Dynamical propagation and all-optical switching in a ladder-type three-level system under the influence of spontaneously generated coherence

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ABSTRACT

We investigate the dynamical of pulse propagation and all-optical switching via a spontaneously generated coherence (SGC) in a three-level ladder-type atomic medium driven by a coupling field under the presence of incoherent pumping. Results show that the SGC causes modulations at the leading edge of the pulse envelope shape. These modulations increase with the together growth of SGC and distance. Furthermore, it is shown that the continuous-wave input probe field is switched ON or OFF by periodically modulating the coupling field. The spontaneously generated coherence has a strong effect on switching efficiency and switching pulse shape. The proposed scheme may have applications in the design of optical switching and optical gain devices in optical telecommunications.

Keywords: Electromagnetically induced transparency; Spontaneously generated coherence; Three-level ladder-type; Incoherent pumping; Pulse propagation; All-optical switching.

1. INTRODUCTION

In the past decades, the propagation of laser pulses in resonant atomic media is an attractive research topic in nonlinear and quantum optics due to its interesting effects and potential applications in quantum engineering and optical communication. The resonant and opaque medium becomes transparent for the probe beam in the presence of the control laser beam due to the effect of electromagnetically induced transparency (EIT) [1-4]. A wide variety of novel phenomena and promising applications have been predicted and explored both theoretically and experimentally in various quantum systems. Not only does the EIT effect produce slow light whereby nonlinear optical processes are remarkably efficient even at the single-photon level [5-7], but also it is possible to modify the propagation dynamics of the medium by changing the absorption and dispersion properties [8-10]. As a result, various nonlinear optical phenomena are obtained, such as Kerr's nonlinearity enhancement [11-14], the formation and optical solitons propagation [15-18], and so on.

On the other hand, optical switching at low-light intensities based on quantum coherent control and quantum interferences has attracted extensive attention because of its’ promising advantages, such as responsible high speed and low switching power compared with electro-optical switching and the switching of silicon waveguides or fiber-based systems. Several approaches for optical switching in EIT media were proposed theoretically and demonstrated experimentally in various quantum systems. Indeed, all-optical switching systems were studied from the basic three-level configurations, namely lambda (Λ), vee (V), and ladder (Ξ) [19-23], to more than three-levels such as four-level N-type atomic system (Λ+V) [24-28], four-level vee-ladder-type (Λ+ Ξ) [29], four-level or five-level inverted Y-type system [30, 31], four-level Y-type system (Ξ+Ξ) [32].

More recently, pulse propagation with optical switching in quantum schemes under the spontaneously generated coherence (SGC) effect also has been studied [33-46]. However, these studies usually focus on a steady-state regime [33-43], while the dynamical response is fundamental for the optical switching [44-46]. Moreover, these studies still lack consideration of the influences of SGC for the generation of optical switching. In the direction of this interest, we propose to use the ladder-type three-level atomic model to investigate the influence of the spontaneously generated coherence on optical switching. By simultaneously numerical solving the coupled Maxwell-Bloch equations for atom and field on a spatio-temporal grid, we show that the continuous-wave input probe field can be switched on or off with a variation of controlling parameters, i.e., the switching status is switched by the coupling field.

2. MODEL AND BASIC EQUATIONS

We consider a three-level ladder-type atomic system with nearly equispaced levels interacting with two laser pulses, as in figure 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 coupled by a strong field with frequency ω_c. Since the dipole moments are not orthogonal, we have considered an arrangement is shown by figure 1(b) where each field (coupling and probe) acts only on one transition. We denote Γ_{21} and Γ_{32} the decay rate of the states $|2\rangle$ and $|3\rangle$, respectively. An incoherent pump with a pumping rate 2R is applied between levels $|1\rangle$ and $|3\rangle$. The Rabi frequency of the probe and coupling fields are defined respectively as $\Omega_1 = 2\vec{\mu}_{12} \cdot \vec{E}_p / \hbar$ and $\Omega_2 = 2\vec{\mu}_{23} \cdot \vec{E}_c / \hbar$, where μ_{12}, μ_{23} are being the electric dipole matrix elements. By defining ϕ_p and ϕ_c as the phase of the probe and coupling fields, respectively, we can set $\Omega_1 = \Omega_p \exp\left(i\phi_p\right)$ and $\Omega_2 = \Omega_c \exp\left(i\phi_c\right)$ with Ω_p and Ω_c being real parameters.

