Optics Communications 402 (2017) 163–166

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Observation of polariton resonances with five-level M-type atoms in an optical cavity

Yutong Liu [a], Gongwei Lin [a,*], Kang Ying [b], Lin Liang [a], Yueping Niu [a], Shangqing Gong [a]

[a] Department of Physics, East China University of Science and Technology, Shanghai 200237, China
[b] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

ARTICLE INFO

Keywords:
Dark-state polariton
Atom–cavity system
EIT
Group velocity

ABSTRACT

We study the polariton resonances with the five-level M-type atoms inside an optical cavity through the observation of the cavity transmission spectrum. The ultranarrow peaks associated with the dark-state polaritons in the system can be achieved by adjusting three coupling fields. Simple theory analysis and numerical simulations are also presented.

1. Introduction

When an atomic medium is coupled into the cavity mode, the cavity transmission spectrum will become more complex than the one for the empty cavity. For example, if the two-level atoms are placed inside an optical cavity, the atom–cavity system exhibits a double-peaked transmission spectrum, which is well-known as 'normal-mode splitting' or 'vacuum Rabi splitting' phenomenon. Such fundamental cavity–QED systems have been widely studied in the experiments [1–7]. When the two-level atoms are replaced by three-level Λ-type atoms with electromagnetically induced transparency (EIT) [8], the dark-state polaritons (DSPs) in the EIT will induce an additional narrow central peak. Such DSP resonance which is first proposed by Lukin et al. [9] has been observed in cold or hot atoms [10–12], in Coulomb crystals [13], and even in a single atom [14].

Besides the DSP in three-level Λ-type atomic ensemble, the study on the DSP has been extended to the multilevel atomic ensemble [15,16]. In particular, the DSPs in five-level M-type atomic ensemble have a good controllability by manipulating three coupling fields and can be used for robust two-channel quantum memory [17]. In this paper, we demonstrate both experimentally and theoretically the DSP resonances with five-level M-type atoms inside an optical cavity, through the observation of the cavity transmission spectrum. In the experiment, the ultranarrow peaks associated with the DSP in the system can be achieved by using ^{87}Rb atoms. We also present a simple theory analysis and numerical simulations to explain the experiment results.

2. Model and theoretical analyze

We first review the three-level Λ-type EIT with N atoms, as shown in Fig. 1(a). A strong coupling field $\hat{E}_1$ with Rabi frequency Ω_1 couples the transition $|2\rangle \to |3\rangle$, while a weaker probe field $\hat{E}_p$ with effective coupling constant g, couples the transition $|1\rangle \to |3\rangle$.

The DSP in the Λ-type system is [18]

$$\Psi_\Lambda(z,t) = \cos\theta_\Lambda(t)\hat{E}_p - \sin\theta_\Lambda(t)\sqrt{N}\,\rho_{12}, \quad (1)$$

with

$$\cos\theta_\Lambda(t) = \frac{\Omega_1}{\sqrt{\Omega_1^2 + g^2 N}}, \quad (2)$$

where $\Omega_1 = -\mu_{23}E_1/\hbar$, and μ_{ij} is the dipole moment between $|i\rangle$ and $|j\rangle$. The velocity of this DSP is

$$v_g^\Lambda = c\cos^2\theta_\Lambda = \frac{c\,\Omega_1^2}{\Omega_1^2 + g^2 N}, \quad (3)$$

where c is the speed of light in vacuum.

Now we consider the five-level M-type system with N atoms, as shown in Fig. 1(b). Two additional coupling fields $\hat{E}_2$ and $\hat{E}_3$ couple the transitions $|2\rangle \to |5\rangle$ and $|4\rangle \to |5\rangle$, respectively. We can derive the DSP according to Ref. [17] and obtain the following expression

$$\Psi_M(z,t) = \cos\theta_M(t)\hat{E}_p - \sin\theta_M(t)\sqrt{N} \times [\cos\phi(t)\,\rho_{12} - \sin\phi(t)\,\rho_{14}], \quad (4)$$

* Corresponding author.
E-mail addresses: gwlin@ecust.edu.cn (G. Lin), yingk0917@siom.ac.cn (K. Ying), niuyp@ecust.edu.cn (Y. Niu).

