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Low light level all-optical switching in a four-level atom-cavity system

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ABSTRACT

We report on an all-optical switching in a double ∧ four-level atom-cavity system both theoretically and experimentally. In this system, an extra coherence between two ground states is induced by two coupling lasers, thus the loss of the cavity field decreases. Then, we can use one weak field to control another weak field at low light levels. Compared to the three-level atom-cavity system, the power of the switching laser can be much weaker in the four-level atom-cavity system.

1. Introduction

Quantum information carried by photons is not sensitive to environment compared with that carried by electrons or atoms, in addition to having the merit of the ultimately highest speed. An all-optical switching operated at low light level is one of the key components in a quantum network [1–3], which has been the subject of many recent studies and has many practical applications in optical communications [4–18]. Utilizing the properties of electromagnetically induced transparency (EIT) [19–21], Harris and Yamamato showed that the all-optical switching can be realized by quantum interference [4]. This has been observed experimentally in cold atoms [5–7] and hot vapor [8,9] in free space. Also, a variety of other methods have been studied for all-optical switching, such as enhanced Kerr nonlinearity [10], parametric instability [3] and phase-controlled interference [13]. Recently, by combining the effects of atomic interference and the enhanced interaction strength of the light and atoms in a cavity, the all-optical switching has been realized by the cavity-atom polaritons [14,15]. In these atom-cavity systems a laser coupled with cavity can be controlled (transmission or reflection) by a free-space control laser. Here, we present a scheme of all-optical switching in double ∧ four-level atom-cavity system with a rubidium atomic vapor cell inside an confocal cavity. Due to the applied two coupling lasers, an extra coherence between the two ground states emerges. With this help the absorption of the atoms is reduced. We find that the power of the switching laser can be much weaker in the four-level system. Thus one weak field can be used to control another field at ultralow light levels.

2. Theoretical analysis and numerical simulation

We begin with a brief theoretical discussion of the four-level system as shown in Fig. 1. The probe laser couples the atomic transition $|1\rangle$–$|4\rangle$ with Rabi frequency Ω_p, the control laser couples the $|2\rangle$–$|4\rangle$ transition with Rabi frequency Ω_c and the other two lasers couple the $|1\rangle$–$|3\rangle$ and $|2\rangle$–$|3\rangle$ transition separately with Rabi frequency Ω_1 and Ω_2, respectively. The frequency detuning for the respective transition are defined as $\Delta_p = \omega_p - \omega_{14}$, $\Delta_c = \omega_c - \omega_{24}$, $\Delta_1 = \omega_1 - \omega_{13}$ and $\Delta_2 = \omega_2 - \omega_{23}$ (ω_i is the angular frequency of the laser field i). Using the method of the density matrix, we can obtain the transition matrix elements. Corresponding to our experimental conditions ($\Omega_{1,2} \gg \Omega_{c,p}$; Δ_1, Δ_2, $\Delta_c = 0$) and using the weak-field approximation, we can get the linear expression of

$$\rho_{14}^{(1)} = -i\frac{A + \rho_{21}^{(0)}\Omega_p[2\gamma\Omega_1^2(2\gamma - i\Delta_p) + \Omega_2^2(2\gamma^2 - i\gamma\Delta_p + \Omega_2^2) - \Omega_c\Omega_1\Omega_2^2]}{B}, \quad (1)$$

where

$$A = \rho_{11}^{(0)}\Omega_c[2\gamma\Omega_1^2(2\gamma - i\Delta_p) + \Omega_2^2(2\gamma^2 - i\gamma\Delta_p + \Omega_p^2)] - \rho_{22}^{(0)}\Omega_c\Omega_1\Omega_2^3, \quad (2)$$

$$B = 2\gamma\Omega_1^4 + \Omega_2^2[-\gamma\Delta_p^2 + \gamma(2\gamma^2 + \Omega_p^2) - i\Delta_p(3\gamma^2 + \Omega_p^2)] + \gamma\Omega_1^2(4\gamma^2 - i6\gamma\Delta_p - 2\Delta_p^2 + \Omega_2^2). \quad (3)$$