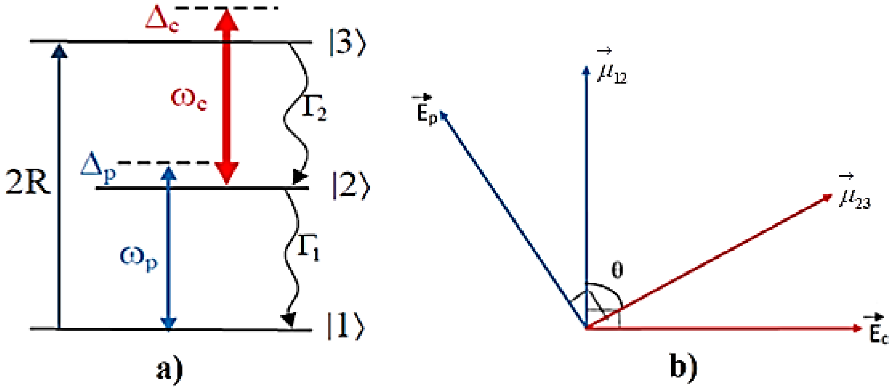

Figure 1. *(a) Scheme of the three-level ladder-type atomic system with nearly equispaced levels; (b) The polarization is chosen such that one field only drives one transition.*

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

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

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

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

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

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

$$\dot{\rho}_{13} = -\left(R + i\Delta + \gamma_{32}\right)\rho_{13} + \frac{i}{2}\Omega_p\rho_{23} - \frac{i}{2}\Omega_c\rho_{12} \tag{6}$$

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. The decay rates from the states |2⟩ and |3⟩ to |1⟩ are given by γ_{21} and γ_{32}; $\Delta_p = \omega_p - \omega_{21}$ and $\Delta_c = \omega_c - \omega_{32}$ are the frequency detuning of the probe and coupling fields from their relevant atomic transitions, respectively; $2p\sqrt{\Gamma_{21}\Gamma_{32}}\eta\rho_{23}$ represents SGC resulting from the cross-coupling between the spontaneous emissions |1⟩↔|2⟩ and |2⟩↔|3⟩, $p = \vec{\mu}_{12}.\vec{\mu}_{23} / \left|\vec{\mu}_{12}\right|\left|\vec{\mu}_{23}\right| = \cos\theta$ with θ is the angle between the two dipole moments; $\eta_\phi = \eta\exp\left(i\phi\right)$ 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 not only the amplitude and detuning of the probe and coupling fields but also their phase. Therefore, we regard the Rabi frequencies as complex parameters.

Under the slowly-varying envelope and the rotating-wave approximation, we obtain the following wave equations for the probe field as:

$$\frac{\partial\Omega_p(z,t)}{\partial z} + \frac{1}{c}\frac{\partial\Omega_p(z,t)}{\partial t} = i\alpha\gamma_{21}\rho_{21}(z,t) \tag{7}$$

here, $\alpha = \frac{\omega_p N\left|d_{31}\right|^2}{4\varepsilon_0 c\hbar\gamma_{31}}$, is the propagation constant. It is convenient to transform equations (1-6) and (7) in the local frame by changing $\xi = z$ and $\tau = t - z/c$, with c is the speed of light in vacuum. In this frame, equations (1-6) will be the same with the substitution $t \to \tau$ and $z \to \xi$, while equation (7) is rewritten as [17]:

$$\frac{\partial\Omega_p(\xi,\tau)}{\partial\xi} = i\alpha\gamma_{21}\rho_{21}(\xi,\tau) \tag{8}$$

The coupled equations (1-6) and (8) are used to investigate propagation dynamics and optical switching of the probe pulse under various values of controllable parameters.

3. RESULTS AND DISCUSSION

In this following, we numerically solve the coupled Bloch-Maxwell equations (1-6) and (8) on a space-time grid by four-order Runge-Kutta and finite difference methods, which developed a computer code for this problem is expanded from the of our previous work [32, 50]. We assumed the initial condition is all atoms start in the ground state |1⟩, namely $\rho_{11}(\xi, \tau = 0) = 1$, and the boundary condition that the probe field is assumed as a Gaussian-type pulsed $f(\xi = 0, \tau) = \exp[-(\ln 2)(\tau - 30)^2 / \tau_0^2]$, with $\tau_0 = 6/\gamma_{21}$ is the temporal width of the Gaussian pulse at the beginning of the vapor cell $\xi = 0$.