http://dx.doi.org/10.1016/j.optcom.2017.05.063
Received 29 November 2016; Received in revised form 17 May 2017; Accepted 22 May 2017
0030-4018/

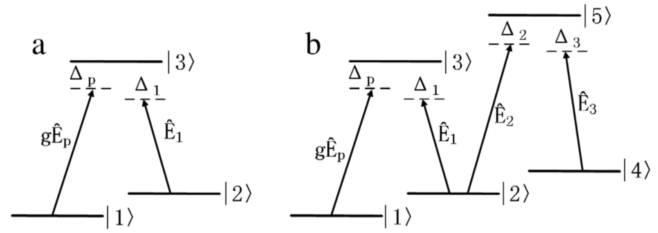

Fig. 1. (a) The three-level Λ-type atomic system. (b) The five-level M-type atomic system.

here,

$$\cos\theta_M(t) = \frac{\Omega_1\Omega_3}{\Omega},$$
$$\cos\phi(t) = \frac{\Omega_3}{\sqrt{\Omega_2^2+\Omega_3^2}}, \tag{5}$$

with $\Omega = \sqrt{g^2N\Omega_2^2 + g^2N\Omega_3^2 + \Omega_1^2\Omega_3^2}$, $\Omega_2 = -\mu_{25}E_2/\hbar$ and $\Omega_3 = -\mu_{45}E_3/\hbar$. Then the reduced group velocity becomes

$$v_g^M = c\cos^2\theta_M = \frac{c\,\Omega_1^2}{\Omega_1^2 + g^2N\left(1+\frac{\Omega_2^2}{\Omega_3^2}\right)}. \tag{6}$$

Compared Eq. (1) with Eq. (4), both of the above DSPs for the three-level Λ-type and five-level M-type system are similar in the form. However, in the three-level Λ-type system, v_g^Λ is related to Ω_1 only, while v_g^M in five-level system is related to Ω_1, Ω_2 and Ω_3, as Eqs. (3) and (6) show. That means the DSP can be manipulated by more coupling fields. Furthermore, the group velocity in the five-level M-type system can be slower than that in the three-level Λ-type system if $\Omega_2 \neq 0$. As the DSP in the cavity can induce an additional ultranarrow peak, we can observe the DSP by detecting the cavity transmission spectrum. The transmission linewidth of the DSP is depended on the group velocity strongly [19]. Therefore, the slower the group velocity of the five-level DSP, the narrower the transmission linewidth will be.

3. Experiment and observations

The energy level of the M-type system we used in our experiment is the D_2 line (780 nm) of Rubidium 87. Three coupling beams and a weak probe beam are both applied between the ground state $5^2S_{1/2}$ and the excited state $5^2P_{3/2}$, as Fig. 2 shows. The coupling beam E_1 drives the transition $F = 2$ to $F' = 1$. The other two coupling beams E_2 and E_3 drive the transition $F = 2$ to $F' = 3$, and the weak probe beam E_p is scanned across the level $F = 1$ to $F' = 1$. A longitudinal magnetic field 114.28 G is applied during our experiment, in order to make atomic levels split into Zeeman sublevels. The frequency separation between the sublevels of $F = 2$ is 80 MHz.

A diagram of the simplified experimental setup is displayed in Fig. 3. ^{87}Rb vapor is loaded into a 75 mm-long and 25 mm-diameter cylindrical cell, at a temperature of approximately 25 °C ($N = 1\times10^{16}$ m^{-3}). We use three single-mode external cavity diode lasers (ECDLs) (New Focus TLB-6900) in our experiment. The lasers have a linewidth of about 300 kHz, keeping by stable current and temperature. The laser beams E_p and $E_{1(2)}$ we used in our experiment, are linear polarization, when the three beams enter into the Rb vapor cell. The probe beam E_p and coupling beams $E_{1(2)}$ are orthogonally polarized. The coupling lasers are rejected by the beam splitter 4 (PBS4) before reaching the detector. The coupling beam E_3 is transformed from linear to circular polarization when it enters into the Rb cell using a quarter-wave plate (QWP). Adjusting the optical axis angle of the QWP appropriately, E_3 will become σ^+, and then if it is reflected by a mirror it will be seen as being σ^- circularly polarized in the atoms' frame. In order to avoid the saturated absorption of the ^{87}Rb atoms and self-focusing effect, the

