

All-optical image switching in a double- Λ system

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Abstract: The coherent control of optical images has garnered attention because all information embedded in optical images is expected to be controlled in a parallel way. One of the most important control processes is switch for information delivery. We experimentally demonstrated phase-controlled optical image switching in a double- Λ system where the transmission of the image through a medium was switched. Two independent laser sources were adopted for a double- Λ system such that images inscribed in two weak probe light beams were incoherent with each other. Arbitrary phase was added to the optical images to show that switching could be accomplished just with the relative phase difference between the probe pixels.

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1. Introduction

Optical image contains a range of information on each pixel depending on the intensity and phase of the light field. Once information is inscribed in each pixel, parallel information processing is possible by controlling the image communication network. Recently, coherent controls including slow light and light storage have been applied to optical images [1–3]. In addition, in the quantum information science, there are considerations on using quantum images for the parallel logical processing of photonic qubits; entangled images have already been generated by four-wave mixing in a four-level system [4, 5]. It has also been demonstrated that the optical image resolution can be improved at the sub-shot-noise level by using entangled images generated by a parametric down conversion [6]. Based on quantum interference, light switching with a light has already been studied and quantum light switching with single photons may have important applications in quantum electronics. Based on electromagnetically induced transparency (EIT), four-state atomic system was suggested as a switching device for controlling two-photon absorption that could be realized at single photon level [7, 8]. Enhanced three-photon absorption induced by large Kerr effect in a four-state system was experimentally observed to investigate the switching feasibility [9]. Furthermore, M. Bajcsy et al. demonstrated a fiber-optical switch that was activated at extremely low energies corresponding to a few hundreds of optical photons per pulse [10]. This was achieved by simultaneous confining both photons and a small laser cooled ensemble of atoms inside the microscopic hollow core of a single-mode photonic-crystal fiber and using quantum optical techniques for generating slow light propagation and large nonlinear interaction between light beams. Y.H. Chen et al. demonstrated that two light pulses could be made motionless and interact with each other through a medium. The scheme with motionless light pulses maximized the interaction time and could work with a considerable efficiency even below single-photon level [11]. Pulse matching in two modes, using a three-level double- Λ system was also studied to show that two mode group velocities could be matched using a controllable four-wave mixing channel [12]. Phase-controlled switching effect was subsequently demonstrated experimentally in a double Lambda four-level system, implemented by rubidium cold atoms [13, 14]. J. Zhang et al. demonstrated all-optical

switching at ultra-low light levels where a signal light pulse was switched on and off by a control light pulse at frequencies different with that of the signal. The control light pulses contained 20 photons each, what corresponds to a control energy density of 10^{-5} photons per atomic cross section [15, 16]. A double- Λ system with non-resonant intermediate states also has been studied to show phase-dependent switching effects [17, 18]. Meanwhile, Rydberg atoms were considered for quantum light switch in order to account for atom-photon and photon-photon correlations, which would open up a general framework for studying many-body physics with strongly interacting photons [19]. Image processes with four-wave mixing really have been done already but our image switching technique is quite different from the previous works [21]. Our image switching is allowed for ultra low intensity images however others need high intensity images due to the low efficiency of four-wave mixing. It is the first work that all-optical switching in a double- system is applied to optical image switching. All-optical image switching might be extended to quantum image switching at the same reason that all-optical switching at ultra-low light level is expected to be applied to nonclassical photon switching.

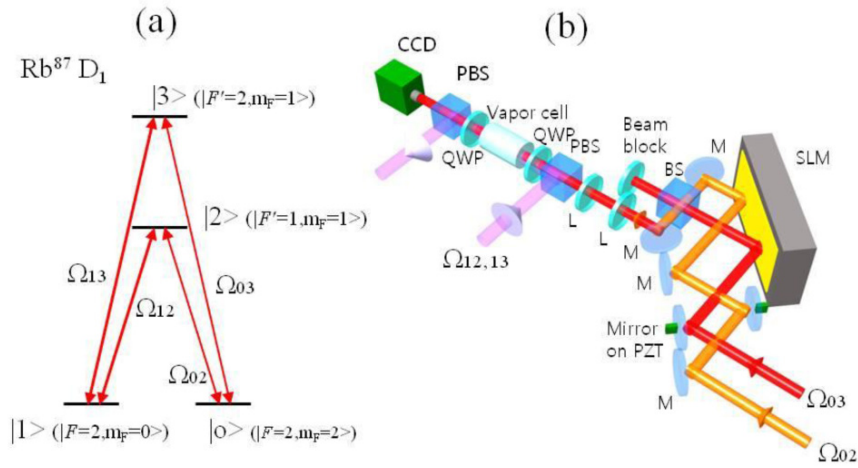


Fig. 1. A double- Λ system and Experimental set-up. (a) A double- Λ system implemented with Zeeman levels of rubidium 87 D1 transition. (b) Experimental set-up for optical image switching with two independent extended-cavity diode lasers, polarization beam splitter (PBS), beam splitter (BS) and mirror (M), imaging lens (L), and spatial light modulator (SLM).

