Optical Materials 35 (2013) 1062–1070

Contents lists available at SciVerse ScienceDirect

Optical Materials

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

Controlling the transition of bright and dark states via scanning dressing field

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ARTICLE INFO

Article history:
Received 6 August 2012
Received in revised form 12 November 2012
Accepted 10 December 2012
Available online 26 January 2013

Keywords:
Four wave mixing
Bright and dark states
Doubly-dressing modes
Avoided-crossing

ABSTRACT

We report the transitions between the bright and dark states of singly-dressed four-wave mixing (FWM) and doubly-dressed FWMs, and the corresponding probe transmissions by scanning the dressing field frequency detuning in a five-level atomic system. Moreover, doubly-dressed six-wave mixing with avoided-crossing plots and triple-dressed eight-wave mixing with the comparison of scanning probe field and dressing field are studied. Such controlled transitions of the nonlinear optical signals can be realizable not only in atomic vapors but also in solid medium. The investigations maybe have potential applications in optical communication, quantum information processing and optoelectronic devices, and maybe also provide a sensitive probe method to study the dressing effect.

1. Introduction

Electromagnetically induced transparency (EIT) [1–3], which utilizes quantum coherence generated by a strong coupling field to make an absorbing medium to be transparent for a weak resonant probe field, can be used in lasing without inversion [4], light speed reduction [5,6], quantum information storage [7], nonlinear optics [8], to name a few. Under EIT conditions, the generated four-wave mixing (FWM) signal which is a third-order nonlinear optical process and can be employed as a versatile spectroscopic technique [9,10], transmits through the medium with little absorption. In last two decades, the related effects interacting with two or more electromagnetic fields in multi-level atomic systems [12–14] attracted many researchers in the world. The singly-dressed FWM signal was studied both theoretically and experimentally by Fu et al. [11]. The interactions among double-dark states and splitting of dark state in a four-level atomic system with EIT were studied theoretically by Lukin et al. [8]. And doubly-dressed states in an N-type cold atoms system were observed experimentally by Zhu et al. [15], in which triple-photon absorption spectrum exhibits a constructive interference between the excitation pathways of two closely-spaced, doubly-dressed states. Similar results obtained in the double-Λ [16] and inverted-Y [17] systems were also reported. Later on, we reported the doubly dressed FWM (DDFWM) in the nested-cascade, close-cycled atomic system [10], and two kinds of DDFWM processes in an open five-level atomic system [18]. After that, we reported three DDFWM processes in Ref. [19], where both the two dressing fields are considered to act as the dressing fields. In addition, we also experimentally studied mutual dressing process existing between two competing dressing fields in a four-level Y-type atomic system [20,21] about Aulter-Townes (AT) splitting.

In this paper, we present two types of singly-dressed (lambda- and cascade-type) FWMs and three types of doubly-dressed (parallel-, sequential-, and nested-cascade modes) FWMs by blocking different laser beams in a five-level atomic system. We show the variation of these dressed FWM signals and the corresponding probe transmissions with the transition between the bright and dark states (i.e., the condition of enhancement and suppression) and the dressing field frequency detuning being scanned. Moreover, we also study the doubly-dressed six-wave mixing (SWM) with avoided-crossing plots and multi-dressed eight-wave mixing (EWM) with the comparison of scanning probe field and dressing field.

2. The singly- and doubly-dressing modes

We consider a five-energy-level system, as shown in Fig. 1a. And the relevant spatial beam geometry diagram is shown in Fig. 1b. The laser beams E_2, E_2', E_5 and E_5' counter-propagate through the vapor cell with E_1, E_3, E_3', E_4 and E_4', and there is always a small angle (~0.3°) between each other. The probe beam E_1 (frequency ω_1, wave vector $\mathbf{k}_1$, Rabi frequency G_1 and frequency detuning Δ_1) drives the transition $|0\rangle \rightarrow |1\rangle$ with horizontal polarization; E_2 (ω_2, $\mathbf{k}_2$, G_2 and Δ_2) and E_2' (ω_2, $\mathbf{k}_2'$, G_2' and Δ_2) connect

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http://dx.doi.org/10.1016/j.optmat.2012.12.018

