Optics Communications 356 (2015) 155–160

Contents lists available at ScienceDirect

Optics Communications

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

Controllable cavity linewidth narrowing via spontaneously generated coherence in a four level atomic system

Si-Cong Tian [a], Ren-Gang Wan [b], Xiao-Nan Shan [a], Cun-Zhu Tong [a,*], Li Qin [a], Yong-Qiang Ning [a]

[a] State Key Laboratory of Luminescence and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
[b] School of Physics and Information Technology, Shanxi Normal University, Xi'an 710062, China

ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form
24 July 2015
Accepted 26 July 2015

Keywords:
Intracavity electromagnetically induced transparency
Cavity linewidth narrowing
Spontaneously generated coherence

ABSTRACT

A scheme for cavity linewidth narrowing in a four-level atomic system with spontaneously generated coherence is proposed. The atomic system consists of three closely spaced excited levels, which decay to one common ground level. In such a system, spontaneously generated coherence can result in the appearance of two narrow transparency windows accomplished by steep normal dispersion. When the medium is embedded in a ring cavity, two ultranarrow transmission peaks locating close to the position of the transparency windows can be obtained simultaneously. The cavity linewidth narrowing is owing to the quantum interference between the three decay channels and can be controlled by the frequency splitting of the excited levels, requiring no coupling lasers.

1. Introduction

The phenomenon of electromagnetically induced transparency (EIT), which is a result of dynamically induced coherence (DIC), plays an important role in the interaction between light and matter [1,2]. EIT can lead to many applications such as light propagation control [3,4], light storage [5], enhancement of nonlinearity at low light levels [6], etc. Steep dispersion and almost vanishing absorption produced by EIT can induce cavity-linewidth narrowing, which is known as intracavity EIT termed by Lukin et al. [7], and was first experimentally observed in a hot atomic vapor [8], then in a cold atomic system [9], in a Doppler broadened medium [10] and in a four-level tripod atomic system [11]. Intracavity EIT can be used for higher resolution spectroscopic measurements and frequency stabilization [7], and contributes to slowdown and delay of the light pulse propagation [12].

The above studies on the intracavity EIT are all based on the laser induced atomic coherence in an atomic system, and it is crucial to have at least one coupling laser to create the necessary coherence. On the other hand, atomic coherence can also be created through spontaneous emission in certain media if relevant decay pathways are correlated via the same vacuum modes, which is defined as spontaneously generated coherence (SGC). SGC gives rise to a variety of quantum effects, such as narrowing and quenching of spontaneous emission [13–19], amplification without inversion [20–23], transparency of a laser field [24,25] and modifying of nonlinearity [26–32] (optical bistability (OB) [26–30], enhancing Kerr nonlinearity [31] and electromagnetically induced grating [32]). Other novel applications of using SGC are the field of quantum photocell [33], high-precision metrology [34] and quantum heat energy [35].

And recently, the resonance fluorescence, the squeezing and the absorption spectra of a four-level atomic system with SGC have been investigated [36]. And in a similar atomic system, the existence of SGC can lead to the double-dark states [37]. Inspired by these works, in this paper, we propose a scheme for obtaining a tunable ultranarrow cavity transmission in a four-level atomic system consisting of three closely spaced excited levels decaying to one common ground level. In such a system, SGC can result in two narrow transparency windows and steep dispersion. And close to the narrowed transparency windows, two ultranarrow cavity transmission peaks can be obtained simultaneously, which can support frequency stabilization of two lasers with different central frequencies. In contrast to the previous studies, the cavity linewidth narrowing obtained in our scheme is due to the decay-induced interference, and no coupling laser is required.