2. Theory

Phase-controlled switching in a double- Λ system can be understood as the quantum interference between one-photon ($\langle 0| \rightarrow \langle 3|$) and three-photon process ($\langle 0| \rightarrow \langle 2| \rightarrow \langle 1| \rightarrow \langle 3|$) when phase matching condition is satisfied (Fig. 1). When the interference of two excitation paths is destructive, there is no excitation under the Rabi frequencies condition, $\frac{\Omega_{02}}{\Omega_{03}} = \frac{\Omega_{12}}{\Omega_{13}}$ where $\Omega_{ij} = |\Omega_{ij}|e^{ij}$, so both probe fields propagate in the medium with no attenuation. It is assumed that coupling fields $\Omega_{12,13}$ are much stronger than probe fields $\Omega_{02,03}$. When $\frac{\Omega_{02}}{\Omega_{03}} = -\frac{\Omega_{12}}{\Omega_{13}}$, the interference is constructive and both probe fields are attenuated. The transmission of the probe field (Ω_{03}) is depending on the relative phase difference between the coupling and probe fields and calculated theoretically as following. Schrödinger equations of a double- Λ system

with dipole interactions reads next three equations in nondepleted ground state assumption.

$$\begin{aligned}
a_0 &= 1, \\
\dot{a}_1 &= i\Omega_{12}a_2 + i\Omega_{13}a_3 + i(\Delta_2 - \Delta_1 + i\Gamma_1)a_1, \\
\dot{a}_2 &= i\Omega_{20} + i\Omega_{21}a_1 + i(\Delta_2 + i\Gamma_2)a_2, \\
\dot{a}_3 &= i\Omega_{30} + i\Omega_{31}a_1 + i(\Delta_2 - \Delta_1 + \Delta_3 + i\Gamma_3)a_3.
\end{aligned} \tag{1}$$

where a_i is the probability amplitude of i level state in Fig. 1(a), Ω_{ij} is the half Rabi frequency between i and j level in the dipole interaction field, Γ_i is decay rate of i level and Δ_i is the detuning of photon energy from interval between two energy levels: $\Delta_1 = \omega_{21} - \frac{E_2 - E_1}{\hbar}$, $\Delta_2 = \omega_{20} - \frac{E_2 - E_0}{\hbar}$, $\Delta_3 = \omega_{31} - \frac{E_3 - E_1}{\hbar}$. To solve above equations, Maxwell equations should be considered with the approximation of slow varying amplitude and phase,

$$\begin{aligned}
\left(\frac{\partial}{\partial z} + \frac{1}{c} \frac{\partial}{\partial t}\right)\Omega_{20} &= i \frac{N}{2\epsilon_0 \hbar c} \omega_{20} |\mu_{20}|^2 a_2 \equiv i\kappa_{02} a_2 \\
\left(\frac{\partial}{\partial z} + \frac{1}{c} \frac{\partial}{\partial t}\right)\Omega_{30} &= i \frac{N}{2\epsilon_0 \hbar c} \omega_{30} |\mu_{30}|^2 a_3 \equiv i\kappa_{03} a_3,
\end{aligned} \tag{2}$$

where N is the number density of atoms and μ_{ij} is the dipole moment between i and j level. With strong coupling field approximation as well as resonant conditions ($\Delta_1 = \Delta_2 = \Delta_3 = 0$), Fourier transformation on three Schrödinger equations and two Maxwell equations gives Fourier transformed solution of the probe field Ω_{30} analytically,

$$\begin{aligned}
w_{30}(z, \omega) &\approx \left(1 - \frac{\kappa_{03} |\Omega_{12}|^2}{\kappa_{02} |\Omega_{13}|^2 + \kappa_{03} |\Omega_{12}|^2}\right) w_{30}(0, \omega) e^{i \frac{\omega}{v_g} z} \\
&+ \frac{\kappa_{03} \Omega_{31} \Omega_{12}}{\kappa_{02} |\Omega_{13}|^2 + \kappa_{03} |\Omega_{12}|^2} w_{20}(0, \omega) e^{i \frac{\omega}{v_g} z},
\end{aligned} \tag{3}$$