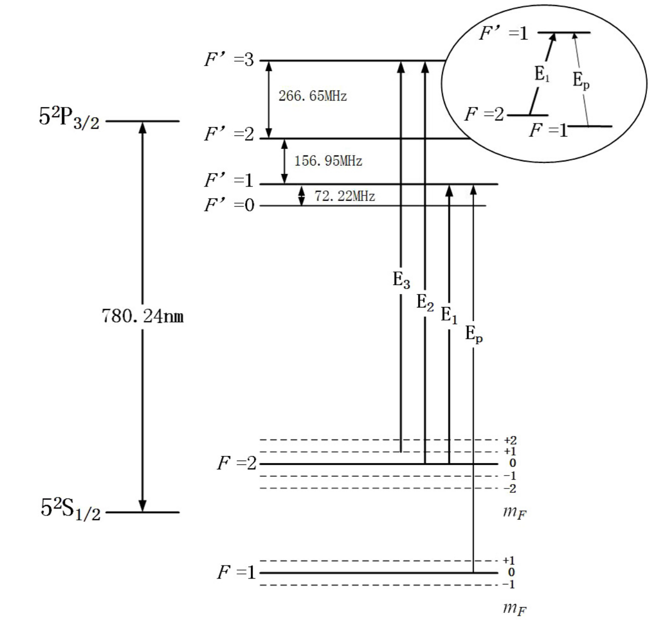

Fig. 2. The relevant energy levels of D_2 transition of ^{87}Rb for our experiment. Inset, three-level Λ-type system.

power of probe laser is below 100 μW. About 10% of two coupling beams E_1 and E_2 power is separated into auxiliary Rb cell to make saturation absorption for frequency stabilization, which are not shown here. The coupling beam E_2 and E_3, being separated by polarized beam splitter 3 (PBS3), come from the same laser, laser 3. An acoustic optical modulator (AOM) is used to modulate the frequency of the coupling beam E_3. The probe beam E_p and coupling beam E_1 are brought together by the polarized beam splitter 2 (PBS2). The coupling beam E_3 is passing a quarter-wave plate (QWP) before being reflected into the Rb cell by a mini-reflective mirror M3, which lead little effect on the cavity finesse. The optical cavity is a confocal cavity with a length of 550 mm, consisting of input mirror 1 (M1) and output mirror 2 (M2), both of which are concave mirrors with a 550 mm radius of curvature and the reflectivity are approximately 99.5%. A piezoelectric transducer (PZT) is mounted on the back cavity mirror 2 for cavity frequency scanning. All the four beams E_p, E_1, E_2 and E_3 are focused at the center of the Rb cell.

First, the probe beam frequency is scanned through the transition $F = 1$ to $F' = 1$ with a zigzag voltage driver. Meanwhile, the coupling beam E_1 and the coupling beam E_2 are staying at a static frequency, being resonant with the transition of $F = 2$, $m_F = 0$ to $F' = 1$, $m_F = 0$ and $F' = 3$, $m_F = 0$, respectively. And the coupling beam E_3 is modulated by AOM to make resonant to level $F' = 3$ with a frequency separation of 80 MHz. The power of probe field entering the Rb cell is kept under 100 μW. We adjust half-wave plates to make $E_1 = E_2 = E_3 = 3.5$ mW. The diameters of the probe and the other coupling beams are estimated to be 250 μm and 500 μm at the center of the Rb cell. We modulate the length of the optical cavity by tuning the driving voltage of the PZT.

Under the condition of two-photon resonance, a high and narrow transmission peak can be observed for the five-level M-type system. For comparison, we also observed the transmission spectrum for the three-level Λ-type atomic-cavity system when we cover the coupling beams E_2 and E_3, while setting E_1 free only. As is shown in Fig. 4, the dashed red curve represents the transmission peak of the three-level Λ-type system with $E_1 = 3.5$ mW and the solid black one stands for the case of the M-type five-level system with $E_1 = E_2 = E_3 = 3.5$ mW. We can find that the transmission peak of five-level M-type system is narrower. In order to make a detailed research on the DSP linewidth, we measure the cavity transmission spectrum under different power of coupling fields. The