Optics Communications 426 (2018) 553–557

Contents lists available at ScienceDirect

Optics Communications

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

Pulse propagation in an atomic medium under spontaneously generated coherence, incoherent pumping, and relative laser phase

Dong Hoang Minh [a,b], Doai Le Van [a], Bang Nguyen Huy [a,*]

[a] Vinh University, 182 Le Duan, Vinh City, Viet Nam
[b] The Central College of Transport No. 4, Vinh City, Viet Nam

ARTICLE INFO

Keywords:
Quantum interferences
Electromagnetically induced transparency
Pulse propagation

ABSTRACT

Influences of spontaneously generated coherence (SGC) and relative phase of laser fields on a probe laser pulse propagating in a three-level cascade atomic medium under incoherent pumping and electromagnetically induced transparency (EIT) are studied theoretically. It is shown that the leading edge of the pulse oscillates during its propagation. Furthermore, the oscillating magnitude is enhanced by growing SGC, however, it can be depressed by choosing a suitable relative phase between the laser fields. Indeed, the probe pulse depends sensitively on the relative phase with a period of 2 π in which it oscillates strongest at $\phi = 0$, π and 2 π; whereas it is unchanged at $\phi = \pi/2$ and $3\pi/2$. On the other hand, the influences of SGC and the relative phase on the pulse envelope are more effective as growing the incoherent pumping rate.

1. Introduction

Electromagnetically induced transparency (EIT) is a quantum interference effect that leads to a reduction of resonant absorption for a weak probe light field propagating through a medium induced by a strong coupling light field. The effect was observed by Harris and coworkers in 1991 [1]. Since then, the EIT has attracted tremendous interest [2–5] due to its unusual optical properties and promising applications in nonlinear and quantum optics [6–13]. Several dynamical processes of light pulses propagate in an EIT medium that permits a remained pulse shape at low intensity, were also studied [14–24] because of their potential applications in the fields of quantum information [25], all-optical switching [26], and storage and retrieval of light pulses [27].

Among various sources resulting quantum interferences, spontaneous emission interference in the atomic systems with nonorthogonality of electric dipole moments induced by coherent fields is a special case. Such interference creates an additional atomic coherence which is called as spontaneously generated coherence (SGC) [28]. The first experiment of SGC in the sodium molecules was carried out by Xia et al. [29]. So far, the influences of SGC on lasing without population inversion [30], absorption and dispersion [31–33], slow light [34–36], enhancement of Kerr nonlinearity [37,38], and optical bistability [39], are investigated in the steady-state regime. It is shown that atomic response under the SGC is sensitive to the relative phase of the applied fields [40]. Fan et al., [41] investigated the effects of SGC and relative phase on the absorption and dispersion in a three-level cascade atomic system with an incoherent pumping at a steady-state regime. Their results show that the atomic medium is switched from absorption to amplification and vice versa by changing the incoherent pumping rate.

Up to date, influences of SGC and relative phase on optical properties of EIT media for the case of steady-state regime are studied by numerous works [28–41], but those for the case of dynamical regime are quite moderate [42–45]. This situation is contradictive with many potential applications of laser pulse propagation in EIT media. Recently, pulse propagation in a three-level cascade EIT medium in which the probe pulse can be maintained as a soliton by choosing proper parameters of laser fields has been studied [45,46]. However, these works neglect the influence of the SGC and the relative phase on laser pulse under EIT condition. In this work, using semiclassical theory and density matrix formalism, we study propagation dynamics of a probe laser pulse in three-level cascade EIT medium under various conditions of the SGC, the relative phase between the probe and coupling fields, and incoherent pumping rate.

2. Theoretical model

We consider a three-level cascade-type system with nearly equispaced levels interacting with two laser pulses as in Fig. 1. A weak probe field with frequency ω_p drives the transition $|1\rangle \leftrightarrow |2\rangle$, while the transition $|2\rangle \leftrightarrow |3\rangle$ is driven by a strong coupling field with frequency

* Corresponding author.
E-mail address: bangnh@vinhuni.edu.vn (B. Nguyen Huy).

https://doi.org/10.1016/j.optcom.2018.06.008
Received 17 March 2018; Received in revised form 1 June 2018; Accepted 3 June 2018

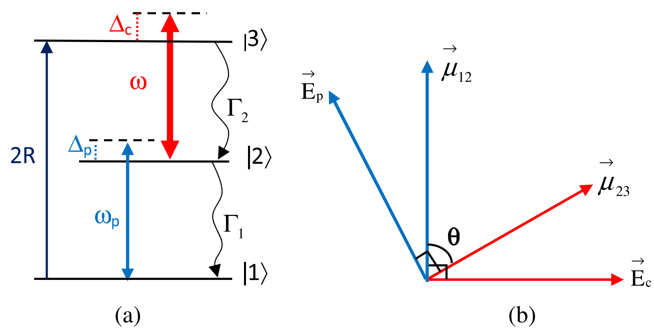

Fig. 1. (a) Scheme of the three-level cascade-type system with nearly equispaced levels. (b) The polarization is chosen such that one field only drives one transition.