where $\frac{1}{v_g} \equiv \frac{1}{c} + \frac{\kappa_{02} \kappa_{03}}{\kappa_{02} |\Omega_{13}|^2 + \kappa_{03} |\Omega_{12}|^2}$. From Fourier transformation of $w_{30}(z, \omega)$, the time evolution of probe field is obtained as

$$\begin{aligned}
\Omega_{30}(z, t) &\approx \left(1 - \frac{\kappa_{03} |\Omega_{12}|^2}{\kappa_{02} |\Omega_{13}|^2 + \kappa_{03} |\Omega_{12}|^2}\right) \Omega_{30}\left(0, t - \frac{z}{v_g}\right) \\
&+ \frac{\kappa_{03} \Omega_{31} \Omega_{12}}{\kappa_{02} |\Omega_{13}|^2 + \kappa_{03} |\Omega_{12}|^2} \Omega_{20}\left(0, t - \frac{z}{v_g}\right).
\end{aligned} \tag{4}$$

The two probe fields were assumed as Gaussian short pulse with time width τ , however the coupling fields were considered as cw (wide pulses) as follows:

$$\begin{aligned}
\Omega_{20}(0, t) &= e^{i\Phi_{20}} |\Omega_{20}(0, t)| e^{-\left(\frac{t}{\tau}\right)^2}, \\
\Omega_{30}(0, t) &= e^{i\Phi_{30}} |\Omega_{30}(0, t)| e^{-\left(\frac{t}{\tau}\right)^2}, \\
\Omega_{31}(0, t) &= e^{i\Phi_{31}} |\Omega_{31}|, \\
\Omega_{21}(0, t) &= e^{i\Phi_{21}} |\Omega_{31}|.
\end{aligned} \tag{5}$$

Transmission of probe field at pulse peak is obtained as follows:

$$\begin{aligned}
T &\equiv \left| \frac{\Omega_{30}(z, t)}{\Omega_{30}(0, 0)} \right|_{\text{at peak}(t=\frac{z}{v_g})} \\
&= \left(\left(1 - \frac{\kappa_{03} |\Omega_{12}|^2}{\kappa_{02} |\Omega_{13}|^2 + \kappa_{03} |\Omega_{12}|^2}\right) + \frac{|\Omega_{20}(0, 0)|}{|\Omega_{30}(0, 0)|} \right) \\
&\times \frac{\kappa_{03} \Omega_{31} \Omega_{12}}{\kappa_{02} |\Omega_{13}|^2 + \kappa_{03} |\Omega_{12}|^2} e^{(\Phi_{21} - \Phi_{31} + \Phi_{30} - \Phi_{20})^2}.
\end{aligned} \tag{6}$$

For the consideration of a simple case, $\kappa_{02} = \kappa_{03}$, $\Omega_{20}(0, 0) = \Omega_{30}(0, 0)$, and $\frac{|\Omega_{12}|}{|\Omega_{13}|} = \tan \eta$,

$$T = \cos^2 \eta (1 + \sin 2\eta \cos (\Phi_{21} - \Phi_{31} + \Phi_{30} - \Phi_{20})). \quad (7)$$

We consider that the phase of one probe field, Ω_{02} could control the transmission of the other probe field, Ω_{03} and vice versa. To form a double- Λ system, two independent laser sources were used to generate each set of coupling and probe fields. Arbitrary phase fluctuation due to incoherence between two independent laser sources is cancelled out by a parametric Raman process in a double- Λ system [20], what can also be seen in above probe transmission equation (Eq.(7)). Therefore, the incoherent phase fluctuation between two lasers does not affect the phase-dependent switching in a double- Λ system.

3. Experiment

We began with experimental observation of the phase dependent probe transmission in a double- Λ system. A warm 87Rb atom vapour, mixed with nitrogen as buffer gas, was used to implement the double- Λ system. The gaseous cell was shielded with a 3-layer μ -metal from geomagnetic field. The 87Rb vapour cell was heated up to 90 Celsius and wound with copper wire to generate a static magnetic field in the direction parallel to the propagation of the coupling/probe laser. Two independent extended cavity diode laser (ECDL) systems were used to generate coupling and probe fields. Each ECDL generated a pair of coupling and probe fields to excite each Λ system composed of Zeeman levels. The phase-difference between probe fields was adjusted by using optical delay line with piezoelectric transducers (PZT). Both probes were overlapped exactly and detected by a gained photo-diode. The probe and coupling beam diameters were 1 and 3 mm, respectively. Both coupling beams were coupled to a single polarization-maintenance-fibre (PMF) for exact overlapping. They were overlapped with the probe beams inside the rubidium vapour cell and tilted 1° from the probe beams to avoid leakage into the photo-diode. Figure 2 shows the transmissions of both probe beams at two differences of the phase induced by PZT with scanning the static magnetic field applied to Rb vapour cell. We