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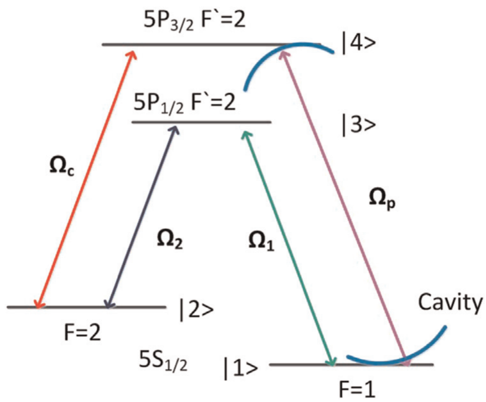

Fig. 1. Four-level atomic system of ^{87}Rb and the corresponding laser coupling scheme.

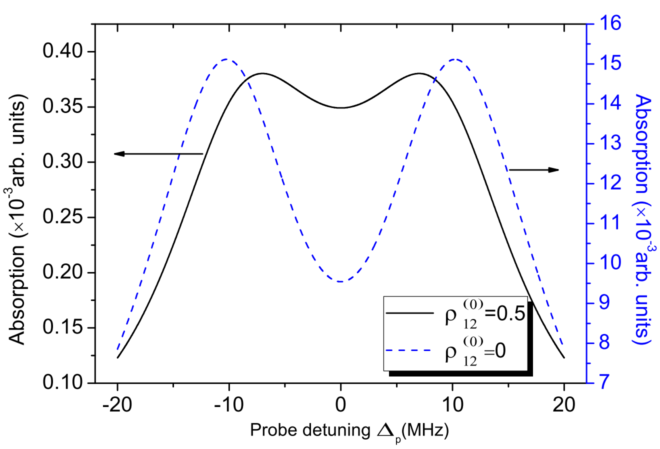

Fig. 2. The absorption part of the $\rho_{14}^{(1)}$ as a function of the probe detuning. The parameters are $\Omega_c = 0.5$ MHz and $\Omega_1 = \Omega_2 = 10$ MHz.

Here γ is the spontaneous rate of the excited states $|3\rangle$ and $|4\rangle$ to the ground states $|1\rangle$ and $|2\rangle$, respectively. (In fact, the spontaneous rates of the excited states $|3\rangle$ and $|4\rangle$ are 5.7 MHz and 6.0 MHz respectively. Here we assume that they are equal for the simplicity of calculation.) The term $\rho_{12}^{(0)} = \rho_{21}^{(0)} = \Omega_1\Omega_2/(\Omega_1^2 + \Omega_2^2)$ represents the coherence between the two ground states in the four-level system. From this expression, we can see that the coherence is generated by the two coupling lasers. We can choose $\Omega_1 = \Omega_2$ for the maximum coherence ($\rho_{12}^{(0)} = 0.5$). That is to say, in the four-level system, the two coupling lasers give rise to an extra coherence between the two ground states. Because of the extra coherence, the probe laser interacts with this extra coherence and the absorption property is changed. To analyse the effect of the coherence on the absorption, we calculate the absorption part of the $\rho_{14}^{(1)}$. The solid line in Fig. 2 is the absorption spectrum of the probe laser when $\Omega_1 = \Omega_2 = 10$ MHz, i.e. under the maximum coherence. For comparison, we also calculate $\rho_{14}^{(1)}$ using the formula (1), but assume that $\rho_{12}^{(0)} = 0$, while Ω_1 and Ω_2 are unchanged. The result is the dashed line shown in Fig. 2. From this figure, we can see that the absorption of the probe laser decreases significantly (about two orders of magnitude) when the coherence exists.

