# Phase-controlled switching by interference between incoherent fields in a double-Λ system

**Hoonsoo Kang,[1,*] Bongjune Kim,[1,2] Young Ho Park,[1] Cha-Hwan Oh,[2] and In Won Lee[1]**

[1]*Quantum optics Laboratory, Advanced Photonics Research Institute, GIST, Gwangju 500-712, South Korea,*
[2]*Department of Physcis, Hanyang University, Seoul 133-79l, South Korea*
**hunskang@gist.ac.kr*

**Abstract:** We showed experimentally interference could be occurred between incoherent lights in a double-Λ lambda transition implemented with rubidium atomic vapor. Switching of probe transmission was controlled by the phases of two` independent probe lasers with low light intensity. More than 70% of the probe transmission could be switched by ultra-weak incoherent field. We suggested optically cryptic information could be delivered by the phase-controlled switching with incoherent fields in a double-Λ system.



**OCIS codes:** (190) Nonliear optics; (130.1670) Coherent optical effects; (020.4180) Multiphoton processes; (060.1660) Coherent communications.

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#139376 - $15.00 USD Received 8 Dec 2010; revised 15 Jan 2011; accepted 9 Feb 2011; published 16 Feb 2011

## 1. Introduction

Coherent laser interference effects show an important role in interaction of radiation and matter, and have a lot of applications in photonics. One of the most popular examples is electromagnetically induced transparency (EIT) [1–2]. EIT has been studied to obtain ultra-slow light speed in a resonant optical material [3–4]. Large Kerr nonlinear effect in EIT based four-level system was studied theoretically and experimentally [5–7]. Coherent control techniques have been focused to manipulate single photons to deliver quantum information [8–9]. Universal quantum logic gate based on large Kerr nonlinear effect in multi-level coupled EIT system have been proposed [10–11].

A double-Λ EIT system has attracted much attention because it has many applications to coherent optical manipulations. Pulse matching in two modes, three-level double lambda system was studied theoretically to show that two mode group velocities could be matched by controllable four wave mixing channel [12]. It was noted that the transparency induced in double lambda system is not collaborating with dark state which is eigenstate decoupled to optical transition in conventional EIT system. Formation and propagation of matched and coupled ultraslow optical soliton pairs was considered in four-level double lambda system. Phase-controlled switching effect was demonstrated experimentally in double lambda four-level system implemented by gaseous Rb atom [13]. The switching effect was more accurately observed with ultra-weak probe intensity as several tens of photon [14].

Georgiades *et al*. observed quantum interference of two-photon transitions in cold atoms [15]. Korsunsky et al. studied the phase-dependent coherent population trapping [16]. Huss et al. observed the correlation of the phase fluctuation in a double-Λ system [17]. Recently, the phase-controlled switching has been implemented with biexcitonic double-Λ system of semiconductor quantum well structure [18]. Meanwhile, the generation of correlated single photon pair has been studied by using Raman scattering followed by four-wave mixing in double lambda four-level system [19].

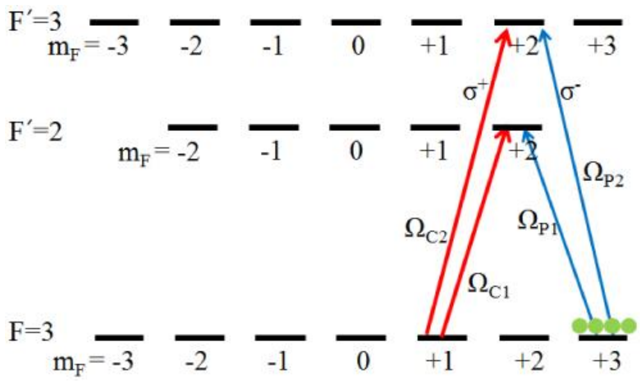


Fig. 1. Double lambda four-level system implemented in Zeeman sublevel of Rb85 D1 transition.

In this work, we showed phase-controlled switching between incoherent ultra-weak probe fields. Previous works to show phase-controlled switching were done with coherent probe fields. Phase dependent switching is implemented with interference between one photon and three photon process. We used two independent diode laser systems which excite each three-level lambda implemented in Zeeman levels of Rb85 $D_1$ transition (Fig. 1). Two strong coupling fields ($\Omega_{C1}$, $\Omega_{C2}$) and two weak probe fields ($\Omega_{P1}$, $\Omega_{P2}$) were split from two independent lasers so that two weak probe fields are incoherent each other and have the coherent counterpart of the coupling fields, $\Omega_{C1}$ and $\Omega_{C2}$.