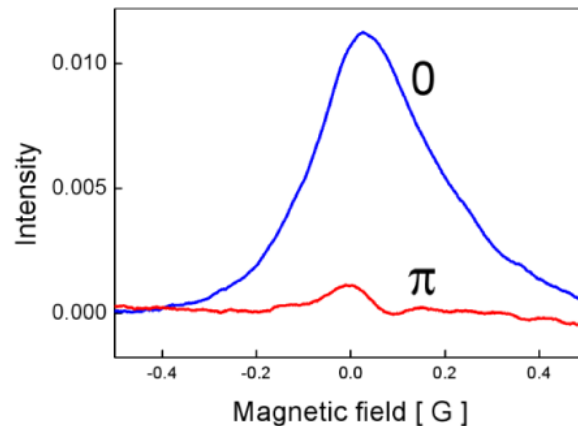


Fig. 2. The probe transmission with a magnetic field at the condition of two relative phase differences between probe fields in a double- Λ system. A two-photon detuning in a double- Λ system was occurred by a scanned magnetic field applied to Rb atoms. The conversion scale from magnetic field to frequency detuning is 1.4 MHz/G. The measured FWHM linewidth of double EIT was 358 KHz.

could observe the double EIT of both probe fields at zero phase difference. The 90 % of the probe transmission was removed at a phase-difference of π , even though theoretical calculations showed up to 100 % transmission removal in ideal situation. The coupling beam power was about several mW and that of probe was sub- μ W. The Rabi frequencies of both coupling fields were about 250 kHz and those of the probe fields were evaluated as $\Omega_{02,03} \sim 0.01\Omega_{12,13}$. The linewidth of the double EIT in Fig. 2 is broader than either coupling Rabi frequency. The conducted theoretical calculation showed that the estimated linewidth of the double EIT was driven by $\sqrt{\Omega_{12}^2 + \Omega_{13}^2}$. For optical image switching, a spatial light modulator (SLM) was employed to control the spatial phase distribution of two probe fields which will be converted to an optical image in a double- Λ system (Fig. 1(b)). The SLM pixel size (Holoeye-Pluto) is 8 μ m, its filling factor is 87 % and its active area is 15.36 \times 8.64 mm^2 . For the experimental easiness, both probe beams illuminated a single SLM of which the different regions were used to induce spatial phase shift to two probe fields respectively. Pixel pairs of two probe fields could

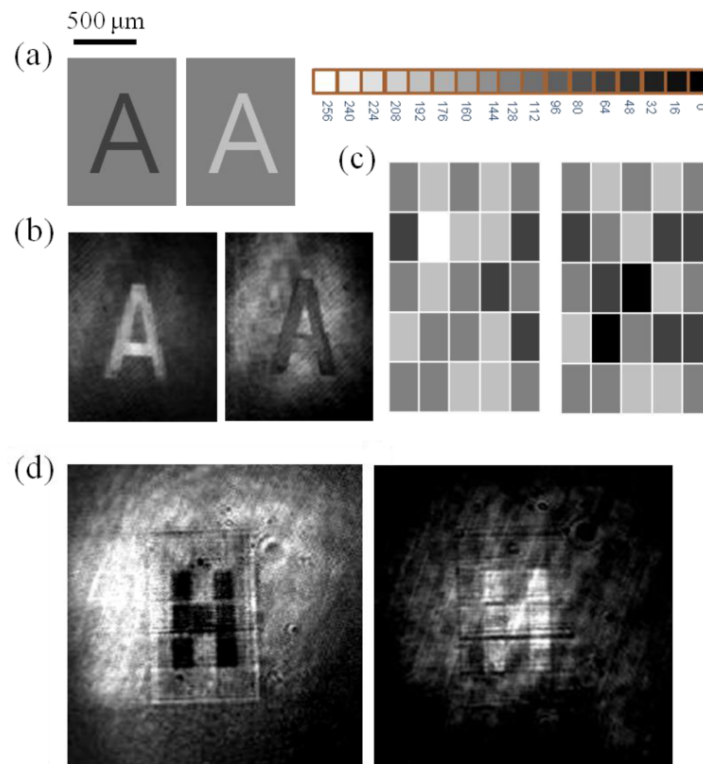


Fig. 3. All-optically switched images and the phase shifts of the probe fields with two cases ((a) and (c)). (a) Phase shift distributions of each probe field induced by SLM. Gray levels corresponds to phase shift induced by SLM. (b) Transmitted image (left) of (a) phase shift and a contrast-inverted image by the PZT-induced π phase over all pixels of one probe field (right). (c) Phase distributions of each probe field induced by SLM. The relative phase shift between two probe fields was H shaped π (a phase box size 40 \times 48 μ m²). (d) Transmitted image (left) of (c) phase shift and a contrast-inverted image with π -phase shifted by PZT (right).