On the other side, combining the above four-level atomic system and the cavity, the interaction strength of the cavity field and the atoms also can be enhanced by the extra coherence. We numerically calculate the cavity transmission in three-level and four-level atom-cavity systems. In the calculation we set $\Omega_p = 0.5$ MHz and $\Omega_1 = \Omega_2 = 10$ MHz. In the four-level system, the cavity transmission can reach more than 95% when $\Omega_c = 0.5$ MHz with the help of coherence. But in the three-level system we need high

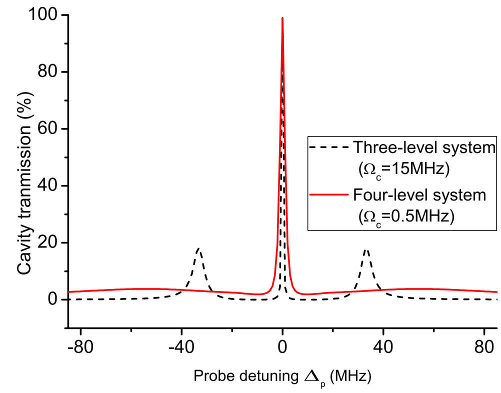

Fig. 3. The cavity transmissions versus the probe laser detuning in three-level atom-cavity system (black dashed line, $\Omega_1 = \Omega_2 = 0$) and four-level atom-cavity system (red solid line, $\Omega_1 = \Omega_2 = 10$ MHz). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

control field ($\Omega_c = 15$ MHz) for the same transmission, as shown in Fig. 3. In the four-level atom-cavity system, the requirement of the intensity of control laser for transmission of cavity can be reduced as the coherence exists. That is to say, we can use one weak control field to realize the transmission of the cavity when the two coupling lasers are on (four-level system).

3. Experiment and result

We now turn to a description of the experiment. We consider a system with four-level rubidium atoms (in a vapor cell) inside an optical standing-wave cavity of 40 cm long. Fig. 4 depicts the setup of the atom-cavity system. The cavity consists of two mirrors of 40 cm curvature with reflectivity larger than 99.5% and is a confocal optical system. One of the mirrors mounted on a piezoelectric transducer (PZT) for cavity frequency scanning and locking. The rubidium vapor cell is 75 mm long with reflection reducing coating. The empty cavity finesse is measured to be about 100. When we insert two PBS and a Rb vapor cell into the cavity, the cavity finesse is about 37. Four energy levels in the D1 and D2 lines ($5S_{1/2}$, $F \rightarrow 5P_{1/2}$, F' and $5S_{1/2}$, $F \rightarrow 5P_{3/2}$, F' transitions) of ^{87}Rb atoms are used for the double ∧ type four-level system, as shown in Fig. 1. In the experiment, four extended-cavity diode lasers are used as control laser, probe laser and two coupling lasers. The probe laser is injected into the cavity and circulates in the cavity as the cavity field, and the output is detected by a photodiode. The control laser and two coupling lasers are injected into Rb vapor cell through PBS1 and reflected out by PBS2. The control laser is aligned to obtain good overlaps with the probe laser. The two coupling lasers cross the control laser with a small angle to avoid circulating in the cavity. The radii of the probe, control and two coupling laser beams are estimated to be 250 μm, 500 μm and 500 μm at the center of the atomic vapor cell, respectively. In the experiment the intensity of the two coupling lasers are equivalent and fixed at 11 mW.

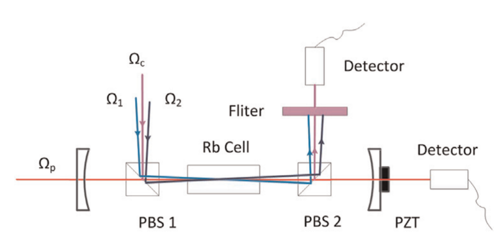

Fig. 4. Simplified diagram of the experimental setup. PBS1, PBS2: polarization beam splitters.