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Gaussian field induced spectral hole burning in a Doppler broadened system and spontaneously generated coherence

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ABSTRACT

The hole burning phenomenon is investigated for a four-level N-type atomic system interacting with three electromagnetic fields. The fields have a typical Gaussian transverse profile, in the presence of a Doppler broadening medium and spontaneously generated coherence due to nearby decaying levels. We present numerical results for the probe susceptibility via non-perturbative treatment of the density matrix elements solution. Some interesting features are enhanced for the spectral hole burning behaviors such as gain spectral hole burning and resonant fluorescence line narrowing. Also, the phenomenon of suppression of spectral curve, the propagation of slow and fast light in the system have been focused.

1. Introduction

In the literature [1,2], the coherence between the different states of the atom which can occur, when the energy between atom and vacuum is exchanged. Another type of induced coherence arises due to the interference between different spontaneous emission radiations. These coherence so-called spontaneously generated coherence (SGC) or vacuum induced coherence (VIC) are archived [3,4]. SGC has played a dominant role, a powerful resource in several optical phenomena and numerous applications e.g. electromagnetically induced transparency [5–7], lazing without inversion [8,9], optical bistability/multistability [10–12], creation of entanglement [13] and left-handed material [14]. Some interesting findings in controlling optical hole burning, due to the presence of SGC, were reported. The possibility of producing optical hole burning phenomenon in a Doppler broadened medium has attracted considerable attention in recent times. A coherent hole burning phenomenon; when the excited state is split into Autler–Townes doublets by the action of a strong coherent beam in a Doppler broadened ladder system is reported [15]. In a Doppler broadened three level $\Lambda-$type atomic system in the presence of a saturating and a coupling laser, the coherent hole-burning has been obtained by saturating transitions within an inhomogeneously broadened spectral band and the hole is modified by driving a hyperfine transition [16]. Another significant advantage in this case is that the propagation of light can be slowed down [17,18] and pulse delays can be produced with hole burning in a Doppler broadened atomic vapor using a counter propagating pump beam to saturate the media and achieve group indices of about 10^3 by Agarwal and Dey [19]. Also, the characteristics of ultraslow light in an inhomogeneously broadened medium have been discussed in Refs. [20,21].

In this paper, we propose to produce the hole burning phenomenon, where the probe susceptibility behavior is investigated, for a four-level N-type atomic system interacting with three electromagnetic fields where the fields have a typical Gaussian transverse profile. In our scheme, we analyze in detail how the combination of the spontaneous generating coherence, Doppler broadening medium and fields of transverse profile can modify the probe susceptibility behaviors via non-perturbative treatment of the density matrix elements solution in the steady-state. Furthermore the non-perturbative treatment, which is rigorously justified in recent paper [22], will be appropriate to study any phenomenon without any restricted conditions such as the phenomena of the hole burning, and electromagnetically induced absorption for all orders of fields as well as for large multilevel nonlinear system.

In this work, the appearance of the hole burning does not need the simultaneous concurrence of a strong saturated field and a probe field in the system, since the spectral hole burning can be enhanced strongly by means of the transverse dependence of the electromagnetic fields in a Doppler broadened medium and in the presence of SGC. The most persistent hole burning materials work at very low temperatures than those operating at the room temperature.

The paper is organized as follows. In Section 2 the model is described with a derivation of the dynamical system equations under the effect of SGC and fields of transverse profile with/without

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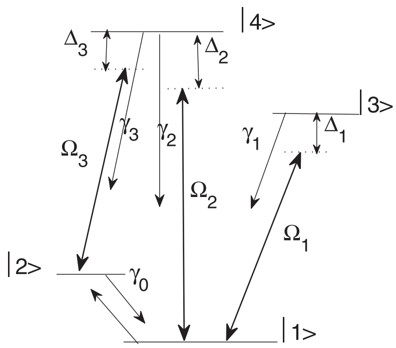

Fig. 1. The schematic diagram of a four-level N-type system.

Doppler broadening. In Section 3, numerical results and discussions are carried into two subsections dealing with Doppler broadening of either different or equal values of the wave numbers. The conclusions are presented in Section 4.