We define the relevant Rabi frequency as $\Omega_{mn} = \mu_{mn} E_{mn}(t)/\hbar$, where $\mu_{mn}$ is the dipole transition matrix element. The coupling field drives the transition

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$|F=3, m_F=+1\rangle \rightarrow |F'=2, m_F=+2\rangle$ ($|F'=3, m_F=+2\rangle$) with the Rabi frequency $\Omega_{C1}(\Omega_{C2})$. Two weak probe fields drive $|F=3, m_F=+3\rangle \rightarrow |F'=2, m_F=+2\rangle$ and $|F=3, m_F=+3\rangle \rightarrow |F'=3, m_F=+2\rangle$ with Rabi frequencies, $\Omega_{P1}$ and $\Omega_{P2}$ respectively. Here, $\Omega_{mn}=|\Omega_{mn}|e^{i\phi_{mn}}$ is characterized by the amplitude $|\Omega_{mn}|$ and phase $\phi_{mn}$ . For $|\Omega_{C1}| \approx |\Omega_{C2}|$, $|\Omega_{P1}| \approx |\Omega_{P2}|$ and $|\Omega_{C1}| >> |\Omega_{P1}|$, the excitation in double lambda system can be divided into two excitation paths because the interference supported by four-wave mixing process is occurred in a double-Λ system [12]: $|F=3, m_F=+3\rangle \rightarrow |F'=2, m_F=+2\rangle$ and $|F=3, m_F=+3\rangle \rightarrow |F'=3, m_F=+2\rangle \rightarrow |F=3, m_F=+1\rangle \rightarrow |F'=2, m_F=+2\rangle$ equivalently, $|F=3, m_F=+3\rangle \rightarrow |F'=3, m_F=+2\rangle$ and $|F=3, m_F=+3\rangle \rightarrow |F'=2, m_F=+2\rangle \rightarrow |F=3, m_F=+1\rangle \rightarrow |F'=3, m_F=+2\rangle$ ).

When the interference of two excitation path is destructive with the condition, $\Omega_{P1}/\Omega_{P2}=\Omega_{C1}/\Omega_{C2}$ as described in Ref 12, excitation does not occur and both probe fields propagate in the medium without attenuation. When $\Omega_{P1}/\Omega_{P2}=-\Omega_{C1}/\Omega_{C2}$, the interference is constructive and both probe fields are attenuated. Destructive interference is switched with the constructive interference by changing the phase of the optical fields. If the coupling and probe fields, $\Omega_{C1}$ and $\Omega_{P1}$ are split from one laser source, these are coherent each other and have same arbitrary phase which comes from the laser source. This arbitrary phase would be cancelled out in four-wave mixing process:

$$|F=3, m_F=+3\rangle \rightarrow |F'=2, m_F=+2\rangle \rightarrow |F=3, m_F=+1\rangle \rightarrow |F'=3, m_F=+2\rangle \rightarrow |F=3, m_F=+3\rangle.$$

The first two-photon process in the transition is a probe-coupling stimulated Raman scattering which cancels the arbitrary phase imposed by the laser source. The other pair of coupling and probe fields, $\Omega_{C2}$ and $\Omega_{P2}$ is split by the other independent laser source. The arbitrary phase imposed by the other laser source could be removed by two-photon process in four-wave mixing transition. The phase dependent switch can be controlled just by the external optical phase delay of the coupling and probe fields. Two probe fields, $\Omega_{P1}$ and $\Omega_{P2}$ generated by two independent laser systems could interfere each other because the transmission of probe field could be phase-dependent upon the relative phase difference between two probe fields. In section 2, it will be shown the interference between two independent probe fields experimentally. To show the possibility of the application of the incoherent interference to phase-controlled switching device, optical information was encrypted in the phase of probe field and it could be decrypted by phase-controlled switching in double-Λ system.