Note that SGC only exists in such a system, which has near-degenerated levels and non-orthogonal dipole matrix elements. That is to say, the closely spaced levels should have the same quantum numbers J and m_J [20]. However, these rigorous

* Corresponding author. Fax: +86 431 861 76020.
E-mail addresses: tiansicong@ciomp.ac.cn (S.-C. Tian), tongcz@ciomp.ac.cn (C.-Z. Tong).

http://dx.doi.org/10.1016/j.optcom.2015.07.068
0030-4018/

conditions are rarely met in real atoms, therefore no experimental work has been carried out in atomic systems to observe SGC directly. However, SGC can be realized in other systems. For example, cavity field [38], anisotropy vacuum [39], photonic crystals [40] and left-handed materials [41] can result in quantum interference even when the dipole moments of the decay channels are orthogonal. And SGC can also be simulated in the dressed atoms interacting with a dc field [42], microwave field [43,44] or laser field [45]. And most recently, by the coherent laser fields we experimentally observed SGC on absorption and fluorescence in rubidium atomic beam [46–48]. Besides, in quantum wells and quantum dots, the tunneling effect can also lead to quantum interference [49–52]. Therefore, although our scheme proposed here is difficult to be carried out with atoms in a free vacuum, it can be equally applied and achieved with the above systems.

The paper is organized as follows: in Section 2, the model and the basic equations are introduced. In Section 3, the absorption and dispersion spectra are plotted. In Section 4, the transmission spectrum is plotted. Section 5 is the conclusions.

2. Models and equations

We consider a four-level atomic system as shown in Fig. 1(a). It has three excited levels $|2\rangle$, $|3\rangle$ and $|4\rangle$, which are coupled by the same vacuum modes to the ground level $|1\rangle$. $E_i = \hbar\omega_i$, $(i = 2, 3, 4)$ is the energy of the excited levels $|i\rangle$, with ω_i being the frequency of the corresponding level (We have taken the ground level $E_1 = 0$ as the energy origin). And $\omega_{32} = \omega_3 - \omega_2$ and $\omega_{43} = \omega_4 - \omega_3$ are the frequency splitting of level $|2\rangle$ and $|3\rangle$, and that of level $|3\rangle$ and $|4\rangle$, respectively. Then we suppose a weak probe field with frequency ω_p scanning over the system. The probe field probes on all transitions $|1\rangle \leftrightarrow |2\rangle$, $|1\rangle \leftrightarrow |3\rangle$ and $|1\rangle \leftrightarrow |4\rangle$ simultaneously. The Rabi frequencies for each transition is $\Omega_2 = E_p \mathbf{e}_p \cdot \boldsymbol{\mu}_{12}/2\hbar$, $\Omega_3 = E_p \mathbf{e}_p \cdot \boldsymbol{\mu}_{13}/2\hbar$, and $\Omega_4 = E_p \mathbf{e}_p \cdot \boldsymbol{\mu}_{14}/2\hbar$, where E_p and $\mathbf{e}_p$ are the amplitude and the polarization vector of the probe field, and $\boldsymbol{\mu}_{12}$, $\boldsymbol{\mu}_{13}$ and $\boldsymbol{\mu}_{14}$ are the dipole moments of the respective transitions. The polarization direction of the probe field and the dipole moments are shown in Fig. 1(b). And the detuning between the $|1\rangle \leftrightarrow |i\rangle (i = 2, 3, 4)$ transition and the probe field is $\Delta_i = \omega_i - \omega_p$. Let $\Delta_3 = \Delta_p$, then $\Delta_2 = \Delta_p - \omega_{32}$ and $\Delta_4 = \Delta_p + \omega_{43}$.

The Hamiltonian for the interaction between the atom and the laser in the frame rotating with $\Omega_i (i = 2, 3, 4)$ takes the form [13]

$$H = (\Delta_p - \omega_{32})\sigma_{22} + \Delta_p \sigma_{33} + (\Delta_p + \omega_{43})\sigma_{44} + [(\Omega_2\sigma_{12} + \Omega_3\sigma_{13} + \Omega_4\sigma_{14}) + H.c.]. \tag{1}$$

Here $\sigma_{ij} = |i\rangle\langle j|$ represents a population operator for $i = j$ and a dipole transition operator for $i \neq j$. And direct transitions between the excited sublevels $|i\rangle (i = 2, 3, 4)$ are dipole forbidden. And we use units such that $\hbar = 1$.