2. The model

A schematic diagram of the four-level N-type system is shown in Fig. 1. In this scheme: the transition $|1\rangle \leftrightarrow |3\rangle$ of energy difference $\hbar\omega_{13}$ interacts with a pump field (with frequency ω_a) having Rabi frequency Ω_{11} while the probe field (with frequency ω_p) is acting on the transition $|1\rangle \leftrightarrow |4\rangle$ (with energy difference $\hbar\omega_{14}$) having Rabi frequency Ω_{22}. Another strong coupling field of Rabi frequency Ω_{33}, at frequency ω_c, applies on the transition $|2\rangle \leftrightarrow |4\rangle$ (with energy difference $\hbar\omega_{24}$). Assuming, all three field beams have Gaussian transverse profiles and are aligned coaxially. They are in a common direction z of the atomic cylindrical sample with radius r_0, and the only relevant transverse variable is the radial coordinate r whose range of variation is $0 \le r \le r_0$ [23]. The Rabi frequency of the ith field beam is given by $\Omega_i(r) = \Omega_{ii}\exp[-(r/w_i)^2]$, $(i = 1, 2, 3)$, where Ω_{ii} is the Rabi frequency without Gaussian function $\exp[-(r/w_i)^2]$ (measure the transverse effect). w_i is the spot size at the beam waist. The radiative decay constants from levels $|3\rangle$ to $|1\rangle$, and the excited state $|4\rangle$ to $|1\rangle$, $|2\rangle$, are $2\gamma_1$, $2\gamma_2$ and $2\gamma_3$, respectively. γ_0 is the non-radiative decay constant of state $|2\rangle$ to state $|1\rangle$. The inclusion of SGC provides the radiative damping rates γ_{ij} $(i, j = 1, 2, 3)$:

$$\gamma_{12} = p_1\sqrt{\gamma_1\gamma_2}, \quad p_1 = \mu \cos\theta_1 \tag{1}$$

$$\gamma_{23} = p_2\sqrt{\gamma_2\gamma_3}, \quad p_2 = \mu \cos\theta_2 \tag{2}$$

The parameter μ will be zero or one if SGC effect is ignored or included, respectively. $\theta_1(\theta_2)$ is the angle between the two induced dipole moments d_{41} and d_{31} (d_{41} and d_{42}). The respective Rabi frequencies are connected to the angle θ_i by the relations $\Omega_1(r) = \Omega_{11}\exp[-(r/w_1)^2]\sqrt{1-p_1^2}$, $\Omega_2(r) = \Omega_{22}\exp[-(r/w_2)^2]\sqrt{1-p_1^2}$ and $\Omega_3(r) = \Omega_{33}\exp[-(r/w_3)^2]\sqrt{1-p_2^2}$ with $0 \le p_i < 1$. For simplicity, we took $w_1 = w_2 = w_3 = w_0$.

In the following, it is assumed that the $\exp[\pm i(\omega_j - \omega_i)t] \simeq 1$, (where $i, j = 1, 2, 3, 4$, $\omega_j - \omega_i = \omega_{ji}$). Under these assumptions and in the rotating wave approximation, the density-matrix equations of motion for the system take the form:

$$\frac{\partial\rho_{22}}{\partial t} = 2\gamma_3\rho_{44} + i\Omega_3(\rho_{24} - \rho_{42}) - 2\gamma_o\rho_{22} \tag{3}$$

$$\frac{\partial\rho_{33}}{\partial t} = -2\gamma_1\rho_{33} - i\Omega_1(\rho_{13} - \rho_{31}) - \gamma_{12}(\rho_{34} + \rho_{43}) \tag{4}$$

$$\frac{\partial\rho_{44}}{\partial t} = -2(\gamma_2 + \gamma_3)\rho_{44} - i\Omega_2(\rho_{14} - \rho_{41}) - i\Omega_3(\rho_{24} - \rho_{42}) - \gamma_{12}(\rho_{34} + \rho_{43}) \tag{5}$$

$$\frac{\partial\rho_{12}}{\partial t} = -F_{12}\rho_{12} - i\Omega_1\rho_{32} - i\Omega_2\rho_{42} + i\Omega_3\rho_{14} + 2\gamma_{23}\rho_{44} \tag{6}$$

$$\frac{\partial\rho_{13}}{\partial t} = -F_{13}\rho_{13} - i\Omega_2\rho_{43} + i\Omega_1(\rho_{11} - \rho_{33}) - \gamma_{12}\rho_{14} \tag{7}$$

$$\frac{\partial\rho_{14}}{\partial t} = -F_{14}\rho_{14} + i\Omega_3\rho_{12} - i\Omega_1\rho_{34} + i\Omega_2(\rho_{11} - \rho_{44}) - \gamma_{12}\rho_{13} \tag{8}$$

$$\frac{\partial\rho_{23}}{\partial t} = -F_{23}\rho_{23} + i\Omega_1\rho_{21} - i\Omega_3\rho_{43} - \gamma_{12}\rho_{24} \tag{9}$$

