. Kurizki, Phys. Rev. A **65**, 033833 (2002); I. Friedler *et al.*, *ibid.* **71**, 023803 (2005).
[21] M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. **84**, 5094 (2000); D. Phillips *et al.*, *ibid.* **86**, 783 (2001); A. V. Turukhin *et al.*, *ibid.* **88**, 023602 (2002); C. Liu *et al.*, Nature (London) **409**, 490 (2001).