be considered as multiple switching fields in a double- Λ system. The pixel phases of one probe field control the transmission of the pixels of the other probe field and vice versa in a double- Λ system. Piezoelectric transducer (PZT) in Fig. 1(b) induced the common phase shift on all pixels of the probe field. The probe fields were just transversely phase-modulated field distribution until Rb vapor cell. We used imaging lenses to place the imaging plane of the probe fields inside of the Rb vapor cell. At the image plane of the probe fields inside Rb vapour cell, the phase distribution was converted to the intensity distribution by the switching in a double- Λ system. After exiting the cell, the probe fields were separated from the coupling fields by polarization optics, and the probe field was imaged again on an electron multiplying CCD (EMCCD) camera sensor (iXon, Andor), with CCD lens focus adjusted to the image plane inside the vapor cell. Regular CCD might be enough to observe our image but EMCCD is better to catch image with high resolution. Our probe power was several μW with 1 mm diameter. The transmission from vapor cell was 10 % even with maximum EIT condition because warm Rb vapor has high decoherence rate. Then, the total power of the probe image was about few hundred nW and the total pixel number to form the image was about 10,000. Therefore, each pixel picked just 10 pW light to form the image. In this situation EMCCD is much better to get high resolution image. Thus, the weak probe field can be considered as the transmission controller of the other incoherent probe field. The switching between the probe fields could generate an optical image only at the exit of a double- Λ system. We observed an image transmission in the case of A-shaped phase shift of the SLM for both probe fields (Fig. 3(a)). The gray leveled stick at the right of Fig. 3 (a) denotes absolute phase shift amount by SLM. The relative phase difference between the left and right of Fig. 3(a) was π phase shaped 'A' and the other part was 0 relative phase difference. Therefore, the transmission of the A-shaped image was blocked. However, the background phase of A in the SLM was the same for both probes, what made the background transmission bright as shown in the left transmission image of Fig. 3(b)). As shown on the right side of Fig. 3(b), the contrast of the transmitted image was inverted due to the PZT-induced π phase shift over all pixels of one probe field. We did experiment with two case of phase shift (a) and (c) to show the image transmission can be controlled just by the relative phase difference between two probe fields. In the case (a), even without switching effect, the transmitted image of one probe field could be seen as letter A even though faint due to edge diffraction of A. To manifest that the switching could be implemented just with the relative phase difference between the probe pixels, an arbitrary phase shift was enforced on one probe field as shown in Fig. 3 (c). Meanwhile, the other probe was adjusted for the relative phase distribution between the probes to be shaped to letter H. The probe fields were imaged in a double- Λ system as shown in Fig. 3(d). The size of each arbitrary phase box on SLM (Fig. 3(c)) was about $40 \times 48 \mu\text{m}^2$.

4. Conclusion

We demonstrate all-optical image switching in a double- Λ system, with optical images generated by two independent laser sources. We added arbitrary phase to both optical images as then, in a double- Λ system, the original image could be recovered by switching the arbitrary phase off. The original image recovery was impossible outside of a double- Λ system because the arbitrary phase of two incoherent probe fields could not be switched off due to lack of other interference effects. As it has been already demonstrated that all-optical switching could be implemented with a double- Λ system in 20 photon-level [15], we expect that it would be employed to a quantum information network where the switching between non-classical photon controls photon routing. Because all-optical image switching is an extension of optical switching for parallel optical information process, we also expect that the result of the present work could be applicable to non-classical optical image information technique such as quantum

image routing. We need to expand this work to manipulate quantum image information. Two photon pair generation in a double- Λ system have been demonstrated to be nonclassical photon by observing the second order correlation at a single photon level [22]. The same method can be adopted to demonstrate all-optical switching between nonclassical field in a double- Λ system. Our method might be implemented with semiconductor nano-structure as the phase dependent switching in a double- Λ system was demonstrated on GaAs quantum well structure [23].

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