In figure 2, we plot the spatio-temporal evolution of the magnitude squared of the normalized probe pulse envelope $\left|f(\xi,\tau)\right|^2$ when the coupling field is on (a) and off (b). The figures show that the probe pulse can propagate with complete transparency and still can preserve its shapes over long distances in the presence of the coupling field, as shown in figure 2(a). However, when the coupling field is off, the probe pulse can be completely absorbed by the medium in a very short propagation distance, as shown in figure 2(b).

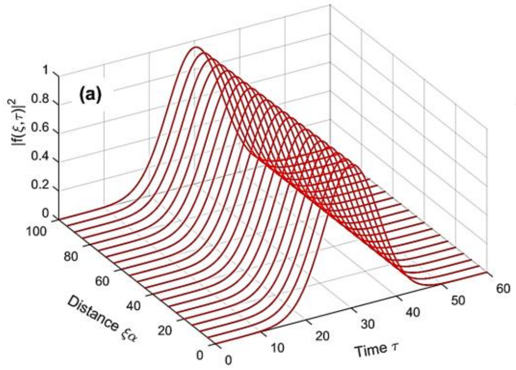

Figure 2. *The space-time evolution of normalized probe field intensity when the coupling field is ON (a) and OFF (b).*

Initial Gaussian-type probe pulsed is assumed as $f(\xi = 0, \tau) = \exp[-(\ln 2)(\tau - 30)^2 / \tau_0^2]$, with pulse width $\tau_0 = 6/\gamma_{21}$ at the entrance to the medium $\xi = 0$. Other parameters are $\Omega_{p0} = 0.1\gamma_{21}$, $\Omega_c = 10\gamma_{21}$, p = 0, R = $0.2\gamma_{21}$, $\Delta_p = \Delta_c = 0$, $\phi = 0$, and $\gamma_{32} = 0.5\gamma_{21}$, respectively. Here and in other figures, the time τ is measured in units of γ_{21}, and the propagation distance ξ of the laser field in the medium is measured in units of α^{-1}.

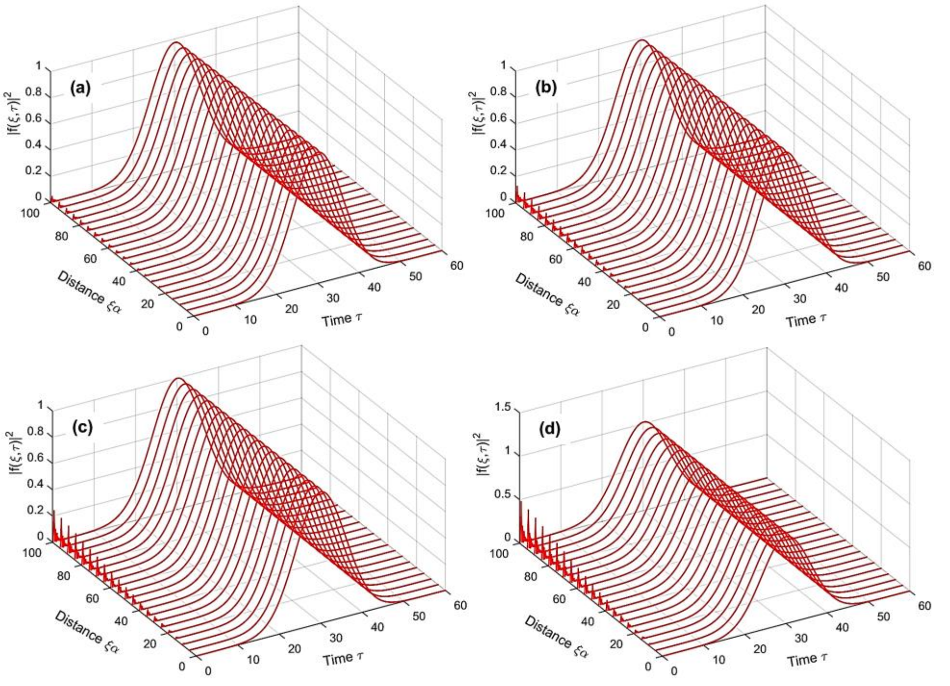

Figure 3. *The space-time evolution of normalized probe field intensity $|f(\xi,\tau)|^2$ at different values of the parameters SGC: p = 0.10 (a), p = 0.50 (b), p = 0.70 (c), and p = 0.99 (d). Other parameters are the same as those in Fig. 2(a).*