ω_c. Under non-orthogonality of the transitional electric dipole moments we choose an arrangement as shown in Fig. 1(b) where each field acts only on a transition. We denote Γ_{21} and Γ_{32} being the decay rate of the states $|2\rangle$ and $|3\rangle$, respectively. An incoherent pump with a pumping rate 2R excites the transition $|1\rangle \leftrightarrow |3\rangle$. The Rabi frequencies of the probe and coupling fields are defined respectively as $\Omega_1 = 2\vec{\mu}_{12} \cdot \vec{E}_p/\hbar$ and $\Omega_2 = 2\vec{\mu}_{23} \cdot \vec{E}_c/\hbar$, with μ_{12} and μ_{23} being the electric dipole matrix elements. We define $\Omega_1 = \Omega_p \exp(i\phi_p)$ and $\Omega_2 = \Omega_c \exp(i\phi_c)$ with Ω_p and Ω_c being real parameters, ϕ_p and ϕ_c are phase of the probe and coupling fields, respectively.

Under the rotating-wave and electric dipole approximations, a set of density matrix equations for the evolution of the system is written as:

$$\dot{\rho}_{11} = -2R\rho_{11} + \Gamma_{21}\rho_{22} + \frac{i}{2}\Omega_p\left(\rho_{21} - \rho_{12}\right), \tag{1}$$

$$\dot{\rho}_{22} = -\Gamma_{21}\rho_{22} + \Gamma_{32}\rho_{33} + \frac{i}{2}\Omega_p\left(\rho_{12} - \rho_{21}\right) + \frac{i}{2}\Omega_c\left(\rho_{32} - \rho_{23}\right), \tag{2}$$

$$\dot{\rho}_{33} = 2R\rho_{11} - \Gamma_{32}\rho_{33} - \frac{i}{2}\Omega_c\left(\rho_{32} - \rho_{23}\right), \tag{3}$$

$$\dot{\rho}_{12} = -(\mathrm{R} + i\Delta_p + \gamma_{21})\rho_{12} + \frac{i}{2}\Omega_p(\rho_{22} - \rho_{11}) - \frac{i}{2}\Omega_c\rho_{13} + 2p\sqrt{\Gamma_{21}\Gamma_{32}}\eta_\phi\rho_{23}, \tag{4}$$

$$\dot{\rho}_{23} = -\left(i\Delta_c + \gamma_{21} + \gamma_{32}\right)\rho_{23} + \frac{i}{2}\Omega_c(\rho_{33} - \rho_{22}) + \frac{i}{2}\Omega_p\rho_{13}, \tag{5}$$

$$\dot{\rho}_{13} = -\left[R + i(\Delta_p + \Delta_c) + \gamma_{31}\right]\rho_{13} + \frac{i}{2}\Omega_p\rho_{23} - \frac{i}{2}\Omega_c\rho_{12}, \tag{6}$$

where, the matrix elements obey conjugated and normalized conditions, namely $\rho_{ij} = \rho_{ij}^*$ $(i \neq j)$, and $\rho_{11} + \rho_{22} + \rho_{33} = 1$, respectively; γ_{ij} describes the coherence decay rates from state $|i\rangle$ to state $|j\rangle$ which relates with the population decay rates Γ_{ij} by [4]:

$$\gamma_{ij} = \frac{1}{2}\left(\sum_{E_k<E_i}\Gamma_{ik} + \sum_{E_l<E_j}\Gamma_{jl}\right). \tag{7}$$

In Eqs. (1)–(6), $\Delta_p = \omega_p - \omega_{21}$ and $\Delta_c = \omega_c - \omega_{32}$ represent frequency detuning of the probe and coupling fields from the relevant atomic transitions, respectively; $2p\sqrt{\Gamma_{21}\Gamma_{32}}\eta\rho_{23}$ represents the SGC resulting from the cross coupling between the spontaneously emissions $|1\rangle \leftrightarrow |2\rangle$ and $|2\rangle \leftrightarrow |3\rangle$, $p = \vec{\mu}_{12}.\vec{\mu}_{23}/\left|\vec{\mu}_{12}\right|\left|\vec{\mu}_{23}\right| = \cos\theta$ with θ is the angle between the two dipole moments. If $\eta = 1$, the SGC effect has to be taken into account and the strength of SGC will vary versus θ; otherwise $\eta = 0$, the effect of SGC vanishes; $\eta_\phi = \eta\exp(i\phi)$ with $\phi = \phi_p - \phi_c$ is the relative phase between the probe and the coupling fields. Due to the SGC, the optical properties of the system depend on the amplitude, phase, and detuning of the probe and coupling fields, we therefore treat the Rabi frequencies as complex parameters.