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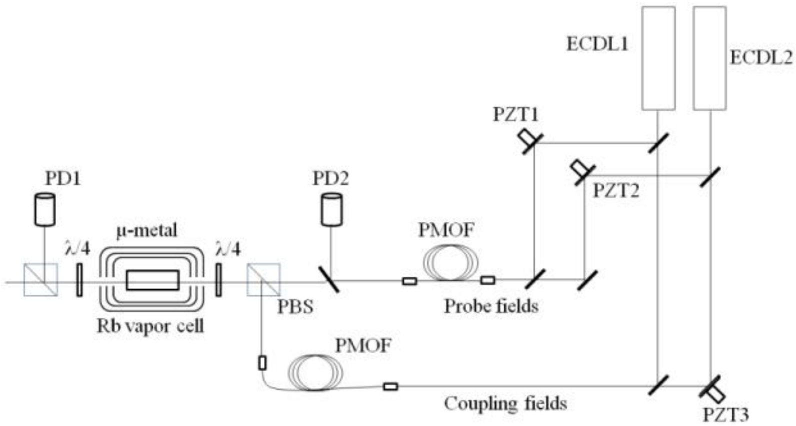


Fig. 2. Experimental setup. Photo diode (PD) and polarization maintenance optical fibre (PMOF).

## 2. Experiment

A double-Λ system was implemented with Zeeman levels of Rb85 D1 transition (Fig. 1). Each coupling ($\Omega_{C1,2}$). -probe ($\Omega_{P1,2}$) transitions were excited with the opposite circular polarizations. We employed two independent ECDL (External Cavity Diode Laser) resonant on Rb85 D1 transition. Each ECDL was split to coupling-probe field pair and PZT (piezoelectric transducer) was employed to induce the phase modulation of probe field by changing the optical path (Fig. 2). Two probe (coupling) fields were coupled to a polarization maintenance optical fibre for the easiness of collinear spatial mode matching. Rb85 atom gaseous cell with nitrogen buffer gas was shield with 3-layer μ-metal to remove geomagnetic field. The Rb85 vapor cell was heated to 60° Celsius and wound by copper wire to generated static magnetic field of the parallel direction with the coupling-probe laser propagation. The population of $F = 2$ ground hyperfine state was optically pumped to $m_F = 3$ Zeeman sublevel by two coupling fields (Fig. 1). A repump laser was used to excite Rb85 D2 transition from $F = 3$ ground hyperfine state to compensate the population to $F = 2$ state, which is not shown in Fig. 2.

To observe two-photon resonance in each Λ system with coupling-probe transition, the transmission of one probe field was measured by photo diode, (PD1 in Fig. 2) with scanning the static magnetic field applied to Rb vapour cell. The static magnetic field induces Zeeman splitting which detunes two-photon resonance from the frequency of the coupling and probe fields. When ECDL are frequency-locked on one-photon resonance of Rb D1 transition, two-photon resonance could be observed to be typical EIT. The amplitude of both coupling Rabi frequencies, $|\Omega_{C1}|$ and $|\Omega_{C2}|$ were adjusted same to be 150×2π kHz and those of both probe field, $|\Omega_{P1}|$ and $|\Omega_{P2}|$ were adjusted to be $|\Omega_{P1}| \approx |\Omega_{P2}| \approx |\Omega_{C1}|/100$ to satisfy the destructive interference condition of double-Λ system. We directly measured the power of coupling and probe beams and estimated the probe Rabi frequency by comparing with the coupling Rabi frequency. The coupling beam power was about several mW and that of probe was sub-μW with similar beam size. Our photo-detector was sensitive enough to observe this range of power. Interference of double-Λ system could be controlled by the phase of coupling and probe fields. PZT attached on the mirror changed the optical path of the probe fields, which changed the phase of probe field in double-Λ transition. The transmission of both probe fields was shown with the probe phase difference $\phi_{P1} - \phi_{P2}$ for the destructive interference (0), an intermediate interference (π/2) and the constructive interference (π) in Fig. 3. PZT3 was adjusted to have the relative phase 0 between the coupling fields.

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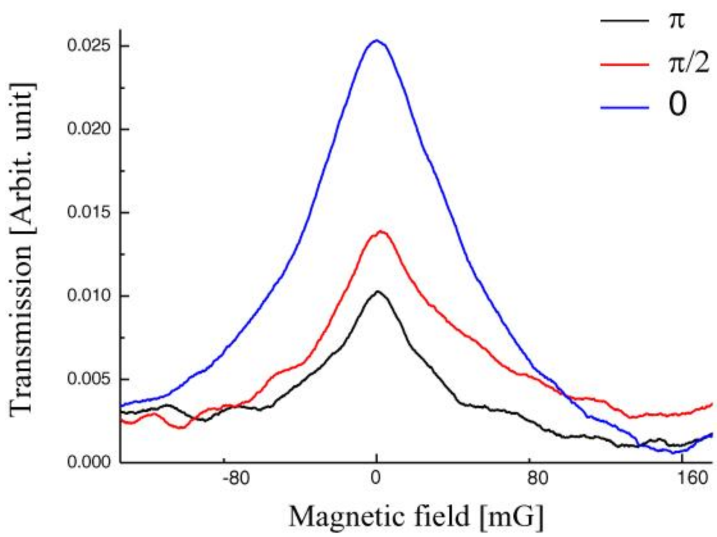