In order to investigate the influence of SGC on the probe pulse, we plot the spatio-temporal evolution of the probe field at different values of the parameters SGC. We then chose $\eta = 1$, $\phi = 0$ and plotted the spatio-temporal evolution of the probe pulse, $|f(\xi,\tau)|^2$ for different values of quantum interference parameter *p*, as shown in figures 3(a-d). The plots show that, when the SGC presents, the leading edge of the probe pulse envelope is significantly modulated during the propagation. The magnitude of modulations of the pulse envelope increases as the parameter *p* increases. It is also noted that the modulations of the envelope are mainly concentrated on the leading edge, and these modulations increase as the propagation distance increases. The primary reason for the modulations under the SGC arises from the influence of SGC on both absorption and dispersion. This influence makes the linewidth of an absorption line deeper and narrower compared to that in the absence of the SGC. As explained in Ref. [43], increasing $p \rightarrow 1$ leads to parallel rearrangement of electric dipole moments, thus increasing atomic coherence.

Next, the dynamics of the possible switching process of the probe field propagating through the ladder-type medium at different values of the parameters SGC is displayed in figure 4. The time evolution of a weak probe field (solid line) is assumed to be a continuous wave, and the switching coupling field (dashed lines) a nearly-square pulse with smooth rising and falling edges. In figure 4, the switching signal field: $\Omega_c(\tau) = \Omega_{c0}\{1 - 0.5\tanh[0.4(\tau - 10)] + 0.5\tanh[0.4(\tau - 35)] - 0.5\tanh[0.4(\tau - 60)] + 0.5\tanh[0.4(\tau - 85)]\}$, which is normalized by its peak value $\Omega_{c0} = 10\gamma_{21}$, is turned on or off at an approximate period of $50/\gamma_{21}$. As is shown in the figure, the probe transmission is either in the 'on' or 'off' situation, which looks like a stepwise profile. It is shown that the SGC parameter has a strong influence on the switching process of the probe field. Specifically, when the parameter SGC is small, p = 0.1 [figure 4(c)], the switching efficiency is significantly reduced compared to the case of no SGC (p = 0) [figure 4(a)]. When the SGC parameter is larger, the switching probe field is disturbed its shape out of the nearly square, as shown in figures 4(e-h). Switching of probe field is not achieved because the coherence reduces between upper levels $|1\rangle$ and $|3\rangle$. Thus, to observe switching is complete, we need have the optimization of the input parameter of the system. Consequently, this ladder-type atomic system could be used for the realization of optical absorptive switching of the weak probe field by a coupling field.