Assuming that such an atomic system is damped by the standard vacuum, the master equation for the reduced density operator ρ of the atom in the rotating frame then takes the form [13]

$$\frac{d\rho}{dt} = -i[H, \rho] + \frac{1}{2}L\rho, \tag{2}$$

with

$$\begin{aligned} L = {} & \gamma_2(2\sigma_{12}\rho\sigma_{21} - \sigma_{22}\rho - \rho\sigma_{22}) \\ & + \gamma_3(2\sigma_{13}\rho\sigma_{31} - \sigma_{33}\rho - \rho\sigma_{33}) \\ & + \gamma_4(2\sigma_{14}\rho\sigma_{41} - \sigma_{44}\rho - \rho\sigma_{44}) \\ & + \gamma_{23}(2\sigma_{13}\rho\sigma_{21} - \sigma_{23}\rho - \rho\sigma_{23}) + \gamma_{23}(2\sigma_{12}\rho\sigma_{31} - \sigma_{32}\rho - \rho\sigma_{32}) \\ & + \gamma_{24}(2\sigma_{14}\rho\sigma_{21} - \sigma_{24}\rho - \rho\sigma_{24}) + \gamma_{24}(2\sigma_{12}\rho\sigma_{41} - \sigma_{42}\rho - \rho\sigma_{42}) \\ & + \gamma_{34}(2\sigma_{14}\rho\sigma_{31} - \sigma_{34}\rho - \rho\sigma_{34}) + \gamma_{34}(2\sigma_{13}\rho\sigma_{41} - \sigma_{43}\rho - \rho\sigma_{43}). \end{aligned} \tag{3}$$

Her γ_2, γ_3 and γ_4 are the spontaneous decay rates from the three excited levels to the ground level, respectively. And γ_{23}, γ_{24} and γ_{34} represent the SGC effect between the three excited levels, and can be written as [24,36,42]

$$\gamma_{ij} = p_{ij}\frac{\sqrt{\gamma_i\gamma_j}}{2}, \quad (i, j = 2, 3, 4;\ i \neq j). \tag{4}$$

Here $p_{ij} = \cos\theta_{ij}$, $(i, j = 2, 3, 4;\ i \neq j)$ measures the degree of SGC, with θ_{ij} being the angle between the two transition dipole moments $\boldsymbol{\mu}_{1i}$ and $\boldsymbol{\mu}_{1j}$. If $\boldsymbol{\mu}_{1i}$ and $\boldsymbol{\mu}_{1j}$ are parallel, then $p_{ij} = 1$ $(\theta_{ij} = 0^\circ)$ and SGC takes the maximum value, while if $\boldsymbol{\mu}_{1i}$ and $\boldsymbol{\mu}_{1j}$ are perpendicular, then $p_{ij} = 0$ $(\theta_{ij} = 90^\circ)$ and SGC disappears.

Then the equations of the time evolution of the reduced density matrix elements take the form

$$\dot\rho_{22} = i\Omega_2(\rho_{12} - \rho_{21}) - \gamma_{23}(\rho_{23} + \rho_{32}) - \gamma_{24}(\rho_{24} + \rho_{42}) - \gamma_2\rho_{22}, \tag{5a}$$

$$\dot\rho_{33} = i\Omega_3(\rho_{13} - \rho_{31}) - \gamma_{23}(\rho_{23} + \rho_{32}) - \gamma_{34}(\rho_{34} + \rho_{43}) - \gamma_3\rho_{33}, \tag{5b}$$

