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Role of strongly modulated coherence in transient evolution dynamics of probe absorption in a three-level atomic system

Pradipta Panchadhyayee *

Department of Physics, P. K. College, Contai, Purba Medinipur 721 401, W. B., India

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ABSTRACT

We investigate the dynamical behaviour of atomic response in a closed three-level *V*-type atomic system with the variation of different relevant parameters to exhibit transient evolution of absorption, gain and transparency in the probe response. The oscillations in probe absorption and gain can be efficiently modulated by changing the values of the Rabi frequency, detuning and the collective phase involved in the system. The interesting outcome of the work is the generation of coherence controlled loop-structure with varying amplitudes in the oscillatory probe response of the probe field at various parameter conditions. The prominence of these structures is observed when the coherence induced in a one-photon excitation path is strongly modified by two-step excitations driven by the coherent fields operating in closed interaction contour. In contrast to purely resonant case, the time interval between two successive loops gets significantly reduced with the application of non-zero detuning in the coherent fields.

1. Introduction

In the last two decades, extensive studies in the area of nonlinear optics and laser spectroscopy have led to considerable interest in the study of optical response of the atomic system interacting with a number of coherent fields. In ideal three-level systems (Λ, V and Ξ) [1], the atomic coherence can be dynamically induced by the application of a strong field driving one excitation path. In the presence of an additional field probing another excitation path, the induced coherence leads to various quantum optical effects like electromagnetically induced transparency (EIT) [2], electromagnetically induced absorption (EIA) [3], gain without inversion (GWI) or lasing without inversion (LWI) [4–9], enhancement of refractive index [10] and generation of quantum beats [11].

The traditional method of generating GWI in an ideal closed three-level scheme producing EIT incorporates the application of an incoherent pump field to the system to populate the upper lasing level of the transition probed by a weak coherent field. The phenomenon of inversionless gain can result in the absorptive response of the probe field due to strong two-photon coherence induced in the system [6]. In a suitable level scheme, without invoking incoherent pumping, the condition of initial population in the upper lasing level is fulfilled by choosing an appropriate relaxation pathway from the excited level [12,13]. In presence of incoherent pumping, interference between two spontaneous decay channels in a *V*-type system with two closely lying upper levels leads to the formation of gain as a result of vacuum induced coherence (VIC) [14,15]. In such scheme, it is possible to obtain the control of absorption and gain by the relative phase of the fields involved in the system [16–22]. In absence of VIC, similar phase control of absorption and gain is also achieved in a *V*-type [23] and Λ-type [24–26] schemes where a microwave field is employed in the low-frequency induced transitions to form the close-loop interaction model. Such model shows its robustness to produce gain when the system is much dissipative [27].

All the works [4–27] relating to GWI as we have addressed so far, are concerned with the steady state properties of probe response. A lot of investigations [28–38] has been made to study the transient evolution of gain at various situations. In closed [29,31,32,34,37,38] and open [33,35,36] folded type schemes, gain-characteristics have been studied with [31,32,35–38] and without [29,30,33,34] inclusion of VIC. By adopting the close-loop interaction in a Λ-type system [32], phase dependent elimination of absorption has been noted in transient regime. Similar scheme using an external magnetic field in the low-frequency induced transition has been analyzed [34] to obtain GWI in transient regime. Motivated by these works [28–38] performed in transient regime, a closed three-level *V*-type scheme (Fig. 1) with close-loop interaction has been considered in this article to represent the three-ways of control of transient response of the probe field in detail.

The close-loop interaction inherent to the present model is exploited in this work to exhibit the transient evolution of absorption, gain and transparency in the probe response with the variation of model parameters. The salient features of the work are presented as follows: (a) Explicit occurrence of absorption and gain in the

* Tel.: +91 3220 255020.
E-mail address: ppcontai@gmail.com

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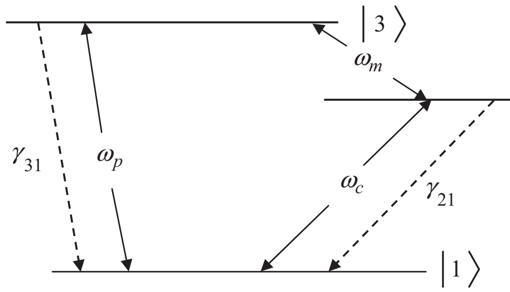

Fig. 1. Schematic presentation of a three-level *V*-type atom interacting with three coherent fields designated by their frequencies: ω_p for the probe field and ω_j $(j=c,m)$ for two control fields. γ_{21} and γ_{31} denote the spontaneous decay rates of the excited levels.

oscillatory probe response is obtained in many ways in the present model. (b) We have shown the generation of multi-loop-structure in the oscillatory probe response of the probe field at various conditions. This structure appears in probe transition due to strong perturbation resulted from two successive transition pathways driven by two coherent fields. Control of such structure by varying Rabi frequency, detuning and the collective phase of the control fields is presented in detail. (c) Unlike the purely resonant case, the time interval between two successive loops is found to be reduced by setting non-resonant detuning in the lasers involved in the system.