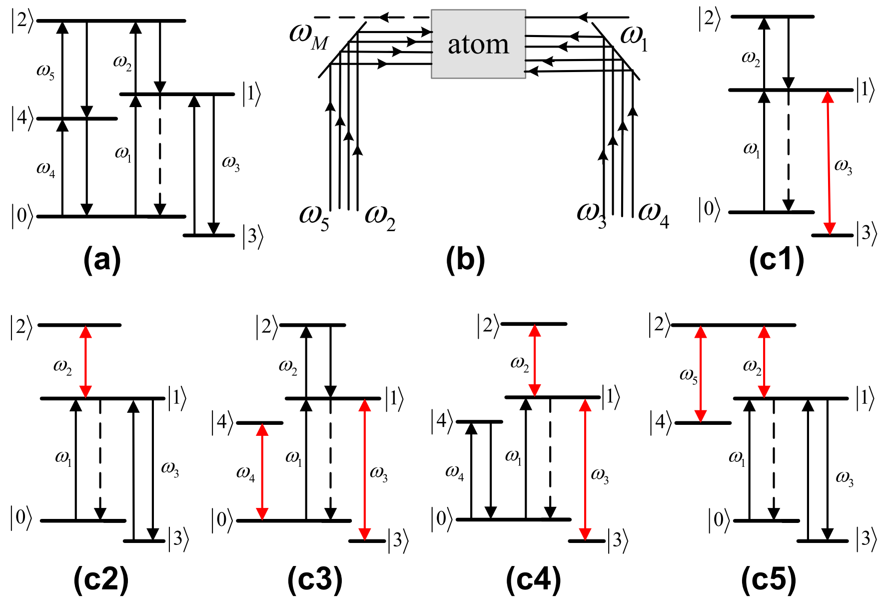

Fig. 1. (a) The scheme of five-level atomic system. (b) The relevant experiment setup. (c1) and (c2) Λ- and Ξ-type single dressed FWM. (c3)–(c5) Parallel-cascade mode, sequential-cascade mode, and nested-cascade mode dressed FWMs, respectively.

the transition $|1\rangle \rightarrow |2\rangle$ with horizontal and vertical polarizations respectively; E_3 (ω_3, $\mathbf{k}_3$, G_3 and Δ_3) and $E'_3(\omega_3,\ \mathbf{k}'_3,\ G'_3$ and Δ_3) connect the transition $|3\rangle \rightarrow |1\rangle$ with vertical polarization; E_4 (ω_4, $\mathbf{k}_4$, G_4 and Δ_4) and $E'_4(\omega_4,\ \mathbf{k}'_4,\ G'_4$ and Δ_4) drive the transition $|0\rangle \rightarrow |4\rangle$ with vertical polarization; E_5 (ω_5, $\mathbf{k}_5$, G_5 and Δ_5) and E'_5 (ω_5, $\mathbf{k}'_5$, G'_5 and Δ_5) drive the transition $|4\rangle \rightarrow |2\rangle$ with vertical polarization. $G_i = E_i\mu_{ij}/\hbar$ and $\Delta_i = \Omega_i - \omega_i$, where μ_{ij} is the transition dipole moment between $|i\rangle$ and $|j\rangle$, Ω_i is the atomic resonance frequency.

In such a beam geometric configuration, there will generate three FWM signals E_{FA} (satisfying $\mathbf{k}_{FA} = \mathbf{k}_1 + \mathbf{k}_4 - \mathbf{k}'_4$) with horizontal polarization, E_{FB} (satisfying $\mathbf{k}_{FB} = \mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}'_2$) with vertical polarization and E_{FC} (satisfying $\mathbf{k}_{FC} = \mathbf{k}_1 + \mathbf{k}_3 - \mathbf{k}'_3$) with horizontal polarization, which can be detected in the different directions and can be dressed differently when different laser beams are blocked, as shown in Fig. 1c1–c5.

In such an energy level system, under the dipole approximation and the rotating wave approximation, the interaction Hamiltonian H_I can be represented in the interaction picture by

$$\begin{aligned} H_I = {} & \hbar[\Delta_1|1\rangle\langle 1| + (\Delta_1+\Delta_2)|2\rangle\langle 2| + (\Delta_1-\Delta_3)|3\rangle\langle 3| + \Delta_4|4\rangle\langle 4|] \\ & - \hbar[G_1 e^{i\mathbf{k}_1\cdot\mathbf{r}}|1\rangle\langle 0| + (G_2 e^{i\mathbf{k}_2\cdot\mathbf{r}} + G'_2 e^{i\mathbf{k}'_2\cdot\mathbf{r}})|2\rangle\langle 1| + (G_3 e^{i\mathbf{k}_3\cdot\mathbf{r}} \\ & + G'_3 e^{i\mathbf{k}'_3\cdot\mathbf{r}})|1\rangle\langle 3| + (G_4 e^{i\mathbf{k}_4\cdot\mathbf{r}} + G'_4 e^{i\mathbf{k}'_4\cdot\mathbf{r}})|4\rangle\langle 0| + (G_5 e^{i\mathbf{k}_5\cdot\mathbf{r}} \\ & + G'_5 e^{i\mathbf{k}'_5\cdot\mathbf{r}})|2\rangle\langle 4| + \text{H.c.}]. \end{aligned} \tag{1}$$

To find the density-matrix element $\rho_{10}^{(3)}$ related to the FWM signals, we use the master equation of motion for the density matrix operator in an arbitrary multilevel atomic system in the interaction picture

$$\frac{\partial\rho}{\partial t} = \frac{1}{i\hbar}[H_I, \rho] - \Gamma\rho. \tag{2}$$