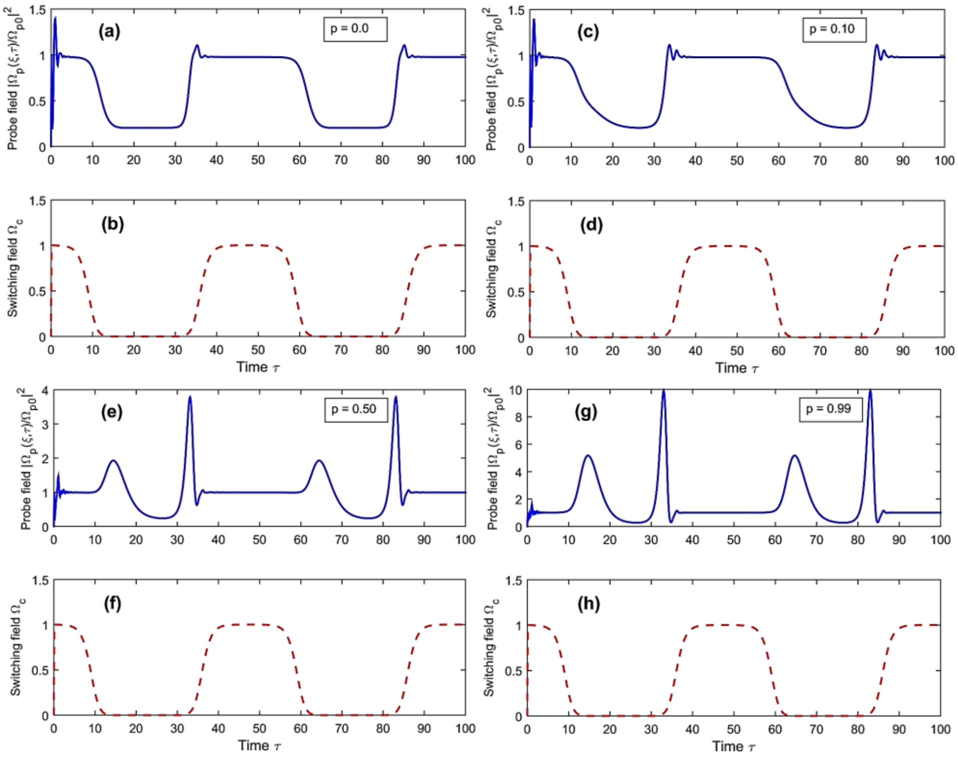

Figure 4. *Time evolution of a cw probe field (solid line) at* $\xi\alpha = 50$ *for different values of the parameter SGC: (a-b) p = 0.1, (c-d) p = 0.5, (e-f) p = 0.7, (g-h) p = 0.99.*

The coupling field (dashed lines): $\Omega_c(\tau) = \Omega_{c0}\{1 - 0.5\tanh[0.4(\tau\text{-}10)] + 0.5\tanh[0.4(\tau\text{-}35)] - 0.5\tanh[0.4(\tau\text{-}60)] + 0.5\tanh[0.4(\tau\text{-}85)]\}$, is normalized by its peak value $\Omega_{c0} = 10\gamma_{21}$, is turned on or off at an approximate period of $50/\gamma_{21}$. Other parameters are $f(\xi=0, \tau) = 1$, $\Omega_{p0} = 0.1\gamma_{21}$, $\Omega_c = 10\gamma_{21}$, $R = 0.2\gamma_{21}$, $\Delta_p = \Delta_c = 0$, $\phi = 0$, and $\gamma_{32} = 0.5\gamma_{21}$, respectively.

4. CONCLUSION

In summary, we have investigated the dynamical behavior of pulse propagation and all-optical switching of the probe field under the influence of spontaneously generated coherence. Shape breaking and creating oscillations on the front edge of the probe pulse are caused by the SGC effect. The behavior of the switching is studied under the modulation of the coupling field. It is shown that transmission of the continuous probe field can be switched to a nearly square pulse train with the same modulation period of the coupling field. The switching pulse shape is disturbed out of the nearly-square shape with the increase of spontaneously generated coherence strength. The proposed scheme can find potential applications in all-optical communication and computation.

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TÓM TẮT

Động học lan truyền xung và chuyển mạch toàn quang trong môi trường nguyên tử ba mức bậc thang dưới ảnh hưởng của độ kết hợp được tạo bởi sự phát xạ tự phát

Chúng tôi nghiên cứu hành vi động học của quá trình lan truyền xung và chuyển mạch toàn quang thông qua độ kết hợp được tạo bởi sự phát xạ tự phát (SGC) trong hệ nguyên tử ba mức cấu hình bậc thang được điều khiển bởi trường laser liên kết dưới sự hiện diện của bơm không kết hợp. Các kết quả cho thấy, SGC gây ra sự biến điệu ở sườn trước của hàm bao xung. Những biến điệu này tăng đồng thời với sự tăng của SGC và khoảng cách lan truyền. Hơn nữa, kết quả cũng chỉ ra rằng trường dò là sóng liên tục được chuyển tới chế độ BẬT hoặc TẮT bằng cách điều biến trường liên kết theo chu kỳ. Độ kết hợp được tạo bởi sự phát xạ tự phát có ảnh hưởng mạnh đến hiệu suất và hình dạng xung chuyển mạch. Mô hình đề xuất có thể có các ứng dụng trong thiết kế chuyển mạch quang và thiết bị khuếch đại quang trong truyền thông tin quang.

Từ khoá: Trong suốt cảm ứng điện từ; Độ kết hợp được tạo bởi sự phát xạ tự phát; Ba mức bậc thang; Bơm không kết hợp; Lan truyền xung; Chuyển mạch toàn quang.