Fig. 3. The blue line is the transmission of the probe fields when destructive interference ( $\phi_{P1} - \phi_{P2} = 0$ ) is occurred in a double-Λ system, the red line is that of the probe fields when $\phi_{P1} - \phi_{P2} = \pi / 2$ and the black line is when constructive interference is occurred ( $\phi_{P1} - \phi_{P2} = \pi$ ).

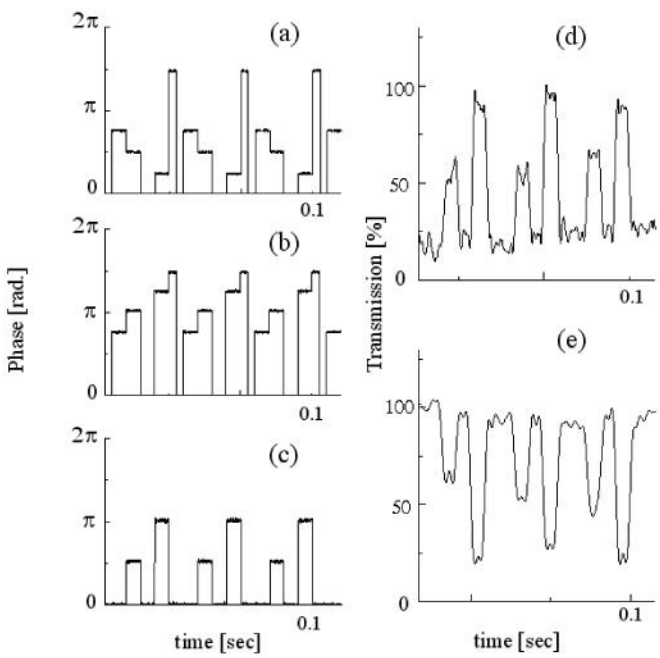


Fig. 4. (a) The phase shift of probe 1 driven by PZT1 in time sequence. (b) The phase shift of probe 2 driven by PZT2. (c) The relative phase difference between the probe fields (d) The transmission signal of the probe fields while the relative phase of the coupling fields was fixed to π. The transmission value of 100% is accord to the maximal value of the blue curve of Fig. 3. (e) The transmission signal of the probe fields while the relative phase of the coupling fields was fixed to 0.

Random noise can be loaded on the phase of both probe fields while transforming target information through a double-Λ system. This might be applied to optical information

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transformation with incoherent lights carrying additional random noise to conceal target optical information. Only relative phase difference between incoherent probe fields could control the transmission of the probe fields while the phase difference between coupling fields fixed. Figure 4(a) shows the phase shift of Probe 1, $\phi_{P1}$ by PZT1 in time sequence. Figure 4(b) shows the phase shift of Probe 2, $\phi_{P2}$ by PZT2. Those might transfer target information with random noise which could be added for encryption. The relative phase difference between Fig. 4(a) and 4(b) controls the probe transmission to decrypt the target information. Figure 4(c) shows the target information which is the relative phase difference between Probe 1 and 2. Figure 4(d) shows the transmission of the probe fields after interacting in a double-Λ system while the relative phase of the coupling fields was fixed to π by PZT3. Photo detector, PD2 in Fig. 2 could not observe any interference fringe. It is impossible to recover the target information without a double-Λ system because the probe fields are incoherent not to be interfered each other. The interference pattern of the transmission could be changed with the relative phase of the coupling fields either. Figure 4(e) shows the transmission of the probe fields with the relative phase of coupling fields fixed to 0 which inverts the transmission curve.