$$\dot\rho_{44} = i\Omega_4(\rho_{14} - \rho_{41}) - \gamma_{24}(\rho_{24} + \rho_{42}) - \gamma_{34}(\rho_{34} + \rho_{43}) - \gamma_4\rho_{44}, \tag{5c}$$

$$\begin{aligned} \dot\rho_{12} = {} & -i\Omega_2(\rho_{22} - \rho_{11}) + i\Omega_3\rho_{32} + i\Omega_4\rho_{42} - \gamma_{23}\rho_{13} - \gamma_{24}\rho_{14} \\ & + [-\frac{\gamma_2}{2} + i(\Delta_p - \omega_{32})]\rho_{12}, \end{aligned} \tag{5d}$$

$$\begin{aligned} \dot\rho_{13} = {} & -i\Omega_3(\rho_{33} - \rho_{11}) + i\Omega_2\rho_{23} + i\Omega_4\rho_{43} - \gamma_{23}\rho_{12} - \gamma_{34}\rho_{14} \\ & + (-\frac{\gamma_3}{2} + i\Delta_p)\rho_{13}, \end{aligned} \tag{5e}$$

$$\begin{aligned} \dot\rho_{14} = {} & -i\Omega_4(\rho_{44} - \rho_{11}) + i\Omega_2\rho_{24} + i\Omega_3\rho_{34} - \gamma_{24}\rho_{12} - \gamma_{34}\rho_{13} \\ & + [-\frac{\gamma_4}{2} + i(\Delta_p + \omega_{43})]\rho_{14}, \end{aligned} \tag{5f}$$

$$\begin{aligned} \dot\rho_{23} = {} & i\Omega_2\rho_{13} - i\Omega_3\rho_{21} - \gamma_{23}(\rho_{22} + \rho_{33}) - \gamma_{24}\rho_{43} - \gamma_{34}\rho_{24} \\ & + (-\frac{\gamma_2 + \gamma_3}{2} - i\omega_{32})\rho_{23}, \end{aligned} \tag{5g}$$

$$\begin{aligned} \dot\rho_{24} = {} & i\Omega_2\rho_{14} - i\Omega_4\rho_{21} - \gamma_{24}(\rho_{22} + \rho_{44}) - \gamma_{23}\rho_{34} - \gamma_{34}\rho_{23} \\ & + [-\frac{\gamma_2 + \gamma_4}{2} + i(\omega_{32} + \omega_{43})]\rho_{24}, \end{aligned} \tag{5h}$$

$$\begin{aligned} \dot\rho_{34} = {} & i\Omega_3\rho_{14} - i\Omega_4\rho_{31} - \gamma_{34}(\rho_{33} + \rho_{44}) - \gamma_{23}\rho_{24} - \gamma_{24}\rho_{32} \\ & + (-\frac{\gamma_3 + \gamma_4}{2} + i\omega_{43})\rho_{23}. \end{aligned} \tag{5i}$$

The above equations are constrained by $\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} = 1$ and $\rho_{ij} = \rho_{ji}^{*}$. And it should be emphasized that the interference terms in Eqs. (5a)–(5i) are significant only for small frequency

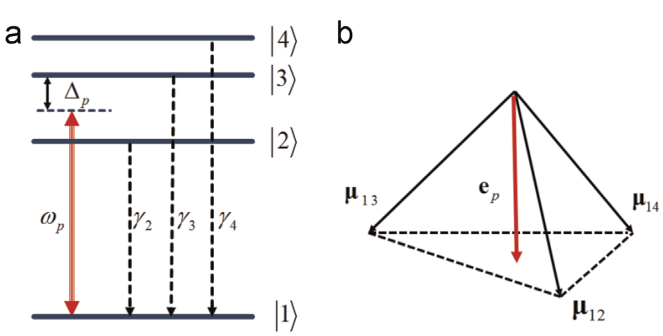

Fig. 1. (a) A four-level atomic system with SGC. (b) The arrangement of the probe field polarization and dipole moments of the transitions.