2. Basic model and related parameters

We consider a closed three-level *V*-type system with the ground state $|1\rangle$ and the excited states $|2\rangle$ and $|3\rangle$ as shown in Fig. 1. The transition $|1\rangle \leftrightarrow |2\rangle$ of frequency ω_{21} is driven by a coherent coupling field of frequency ω_c and amplitude E_c in optical regime, and the other transition $|2\rangle \leftrightarrow |3\rangle$ of frequency ω_{32} is driven by another coherent coupling field (microwave) of frequency ω_m and amplitude E_m. A weak optical field of frequency ω_p and amplitude E_p probing the transition $|1\rangle \leftrightarrow |3\rangle$ of frequency ω_{31} is so chosen that the population transfer to the uppermost level by this field becomes negligible. All the fields are considered in the continuous wave (CW) regime. In the semiclassical formulation, fields are defined as $E_i(x,t)=\epsilon_i \cos(\omega_i t - k_i z)$ $(i=p,c,m)$ where k_i is the propagation vector along the *z*-direction. The spontaneous decay rates from level $|3\rangle$ ($|2\rangle$) to level $|1\rangle$ is taken to be γ_{31} (γ_{21}). For the transitions $|1\rangle \leftrightarrow |2\rangle$, $|1\rangle \leftrightarrow |3\rangle$ and $|2\rangle \leftrightarrow |3\rangle$, the coherence dephasing rates are designated by $\Gamma_{21}(=\gamma_{21}/2)$, $\Gamma_{31}(=\gamma_{31}/2)$ and $\Gamma_{32}(=(\gamma_{21}+\gamma_{31})/2)$, respectively. In the context of decay-induced coherence we neglect the role of vacuum modes in the transitions $|1\rangle \leftrightarrow |2\rangle$ and $|1\rangle \leftrightarrow |3\rangle$ with the approximation that the Raman coherence originated by the application of the microwave field E_m between two upper states of the *V*-type system predominates over the decay-induced coherence in the limit of spontaneous decay rates much smaller than ω_{32}.

The Hamiltonian of the atomic system assuming the electric-dipole and rotating wave approximations can be expressed in the interaction picture as

$$H=-\hbar[R_c e^{-i\Delta_c t}|1\rangle\langle 2| + R_m e^{-i\Delta_m t}|2\rangle\langle 3| + R_p e^{-i\Delta_p t}|1\rangle\langle 3| + H.c.] \quad (1)$$

where $\Delta_c=\omega_{21}-\omega_c$, $\Delta_m=\omega_{32}-\omega_m$ and $\Delta_p=\omega_{31}-\omega_p$ are the detunings and $R_c=\overline{\mu}_{12}.\overline{\epsilon}_c^*/2\hbar$, $R_m=\overline{\mu}_{23}.\overline{\epsilon}_m^*/2\hbar$ and $R_p=\overline{\mu}_{13}.\overline{\epsilon}_p^*/2\hbar$ are the complex Rabi frequencies which can be presented as $R_j=r_j e^{i\phi_j}$ $(j=p,c,m)$, r_j being real parameters. The relation among the frequencies of coupling fields obeying the condition, $\omega_p=\omega_c+\omega_m$ obviously implies that $\Delta_p=\Delta_c+\Delta_m$.