$$\frac{\partial\rho_{24}}{\partial t} = -F_{24}\rho_{24} + i\Omega_2\rho_{21} + i\Omega_3(\rho_{22} - \rho_{44}) - \gamma_{12}\rho_{23} \tag{10}$$

$$\frac{\partial\rho_{34}}{\partial t} = -F_{34}\rho_{34} - i\Omega_1\rho_{14} + i\Omega_2\rho_{31} + i\Omega_3\rho_{32} - \gamma_{12}(\rho_{33} + \rho_{44}) \tag{11}$$

the above equations are constrained by traced conditions $\sum_{i=1}^{4}\rho_{ii} = 1$, $\rho_{ij} = \rho_{ij}(r, t)$, $\Omega_i = \Omega_i(r)$, and
$F_{12} = \gamma_0 + i(\Delta_2 - \Delta_3)$, $F_{13} = \gamma_1 + i\Delta_1$,
$F_{14} = \gamma_2 + \gamma_3 + i\Delta_2$, $F_{23} = \gamma_1 + \gamma_0 + i(\Delta_1 - \Delta_2 + \Delta_3)$,
$F_{24} = \gamma_2 + \gamma_3 + \gamma_0 + i\Delta_3$, $F_{34} = \gamma_1 + \gamma_2 + \gamma_3 - i(\Delta_1 - \Delta_2)$
The atomic detunings are defined as $\Delta_1 = \omega_{31} - \omega_a$, $\Delta_2 = \omega_{41} - \omega_p$ and $\Delta_3 = \omega_{42} - \omega_c$.

One can perform a non-perturbative treatment on the density matrix Eqs. (3)–(11) and solve them simultaneously in the limit of the steady-state. In order to consider the effects of Doppler broadening, we compensate for the Doppler shift; three fields are assumed to propagate in the same direction (co-propagation) with respect to the probe field. The atomic detuning Δ_i $(i = 1, 2, 3)$ can be replaced by $(\Delta_i - k_i v)$, where v is the velocity of moving atoms and k_i is the wave number. Thus, susceptibility χ_{41} for moving atom is to be averaged over the Maxwellian distribution for the atomic velocities and the transverse field profiles, which can be expressed in the general form [24]:

$$\chi_{41} = \frac{4N_0 d_{41}^2}{\hbar\varepsilon_0\Omega_{22}\sqrt{1-p_1^2}(w_0^2/4)(1 - e^{-2(r_0/w_0)^2})u\sqrt{\pi}}\int_0^{r_0} r\,dr \times \int_{-\infty}^{\infty} \rho_{41}(r, v, t \to \infty)e^{-v^2/u^2}\,dv \tag{12}$$

where $u = \sqrt{2KT/m}$ with m being the mass of atoms, K is Boltzmann's constant, T is the absolute temperature, N_0 is the density of atoms and d_{41} is the dipole moment between the states $|1\rangle$ and $|4\rangle$.

Note that, the possible experimental system, for a four-level N-type atomic structure, can be realized by ^{87}Rb atomic vapor. The atomic states for ^{87}Rb are $|5S_{1/2}, F = 1\rangle$, $|5S_{1/2}, F = 2\rangle$, $|5P_{1/2}, F = 2\rangle$ and $|5P_{3/2}, F = 2\rangle$ as the levels in this work $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$, respectively (as shown in Fig. 1).

Now we are interested to see the behavior of the susceptibility (χ_{41}) in a situation where the fields are treated to all orders and co-propagating. Thus, the solutions of the density matrix equations can be derived analytically with non-perturbative treatment in the limit of the steady-state. So, this method is valid for any values of intensity fields. However, the solutions have tedious expressions owing to the presence of SGC. Also, it is difficult to carry out the integrations of Eq. (12) presenting with Doppler effect and Gaussian fields. Therefore, we have calculated both integrations numerically to get the susceptibility (χ_{41}) for the probe field in the unit of $(4N|d_{41}|^2/\hbar\varepsilon_0)$ as a function of the probe detuning Δ_2/γ_2 and measuring all parameters in terms of γ_2. The system parameters for the figures are chosen as $\Delta_1 = \Delta_3 = 0$, $\Omega_{11} = 3\gamma_2$, $\Omega_{22} = 0.01\gamma_2$, $\Omega_{33} = 5\gamma_2$, $\gamma_0 = 0.01\gamma_2$ and $\gamma_1 = \gamma_3 = \gamma_2$ if not stated