Then, based on the Eqs. (1) and (2), and the following perturbation chains (i.e., Liouville pathways with perturbation theory and satisfying phase-matching condition)

$$\text{(FA)}\quad \rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{10}^{(1)} \xrightarrow{-\omega_4} \rho_{14}^{(2)} \xrightarrow{\omega_4} \rho_{10}^{(3)},$$

$$\text{(FB)}\quad \rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{10}^{(1)} \xrightarrow{\omega_2} \rho_{20}^{(2)} \xrightarrow{-\omega_2} \rho_{10}^{(3)},$$

$$\text{(FC)}\quad \rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{10}^{(1)} \xrightarrow{-\omega_3} \rho_{30}^{(2)} \xrightarrow{\omega_3} \rho_{10}^{(3)},$$

in which the superscript (0), (1), (2) or (3) express the perturbation order, the corresponding density matrix elements for E_{FA}, E_{FB} and E_{FC} in the $|0\rangle - |1\rangle - |4\rangle$, $|0\rangle - |1\rangle - |2\rangle$ and $|0\rangle - |1\rangle - |3\rangle$ subsystems can be obtained as

$$\rho_{\rm FA}^{(3)} = \rho_{10}^{(3)} = \frac{-iG_{\rm FA}}{d_1^2 d_4},\quad \rho_{\rm FB}^{(3)} = \rho_{10}^{(3)} = \frac{-iG_{\rm FB}}{d_1^2 d_2},\quad \rho_{\rm FC}^{(3)} = \rho_{10}^{(3)} = \frac{-iG_{\rm FC}}{d_1^2 d_3}, \tag{3}$$

where $G_{\rm FA} = G_1 G_4 G'^{*}_4 \exp(i\mathbf{k}_{\rm FA}\cdot\mathbf{r})$, $G_{\rm FB} = G_1 G_2 G'^{*}_2 \exp(i\mathbf{k}_{\rm FB}\cdot\mathbf{r})$, $G_{\rm FC} = G_1 G_3 G'^{*}_3 \exp(i\mathbf{k}_{\rm FC}\cdot\mathbf{r})$, $d_1 = \Gamma_{10} + i\Delta_1$, $d_2 = \Gamma_{20} + i(\Delta_1 + \Delta_2)$, $d_3 = \Gamma_{30} + i(\Delta_1 - \Delta_3)$, $d_4 = \Gamma_{14} + i(\Delta_1 - \Delta_4)$, and Γ_{ij} is the transverse relaxation rate between $|i\rangle$ and $|j\rangle$.

As shown in Fig. 1c1, the dressing field E_3 can dress the level $|1\rangle$ via subchain $\rho_{10} \xrightarrow{-\omega_3} \rho_{30} \xrightarrow{\omega_3} \rho_{10}$, and the corresponding FWM chain (FB) can be modified as (SDF1) $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{G_3\pm 0}^{(1)} \xrightarrow{\omega_2} \rho_{20}^{(2)} \xrightarrow{-\omega_2} \rho_{G_3\pm 0}^{(3)}$. By Eqs. (1) and (2), such single-dressing FWM signal $E_{\rm SDF1}$ can be well described by the following equations:

$$\begin{aligned} &\partial\rho_{10}^{(1)}/\partial t = -d_1\rho_{10}^{(1)} + iG_1\rho_{00}^{(0)} + iG_3\rho_{30}, \\ &\partial\rho_{20}^{(2)}/\partial t = -d_2\rho_{20}^{(2)} + iG_2\rho_{10}^{(1)}, \\ &\partial\rho_{10}^{(3)}/\partial t = -d_1\rho_{10}^{(3)} + iG'^{*}_2\rho_{20}^{(2)} + iG_3\rho_{30}, \\ &\partial\rho_{30}/\partial t = -d_3\rho_{30} + iG_3^{*}\rho_{10}. \end{aligned}$$

With the steady state approximation and the condition $\rho_{00}^{(0)} = 1$, we finally obtain

$$\rho_{\rm SDF1}^{(3)} = \frac{-iG_{\rm FB}}{(d_1 + |G_3|^2/d_3)^2 d_2}. \tag{4}$$

Similarly, as shown in Fig. 1c2, for this single-dressing FWM signal $E_{\rm SDF2}$, we have

$$\rho_{\rm SDF2}^{(3)} = \frac{-iG_{\rm FC}}{(d_1 + |G_2|^2/d_2)^2 d_3}, \tag{5}$$

with the perturbation chain (SDF2) $\rho_{00}^{(0)} \xrightarrow{\omega_1} \rho_{G_2\pm 0}^{(1)} \xrightarrow{-\omega_3} \rho_{30}^{(2)} \xrightarrow{\omega_3} \rho_{G_2\pm 0}^{(3)}$. In this paper, we call the two single dressing types as lambda (Λ)-and cascade (Ξ)-single-dressing modes according to their dressing ways.

As shown in Fig. 1c3, two dressing fields E_3 and E_4 can dress different levels $|1\rangle$ and $|j\rangle$ via the subchains $\rho_{10} \xrightarrow{-\omega_3} \rho_{30} \xrightarrow{\omega_3} \rho_{10}(\rho_{(G_3\pm)0})$