It should be noted that in a usual EIT medium, its' size is so small (few cm). As a result, a delay between probe and coupling pulse is negligible after passing through the medium. On the other hand, for a simple consideration we neglect effects of group dispersion. Therefore, under the slowly-varying envelope (SVE) and rotating-wave approximations, propagation of the laser fields in the atomic medium is governed by the coupled Maxwell–Bloch equations:

$$\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)\Omega_p(z,t) = -2i\mu_p\rho_{12}(z,t), \tag{8}$$

$$\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)\Omega_c(z,t) = -2i\mu_c\rho_{23}(z,t). \tag{9}$$

here, $\mu_m = \frac{\omega_m N\left|d_{n2}\right|^2}{2\epsilon_0 c\hbar}$ being the propagation constant (with $n = 1$, 3 and μ_m represent μ_p or μ_c). It is convenient to transform Eqs. (1)–(6), (8) and (9) into a local frame by changing $\xi = z$ and $\tau = t - z/c$, with c is the speed of light in vacuum. In this frame, Eqs. (1)–(6) will be the same with the substitution $t \to \tau$ and $z \to \xi$, while Eqs. (8) and (9) are rewritten as [45]:

$$\frac{\partial}{\partial\xi}\Omega_p(\xi,\tau) = -2i\mu_p\rho_{12}(\xi,\tau), \tag{10}$$

$$\frac{\partial}{\partial\xi}\Omega_c(\xi,\tau) = -2i\mu_c\rho_{23}(\xi,\tau). \tag{11}$$

The coupled Eqs. (10) and (11) are used to study dynamics of the probe pulse under various values of controllable parameters. We represent the propagation length in units of $\mu_p\xi$ which is called optical depth [22]. Under the SVE approximation, we assume the envelope of both probe and coupling fields at the entrance of the medium as same as

$$f(\xi = 0, \tau) = \mathrm{e}^{-\pi(\tau/\tau_0)^2}, \tag{12}$$

where, τ_0 is the temporal width of the laser pulse at the entrance.

3. Results and discussions

In order to study the influences of the SGC and relative phase on the probe pulse propagation we solved numerically Eqs. (1)–(6), (10) and (11) by developing a computer code used in Ref. [45]. Firstly, we search an ideal EIT or soliton of probe pulse in the absent of SGC and relative phase by choosing $\eta = 0$, $p = 0$, $\phi = 0$, $\Omega_{p0} = 0.05$ GHz, $\Omega_{c0} = 25$ GHz, and $\tau_0 = 25$ ns, as shown in Fig. 2(a). Influence of the SGC on the probe pulse is then studied by choosing $\eta = 1$, $\phi = 0$ and plotting spatio-temporal evolution of the probe pulse $\Omega_p(\xi,\tau)$ for different values of quantum interference parameter p, as shown in Fig. 2(b–d). Other used parameters in Fig. 2(b–d) were chosen as same as those in Fig. 2(a).

The plots in Fig. 3 show that the leading edge of the probe pulse is modulated significantly during its propagation. The magnitude of the modulations increases as growing p. Also, the modulations mainly focus on the leading edge of the pulse, and their magnitudes increase as prolonging propagation distance. The reason of these modulations arises from the influence of SGC on both absorption and dispersion of the medium that makes the linewidth of absorption line deeper and narrower compared to in the case of SGC absents [33]. The dispersion curve is also steeper as p increases. As explained in Ref. [43], increasing $p \to 1$ leads to parallel rearrangement of electric dipole moments, thus increasing atomic coherence.

In Fig. 3, we plot peak of the probe pulse versus optical depth for different values of parameter p. It shows that the peak of the probe pulse is almost unchanged during its propagation when $p = 0$. However, the peak is amplified when parameter p increases from 0 to 1. This can be explained by noting that the SGC contributes atomic coherence as p increases, as shown in Refs. [33,45].

In order to see the influence of the relative phase on the probe pulse we plotted $\Omega_p(\xi,\tau)$ versus ϕ at $\mu_p\xi = 5$ ns^{-1} and $p = 0.7$, as Fig. 4. It is shown that the pulse envelope oscillates accordingly with the relative phase in a period of 2π. Indeed, the strongest oscillating amplitudes occur at $\phi = 0$ and $\phi = 2\pi$ whereas they are undistorted at $\phi = \pi/2$ and $3\pi/2$. To explain these results, we plotted both absorption and dispersion versus the relative phase in the presence of SGC and incoherent pumping, as shown in Fig. 5. It shows that the absorption and dispersion also vary periodically with a period of 2π. Indeed, the