The time evolution dynamics of the system can be represented by the following density matrix equations of motion:

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H,\rho] + \frac{\partial \overline{\rho}}{\partial t} \quad (2)$$

where $\partial\overline{\rho}/\partial t$ stands for the inclusion of irreversible decay effects with the expression

$$\frac{\partial \overline{\rho}}{\partial t} = -\sum_{j=2,3} \frac{\gamma_{j1}}{2}(\{|j\rangle\langle j|,\rho\} - 2|1\rangle\langle j|\rho|j\rangle\langle 1|) \quad (3)$$

In order to simplify the component equations of motion in Eq. (2), we introduce the unitary transformations for the atomic responses $\rho_{12}=\rho_{12}e^{i\phi_c}$, $\rho_{13}=\rho_{13}e^{i\phi_p}$ and $\rho_{23}=\rho_{23}e^{i\phi_m}$ and finally obtain the following equations for the density matrix elements:

$$\dot{\rho}_{11}=\gamma_{21}\rho_{22}+\gamma_{31}\rho_{33}+ir_c(\rho_{21}-\rho_{12})+ir_p(\rho_{31}-\rho_{13}) \quad (4)$$

$$\dot{\rho}_{22}=-\gamma_{21}\rho_{22}+ir_c(\rho_{12}-\rho_{21})+ir_m(\rho_{32}-\rho_{23}) \quad (5)$$

$$\dot{\rho}_{33}=-\gamma_{31}\rho_{33}+ir_m(\rho_{23}-\rho_{32})+ir_p(\rho_{13}-\rho_{31}) \quad (6)$$

$$\dot{\rho}_{12}=-(\Gamma_{21}-i\Delta_c)\rho_{12}+ir_c(\rho_{22}-\rho_{11})-ir_m\rho_{13}e^{-i\phi}+ir_p\rho_{32}e^{-i\phi} \quad (7)$$

$$\dot{\rho}_{13}=-(\Gamma_{31}-i\Delta_p)\rho_{13}+ir_p(\rho_{33}-\rho_{11})-ir_m\rho_{12}e^{i\phi}+ir_c\rho_{23}e^{i\phi} \quad (8)$$

$$\dot{\rho}_{23}=-(\Gamma_{32}-i(\Delta_p-\Delta_c))\rho_{23}+ir_m(\rho_{33}-\rho_{22})+ir_c\rho_{13}e^{-i\phi}-ir_p\rho_{21}e^{-i\phi} \quad (9)$$

where $\rho_{jk}=\rho_{kj}^*$. The closure of the system requires, $\rho_{11}+\rho_{22}+\rho_{33}=1$. The phase term $\phi=\phi_c+\phi_m-\phi_p$ is named as collective phase which arises due to the interaction of the coherent fields operating in close-loop configuration (Fig. 1). It controls the coherence property of the system dynamics for a definite set of Rabi frequencies and detuning parameters.

The Fourier component of polarization $P(\omega_p)$ induced by the probe field can be determined by performing the quantum average of the dipole moment over an ensemble of homogeneously broadened atoms. As is well known, the imaginary part of the polarization represents the absorptive properties in probe response. Here, the absorption coefficient for the probe field operating on transition $|1\rangle \leftrightarrow |3\rangle$ is directly proportional to the imaginary part of ρ_{13}.

3. Numerical results

In order to comprehend the absorptive response of the probe field at various parameter conditions, we investigate the time-dependent numerical solutions of Eqs. (4)–(9) and present the temporal evolution of probe absorption by showing the time dependence of $\mathrm{Im}(\rho_{13})$ in resonant and non-resonant conditions of the applied fields. For our model, the condition $\mathrm{Im}(\rho_{13})>0$ indicates that the probe laser will be amplified. In other words, the system exhibits gain for the probe field. Other conditions like $\mathrm{Im}(\rho_{13})<0$ and $\mathrm{Im}(\rho_{13})=0$ are for probe absorption and transparency respectively.

3.1. Resonant case

This subsection deals with the coupling lasers and the probe laser producing zero detuning $(\Delta_c=\Delta_m=\Delta_p=0)$ for the fields E_c, E_m and E_p. We present the temporal dynamics of absorption with the variation of distinctive controlling parameters as follows:

3.1.1. Rabi frequency-induced modulation

To comprehend the Rabi-frequency-induced modulation of probe absorption in the given model, we show the time evolution of atomic response $\mathrm{Im}(\rho_{13})$ in Figs. 2 and 3 for two sets of resonant coupling fields $(r_c=r_m=40\gamma$ and $r_c=10\gamma$, $r_m=40\gamma)$ respectively for a fixed resonant probe field $r_p=0.8\gamma$ in zero-phase $(\phi=0)$ condition. All the rate-parameters used in computation are scaled by the decay rate γ_{31} denoted as γ. To have an estimate of the population inversion $(\rho_{33}-\rho_{11})$ contributed in probe gain and absorption we present the atomic population distribution of the