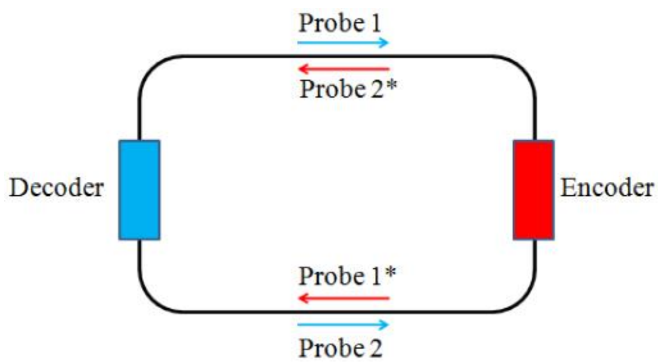


Fig. 5. The schematics of encrypt optical information transportation with incoherent light phase-controlled switching.

Schematics of encrypt optical information with incoherent light phase-controlled switching is shown in Fig. 5. There are two parts for transforming encrypted optical information. One of them is Encoder which encrypts target information on two probe fields. The other part is Decoder which decrypts the encrypted optical information. At first, Decoder sends random noised two probe fields, Probe 1 and 2 through free space or optical fiber to Encoder. Then Encoder modulates optical phase of two incoherent probe fields to encrypt the target information with adding random noise on both probe fields as conducted in Fig. 4. The modulated probe fields, Probe 1* and 2* are delivered back to Decoder who will decrypt the target information in a double-Λ system. Decoder should prepare laser sources and atomic material to implement a double-Λ system while Encoder needs to have optical phase shifter. Eavesdropping is nearly impossible because interference between probe fields cannot be observed without the original double-Λ system. Eavesdropper might wiretap by interfering each probe signals of before and after Encoder's encryption to read the modulate pattern on each probe fields. This eavesdropping might be even difficult to prepare right optical delay in reality because Encoder station has various delay process sending stream of optical signals. Furthermore, there might be a key code of the random relative phase difference between coupling fields which could be shared between Encoder and Decoder before encrypt information transformation. Coherence length of laser sources for coupling-probe field is critical factor for long range information transformation with a double-Λ system. Our laser source has about 200 m coherence length but it is feasible in modern technology to increase coherence length to more than 10,000 times with frequency stabilized laser source with high

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finesse cavity. We can consider the encrypt information transformation between earth stations via satellite (Fig. 6). The satellite needs to be equipped with telescope to receive and send optical signal from earth stations. Decoder station is equipped with a telescope, long coherence length laser system and a double-Λ system. Decoder sends random noised probe fields to satellite which receive the optical signal and send to Encoder station. Encoder encrypts target information on probe fields with random noise. The optical information is send back to Decoder via the satellite. We expect encrypt optical information transformation can be realized between multi-site earth stations to cover the whole planet.

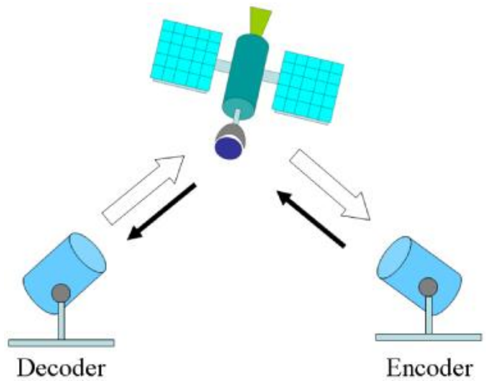


Fig. 6. The schematics of the encrypt information transformation between earth stations via satellite.

## 3. Conclusion

We studied experimentally the phase-controlled switch between incoherent probe fields. The transparency of the resonant probe field was considered as the destructive interference between one- and three-photon processes in a double-Λ system. The transmission of the probe field was observed with scanning magnetic field which detunes two-photon resonance. The interference pattern could be controlled by shifting the phase of the probe fields. The main physics of this work is same to the previous work but the implementation is quite different in the view of the application to cryptic information transformation. In the previous work, the phase controlled switching was shown between two probe fields from one laser source. Even without a double-Λ system, the two probe fields can be interfered each other, so the cryptic information transformation is impossible. The strong point of this work is that phase controlled switching can be done between incoherent probe fields from two independent laser sources, so the interference can be seen only in the double-Λ system, which make it possible to conceal the target information in relative controlled phase between two incoherent probe fields. We showed experimentally optical information could be delivered by encoding with probe phase modulation. It was shown for the application to cryptography that target information added by random noise could be recovered in a double-Λ system. We suggested optically cryptic information could be delivered by the phase-controlled switching with incoherent fields in a double-Λ system, however, more accurate evaluation should be conducted for the application to cryptography technology.

## Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0013310) and partly Asian Laser Center Program through a grant provided by the Gwangju Institute of Science & Technology.